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DAKOTA OUTCROP GEOLOGY AND SEQUENCE STRATIGRAPHY, CHAMA BASIN, NEW MEXICO

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Abstract.—The Dakota Formation of the Chama Basin records the initial incursion of the Western Interior Seaway into the study area. Dakota outcrops on US Highway 84, northwest of the Ghost Ranch, and at Heron Dam, south of Chama, New Mexico correlate with each other and with well logs located 19 and 44 miles (30.4 and 70.4 km) to the west based on comparison with outcrop gamma-ray logs. The outcrops contain three Dakota depositional sequences defined by unconformities. One of the sequence-bounding surfaces within the formation, S3, truncates and replaces the K2 unconformity between Lower and Upper Cretaceous units and, thus, has regional importance. Sequence stratigraphic variations in the Dakota have economic significance because they may control fluid distribution in the subsurface.

INTRODUCTION

The Dakota Sandstone of the Chama Basin records the initial Late Cretaceous incursion of the Western Interior Seaway. The formation, too, is a prolific gas producer in the San Juan Basin. Because of this, understanding the nature of the rocks on outcrop is useful, particularly if the outcrop section correlates to the subsurface. The Chama Basin, in which this study took place, is adjacent to the east side of the present San Juan Basin. During the Cretaceous, there was no separation between the two. The Dakota sections this paper describes are located on US Highway 84, northwest of the Ghost Ranch about 9 miles (2.75 km) south of Cebolla, and at Heron Dam, both in New Mexico south of the town of Chama in Rio Arriba County (Fig. 1).

The following discussion of outcrop stratigraphy at both locations includes summary lithologic descriptions, outcrop gamma ray logs and sequence stratigraphic interpretations.

There appear to be three depositional sequences within the Dakota, and one of the identified sequence-bounding surfaces has significant regional importance. Previous work by the author (Varney, 2000) supports this interpretation and presents detailed lithology on a foot by foot basis, thin section analyses and other details. In the interest of saving space, these details are not repeated here except where necessary for clarity.

BACKGROUND STRATIGRAPHY

Lithostratigraphic nomenclature Upper and Lower Cretaceous rocks in the study area, in normal stratigraphic order, is as follows:

Greenhorn Limestone
Graneros Member of the Mancos Shale
Dakota Formation
- Twowells Sandstone Tongue of Dakota
- Whitewater Arroyo Tongue of Mancos Shale
- Paguate Sandstone Tongue of Dakota
- Clay Mesa Tongue of Mancos Shale
- Cubero Sandstone Tongue of Dakota
- Oak Canyon Member
- Encinal Canyon Member

~~~~~ *(Unconformity K2 between Lower and Upper Cretaceous)*
Burro Canyon Formation
~~~~~ *(Unconformity K1 between Lower Cretaceous Burro Canyon and Upper Jurassic Morrison Formations.)*

Note that the Dakota and Mancos intertongue above the basal Dakota sand interval and that they are, therefore, age equivalent in part (Landis et al., 1973; Nummedal and Molenaar, 1995).

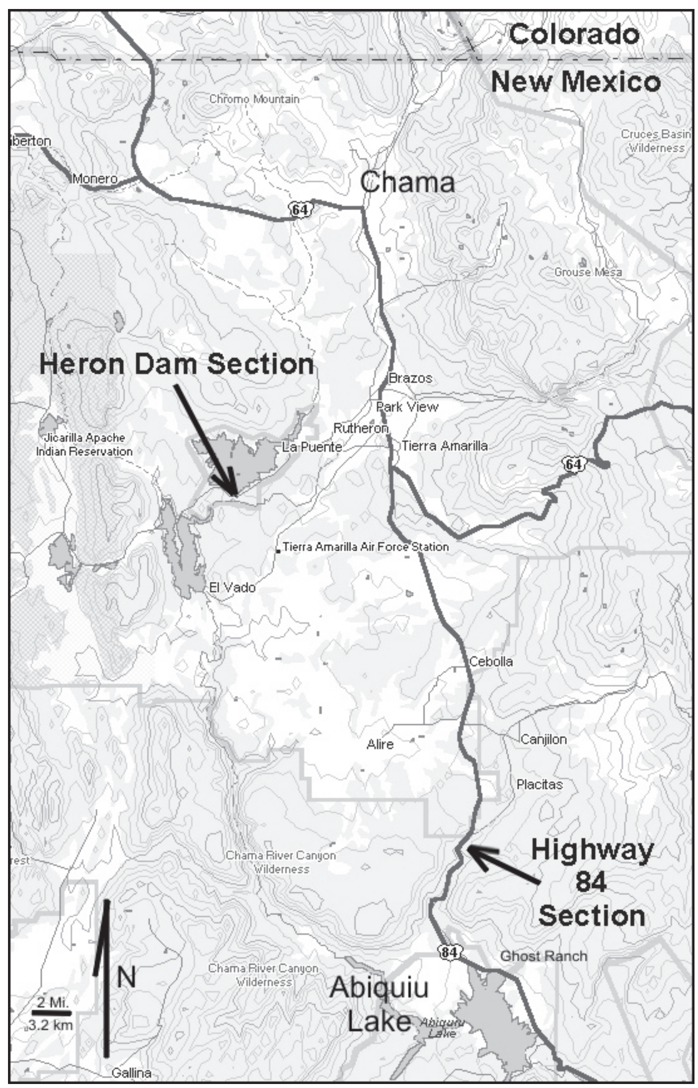

FIGURE 1. Index map showing the two outcrop locations discussed in this paper and their relationship to Chama, Abiquiu Lake and the Ghost Ranch.

ENVIRONMENTS: CHARACTERISTICS AND BASIS FOR INTERPRETATION

All of the rocks within the Dakota in the study area are shallow and deeper water marine. They rest, however, on continental rocks of the Burro Canyon Formation. Most authors interpret the Burro Canyon as braided stream or alluvial plain deposits marginal to a positive area. The Zuni-Defiance uplift southwest of the study area was active at the end of Late Jurassic time.

Outcrop analysis shows that the Dakota section was deposited in two main environments of deposition: very shallow tide-dominated and more open marine wave and storm-dominated.

Wave and storm-dominated rocks fit into six facies classifications (A through F) as follows:

A. Black shales with thin bentonites
B. Medium gray shales with very thin siltstone to very fine grained sandstone interbeds and rare, very thin bentonites. Widely separated, rare burrows casts.
C. Light gray, bioturbated to thin-bedded, fine to very-fine grained sandstones that display hummocky cross stratification in less bioturbated intervals.
D. Fine to very-fine grained, bioturbated to burrowed, cross-bedded sandstones.
E. Fine to medium-grained, very locally burrowed, cross-bedded to parallel bedded sandstones.

These facies closely parallel the shoreline succession from deep offshore, A, to shallow water foreshore, E, presented in Table 1.

Shallow, tide-dominated rocks of the Dakota comprise facies F. Facies F contains four subdivisions as follows:

F4. Fine to very-fine grained sandstones with thin herringbone crossbed sets, shale drapes and flaser bedding.
F3. Very fine-grained, thin, wavy bedded sandstones with abundant shale drapes.
F2. Very thin, laminated, dark gray siltstones and shales with remnant lenticular bedding.
F1. Light gray, gravelly, cross-bedded, very-fine grained sandstones and shales.

These facies closely parallel the tidal flat succession from distal sand flat, F4, to proximal gravel flat, F1, shown in Table 2. A regressive tidal flat depositional environment is shown in Figure 2.

The usefulness of these facies categories will become apparent in the following discussion of lithologies and unconformities. They are very important for constructing the sequence stratigraphic history.

DAKOTA UNCONFORMITIES

The definition of a depositional sequence is “a relatively conformable succession of genetically related strata bounded by unconformities and their correlative conformities” (Mitchum, 1977; VanWagoner, et al., 1988). There are several other definitions (Mitchum, 1977; Jervay, 1988; Posamentier, et al., 1988; Scott, et al., 1988), but all agree that the sequence-bounding unconformity surface represents erosion. Weimer (1992) and Pemberton and MacEachern (1995) allow the erosion to be either subaerial or submarine. This refinement of the definition in the marine environment is very important because it allows identification of unconformities in a marine section based on criteria such as interrupted facies successions where there is no indication of subaerial exposure. This can be helpful in tracing lithologically similar units containing a correlative conformity. Correlative conformities are the basinward expression of nearly every unconformity identified on the sea margin (Fig. 3). Because they are bounded by unconformities, defining sequences becomes a matter of identifying bounding erosional surfaces. In this study, conventional criteria (Varney, 2000) were used to help identify unconformities on outcrop.

AN INTERPRETATIONAL PROBLEM IN THE STUDY AREA

As mentioned earlier, all sandstones and shales in the study area are marine - a setting in which many unconformities are not obvious because they are correlative conformities. Help in determining what comprises sequence boundaries under conditions where there may not have been subaerial exposure comes from several authors.

Nummedal and Molenaar (1995), in their work on the Gallup Sandstone in the San Juan Basin, showed how both transgressive and lowstand surfaces relate to shallow shelf distal strata by proposing two new terms: the regressive surface of marine erosion (RSME) and the regressive surface of subaerial exposure (RSSE) (Fig. 5). The surfaces come in pairs. The surface at the base of the regressive shoreface is the RSME. The surface at the base of overlying incised channels is the RSSE and is considered by the authors to represent the sequence boundary. Both surfaces are initiated by forced regression in the sense of Posamentier et al. (1992). Figure 4 is a schematic illustration of their mostly regressive shoreface tongues in the Gallup Sandstone. In the most seaward direction, on the right side of the diagram, the only visible sign of changes in relative sea level is stacked, trun-

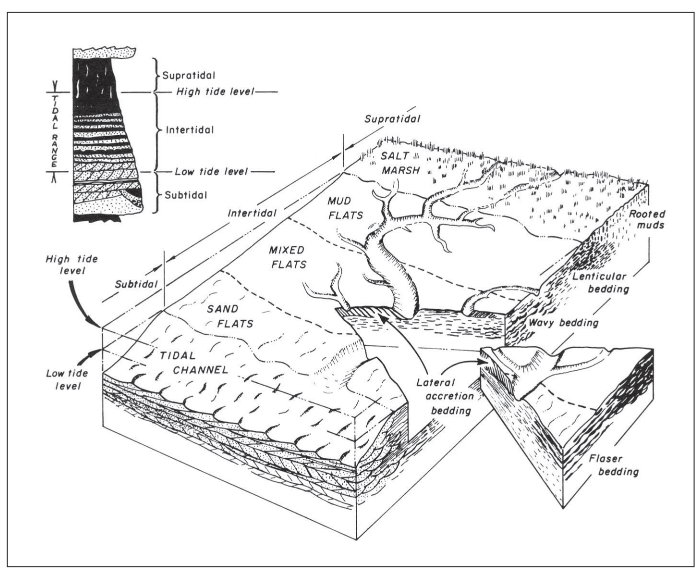

FIGURE 2. An example of the tidal flat environment with an idealized regressive succession in the upper left. From Dalrymple (1992).

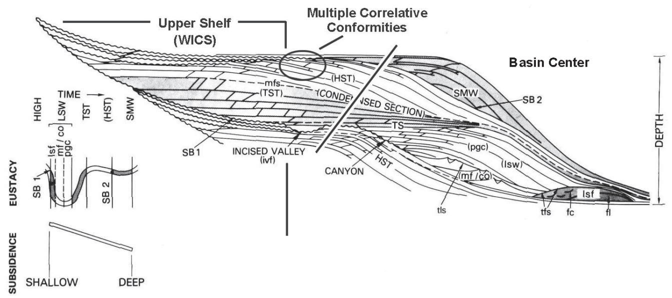

FIGURE 3. The classical Exxon sequence diagram. The upper shelf is, on the left side of the diagram, is well exposed the Dakota of the Chama Basin. In the upper shelf position, there are many unconformities that pass basinward into correlative conformities. Further, note how sequence boundaries 1 and 2 (SB1 and SB2) show no subaerial exposure on the basinward side – they are marine unconformities. Modified from Baum and Vail (1988).

cated shorefaces. The authors use the term "ravinement surface" as a transgressive surface. This is similar to Weimer's (1992) "transgressive surface of erosion" and is, again, in the same sense as Posamentier et al. (1992). There are differing interpretations about the significance of a surface in the position of Nummedal and Molenaar's RSME. Other workers give it greater sequence stratigraphic meaning.

Pemberton and MacEachern (1995) describe forced regressions causing a regressive marine erosion surface that has never been subaerially exposed. Its signature is sharp based sands, like those in the Dakota and like those Posamentier et al. (1992) have documented in the Cardium Formation in Alberta, Canada. The idea is that falling sea level causes a zone of basinward-moving wave action that erodes the shoreface and creates a sequence boundary. Posamentier et al., call this surface a "regressive surface of erosion" and in this paper it will be abbreviated as RSE. The fine-grained shoreface sandstones above the RSE are most correctly considered part of the lowstand of the overlying sequence. Outcrop work in the present study suggests that much of the Dakota can be explained by applying the RSE concept because the overlying regressive surface of subaerial exposure, the RSSE of Nummedal and Molenaar, is not present.

SURFACE NAME ABBREVIATIONS USED IN THIS STUDY

Kd is the abbreviation used for Cretaceous Dakota Formation throughout this paper. There are two K, or Cretaceous, unconformities of primary significance in this study: K1 is the unconformity between the Jurassic Morrison Formation and the base of the Lower Cretaceous Burro Canyon Formation, and K2 is the unconformity between the Lower Cretaceous Burro Canyon Formation and the Upper Cretaceous Dakota Formation. These designations fit with current use in the area, though it must be pointed out that at least one author begins the sequence with K0 at the base of the Cretaceous (Dolson and Weimer, 1992).

S1, S2 and S3 are identified surfaces in this study that are within the Dakota Formation and that have sequence stratigraphic significance. At least one, S3, has regional extent (Varney, 2000, Owen and Head, 2001).

HIGHWAY 84 SECTION

The section at Highway 84 is located approximately nine miles (14.4 km) south of Cebolla, New Mexico on the west side of US Highway 84 (Fig. 1). The roadcut rises northward through a nearly complete Dakota section starting with an excellent exposure of the Burro Canyon Formation.

There has been much debate over the years about the positions and names of sandstones and shales in the Dakota section at Highway 84 and even over the precise location of the K2 unconformity (e.g. Burrows et al., 1974, Grant and Owen, 1974; Saucier, A.E., 1974; Gries and Vandersluis, 1989). This discussion sidesteps most of that by considering only significant surfaces and sandstone stacking patterns between those surfaces. It will be seen later that it is possible to correlate this section to the north and to wells in the subsurface using sequence stratigraphic methods in addition to lithostratigraphic methods. Subsurface names can be traced with some confidence to the various outcrops, and the results are sometimes surprising. A table of name equivalents is provided at the end of this section.

The Highway 84 section contains three unconformities (Fig. 5) and at least two shoreface parasequences. The lowest unconformity is the regional K2 surface that separates the underlying Burro Canyon Formation from the Dakota. This discussion refers to lithologic "units," such as unit 1, unit 10, etc. These are numbered stratigraphic intervals on both the columnar sections and the narrative descriptions of Varney (2000).

Description, Analysis and Interpretation

The section at Highway 84 has a measured thickness of about 160 feet from the K2 unconformity to the top of the uppermost sandstone. The following discussion breaks the section into three intervals each of which includes an enlarged portion of the strati-

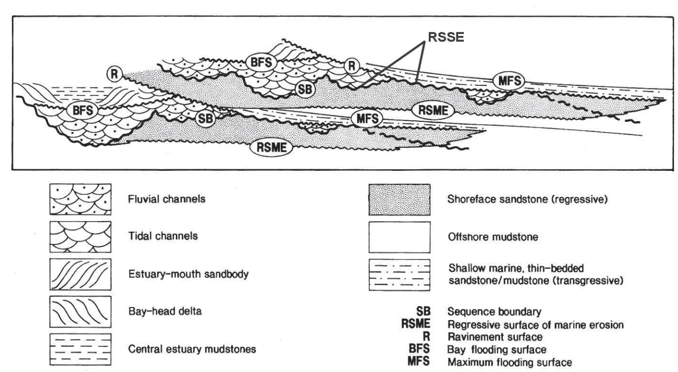

FIGURE 4. The regressive shoreface model of Nummedal and Molenaar (1995) with the term "RSSE" added to clarify its position as a sequence boundary. The authors do not consider the RSME a sequence boundary because the contact is not always erosional "nor would such a surface be expected to have chronostratigraphic significance." They assign the sandstones overlying the RSME to the "falling stage systems tract." From Nummedal and Molenaar (1995).

