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Sequence Stratigraphy of the Dakota Sandstone,
Eastern San Juan Basin, New Mexico,
and its Relationship to Reservoir Compartmentalization

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ABSTRACT

This research establishes the Dakota-outcrop sequence stratigraphy in part of the eastern San Juan Basin, New Mexico, and relates reservoir quality lithologies in depositional sequences to structure and reservoir compartmentalization in the South Lindrith Field area. The result is a predictive tool that will help guide further exploration and development.

Analysis of Dakota outcrops shows that the interval contains three depositional sequences within an overall third-order transgressive systems tract. Sequence 1 lies on the regional K2 unconformity above the Early Cretaceous Burro Canyon Formation and extends upward to Dakota Surface 2 (S2), a combination lowstand surface of erosion/transgressive surface of erosion that was subaerially exposed. Sequence 2 extends from S2 upward to Surface 3 (S3), a regressive surface of erosion that extends throughout the research area and perhaps much further. The interval between S2 and S3 comprises a transgressive systems tract in which there are two or more shorefaces that prograded basinward during fourth-order relative sea level fluctuations. Sequence 3 extends from S3 upward to the top of the Dakota and its contact with the overlying Graneros Shale. It contains fourth-order lowstand, transgressive and possible highstand systems tracts (HST).

Sequence 2 contains a bentonite dated at $93.12 \text{ Ma} \pm 0.5$ (late Cenomanian, early Turonian) making the Dakota of the study area at least 2.5 million years younger than the lithostratigraphically equivalent section to the north in the Denver Basin.

Dakota parasequence characteristics are continuous over great distances along paleostrike, allowing outcrop gamma ray profiles to tie to, and permit calibration of, well logs in the South Lindrith Field, 44 miles to the southwest. Subsurface well log cross sections show that the sequence framework established on outcrop applies to the subsurface.

Within the Sequence 3 HST, northwest to southeast trending shoreface deposits, previously thought to be shore-parallel, linear offshore bars, prograded northeastward. Syndepositional faults, detected through very close-spaced contour mapping, helped determine their orientation. One of these shoreface deposits produces gas from abundant porosity in a fault bounded, stratigraphic reservoir compartment. It helps confirm the importance of structurally enhanced reservoir compartmentalization in the Rocky Mountain area.

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CHAPTER 1

INTRODUCTION

Two concepts have evolved in the last few years that have markedly changed the approach of petroleum geologists: sequence stratigraphy and the idea of compartmentalized reservoirs. As late as the early 1990s, many workers agreed that production from Rocky Mountain oil and gas reservoirs was mainly from stratigraphic traps in structurally simple settings. Detailed analysis of reservoir data using sophisticated technologies has revealed that such simplicity is the exception rather than the rule (Slatt, 1998). The Rangely field in northwestern Colorado, the region's largest oil field with over 800 million barrels total production, is a perfect example. When first developed, operators considered it a simple anticlinal fold with one reservoir, but the field is now known to contain several stacked pays, stratigraphic variations and multiple faults. These elements comprise compartments. Recent work by Weimer (1996), Martinsen and Olsen (1996) and Slatt et al. (1997), demonstrates that compartments bounded by stratigraphic and structural changes control production in other Rocky Mountain fields as well. In the San Juan Basin, stratigraphic traps such as those in the Dakota Formation are common and in modern thinking are properly considered stratigraphic compartments. Structural compartmentalization is also probable and is most likely related to basement faulting and growth faulting (discussed in Chapter 5).

This dissertation presents the results of a study of sequence-related stratigraphic variations in the Dakota Sandstone in the eastern San Juan Basin, New Mexico (Figure 1.1), and the possible contribution they make to reservoir compartmentalization of the type mentioned above. Outcrop work yielded the basic sequence framework and the lessons learned were used to evaluate the stratigraphy and structure within the Lindrith South Gallup-Dakota field area in the south part of the Jicarilla Apache Indian Reservation in Rio Arriba and Sandoval Counties (Figure 1.2). The New Mexico Oil and Gas Conservation Commission assigned the name “Lindrith South Gallup-Dakota Field,” but in this dissertation it is called by the less cumbersome name South Lindrith.

The South Lindrith field area appears to be more stratigraphically complex than has been previously recognized. Throughout the Rocky Mountain region, the Dakota accumulated in a marginal to shallow marine environment. In the northwest part of the San Juan Basin, the Dakota comprises non-marine channel fill deposits as well as shallow marine sands (Deischl, 1973). To the northeast, MacMillan and Weimer (1976) characterize the Dakota along the Colorado Front Range as a delta plain sequence with associated incised valley fill and shallow marine sandstones. As mapped by McGookey et al. (1972), both of the areas are along the west side of the Western Interior Cretaceous Seaway (WICS), so they probably share a similar depositional environment. Most workers accept that the Dakota formation has complex internal stratigraphy (Owen and Siemers, 1977) and that it marks the first significant deposits of the advancing Cretaceous sea. The specific distribution of each facies within the Dakota Sandstone can have a critical effect on oil and gas accumulation.

Figure 1.1: Geologic map of northern New Mexico and southern Colorado. The San Juan Basin of common usage is within the outline of the lower Tertiary, Txc on this map. The Dakota Sandstone is the olive colored uK1 interval. Extracted from USGS Tectonic Map of the United States. Inset map shows the location of the San Juan Basin.

The Skelly Oil Company No. 2 Jicarilla "D" well in the NE quarter of Section 5, T 23 N, R 4 W discovered Dakota oil in the South Lindrith field on 29 January, 1958 (Figure 1.2). The field produces from stratigraphic traps enhanced by natural fracturing (Matheny, 1983) and has produced more than 85 MMBO and 190 BCFG to date (Dwight's Energy Data, 1997), with about 14.7 MMBO of the total within the reservation. Estimated primary recovery per well is 40,000 to 80,000 barrels. The oil averages 43 degrees API, is low sulfur, sweet and paraffin based. At the time of Matheny's (1983) report, average daily production per well was 327 BO and 554 MCFGD. Wells are on 80 acre spacing. Production from the Gallup and Dakota Formations is comingled and there are no public data available on original oil and gas in place. The formations are tight with matrix permeabilities reported to be less than 1 millidarcy (Matheny, 1983, Byrnes, 1997).

To adequately describe the Dakota Formation in the South Lindrith field area, it was necessary to tie the outcrop data to subsurface well logs. This presented a rare opportunity to combine the disciplines of outcrop and subsurface geology.

The outcrop geologist has the benefit of working with real data that have "ground truth," but typically complains about outcrops that are difficult to reach, fossil distributions that are not diagnostic, overly weathered bentonites that are not suitable for age dating, the high cost of laboratory procedures, bad base maps, poor air photos, missing pieces of the puzzle and more. Subsurface geologists, on the other hand, have concerns that are quite different. They typically use seismic data, well logs and other common working tools that are, at best, first approximations of reality and except for

Figure 1.2: Index map of the San Juan Basin area showing prominent structural features and the locations of the Jicarilla Apache Indian Reservation and Lindrith South Gallup-Dakota field area (inset). Tectonic base map after Peterson (1965).

the rare core or well cuttings that may tie to a log, they must rely on the work of others to place what they see into a geologic context. Calibrating the tools requires extrapolating outcrop data into the subsurface. The process has uncertainties that in many instances require an imaginative approach that may lead to equivocal conclusions, but it is the only way to create a subsurface interpretation that has its basis in reality.

This dissertation is such a combined approach. The sequence stratigraphic interpretation in the Chama Basin, adjacent to the east side of the San Juan Basin, is tested in the subsurface of the South Lindrith field area in the southeast part of the San Juan Basin more than 40 miles away. The results (Chapter 5) suggest that the method works and that it will be possible to predict the location of new production by applying sequence stratigraphic methods.

Problem and Purpose

This paper presents the results of research undertaken to partially satisfy the requirements for a Ph.D. in geology at the Colorado School of Mines. The research was undertaken for the benefit of the Jicarilla Apache Indian Tribe, was sponsored in part by the US Department of Energy, and is designed to help extend known Dakota production within the Reservation.

The Dakota Formation is an important oil and gas producing horizon in the San Juan Basin of New Mexico and Colorado, but several fields, such

as South Lindrith, are mature and will soon cease production unless they can be rejuvenated or expanded. How to do that is a complex problem.

Many workers feel that the petroleum reservoir quality of the Dakota Sandstone is so poor that without fractures, it would either not produce or would produce far less than it does. According to Matheny (1983), production is fracture enhanced in the South Lindrith field. As critical as the fractures are to enhanced production, they act as an impediment to secondary recovery efforts such as waterflooding because they are preferential fluid pathways. Flooding, therefore, may not be an option for extending production in this area (Jim Lister, 1997, pers. comm.). Indeed, Matheny (1983) indicated that secondary recovery is not planned. Thus, infill drilling and stepouts provide the main opportunity for enhanced production. However, knowing where to drill, and at what spacing and orientation requires knowledge of the extent of both stratigraphic and structural compartmentalization.

Using maps of sequence related facies variations, it is possible to predict the specific location of clean sandstones - competent lithologies. Because it is far easier to read these sequence data from subsurface information, such as well logs, than it is to directly measure faults and fractures, a primary goal of this research is to see if there is a relationship between the clean sandstones and fault bounded compartments. The tie between outcrops and subsurface logs in the South Lindrith field area will help establish whether sequence-related lithologies exert a primary control on favorable primary matrix characteristics and whether there is a predictable sequence connection to post depositional faulting/fracturing and reservoir compartmentalization. If there is, then carefully defining and

mapping the sequences can become a predictive tool for extending favorable Dakota production.

The bias that fracturing is necessary for production may be partly true, but it is likely that other conditions are at least as important and, locally, more important. The problem is to identify additional factors that contribute to Dakota production and define their interrelationships in a manner that can be used to locate additional Dakota resources in the South Lindrith field area and throughout the San Juan Basin.

It is the purpose of this research, then, to delineate the sequence stratigraphy of the Dakota in the eastern San Juan Basin, map Dakota structure in the South Lindrith field area and, finally, determine if there is a relationship between the two that can predict a trend of reservoir compartments. The results will be applicable in those parts of the San Juan Basin and Rocky Mountain region where marine and marginal marine facies of the Dakota occur. Such an area is, of course, much bigger than the limits of the Jicarilla Reservation. When all results are combined, the ultimate purpose of this research is to help guide the search for new Dakota oil and gas reserves and maximize those already discovered.

Location and Scope

The Jicarilla Apache Reservation is located on the east side of the San Juan Basin in northwest New Mexico (Figures 1.1 and 1.2), and covers approximately one million acres in parts of Townships 22 to 32 North and

Ranges 1 East to 5 West of the New Mexico Principal Meridian. The outcrop of the Upper Cretaceous Fruitland Formation is generally accepted as the outer limit of the geologic San Juan Basin and the outcrop trends generally north to south on the east side of the Reservation. The east edge of the basin marks the approximate eastern edge of the Colorado Plateau physiographic province (Figure 1.1).

Approximately 24 townships in the southwestern part of the Reservation contain several producing oil and gas fields developed in the Pictured Cliffs, Mesaverde, Gallup, Greenhorn and Dakota Formations of Cretaceous age. The South Lindrith field , discussed in this report, is in the north half of Township 23 North and south central Township 24 North, Range 4 West (Figure 1.2). It occupies an area of about one half township. Other Dakota fields in the area include Lindrith West to the east and northeast in parts of Townships 22 to 24 North, Range 3 West, Ojito to the north in Township 25 North, Range 3 West, and Five Lakes to the southeast in Township 22 North, Range 3 West.

Geographically, the study area comprises a triangle that extends from the South Lindrith field eastward to the north and south parts of the Chama Basin which is east of the east edge of the San Juan Basin as defined above (Figure 1.3). The Chama Basin is separated from the San Juan Basin by a north-trending monoclinal flexure, called the Hogback Monocline on some maps, that appears to be a northern extension of the bounding thrust fault on the west side of the Nacimiento Uplift (Figure 1.1). In addition, outcrops were visited, but not described in detail, on the north side of the San Juan Basin south and west of Pagosa Springs, Colorado.

