Field Trip 4

2004 AAPG Annual Convention, Dallas, TX

Saturday, April 17, 2004

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Sponsored by the Dallas Geological Society

Pennsylvanian Adventures in Palo Pinto County

AAPG Field Trip, Saturday, April 17th, 2004

Field Trip Leaders

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Safety Considerations:

The outcrops that we will visit include roadside exposures and railway cuts. Take special care watching for traffic, especially if you cross the road or track. There are numerous cacti, so take care where you walk. Long pants are recommended. Also, there are rattlesnakes. If you climb an outcrop, avoid putting your hand above you. Usually the snakes will give plenty of warning, but be on the lookout. Weather can be very variable, so bring a raincoat and hat. Temperature can be anywhere from freezing to in the 80's. If it is warm, bring fluids on the longer hikes. The field trip will be moderately strenuous. We will have one hike up a hill and a 2-mile hike at the end of the day (1 mile each way). Wear appropriate footwear, preferably hiking boots. Sneakers have a tendency to be easily punctured by cacti.

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Introduction

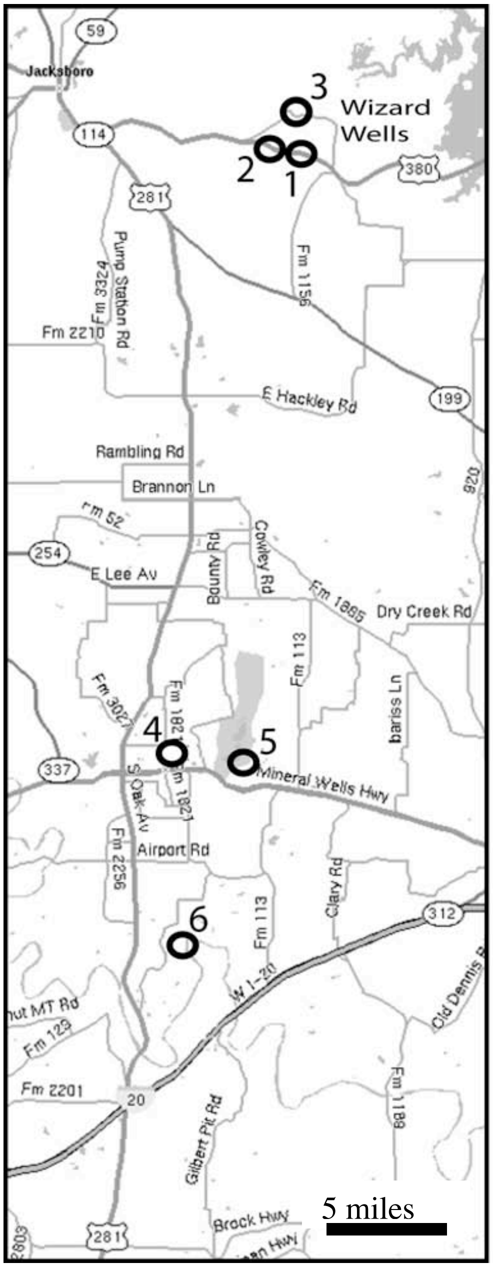
This one-day field trip examines outcrops of the Pennsylvanian succession in the Fort Worth basin in and around the town of Mineral Wells (Fig. 1). We will examine exposures, primarily of the siliciclastic depositional systems, ranging from gravelly fluvial deposits to distal marine mudstones with good examples of the fluvial and wave-influenced shoreline depositional systems that lie between the marine and non-marine domains. The sedimentology of these deposits is well documented in various field guides and other reports (e.g. Brown et al., 1973; Cromwell, 1982) and there are numerous papers on the subsurface stratigraphy (e.g. Brown et al., 1987).

Although the primary author is a relative newcomer to the Pennsylvanian stratigraphy of Texas, this field trip will attempt to add to previous interpretations by discussing the possible sequence stratigraphic implications of several key facies relationships, as well as describing the ichnological aspects of these rocks, which to date have been little studied. The final stop of the trip will focus on integrating structural and sedimentological characteristics of a well exposed, "growth" faulted succession. We will also use the rocks as a point of discussion about the different types of delta systems that can be recognized and the implications for reservoir continuity.

Regional Setting

The Pennsylvanian succession in Texas formed during a time of major changes in earth history. Pangean assembly resulted in a complex series of mountain chains, formed by continent-continent collision (Fig. 2), the scale of which is probably unparalleled in earth history but similar in scale to the present day Himalayas. Complex tectonics resulted in a series of foreland basins, with highly compartmentalized sediment transport pathways (Fig. 3). Areas free of clastic sediment experienced deposition of shallow-water shelf carbonates, but these commonly pass laterally over small distances of as little as a few hundred meters into shallow-water clastic depositional systems. The Pennsylvanian system was primarily bounded to the east by the Ouachita Mountain belt, but various uplifts to the north (e.g. Wichita uplift) and west (e.g. Ancestral Rockies) allowed sediment to be supplied from many directions (Fig. 3). Structurally, the Pennsylvanian dips broadly westward and the outcrops that we will visit young to the northwest (Fig. 4).

In Texas, the sea lay broadly to the west and southwest, where it eventually connected to the paleo-Tethyan ocean (Figs. 2 and 3). From the climatic perspective, this was an icehouse time in Earth History, characterized by high frequency, high amplitude glacio-eustatic sea level changes. The Pennsylvanian is thus exceedingly complex, with high frequency tectonic and eustatic controls on deposition. More recent stratigraphic interpretations emphasize the cyclic nature of the Pennsylvanian in the context of high frequency sea-level change (e.g. Brown, 1987).



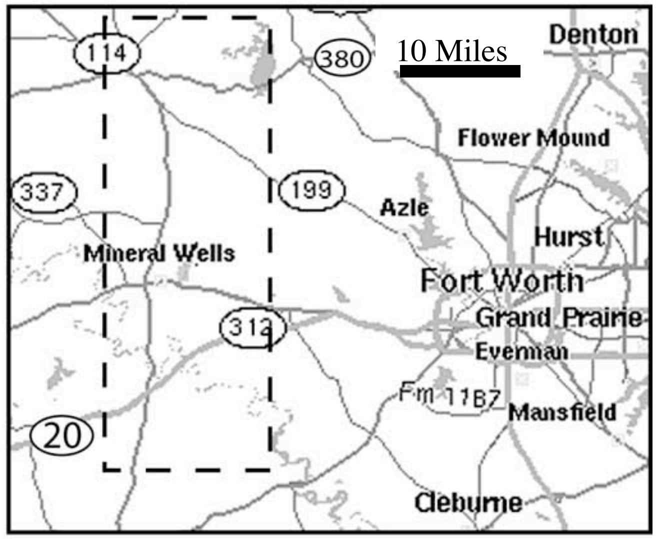


Figure 1. Location map of major roads and stops. Detailed geological maps are shown in figures 9 and 10.

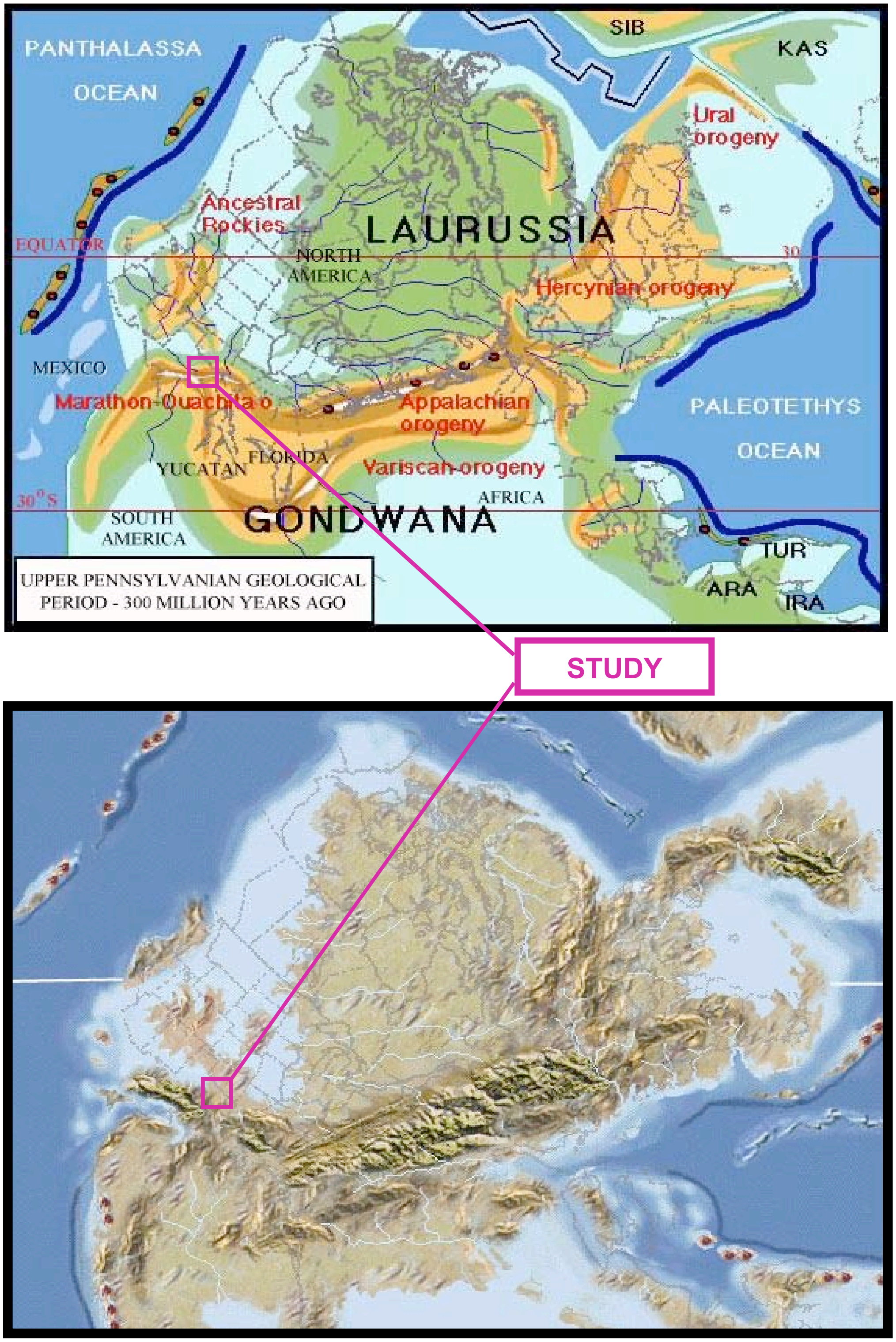
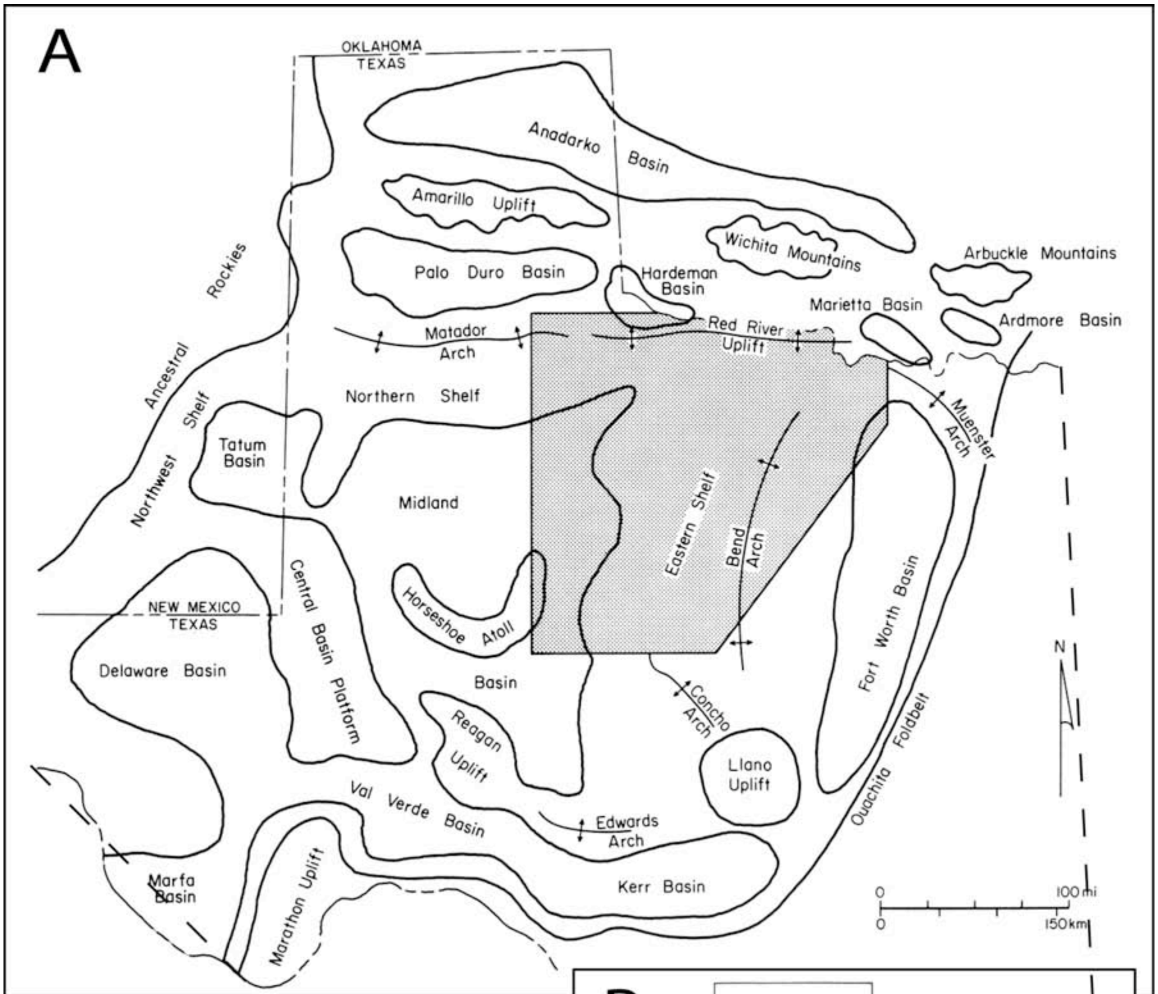


Figure 2. Pangean Paleogeography. Texas area was largely surrounded by mountains during the late Pennsylvanian (from Blakey, 2001).



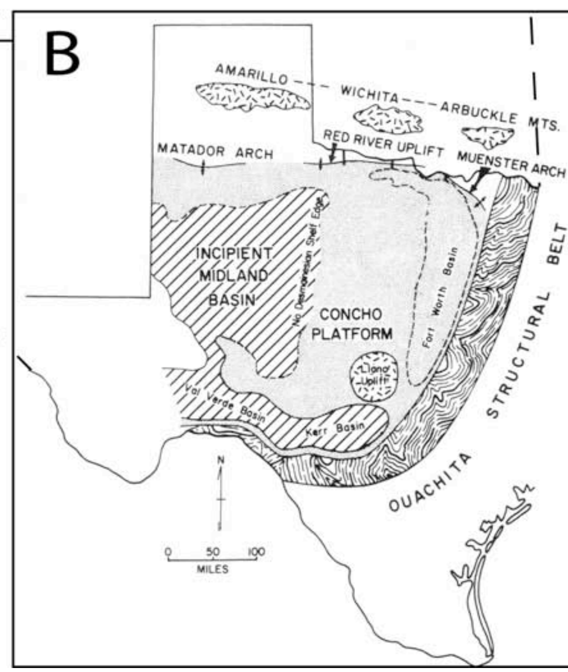


Figure 3. A. Detail of structural elements in north and west Texas. Note that Fort Worth Basin and eastern Shelf were fed by rivers draining from both north and west. The Midland and Delaware basins were connected to the south west to the open ocean (from Brown et al., 1987). B. General structural elements of Texas (from Erxleben and Cleaves, 1982; modified after Wermund and Jenkins, 1969).