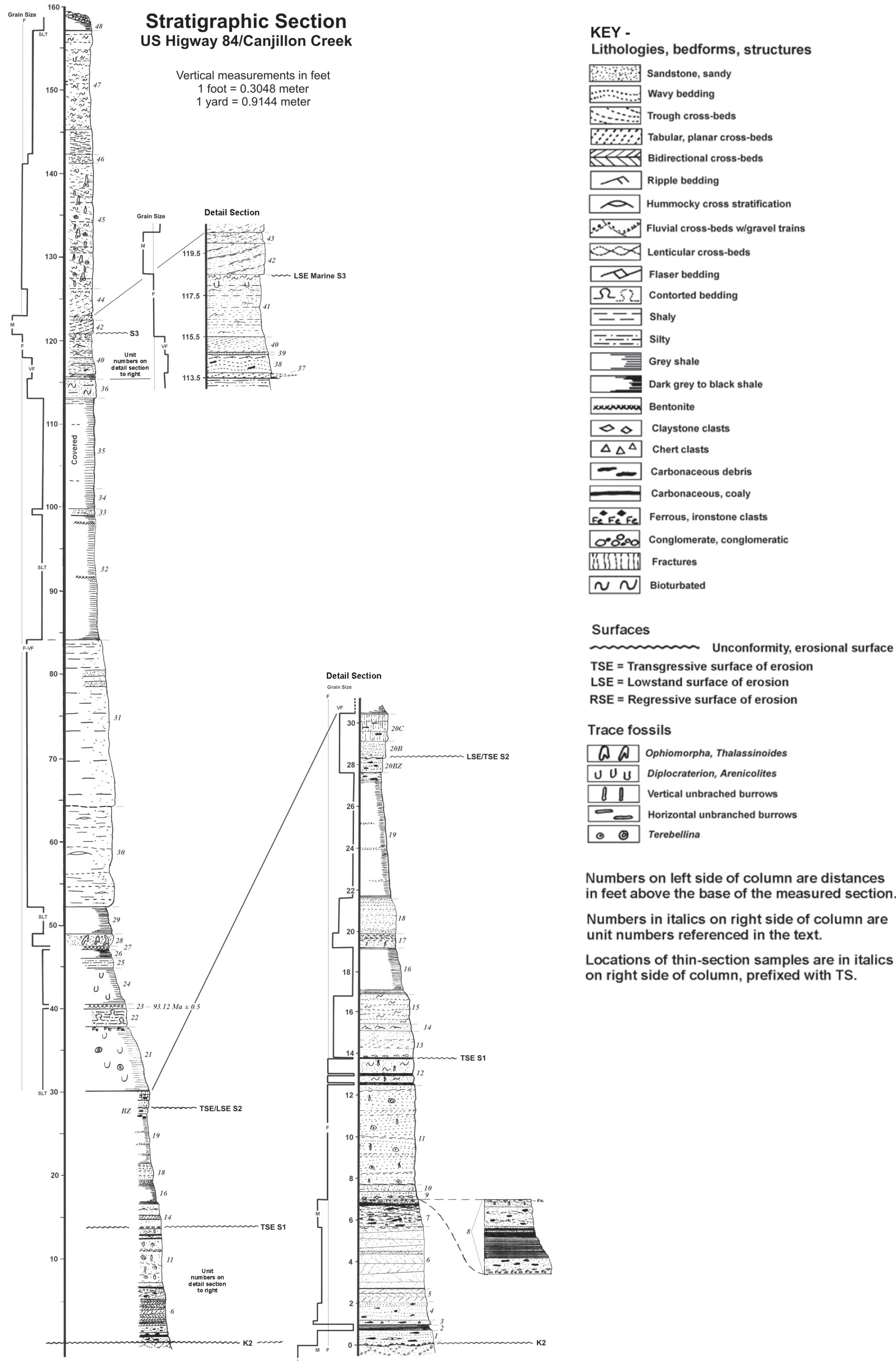

FIGURE 5. The stratigraphic column at Highway 84 with a key to lithologies, bedforms and structures. The overall section is on the left with detail sections to the right. The numbers on the right sides of the columns are lithologic unit numbers and the units are described in detail in Varney (2000). Numbers on the left sides of the columns are distances in feet above the base of the measured section.

graphic column shown in Figure 5 as well as pertinent photographs. Numbers on the right sides of the columnar sections are the lithologic unit numbers.

Interval K2 to S1

This interval is depicted in the short column on the right side of Figure 5. Figure 6 is a photographic panorama, in two parts, of the outcrop.

Burro Canyon rocks are fluvial conglomerates with abundant cross-bedding and gravel trains on the cross-bed surfaces. The K2 surface is defined by an ironstone hardground that contains a lag gravel and that is disconformable on the Burro Canyon. Laterally, the surface is uneven and truncates several units in the Burro Canyon. The lithology immediately on top of the unconformity is a thin, medium-grained, wavy-bedded shaly sandstone containing carbonaceous debris and weathered chert fragments. The sandstone is similar to that in the Burro Canyon and is likely reworked from that formation. The presence of carbonaceous debris and scattered tripolitic chert like that in unit 1 has been used by several authors to define the base of the Dakota (Stokes, 1952; Owen, 1973; Aubrey, 1986, 1988).

At slightly less than 14 feet (4.3m) above the K2 unconformity, there is a subtle surface developed on a medium-grained, bioturbated sandstone that contains a layer of mudstone clasts on a very thin shale. The overlying sandstone is medium to fine grained, non-bioturbated and contains a zone of tabular-planar cross-beds. The nature of the section overlying the mudstone clasts is one of fining grain size, reflecting deepening water upward. The surface may represent the increased energy of a landward-stepping rising water wave base and, therefore, be a transgressive surface of erosion (TSE) here designated S1. As shown later, this surface does not appear to have regional extent. There are other levels between the K2 unconformity and this one that also concentrate mudstone clasts, but they are clearly related to local channels within the interval.

The section between K2 and S1 has the characteristics of a *transgressive* tidal flat. An idealized estuary/tidal flat is shown in Figure 7 (from Dalrymple, 1992). For comparison, Dalrymple's *regressive* tidal flat succession is shown in Figure 8 along with a possible *transgressive* succession. Starting at unit 1, which lies directly on the K2 surface, and working upward through unit 7, there is carbonaceous sandstone, thin bedded black shale, thin to wavy bedded carbonaceous sandstone, planar bidirectional-cross-bedded sandstone and, at the top, flaser-bedded carbonaceous sandstone. Except for the black shale at the base, the interval varies only slightly in grain size. The sequence of these units is inverted from that shown on the left side of Figure 8 and marks a transgressing shoreline in which the mud flat was overridden by mixed flat that was overridden by sand flat.

At the top of the tidal flat unit there is an iron-stained, thin interval with mudstone clasts. It thickens to the north and

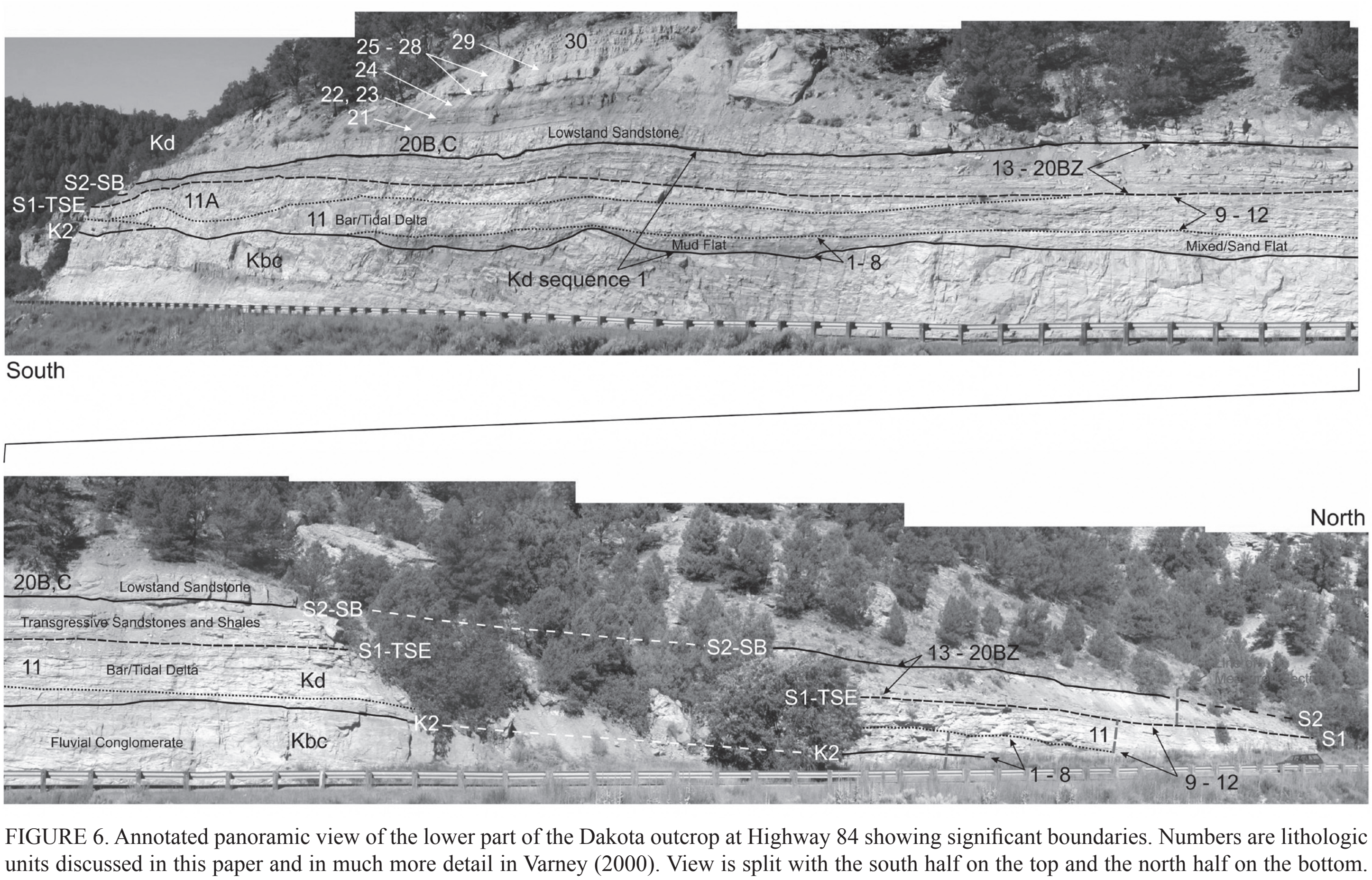

FIGURE 6. Annotated panoramic view of the lower part of the Dakota outcrop at Highway 84 showing significant boundaries. Numbers are lithologic units discussed in this paper and in much more detail in Varney (2000). View is split with the south half on the top and the north half on the bottom. See Plate 5 for a color version of this figure.

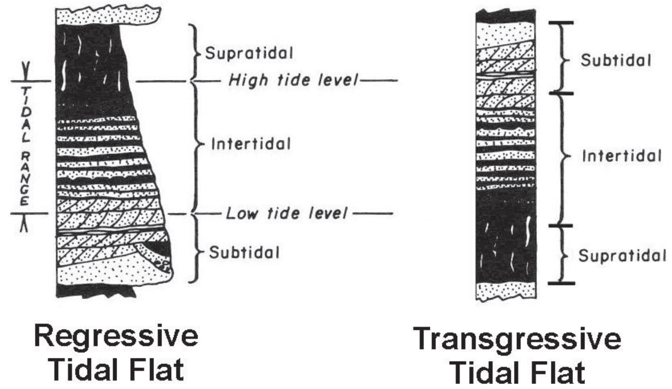

FIGURE 7. On the left is Dalrymple's (1992) diagram of the bed succession in a regressive tidal flat environment. Grain size becomes finer upward. On the right, the graphic has been inverted to show the expected succession in a transgressive tidal flat. The grain size is coarsening upward. The interval between K2 and the base of the overlying barrier island/tidal delta/washover fan beds at Highway 84 Dakota outcrop is similar to the graphic on the right.

becomes unit 8, a possible tidal channel deposit (Figs. 5, 6 and 7). Similar to the succession from units 2 to 7, unit 8 also contains carbonaceous, flaser-bedded to lenticular-bedded sandstones and a thick black shale interval that represents either abandoned channel fill or mud flats at times of lower water. Like unit 8, unit 9 also contains a zone of mudstone clasts in a thin, wavy-bedded sandstone. The surface between the two mud clast zones is the time equivalent of the channel deposits in unit 8, therefore it is here considered a local diastem.

Between the zone of clasts at the base of unit 9 and about 12.5 feet (3.8m) above K2, is a large scale feature, unit 11 (Fig. 8) that displays sweeping tangential cross-beds that alternate in direction from north to south. Grain size over the interval is remarkably uniform at fine to medium-grained sand. Individual beds in the interval contain tabular/planar cross-beds. There is rare vertical and horizontal burrowing. The top of unit 11 is capped by a thin shale. Unit 12 contains both thin shales and bioturbated fine to medium-grained sandstone. The top of unit 12 is marked by a thin zone of clay pebble lag. This lag is not associated with a channel and is here named S1. It is a candidate for a transgressive surface of erosion (TSE) because the character of the sediments above is increasingly deep water, i.e., decreasing grain size and increasing shaliness.

Bedforms on the open ocean side of a tidal flat system can grade seaward into megaripples and sand waves (Belderson et al., 1982, Dalrymple, 1992). However, if the tidal flat is within a lagoonal setting, it would be reasonable to expect a barrier island/ tidal delta on the oceanward side. Unit 11, because of its bidirectional nature, appears to represent either reciprocal washover deposits across a barrier island or part of a tidal delta in which flood and ebb tidal flow were nearly identical. Unit 11 overrides the tidal flat, moving shoreward, as would be expected in a transgressive system. Further, it is capped by the clay pebble lag of surface S1, a TSE. A TSE is characteristic of a shoreface transgressing a barrier bar (Fig . 9).

A reasonable question is how do you preserve a mud flat in a transgressive environment? The barrier island is a possible key. As the island moves shoreward across the lagoon, washover

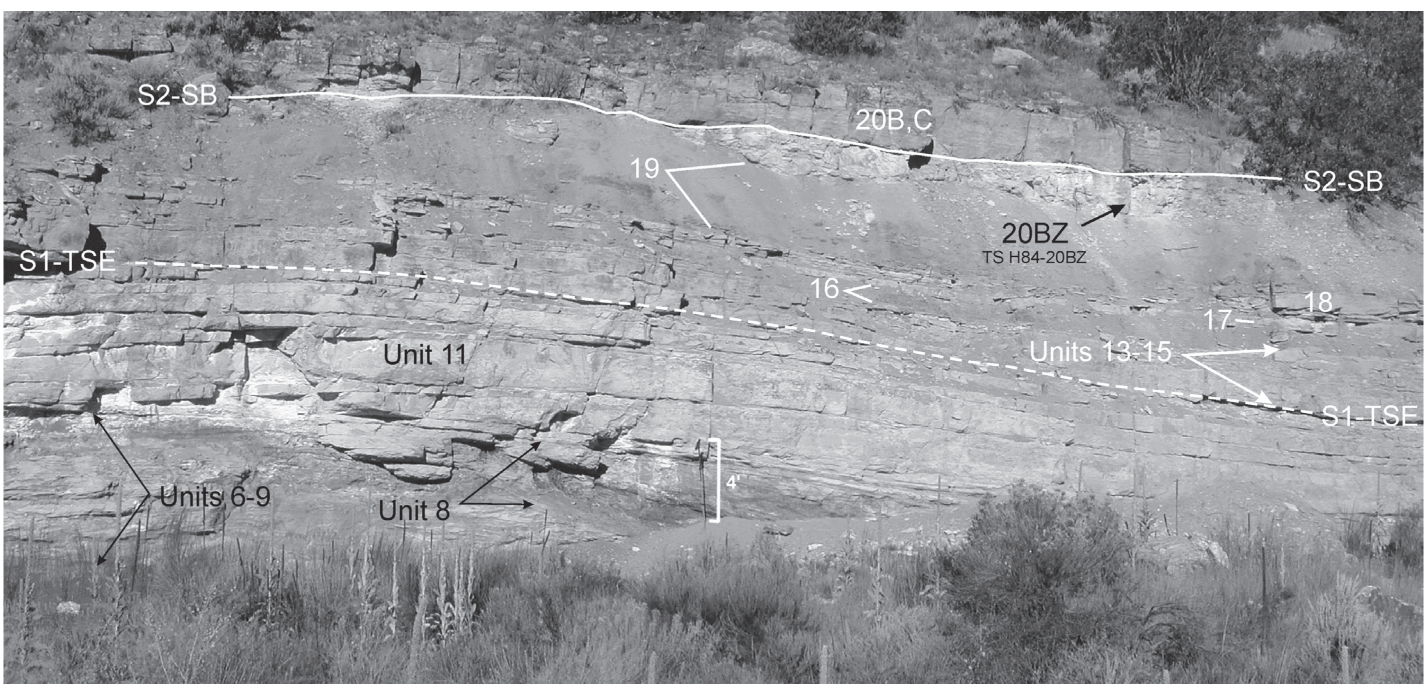

FIGURE 8. Units 6 through 20C at the north end of the base of the Highway 84 outcrop (see figure 6). Note position of unit 11, part of a suspected barrier bar sandstone beneath TSE surface S1. Unit 8 is a tidal channel that thins to 0 southward (see figure 5). X-ray diffraction analysis of a sample from Unit 20BZ shows a high concentration of kaolinite. The notation TS H84-20BZ refers to a thin section described in Varney (2000). Hiking staff for scale is about 4 feet high. See Plate 6A for a color version of this figure.