Figure 1.3: The study area includes two outcrops east of the Jicarilla Apache Reservation at Heron Dam and on US Highway 84 north of Abiquiu Reservoir on Canillon Creek. The South Lindrith field area is on the Rio Arriba and Sandoval County line west of the small town of Lindrith, New Mexico.

Emphasis centers on two areas: the outcrop belt on the east side of the San Juan and Chama Basins and the greater South Lindrith field area in the south part of the Jicarilla Apache Reservation. The study comprises a detailed geologic investigation based on correlation of outcrop with subsurface data represented by about 214 wells in the South Lindrith field area. Lack of engineering data such as dipmeter logs, DSTs, pressure tests, production tests, cores and associated laboratory core information prevents the study from being a full reservoir characterization. Furthermore, production from the Dakota and Gallup Formations is comingled and it is impossible to determine the precise contribution each zone makes to total production. However, quality of well logs and outcrop data allow a high level of sequence definition that can be directly applied to explaining production in the South Lindrith field , and as this dissertation later shows, it is possible to infer production contributions based on existing cumulative production data.

The stratigraphic scope includes the entire Dakota interval starting at the regional unconformity between the Dakota and the underlying Burro Canyon Formation (K2) and going upward to the unconformity between the Twowells Sandstone and Graneros (Mancos) Shale (Figure 1.4). Outcrop data for the present study include the interval from just below the top of the Burro Canyon Formation to the top of the Twowells Sandstone. Well log data are, for the most part, complete over the same interval.

All available data are incorporated in the study including well logs, thin sections, outcrops, partial cores from nearby areas and previous studies. This is a synthesis of existing data, but more importantly, it is also an expansion of the Dakota knowledge base.

Figure 1.4 - Abbreviated stratigraphic column for the eastern San Juan Basin. The interval this study examines is from the top of the Burro Canyon Formation to the base of the Graneros Shale. Major unconformities recognized in the literature are K1, K2. Figure also shows significant surfaces within the Dakota identified in this dissertation. Dakota nomenclature from Landis et al. (1973) and Aubry (1988a). This dissertation does not use the formal stratigraphic division names except where it is necessary to correlate observations from different areas.

Methods and Approach

Much of the present work uses the methods of classical field geology including measuring and describing outcrop sections with Brunton compass and tape, sampling, fracture measurement, outcrop photography and so forth. Measured section descriptions are in Appendix A. Thin sections were made from selected samples and the descriptions are in Appendix B. In addition, one shale sample at the Highway 84 outcrop was analyzed for total organic carbon content and one bentonite was age-dated using the Argon/Argon method. Gamma ray profiles were made at both the Highway 84 and Heron Dam outcrops with a Scintrex scintillation counter (Slatt et al., 1995) and the results were scaled to match the stratigraphic columns at both locations and the subsurface gamma-ray logs in the South Lindrith field area.

For the purposes of this dissertation, and in general agreement with practice in the area, the base of the Dakota Sandstone is picked at a lag on an unconformity and is confirmed by the presence of carbonaceous debris and white, tripolitic (weathered) chert above the surface. The top of the formation is the flooding surface/unconformity at the top of the highest sandstone beneath the Graneros Shale and Greenhorn Limestone. Using this working definition places Aubry's Encinal Canyon Member (1988a) at the base and the Twowells Sandstone of the subsurface at the top. This study does not use the conventional member names, rather it uses significant surfaces and parasequence stacking relationships.

The regional fault pattern was taken from published maps. An air photo of the Heron Dam area confirmed fracture directions measured in that

area. In the subsurface, faults near the South Lindrith field are from Franklin and Tieh (1989), Taylor and Huffman (1998), and interpreted from proprietary seismic data provided by Burlington Resources. Faults within the field are interpreted from marker bed offsets and zones of closely spaced isopach and structural contours.

Photographs of the outcrops visited have been digitized and many are presented in this dissertation. Larger, more detailed versions of the photos and illustrations are included in non-reduced format on the enclosed CD-ROM.

The subsurface work was computer-aided, primarily using TerraSciences' TerraStation II software. All available field wells were digitized with TerraSciences' software and petrophysical analyses done within TerraStation II. Digital base map information came from Tobin Map Service Company in San Antonio, Texas. Production data are from Petroleum Information data files on CD-ROM.

An important characteristic of this type of study is its iterative aspect. Too often we assume that if we don't see something in the field, then it doesn't exist. Many times in the course of this work, the outcrop helped explain subsurface observations, but equally as often, subsurface indicators pointed back to the outcrop and led to new findings. This is an important lesson and emphasizes the absolute need for integrating both types of study.

Mathematician Charles Dodgson (1865) said, "Begin at the beginning

. . . go on till you come to the end; then stop”. Following this advice, the approach from the very beginning has been to thoroughly determine the Dakota sequence stratigraphy on outcrop before applying the results to the South Lindrith field area. It is the nature of geological research, however, that the end of one study becomes but the beginning of another - there is no stop in sight.

Historical Overview and Previous work

Geologists have noticed and commented upon the Dakota Sandstone for nearly 150 years. Thinking about the genesis of the rocks in the interval has changed considerably in that time.

History records Meek and Hayden (1861) as the first to apply the name “Dakota Formation.” Their type section was a stratigraphic interval near Dakota in Dakota County, Nebraska, that they had previously described but not named, and that included the section between the Jurassic Morrison Formation and the overlying marine Cretaceous rocks. Hayden (1857) had noted that the interval would likely be found over a broad area and Peale (1876) later described rocks he assigned to the Dakota in the Gunnison Valley of south central Colorado on the north side of the San Juan Mountains. In 1877, Holmes used Dakota for equivalent rocks in northwestern New Mexico even though many earlier workers, including Gilbert (1875), and Hayden (1857), had recognized the lateral continuity of Cretaceous rock units in that area. Dutton (1885), in describing the section in the San Juan Basin, noted that the base of the Cretaceous started with the

Dakota. Gregory (1938) formally extended the Dakota nomenclature to southeastern Utah and since he did, most workers have accepted the existence of Dakota equivalent sediments throughout the Four Corners area and the San Juan Basin.

During the 45 years between 1915 and 1960, the US Geological Survey posted the Dakota name as “Dakota (?) Sandstone” in the Four Corners area because of uncertainty about the relationship between the hard-to-locate type area and local basal Cretaceous rocks. Authors such as Young (1960), have omitted the query, but many still question the use of Dakota as a formal stratigraphic name. The Dakota is more of an event than a discrete package of rocks.

Young (1960) extended the Four Corners area Dakota nomenclature geographically but confined its definition to “all the predominantly non-marine basal Cretaceous deposits of the Colorado Plateau,” thus carrying on a tradition of classifying the formation as mostly continental. Young’s Dakota correlated to what we today call the Burro Canyon and Cedar Mountain Formations. He, too, recognized that the term “Dakota” was inexact because of questions about the original definition by Meek and Hayden and the location of their type section.

McPeck (1965) recognized the distinction between the continental Burro Canyon of Stokes and Phoenix (1948) and Stokes (1952) and the marginal marine section above. He still placed the Burro Canyon in the lower part of the Dakota Formation, but was one of the first to note that the division point between continental and marginal marine deposits was

between the greenish gray shales of the Burro Canyon and the carbonaceous sandstones and shales above. This distinction is still a primary lithologic basis for defining the break between the two depositional styles.

Owen (1966) clarified the nomenclature of the upper part of the Dakota in the San Juan Basin and formally named the interval between the uppermost Twowells Sandstone and the sandstones below as the Whitewater Arroyo Shale Member. This paper marked the beginning of what might be called the modern understanding of the Dakota in northwest New Mexico. Owen (1973) went on to formally eliminate the Burro Canyon from membership in the formation and to accept the USGS divisions of the Dakota as formalized in the same year by Landis et al. (see below). His work mentioned the lithologic similarity of some Burro Canyon rocks and some basal Dakota rocks and in this way he foresaw Aubry's later formal classification of the basal Dakota Encinal Canyon Member. Owen's 1973 paper was followed by additional work by Owen and Siemers (1977) and Owen and Sparks (1989).

In the 1970s, the Dakota was clearly coming to be seen as mostly of marine origin and this is reflected in the subtitle of USGS Bulletin 1372-J on the Dakota Sandstone and Mancos Shale: *A study of the generally transgressive rock sequence at the base of the Cretaceous System*. Landis et al. (1973), authors of Bulletin 1372-J, clearly saw the marine nature of parts of the Dakota Formation and formally named the various members in ascending order: Oak Canyon Member, Cubero Sandstone Tongues of the Dakota Sandstone, Clay Mesa Tongue of the Mancos Shale, Paguate

Sandstone Tongue of the Dakota Sandstone, Whitewater Arroyo Shale Tongue of the Mancos Shale and Twowells Sandstone Tongue of the Dakota Sandstone. The authors based their divisions of the Dakota on field observations at many locations in the San Juan Basin area. Their nomenclature is still widely used, although with the advent of the sequence stratigraphic approach, many workers use the names less formally than previously.

Grant and Owen (1974) clearly set out the lithologies of the Dakota Formation, the paleocurrent directions and the trends of its continental, mixed and marine parts. Publication of their paper helped clarify the Dakota as transitional with continental and marine endpoints and cleared away much of the confusion about the different appearance of the formation in different areas. Aubry (1986, 1988a and b, 1989, 1991, 1992) formally defined the coarse-grained lower part of the Dakota, that rests on the Burro Canyon in the study area, as the Encinal Canyon Member. Everything above the Encinal Canyon, according to Aubry, is marine. This marks the first clear division of the formation on a marine versus non-marine basis even though McPeck (1965) had gone in that direction when he identified the Burro Canyon as distinct from the marine Dakota above. Molenaar (1983) defined the Dakota stratigraphic framework with his detailed cross section of the San Juan Basin, and this was later extended by Molenaar and Baird (1989).

Clearly, there has been much work and careful thought about Dakota equivalent rocks in the Rocky Mountain Region in the last 50 years or so. In the San Juan Basin region notable papers, in addition to those mentioned above, have appeared from Stokes (1952), Dane (1960), Peterson et al. (1965),

Mc Gookey (1972), Waage (1975), Molenaar (1977, 1983) and Nummedal and Molenaar (1995). Carey (1992) was the first to use the term “main body” to refer to Dakota sediments on the northwest side of the San Juan Basin in which it is no longer possible to differentiate the various members. Use of the term hints at the problems workers face in trying to decipher the depositional history of the formation regionally. Even with the amount of work done, many studies mention the Dakota Formation in passing and have simply called it the first Cretaceous marine formation at the bottom of the section. Considering that for at least the first half century of use in the San Juan Basin the name Dakota referred to continental deposits above the Morrison Formation, even casually calling them marine marked an advance in understanding.

Exxon’s publication of the depositional sequence approach to stratigraphic analysis in AAPG Memoir 26 (Vail, 1977) reinvigorated the study of stratigraphy. The Exxon sequence stratigraphic approach is based on defining events that occur between unconformities on passive continental margins. It is a time-based, chronostratigraphic system. In the original definition, there are systems tracts between unconformities that correspond to relative sea level lowstand, transgression and highstand. Part of the value of the sequence stratigraphic approach is that the positions of systems tracts and their internal components can be predicted in relation to the unconformity surfaces. Because favorable reservoir lithologies tend to be associated with particular systems tract elements, such as coarse sands in basin floor fans, the approach has allowed identification of petroleum accumulations that were previously overlooked or not considered.

Before Memoir 26, lithostratigraphic correlation was the most common type used. This method bases correlations strictly on lithology and relative positions of lithologic units. The method encounters problems when, for example, two contiguous sandstones are separated by an unconformity and represent two depositional episodes, and possibly two depositional styles, that are not related. The lithostratigraphic interpretation describes only one event when there may be two or more. Recognizing the unconformity makes it possible to predict sandstone distribution and, possibly, the location of favorable petroleum reservoirs within rock units that would otherwise be seen as one homogeneous sandstone.