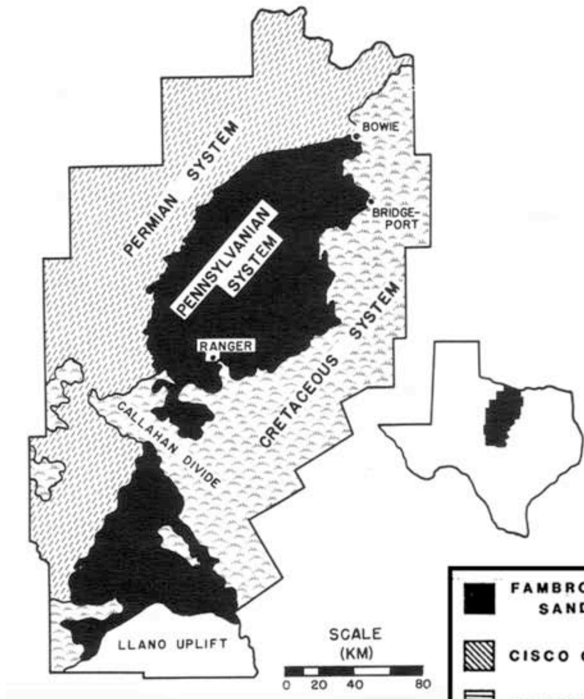
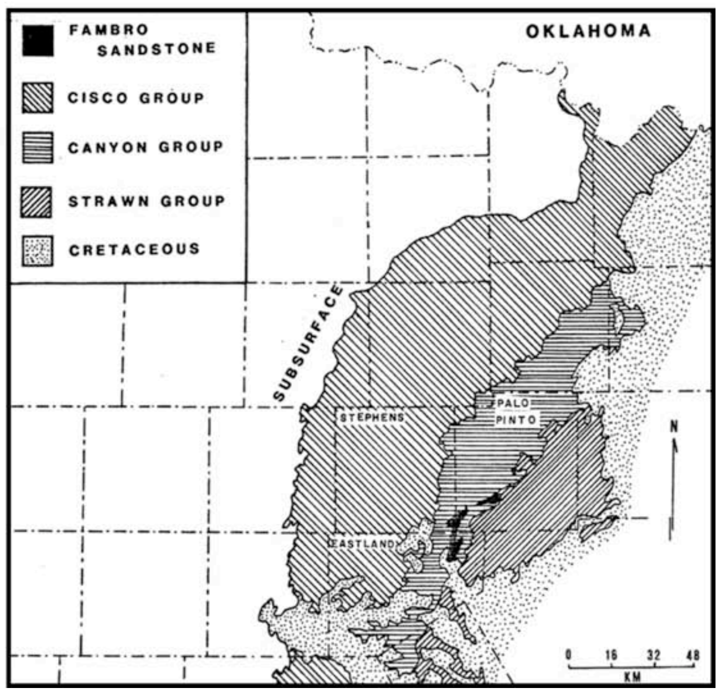


Figure 4. Outcrop geology of Northwest Texas from Macleod (1982) and Spaid (1982). Pennsylvanian strata dip broadly northwest where the form important resevoirs for oil and gas.



Stratigraphy

The Pennsylvanian strata in the Fort Worth basin have a complex stratigraphic nomenclature, reflecting the rapid facies changes and cyclic nature of this time in earth history (Fig. 5). The Pennsylvanian section is subdivided into three major Groups, the Strawn, Canyon and Cisco (Fig. 6). This field trip will examine outcrops of the Strawn and Canyon Groups.

The Canyon Group in North-Central Texas consists of four thick limestones with interstratified shales and sandstones (Fig.5). The Perrin delta system (Brown et al., 1973) is composed of terrigenous clastic facies within the Wolf Mountain, Placid, and Colony Creek Formations (Fig. 7). The paleogeographic reconstructions are based on detailed outcrop mapping and subsurface stratigraphic work (Brown et al., 1973). An example of a typical lithofacies maps (Fig. 8) indicate highly elongate sandstone bodies that are interpreted as fluvial-dominated, "birdfoot" deltas (Brown et al., 1973).

The first part of the field trip will visit sandstones within the Placid Shale formation exposed along I380 near Jacksboro and Wizard Wells (Fig. 9). This area was interpreted as the site of relatively permanent distributary channels during deposition of the upper part of the Placid Shale. These distributaries are elements of a principal lobe of the Perrin delta system that prograded northwestward over a tectonically stable shelf (Brown et. al., 1973; Figs. 6, 7, and 8).

The Perrin delta system was interpreted to be fed by low gradient fluvial systems, which crossed a broad coastal plain east of the Ouachita Mountains. The Perrin is interpreted to have prograded northwestward and westward across northern Jack, northwestern Wise, and southern Clay and Montague counties. In addition to the elongate sandstone bodies, lobate bodies have also been mapped (Brown et al., 1973) (Figs.7 and 8).

In outcrop, upward-coarsening facies successions, typical of prograding deltas, are capped by sharp-based channelized sandstones interpreted as distributary channel deposits (Brown et al., 1973). At the Jacksboro Roadcut (Stop 1) an excellent example of a wave-dominated shoreface of the Perrin delta is exposed. Immediately west, the Placid Shale changes into the Ranger Limestone Formation, which is typical of the carbonate lagoonal shelf deposits (Stop 2). From there we will head to Wizard Wells (Stop 3) where we will examine spectacular delta front sandstones and mouth bars of the Placid Shale formation that show over-thickening, possibly related to growth faulting. Only the top parts of the growth strata are exposed here, but at the end of the day we will visit similar features in which the bottom strata are exposed at Stop 6.

At Mineral Wells (Stops 4 and 5) we will examine coarse-grained fluvial to estuarine valley-fill deposits of the Mineral Wells and Brazos River Formations in the underlying Strawn Group (Fig. 6 and 10). We will have lunch at Mineral Wells State Park, where there are some excellent examples of gravelly fluvial deposits.

Finally, at Stop 6 we will example the lower portion of a mud-prone pro-delta to delta front succession that shows well-exposed synsedimentary faults. These are the oldest rocks that we will visit and belong to the Dobbs Valley member of the Mingus Formation within the Strawn Group (Fig. 6). They have been previously interpreted as classic growth faults, but our detailed work suggests less growth than has been previously suggested (Brown et al., 1973).

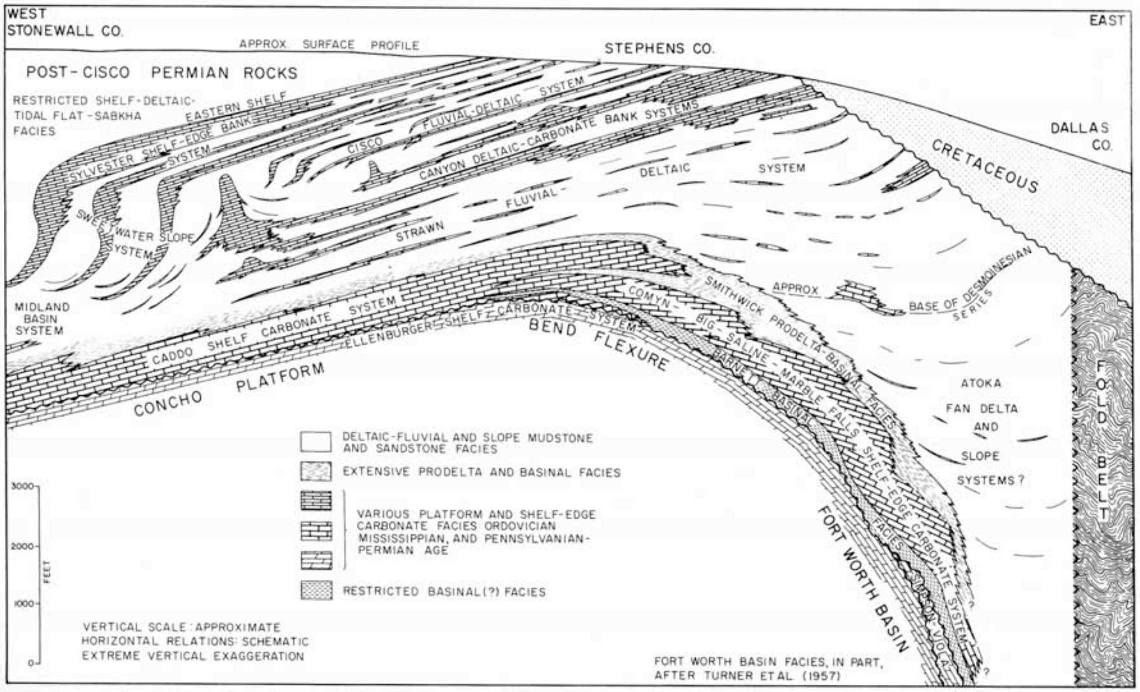


Figure 5. Structural and stratigraphic cross section across northwest Texas. The Caddo System represents a series of backstepping shelf carbonates that faced east. With the onset of Pangean collision, the east facing passive margin was loaded and depressed, evolving into an underfilled, deep-water foreland basin. The carbonates were largely drowned by easterly derived prodelta shales of the Smithwick that were linked into the more proximal sands and conglomerates of the Atoka deltas that fed off the newly accreted lands to the east. This represents the transition of the eastern margin of southern North America from a passive to an active margin. The Pennsylvanian marks a total paleogeographic reversal, with the shelf now facing west. This broad shelf was overlain by a mixture of fluvio-deltaic clastics and shelf carbonates, which grew in uneasy tension. Subtle basin uplifts, probably related to foreland tectonics, created high areas, which the delta systems generally avoided, and on top of which carbonates grew. The structural complexity is compounded by high-fequency glacio-eustatuc fluctuation that result in a remarkably cyclic stratigraphy (from Brown et al., 1973).

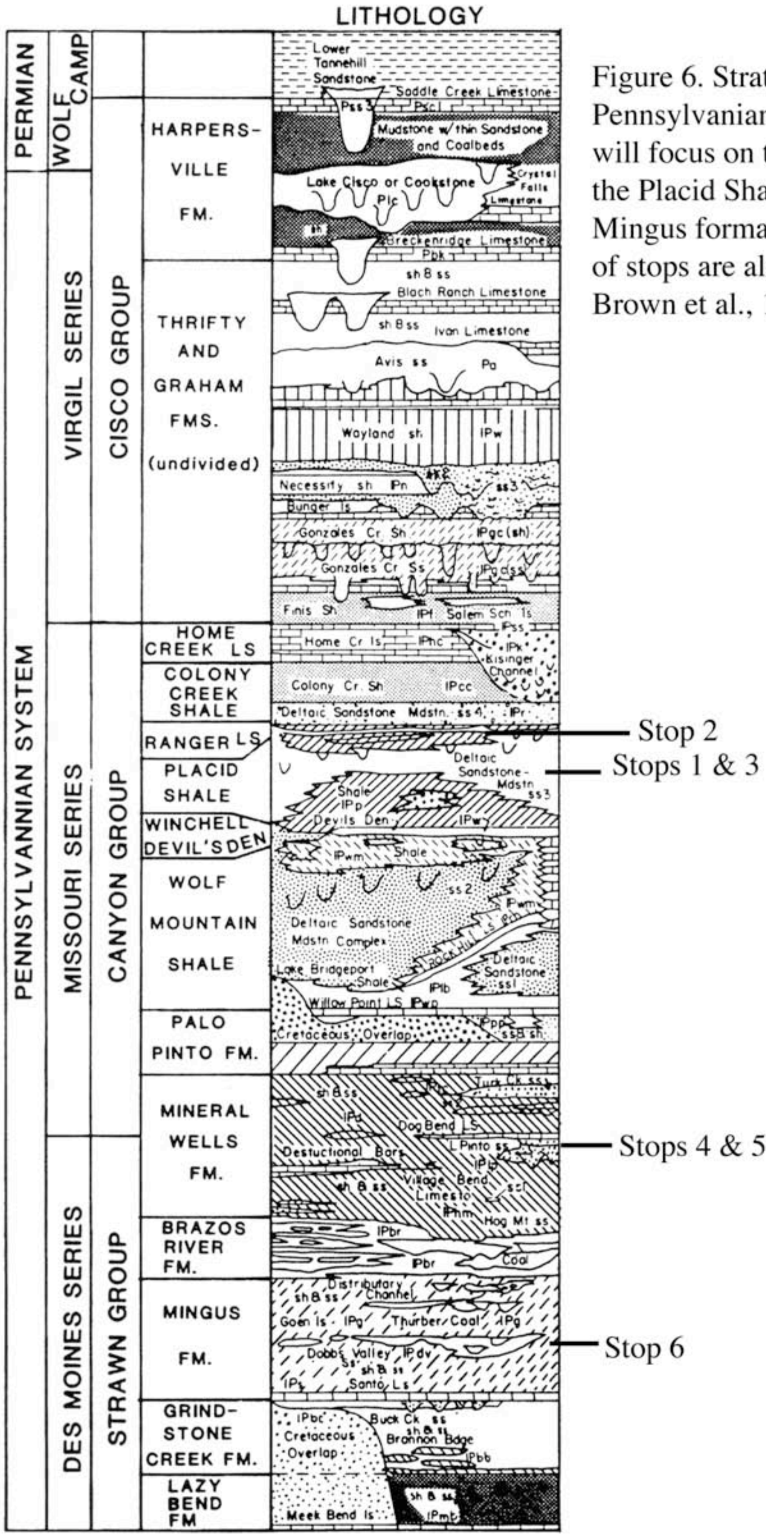


Figure 6. Stratigraphy of the Pennsylvanian System in North Texas. We will focus on the siliciclastic deposits of the Placid Shale, Mineral Wells and Mingus formations. Stratigraphic locations of stops are also indicated. Modified from Brown et al., 1973.

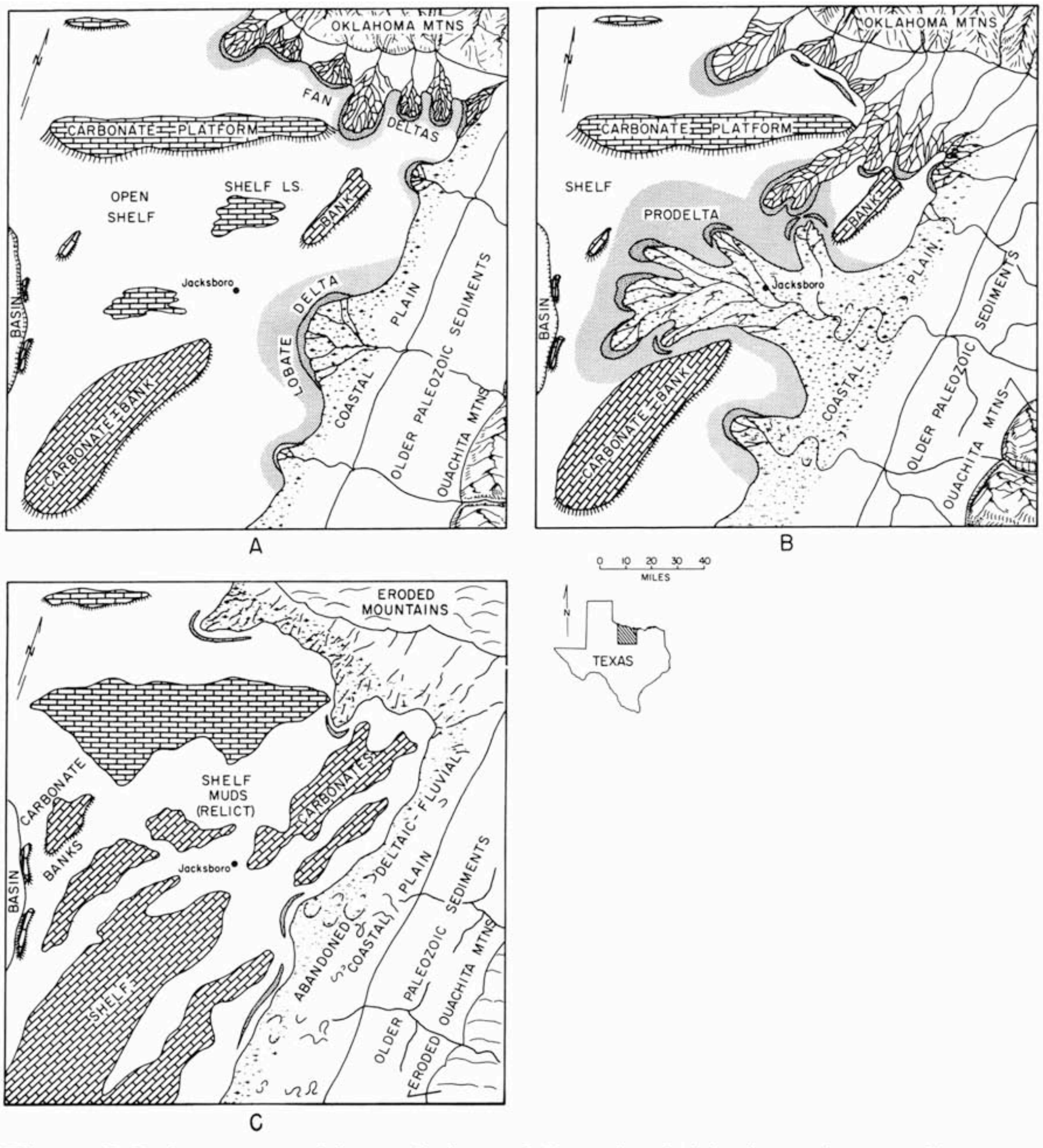


Figure 7. Paleogeographic evolution of the mixed deltaic-carbonate Canyon Group. A. Initial progradation of the Perrin delta onto the carbonate-dominated open Concho shelf to the east. B. maximum progradation of the Perrin delta system. Elongate sandstone isopachs (Fig. 8) are used to infer "birdfoot"-type, fluvial-dominated delta systems. C. General transgression marking a resumption of carbonate dominance on the shelf and the formation of more wave-dominated siliciclastic systems (from Brown et al., 1973).