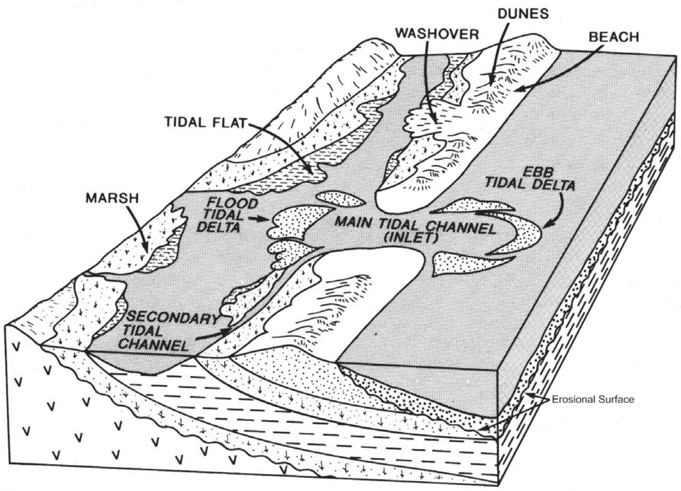

FIGURE 9. The shoreface/lagoon model of Reinson (1992). Note erosional surface on seaward side of barrier island caused by wave action. As relative sea level rises, this becomes a TSE.

sands cover the flat and protect the mud (Fig. 10). This movement would produce the vertical succession observed at this location. Furthermore, the presence of the mud flat sediments strongly suggests that a protective mechanism such as the one proposed was at work. This area, therefore, had at least a partially protected coastline at least until the rate of transgression increased and a TSE truncated the island, as suggested by Figure 9 and diagrammed in Figure 10.

Interval S1 to S2

Unit 13, at the base of which the S1 lag is located, is a fine-grained sandstone with zones of tabular/planar cross-beds. Moving up to the base of unit 16 (Fig. 8), there is first a zone of rippled beds and finally a bioturbated sandstone with remnant wavy laminations. This is typical of a gradation from upper through middle shoreface. Unit 16, a dark gray non-bioturbated shale, rests sharply on top of the bioturbated sandstone of unit 15 and represents deeper water, offshore conditions.

Unit 17 is a medium-grained sandstone that displays bidirectional tabular/planar cross-beds and minor burrowing that lies with abrupt contact on unit 16. It is overlain by a fine-grained sandstone in which faint horizontal to wavy laminations decrease in spacing upward. Unit 19 is a black marine shale containing thin bentonites. Units 17 and 18 do not contain hummocky cross stratification or other obvious signs of storm deposition, so they may represent a minor lowering of relative sea level during a pulse related to a high- frequency sea level event. The deep water nature of unit 19 sitting sharply on unit 18 implies that the pulse was a minor event in an overall deepening cycle.

In the field, unit 20 was initially considered one sandstone. However, as the columnar section and written descriptions show, it is actually three separate sandstones of which the lowest is of greatest importance. From the base upward, they are unit 20BZ, unit 20B and unit 20C. At approximately 28 feet (8.6m) above unconformity K2 on the measured section, there is a very prominent bleached zone designated unit 20BZ. Petrographic analysis of this unit and x-ray diffraction analysis of a sample taken from the same location reveals that the zone contains, in addition to quartz and minor chert, K-spar and abundant kaolinite. Because kaolinite can form as an alteration of feldspar under exposure to acidic freshwater (Pettijohn, 1957; Weaver, 1989), it is a good indicator that the environment changed at this level from marine to fresh, or that the surface was subaerially exposed.

Unit 20BZ is a carbonaceous, very soft, very fine-grained clayey sandstone. The sandstone above, 20B, is harder, blocky weathering, very fine-grained and lacks carbonaceous debris. The surface itself is uneven and appears eroded although there is no evidence of a lag gravel or of subaerial exposure such as rooting. Several hundred feet to the north of the location in Figure 8, unit 20BZ thins and is overlain with angular unconformity by the continuation of unit 20B. Because of the depth of weathering at the original location and the angular relationship to the north, this surface is interpreted to represent a lowstand surface of erosion (LSE) and is here designated S2.

The interval from S1 to S2 marks a transgression caused by a rise in relative sea level. The rise was interrupted by a high-frequency regressive event that exposed unit 20BZ and allowed formation of a weathered zone. Unit 20BZ may have been deposited during a very short-lived highstand preceding a forced regression marked by surface S2. It follows that units 20B&C represent lowstand sandstones deposited on the unconformity before the transgressive phase marked by higher units.

Dakota Sequence Kd1 is the interval between unconformities K2 and S2. At least one local diastem is present in the interval between K2 and S1, as previously mentioned.

Based on facies types, the interval from S1 to S2 alternates between shallow-water sandstone facies F and dark gray shale facies B (see Tables 1 and 2) that contains a few thin sandstones such as units 15 and 18. Because there are several facies zones missing between facies F and B, the question becomes one of how to explain the association. One of two mechanisms seems appropriate: either high frequency water depth changes, or, a combination of tidal changes and storm activity that produced storm beds. The simplest explanation for the thin sandstones in the deeper

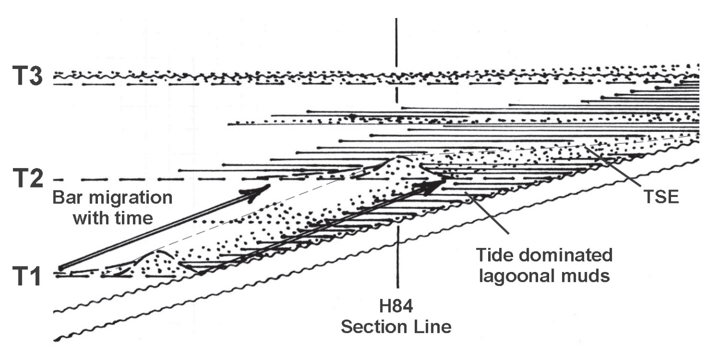

FIGURE 10. Diagrammatic representation of how a tidal flat shoreward of a barrier island can be preserved during a transgression. T1, T2 and T3 are time lines. The TSE across the top of the barrier bar most likely forms during times of peak transgression at a rising inflection point on the sea level curve.

TABLE 1 – The shoreline environment. Letters A through E after the environment names correspond to facies A through E mentioned in the text and used on the columnar sections.

	Foreshore - E	Shoreface			Offshore - A
		Upper –D	Middle – C	Lower -B	
Bedding	Subparallel to low angle seaward dipping laminations – wedge sets	Subparallel to low angle seaward dipping wedge sets, multidirectional trough cross stratification, bi-directional planar cross bedded sets	Low angle wedge sets of parallel laminae, trough cross stratification, SCS, rare HCS	Ripple cross stratification, disturbed horizontal to undulatory lamination	Disturbed undulatory parallel lamination
Bed forms, physical sedimentary structures	Some convolute laminae and flame structures	Some convolute laminae and flame structures	Oscillation and flow ripples	Flow ripples, rare oscillation ripples, HCS and SCS	HCS and SCS, rare oscillation ripples
Grain size	C+ → MG	C+ → MG	M → FG	FG → VFG	VFG → silt
Distribution	Well sorted, well winnowed	Well sorted, well winnowed	Well sorted, well winnowed, minor silt	Moderately well sorted, graded	Moderately well sorted
Energy	Very high, swash zone	Very high, within breaking wave zone	Moderate to very high, shoaling to breaking wave zone, storms very important	Low to high, storm wave dominated	Very low to moderate, below fair-weather wave base
Boundaries	Much scour and crossbedding		Gradational to sharp, erosive	Gradational to sharp, erosive	Gradational to sharp, erosive
Ichnofossils*	*Skolithos, Macaronichnus*	*Skolithos* ichnofacies	*Skolithos* ichnofacies	*Cruziana* ichnofacies	Restricted to full *Cruziana* ichnofacies
Diversity	Low	Moderate	High	Very high	Very high
Abundance	Low	Moderate	Highly variable	Highly variable	Very high

**Cruziana* ichnofacies (deposit feeders): *Planolites, Teichichnus, Terebellina, Palaeophycus, Thalassinoides, Cylindrichnus, Chondrites, Asterosoma, Rosselia.*
**Skolithos* ichnofacies (suspension feeders): *Skolithos, Conichnus, Diplocraterion, Ophiomorpha, Arenicolites, Bergaueria, Palaeophycus.*
References: MacEachern and Pemberton (1992); Reinson (1992); Walker and Plint (1992)

water shale interval is the last, storm activity. Sedimentary structures within the sandstones support that interpretation.

Interval S2 to Top of Section

Working upward from surface S2, the upper two sandstones of unit 20, 20B and 20C, are hard, blocky, carbonaceous and in the uppermost, unit 20C, there are numerous plant impressions. Unit 20B may contain root traces, but it is difficult to be sure because the unit contains numerous small vertical fractures. The bleaching seen in unit 20BZ may reflect plant growth in a fresh to brackish water pond/lagoon evidenced by the abundance of impressions in unit 20C.

Unit 21 is a medium gray, shaly siltstone, depicted as a shale on the columnar section, that contains trace fossils *Terebellina* and *Diplocraterion.* Immediately above it is a two-foot (0.61m) thick, medium gray sandstone with horizontal and highly contorted bedding that contains silicified trace fossils of *Ophiomorpha*. The contorted bedding is similar to what would be expected as a result of soft sediment slump on a delta front. It is overlain by a thin bentonite that was sampled and age dated using the Ar/Ar technique yielding an age date of 93.12 ± 0.5 Ma (latest Cenomanian/earliest Turonian; Gradstein, 1995). Above the bentonite is more medium gray shale like that below, a thin siltstone, a dark gray to black, thin-bedded shale (unit 26, with a TOC content 1.65), and a thin bentonite, unit 27, which is capped with an 18 inch (0.46m) thick, very hard, silica-cemented, shaly, medium reddish gray sandstone, unit 28. The sandstone contains vertical *Ophiomorpha, Thalassinoides* and other trace fossils and is notable not only for its hardness, but because it contains thin alternating zones that are heavily burrowed and others that are not. Sand grains from the unburrowed zones fill burrows in the underlying zones, so this sandstone was deposited in an area with thin, sheet-like sand pulses such as could result from storm events washing sand from a nearby shoreface. There is a four-foot (1.2m) thick gray shale, unit 29, above, that contains numerous U-shaped burrows *(Diplocraterion?)*. From this description, it is apparent that the interval from unit 20C upward to unit 29 is dominated by shales and siltstones with a few burrowed, very fine grained sandstones. The very fine grain sizes, dark gray shales and bentonites give some credence to this being an offshore environment, like facies A, that occasionally saw sandstone deposition initiated by storms.

Units 30 and 31 are fine to very fine grained soft sandstones with an appreciable shale content, and thin, discontinuous bedding. There is very little indication of burrowing, if any. However, the entire interval contains rare hummocky cross stratification (HCS) that increases both in amplitude and wavelength above the base. Thin, clean sandstone intervals occur near the top of the interval. In the classical sense of Harms et al. (1975), this interval would represent a shelf sand because of the HCS. Pemberton and MacEachern (1995) use HCS as one of the criteria for identifying the lower shoreface. Even though there are not obvious trace fossils in this interval, its relationship to the shaly intervals above and below support a lower foreshore to upper shoreface environment.

Units 32 to 36 comprise a shale/shaly sandstone section almost 30 feet (9.2m) thick containing a 6 inch (0.15m), medium reddish

TABLE 2 – The tidal flat environment. Letters F1 through F4 after the environment names correspond to facies F1 through F4 mentioned in the text and used on the columnar sections.

	Gravel Flat* - F1	Mud Flat – F2	Mixed Flat – F3	Sand Flat – F4
Tidal Flat Zone →	Upper supratidal	Lower supratidal	Intertidal	Subtidal
Bedding	Shallow cross bedded to parallel inclined	Thin, parallel horizontal, lenticular to wavy	Wavy to flaser beds, climbing ripples, lateral accretion beds associated with small channels	Thin to thick bedded, flaser beds, bi-directional crossbeds, reactivation surfaces
Bed forms, physical sedimentary structures	Scour surfaces, tidal channels	Minor ripples, tidal channels	Ripples, reactivation surfaces, small channels	Ripples, reactivation surfaces, climbing ripples, herringbone, small channels
Grain size	Gravel → Slt	Slt → VFG	VFG → MG (rare)	F → CG (rare)
Grain Size Distribution	Gravel particles as trains, otherwise uniform within beds	Fairly uniform, fining upward within lamina	Fining upward within lamina	Uniform to abrupt fining to clay drapes
Horizontal tidal oscillation	Very high to low – storm tides, spring tides	Low to high – upper normal tide zone	Low to moderate	Moderate, bi-directional
Boundaries	Sharp on underlying reworked beds	Gradational from underlying mixed flat	Gradational to scour	Gradational, much scour
Ichnofossils*			*Skolithos, Planolites*	*Skolithos, Arenicolites, Diplocraterion*
Diversity		Low	Low	Moderate
Abundance		Rare	Low to moderate	Moderate

*Gravel flat characteristics inferred from Dalrymple (1992) and Belderson et al. (1982). Field relationships suggest that the gravel flat results from winnowing of silt and clay from underlying braided stream deposits. The gravel flat is thus the proximal end of the tidal flat system.
References: Pemberton and Frey (1992); MacEachern and Pemberton (1992); Dalrymple (1992); Sellwood (1975); McKenzie (1975)

gray, very fine grained sandstone, unit 33, in about the middle of the interval. Below the sandstone, the shale is dark gray to black and contains thin bentonites. Above the sandstone, the shale is medium gray and silty. The color change represents a change in water depth from a lower offshore environment to an upper offshore environment and on this basis, the shales are assigned to deep-water, shale facies A, unit 32, and shallow-water sandstone facies B, unit 35.

The descriptions of units 36 through 41 suggest that they were deposited in a middle to lower shoreface environment. Unit 36 is a fine to very fine-grained, shaly, medium gray sandstone with large-scale hummocky cross-beds near the base and intense bioturbation above. Unit 37 is a light gray, hard, very fine-grained sandstone. Units 38 to 41 are fine to very-fine grained, shaly, contain some ripple cross-beds and are burrowed to bioturbated. The interval, units 36 to 41, fits into shaly sandstone facies C, thus continuing a shallowing upward pattern that started with black shale facies A in unit 32 and progressed through the dark gray shale facies B of unit 35.

There is an abrupt change in grain size and depositional style between units 41 and 42. Unit 41 is fine grained, shaly, thin-bedded and bioturbated at the top whereas unit 42 is medium grained, strongly cross-bedded, non-bioturbated and sharp based. The characteristics of unit 42 place it in shallow-water sandstone facies F. Shalier facies D and E are, therefore, missing.

The sharp contact between units 41 and 42 combined with the missing facies suggest that there is a marine erosional surface between them, here called S3. The designation is provisional because the surface is subtle and the only criteria suggesting it exists are missing facies and a grain size change. The overall succession is one of shallowing upward. In a normal shoreline progression with uninterrupted, uniform rate shallowing, the expected result is a gradational contact in which there is not a sudden shift in facies. If the shallowing rate was not uniform, however, there may have been a forced regression (*sensu* Catuneanu, 2003). In such an instance, Posamentier et al. (1992) indicate that "the major feature of forced regressions will be the abrupt occurrence of anomalously coarser and more proximal sediments in a distal marine setting." Pemberton and MacEachern (1995) state that forced regression shorefaces overlie a sequence boundary and "are sourced from sediment derived from the cutting of the unconformity." Thus, S3 may represent a sequence boundary that correlates to a more landward subaerially-exposed erosion surface. Units 36 to 41 represent a highstand systems tract under surface S3 and the overlying sandstone, unit 42, becomes a member of the lowstand systems tract of the overlying sequence if this interpretation is correct.

In a sense, S3 could be a regressive surface of marine erosion (RSME) as proposed by Nummedal and Molenaar (1995) for sharp-based shoreline sandstones. As such, it would not represent a sequence boundary, rather it would mark the base of what the authors call "the falling stage systems tract" in their work on the Gallup Sandstone, which is stratigraphically above the Dakota. The sequence boundary would be at the top of the falling stage systems tract on what the authors call a regressive surface of subaerial exposure, their RSSE, and would correlate to the movement of fluvial and estuarine sediments over truncated shorefaces. On the other hand, Pemberton and MacEachern (1995) believe that sharp based sandstones, such as unit 42, are a response to a forced regression and are thus properly assigned to the lowstand systems tract of the overlying sequence. Later, it will be shown that S3 is a likely correlative to a similar surface at Heron Dam.

The top of the measured section appears to be a marine flooding surface in which a deep-water offshore shale sits with abrupt contact on top of the stratigraphically highest sandstone. The top of the exposure is covered with Quaternary alluvium and the exact nature of the contact is unclear.

The interval between S2 and S3 is provisionally identified as Sequence Kd2 at Highway 84. The interval from S3 to the top of the section is an incomplete part of Sequence Kd3.

Other Surfaces at Highway 84

Units 24, 26 and 32 (Figure 5) are facies A, black, thin-bedded marine shales that contain thin bentonites. They represent condensed sections and correspond to periods of maximum coastal onlap.

The black shale sections represent maximum flooding that occurred in the transgressive systems tract. The tops of the black shale sections correspond to the beginning of aggradation/progradation that occurs in the highstand systems tract. The base of each black shale is a marine flooding surface. The flooding surface present on top of unit 31 is transitional, does not contain evidence of erosion and is not, therefore, a TSE.

Summary, Highway 84

Based on the surfaces and lithologies described above, a sequence of changes in relative sea level and the associated events at Highway 84 is as follows (Figure 11):

1. Initial flooding during expansion of the Western Interior Cretaceous Seaway.
2. Erosion and reworking of the Burro Canyon Formation.
3. Development of shoreline with offshore barrier islands and protected lagoons.
4. Development of tidal flats in the lagoon.
5. Rise in relative sea level.
6. Onshore movement of islands across the tidal flats.
7. Development of TSE across barrier bars in deepening water.
8. Deposition of deeper water shales and a few storm beds.
9. Lowering of relative sea level.
10. Exposure and development of LSE, surface S2, top of Sequence Kd1 .
11. Rise in relative sea level.
12. Deposition of offshore shales with a few storm beds.
13. Maximum flooding shown by black shale, unit 26.
14. Minor lowering of relative sea level, deposition of lower shoreface sandstones.
15. Rise in relative sea level and deposition of offshore shales.
16. Abrupt lowering of sea level and development of marine erosion surface, S3. Provisional top of Sequence Kd2.
17. Deposition of lower foreshore sandstones.
18. Continuous rise in relative sea level to top of section resulting in deeper water shoreface deposition.