As knowledge of different depositional systems has increased, it has become apparent that the sequence stratigraphic approach can be modified to apply to other than passive continental margins. Weimer (1992) greatly clarified the sequence stratigraphic terminology for intracratonic and foreland basins and pointed out the differences between these and passive margins. His approach is used in this dissertation.

Increased understanding of depositional sequences has prompted reanalysis of many petroleum producing basins including the San Juan. Since the publication of Memoir 26, it is interesting to note that the few papers that concern themselves with detailed sequence stratigraphy in the San Juan Basin are in stratigraphically higher units such as the Gallup Sandstone (for example Nummedal and Molenaar, 1995). These efforts go far in developing a descriptive nomenclature for shelf sequences; sequences that are very different from those formed in the passive margins that were the birth places of classical sequence stratigraphy (Vail, 1977, VanWagoner et al.,

1988, 1990, Galloway, 1989, Mitchum and Van Wagoner, 1991, Van Wagoner and Bertram, 1995). Sequence stratigraphic work in other areas, particularly in Colorado's Denver-Julesburg Basin and the northern Rocky Mountain basins, has helped in developing the Dakota history in the San Juan Basin.

Much recent work both within and outside the San Juan Basin influences the present study and those of others. For example, Weimer (1978) pointed out the influence the transcontinental arch may have had during upper Cretaceous sedimentation. The southern part of his map indicates how the arch may fit with shorelines proposed by Cobban and Hook (1984) and Cobban et al. (1994), for the early Cenomanian in the San Juan Basin. That the shorelines seem to fit with observed lithologic changes in the Dakota is discussed in a later part of this dissertation. Carey (1992) gives support for the early Cenomanian shoreline interpretations. Dolson et al. (1991) and Dolson and Weimer (1992) demonstrated the importance of regional unconformities in the northern Rockies and Front Range, Colorado areas and the concepts they discussed are directly applicable to the San Juan Basin. Dolson et al. (1991) was the first to publish a numbered sequence of Cretaceous unconformities with K0 at the bottom of the section. In the San Juan Basin, however, conventional use assigns K1 to the first Cretaceous unconformity.

Dea (1995) nicely summed up the way people think about and approach the Dakota interval in the San Juan Basin at the present time:

It contains coastal barrier marine sandstones, mostly to the east, and continental fluvial sand units, mostly to the west. The

rocks represent a wide variety of depositional environments, ranging from braided streams, meandering stream complexes, foreshore and more distal shoreface deposits. Lithologies vary considerably as do reservoir quality and trapping mechanisms.

Regarding the importance of the Dakota as an oil and gas producing interval, Dea (1995) stated:

The first Dakota discoveries were made in the early 1920's on the northwestern flank of the basin and a central basin discovery well was drilled in 1947 south of Bloomfield, New Mexico in the Angel Peak area. A few additional discoveries were made in the 1950's. In 1961 several fields were combined to form the Basin Dakota field which by the end of 1976 contained 2,400 producing wells that had produced over 2.7 trillion cubic feet (TCF) of gas with an estimated total production of over 5 TCF. . . . Dakota fields range in size from 40 to 10,000 acres with most production from fields of 100 to 2,000 acres. Production of oil ranges from field totals of 1-7 MMBO. Over 14 BCF of associated gas has been produced (Huffman, 1987).

There is certainly both economic and scientific value in studying the Dakota rocks. Several oil companies are active in the area and Burlington Resources has recently completed a basinwide sequence stratigraphic analysis including subsurface mapping and seismic interpretation. The results of the Burlington study were given in an oral presentation by Head et al., 1999.

Because of its economic importance as a prolific petroleum reservoir, much of the previous Dakota work was from subsurface data. However, studies by Weimer (for example Weimer, 1996) and others (for example

Porter and Sonnenberg, 1994) have successfully applied outcrop and core data to the subsurface, thus greatly increasing the accuracy of interpretations. This study follows their example by using a combination of field and subsurface observations to analyze the Dakota formation. Because of studies such as the one sponsored by Burlington Resources, the picture is clearer today than it was before, but there is much work left for those who may be drawn to this, at times, enigmatic stratigraphic interval.

Research Contributions

This study makes several contributions to the knowledge base for the Dakota interval in the Chama and eastern San Juan Basins.

1. By abandoning the need to force fit all observed sandstones in the Dakota interval into an established lithostratigraphic naming convention and by adopting a correlation based on observable surfaces and parasequence stacking, it is possible to start to define the complete depositional history of the beginning of the late Cretaceous in the San Juan Basin. The conclusions developed here are somewhat different from “conventional wisdom.” It follows, then, that this study offers a new interpretation of the sequence stratigraphy for the Dakota interval on the east side of the San Juan Basin and the Chama Basin. Further, results may tie to outcrops to the north in the vicinity of Pagosa Springs, Colorado.

2. By using a sequence stratigraphic approach, previously named shale tongues of the Mancos Shale are more correctly seen as parts of marine parasequences within the Dakota.

3. It is apparent that Dakota production in the study area is from prograding shoreface sandstones. Conventional wisdom in the past has attributed Dakota production to shore-parallel, linear offshore bar sandstones.

4. The Dakota of the San Juan Basin is younger than it is in areas to the north. The valley cutting and valley filling in the Denver Basin was probably related to an Albian expansion. It was only when the Cenomanian Western Interior Cretaceous Seaway expanded after the late-late Albian closure that the Dakota of the San Juan Basin was deposited. This is significant because it shows that there is no chronologic relationship between rocks named Dakota in different areas. Only the depositional style is the same.

5. In this dissertation, the age near the base of the second Dakota sequence is clearly established as late Cenomanian to early Turonian ($93.12 \text{ Ma} \pm 0.5$). This is a few million years younger than lithologically equivalent Dakota strata in other parts of the Rocky Mountain Region, further supporting the sequence stratigraphic approach.

6. The outcrop at Heron Reservoir is tied to the subsurface, over a distance of 44 miles, through an outcrop gamma-ray profile and well logs. It shows that virtually the entire Dakota interval of the subsurface is present at Heron Dam. Comparison of the Heron Reservoir section with that at Highway 84 makes possible a three dimensional look at the Dakota interval on the east side of the San Juan Basin.

7. The results of the study show that production in the Lindrith South field is at least partly controlled by reservoir compartmentalization resulting from sequence-related lithology distribution and basement related vertical faulting along with syndepositional growth faulting. The conditions leading to petroleum entrapment are more complex than previously recognized.

8. Gas production from the uppermost parasequences in Dakota Sequence 3 is from mappable porosity. Previously, it had been assumed by most workers that Dakota production was exclusively from fractured reservoirs.

9. A regressive surface of erosion that shows no evidence of subaerial exposure (S3) is an important sequence boundary in the Dakota Sandstone of the eastern San Juan Basin. This dissertation shows that such surfaces can be identified through detailed examination of outcrop data and that they can be correlated to the subsurface using outcrop gamma ray profiles. Recognition that regressive surfaces of erosion have sequence stratigraphic significance in very low relief, shallow shelf settings may help better define the regional depositional history of the Dakota Sandstone and other formations deposited under similar conditions.

CHAPTER 2

DAKOTA DEPOSITIONAL CONDITIONS

Chapter 1 provided historic background information on previous Dakota studies. This chapter continues the discussion, but adds important details about the immediate pre-Dakota depositional setting. Waage (1975) pointed out how very long it took geologists to be aware of the problems correlating Cretaceous strata in general. The Dakota has its proportionate share of correlation challenges, so it is important to understand the conditions just prior to, as well as during, its deposition.

After Gregory (1938) formally extended the Dakota nomenclature to southeastern Utah, geologists have accepted the existence of Dakota equivalent sediments throughout the Four Corners area. We now know that the rocks earlier workers called Dakota in the San Juan Basin correlate to non-marine coarse clastics that comprise the Burro Canyon Formation and Cedar Mountain Formations.

As mentioned in Chapter 1, the first documented use of complete, formal, modern terminology for the Dakota in the San Juan Basin appears in Landis et al. (1973). In the west part of the basin, these sediments are all continental (Aubrey, 1992). The term Dakota Sandstone is now commonly confined to marine sediments and their landward correlatives that lie above the early Cretaceous Burro Canyon Formation and below the late Cretaceous Graneros Shale (Dyman et al, 1994). The rarely used term Dakota Group

includes the Burro Canyon Formation and its equivalents in the definition. In this dissertation, Dakota refers to all sediments below the Graneros Shale and above the K2 unconformity at the top of the Burro Canyon Formation.

Over the years, a complex lithostratigraphic nomenclature has developed for the Dakota (Figure 2.1), resulting in considerable confusion about its areal distribution. This is particularly noticeable on completion cards. It appears to be common practice to name the first sandstone penetrated by the drill in the Dakota interval as Twowells, Paguate, etc., based on expected regional lithostratigraphic relationships rather than on position within a chronostratigraphic framework. Recognizing the problem, some workers use informal subsurface divisions such as Dakota A, Dakota B, and Dakota C (Molenaar, 1977, Ridgley, 1987), but due to their local nature, this method of naming the various sandstones does little to clarify the situation. For example, in the central San Juan Basin, Molenaar's Dakota A commonly correlates to the Twowells member, but to the east, the Dakota A might correlate to the Paguate member, lower in the section. Classical nomenclature is useful for orientation, but care must be used so that final correlation is from genetic unit to genetic unit rather than just from name to name.

This dissertation subdivides the Dakota using the sequence stratigraphic approach as defined by Exxon (Vail et al., 1977). Unconformities are the master sequence boundaries. While various surfaces of erosion associated with both transgression and regression may coincide with sequence boundaries, they more commonly define internal breaks (Figure 2.1). Stacking patterns combined with grain size variations help

San Juan Basin (Northeast) Stratigraphy

With Comparison to East Central Colorado's Denver Julesburg Basin

Period	Formations	Apparent Denver Basin Equivalent
Cretaceous	Mancos Shale	Pierre Shale
Late	Greenhorn Limestone	
	Graneros Shale	
	Dakota Group	"D"
	Twowells Sandstone Tongue Kd	Huntsman (?)
	Whitewater Arroyo Shale Tongue Km	
	Paguate Sandstone Tongue Kd	Muddy ("J")
	S3 ~~~~~RSE/LSE	~~~~~
	Clay Mesa Shale Tongue Km	
	Cubero Sandstone Tongue Kd	Skull Creek (?)
	Oak Canyon Member Kd	
	S2 ~~~~~LSE/TSE	~~~~~
Late	Encinal Canyon Member Kd	Plainview (?)
~~~~~	K2 ~~~~~LSE	~~~~~
Early	Burro Canyon Formation	Lytle (?)
~~~~~	K1 ~~~~~LSE	~~~~~
Jurassic	Morrison Formation	

Figure 2.1: Abbreviated stratigraphic column for the eastern San Juan Basin with apparent east-central Colorado lithostratigraphic equivalents. The interval this study examines is from the top of the Burro Canyon Formation to the base of the Graneros Shale. Figure also shows significant surfaces within the Dakota Group identified by Weimer (1996) and several others in the Denver Basin and possible San Juan Basin correlatives that were identified in this study, including S2 and S3. This chapter uses the formal stratigraphic division names only to tie together observations by different authors in different areas. Kd = Dakota, Km = Mancos, LSE = lowstand surface of erosion, RSE = regressive surface of erosion, TSE = transgressive surface of erosion. After Young (1960), Owen (1966), Landis et al. (1973), and others.

define parasequences and sequence divisions between unconformities. When approached this way, it quickly becomes evident that the lower part of the Dakota records marine transgression and some possible low stand valley cutting and filling. The upper part of the Dakota records continued transgression and finally deposition of a sandstone marking a significant stillstand or regression.

This chapter uses the conventional lithostratigraphic nomenclature in Figure 2.1 only for the purpose of tying together the work of other authors. The sequence stratigraphic equivalents will be presented in detail in a later chapter.