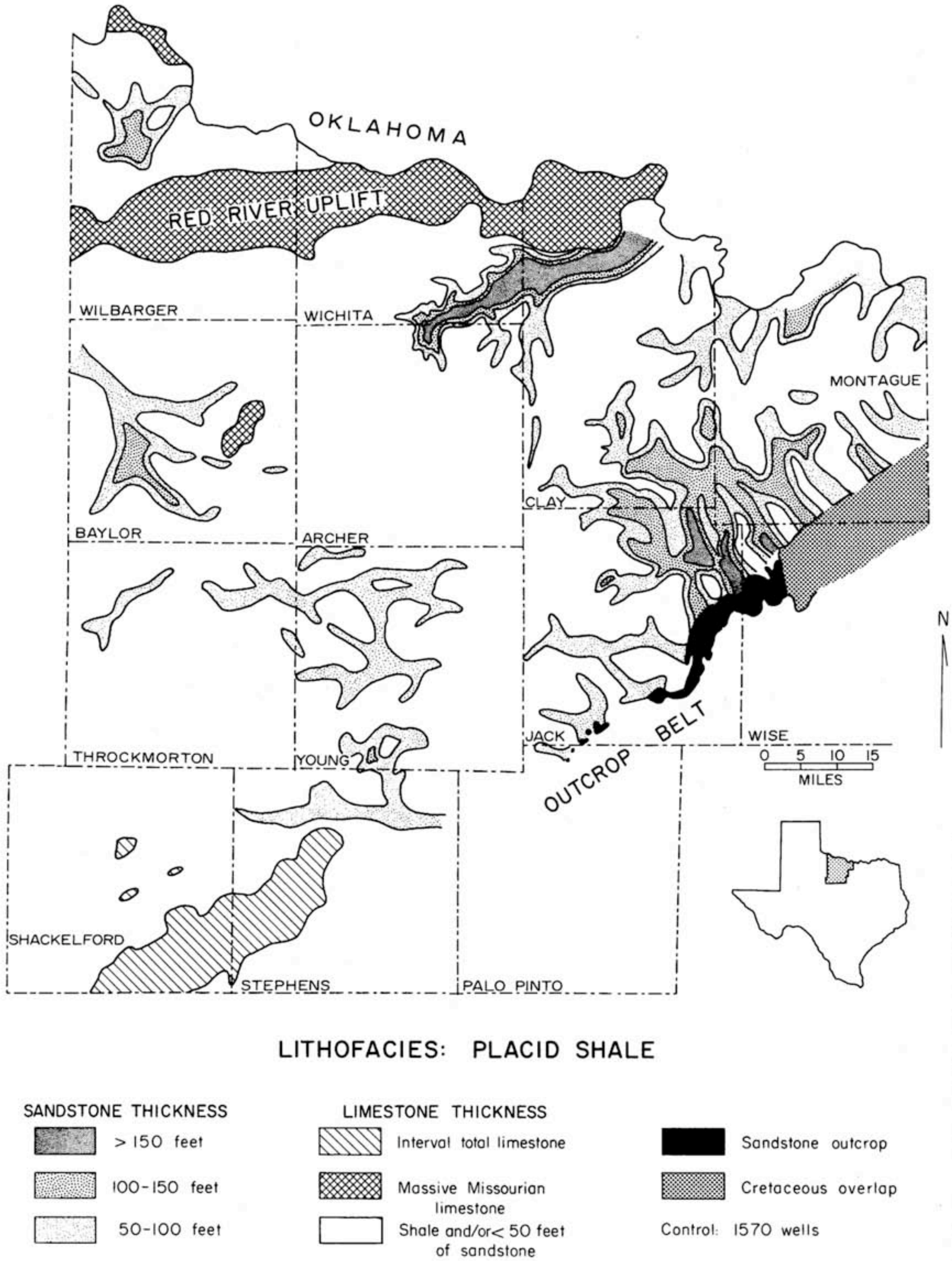


Figure 8. Lithofacies map of the Placid Shale Formation showing highly elongate sand bodies of the Perrin delta system (from Brown et al., 1973).

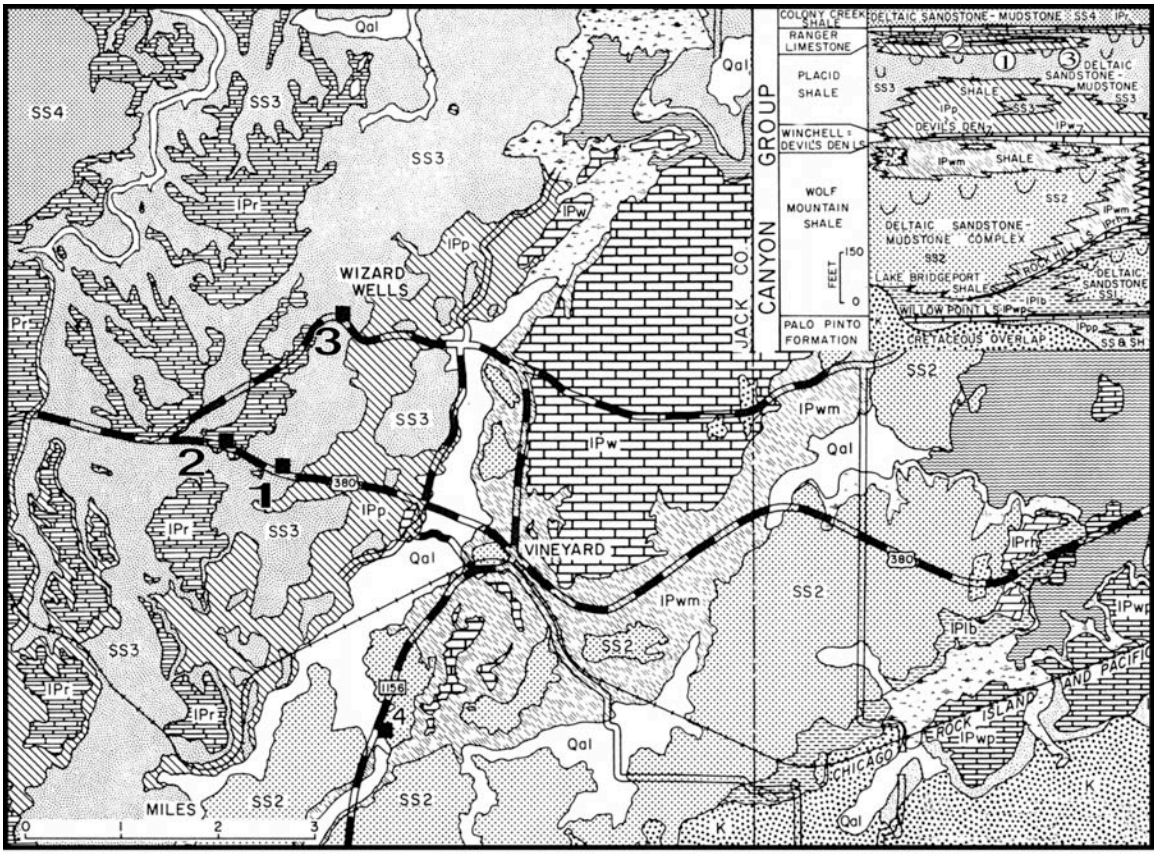


Figure 9. Outcrop geology of the Wizard Wells area showing stops. Stops 1 and 3 are within SS3 (sandstone 3) of the Placid Shale Formation. Stop 2 is within the age-equivalent lagoonal shelf carbonates of the Ranger Limestone Formation (modified after Brown et al., 1973).

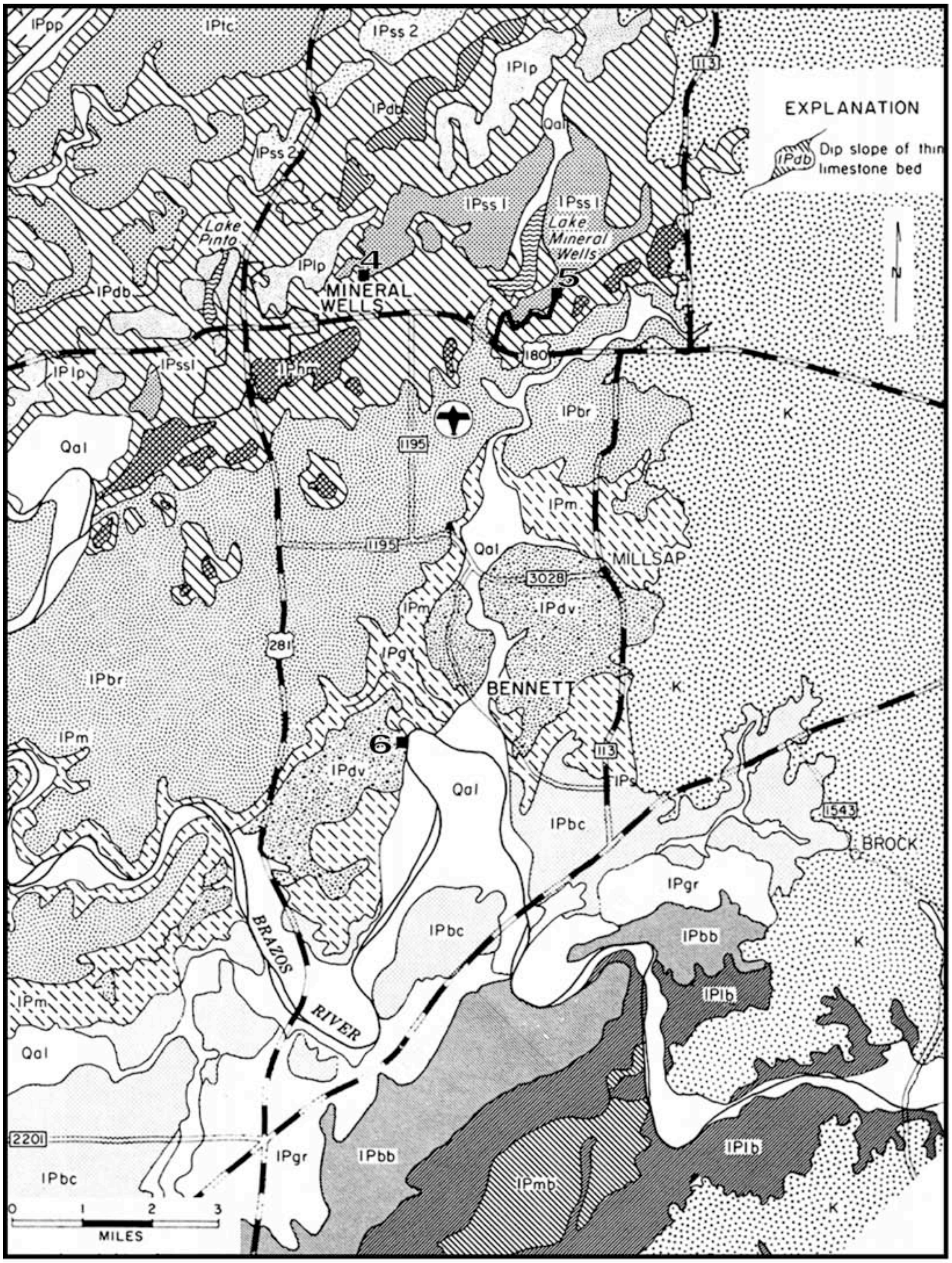


Figure 10. Geologic map of the Mineral Wells area showing stops 4, 5 and 6. Stop 4 is within the Mingus Formation. Stop 5 represents a window into the underlying Brazos River Formation fluvial conglomerates at Mineral Wells State Park. Stop 6 is within the Dobbs Valley sandstone of the Mingus Formation, Strawn Group (modified after Brown et al., 1973).

Stop 1. Jacksboro Roadcut I – Placid Shale Formation, Canyon Group

- Wave-dominated shoreface successions
- Excellent examples of Hummocky Cross stratification
- Moderate level of bioturbation
- SS3 sandstone of the Placid Shale Formation

Questions:

1. Is this a shoreface or delta front?

2. What is difference between wave-dominated and storm-dominated?

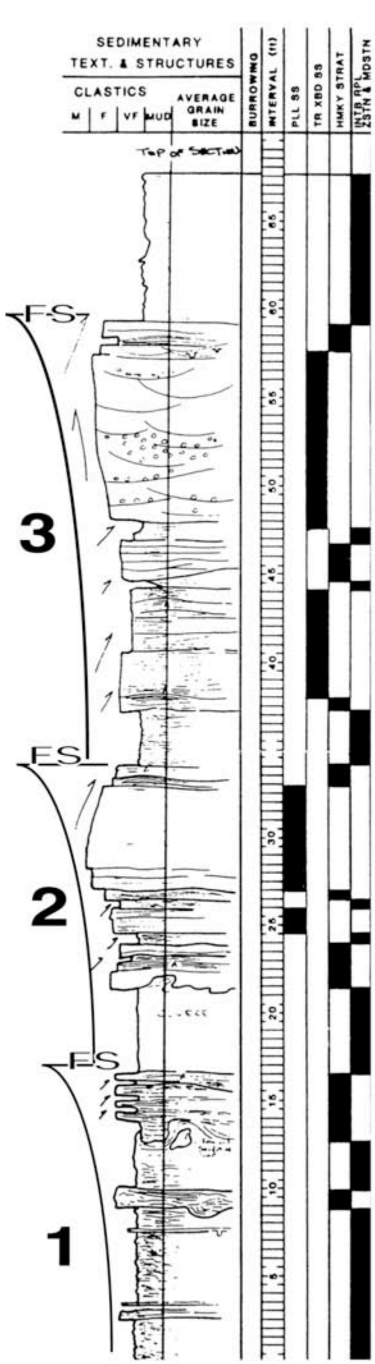
3. What kind of bioturbation and body fossils are diagnostic of depositonal conditions?

4. What is the bedding geometry?

This first stop is of the SS3 member of the Placid Shale Formation along US Hwy. 380 (3 miles east of the intersection with Hwy 1156). The road cut illustrates a classic example of shoreface-to deltaic deposits (Fig. 11). Three upward-coarsening facies successions can be observed, although the top sandstone is partly covered (Fig. 12). Each facies succession consists of a several nested sandstone-mudstone “” bedsets (Fig. 11). Thicker sandstones fine-upwards, suggesting waning flows in an overally progradational environment. The sharp contact between sandstone and mudstone at the top of each succession defines a marine flooding surface. These successions thus define parasequences (*sensu* Van Wagoner et al., 1990). The middle parasequence is relatively mud-free and contains hummocky cross stratification (Fig. 13), suggesting a storm-wave—dominated shoreface, probably reflecting a prograding wave-influenced delta. Distinctive apparently west-dipping clinoform strata can be seen and are interpreted to reflect the dipping shoreface sandstones (Fig. 12). Beds toplap to the east and are truncated by a flooding surface.

The shoreface is defined as the seaward dipping profile that forms in response to the asymmetry of shoaling waves. It an equilibrium surface that can form an erosional ravinement surface during transgression (transgressive surface of erosion) or may accumulate as a prograding shoreface if sediment is supplied to the surface during shoreline progradation. If there is a relative fall of sea level, with no corresponding sediment supplied, it will form a regressive surface of marine erosion.

Ichnology - Only a preliminary assessment of the ichnological suite of this interval was accomplished. The interval probably contains an overall higher diversity and higher abundance assemblage compared to that of the prodelta and distal delta front deposits that we will see in later stops. Trace fossils remain sporadically distributed, reflecting the episodic emplacement of HCS tempestites. Bioturbation intensities vary from BI 0 to BI 3. Identifiable ichnogenera include *Phycosiphon*, *Helminthopsis*, *Planolites*, *Palaeophycus*, *Psammichnites*, *Skolithos*, and fugichnia. This higher abundance and presumed diversity is consistent with wave-dominated delta front and prodelta deposits (Coates and MacEachern, 1999, 2001), and reflects the archetypal *Cruziana* ichnofacies.