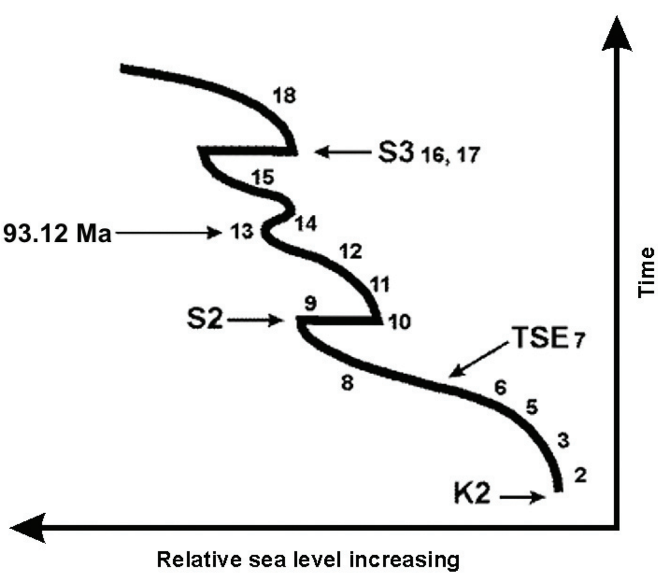

FIGURE 11. The Dakota was deposited during a continuous rise in sea level punctuated with high frequency fluctuations. Forced regressions created surfaces S2 and S3 as shown here. Note position of age dated bentonites sample. Haq, et al. (1978) show sea level spikes similar to those at S2 and S3 occurring at 93Ma and 94Ma. Numbers refer to discussions in the text.

Gamma Ray Survey

Figure 12 presents a surface gamma ray profile of the measured interval along with the facies interpretations.

HERON DAM SECTION

Figure 1 shows the location of the Heron Dam sections. The main section was measured on the north side of the Chama River along a service road that goes from the top of the uppermost sandstone, down to the west to the Burro Canyon Formation located near the base of Heron Dam. A complete section of the Dakota Formation is available at this exposure (Fig. 13).

The lowest part of the outcrop has two very distinct parts: a south-facing exposure on the north side of the river, described in the main section, and a southwest-facing exposure by the dam spillway, described in a short supplemental section. These nearly right-angled exposures afford a rare, three-dimensional view of the lowest part of the Dakota section, the Burro Canyon Formation and the K2 unconformity. Slope wash, unfortunately, obscures many of the details in parts of the interval in the main measured section.

A short supplemental section describes the nature of the rocks immediately overlying the K2 unconformity. There is much lateral lithologic variation over a short distance within this interval, and by examining the section near the dam spillway, it was possible to relate the changes to the main section and build a more complete Dakota depositional history. A photo of the supplemental section is shown on Figure 14.

Description, Analysis and Interpretation

The section at Heron Dam has a measured thickness of about 280 feet (87m) from the K2 unconformity to the top of the upper-

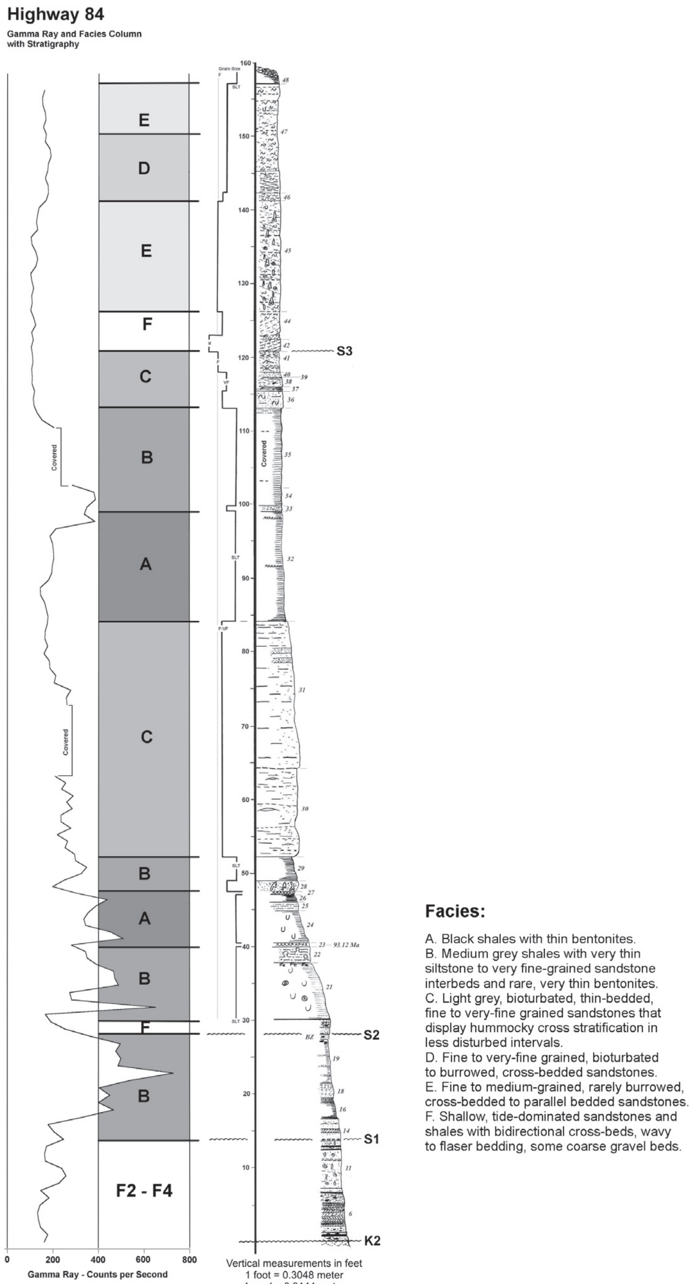

FIGURE 12. The stratigraphic column at Highway 84 with gamma-ray curve and facies on the left side. Note key to facies on the right. Please see the key to lithologies, bedforms and structures on Figure 5.

most sandstone. The following discussion breaks the section into three intervals. As before, stratigraphic units are numbered and the numbers key to the graphic columns in this paper and to the narrative descriptions in Varney, 2000. Tables 1 and 2 contain tables of criteria used for determining depositional environments.

Interval K2 to S2

The Dakota section at Heron Dam rests on the Burro Canyon Formation, which is essentially the same here as at Highway 84. The Dakota is separated from the Burro Canyon by the K2 unconformity (Figs. 14 and 15).

Figure 15 is the first 90 feet (27.5m) of the main Dakota columnar section. Figure 16 is a correlation of the main and supplemental sections. The following discussion refers to both sections and abbreviates supplemental section as "SS" and main section as "MS." The supplemental section ends about 7 feet (2.1m) above the interpreted S2 surface.

The K2 unconformity at Heron Dam (Figs. 14 and 15) marks the boundary between greenish-gray siltstones of the Burro Canyon Formation and carbonaceous sandstones of the Dakota that contain abundant white, tripolitic chert. The rock units immediately above the unconformity are highly variable over short distances laterally.

In the supplemental section (Figure 16), at approximately 8 feet (2.5m), surface K2 is picked at a horizontally bedded, very coarse to medium-grained sandstone that contains carbonaceous debris and tripolitic chert (unit SS3). Two feet (0.61m) above, in units SS4 and SS5, there is a pebble zone. Walking the outcrop on the base of unit SS3, it becomes clear that SS3, and not the pebble zone, correlates to surface K2 at the base of unit MS1.

Units SS4 through SS8 are not present in the main section, having been removed by channel cutting. Units MS1 through MS3, silty to sandy dark-gray shales, fill the channel. They occupy a stratigraphic position similar to that of the mud/sand flat deposits at Highway 84 (H84 units 1 to 12) and may represent estuarine/lagoonal tidal flat deposits.

Units SS4 through SS7 in the supplemental section comprise a very coarse to fine-grained, cross-bedded sandstone that grades up through horizontally-bedded to short-period planar cross-bedded at the top. There are no indications of trace fossils and nothing else that suggests that the interval is marine, so it is assigned a fluvial origin and it may represent a shallow valley fill on the K2 surface.

Unit SS8 is not present in the main section. Along the line of the supplemental section it is two feet thick but it thickens to 12 feet (3.7m) laterally. Unit SS8 consists of shaly, fine to medium-grained sandstone with granule trains in thin, graded, horizontal to gently inclined crossbed sets. The granule composition includes wood fragments and weathered, tripolitic chert. The overall appearance of the unit is similar to that of braided stream deposits.

Unit SS9 is a medium grained, horizontally bedded sandstone that marks the base of a channel cut into unit SS8 in the supplemental section. Unit SS10 fines upward from medium to fine-grained in bedsets that become thinner upward. All bedsets contain tabular-planar cross-beds and two thinner zones in the upper part of the unit contain bidirectional to herringbone cross-beds. There are possible vertical burrows *(Ophiomorpha?)* near the top of unit SS10. Unit SS11 is uniformly fine-grained throughout. It grades upward from horizontally bedded to faintly ripple bedded to distinct ripples. The top of unit SS11 is sharp and overlain by a carbonaceous shale of unit SS12 (Fig. 16).

Because of the erosional relationship of units SS9 through SS11 to unit SS8, and their tabular-planar cross-bedding, bidirectional crossbed sets and possible marine trace fossils near the top of unit SS10, the interval is interpreted as a channel filled with tide-dominated deposits. Unit SS11 appears to represent filling of the channel with shoreface sandstones. If this scenario is correct, then the

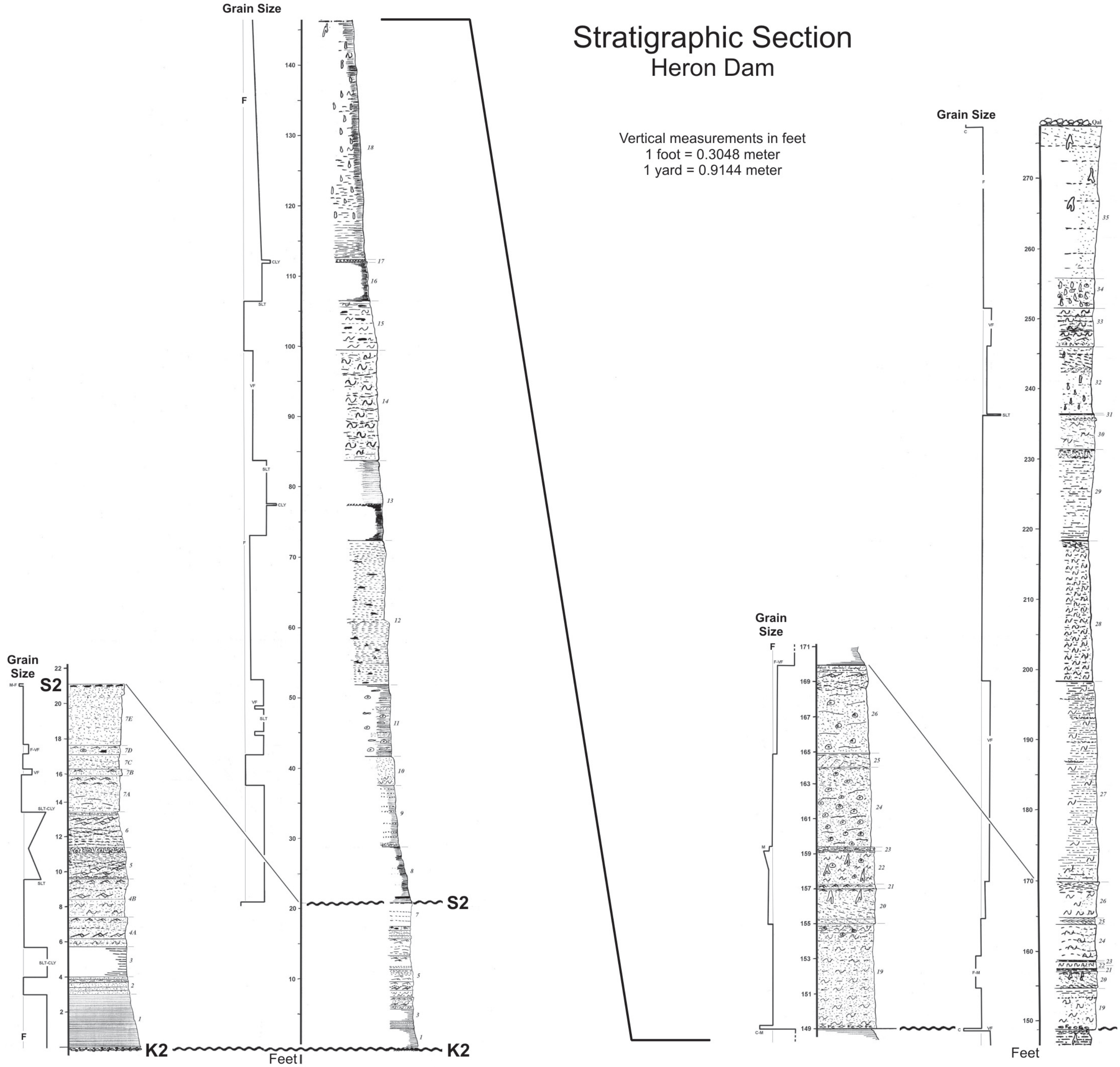

FIGURE 13. The stratigraphic column at Heron Dam. Note that the column is split with the left part continuing upward on the right. Details of two intervals are on the left side of the main column. Enlarged parts of this section are in figures that follow. Please see the key to lithologies, bedforms and structures on Figure 5.

gravelly shale of unit SS8 represents a coastal plain/proximal tidal flat marginal to the sea. Along the line of the main section, units MS1 through MS3 represent an overlying transgressive tidal flat that is also cut by the channel under units MS4 through MS7.

The above correlations may seem unlikely, but the relationships observed on outcrop can be traced horizontally with confidence (Figures 14 and 16). What is particularly interesting is the succession of units MS1 through MS7E in the main section (Fig. 15).

Unit MS1 is a medium gray, platy, hard shale. It is overlain by a soft weathering, fine grained shaly sandstone which is, in turn, overlain by another shale that appears to be similar to unit MS1 - the interval is partly covered. Unit MS4 is an interesting couplet of sandstones, each of which grades upward from a fine-grained, bioturbated sandstone to very fine grained, ripple to flaser-bedded sandstone.

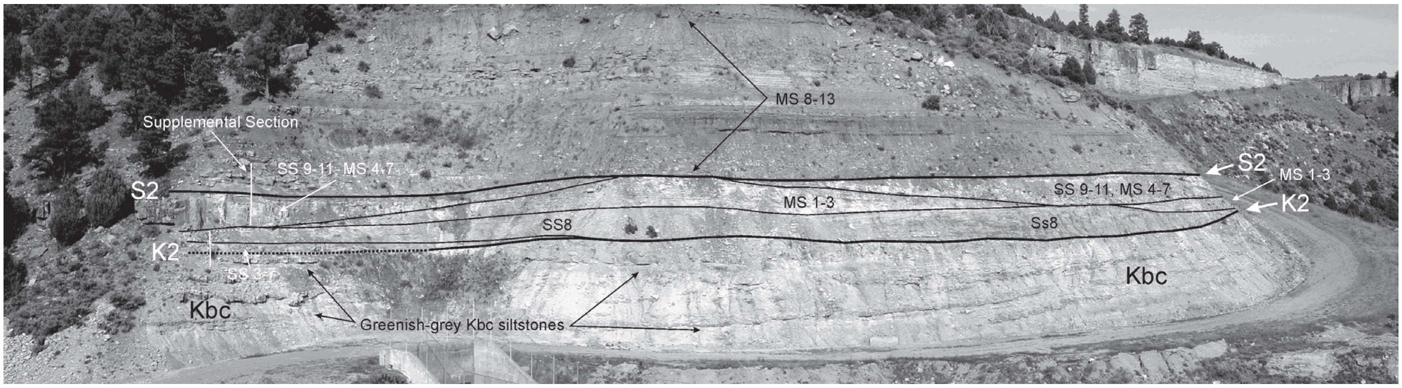

FIGURE 14. View to the east of the west end of the Dakota outcrop at Heron Dam. The position of the supplemental section is shown on the left. The main section was measured behind the nose on the right and up to the top of the prominent sandstone on the skyline in the background. The Burro Canyon Formation (Kbc) forms the base of this outcrop. Note the presence of characteristic greenish gray shales in the Kbc. In this illustration, “MS” designates rock units in the main measured section and “SS” designates rock units in the supplemental section. Unit numbers tie to the discussions in the text. The Dakota rests on the K2 unconformity and here it comprises proximal tidal flat gravelly shales, SS8,mixed sandstone shale tidal flat sediments, MS 1-3, and a tidal channel, SS 9-11, MS 4-7. The S2 surface is both a lowstand surface of erosion and a transgressive surface of erosion. Clay mineral analyses here and at the Highway 84 outcrop show that S2 is highly kaolinitic and most likely the same surface at both locations. See Plate 6B for a color version of this figure.