Before the results of the present study can be fully appreciated, it is important to understand the setting in which rocks of the Dakota interval accumulated. This includes the structural framework just prior to Dakota time, the locations of source terrains and formations, the configuration and composition of the depositional surface, water depths, movements and variations, time of the onset of deposition, and other factors that influenced Dakota deposition and preservation. While all of these factors may be considered immediately pre-Dakota, they are critical to the Dakota's character. Thinking about the Dakota has changed in recent years, much of it due to redefinition of the time frame of its deposition.

Cenomanian Time Scales

The rest of this dissertation makes frequent mention of the age of the Dakota and various related events. Changing definitions of Cretaceous time divisions (Figure 2.2) have changed interpreted relationships and as a result, some older papers describe events that are no longer regionally time equivalent (e.g. Eicher, 1969, Berman et al., 1980). For example, there is more than a superficial lithologic similarity between the San Juan Basin Dakota and the section in the northern Rockies (Fig 2.1), so there is a tendency to want to consider the rocks the same age in both places. This points out a major weakness in lithostratigraphic correlation: just because two rock successions look the same and are named the same does not mean they are time related. As the next section shows, there is considerable difference in age at different regional Dakota outcrops.

Age of the Dakota Interval in the San Juan Basin

The age of the Dakota is important for purposes of determining the dominant flooding direction and for absolute time correlation to other areas.

The Western Interior Cretaceous Seaway (WICS) was not always continuous from north to south. Williams and Stelk (1975) showed that at times it had distinct, mappable northern and southern parts. The problem of deciding which sea was dominant in the San Juan Basin and how that helped determine distribution of Dakota sediments depends upon timing.

The surface separating the Burro Canyon and base of the Dakota, the K2 unconformity of San Juan Basin usage, is late Albian or latest early Cretaceous in age based on pollen data from the upper Cedar Mountain Formation, which overlies the Burro Canyon Formation in the western part of the basin (Tschudy et al. 1984).

Encinal Canyon sediments that fill valleys in the underlying Burro Canyon and Morrison Formations are earliest Cenomanian in age based on presence of the pollen *Nyssapollenites albertensis* (Aubrey, 1992). This is a problematic age assignment because Nichols (1994) assigns *N. albertensis* to the range from *Late* Cenomanian through mid-Coniacian.

Carey (1992) shows the surface at the top of the Cubero Sandstone, middle Dakota, as having a late middle Cenomanian age based on presence of the foram *Rotalipora reicheli* (Figure 2.2). Haq et al. (1988) show the range of *R. reicheli* restricted to about a one half million year range from upper lower Cenomanian to lower middle Cenomanian (94.5 to 95 Ma).

One thing appears certain. The entire Dakota interval of the San Juan Basin is Cenomanian or younger. Dolson and Muller (1994) show the Dakota of central Colorado as Albian in age and Berman et al. (1980) report an Aptian age for part of the Dakota in northern Colorado.

It is significant that late Cretaceous valley fill sediments in east-central Colorado are apparently older than those in the San Juan Basin. Weimer (1978) presents Graneros Shale isopach evidence that suggests those

Figure 2.2: Redefinition of the Cenomanian interval, 1972 to 1995. The duration of the Cenomanian in the western interior is now considered about five million years, between approximately 93.5 and 98.5 Ma. Ages of two commonly used index fossils referred to in the text are shown.

valley fills are related to the late-late Albian/Cenomanian northward regression off the remnant Transcontinental Arch. Aubrey (1992) shows that the Horsetooth Member of the Muddy Sandstone in the Denver Basin is probably late Albian and states that it is part of the same drainage system as the Encinal Canyon of the San Juan Basin. This dissertation proposes that the Encinal Canyon is more closely related in depositional style and position to the Plainview Sandstone in the Denver Basin, rather than the Horsetooth, and that makes the interval to the north even older.

Age Dating Using the X Bentonite

In the study area, there are several bentonites present in dark gray marine shales within the Dakota. Because they represent instantaneous time markers, they are important “clocks” in the geologic sense. In the dissertation area, it is possible to develop a time frame by projecting in the position of the X bentonite, an important marker to the north and northeast.

If the Encinal Canyon Member is earliest Cenomanian (Aubrey, 1988b) and the top of the Cubero Sandstone, middle Dakota, is lowest middle Cenomanian (Carey, 1992), and if the Haq et al. (1988) age dates are correct for *Rotalipora reicheli* (Figure 2.2), the bentonite present in the Oak Canyon Shale, between the Encinal Canyon Member and the Cubero Sandstone, could be the X bentonite of common usage in other areas (McGookey et al., 1972). Locally, it is called the Y bentonite (Owen, 1998, pers. comm.). The X, if that’s what it is, is thicker to the north than it is in the study area.

It is significant that the X bentonite is considered 95 million years old (Roberts and Kirschbaum, 1995). The X is a thin bentonite in the upper part of the Graneros Shale in eastern Colorado, western Nebraska, western South Dakota, and eastern Wyoming. It is an important time marker for interbasin correlation and lies in the zone of *Acanthoceras amphibolum* (Figure 2.3 and McGookey et al. 1972, p. 196).

Picking the X bentonite in the San Juan Basin, if it exists, could be difficult. Kauffman and Caldwell (1993), for example, speak of 1300 bentonites in the Cretaceous of which it is only one. However, McPeck (1965) shows a possible correlation of the X bentonite from the Colorado Front Range to the San Juan Basin in which the interval between the bentonite and the conglomeratic unit at the base of the Dakota is thinner in the San Juan Basin than elsewhere. If this correlation is correct, it is further confirmation that the Dakota of the San Juan Basin is, indeed, younger than it is in the Denver Basin.

The 95 million year date for the X bentonite and its associated index fossil, *A. amphibolum*, fits with the 92 to 96 Ma (Figure 2.2) lower Cenomanian of Haq et al. (1988), so it is within the lower Dakota interval of Carey (1992).

Roberts and Kirschbaum (1995) show the Cenomanian as 93.5 to 98.5 Ma and that would place the X bentonite at the top of the Dakota interval of the San Juan Basin (Figure 2.4) as they define it. To quote Cobban and Hook (1984) "In the northern part of New Mexico in the Chama-Tierra Amarilla

Figure 2.3: Index fossil *Acanthoceras amphibolum* like those from the San Juan Basin. The most recent age assignment for this ammonite is 95 million years - the same as the X bentonite. From Kauffman (1977).

Figure 2.4: General chronostratigraphic relationships between the San Juan Basin, SJB-SW, and Denver Basin, DB-NE. Note position of Dakota Sandstone and X bentonite at bottom of right column. From Roberts and Kirschbaum (1995).

area, the oldest fossils in the Dakota Sandstone represent the range of *Acanthoceras amphibolum* Morrow” Note that these *oldest fossils* are the same age as the X bentonite - 95 million years.

This dissertation uses the age date of Gradstein et al. (1995), for *A. amphibolum* of $94.93 \text{ Ma} \pm 0.53$. A sample collected during this study from the Oak Canyon Shale, in the lower part of the Dakota, yielded an Ar/Ar date of $93.12 \text{ Ma} \pm 0.5$ (Appendix D). It is, therefore, possible that the uppermost sandstones in the Dakota of the San Juan Basin are lowest Turonian and were deposited just before the eustatic Turonian maximum flood (Haq et al., 1988). *A. Amphibolum* is, in the most recent time scales, mid-Cenomanian and the results of the age data analysis suggest that the equivalent zone is near the *base* of the Dakota interval, not at the top as placed by Roberts and Kirschbaum (1995).

Cobban, 1993, indicates that the Oak Canyon Shale Member of the Dakota contains a diverse molluscan fauna. He and others (e.g. Obradovich, 1993) call this the “Thatcher” fauna because it is present in the Thatcher Limestone Member of the Graneros Shale in eastern Colorado and northeastern New Mexico. If the Oak Canyon Shale Member is age equivalent to the Thatcher limestone of eastern Colorado as Cobban (1993) suggests, it again confirms that the San Juan Basin Dakota section is younger than rocks of the same name to the north.

The uppermost part of the Dakota section is about one million years younger to the west in central Utah, near the Sevier Uplift source area (McGookey et al., 1970, 1972).

Duration of Transgression

The Dakota is commonly placed in the lower part of the Cenomanian/Turonian Greenhorn transgression (Molenaar, 1983), which also includes the overlying lower Mancos Shale of Molenaar (1977). The rocks within the Greenhorn transgression are bounded above and below by unconformities and comprise the lowest transgressive cycle in the Late Cretaceous of the San Juan Basin area.

Kauffman and Caldwell (1993) specify that there was one third order relative sea level cycle in the middle Cenomanian. If the Oak Canyon Shale records the transgressive phase of the cycle and the Cubero Sandstone Tongues record regressive phases, then the duration of that part of Dakota time was from 94.71 to 95.98 Ma (Kauffman and Caldwell, 1993) or approximately 1.25 million years. This figure is somewhat less than the two million year duration proposed by McGookey et al. (1970, 1972), because it does not include Aubrey's Encinal Canyon, below the Oak Canyon. The Encinal Canyon is properly considered part of the Dakota and extends it into the earliest Cenomanian based on fossil evidence presented earlier.

Roberts and Kirschbaum (1995) independently confirm the duration, but not the timing, calculated by Kauffman and Caldwell (1993). They map the Raton basin on the axis of the WICS during the earliest Cenomanian

when the seaway was reconnecting following the latest Albian closure, so it is a good starting point from which to calculate the amount of time needed for transgression to the west. The base of the Dakota is at 97.5 million years in the Raton Basin (Dyman et al., 1994), and at 96.25 million years in the San Juan Basin. The Dakota took 1.25 million years to transgress westward from the Raton Basin to the San Juan Basin. The time scale that Dyman et al., used appears to be the same as that in Roberts and Kirschbaum (1995) and differs only slightly from that of Gradstein et al. (1995).

Dyman et al. (1994), present evidence that the interval between the top of the Burro Canyon Formation and the base of the Dakota in the study area is about seven million years. The same interval in the Denver Basin is about 4.5 million years (Weimer, 1983). The conclusion we can reach here is that it took at least 2.5 million years (7 minus 4.5) longer for the WICS to reach the San Juan Basin than it did to reach the Denver Basin or that the base of the Dakota in the San Juan Basin is about 2.5 million younger than it is in the Denver Basin. This conclusion still does not imply a direction of flooding for the advance of the WICS into the San Juan Basin area.

Roberts and Kirschbaum (1995) show that the base of the Dakota in the Denver Basin has an age of 98.5 Ma and in the San Juan Basin, 96 Ma (Figure 2.4). This is further confirmation that it took 2.5 million years for the Dakota sea to cover the distance between the two locations.

The K2 Unconformity

Geologists working in the San Juan Basin recognize two regional unconformities within the Cretaceous section beneath the Dakota, but there is inconsistency in the literature about how these unconformities are named. There is a regional unconformity at the top of the Jurassic section and beneath the early Cretaceous that is not everywhere well expressed (Aubrey, 1991). Another is on top of mostly fluvial sediments of early Cretaceous age. Most authors agree that the fluvial rocks between the two unconformities belong to either the Burro Canyon or Cedar Mountain Formation (Craig et al. 1955, Owen and Siemers, 1977, Aubrey, 1992). Owen (1998, personal communication) and others use the terms K1 for the basal Cretaceous unconformity and K2 for that above the Burro Canyon. Ridgely (1987) and the present study confirm that the two unconformities are present in the Chama and San Juan Basins and that they can be seen both on electric logs and in measured outcrop sections. We can conclude from the preceding discussion on the amount of time that it took for the Dakota to transgress the K2 surface that the surface represents at least a 2.5 million year time interval.

The first use of formal unconformity designations in the western interior, based on the geologic periods in which they occur, seems to have been by Pippiringos and O'Sullivan (1968). They identified Triassic Tr1 through Tr3 and Jurassic J0 through J5. The top of the Jurassic in their study area is, simply, the K unconformity. As other workers have studied details of Cretaceous stratigraphy, the various K unconformities have been numbered from the base of the Cretaceous upward. In the San Juan Basin,

K1 separates the Cretaceous from the Jurassic everywhere and successive unconformities bound units upward. The K2 unconformity is a regional unconformity at the top of the Burro Canyon Formation.