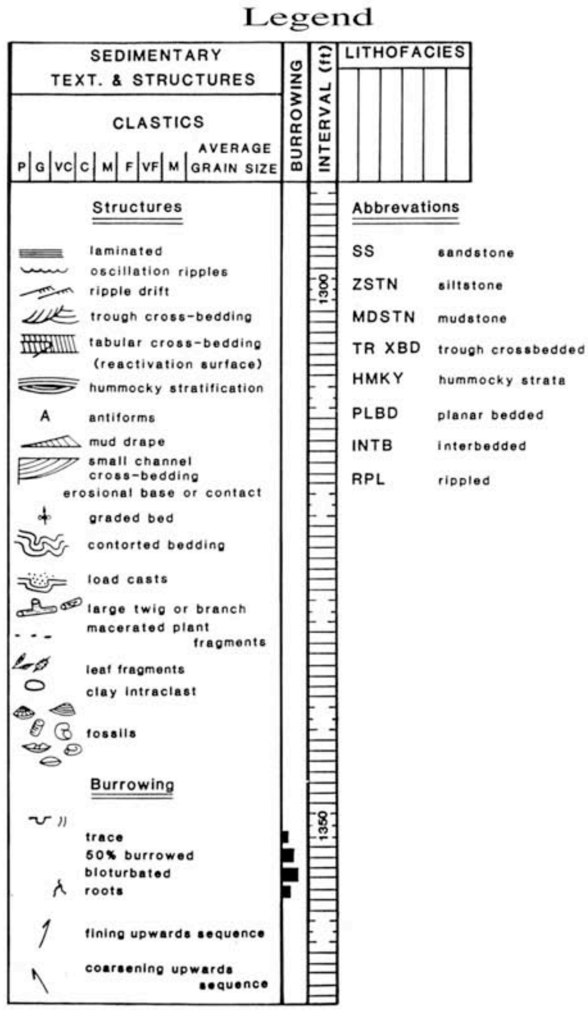


Figure 11. Measured section along Hwy 380 Roadcut, at stop 1. 3 upward coarsening units are bounded by flooding surfaces that define "parasequences". Note bedsets within each parasequence. Hummocky cross stratified sandstones, suggest wave-dominated prograding shorefaces (modified after A.J.Scott, 1985).

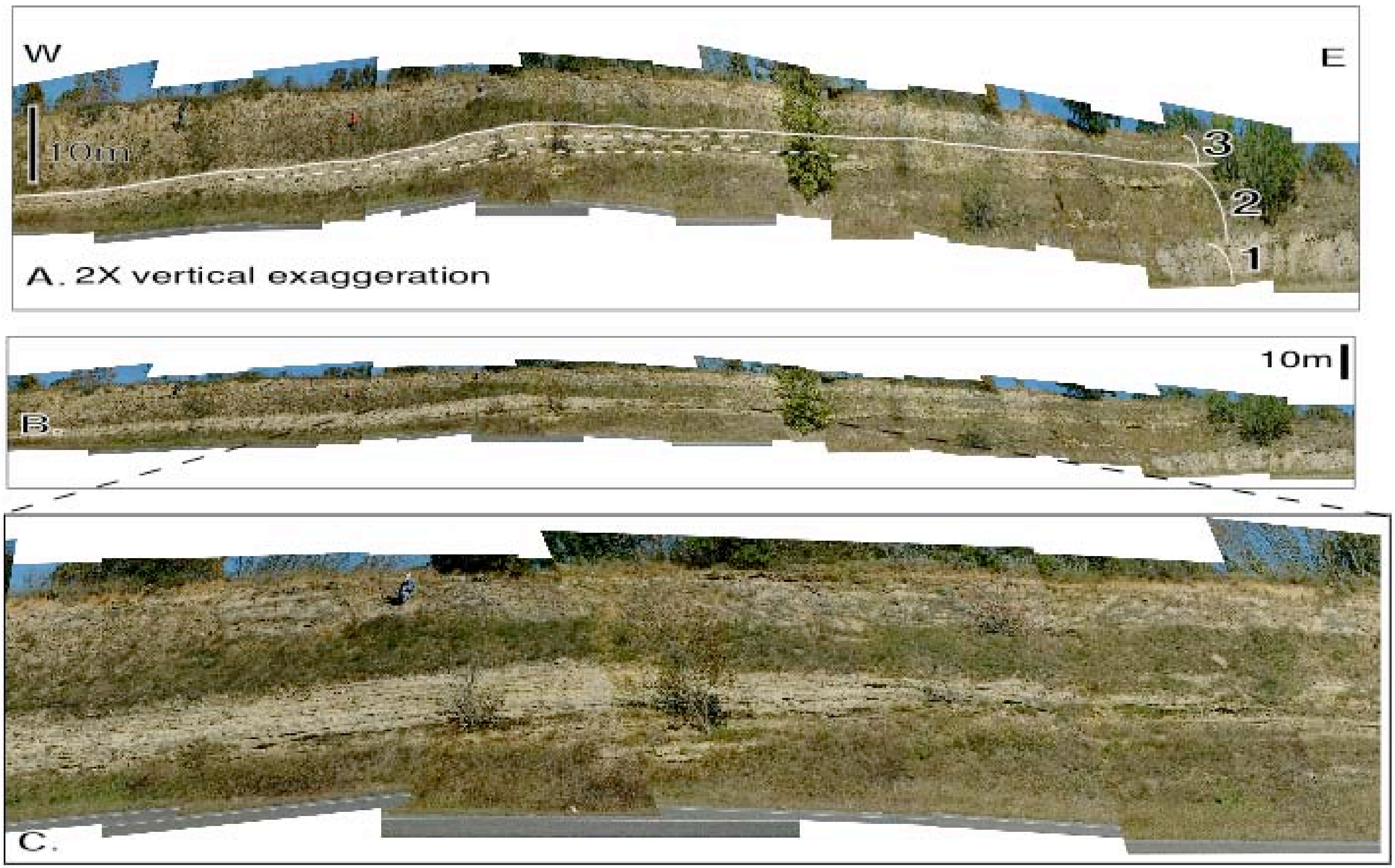


Figure 12. Photomosaic of SS3 sandstone of the Placid Shale Formation at Stop 1 along Hwy 380, near Wizard Wells, north side of road (Fig. 9). Note low angle clinoforms dipping to the west (left).

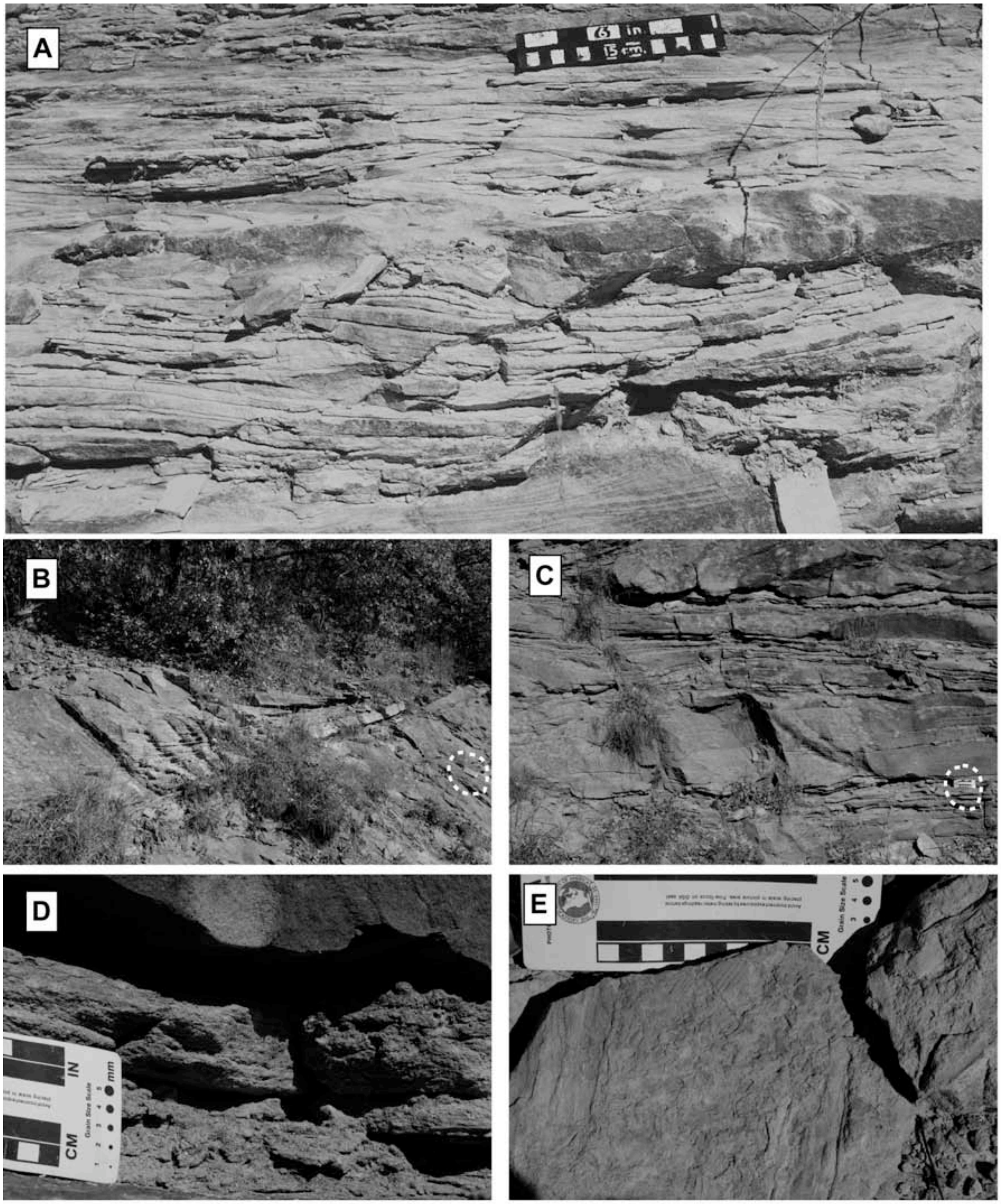


Figure 13. A. Hummocky cross stratified sandstones, SS1 sandstone of the Placid Shale Formation indicate storm-wave reworking of the Perrin delta front. B. Large-scale angle-of-repose cross strata, interpeted to represent the foreset deposits of distributary mouth bars. These pass into C. flat stratified to rippled sandstones and siltstones that represent distal bar deposits, probably deposited as frontal splays. D. Scour and fill features are interpeted as representing "terminal" distributary channel deposits. E. abundant plant debris also suggests a deltaic setting.

Stop 2. Jacksboro Road cut II. – Ranger Limestone Formation

Hwy. 380 (2.9 miles east of Hwy 1156).

- Skeletal packstones of the Ranger Limestone Formation
- Carbonate lagoonal shelf
- Abrupt lateral transition from clastic into carbonate environments

Questions to ponder:

1. *Would this make a good marker bed?*
2. *What controls the abrupt lateral transition from wave-dominated sandy shorefaces into a shelf limestone?*
3. *Why do the clastic sediments avoid this area?*

Driving a few hundred meters west (Fig. 9) we observe a complete change in facies and lithology. The Placid Shale siliciclastics are gone and instead we observe carbonates of the Ranger Limestone Formation. The carbonates are medium-bedded, gray fossiliferous mudstones and wackestones, indicating a shallow shelfal setting. Stratigraphic cross sections (e.g. Fig. 6) show the Placid Shale interfingering with the Ranger Limestone, showing that that are time equivalents.

Stop 3. Wizard Wells – SS3 member of the Placid Shale Formation

- Over-thickened, growth faulted strata
- Distributary mouth bar and terminal distributary channel sandstones
- Fluvial-dominated Perrin delta front

Questions:

1. *What causes growth faulting?*
2. *What arethe main sandy architectural elements?*
3. *Is there a relationship between the faults and the sandy elements?*

This outcrop is on FM 1156, about 2.6 miles E of 380, W of Wizard Wells (location in Fig. 9). The outcrop shows a good example of proximal delta front facies of the Perrin delta system. The photomosiac (Fig. 14) shows well-developed growth strata with one well-exposed fault in the middle of the outcrop. The measured sections show large, meter-thick medium to coarse-grained cross strata (Fig. 13B), interpreted to represent the front of distributary mouth bars that were building approximately southeast. The trough-cross beds pass laterally into parallel-stratified beds (Fig. 13C) interpreted as the distal toes of the mouth bars. Individual sandstone beds likely represent frontal splays. Despite a generally northwest progradation direction for the Perrin delta, locally, distributary channels (Fig. 14) were oriented at high angles to the generally mapped, North-South shoreline orientation.

Trough cross bedded medium to coarse-grained distributary channel sandstones also show large scour and fill structures (Fig. 14) with load cast and flute cast common at the base (Fig. 13D). Mud-chip conglomerates, as well as abundant plant stems and leaves, are also common (Fig. 13E). All these observations suggest a relatively high-energy proximal delta front environment characterized by rapidly decelerating flows and high sedimentation rates.

Studies of similar growth strata in the Cretaceous Ferron sandstone member in Utah (Bhattacharya and Davies, 2001) show that growth faults are commonly initiated by the rapid deposition of mouth bars, such as is also seen here. At stop 6 we will examine the lower portion of a series of possible growth faults along the Brazos River. The top part of that exposure is difficult to get to, so this outcrop may give you an idea of what is happening at the top of the faults at Stop 6.

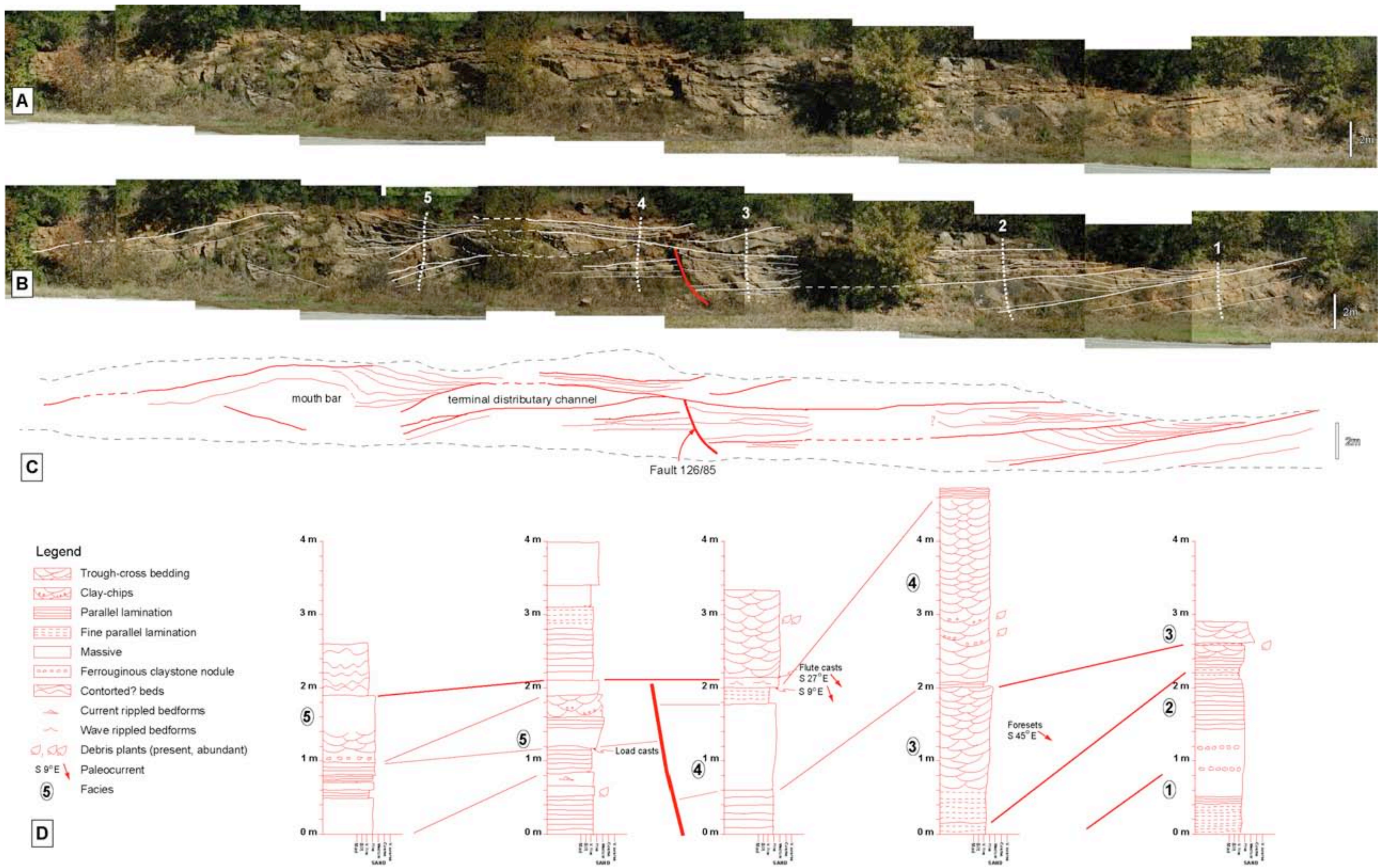


Figure 14. Photomosaic interpretation of proximal delta front deposits near Wizard Wells. A. Photos, B. Photo plus interpretation, C. Line intepretation and C. measured sections with correlations. Outcrop shows a complex association of shallow "terminal" distributary channel and mouth bar sandstones. Photo is of the north side of the road (location in Fig. 9).