Unit MS5 is a siltstone that grades up through flaser to lenticular bedded to thoroughly distorted bedding with shale drapes in the upper 8 inches (0.23m). Unit MS6 is much the same as unit MS5, but in reverse bedding order. Unit MS7, subdivided A through E, is a mostly medium-grained sandstone with indistinct wavy bedding, some indication of horizontal burrowing and a few rippled intervals. The most noticeable feature of unit MS7 is that the upper part of the unit is bleached white. Petrographic analysis shows that there is 30% intergranular clay in the bleached zone, which x-ray diffraction analysis indicates is predominantly kaolinite. The upper 1 inch of unit MS7 is harder than the underlying sandstone and the contact is sharp and overlain by a thin zone of charcoalized wood fragments.

The top of unit MS7E is a ½ to 1 inch (0.015 to 0.03m) thick zone of concentrated charcoalized wood fragments in a fine to medium-grained sandstone. This characteristic fits some of the criteria for a transgressive surface of erosion (Weimer, 1992) but it lies on a heavily bleached zone. For this reason, it is here considered to represent a composite lowstand surface of erosion/transgressive surface of erosion (LSE/TSE).

The weathered aspect of unit MS7 is very similar visually to that of unit 20BZ at the Highway 84 outcrop and it occupies a similar stratigraphic position near the base of the Dakota section. Thin-section analysis (Varney, 2000) shows that it contains more quartz than unit 20BZ at Highway 84, but considerable kaolinite as well. Furthermore, there is an abrupt facies change above unit MS7E. For these reasons, the surface at Heron Dam S2 is correlated with S2 at Highway 84. The TSE between K2 and S2 at Highway 84 is not evident here and therefore, may be merged with S2. This interpretation would mean there is a dominantly deeper water marine facies interval at Highway 84 that is not present in the section at Heron Dam.

Because lateral relationships show channel cutting at the base of the main Heron Dam section, the shale/sandstone/shale of units MS1 through MS3 may represent a tidal channel infill of the type in unit 8 at Highway 84. And, like unit 8 at Highway 84, the shale sequence is overlain by a shoreface sandstone succession. This suggests that the sections between K2 and S2 at both locations were deposited as part of the same depositional system. The previously mentioned gravelly shale of unit SS8 lies under the channels. If it is a proximal gravel flat/coastal plain facies marginal to the Cretaceous seaway that was incised by a tidal channel, then these relationships place the Highway 84 section seaward of the Heron Dam section during the same time. The depositional slope was < 0.2° during lowest Dakota deposition (Varney, 2000), so it is likely that there was a certain amount of tidal facies “smearing” that complicates the interpretation.

The interval between K2 and S2 is Sequence Kd1.

Interval S2 to S3

Figure 17 is the interval from 90 to 180 (27.5 to 55m) feet at Heron Dam. The rest of this discussion drops the abbreviation for “supplemental” and “main” section unit numbers. With the exception of a few feet (m) above the S2 surface at Heron Dam shown on the supplemental section, the main section shows all of the measured and described stratigraphy. Therefore, references to unit 8 and above are all on the main section.

For approximately 115 stratigraphic feet (35.2m) above the S2 surface, the Dakota consists of a series of lower shoreface sandstones and deeper-water shales. These alternate mostly between deeper water, silty shale and shaly sandstone facies B and C but there are also three black shale facies A intervals that are significant because they rest sharply on surface S2 and on facies C shaly sandstones higher in the section (Figs. 15 and 17).

Unit 8, for example is a black facies A shale that lies sharply on unit 7E, a shallower water facies E sandstone. The abrupt vertical change from shallow water facies E to deeper water facies A gives additional support for surface S2 being a flooding surface, that is, a transgressive surface.

Above unit 8, relative shallowing culminates in unit 12, a fine to very fine-grained, medium gray, shaly sandstone. Unit 12 is 21 feet thick and about midway contains a ripple bedded zone. Laterally to the east, the equivalent position contains well defined

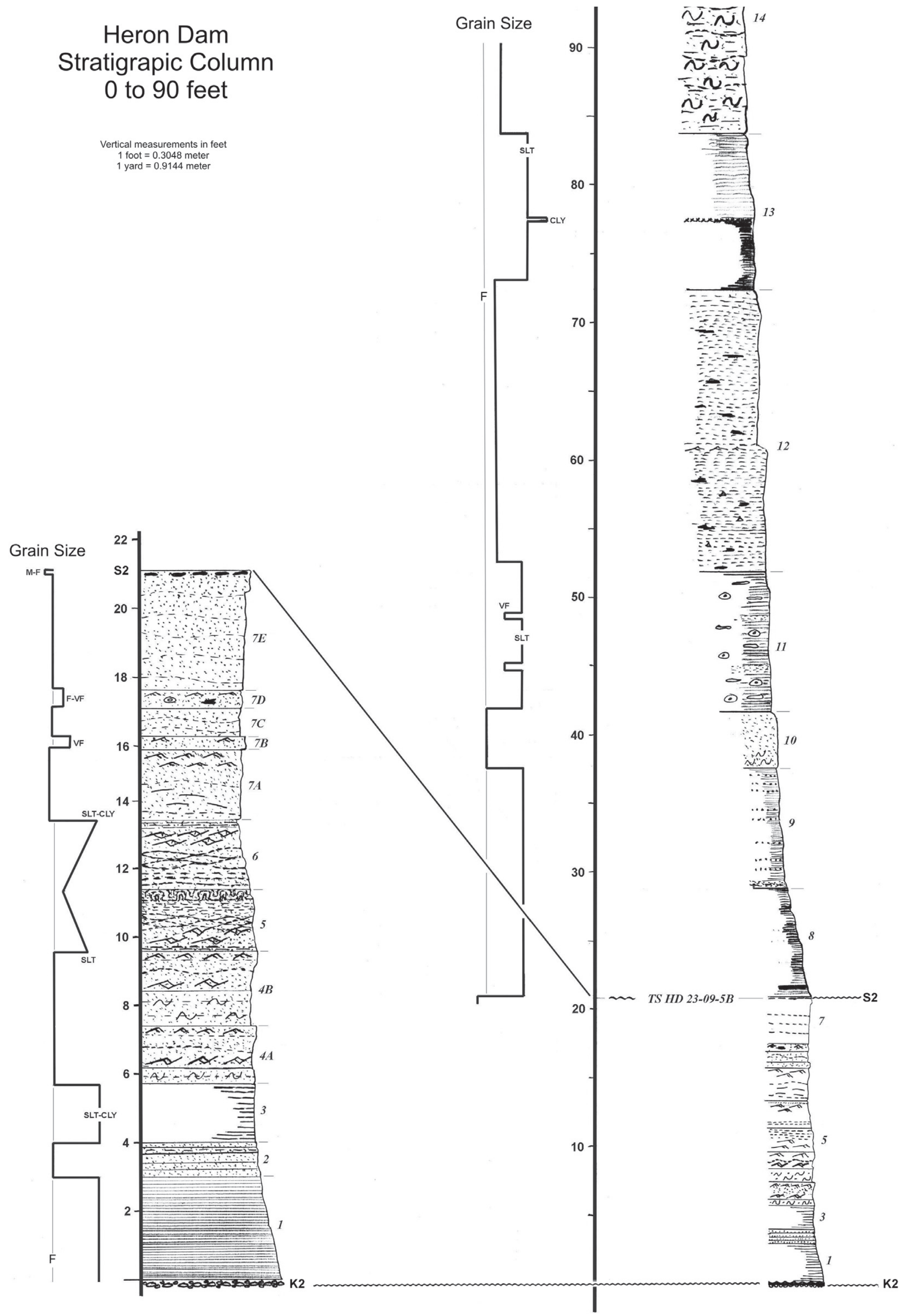

FIGURE 15. Stratigraphic column for the interval from 0 to 90 feet (27.5m) at Heron Dam with lithologic unit numbers on the right side. Column on left is enlarged detail section and has complete unit numbering. Please see the key to lithologies, bedforms and structures on Figure 5.

HCS. Unit 13 is the second facies A black shale that is overlain, again, by a relative shallowing succession that is topped by unit 15. Units 14 and 15 are fine to very fine grained, bioturbated sandstones. Unit 14 has poorly defined indications of HCS in its lower half. The top of unit 15 grades up into unit 16, the third facies A black shale.

Unit 16 is a black shale overlain by a bentonite, unit 17, that was sampled for age dating. Unit 17 was found to contain no K-spar and, therefore, could not be dated. Once again, relative shallowing is seen up through unit 18, a facies B dark gray shale that is bioturbated at its base, becoming more burrowed and sandier upward.

Unit 19 is a facies D shallow water sandstone that is medium to coarse-grained in the basal 2 inches. The lowest 1 inch is ferruginous and contains mudstone clasts. The contact with underlying facies B dark gray shale is sharp and marked by the presence of a brown, very soft, silty to sandy shale in the uppermost inch of unit 18. There is no apparent angular relationship between the two units, but the mudstone clasts and coarse grain size in the lowest part of unit 19, combined with the abrupt facies transition suggests that the surface separating units 18 and 19 is a marine erosional surface in the sense of Pemberton and MacEachern (1995). It is here designated S3.

The interval between surfaces S2 and S3 is Sequence Kd2. The black shales in units 8, 13 and 16 (Figs. 15 and 17) mark maximum flooding events. Units 8 through 12 and 13 through 15 represent two complete, coarsening upward marine parasequences that record shoreline progradation due to periodic lowering or stillstand of relative sea level. A third, incomplete, parasequence includes units 16 through the top of 18. Surface S3 truncates the third interval. It appears that the sequence contains an overall transgressive systems tract, but the two parasequences show that there was highstand progradation during two high frequency, short term relative sea level falls. The truncated third, and stratigraphically highest, parasequence may have been forming during a final Sequence 2 highstand.

Interval S3 to Top of Section

If S3 is a marine erosional surface then, using the reasoning of Pemberton and MacEachern (1995), units 19 through 26 comprise a lowstand systems tract within the overlying sequence. This interval (detail section on left side of Fig. 17) has a unique appearance within the Heron Dam section and has several interesting characteristics.

As mentioned, unit 19 is a bioturbated, medium gray sandstone. Its top 6 inches (0.15m) includes shale laminae that are nearly horizontal and contain large, horizontal to inclined, sand-filled burrows. The upper foot (0.3m) contains some poorly defined tabular/planar cross-beds that dip to the south. Throughout, the sandstone is hard to the hammer, likely because it contains a high quartz content in which the grains are interlocking (Varney, 2000). The presence of rounded overgrowths shows that this is a second-cycle sandstone.

Unit 20 is a medium gray, fine to medium-grained sandstone with well defined trough to planar cross-beds facing southeast. Cross-bedding becomes less well defined upward because of

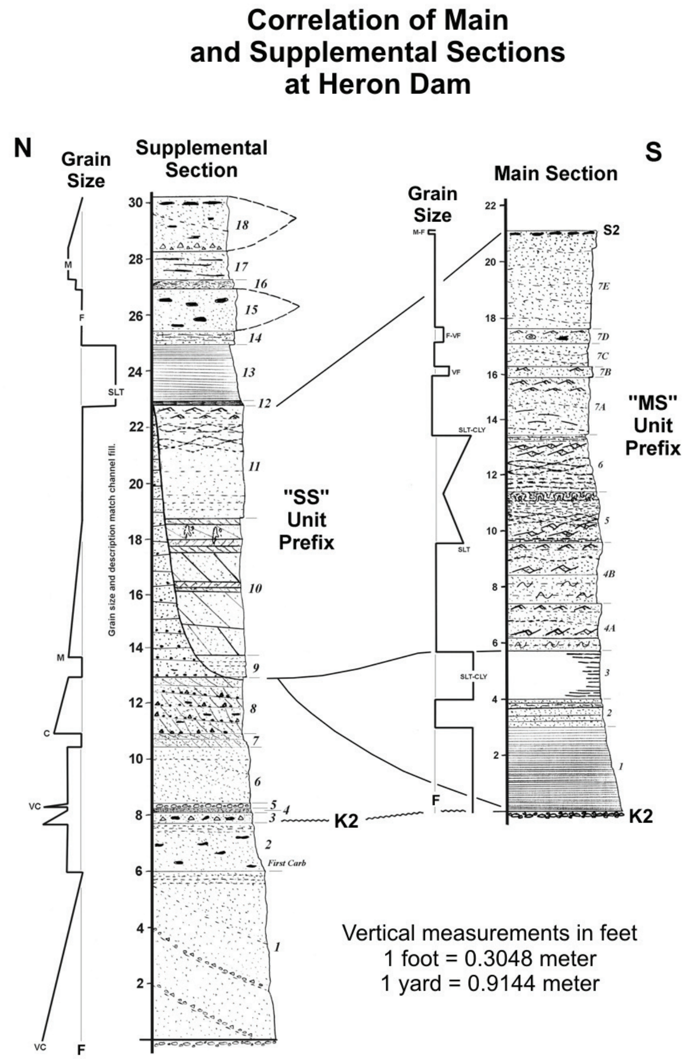

FIGURE 16. Correlation of main and supplemental sections at Heron Dam. See Figure 14 for a photograph that illustrates the relationships shown here. Please see the key to lithologies, bedforms and structures on Figure 5.

extensive burrowing by *Ophiomorpha*. The top of this sandstone is ripple modified. It, too, is hard and has a high quartz content with interlocking grains and rounded overgrowths.

Unit 21 is a 2 inch (0.05m) thick light gray, fine to medium-grained sandstone with ripple bedding and thin, wispy, carbonaceous shale laminae in horizontal to undulatory layers. Thin section analysis shows that it has internal character similar to the other sandstones in this section, but that it is only moderately well-sorted.

Unit 22 shows a change. It is a light gray, fine to medium-grained sandstone with relict horizontal to trough cross-beds and is heavily burrowed by *Ophiomorpha* and an indeterminate horizontal trace fossil *(Planolites?)*. The overall nature of this sandstone is that of a sand waveform filling lows in the underlying unit 21. The sand grains in this unit are the same as those in the underlying units, but there is no observable clay.

Unit 23 is a 2-inch (0.051m) thick interval of fine to medium grained, medium gray, shaly lenticular bedded to flaser bedded, heavily burrowed sandstone. The burrows are outlined by carbo-

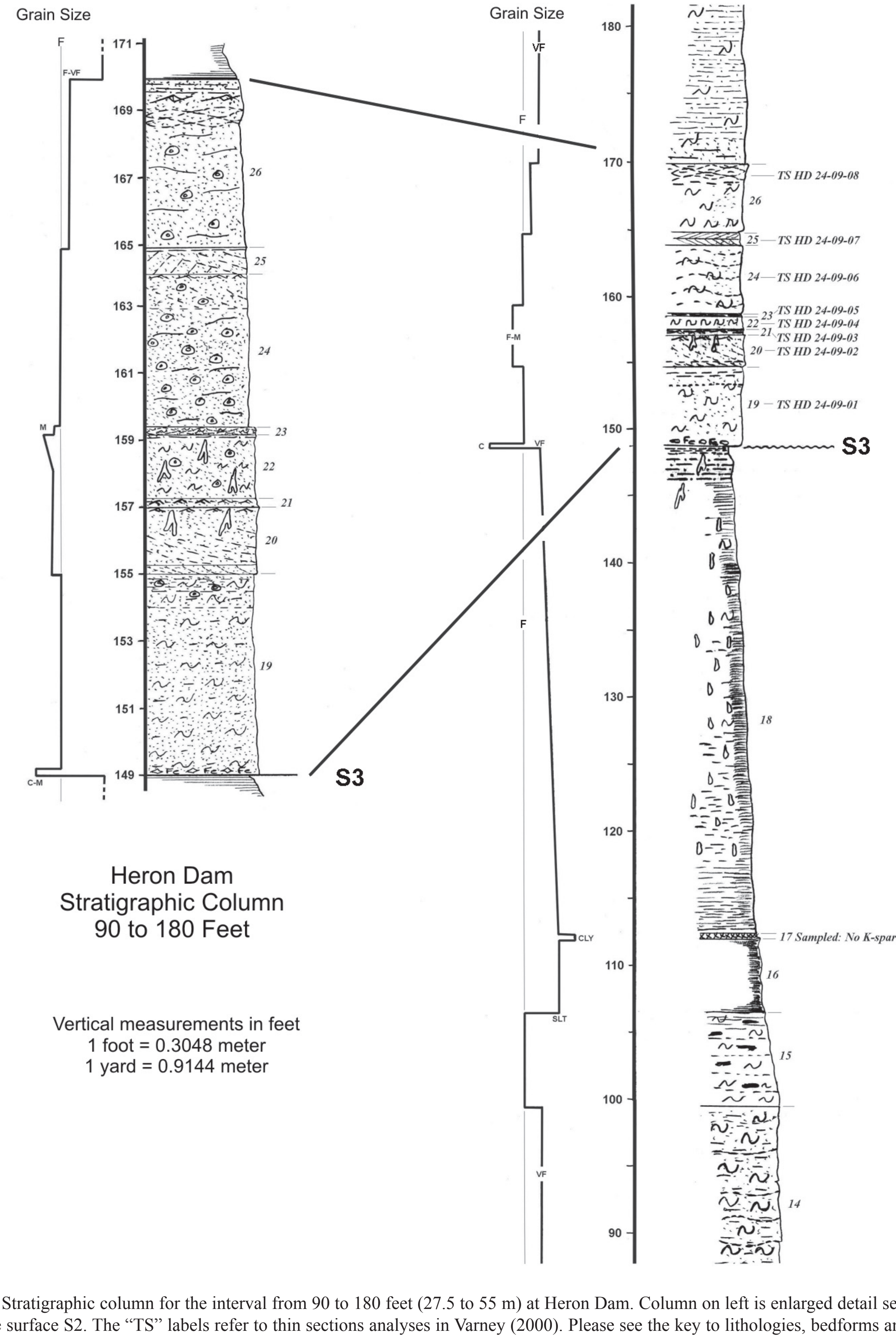

FIGURE 17. Stratigraphic column for the interval from 90 to 180 feet (27.5 to 55 m) at Heron Dam. Column on left is enlarged detail section immediately above surface S2. The "TS" labels refer to thin sections analyses in Varney (2000). Please see the key to lithologies, bedforms and structures on Figure 5.

naceous shale streaks. This unit fills the undulatory crest of unit 22. The sand grain character is the same as the underlying units, but sorting is poor in this interval.