Schwans (1995) uses the terms U1, U2 and higher for the various Cretaceous unconformities and their related correlative conformities in central Utah (Figure 2.5). The U2 is at the top of the upper Cedar Mountain Formation and is the surface on which the Dakota was deposited. Schwans' unconformity numbers seem to be the same as the K1 and K2 number sequence in the San Juan Basin. On the west side of Schwans' area, the Dakota appears to be correlative with the Sanpete Sandstone and underlies the Indianola Group. He shows the Dakota to be bounded at the base by a lowstand surface of erosion and at the top by a transgressive surface of erosion. The Dakota is overlain by the Tununk Shale (the Allen Valley Shale to the west) in the highstand systems tract. He places unconformity U3 at the top of the Tununk Shale separating it from the overlying Ferron Sandstone. The equivalent position of U3 in the San Juan Basin is the base of the Niobrara Formation, separating the Greenhorn and Niobrara transgressive cycles of Molenaar (1983).

Molenaar (1983) used a numbering system that was only tangentially related to unconformities. He added one more cycle to Weimer's four transgressive/regressive cycles (Weimer, 1960) and defined five cycles in the southern Colorado Plateau and adjacent areas. The R2, or Gallup, regression is limited to New Mexico and northeastern Arizona. The initial transgression, T1, was the Greenhorn transgression and was the most extensive throughout

Figure 2.5: Chronostratigraphic diagram from Schwans (1995) that shows his assignment of unconformities in the Cretaceous. Note on the right side of the chart that the Dakota Ss. rests on the U2 unconformity. His U3 unconformity seems to be equivalent to a recognized unconformity (Molenaar, 1977) in the San Juan Basin that lies beneath the Niobrara Formation.

the area. The base of Molenaar's T1 transgression is the K1 unconformity of local San Juan Basin usage.

Dolson et al. (1991), use the nomenclature K0, K1, K2 in their report on regional paleotopographic trends. Their K0 would be at the base of the T1 transgression of Molenaar (1983). Dolson and Weimer (1992) also show K0, K1, etc. Their K0 is on top of the Morrison, K1 is at the top of the Lakota (Burro Canyon), and K2 appears to be at the base of the Muddy Sandstone of the northern Rockies.

It is unfortunate that different workers appear to have used the same nomenclature for different time breaks. There are abundant unconformities within the Cretaceous, many of which seem related to local, or more localized than regional, events. Further, because there is evidence that the Dakota, for example, is not everywhere the same age, a regional unconformity noted in Wyoming or the Denver Basin may intersect the section in the San Juan Basin in a lithologically different position. In other words, it is very difficult to definitively tie surfaces throughout the region until there are many more age dates.

There is value in numbering unconformities in relation to the rock interval to which they are genetically related. For example, if a section is cut out by a surface, the surface logically is part of the next higher sequence - it is that sequence's base - its beginning. The unconformity that defines the top of the sequence is the start of the next sequence and so on. Berman et al., (1980) divided the Cretaceous into intervals designated JK-1, K-2, K-3 through K-5. At least as far as interval K-2 is concerned, its basal

unconformity fits the K2 use in the San Juan Basin. However, they call the interval below their K-2 the JK-1 and if we follow the same reasoning as above, the unconformity at the base of *interval* JK-1 becomes *unconformity* JK-1 not K-1. The problem remains.

The use of the terms K1, K2, etc. in this study is intended as working terminology only. It is clear that there is an unconformity between the Jurassic and Cretaceous systems and it seems logical that this fundamental break should be called K0. In the San Juan Basin it is not, it is called K1. The first unconformity within the Cretaceous occurs at the top of the Burro Canyon Formation and is here designated the K2. That these surfaces are K1 and K2 in the working language of the San Juan Basin is unfortunate, but in this dissertation, such use is maintained for local consistency.

Structural Setting

Western North America has been the site of numerous orogenies since the early Paleozoic. Each younger structural event centered slightly east of its predecessor and comprised highlands and associated east-side foreland basins. The highlands eventually wore down and the basins eventually filled, but west-central North America was anything but flat at the end of the Jurassic. The Sevier Uplift (Figure 2.6) was underway in western Utah and during the early Cretaceous it was shedding coarse sediments into an actively subsiding foreland basin that was the precursor of the Western Interior Cretaceous Seaway.

Figure 2.6: West to east cross section across the Cretaceous foreland basin from central Utah to Kansas. Note position of Dakota interval and how the source area for both the Dakota and Morrison has been eliminated through continued uplift and erosion. After Armstrong in McGookey et al. (1972).

North of the San Juan Basin, in what is now Colorado, the late Jurassic landscape featured remnants of the Pennsylvanian Ancestral Rockies that most authors call the Central Colorado Uplift (Peterson, 1972). A thinning of pre-Morrison sediments on a northeast trend in the eastern part of Colorado may reflect the old Transcontinental Arch (Weimer, 1978). By the end of Morrison time, however, these features were subtle at most and there was Morrison deposition over the entire area. Weimer (1978) showed isopach thinning during the Cretaceous that suggests recurrent Transcontinental Arch movement. Haun (1959) reported Dakota sediments on Precambrian in south central Colorado, but those observations are not confirmed in the present study.

Periodic uplifts in southeastern Arizona shed sediments to the northeast into the San Juan Basin during the late Cretaceous (Cummela, 1983), but this may not have been the only source during the earlier parts of the Period. An isopach of Jurassic strata suggests that there was a proto San Juan Basin that opened northwest into the Utah-Idaho Trough and that was positioned in such a way as to accumulate sediments derived from the northeast, off the Central Colorado Uplift, as well as the southwest (Peterson, 1972). By latest Jurassic, during Morrison time, the western uplift had intensified and the depositional belt had moved slightly eastward closing the south end of the Utah-Idaho Trough (McGookey, et al, 1972), but the northwest aligned proto San Juan Basin remained a depocenter in which the Burro Canyon Formation and related rocks accumulated.

What may be concluded from this is that at the beginning of Late Cretaceous deposition at the start of Dakota time, the Zuni-Defiance

highlands were to the southwest, the Sevier Uplift was to the far northwest and there may have been a slight positive feature to the north and northeast. The old Jurassic northwest axis was still low, but would soon fill in. As time passed, possible source areas to the north and northeast were submerged and became areas of open marine sedimentation that no longer had a direct affect on Dakota sedimentation. Based on fossil content, Cobban and Hook (1984) and Cobban et al. (1994) show that the early Cenomanian WICS western shoreline had embayments but that it moved westward and became straighter and more north-south oriented by middle and late Cenomanian (Figure 2.7). It is possible, therefore, that the first Dakota shoreline through the study area had a northeast-southwest orientation. Later shorelines trended more north-south and were west of the study area.

Marine Flooding and Expansion of the Seaway

The literature is indefinite when it considers the question of the direction of flooding during the Cretaceous in the San Juan Basin. Part of the reason is that the Basin is located very near the geographic point where the WICS came together from the north and south (Figure 2.8). There are many studies that discuss the advance of the Boreal, or northern, Sea, and some that talk about the advance of the Gulf, or southern, Sea, but none that answer the question near the area where they joined. It is possible, however, to piece together various ideas that, combined with the results of the present study, suggest that at different times the incursion direction was different. The flooding direction had significant influence on the distribution of Dakota

Figure 2.7: Map on right shows general position of shoreline in the study area during middle Cenomanian time and the classical Dakota division names for the units controlled by the shoreline. Map on left shows position of late Cenomanian shorelines. Note that through time, the shoreline moved west and became more north-south oriented. Black dots are fossil localities used by Cobban and Hook (1984). After Carey (1992) as modified from Cobban and Hook.

Figure 2.8: Configuration of the WICS during the late-late Albian just before the seaway reconnected in the early Cenomanian. Note the northwest tongue of the Gulf seaway, here in southeast New Mexico, that may have been a predecessor to Seboyeta Bay. After Williams and Stelck (1975).

sediments, particularly during the earliest phases. At the end of the Jurassic, there was a time of non-deposition in the San Juan Basin area that, like elsewhere, we see today as an unconformity surface - a surface of regional degradation (Aubrey, 1986).

Conventional wisdom holds that in the study area, the Cretaceous sea arrived from the north during the Albian, reached maximum depth during the Turonian and receded both to the north and to the south during the Maastrichtian. Because the effects of the Laramide orogeny were being felt during latest Cretaceous time, it is possible that crustal thinning in the area of the present Rio Grande Rift influenced the southeast direction of withdrawal. This overall picture may be correct, but there are important details that need to be considered. The question remains, for example, as to whether the San Juan Basin flooded from north or south.

The initial foreland basin east of the Sevier uplift and the seaway to follow were asymmetric with the deepest part in front of and adjacent to the uplift. The east coast of the WICS was the gentle slope of the Canadian shield. Weimer (1978) presents isopach evidence that the Transcontinental Arch affected the depth of the seaway, but the maps only reflect this during restricted time intervals such as during the late-late Albian/Cenomanian (Figure 2.8).

Williams and Stelck (1975) show that by the early-late Albian, the Boreal and Gulf seas had combined to cover the entire western interior seaway. A headland extended eastward into Colorado and New Mexico and the San Juan Basin area was emergent. In late-late Albian time, a land

bridge existed across northern New Mexico and southern Colorado linking Utah to northern Texas, Nebraska and Kansas and closing the seaway. Both the headland and the land bridge were roughly coincident with the trend of the Transcontinental Arch. That the San Juan Basin area was again emergent is shown by an unconformity, K2, across the top of Albian age conglomeratic sandstones and shales.

Seboyeta Bay

During the late-late Albian closure, there was an embayment in the Gulf Sea trending towards the San Juan Basin area that may have been the precursor to Cobban and Hook's (1984) Seboyeta Bay (Figure 2.7). Seboyeta Bay is inferred from fossil evidence the authors have collected in the San Juan Basin and that they have designated as early Cenomanian in age. Cobban, (1999, pers. comm.) indicates, unfortunately, that "we don't have any fossils to establish the *northern* limit to the Seboyeta embayment." We must look, then, to the rock record for evidence (Chapter 3).

Cobban and Hook (1984), define the shoreline of Seboyeta Bay at the time of lower Dakota (Oak Canyon Shale and Cubero Sandstone) deposition on the basis of locations in which they found the ammonite *Conlinoceras tarrantense* (Figure 2.7). Gradstein et al. (1995) date a related species, *C. gilberti*, at $95.78 \text{ Ma} \pm 0.61$. A later upper Dakota shoreline (perhaps Clay Mesa Shale and Paguate Sandstone) was straighter and slightly west of the first. It is defined by locations of *Acanthoceras alvaradoense*.

Molluscan fossils are abundant in the western or shoreward part of Seboyeta Bay, especially in the area east and northeast of Grants, New Mexico, where the lower part of the Cubero Tongue of the Dakota and dark brown weathered ferruginous sandstone concretions in the Oak Canyon Member contain a diversified assemblage of bivalves, gastropods and ammonites . . . Five genera of ammonites are present, and *Conlinoceras tarrantense* is the most common species. (Cobban and Hook, 1984, page 260.)

The difference in age between the Albian/Cenomanian boundary and *C. gilberti* is about 2.7 million years (98.5 to 95.8).

If Cobban and Hook are right, then we would not expect to find the Oak Canyon Member (Figure 2.1) outside the limits of Seboyeta Bay. There could, however, be Cubero Sandstone shorefaces related to the next higher, less geographically restricted, more linear shoreline. The sequence significance of this is that progressively younger Dakota shorefaces should lie on the Morrison/Burro Canyon to the northwest and west.

Cobban (1993) later refined the age duration of the possible Seboyeta Bay. His map (Figure 2.7) shows that the embayment was in existence during the early part of the middle Cenomanian based on the distribution of *Conlinoceras tarrantense*.