Stop 4. Incised Valley, Mineral Wells Radio Tower

- Stacked upward coarsening marine facies succession capped by possible incised valley
- Valley fill is about 6m (20 feet) thick
- Floored by a pebble conglomerate
- Tidally-influenced cross bedding with a low diversity trace fossil suite
- East Mountain Shale member of the Mineral Wells Formation

Questions:

1. Is this a distributary channel, fluvial channel, or incised valley?

2. How far seaward could the shoreline facies fed by the channel lie?

3. What is the 3D geometry of this sandstone body and what are the implication of the depositional model for reservoir heterogeneity and extent?

From Wizard Wells we will head back to Hwy 380 until we reach Hwy 281. We will drive about 20 miles south to the town of Mineral Wells stopping at the Radio Tower. This outcrop is virtually on the northeast side of downtown Mineral Wells (Fig. 10). There is excellent fossil hunting in the mudstones at the base of the cliff. For the more adventurous, we will hike about 100 feet up to the base of the sandstone at the top of the tower. There is a path up, but there are numerous cacti on the climb up so be vary careful. You won't get into serious trouble, but the cacti are sharp. At the top, the way up is narrow and moderately difficult to navigate. Be very careful of people below you, especially when you reach the exposed rock at the top.

The measured section (Fig. 15 and 16) shows two stacked coarsening-upward shelf parasequences capped by a sharp-based pebbly sandstone. The mudstones contain well-preserved brachiopods, crinoid stems and other typical Pennsylvanian body fossils, suggesting fully marine conditions. The ichnofacies are described below.

These mudstones are sharply overlain by a 20m medium to coarse-grained pebbly sandstone floored by a chert-pebble and mud-chip lag conglomerate (Fig. 16B), suggesting an erosional base, although the outcrop is not wide enough to observe a distinctive cut-bank or valley-margin. Internally, the sandstones are trough cross bedded (Fig. 16C). Cross beds contain numerous thin mud laminae and mud drapes, suggestive of tides. Paleocurrents were difficult to measure but appear to indicate flow towards the west. Syneresis cracks can be seen on bedding planes and are suggestive of brackish water conditions. The trace fossils (see below) also suggest a brackish, estuarine type setting.

Many sharp, erosionally-based, fining-upward sandstone deposits, such as exposed here, have been historically interpreted as distributary channel deposits. The abrupt juxtaposition of conglomerate over offshore prodelta mudstones suggests a rather more abrupt seaward shift in facies, than would be expected during the normal progradation of distributary channels over a delta front. The thickness of the overlying deposit, the top of which is not observed, suggests deep incision of at least 7m, and possibly more. The suggestion of tidal cross bedding and brackish water conditions indicates that this sandstone is an estuarine incised valley fill, rather than a distributary channel. Such abrupt facies changes are quite typical of the Pennsylvanian, and are predicted in icehouse times.

Ichnofacies - The succession shows two principal ichnological suites: a suite associated with the finer-grained lower portion of the succession, and an upper suite associated with the overlying sandstone at the top of the succession. The lower suite is more diverse and bioturbation is both uniformly distributed and intense (BI 3-5; typically 4). Sandstone interbeds display mud lined (locally siderite cemented) vertical shafts attributable to *Skolithos*, and less commonly, possibly *Diplocraterion*. Possible subtle fugichnia (escape traces) are also present. Some beds also contain hematite-stained sideritic small-diameter *Thalassinoides* mazes. The silty mudstones and muddy siltstones display the higher bioturbation intensities (BI 4-5) and contain *Chondrites*, *Phycosiphon*, *Planolites*, *Palaeophycus*, *Thalassinoides*, and *Helminthopsis*.

The suite developed reflects the alternation from a low diversity expression of the *Skolithos* ichnofacies, to a fairly high diversity expression of the archetypal *Cruziana* ichnofacies. This corresponds to the mixed *Skolithos*-*Cruziana* ichnofacies, consistent with distal marine conditions subject to episodic deposition consistent with a storm-influenced shelf or offshore environment. Preliminary assessment of the assemblage shows no marked evidence of impoverishment, and therefore, no indication of paleoenvironmental stress, suggesting that sedimentation rates were generally lower, and suspended sediment at the bed and in the water column were not pronounced.

The upper sandstone unit displays few identifiable trace fossils, most confined to the tops of bedding planes. Bioturbation is of very low intensity (BI 0-1), with ichnogenera of low diversity and abundance. Trace fossils are sporadically distributed through the interval. Traces are generally poorly preserved and correspond to unidentified locomotion structures of gastropods and possibly bivalves. *Planolites*, and possibly *Curvolithus* are present as well. The suite is consistent with rapid deposition, mobile bedforms, and reduced salinity conditions, consistent with estuarine incised valley deposition. The local preservation of syneresis cracks may support reduced salinity conditions. The paucity of identifiable forms precludes assignment to a particular ichnofacies, though the identifiable forms are typical of the *Cruziana* ichnofacies.

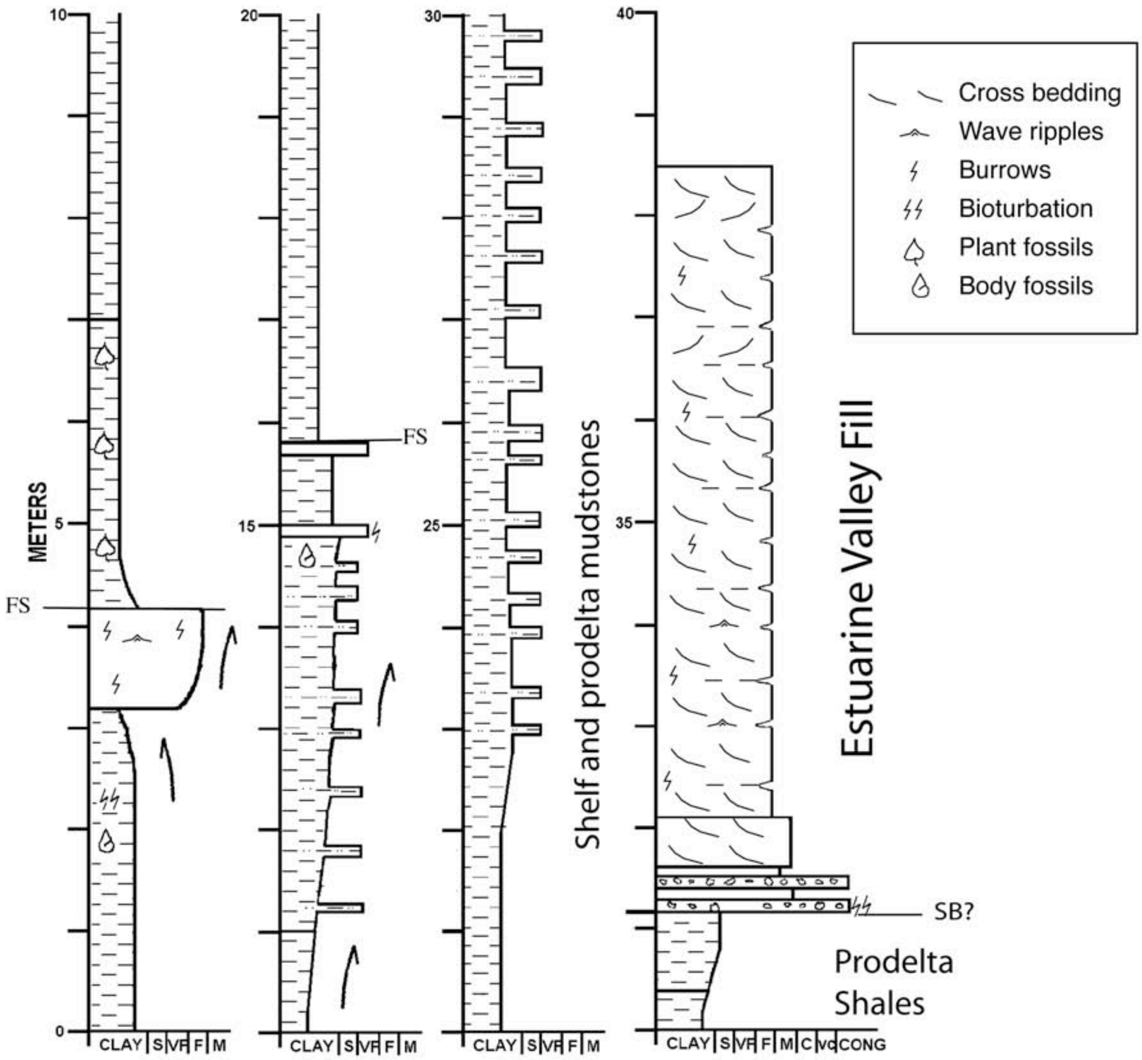


Figure 15. Measured section of the Mineral Wells Formation (East Mountain Shale and overlying Turkey Creek sandstone). Flooding surfaces (FS) at 4.2m, and 15.7m mark the tops of upwards coarsening prodelta shelf deposits. Chert-pebble conglomerate at 31m marks a candidate sequence boundary at the base of a probable incised valley. Valley fill facies cut into distal prodelta and shelf mudstones. No intervening delta front or shoreface deposits are present below the valley, which is evidence of an abrupt seaward shift of facies. The valley fill deposits comprise tidally-cross bedded sandstones, showing classic double mud drapes and an impoverished, brackish ichnofauna, typical of estuarine settings.

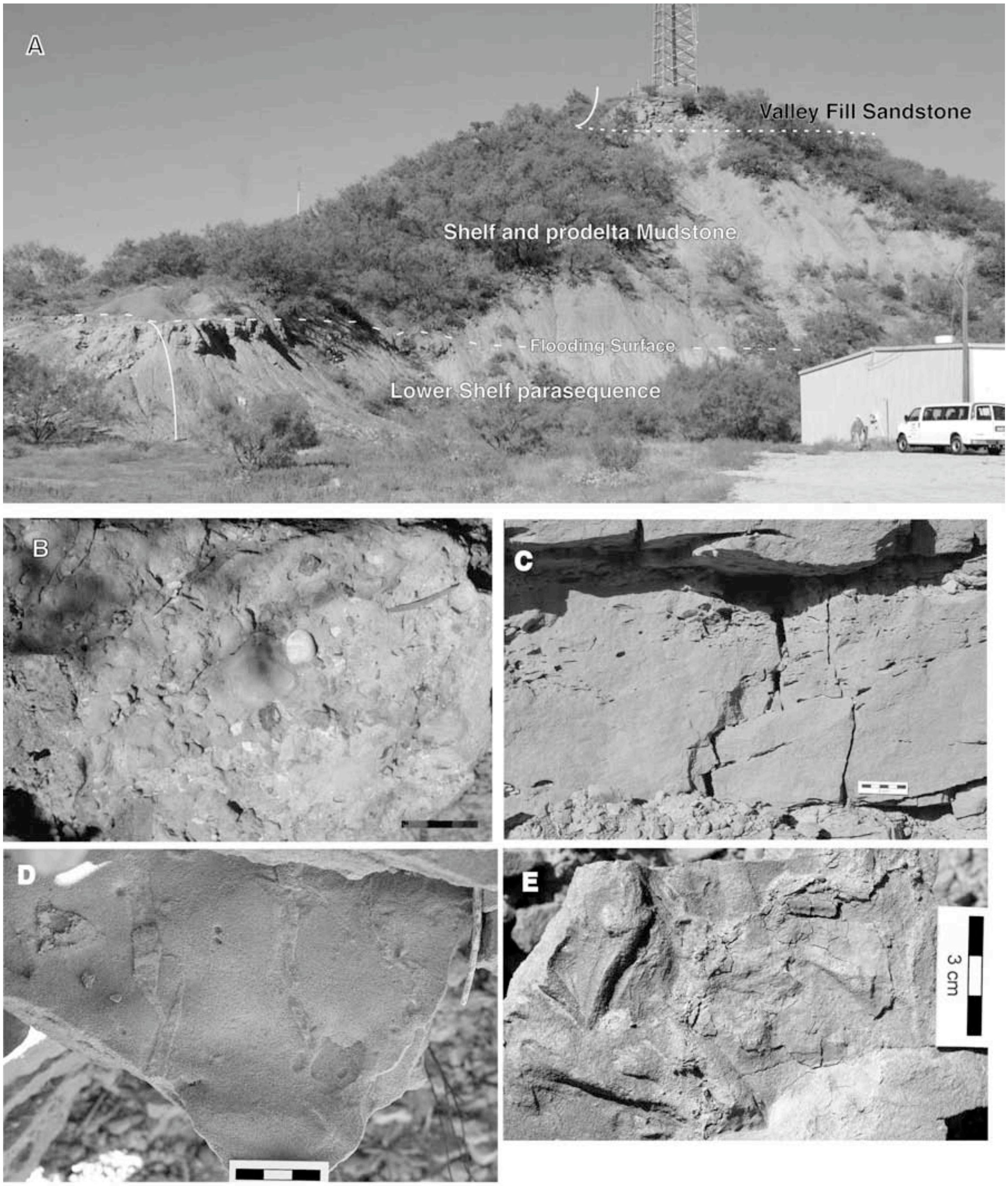


Figure 16. A. Outcrop section at Mineral Wells. B. Chert-pebble lag at base of valley fill.C. Mud-chips and mud--draped trough cross bedded sandstones suggest tidal processes D. Syneresis cracks within valley fill sandstone suggest salinity changes and estuarine, brackish water. E. Phycodes burrows suggest a marine influenced (estuarine) valley fill.

Stop 5. Lake Mineral Wells State Park – Brazos River Fm. Conglomerates

- Coarse-grained fluvial conglomerates, sourced from Arkansas Novaculite.
- Eroded from Ouachita facies (Dev-Miss)
- Probable incised valley-fill deposits

We will now drive about 5 miles east to Mineral Wells State Park. Minerals Wells State Park is a popular area for rock climbers because of the steep cliffs. These cliffs cut down into fluvial conglomerates of the Brazos River Formation but are likely older than the pebbly sandstones observed at Stop 4.

We have no measured section here, but you will see good examples of cross-bedded channel and bar deposits. The nearly 10 meter thick conglomerates are likely multistorey, consisting of numerous amalgamated channel deposits. Some individual cross strata are over 1 meter thick, suggesting large-bar-scale bedforms.

The very course-grained nature of these deposits led Erxeleben (1973 in Brown et al. 1973) to suggest that these are incised valley fills. Certainly they represent a considerably coarser facies than we have observed on the trip so far.

In general, sorting tends to decrease in fluvial deposits as grain size increases. This results as a natural consequence of bed-scale processes. Marine shoreface conglomerates tend to show far better sorting than fluvial conglomerates (Hart and Plint, 1989).

Stop 6. Brazos Railroad Cut off Bennett Road

Stop 6A: Undeformed distributary channels and ravined delta front sandstone.

• Distributary Channels

• Ravined delta front

Leaving Mineral Wells State Park we will head back to Hwy 180 heading west for about 1.5 miles. We will then drive south on 1195 for about 3 miles until we hit Bennett Road. We will turn left, heading southeast on Bennett Road. We will stop near a Brick factory, next to the Railroad. We will leave the Bus and take about a 1 mile hike down the tracks (Fig. 17). Please exercise care on the railroad. Trains come through regularly in both directions. Please try and stay off the tracks as much as possible.

These strata form part of the Dobbs Valley sandstone member of the Mingus Formation (Figs. 6 and 10) and are stratigraphically the oldest rocks that we will visit.

About half a mile down the road is a well-exposed, primarily west-east oriented cliff (Fig. 18). At the base is an upward-coarsening delta front sandstone. Beds within the lower parasequence are truncated to the west (left). Truncation is likely related to wave erosion (ravinement) during transgression of the delta top. The overlying bay fill mudstones are in turn overlain by red-weathering sandstones that exhibit a sharp, undulating, erosional base. Dipping beds within the sandstone mark bar accretion surfaces and the sandstone is interpreted as a migrating distributary channel deposit. The accretion surfaces extend from the top to the base of the sandstone body, suggesting a single storey sandstone, unlike the thicker cross bedded valley fill deposits seen at the other stops.