Unit 24 is a thick, medium gray, shaly sandstone with extensive burrowing. The interval is rippled at the top and in sharp contact with the overlying sandstone. Sorting in unit 24 is only moderate, but quartz content is 95%, so it appears as a “clean” sandstone. Thin section analysis shows that it, like the underlying sandstones, has interlocking quartz grains.

Unit 25 is a 1 foot (0.31m) medium gray, fine-grained, non-shaly sandstone with long period bidirectional trough cross-beds. The top of the unit grades into unit 26. Sorting and grain characteristics are similar to unit 24. A thin section confirms that this unit is compositionally identical to unit 24.

Unit 26 is a medium gray, fine to very fine-grained sandstone, like unit 24 below. Unit 26 is heavily burrowed but burrowing density decreases in the upper half of the unit. Shale content increases upward and the unit becomes lenticular to flaser bedded at the top. However, there is considerable lateral variation in the top of this unit, and in places there is a resistant ledge at the top about 3 inches (0.076m) thick. Thin section analysis shows good sorting in this sandstone, 10% clay and subangular grains.

This sequence of sandstones, units 19 through 26, seems to owe its distinctive character more to changes in bioturbation and current-related sand movements than to any significant changes in grain size and mineralogy. Thin sections show a relatively uniform sandstone sequence in which there is a little variation in clay content and sorting, but the grains in this interval tend to be more rounded than in the rest of the section. There are rounded quartz overgrowths scattered throughout, showing that these sand grains were derived from a previously altered sandstone. All the sandstones are hard to the hammer and this is related to interlocking, subangular quartz grains found in all units.

Referring to the table of shoreline environments in Tables 1 and 2, it is clear that this sequence of sandstones represents a shoreface environment. The more bioturbated parts fit into the middle shoreface, and the higher energy, cross-bedded parts fit into the lower part of the upper shoreface. This fits with the assignment of the package to the marine equivalent of a lowstand systems tract - the shoreface moved basinward in response to a lowering of sea level that produced a forced regression (Catuneanu, 2003, Pemberton and MacEachern, 1995).

It could be argued that the unit 19 to unit 26 sandstone succession represents a local autocyclic shoreline response, perhaps related to a deltaic depositional environment. Evidence from gamma ray correlations presented later shows that the interval represented by these sandstones can be correlated over a wide area, an area much larger than would be expected from a local feature.

Figure 18 is the part of the Heron Dam stratigraphic column from 180 feet (55m) to the top of the section.

From the top of unit 26 to the top of the uppermost sandstone, unit 35, there is one unbroken, gradational progression from a medium gray, very fine-grained sandstone/sandy shale to a hard, medium to light-yellowish gray, fine grained sandstone. Bioturbation increases upward until about 220 feet (67.3m) above the base of the section and then the sandstones become increasingly

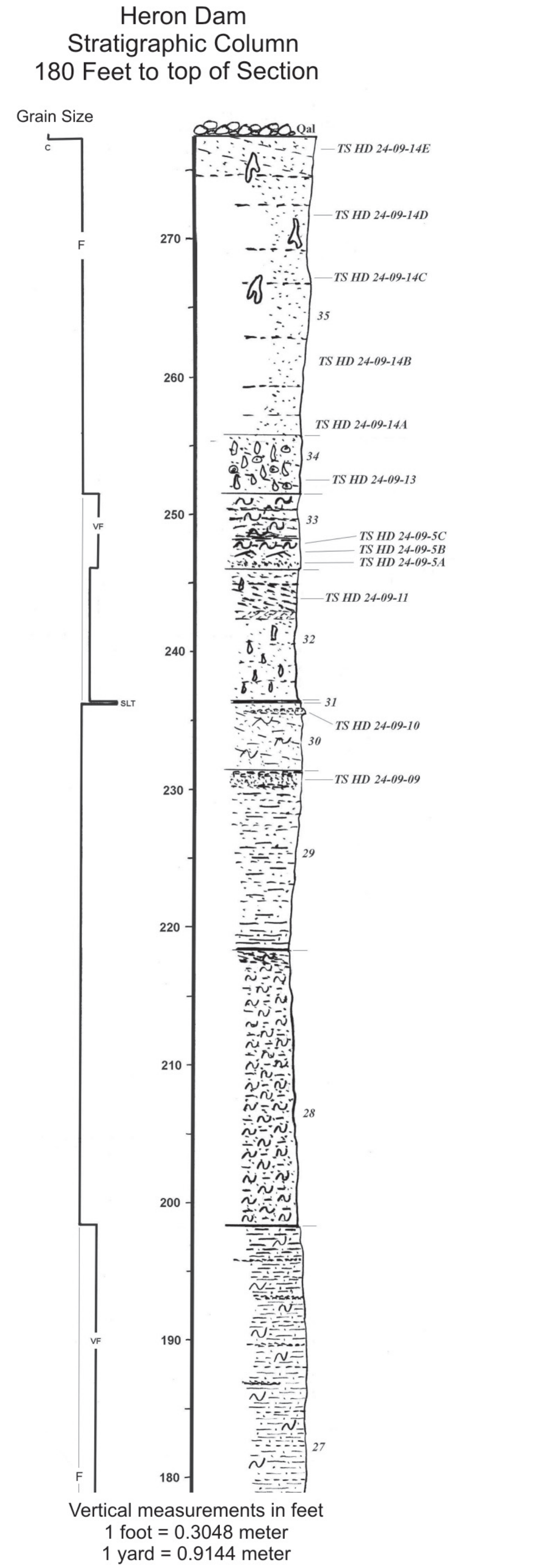

FIGURE 18. Stratigraphic column from 180 feet (55m) to the top of the Dakota section at Heron Dam. The “TS” labels refer to thin sections analyses in Varney (2000). Please see the key to lithologies, bedforms and structures on Figure 5.

burrowed. The uppermost beds are thick and display scattered *Ophiomorpha*. Weathering resistance increases upward and the upper part of the succession supports a steep cliff at the top of the outcrop (Fig. 19).

The interval from the top of unit 26 to unit 35 (Fig. 19) represents a prograding shoreface from shallow-water facies D through shallowest water facies F. The sandstones become cleaner, less shaly, upward without an appreciable variation in grain size - all are fine to very fine grained. Continuing the assignment of sandstones above S3 to systems tracts, we see a progression through a retrogradational transgressive system tract with its base on top of unit 26 upward through aggrading transgressive systems tract in units 27 through 29 and a highstand systems tract from units 30 to the top of the section, unit 35.

The Graneros Shale Member of Mancos Shale lies across the top of the highest Dakota Sandstone outcrop on what is clearly a marine flooding surface. A few scattered coarse quartz grains in the quarter inch (6.4mm) below the exposed top suggest that it may be a transgressive surface of erosion. From a sequence stratigraphic standpoint, this could imply that the top of the Dakota actually lies above the Heron Dam exposure. Subsurface maps and cross sections (Varney, 2000) suggest that the uppermost surface in the Dakota, under the Graneros, is an unconformity. Therefore, here it is provisionally considered an LSE/TSE.

The interval between S2 and S3 is Sequence Kd2 at Heron Dam. The interval between S3 and the Graneros Shale is Sequence Kd3.

Other surfaces at Heron Dam

Units 8, 13 and 17 (Figs. 15 and 17) contain black, thin bedded marine shales that include thin bentonites. They represent condensed sections and correspond to periods of maximum coastal onlap.

The mid points of the black shale sections represent maximum flooding surfaces and the slowing of relative sea level rise. In each example, the base of the black shale is a marine flooding surface. Unit 8 near the base of the section lies sharply on unit 7, is separated from it by a facies gap and is, therefore, considered a transgressive surface of erosion. Units 13 and 16 also have a facies gap, but it is more subtle. Their bases are interpreted as marine flooding surfaces.

The intervals between flooding surfaces are marine parasequences in the sense of Van Wagoner (1985).

Summary, Heron Dam Section

The preceding discussion shows that we can identify the following sequence of depositional events related to relative changes in sea level at Heron Dam during the Dakota (Figure 20):

1. Initial flooding during expansion of the Western Interior Cretaceous Seaway.
2. Erosion and reworking of the Burro Canyon Formation causing development of a supratidal, proximal gravel flat on the coastal plain.
3. Relative sea level rise and tidal channel development across the coastal plain/proximal tidal flat.
4. Development of tide-related mud flats in the channels.
5. Continued rise in relative sea level.
6. Development of tide-dominated estuarine deposits in the channels.
7. Lowering of relative sea level.
8. Exposure and development of LSE/TSE surface S2, top of Sequence Kd1.
9. Rise in relative sea level, marine flooding.
10. Deposition of offshore marine shales with a few storm beds (units 8 through 10).

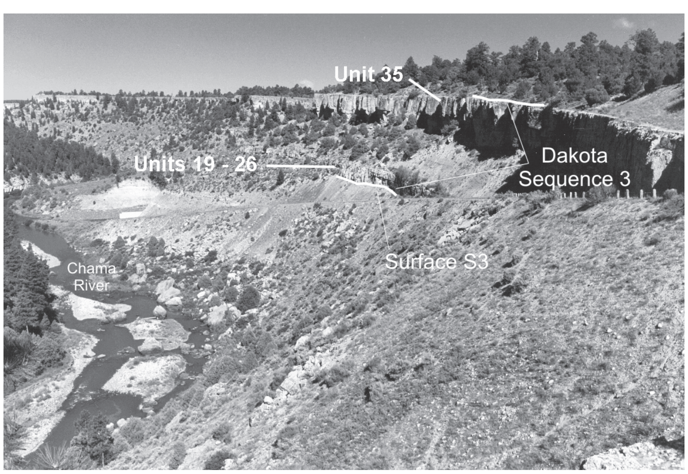

FIGURE 19. View of the Dakota outcrop at Heron Dam showing the cliff at the top of the section supported by unit 35 and the mid valley break in slope supported by units 19 through 26. The Chama River is in the left foreground. S3 is at the base of unit 19. Dakota Sequence 3 includes the interval between S3 and the top of the uppermost sandstone. Upper cliff (includes unit 35) is about 45 feet (13.8m) thick.

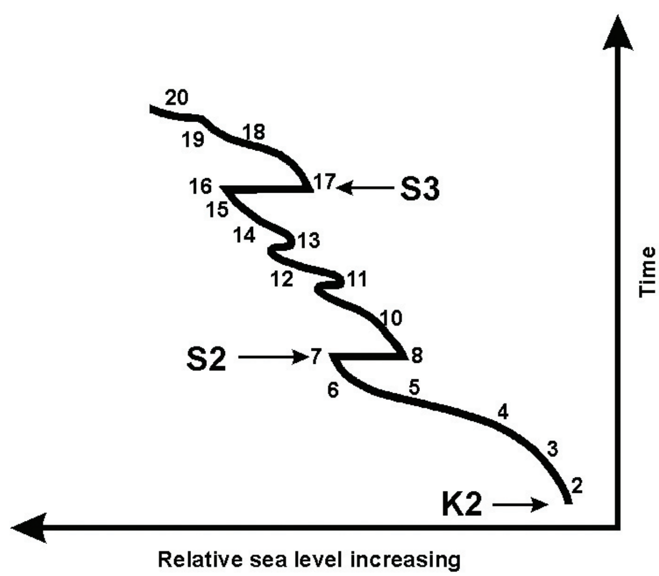

FIGURE 20. Heron Dam sea level curve. The Dakota was deposited during a continuous rise in sea level punctuated with high frequency fluctuations. Forced regressions created surfaces S2 and S3 as shown here. S2 and S3 may be related to sea level spikes dated by Haq, et al. (1987) at 93Ma and 94Ma. Note similarity to the sea level curve for Highway 84 in Figure 11.

11. Drop in relative sea level and shoreface progradation (units 11, 12).
12. Rise in relative sea level, marine flooding, deposition of offshore shales (unit 13).
13. Relative drop in sea level, shoreface progradation (units 14, 15).
14. Rise in relative sea level, marine flooding, deposition of offshore shales (units 16, 17).
15. Slowing of relative sea level rise, beginning of shoreface progradation and deposition of upper offshore to lower shoreface silty shales (unit 18).
16. Rapid drop in relative sea level causing development of marine erosion surface, an RSE - surface S3, on unit 18. This is the top of Sequence Kd2.
17. Deposition of shoreface on LSE, base Dakota Sequence 3.
18. Long period rise in relative sea level causing shoreface retrogradation and aggradation.
19. Slowing of relative sea level rise causing shoreface progradation. This created a high frequency, relative highstand culminating in deposition of unit 35.
20. Development of marine flooding surface, possible TSE, on topmost Dakota Sandstone.

Gamma Ray Survey

Figure 21 is a gamma ray survey over the entire Heron Dam main section with facies assignments.

CORRELATION

A primary objective of this study has been to correlate the observations made on outcrop to the subsurface. The benefit is that log curves and their characteristics can be better calibrated from comparison to outcrop data than they can by comparison to such imprecise sources as completion cards, DSTs and tests, or even cuttings and cores. There are two caveats that must be considered. Not only are outcrops typically several miles or tens of miles from test wells, but the variations present in all sandstone/shale sequences from place to place can create log patterns that appear similar when there is no actual correlation. Such reservations notwithstanding, careful comparison of gamma ray logs generated on outcrop with those run in oil and gas wells can yield powerful insights about the geology. This section starts with comparison of the outcrop gamma ray curves and then ties the correlations to a well in the South Lindrith Field.

Outcrop Gamma Ray Profiles and their Correlations

Figures 12 and 21, are the gamma ray profiles at Highway 84 and Heron Dam respectively. They were generated with a Scintrex GRS 500 scintillation counter. Each log is presented with a stratigraphic profile and the facies assignments previously discussed. Figure 22 presents a correlation of the two gamma ray profiles, the facies assignments and lithologic columns.

At Highway 84, the shallow-water facies F sediments at the bottom of the section have a low gamma ray count as expected

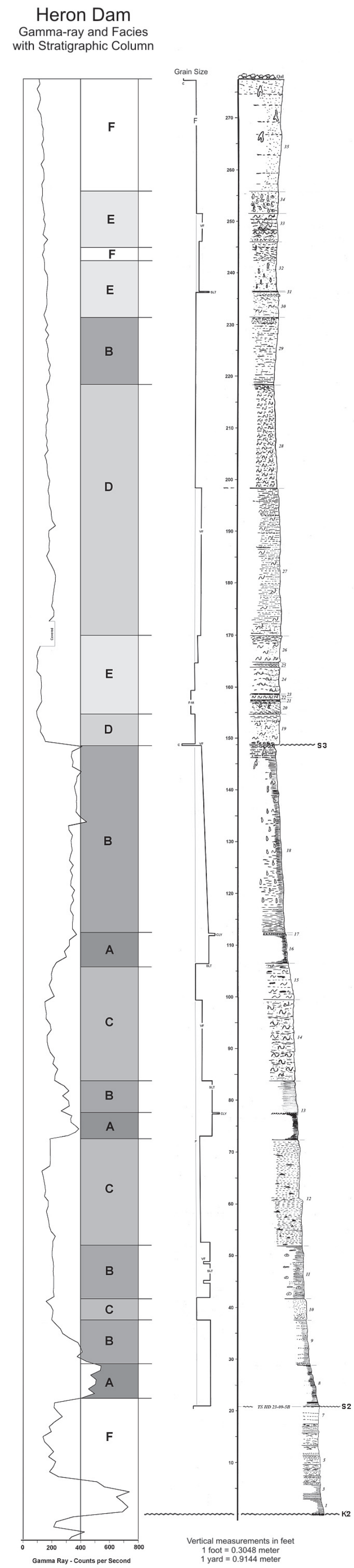

FIGURE 21. Stratigraphic column for Heron Dam with gamma-ray curve and facies shown on the left side. Please see the key to lithologies, bedforms and structures on Figure 5.