Molenaar (1977) suggested that “The Dakota transgression advanced generally from east to west or possibly east-southeast to west-northwest across the San Juan Basin. This was quite different from the southwesterly directed transgressions of later Cretaceous time.” He supports this by showing depositional thinning of the Oak Canyon member, next above the

Encinal Canyon member, from southeast to northwest and noting stratigraphic rise of about 350 feet in the same direction. Molenaar proposed that it took five to six million years for the Dakota to transgress the basin. If that is correct, it means that either expansion of the WICS slowed markedly or that positive local structure had a significant influence on the rate of advance. Regardless, Molenaar's five to six million year figure fits nicely with the previously cited, most recent estimated interval length of five million years for the Cenomanian (Figure 2.2).

The significance of these observations is that Seboyeta Bay contained Gulf, not Boreal, waters. There is some support from McGookey et al. (1972), "the sea again met waters from the Gulf of Mexico in early Cenomanian time." Obradovich and Cobban (1975) believe that the Boreal/Gulf link happened in the middle Cenomanian, not before, based on molluscan faunas. This furthers the conclusion that earliest Dakota sediments were laid down by a sea from the south, not the north.

The lowest Dakota of this study resulted from the WICS Cenomanian expansion and evidence is presented later for lithology distribution that supports an initial north to northwest source area. The expansions and contractions of the seaway in the San Juan Basin area were likely related to relative changes in sea level and local tectonics.

Circulation Patterns in the Western Interior Cretaceous Seaway

If Seboyeta Bay really existed, what were its circulation patterns? Contributing factors are water depth and the direction to the deepest part of the Western Interior Cretaceous Seaway (WICS).

Slingerland et al. (1996), concluded that in general terms, the late Cenomanian/early Turonian circulation pattern in the WICS was counterclockwise. They used the GENESIS program from the National Center for Atmospheric Research in Boulder, Colorado to calculate their results and based their conclusions on biostratigraphy, oceanic and atmospheric temperatures, salinities, isotopic data, and precipitation/evaporation magnitudes.

The east margin of the seaway had a northern flowing brackish jet, the west margin a southern flowing jet. On balance, the seaway was exporting fresh water. There is only one exception to the general flow pattern. On Slingerland's maps (Slingerland et al., 1996), there is a southwestern embayment in Arizona and southeast Utah (Figure 2.9). The dominant foram in the embayment is *Hedbergella*, a high salinity genus. The circulation in this area was apparently counter to the norm: there was a small clockwise gyre that drew in warm Gulf water (Slingerland et al. 1996). Slingerland quotes Sageman and Arthur (1994) as saying that water depths over the southern sill during the early Turonian highstand were not great, perhaps 100 meters.

Figure 2.9: Map of North America during the Late Cenomanian/Early Turonian showing the Western Interior Cretaceous Seaway (WICS) and possible surface circulation pattern. Interpreted and drawn from discussions and maps in Slingerland et al. (1966).

Slingerland et al.'s results apply to the late Cenomanian/Turonian so the question remains, what was the circulation pattern during the earliest Cenomanian? We can indirectly conclude from Slingerland et al., that because the Seboyeta Embayment was a reentrant on the west side of the WICS, it had clockwise circulation. If the water depth was less than 100 meters, there must have been significant currents generated simply by predominant wind from the northwest. If Seboyeta Bay had clockwise circulation and drew in warm Gulf waters, then its salinity was probably high enough to support a diverse fauna. This may not have been true later as the shoreline straightened out north-south and the fauna became more restricted as salinities dropped.

It is significant that if Slingerland is correct, the direction of longshore transport changed from clockwise during the earliest Dakota time to counterclockwise later as the embayments in the west edge of the WICS opened to unrestricted shorelines.

The Depositional Gradient, Surface Geometry and Tides

Eicher (1969) calculated a 400 mile pediment extending eastward from the Utah highlands with maximum relief of 1,400 to 6,600 feet. At 6,600 feet, the gradient is 16.5 feet per mile or just under 0.18° . This very low basinward dip is an average over the distance. The surface had an exponential expression with the steepest slopes towards the west and in the San Juan

Basin, the inclination of the depositional surface may have been less than the average.

If a body of water was spreading across a surface with a slope of 0.18° , a one foot vertical change would move the shoreline approximately 318 feet and each three feet would move it approximately 955 feet. In metric units, with each meter of vertical change, the shoreline would move about 300 meters. Sageman and Arthur (1994) indicate that there was a narrow north/south trending part of the WICS that was greater than 300 meters deep. It appears from their map that the average depth was between 100 and 200 meters. In the area of the southern sill, water depth may have been as shallow as 100 meters (Slingerland, et. al, 1966). Because the seaway was at least 1,800 kilometers wide at maximum extent, the depositional slope must have been much less than the figures above would suggest. This argument suggests that tides were important factors during Dakota deposition, so we must ask, were there tides in the WICS that could result in periodic water depth variations? According to Dalrymple (1992):

Because the tide-generating forces are small, only the open oceans develop significant tides, and even these typically have a range of less than 1 m. Smaller bodies of water (including enclosed seas such as the Mediterranean and the water overlying the present-day continental shelves) cannot develop an appreciable tide of their own. The tides which are observed on continental shelves are due to the *forcing* action of the oceanic tide.

Tidal effects, therefore, were probably forced onto what amounted to the high shelf, but may have been attenuated by the distance from open

ocean. Suffice it to say that shoreline positions changed horizontal position rapidly in response to tidal changes and we would see this as thin, laterally continuous marginal marine units.

Because the Cenomanian sea was shallow (300 to 600 feet, Sageman and Arthur, 1994, Slingerland, 1996), the depositional slope was less than 0.25° , and the San Juan Basin was far from the open ocean, the Dakota shoreline was probably microtidal. In such a situation, Reinson (1992) expects the following in a transgressive environment:

Microtidal barrier islands tend to be long and narrow, with abundant storm washover features but few well developed tidal channels and associated tidal deltas. Because there are few channels, storm surges tend to overtop the barrier forming extensive overwash conduits.

Tides are more pronounced in more northerly areas, at higher latitudes rather than lower (Youngquist, 1997). The San Juan Basin was at about 32° north during the late Jurassic (Brenner, 1983) and at about 43° to 44° north during the peak Turonian transgression (Roberts and Kirschbaum, 1995). We may conclude that wave action probably dominated most of the shoreline energy during Dakota deposition, but that tidal features were also present because of the very flat depositional surface. Storm surges may also have been very important.

During the 9 to 12 November, 1998, storm that moved across the Midwest, news accounts reported storm waves on Lake Erie estimated at 15 feet, or about three meters. According to historic records, the same type of

storm sank the ore carrier Edmond Fitzgerald in 1975. Lake Erie is not an inland sea, but the power of wind to generate high storm surge was well illustrated during both events. Similar storms in the Cretaceous could have had profound affect on shorelines through erosion and redistribution of sediments laid down under more normal conditions. Breached barrier bars would be a principal result.

Incised Valleys

The low depositional slope suggests that any incised valleys were not very deep and would probably be wide because of streams meandering at a very low gradient. Sediment grain sizes must have been small because of low stream energy. It also suggests that shoreline deposits would easily be redistributed by longshore currents and would rarely be preserved during uninterrupted transgressions. However, there are many detached shorefaces in the Dakota, similar to those described by Pemberton and McEachern (1995, p. 458), that represent transgressive/regressive pulses. Because the classical shore/shoreface profile tends to become obscured under very flat depositional surface, shallow water conditions, estuarine, paralic coals may be the best indicator of valley flooding conditions.

Based on observation of many systems, including the Mississippi River, John Warne (pers. comm., 1997), suggests that there is an apparent 10 to 1 relationship between channel and meander belt width and meander belt and valley width. If this “rule of thumb” applies to the valleys of the Cenomanian in the San Juan Basin area, 100 meter wide channels created

meander belts 1000 meters wide and valleys 10,000 meters wide. A 10,000 meter wide valley with vertical relief of even 100 meters would be very difficult to find both on outcrop or in well logs.

Paleobathymetry and depositional slope

Sageman and Arthur (1994) indicate that during the Turonian there was a narrow north/south trending part of the WICS that was greater than 300 meters deep. It appears from their map that the average depth was between 100 and 200 meters. Based on foraminifera, Eicher (1969) suggests that during the maximum Greenhorn transgression, the depth could have reached 1000 meters.

If the figure calculated above for each vertical change of one meter moving the shoreline 300 meters is used, then if the seaway was 300 meters deep, the width of the seaway must have been $2 \times 300 \times 300 \text{ meters} = 180$ kilometers. From any map of the WICS it is apparent that the seaway was much wider than that, perhaps as much as 1800 kilometers. The seaway was either deeper or the depositional surface was much flatter than calculated. If Eicher is correct in his depth estimates, then the 0.18° average depositional slope is reasonable.

The Source for Dakota Sediments

McGookey et al. (1972) show the pre-middle Albian drainage from Arizona, north Texas and New Mexico flowing north into Canada. They also show that the lower Cretaceous geography included remnants of the Ancestral Rockies that were source areas for sediments. The San Juan Basin was a shallow low that trended northwest/southeast and was bounded by the Zuni/Defiance Uplift to the southwest and the Uncompahgre highland to the northeast.

The question of the source of Dakota sediments has different answers in different areas and for different parts of the formation, so its importance depends upon where you are looking at the section. In the study area, almost all of the rocks are marine and, based on observed relationships, their primary source was reworking from the underlying formations. The sandstones are, for the most part fine to very fine grained except on exposure/erosional surfaces where they can be conglomeratic. To the northwest, most authors use the term “main body” for the Dakota to refer to a section that is dominantly continental. While the western sediments may continue to be derived from reworking of the Morrison Formation, their coarser grain sizes and lack of marine character reflect at least some connection to the Sevier uplift (Figure 2.6).

There is a tendency to want to follow the increases in grain size in the Dakota westward to the ultimate source area. Unfortunately, the series of thrust sheets that characterized the Sevier and subsequent post-Dakota orogenies have eliminated the original Dakota source area. What is left is an

indication that the westernmost Dakota originated on high terrain, but the terrain itself has been removed through faulting and erosion (Figure 2.6).

Some of western San Juan Basin Dakota continental rocks may have been an intermediate source for the marine Dakota to the east. There also may have been a source area during earliest Dakota time to the north.

The Seboyeta Embayment of Cobban and Hook (1984) is bounded on its north side by a westward deflection of the shoreline south of the New Mexico/Colorado state line with consequent ponding against a remnant of the Transcontinental Arch (Weimer, 1978) or the Uncompahgre Highland (McGookey et al., 1972). The existence of Seboyeta Bay would have changed the Early Cenomanian source direction of the Dakota in the San Juan Basin by intensifying reworking of Burro Canyon and older rocks on the north. As the San Juan Basin area continued to flood, the shoreline straightened out through time (Cobban and Hook, 1984) and became more north/south oriented. By late Dakota time, the predominant source area was, again, to the west. This is supported by stratigraphic relationships in Utah that show the early Cretaceous sediments cut by an unconformity at the early/late Cretaceous boundary (Figure 2.6).

Eustatic Sea Level Changes in the WICS

There are several formation picks and bentonites in the San Juan Basin that many authors consider time lines. The many basinwide cross sections from Molenaar (e.g. Molenaar and Baird, 1989, Nummedal and Molenaar, 1995) show dashed lines that represent time (Figure 2.10). McPeck (1965) fixes the top and base of the Greenhorn Limestone as time lines as well as the top of the Juana Lopez Member of the Carlile Formation. Molenaar and Baird (1989) place a possible unconformity at the top of the Juana Lopez, but Nummedal and Molenaar (1995) show the unconformity only in the north-northeast part of the basin, not in the south-southwest, so the unconformity is local. All authors place a time line between the Bridge Creek (Greenhorn) Limestone and the top of the Paguate Sandstone member of the Dakota.