Although this cliff is too steep to climb safely, large blocks of the channel fill sandstone can be examined along the railroad and show some spectacular examples of well-preserved typical Pennsylvanian fossil plants (Fig. 19).

We do not have any detailed measured sections of this cliff.

Stop 6B – Synsedimentary Faults in a prodelta to delta front succession

• Possible growth faulted delta front and channel mouth bar facies

• Dobbs valley sandstone of the lower Mingus Formation (Strawn Group)

Questions:

1. *Are these listric or normal faults?*
2. *How much growth is evident?*
3. *What would the effective properties of these faults be?*
4. *How does facies reflect the structure?*

As we continue another half mile down the track we will come upon a north-south oriented cliff about 100m in length (Fig. 17) that shows spectacular examples of synsedimentary growth faults (Fig. 20). A photomosaic and 6 measured sections allows us to make an integrated analysis of sedimentation and development of the structures.

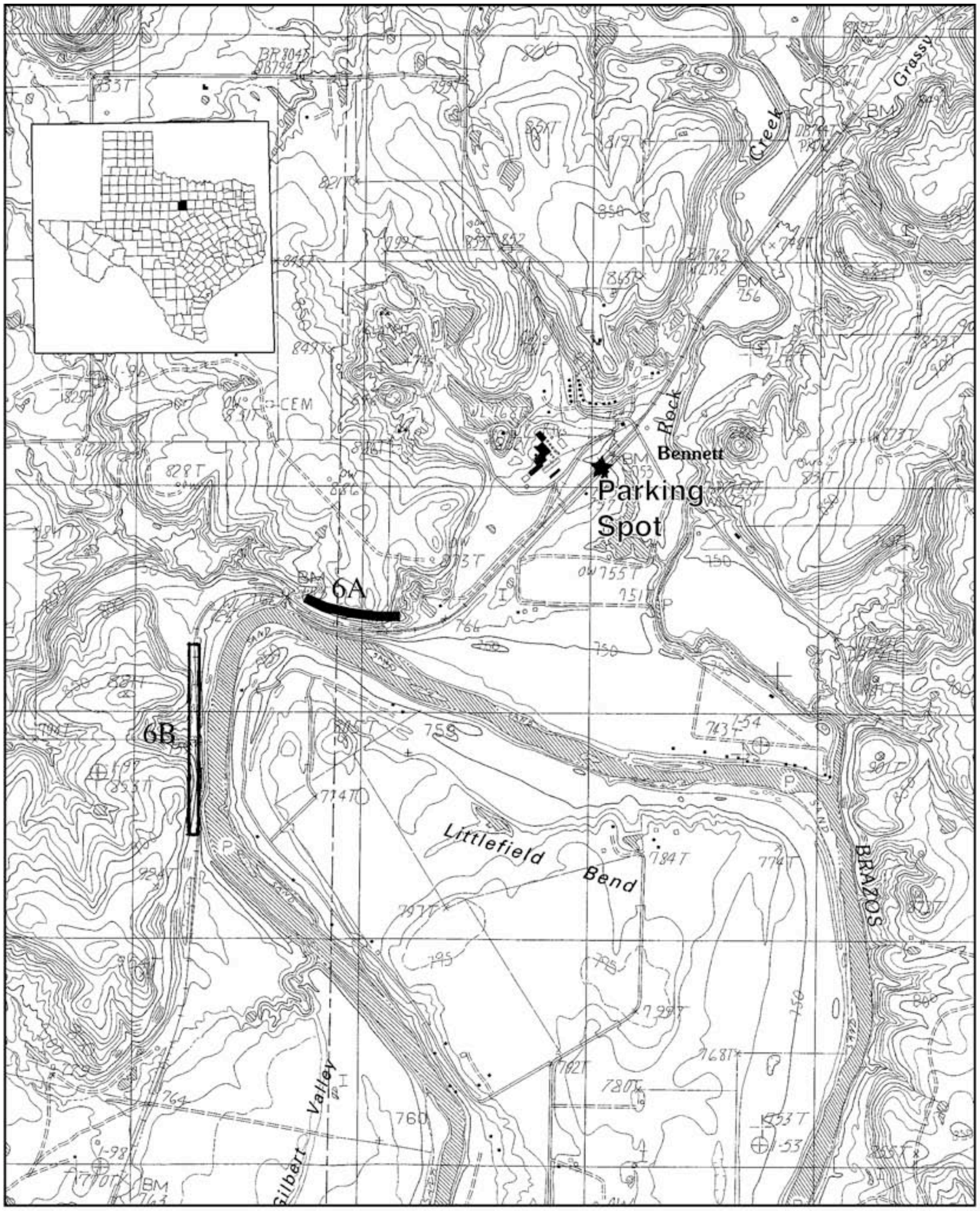


Figure 17. Topographic map of Stop 6.

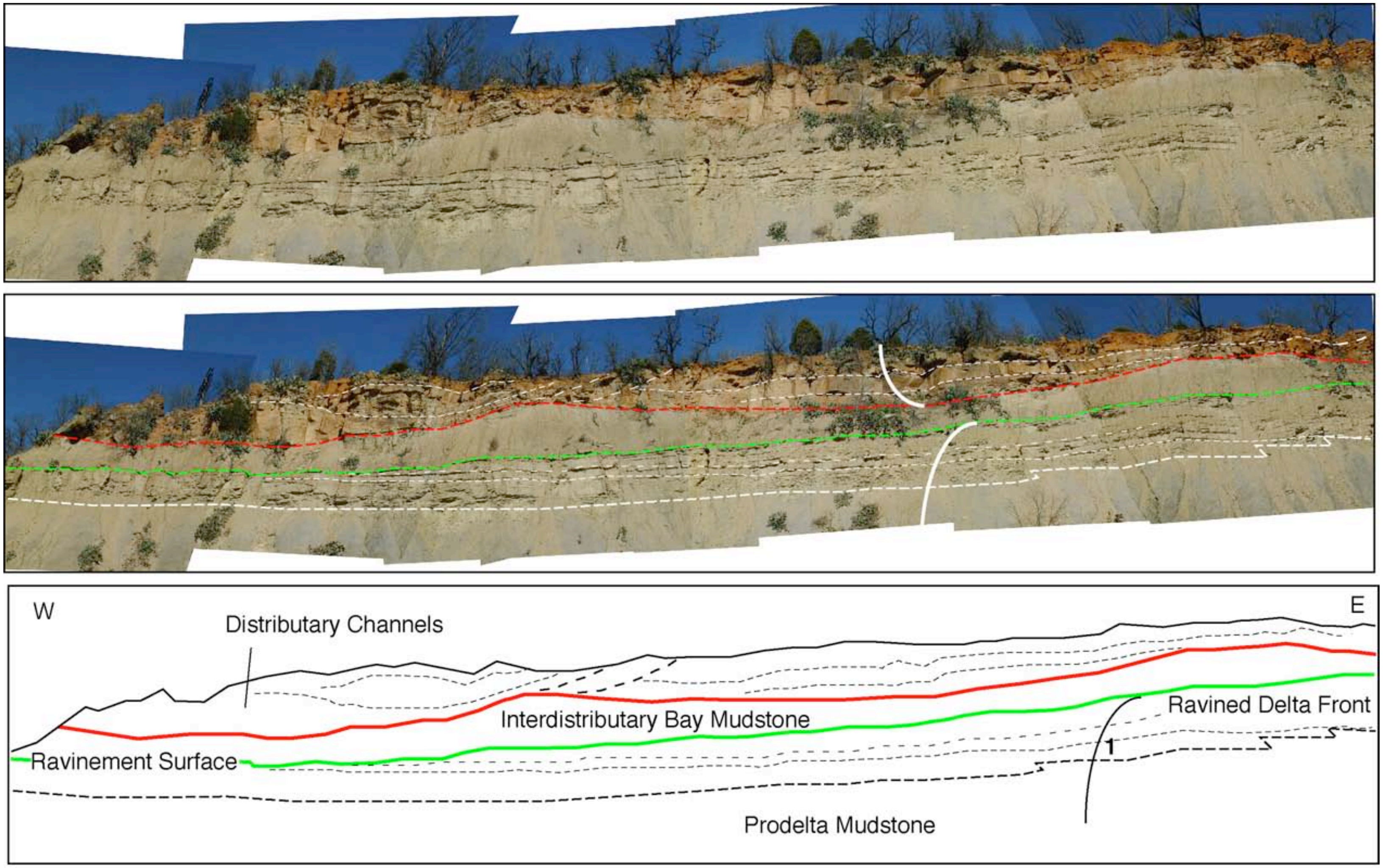


Figure 18. Upward-coarsening delta front facies in the lower parasequence (1) show relatively flat beds that are truncated to the west by an overlying ravinement surface (transgressive surface of erosion). The sandstone appears to thin to the east, perhaps suggesting progradation in that direction. The overlying interdistributary bay mudstones are overlain by distinctly channelized sandstones interpreted as single storey, distributary channels.

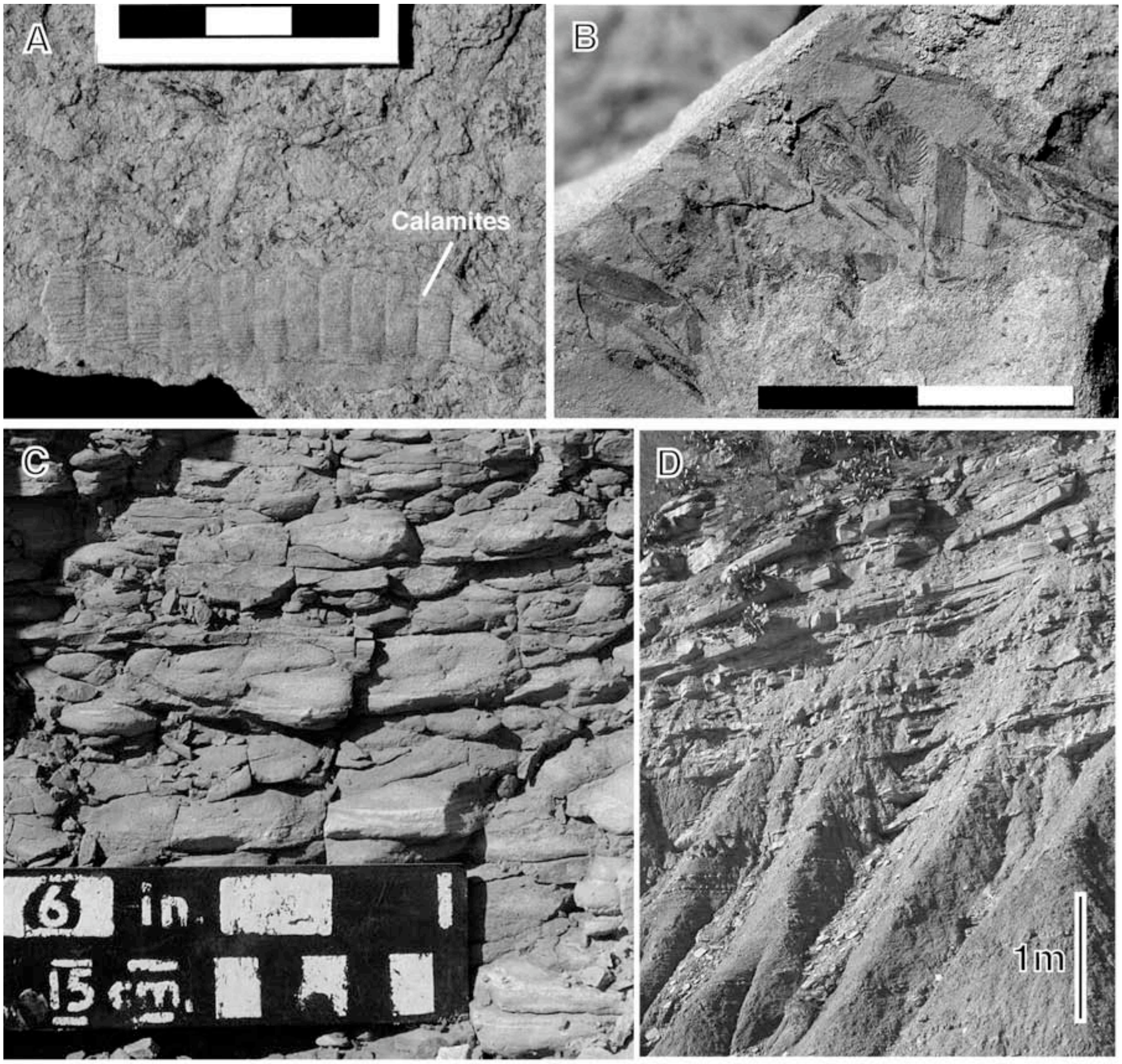


Figure 19. Facies along the Brazos River, Railroad cut. A. *Calamites* stem, a typical Pennsylvanian plant fossil. B. Well preserved plant material probably *Praeramunculus* with rare branching. C. Laminated, virtually unbioturbated prodelta mudstone at base of section under synsedimentary faults. D. Base of faulted section showing well developed upward coarsening.

This area is a haven for rattlesnakes and there is always a risk of falling rocks. Take special care on these cliffs, and if you clamber up, make absolutely sure that there is no one below you. Also, **do not climb the fence**, as this will trigger an alarm and we will be visited by the UPR safety inspectors. If you want to examine the exposures close-up, go through the gates.

These faults have been previously interpreted as classic growth faults by Brown et al. (1973). The outcrop is oriented nearly perpendicular to the fault strikes (Fig. 21). This study demonstrates that although the faults are listric, the growth occurs only locally within a 30 meter upward-coarsening, mudstone to sandstone facies succession.

The succession in this outcrop records progradation of a small delta lobe, which overlies distal prodelta facies of the lowest Mingus Shale and underlies interdistributary bay mudstones (Fig. 22).

Sedimentology and stratigraphy- Approximately 9 meters of the base of the outcrop comprises proximal prodelta facies (Brown, et al., 1973) in which, laminae of very fine sandstone are observed within a silty mudstone (Figs. 19C, 22, 23A). Plant material is observed in both the shale and sand beds. Material has slid down from the overlying delta-front sandstone facies and is seen in flow rolls and rotated sandstone blocks. Total sand increases upwards through the section (Fig. 19D).

Sandstones are predominantly structureless and graded to current rippled (Fig. 23 B and C). Climbing ripples suggest relatively rapid sedimentation and the graded beds are interpreted to possibly represent hyperpycnal type delta front turbidites. These may form as frontal splays flowing down a steep front of the associated mouth bars.

Distinctive bedsets (labeled A through G) could be identified across the outcrop belt. Unit G is characterized by a distinctive doublet that can be idnetified in each of the fault blocks. The major growth section appears to be within the relatively sandy facies of unit between faults F2 and F3 (Fig. 20).

Ichnology and Paleobotany - Like most prodelta and distal delta front complexes, this interval is characterized by highly sporadic distributions of trace fossils, and generally low to absent bioturbation intensities (BI 0-1, Fig. 19C and 24). Traces, where preserved, are more typically concentrated at the bases of non-erosively emplaced event beds, and at the tops of event beds. Along these interfaces, bioturbation intensities may reach BI 3, but typically BI 1-2. The assemblages produced, though of low abundance and generally low diversity, are nonetheless, marine in character. The trace fossil suite consists of very low numbers of *Planolites*, *Psammichnites*, *Palaeophycus* (originally referred to *Terebellina*), *Lockeia*, *Skolithos*, *Phycosiphon* (very rare), and *Chondrites* (very rare)(Fig.24). A possible meniscate-filled horizontal tube was tentatively identified as *Taenidium*. Some bedding planes show locomotion structures of bivalves and gastropods, but are too poorly preserved to assign ichnogenera designations.

The suite is consistent with deposition in a marine, though stressful environment. The paucity of bioturbation reflects high sedimentation rates, episodic deposition, and possible high suspended-sediment concentrations in the water and on the bed. Some substrates may reflect soup-ground conditions, limiting both the ability of infaunal organisms to inhabit the area, and the preservation potential of any structures that were developed there. The assemblage corresponds to a highly impoverished expression of the archetypal *Cruziana* ichnofacies, and is typical of prodeltaic and delta front settings, particularly those that show strong river domination. Similar suites have been identified from the prodelta of river-dominated lobes in the Dunvegan Formation and the basal Belly River Formation of west-central Alberta, Canada (Gingras *et al*., 1999; Coates and MacEachern, 1999, 2001)

This section also contains a large number of allochthonous plant fragments (Fig. 19A and B), some well preserved and identifiable. Included in this assemblage are *Praeramunculus*-like detritus with rare branching preserved; fragments of lycopods (club mosses); cone scales probably representing up to 3 taxa; and *Equisetum*-like stems (no leaves attached). Leaves representing 2 taxa are also represented, one of which appears compound and fern-like. One large floral specimen was encountered that may reflect a possible fruit body.