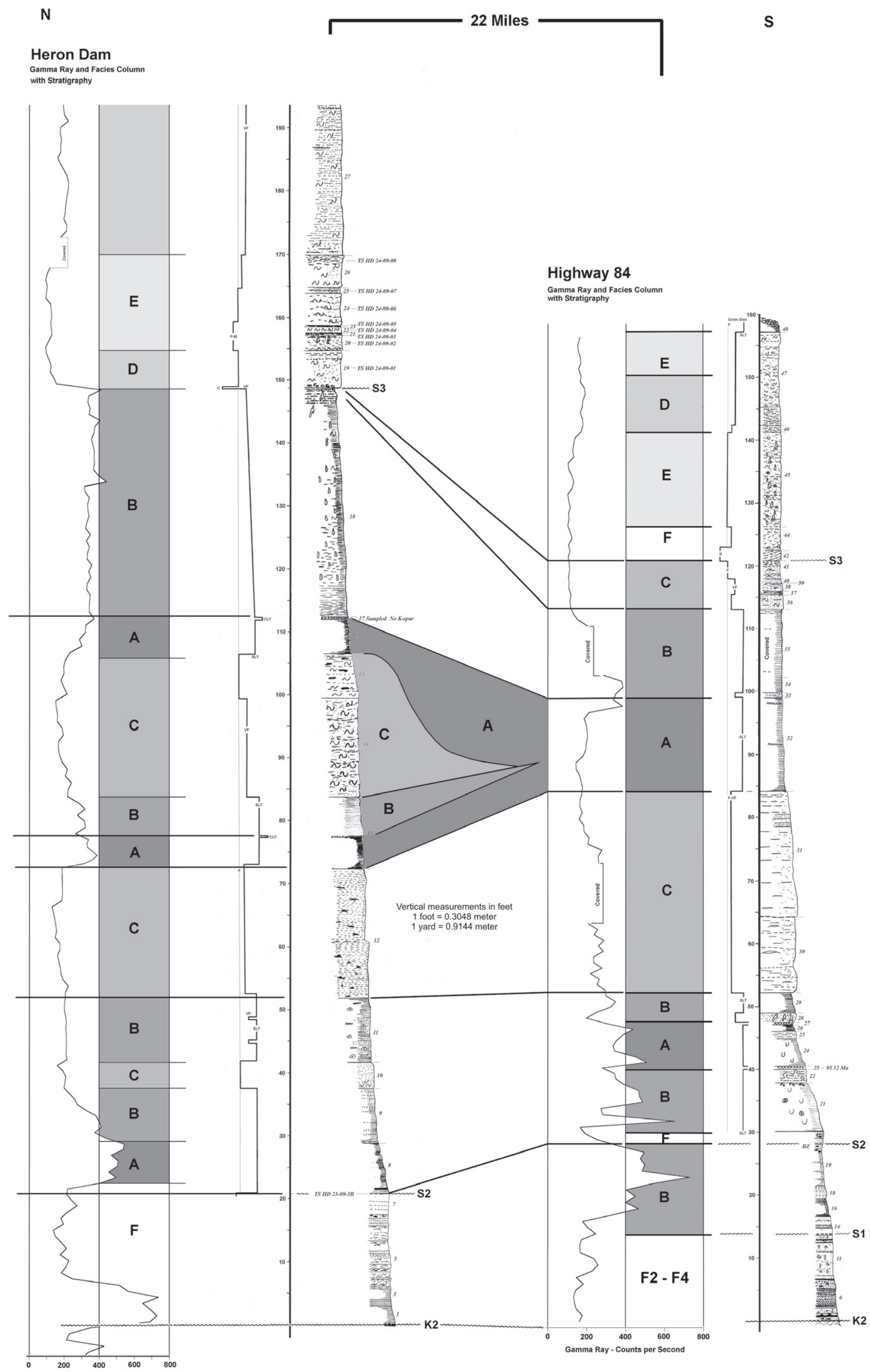

FIGURE 22. Correlation of the Heron Dam and Highway 84 sections using gamma-ray, facies and lithologies. Note parasequence at Heron Dam that is present at Highway 84 only as a basinal correlative shale section. The Heron Dam column has been reduced to the equivalent portion at Highway 84. Key to lithologic symbols is in Figure 5. Facies definitions are on Figure 12. Distance between the two sections is 22 miles (35 km).

from their larger grain sizes, higher quartz content and general lack of clay and organics. Above about 13 feet (4m), there is good agreement between deeper water facies groups A and B and higher gamma ray counts upward to about 85 feet (26m). However, the zone from about 85 feet (26m) to about 115 feet (35m) has facies A and B designations, based on lithologic descriptions, that are not reflected in high gamma ray readings. There can be several reasons for this, principally low radioactive mineral content, but extensive weathering of this zone on outcrop may have contributed. The sandy zone at about 100 feet (31m) stands out because it is bracketed by higher readings that reflect the bentonite just below and the dark gray to black shale just above. From about 115 feet (35m) to the top of the section, the gamma ray profile once again seems to reflect clay content of the lithologies.

The surfaces identified by lithology at Highway 84 are not as easy to pick on the gamma ray log. S1 corresponds to a slightly higher count notch in a sandstone section under unit 13, S2 is near the base of a low gamma ray count sandstone in unit 20B and S3 is within a sandstone section between units 41 and 42 that has little gamma ray variation. It is tempting to place S3 at the gamma ray profile change between units 35 and 36, but doing so would not honor the abrupt facies change between units 41 and 42. The problems with gamma ray correlation in the middle and upper parts of the Highway 84 section require caution when comparing this log with the subsurface.

On Figure 21 there is good agreement between the lithologies and the expected radioactivity readings at Heron Dam. The gamma ray reveals subtle details that are not obvious in the lithologic descriptions. For example, starting at about 133 feet (41m) and going up to the S3 surface at about 148 feet (45m), there is an increased gamma ray level that may indicate this zone is better assigned to facies group A, rather than B. Except for a moderately darker color and increased shaliness, this zone does not appear different visually from that immediately below - there is not the lithologic break that the gamma ray implies. The gamma ray does, however, reflect the silty character at the very top of the unit, just beneath surface S3. The overall gamma ray character in this zone is correlateable to subsurface logs.

The lowstand sandstone unit above surface S3 (units 19 through 26) has a low gamma ray count that, once again, reflects grain size and reduced shaliness. Surfaces K2, S2 and S3 all have a gamma ray character that fits their descriptions from the outcrop. Surface S1, a TSE at Highway 84, is not expressed at Heron Dam either visually or by gamma ray.

Overall, the Heron Dam gamma ray profile matches the lithologies and is of sufficient quality to use for subsurface correlations. Vertical variations in the appearance and weathering characteristics of the various Dakota sandstones seem more related to changes in shale/clay content than to large variations in grain size. This is true at both the Highway 84 and Heron Dam outcrop sections where the grain size is mostly in the fine to very fine grained category. Based on the numbered unit descriptions and on the thin sections, the gamma ray lives up to its reputation as a shale measuring tool.

Figure 22 shows the correlation of the outcrop sections at Highway 84 and Heron Dam. Based on the surfaces and sequences identified previously, it is possible to tie the sections with some confidence. As drawn, units 1 through 12 at Heron Dam correlate to units 1 through 31 at Highway 84. There is general agreement in the facies relationships, as would be expected on a low relief depositional surface. The differences evident in the details of the lower part of the two stratigraphic columns may be related to the line of section between the two outcrops being 22 miles (35km) long and oriented in the dip direction. The facies relationships make sense if the Highway 84 outcrop is basinward of the Heron Dam outcrop and the tidal flat/barrier island lithologies at Highway 84 are closer to the distal end of a protected shoreline than the more proximal tidal flat/tidal channel lithologies at Heron Dam.

Units 32 through 35 at Highway 84 total a considerably thinner section than their correlatives at Heron Dam, units 13 through 18. The shoreface represented by Heron Dam units 14 and 15 is either not present at Highway 84, or it has become the thin sandstone in unit 33. Considering the shale sections above and below unit 33, the sandstone is more likely a storm bed. The Highway 84 interval represents a condensed section related to a transgression that was moving the shoreline northnorthwestward during most of the first half of Dakota deposition. Support for a north moving shoreline can be found to the north at the Dakota outcrop on the Piedra river in Colorado where surface S3 appears to truncate the K2 surface and become the unconformity between the Dakota and Burro Canyon Formations. The correlation of the two outcrop sections makes such an interpretation possible, but further work is needed to clarify the relationships.

Preliminary Correlation to the Subsurface

Comparison of the Heron Dam outcrop gamma ray profile of this study with log cross sections in the Chama-El Vado Reservoir area (Ridgley, 1987) shows some variability in the sands, but confirms that the S3 surface correlates in the study area. Because of the significance of S3, a preliminary cross section was made along the line in Figure 23 to see if long-distance correlation is possible.

Figure 24 incorporates the Heron Dam stratigraphic section and gamma ray profile, and gamma ray logs from the Benson #43-8 Canada well in the SENE 8, T26N, R 1W, and the Chace Oil Company #6 Jicarilla Tribal well in the SWNE 12, T23N, R

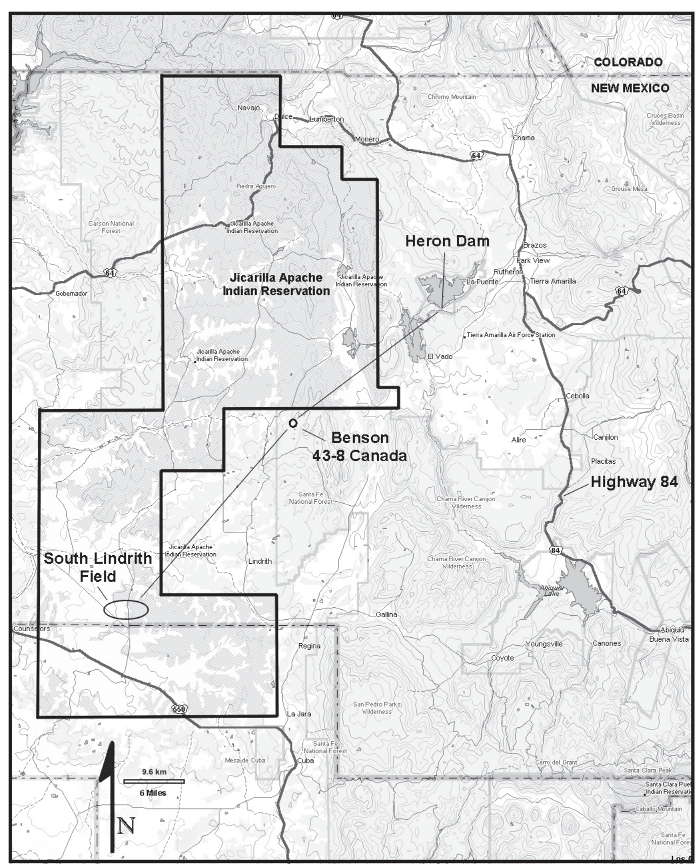

FIGURE 23. Map showing locations of outcrop measured sections and wells used in Figure 24. Please see the key to lithologies, bedforms and structures on Figure 6.

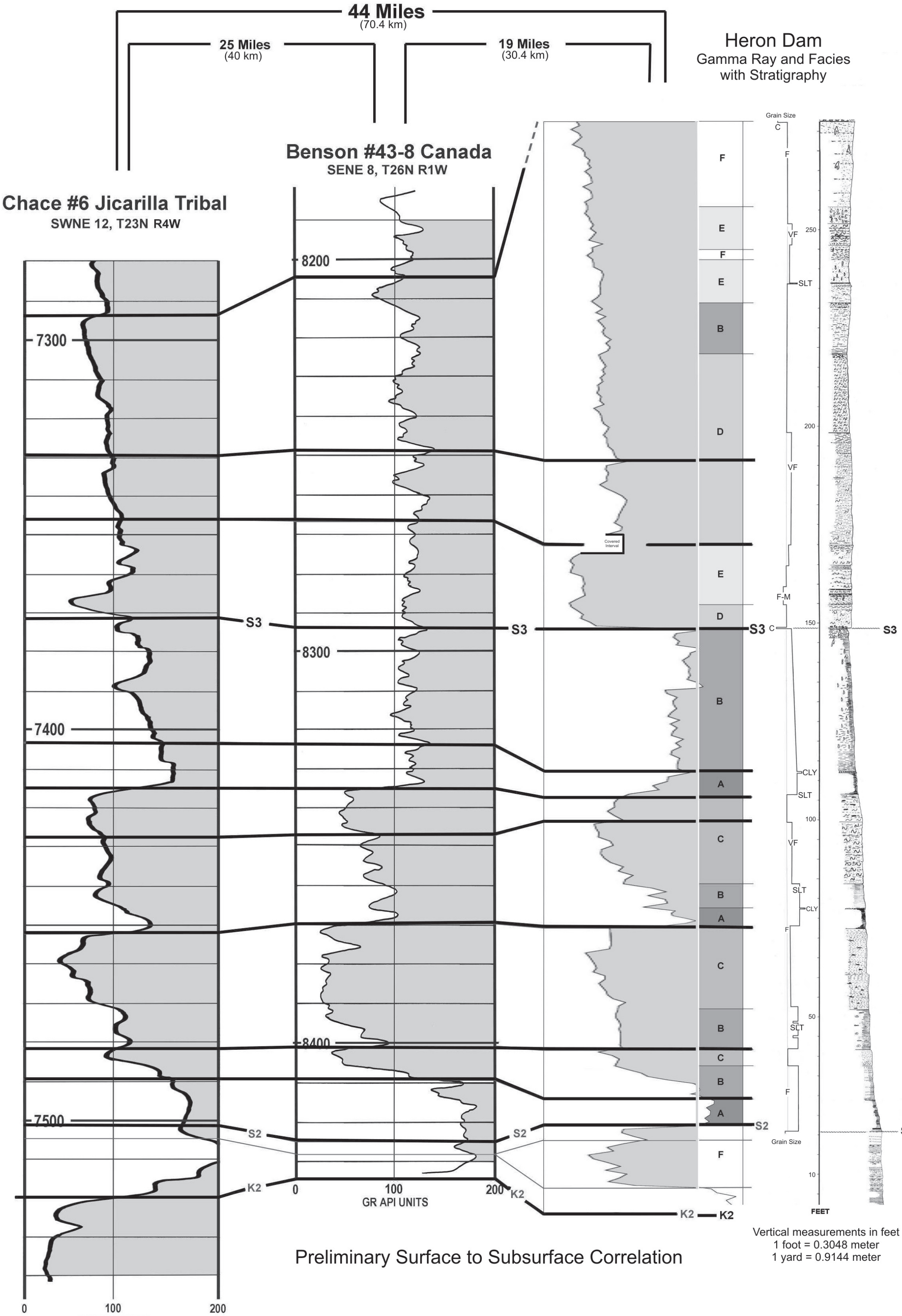

FIGURE 24. Correlation from Heron Dam, on the right, to South Lindrith Field on the left. The Benson well is about halfway between the two locations. Total correlation distance is 44 miles (70 km).

4W within the South Lindrith Field. The Benson well is about midway between the other two. The distance from Heron Dam to the South Lindrith Field is about 44 miles (70 km).

From the K2 unconformity upward, there is good agreement in the gamma ray curves despite the 44 miles (70 km) from Heron Dam to South Lindrith. It is possible that the line of section is close to, but not on, depositional strike (Cobban and Hook, 1984; Carey, 1992), thus there is little significant variation in the rocks. Between K2 and S3, even minor details of the curves match. The one area where this is not true is in the lowest part of the Heron Dam section immediately above the K2 unconformity. The interval is not only thicker than the equivalent interval in the subsurface logs, its character is different as well. On outcrop, the sandstone in this position appears to be a tidal channel and part of a proximal tidal flat, both shallow water phenomena. The subsurface logs may record a deeper water facies and the line of section may be aligned south and west of the Dakota Sequence 1 shoreline.

Correlation of the section above surface S3 is not as good as that below. This is possibly because the line of section represents a dip section reflecting a change of shoreline orientation to more north/south with time (Cobban and Hook, 1984; Carey, 1992). In the Chace and Benson wells, the top of the uppermost Dakota Sandstone is picked on a gamma ray shoulder that is overlain by Graneros (Mancos) Shale. On outcrop, the top of the uppermost Dakota Sandstone is overlain by Mancos Shale. In all three instances, it is clear that the pick for the top of the Dakota is real in a lithostratigraphic sense. What Figure 24 shows is that above the S3 surface, the uppermost Dakota Sandstone, if it is correlative over the distance, is thickening eastward. Therefore, uppermost Dakota may represent a prograding highstand depositional system. In the subsurface, the uppermost Dakota sandstone in the South Lindrith Field contains horizontally accreting sigmoidal sand units that thicken the section to the northeast and control gas distribution on the west side of the West Lindrith Field (Varney, 2000).

Because of the distances between the wells discussed here, and the numerous other well logs in the area that were not examined, this subsurface correlation must be considered preliminary. However, the outcrop to outcrop and outcrop to subsurface correlations set the framework for additional subsurface correlation and interpretation west of the outcrop area. There also appears to be a good correlation eastward to northeastern New Mexico/ Oklahoma Panhandle area (Scott, et al, 2004). Owens and Head (2001) attach significance to surface S3 similar to that reflected in Figure 25.