In 1977, presumably on the basis of time line divisions, Molenaar (1977) produced a chronostratigraphic chart that runs southwest to northeast across the basin. The chart shows several tongues of continental rocks that project northeastward into the Mancos shales until latest Cretaceous and withdrawal of the sea. To adapt his work to the present study, it was necessary to correct the time scale.

Molenaar's original chronostratigraphic chart is sufficiently accurate back to about 90 Ma, but he puts the Albion/Cenomanian time division at 110 Ma and the Cenomanian/Turonian at about 101 Ma. Time scales for the Cretaceous have been converging on some now commonly accepted numbers

Figure 2.10: Stratigraphic cross section showing Upper Cretaceous rocks across the San Juan Basin. Note dashed lines that are time marker beds, either bentonites or calcareous zones. This diagram is similar to others Molenaar produced over the years but is noteworthy because of the density of timeline control shown. Note position of Bridge Creek (Greenhorn) limestone above the Dakota interval. From Nummedal and Molenaar (1995).

for this important interval (Figure 2.2). The Albion/Cenomanian boundary is at about 98.5 Ma and the Cenomanian/Turonian at about 93.5 Ma. By scanning the chart, then dividing it into a 90 to 95 million year segment and a 95 to 110 million year segment, and changing the vertical scaling with an image editing program, it was possible to correct the time scale (Figure 2.11).

Once there is a correct scale on the chronostratigraphic chart, it is possible to convert it into a pseudo sea level chart (Figure 2.12). By comparing the resulting chart with the sea level and onlap curves of Haq et al. (1988), it becomes clear that a great part of the Cretaceous flooding was due to eustatic changes in sea level. Structural changes, if they were happening at all, were minor.

There are some assumptions made in converting the corrected chronostratigraphic chart into a sea level/onlap chart. These include:

1. Maximum coastal onlap is the “. . . landward limit of terrigenous deposition and comprises either nonmarine or marine sediment” (Posamentier et al., 1988). As sea level rises, stream base levels rise and there is a space between the new and old gradient. The subaerial accommodation thus resulting is part of the depositional effect of a relative change in sea level.
2. Molenaar's chart does not show the extent of coastal onlap in the southwestern part of the basin in the vicinity of the Zuni uplift. However, the Greenhorn Limestone represents deep basin sedimentation that corresponds to a distant shoreline. The very

Figure 2.11: Time-scale corrected version of Molenaar's chronostratigraphic chart of the San Juan Basin. Lower Cretaceous boundary was moved from 110 million years to 98.5 million years resulting in significant time compression of the Cenomanian and Turonian intervals. After Molenaar (1977).

Figure 2.12: Time corrected chronostratigraphic chart of the San Juan Basin with an interpreted sea level curve, blue, and the sea level curves from Haq et al. (1988). Note the general agreement during the Cenomanian and Turonian. It is particularly significant that the K3(?) unconformity corresponds to a eustatic lowstand. Modified from Molenaar (1977) and Haq et al. (1988).

fossiliferous Juana Lopez member of the Carlile interval may represent a condensed section. In a sequence, of course, a condensed section is formed far from sediment supply and commonly forms in the basin during maximum transgression.

It is interesting to compare the results to those of Dyman et al. (1994) and see how similar they are. One of the most important results of the Dyman chronostratigraphic chart (Figure 2.13) is the increased definition in the Dakota section. Note how between the San Juan Basin and Pagosa Springs, there is increased thickness of the unnamed marine shale section and that only the middle Dakota sandstone remains. In a later part of this dissertation, sections are described on the Piedra and San Juan Rivers. The Dyman chart gives powerful support for the unconformable basal sand at both locations being only mid Dakota in age.

Summary

In the San Juan Basin, as elsewhere, the Dakota interval represents the first marine depositional unit in the Cretaceous. Here, it is Cenomanian, to the north it is older, perhaps as old as Aptian (Berman et al., 1980). The interval's base is a regional unconformity within the Cretaceous, the K2, and its top is a marine flooding surface/transgressive surface of erosion (TSE). Based on a 93.12 million year argon/argon date from a bentonite sample at Highway 84, the Dakota section is latest Cenomanian, thus confirming that it is younger than its lithologic equivalents to the North.

Figure 2.13: Chronostratigraphic cross section from east-central Arizona to the Oklahoma Panhandle. Note ammonite biozones. Note Dyman et al.'s use of the term Dakota Group to include the Dakota Sandstone and Burro Canyon Formation. Modified from Dyman et al., 1994.

The Dakota group of common usage lies above the K2 unconformity at the top of the Burro Canyon and extends upward to the top of the Twowells Sandstone/base Graneros Shale. According to the New Mexico Oil Conservation Commission, the Dakota producing interval is 400 feet below the top of the Greenhorn. In a purely geologic sense, the Commission's definition places much of the upper Dakota within the Graneros Shale interval.

The K2 unconformity represents about seven million years in the study area. The Dakota Group is about 1.25 million years younger than its lithologic equivalents in the Raton Basin and about 2.5 million years younger than those in the Denver-Julesburg Basin. Deposition of the entire Dakota interval took approximately two million years.

If anything can be learned from the diachronous nature of the Dakota, it is that given similar source rocks and depositional conditions, transgressive marine conditions work in equivalent ways in different areas. As the Cretaceous sea expanded westward, the deposits produced were lithologically analogous. Lithologic and stratigraphic position similarity do not mean time equivalence, however, and the term "Dakota Formation" should probably be reduced to the less formal "Dakota interval" when it is used to describe the first marine rocks of the Cretaceous. The Dakota was an event. It is not a formal geologic formation regionally. Waage (1955) noted that the Dakota of the northern Front Range in Colorado comprises several different members and elevated it to group status.

This is what may be concluded about conditions during deposition of the Dakota and its various members in the study area.

- ✓ 1. Earliest Dakota sediments accumulated in a westward oriented shallow embayment on the west side of the Western Interior Cretaceous Seaway. There were source areas to the southwest, northeast and far west. The shoreline through the dissertation study area was on the north side of the embayment and had a northeast trend.

Oceanic circulation in the study area was initially clockwise and was related to invasion of the Gulf Sea. Salinities allowed for a normal marine fauna.

- ✓ 2. Later Dakota sediments accumulated along the more or less north-south oriented west shoreline of the WICS. Source areas were to the southwest and west.

Oceanic circulation in the study area was counterclockwise and related to the southwestern jet on the west side of the WICS. More brackish water conditions led to a more restricted fauna.

- ✓ 3. The dominant energy along Dakota shorelines in the San Juan Basin came from waves and storms. Tidal effects were present, but minor.

CHAPTER 3

FIELD OBSERVATIONS AND INTERPRETATIONS

A fundamental part of this dissertation is the description and analysis of Dakota outcrops. Six were visited and two were complete and accessible enough to become the basis for interpretation and later correlation to the subsurface. All exposures are on the north and east sides of the greater San Juan Basin area within an inward dipping outcrop belt that parallels the basin edge (Figure 3.1).

The appendices contain the complete raw data that support the discussions in this chapter. Detailed narrative outcrop descriptions are in Appendix A. This chapter extracts data from the descriptions that are pertinent to interpretation, but it does not repeat many details. Graphic columns constructed from the descriptions are presented in this chapter both as partial sections to match the flow of a particular discussion and as complete sections. Appendix B is a table of thin section descriptions. Appendix C contains tables of criteria for recognizing various depositional environments and guidelines on how to recognize unconformities. Full sized copies of all figures are located on the enclosed PC-formatted CD-ROM.

The outcrop descriptions comprise two measured sections and four reconnaissance sections shown on Figure 3.1. In this dissertation, all are referred to by name: Highway 84, Heron Dam, North Gallina, West Gallina,

Figure 3.1: Outcrop area of the Dakota Group on the northeast side of the San Juan Basin, in dark gray, and the location of measured and described sections referred to in this chapter.

Holiday Acres and Piedra River. Of these, Highway 84 and Heron Dam are the most significant because they are the best exposures. They comprise the bulk of the analysis below. The Heron Dam section is the most complete.

Each outcrop description starts at the base and works upward with emphasis on identifying time-significant surfaces, describing the lithologies within, and interpreting the sections on a sequence stratigraphic basis. The outcrop sections tie to one another and to the subsurface through the sequence framework.

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 (Figure 3.2) was active at the end of Morrison time.

Careful analysis shows that the Dakota section consists of 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:

Figure 3.2: The Zuni Uplift in the southwest part of this map is considered by many to be the source of Dakota sediments. Dakota streams may have flowed northeast in the direction of the black arrow.

- 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. Scattered, rare burrows.
- C. Light gray, bioturbated, 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, rarely burrowed, cross bedded to parallel bedded sandstones.

These facies closely parallel the shoreline succession from deep, A, to shallow water, E, presented in Table B in Appendix C.

Shallow, tide dominated rocks of the Dakota comprise facies F. In some places, such as between K2 and S1 at Highway 84, it is useful to identify subdivisions of the facies 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 flat, F4, to proximal flat, F1, shown in Table A in Appendix C. A regressive tidal flat depositional environment is shown in Figure 3.3.

The usefulness of the 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 stratigraphic 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, 1988, and Scott, 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 on such criteria 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 (Figure 3.4). Because they are bounded by unconformities, defining sequences becomes a matter of identifying bounding erosional

Figure 3.3: An example of the tidal flat depositional environment with an idealized regressive succession in the upper left. From Dalrymple (1992).

Figure 3.4: The classical Exxon sequence diagram. Only the upper part, on the left side of the diagram, is present in the Dakota of the San Juan 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).

surfaces. In the present study, the following criteria were guidelines used to help identify unconformities on outcrop.

- 1) Continental on marine sediments with abrupt change - no facies gradation.
- 2) Downward shift of coastal onlap - incised valley fill phases.
- 3) Subaerial exposure demonstrated by the presence of:
 - a. Root zones,
 - b. Weathered zones,

1. Karsting
 2. Clay mineral alteration or leaching
 3. Presence of paleokarsts and regoliths
-
- 4) Coals on deep water marine sediments, perhaps with root zones extending into the marine sediments.
 - 5) Anomalous vertical stacking of lithologies or parasequences, e.g., coarse on very fine-grained sandstone.
 - 6) Abrupt change in microfossil assemblages and ichnofacies including missing faunal zones.
 - 7) Physical evidence of scour on a regional basis, such as lag gravels on a rock unit that is not genetically related to the overlying rocks.
 - 8) Angular bedding relationships - stratal onlap or truncation.
 - 9) On electric logs, appropriate log characteristics, including:
 1. Anomalous parasequence stacking
 2. Removal of key marker beds.

Thin Sections

In the discussions about the stratigraphic sections at Highway 84 and Heron Dam, mention is made of thin sections. Twenty seven thin sections were made from hand samples collected at both locations, twenty three of them at Heron Dam. The summarized thin section data are presented in Appendix B.

Particle sizes in thin section were measured against a millimeter scale and closely match the grain size descriptions recorded in the field. Most of the sandstones in the study are fine to very fine-grained, five of the total are up to medium-grained or coarser. Their locations are noted in the discussion.

Most of the grains are angular to subangular except for thin sections HD 24-09-08 to HD 24-09-13, in which the grains are subangular to subrounded. This series of sections is in the uninterrupted shallowing upward interval between units 26 and 34 at Heron Dam. Note, however, that samples HD 24-09-5B and 5C fall near the top of this interval and their grain shape is angular.

The thin sections show that the samples are mineralogically very similar: quartz is the major component with clay (undifferentiated) and chert making up the remaining total. Sample 20BZ contains appreciable kaolinite (Anne Grau, 2000, personal communication). Plagioclase feldspars are remarkable for their absence. What appears optically to be potassium feldspar is present in only three sections, all at Highway 84: 20BZ, H84-21-09-02 and H84-21-09-11. This suggests that there has been some

outcrop weathering, that some of the observed clay is from diagenetic alteration of feldspar or that these are second cycle sandstones in which there never was an appreciable feldspar content. This last interpretation is strengthened by the presence of a small percentage of rounded quartz overgrowths in several samples that shows that these sandstones were derived from previously diagenetically altered source rocks.