Faulting - Four fault zones occur 5 to 10 meters apart across the outcrop (Fig. 20) and are concave to the north with paleocurrents flowing approximately southeast to northwest. The faults strike broadly WNW-ESE and dip to the north (Fig. 21). Many smaller synthetic and antithetic faults are also observed (e.g. Figs. 23A, 25C). Sand and shale smears and termination of faults within the succession show that faults were active during deposition (Fig. 25).

The fault zones were active at different times. Fault F5, for example, stopped moving before the formation of the major flooding surface, whereas Faults 1 to 4 were active after the lowest delta lobe was flooded. It also appears that the faults migrated from north to south up depositional dip, versus initiating in a progressively more distal direction as the delta prograded. Similar complex fault history was also observed in the Cretaceous Ferron sandstone (Bhattacharya and Davies, 2001).

In the hanging wall of fault F1, sand appears to be dragged down the fault zone (Fig. 25A). Offset along the faults ranges from as little as 0.5 meters near fault terminations up to 10meters across longer faults. The base of the faults occurs in distal prodelta muds with some soft-sediment deformation. Composite throw is about 30 meters across all the faults.

Measured sections (Fig. 22) show the sedimentologic variations associated with different parts of the major faults, which allows for an evaluation of the relationship between fault timing and depositional processes. Although exposure is poor toward the top, we infer that deposition of thick-bedded delta mouth bar sands may be responsible for initiating some of the growth faults, such as Fault F5, similar to the fault observed at Wizard Wells (Stop 3). An over-thickened sandy section B, in the hanging wall adjacent to Fault F2 (Fig. 20) likely initiated the movement of that fault, although the fault continues to move after flooding of the delta

Our preliminary interpretations suggest that the faults in the Mingus Formation may form by a combination of mechanism, including slumping associated with the failure of an unstable slope, as well as initiation by deposition of thick delta front sands in the hanging walls.

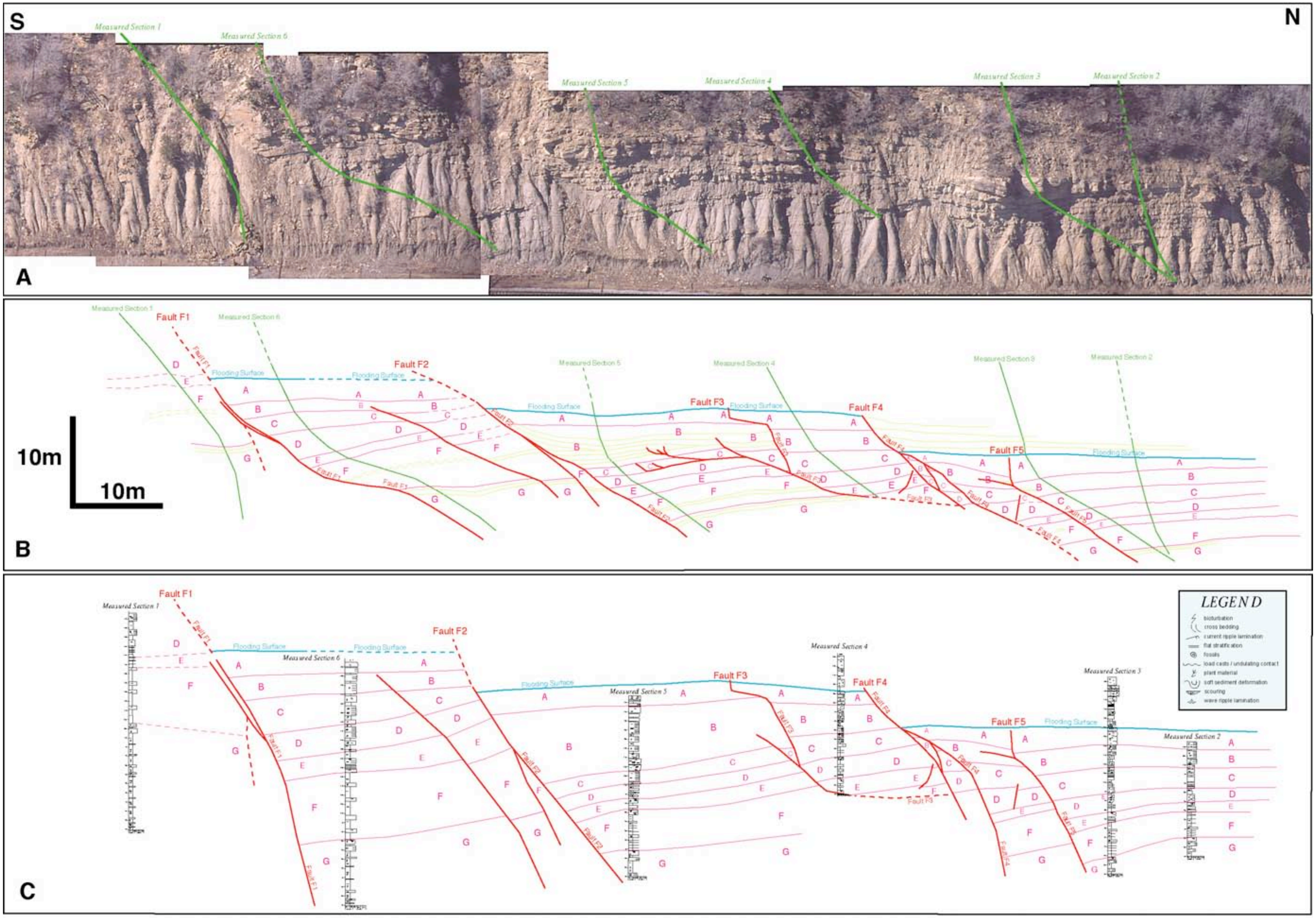


Figure 20. Photomosiac and interpretation of synsedimentary normal faults within prodelta and delta front facies within the Dobbs Valley Member of the Mingus Formation. A. Photo, B. line interpretation and C, interpretation with measured sections. The detailed measured sections allow specific bedsets to be correlated between faults blocks, allowing us to calculate composite throws.

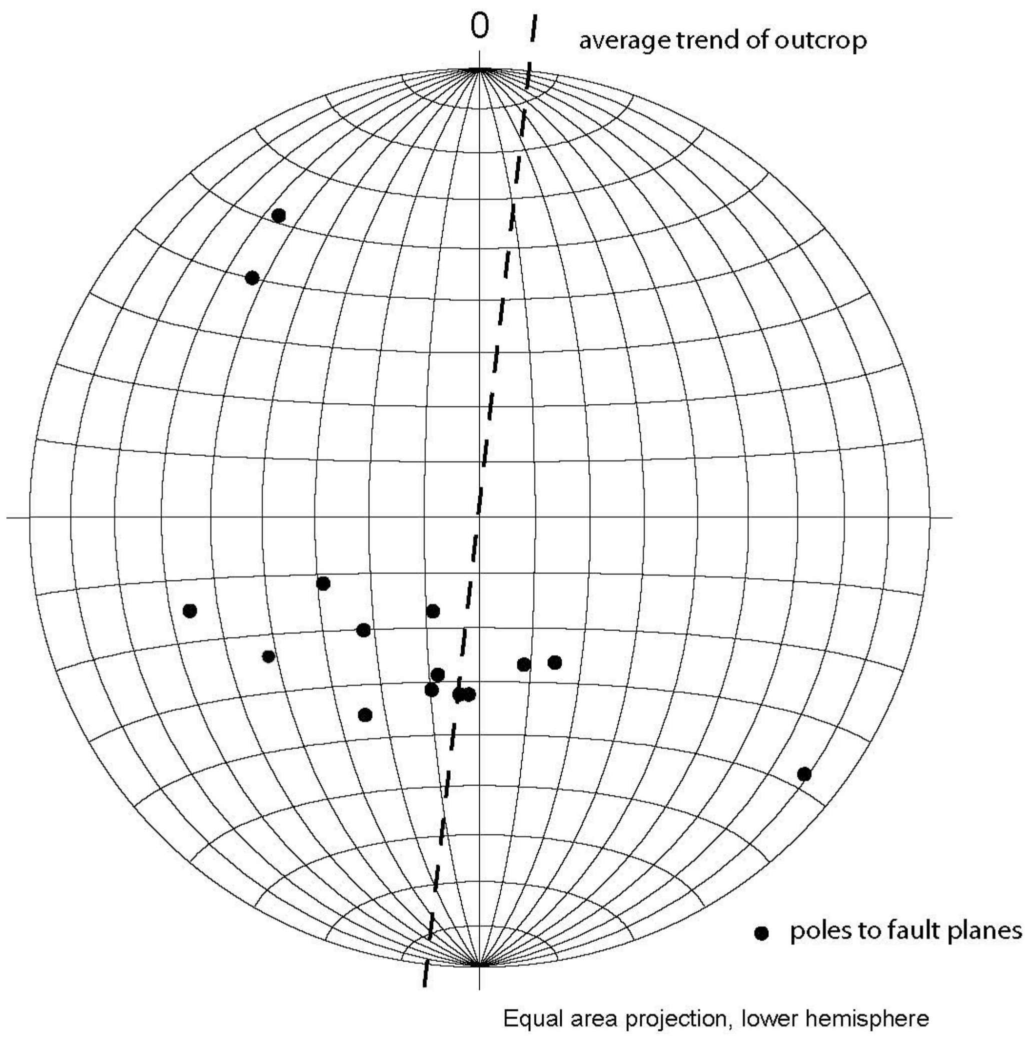


Figure 21. Steronet of faults shows the broadly WNW-ESE orientation, practically perpendicular to the N-S orientation of the outcrop. The outcrop this provides a dip-oriented view of the faults.

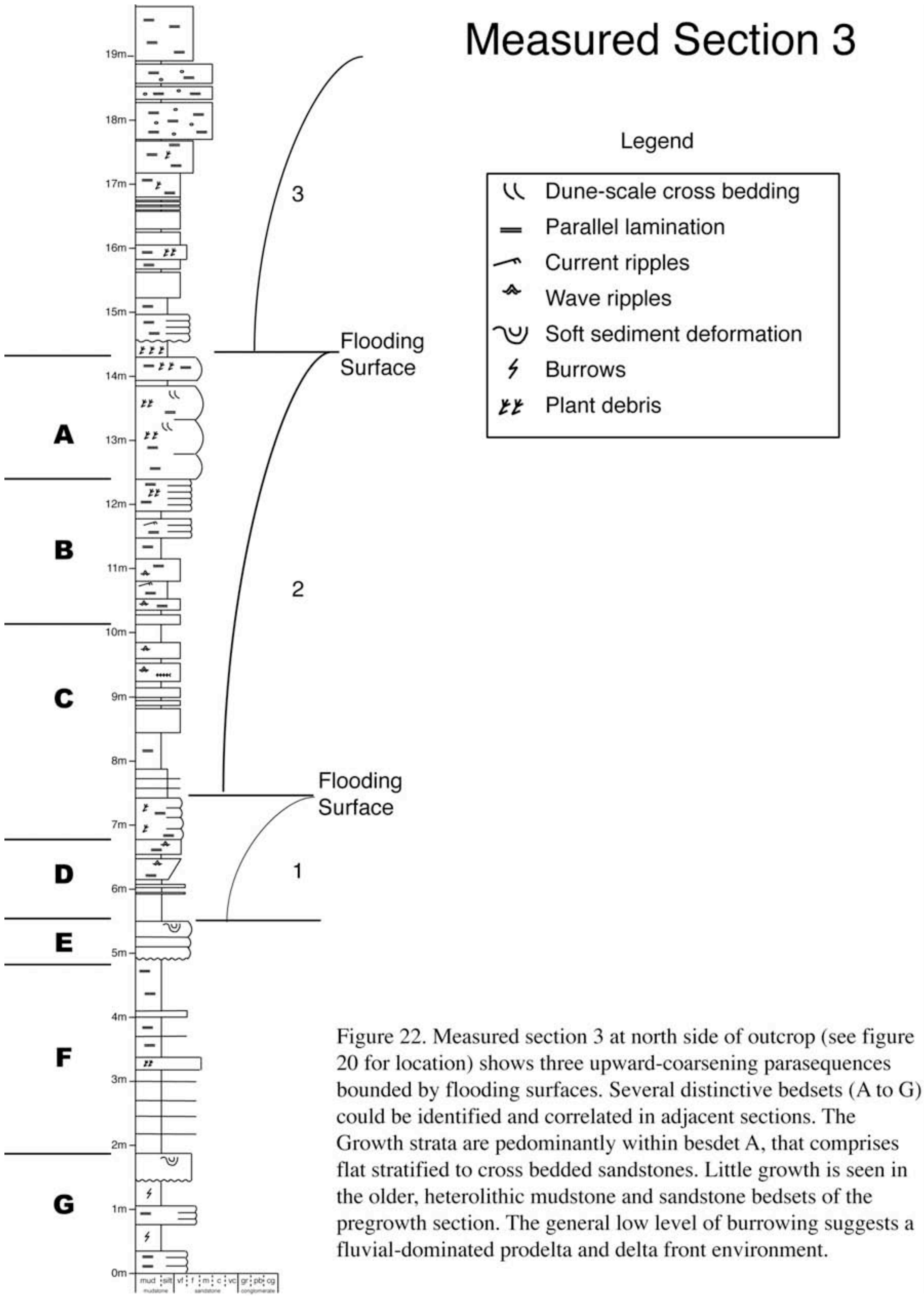


Figure 22. Measured section 3 at north side of outcrop (see figure 20 for location) shows three upward-coarsening parasequences bounded by flooding surfaces. Several distinctive bedsets (A to G) could be identified and correlated in adjacent sections. The Growth strata are pedominantly within besdet A, that comprises flat stratified to cross bedded sandstones. Little growth is seen in the older, heterolithic mudstone and sandstone bedsets of the pregrowth section. The general low level of burrowing suggests a fluvial-dominated prodelta and delta front environment.

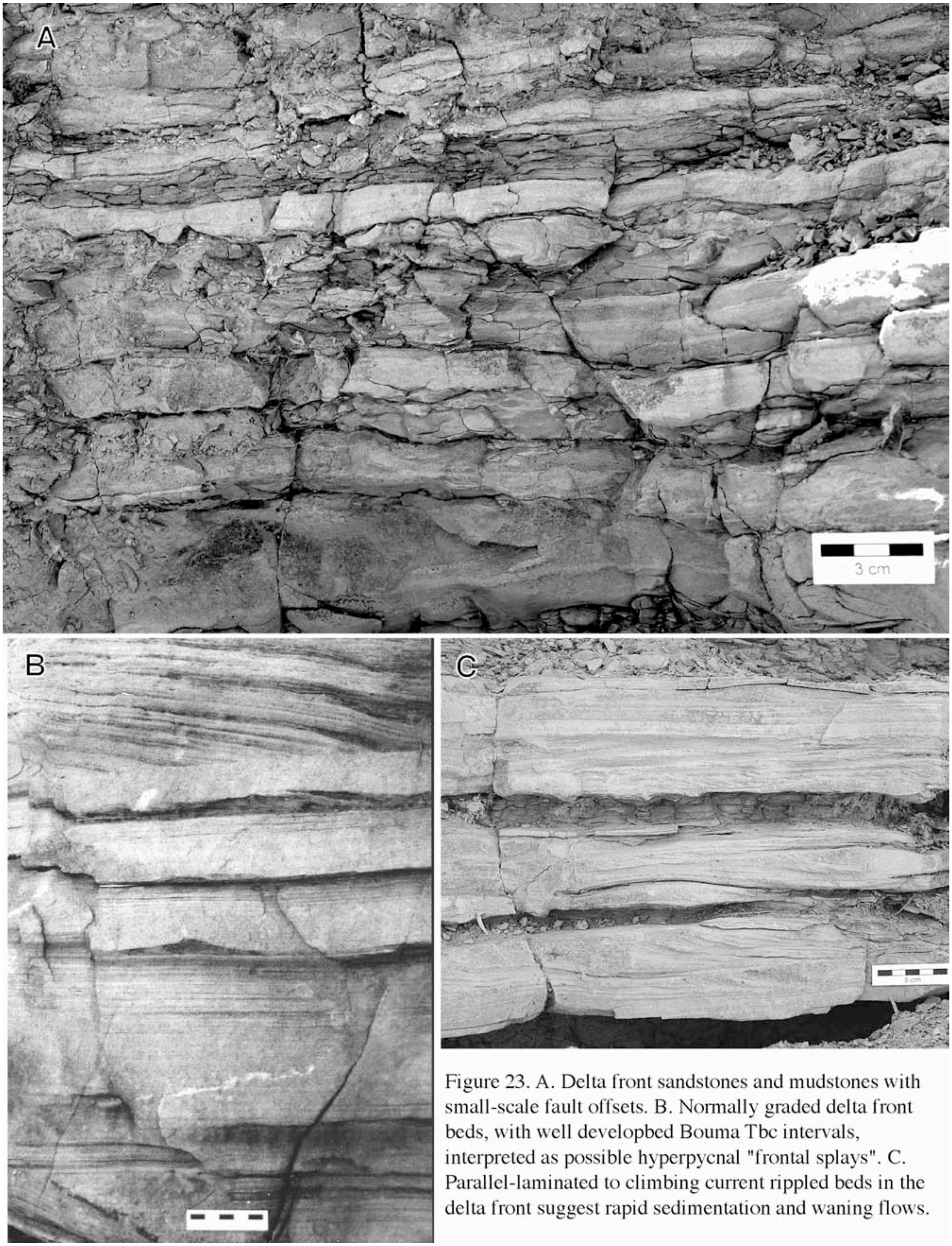


Figure 23. A. Delta front sandstones and mudstones with small-scale fault offsets. B. Normally graded delta front beds, with well developbed Bouma Tbc intervals, interpreted as possible hyperpycnal "frontal splays". C. Parallel-laminated to climbing current rippled beds in the delta front suggest rapid sedimentation and waning flows.