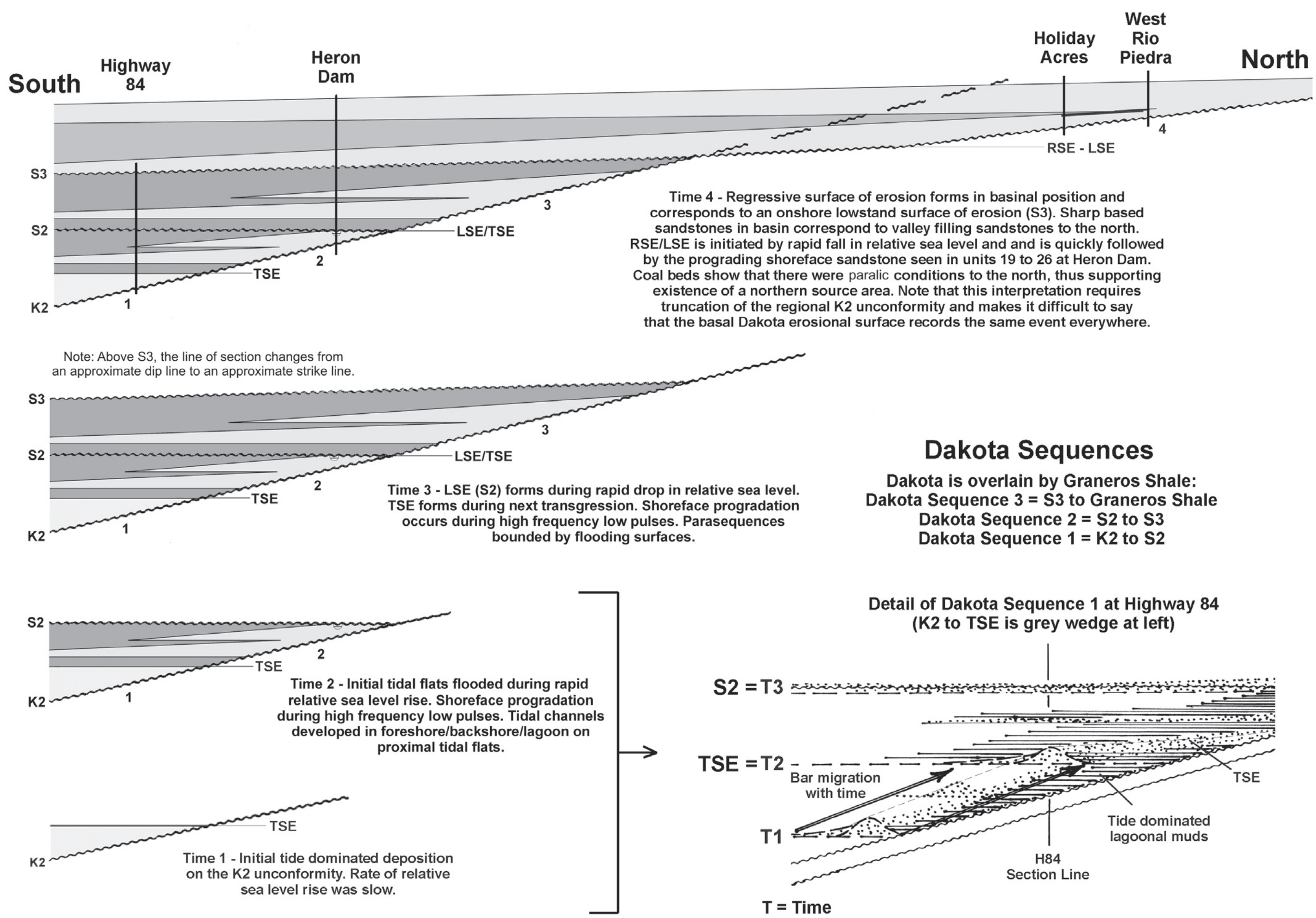

FIGURE 25. Diagramatic cross section from Highway 84 on the south to the West Rio Piedra Dakota section (Varney, 2000) on the north. The sequence of Dakota depositional events is interpreted from outcrop observations. The Dakota records an overall transgression punctuated by high-frequency drops or stillstands in sea level that allowed shoreface progradation. Please note that below S3 this diagram presents a dip section and above S3 it presents a strike section.

CONCLUSIONS

It is clear that the sections at Highway 84 and Heron Dam correlate and that they correlate to the subsurface.

There are three depositional sequences in the Dakota (Fig. 25). However, as the Western Interior Seaway expanded, the shoreline moved from a mostly southwest/northeast orientation within the study area to a more north south direction west of the study area (Cobban and Hook, 1984; Carey, 1992). This complicates lithostratigraphic correlation in the subsurface. However surface S3 seems to be present over a large area and it effectively divides the Dakota section into two main chronostratigraphic intervals. Dakota sequences 1 and 2 lie below S3 and Dakota sequence 3 lies above. This may explain some of the correlation difficulties subsurface geologists observe in the subsurface Dakota. Because of shoreline reorientation through time, lateral variations within the named sandstone members such as Cubero, Paguate and Twowells will not follow similar trends.

Examination of the grain sizes on the columnar sections in this study shows that sandstones in the Dakota section are commonly no coarser than fine grained. In those intervals with well developed gamma ray curves, the sands may coarsen but the primary change in sandstone character in the lower count gamma ray intervals is less clay content. On outcrop, the uppermost Dakota sandstone not only had lower clay content, but increased silica cement as well. These variations in the sandstones have significant petrophysical importance that may impact exploration and development of oil and gas resources in the area.

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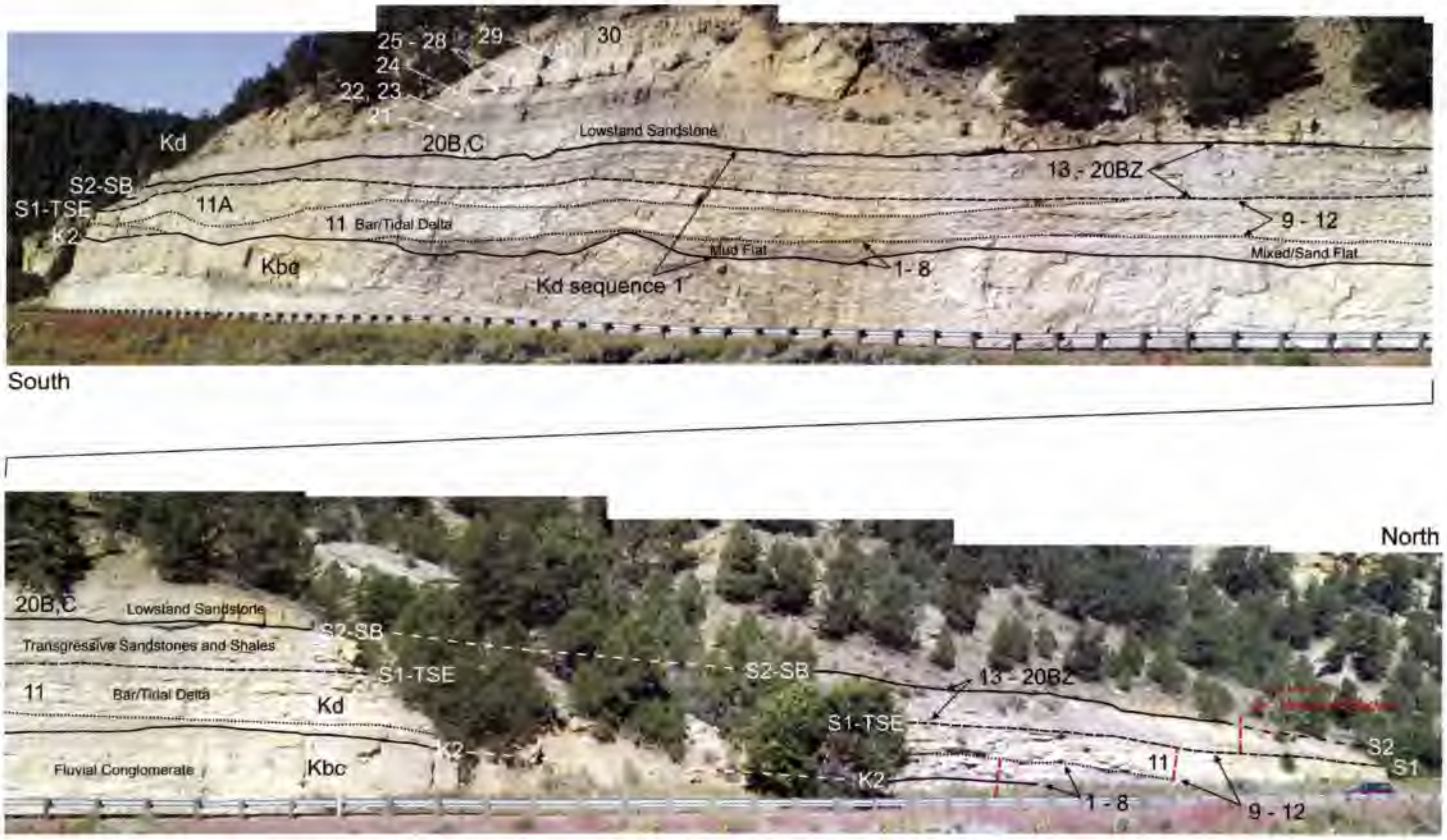

PLATE 5. Annotated panoramic view of the lower part of the Dakota outcrop at Highway 84 showing significant boundaries. Numbers are lithologic units discussed in Varney (this volume) and in much more detail in Varney (2000). View is split with the south half on the top and the north half on the bottom.

PLATE 4. Maps showing distribution of contraction and extension for Phanerozoic tectonic events in the southwestern U.S. and resolved shear stress on north-striking faults in northern New Mexico. For simplicity, only the Picuris–Pecos fault is depicted. See text in Cather et al. (this volume) for discussion. Symbols are explained in Plate 3. (a) Cambrian extension during opening of the southern Oklahoma aulacogen. 1. Extension direction in southern Oklahoma aulacogen (Keller and Baldridge, 1995). 2. Extension direction in the hypothetical westward continuation of the aulacogen in the Apishipa uplift area of southeastern Colorado (Larson et al., 1985). (b) Late Mississippian, Pennsylvanian, and early Permian Ancestral Rocky Mountain orogeny. 1. Directions of major crustal shortening and probable sinistral deformation in the Wichita uplift area (Brewer et al., 1983; Budnik, 1986). 2. Direction of major crustal shortening in the Uncompahgre uplift (Frahme and Vaughn, 1983). 3. Shortening direction for northwest-trending en echelon folds adjacent to the Pleasant Valley fault (Wallace et al., 2000). 4. Shortening direction for en echelon folds adjacent to the Fresnal fault (Otte, 1959). 5. Approximate shortening direction for en echelon basins and uplifts in the southern Sangre de Cristo Mountains (Baltz and Myers, 1999, fig. 71). 6. Dextral deformation in the Central Basin Platform area (Yang and Dorobek, 1995). 7. Approximate extension direction for striated late Pennsylvanian fault, Joyita Hills (Beck and Chapin, 1994; note that this extension direction is at odds with the other kinematic indicators in this figure). (c) Late Cretaceous–Eocene Laramide orogeny. 1. Contraction direction from dominant trend of folds in the central Colorado Plateau (Kelley, 1955; Woodward, 1984). 2. Contraction direction from dominant trends of basins and uplifts, central Wyoming (Brown, 1993, figs. 3, 4). 3. Generalized shortening direction from minor-fault data, Front Range (Erslev et al., 2004). 4. Shortening direction for en echelon folds in eastern San Juan Basin (Baltz, 1967). 5. Generalized shortening direction from minor-fault data in central Colorado (Wawrzyniec et al., 2002). 6. Generalized shortening direction in southwestern New Mexico (Seager, 2004). (d) Miocene extension in the Rio Grande rift. 1. Generalized extension direction from several late Oligocene–early Miocene dikes west of Socorro (Aldrich et al., 1986). 2. Extension direction from early Miocene dikes in the Questa caldera area (Aldrich et al., 1986). 3. Extension direction in Browns Park (1984, 1986). 4. Extension direction in Split Rock Basin, Granite Mountains area (Love, 1970; Chapin and Cather, 1994).

PLATE 6: DAKOTA FORMATION OUTCROPS

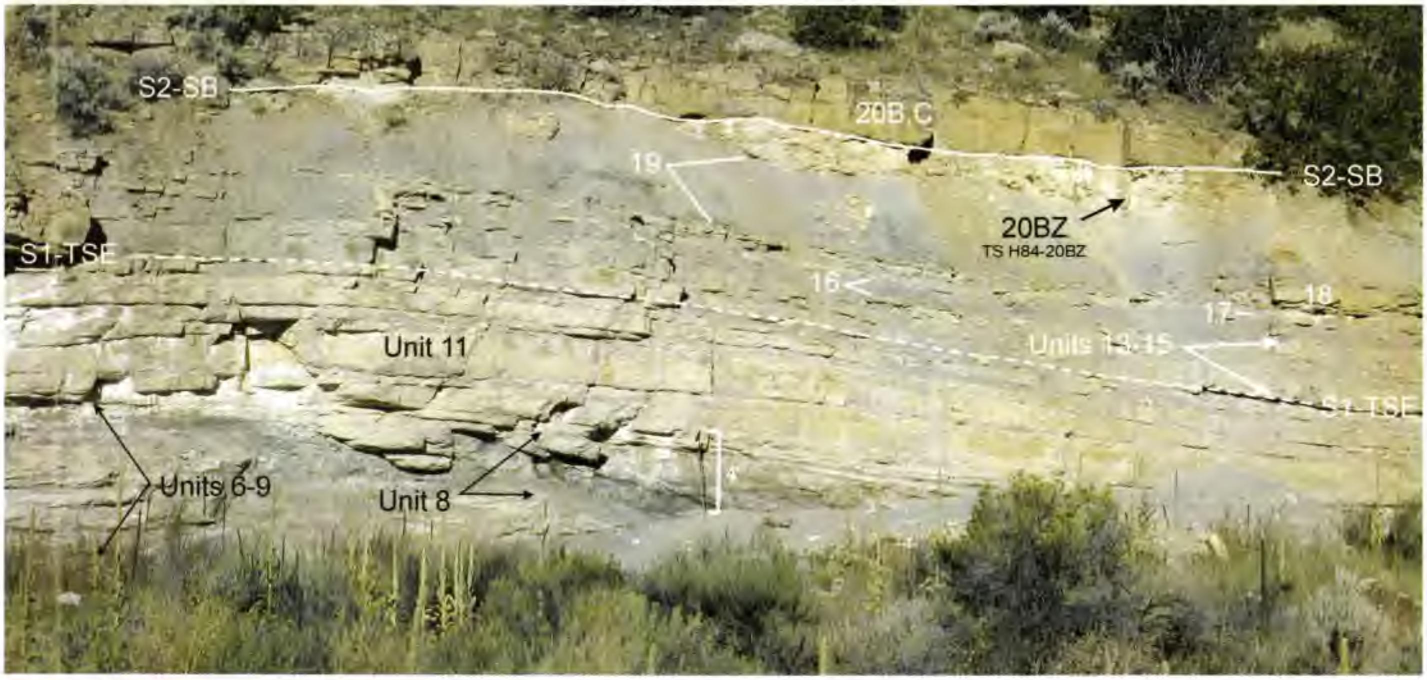

PLATE 6A. Units 6 through 20C at the north end of the base of the Highway 84 outcrop (see figure 6 in Varney, this volume). Note position of unit 11, part of a suspected barrier bar sandstone beneath TSE surface S1. Unit 8 is a tidal channel that thins to 0 southward (see figure 5 in Varney, this volume). X-ray diffraction analysis of a sample from Unit 20BZ shows a high concentration of kaolinite. The notation TS H84-20BZ refers to a thin section described in Varney (2000). Hiking staff for scale is about 4 feet high.

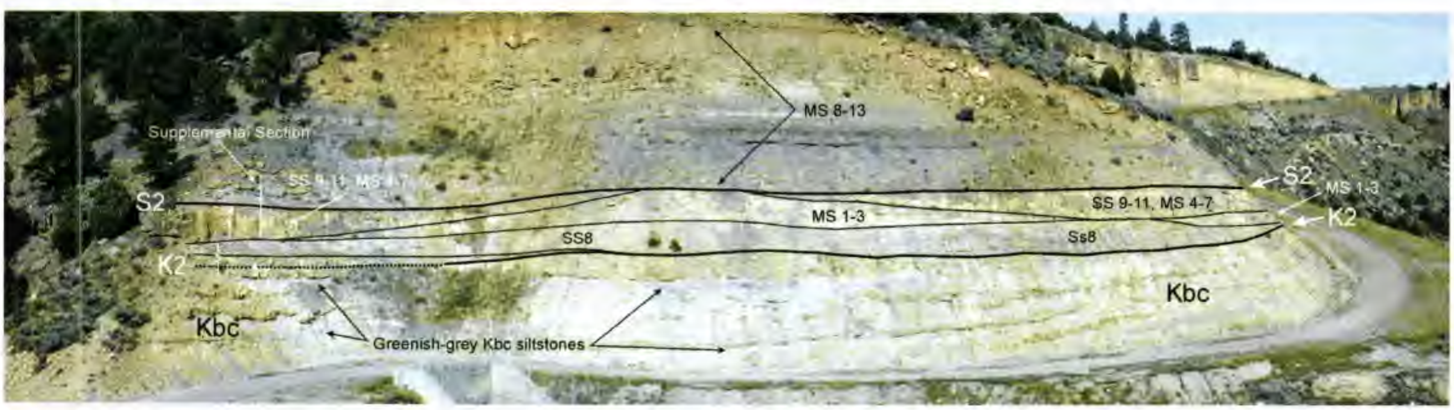

PLATE 6B. View to the east of the west end of the Dakota outcrop at Heron Dam. The position of the supplemental section is shown on the left. The main section was measured behind the nose on the right and up to the top of the prominent sandstone on the skyline in the background. The Burro Canyon Formation (Kbc) forms the base of this outcrop. Note the presence of characteristic greenish gray shales in the Kbc. In this illustration, "MS" designates rock units in the main measured section and "SS" designates rock units in the supplemental section. Unit numbers tie to the discussions in the text. The Dakota rests on the K2 unconformity and here it comprises proximal tidal flat gravelly shales, SS8,mixed sandstone shale tidal flat sediments, MS 1-3, and a tidal channel, SS 9-11, MS 4-7. The S2 surface is both a lowstand surface of erosion and a transgressive surface of erosion. Clay mineral analyses here and at the Highway 84 outcrop show that S2 is highly kaolinitic and most likely the same surface at both locations.