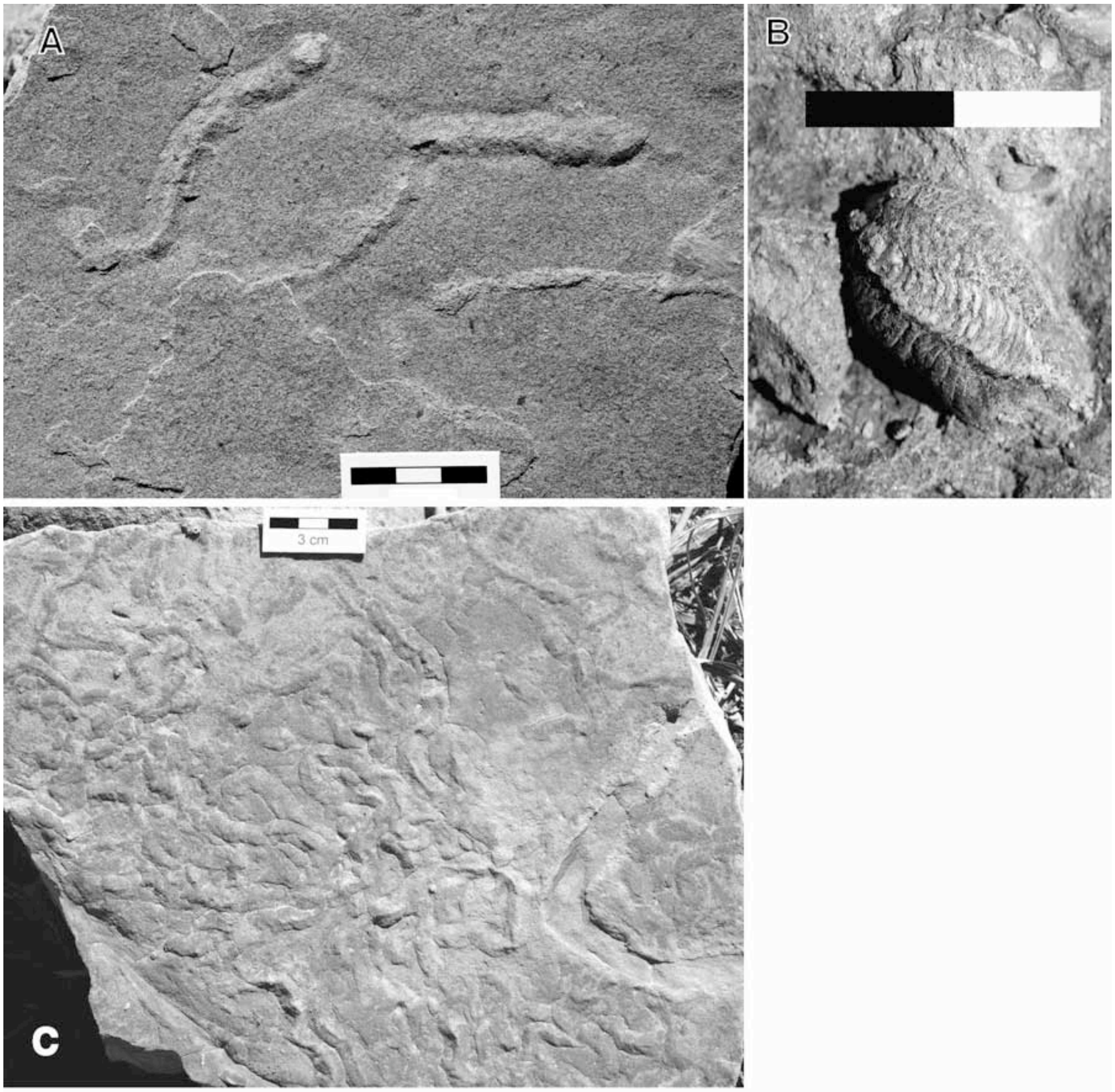


Figure 24. Typical trace fossils from Stop 6. A. Single bi-lobed *Psammichnites* trace. B. Possible *Pentremites,* C. Gregarious *Psammichnites*. These traces are typical of a a Cruziana ichnofacies. The low abundance and diversity of forms is suggestive of stressed environmental conditions, typical of that found in the proximal fluvial-dominated delta front setting.

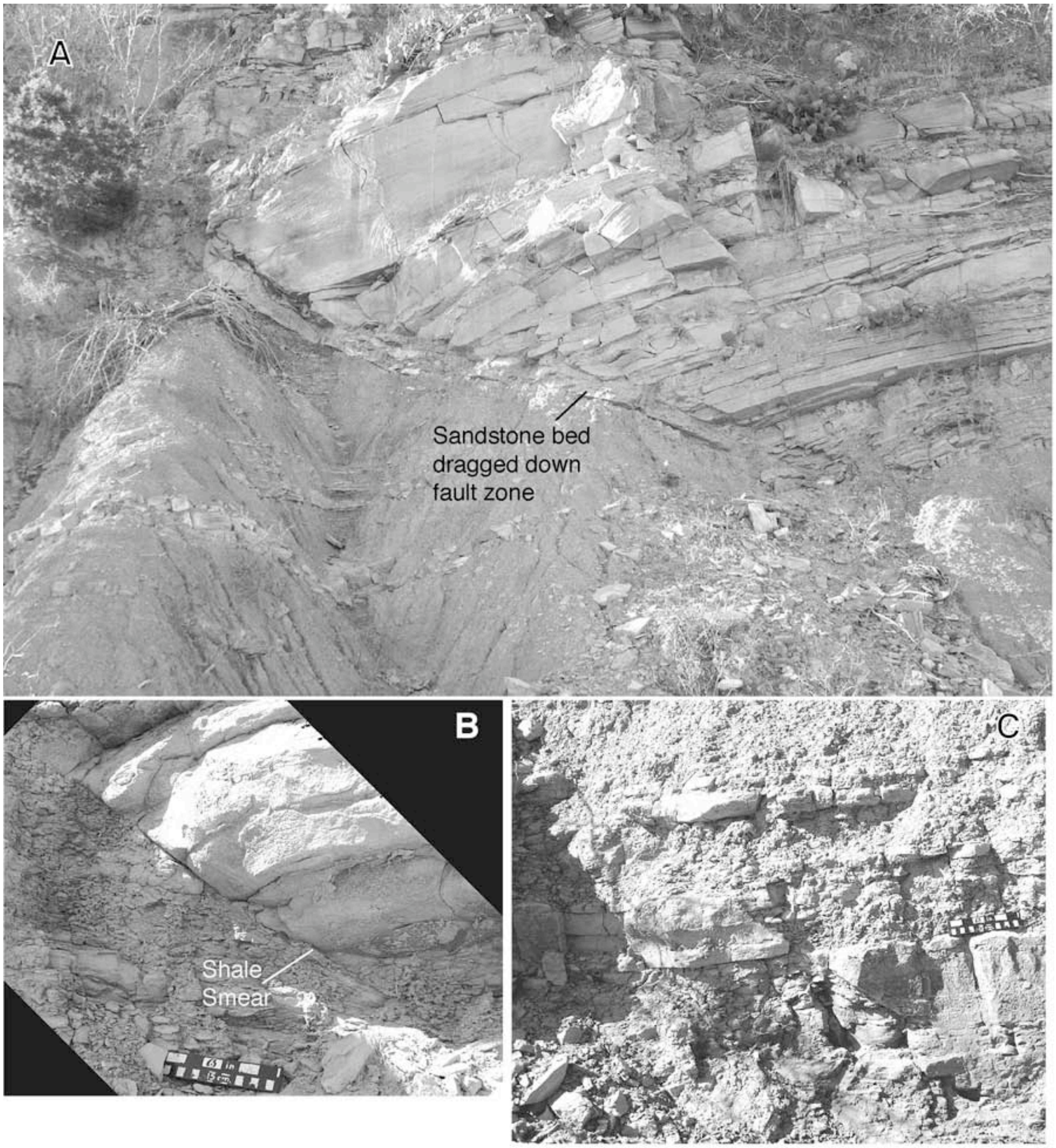


Figure 25. Close-ups of faults. A. Sandstone bed has been dragged along the fault zone. Note thick sandstones representing growth strata in hanging wall. B. Close up of fault juxtaposing sand against a pre-growth shale. Shales are smeared along fault zone. C. Close-up of small-throw fault within heterolithic pre-growth section.

Fault Rocks: Description and Analysis

Description

Fault rock is a term for the internal structure of fault zones. Following Fisher & Knipe (1998) a threefold subdivision of fault rock types is based on the percent of clay within the protolith that is incorporated into the fault zone. The fault rock types are ***cataclasites*** which contain <15% clay, ***phyllosilicate framework fault rocks*** (PFFR) with 15-40% clay and ***clay smears*** with >40% clay. The sealing potential or amount of hydrocarbon column supported by the fault rocks is calibrated to these fault rock types. The growth faults along the railroad cut in the Mingus formation cut primarily a shale and sand section. In this case, we expect primarily the development of cataclasites and clay smears.

Cataclasites form in clean sandstones by deformation-induced grain fracturing and porosity collapse. These fault rocks have relatively low seal potential compared with more clay-rich fault rocks, particularly if faulting took place at shallow to moderate burial depths (<1.5km). Cataclasites have permeabilities reduced by between 1 and 6 orders of magnitude compared with their host sandstones.

The faults in the growth fault section are interpreted to develop in shallow water depths when the sediments are weak. Faults formed in poorly consolidated clean sandstones form disaggregation seams by grain rolling and sliding but with little or no fracturing. Disaggregation seams are more likely to have permeabilities and capillary entry pressures comparable with their host sediment, although 'cleaning' of grain contacts by abrasion during grain-sliding can be important in that clean quartz grain boundaries act as sites for the preferential nucleation of quartz cement. This effect becomes more pronounced at temperatures greater than 90°C. With a normal thermal gradient of approximately 30°C/km, the section would have to be buried to greater than 3 km for significant quartz cements to have developed along the growth faults in the Mingus Fm. How deep do we expect this section to have been buried? Could we have developed cataclasis across these fault zones?

Phyllosilicate framework fault rocks have petrophysical properties controlled by the presence of fine-grained phyllosilicates. These have heterogeneous microfabrics dominated by domains where a framework comprised of mixed orientated phyllosilicate plates is present. These fault rocks experienced a reduction in porosity as a result of three processes. First, during deformation, phyllosilicates were mixed with framework grains resulting in a replacement of macroporosity with microporosity. Second, following deformation, some of these faults experienced enhanced grain-contact quartz dissolution due to the presence of phyllosilicates at grain contacts. Third, in some cases, cataclasis contributes to porosity reduction in these fault rocks. These fault rocks have far lower permeabilities and higher entry pressures compared to their host sandstones and are likely to form significant barriers to fluid flow. In general, the sands in the Mingus formation are expected to have a low clay content, which would minimize the development of these types of fault rocks. Is there any field evidence of more clay rich rocks that may also serve as an impure sandstone or poorer quality reservoir?

Clay smears are fault rocks that contain coherent domains of aligned phyllosilicates, the majority of which form in sediments containing over 40% total fine grained phyllosilicates. Such clay smears are likely to have a high seal potential with capillary entry pressures of >1000psi. The shales between the sands in the Mingus section are good candidates for smear between two juxtaposed sands. Do you see any evidence for these smears in the outcrop?

Analysis

Important controls on fault seal include the fault rock types and their sealing capacity, but also the distribution of the fault rocks across the fault surface. Several algorithms have been developed to estimate the distribution of the clay across the fault surface. The clay percent is linked to the fault rock types defined above.

Two principal algorithms for predicting fault seal in shale and sand sequences is shale smear factor and shale gouge ratio. Shale or clay smear factor considers the mechanism by which shale is dragged into a fault zone from a shale source layer (Smith, 1980; Lehner and Pilaar, 1997). The thickness of the shale in the fault zone may taper and thin away from the original source layer (Fig. 26). This algorithm best describes the

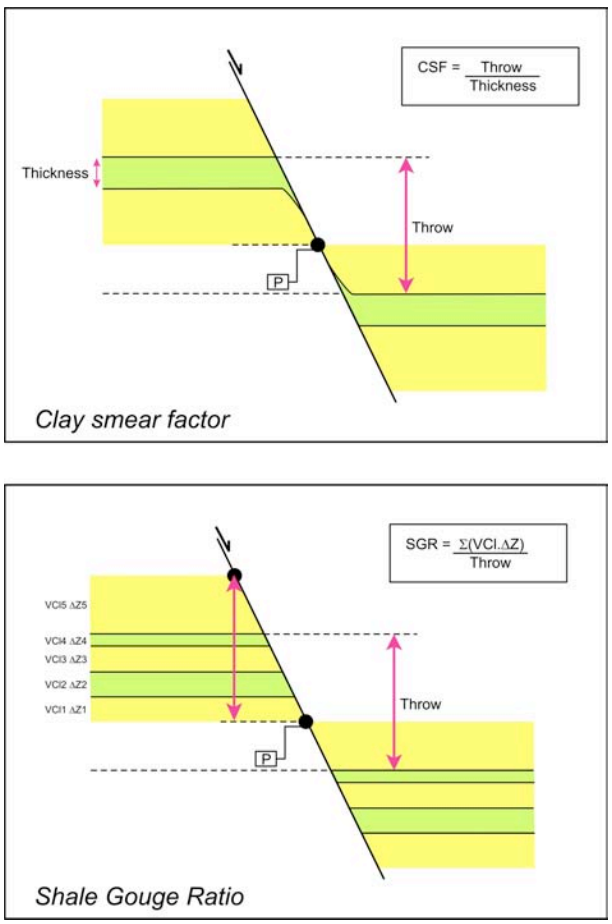


Figure 26. Illustration of clay smear factors and shale gouge ratios across a normal fault.

process when the sediments are weak and mobile. The predictive algorithm for determining the distribution of shale smear as a sealing mechanism in a fault zone defines the length of the continuous or unbroken taper, or characteristic sealing length, versus the discontinuous taper that is deemed nonsealing (Yielding et al., 1997; Lehner and Pilaar, 1997; Lindsay et al., 1993). The clay smear factor, CSF, is the ratio of the throw to the thickness. The Rock Deformation Research group has determined that a CSF of 3, which correlates to a smear thickness equal to the source bed thickness, is an average value that can be applied as a rule of thumb in an undercalibrated region.

Shale gouge describes a mechanism of uniform mixing of shale from the host rock with other lithologies in the fault zone (Yielding et al., 1997). This algorithm applies principally to rocks that are more lithified. Predictive algorithms for shale gouge calculate the ratio or percent of shale in the fault zone at each point along the fault surface. The shale gouge is generally calculated as a ratio of shale thickness to fault throw, T. The percentage of shale, Si, in a lithological unit times the layer thickness, Hi, summed over an interval of host rock for each layer displaced past a point on the fault define a shale gouge ratio:

$$\mathrm{SGR} = \sum_{i=1}^{n} H_i S_i / T$$

where n is the number of layers. This algorithm is generally considered to represent uniform mixing of the clays and sands. The March 2003 AAPG Bulletin on fault seal edited by Davies and Handschy offers a more comprehensive review of the fault seal process, calibration and prediction.

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Notes