Sandstones described in the field as hard and resistant are seen in thin section to have a high percentage of subangular, interlocking to interpenetrating grains. Silica cement, *per se*, is visible in 10 thin sections and is inferred from pitted and interpenetrating grains in the remainder. There is calcite cement in five samples. Hematite cement, possible from surficial weathering, is seen in six samples and, for the most part, it is responsible for the color observed in hand sample.

All in all, these thin sections show that the sandstones at Highway 84 and Heron Dam are second cycle or greater, and mineralogically mature.

Clay Mineral Analyses

Two samples were selected for x-ray diffraction analysis (XRD): H84-BZ from the base of unit 20 at the Highway 84 outcrop and HD 23-09-5B from the top of unit 7 at the Heron Dam outcrop. The sample numbers are the same as the thin section numbers and are posted on the columnar

sections. Each of these intervals has been identified on outcrop as a suspected weathered zone that possibly correlates between the two outcrops.

The results of the analyses are presented in Appendix D. Because of the high percentage of kaolinite in both samples, the analyses support the interpretation of the two outcrop zones being weathered intervals. Of perhaps greater significance is that the elemental analyses and the x-ray plots are very similar and show that the two samples may represent the same weathered zone.

On the basis of XRD analysis, surface S2 is considered correlative across the study area in the remainder of this dissertation.

A Dakota 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. 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) (Figure 3.5). The surfaces come in pairs.

Figure 3.5: The regressive shoreface model of Nummedal and Molenaar (1995) with 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).

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 3.5 is a schematic illustration of their mostly regressive shoreface tongues in the Gallup Formation. In the most seaward direction, on the right side of the diagram, the only visible sign of changes in relative sea level is stacked,

truncated 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 dissertation 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.

Highway 84 Section

The section at Highway 84 is located about nine miles south of Cebolla, New Mexico on the west side of US Highway 84 (Figure 3.1) . The highway cuts up northward through a nearly complete Dakota section starting with a classical 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. 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 others to the north and to wells in the subsurface using sequence stratigraphic methods (Chapter 4). Subsurface names can be traced with some confidence to the various outcrops and the results are sometimes surprising. A table of equivalents is provided at the end of this chapter.

The Highway 84 section contains three unconformities (Figure 3.6) 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 “units,” such as unit 1, unit 10, etc. These are numbered stratigraphic intervals on both the columnar sections and narrative descriptions.

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 stratigraphic column shown in Figure 3.6 as well as pertinent photographs.

Interval K2 to S1 - Figure 3.7 is a stratigraphic column for the interval K2 to S2. It is an enlargement of the detail column on the lower right side of Figure 3.6.

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 (Figures 3.8 and 3.9, thin section H84-21-09-02) 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 (Figure 3.10a, b, c). 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, 1988).

Figure 3.7: Stratigraphic column for the interval between unconformity K2, at the bottom, and S2, near the top. Vertical scale in feet.

Figure 3.8: Closeup of K2 surface showing coarse grains and chert pebbles. Kbc is Burro Canyon, Kd is Dakota Sandstone. White arrow is 8 inches high.

Figure 3.9: K2 surface and overlying units in the Dakota. Hammer, in oval, for scale.

Figure 3.10a: Outcrop on the west side of US Highway 84, about 9 miles south of Cebolla, New Mexico. Early Cretaceous Burro Canyon Formation (Kbc) is at the base of the section under the K2 unconformity. Late Cretaceous Dakota Sandstone overlies K2. This outcrop shows three significant surfaces: K2, S1 and S2. The interval between K2 and S2 is Dakota Sequence 1 of this study. Numbers refer to Dakota stratigraphic units discussed in the text. This photograph continues in Figures 3.10b and 3.10c.

Figure 3.10a: Outcrop on the west side of US Highway 84, about 9 miles south of Cebolla, New Mexico. Early Cretaceous Burro Canyon Formation (Kbc) is at the base of the section under the K2 unconformity. Late Cretaceous Dakota Sandstone overlies K2. This outcrop shows three significant surfaces: K2, S1 and S2. The interval between K2 and S2 is Dakota Sequence 1 of this study. Numbers refer to Dakota stratigraphic units discussed in the text. This photograph continues in Figures 3.10b and 3.10c.

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Figure 3.10b: Continuation of Figure 3.10a. Outcrop on the west side of US Highway 84, about 9 miles south of Cebolla, New Mexico. Early Cretaceous Burro Canyon Formation (Kbc) is at the base of the section under the K2 unconformity. Late Cretaceous Dakota Sandstone overlies K2. This outcrop shows three significant surfaces: K2, S1 and S2. The interval between K2 and S2 is Dakota Sequence 1 of this study. Numbers refer to Dakota stratigraphic units discussed in the text. This photograph continues in Figures 3.10a and 3.10c.

Figure 3.10b: Continuation of Figure 3.10a. Outcrop on the west side of US Highway 84, about 9 miles south of Cebolla, New Mexico. Early Cretaceous Burro Canyon Formation (Kbc) is at the base of the section under the K2 unconformity. Late Cretaceous Dakota Sandstone overlies K2. This outcrop shows three significant surfaces: K2, S1 and S2. The interval between K2 and S2 is Dakota Sequence 1 of this study. Numbers refer to Dakota stratigraphic units discussed in the text. This photograph continues in Figures 3.10a and 3.10c.

Figure 3.10b: Continuation of Figure 3.10a. Outcrop on the west side of US Highway 84, about 9 miles south of Cebolla, New Mexico. Early Cretaceous Burro Canyon Formation (Kbc) is at the base of the section under the K2 unconformity. Late Cretaceous Dakota Sandstone overlies K2. This outcrop shows three significant surfaces: K2, S1 and S2. The interval between K2 and S2 is Dakota Sequence 1 of this study. Numbers refer to Dakota stratigraphic units discussed in the text. This photograph continues in Figures 3.10a and 3.10c.

Figure 3.10b: Continuation of Figure 3.10a. Outcrop on the west side of US Highway 84, about 9 miles south of Cebolla, New Mexico. Early Cretaceous Burro Canyon Formation (Kbc) is at the base of the section under the K2 unconformity. Late Cretaceous Dakota Sandstone overlies K2. This outcrop shows three significant surfaces: K2, S1 and S2. The interval between K2 and S2 is Dakota Sequence 1 of this study. Numbers refer to Dakota stratigraphic units discussed in the text. This photograph continues in Figures 3.10a and 3.10c.

Figure 3.10b: Continuation of Figure 3.10a. Outcrop on the west side of US Highway 84, about 9 miles south of Cebolla, New Mexico. Early Cretaceous Burro Canyon Formation (Kbc) is at the base of the section under the K2 unconformity. Late Cretaceous Dakota Sandstone overlies K2. This outcrop shows three significant surfaces: K2, S1 and S2. The interval between K2 and S2 is Dakota Sequence 1 of this study. Numbers refer to Dakota stratigraphic units discussed in the text. This photograph continues in Figures 3.10a and 3.10c.

Figure 3.10c: Continuation of Figure 3.10b. Outcrop on the west side of US Highway 84, about 9 miles south of Cebolla, New Mexico. Early Cretaceous Burro Canyon Formation (Kbc) is at the base of the section under the K2 unconformity. Late Cretaceous Dakota Sandstone overlies K2. This outcrop shows three significant surfaces: K2, S1 and S2. The interval between K2 and S2 is Dakota Sequence 1 of this study. Numbers refer to Dakota stratigraphic units discussed in the text. This photograph continues in Figures 3.10a and 3.10b.

Just below the 14 foot measurement point, 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 3.3 (from Dalrymple, 1992). For comparison, Dalrymple's *regressive* tidal flat succession is shown in Figure 3.11 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 crossbedded bidirectional sandstone and finally, 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 3.11 and marks a transgressing shoreline in which the mud flat was overridden by mixed flat that was, in turn, overridden by sand flat.

Figure 3.11: 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 bar/tidal delta/washover fan beds is similar to the graphic on the right.

At the top of the tidal flat unit there is an iron stained, thin interval with mudstone clasts. It thickens to the north and becomes unit 8, a possible tidal channel deposit (Figures 3.7 and 3.12). Similar to the succession from units 2 to 7, unit 8 also contains carbonaceous, flaser to lenticular-bedded sandstones and a thick black shale interval that represents either abandoned channel fill or mud flat conditions 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.

Figure 3.12: Units 6 through 20C at the north end of the Highway 84 outcrop (see Figure 3-10c). 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 3-7, the stratigraphic column). A thin section was made and an x-ray diffraction clay analysis was performed on a sample from unit 20BZ near the point indicated. Hiking staff for scale is about 4 feet high.

Between the zone of clasts at the base of unit 9 and about 12.5 feet above K2, is a large scale feature, unit 11 (Figure 3.12 and thin section H84-21-09-11) 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 crossbeds. 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.

Sediments 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 bar/tidal delta on the oceanward side. Unit 11, because of its bidirectional nature, appears to represent either reciprocal washover deposits across a barrier bar 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 (Figure 3.13). Figure 3.10 (panorama) shows that unit 11 is but one of a series of similar features within the same stratigraphic interval.

Figure 3.13: Shoreface/lagoon model of Reinson (1992). Note erosional surface on seaward side of barrier bar caused by wave action. As relative sea level rises, this becomes a TSE.

A reasonable question is how do you preserve a mud flat in a transgressive environment? The barrier bar is a possible key. As the bar moves shoreward across the lagoon, washover sands cover the flat and protect the mud (Figure 3.14). This movement would produce the vertical succession observed at this location. Furthermore, the presence of the mud flat sediments strongly suggest 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 topped the bar, as suggested by Figure 3.13 and diagrammed in Figure 3.14.

Figure 3.14: Diagrammatic representation of how a tidal flat shoreward of a barrier bar 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.

Interval S1 to S2 - Figure 3.7 includes the stratigraphic interval S1 to S2

Unit 13, at the base of which the above S1 lag is located, is a fine grained sandstone with zones of tabular/planar crossbeds. Moving up to the base of unit 16 (Figure 3.12), 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 crossbeds 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 as it does 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 about 28 feet above unconformity K2 on the measured section, there is a very prominent bleached zone (Figure 3.15) designated unit 20BZ. Petrographic analysis of thin section H84-BZ 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 (Appendices B and D). Because kaolinite can form as an alteration of feldspar under exposure to acidic fresh water (Weaver, 1989, Pettijohn, 1957), 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

Figure 3.15: Units 15 through 20C at north end of Highway 84 outcrop (see Figure 3-12). For scale, units 20B and 20C total about two feet thick.

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 north of the location in Figure 3.15, unit 20BZ thins and is overlain with angular unconformity by the continuation of unit 20B (Figure 3.16). 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

Figure 3.16: Angular relationship between units 20BZ and 20B&C at Highway 84. Hiking staff for scale.

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.

It is interesting to note that based on facies types, the interval from S1 to S2 alternates between shallow-water sandstone facies F and dark gray shale facies B that contains some thin sandstones such as units 15 and 18. Considering that there are several facies zones missing between those extremes, the obvious question becomes one of how to explain the association. One of two mechanisms seems most plausible: 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 water shale interval is the last, storm activity, and the sedimentary structures within the sandstones support that interpretation.

Interval S2 to Top of Section - Figure 3.17 is a stratigraphic section for the interval from 30 to 90 feet.

Figure 3.17: Columnar section for the interval from 30 to 90 feet at the Highway 84 outcrop. A full sized version of this illustration is located on the enclosed CD-ROM.

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 say for 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. The question then becomes, what is the exact placement of the unconformity, surface S2. Because of the previously mentioned angular relationship between unit 20BZ and those above, surface S2 remains where placed.

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 thick, medium gray sandstone with horizontal and highly contorted bedding (Figure 3.18) 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, although there is little evidence of deltaic sedimentation nearby. It is overlain by a thin bentonite (Figure 3.19) 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, Appendix E). Above the bentonite is more medium gray shale like that below, a thin siltstone, a dark gray to black, thin bedded shale (unit 26, TOC content 1.65, see Chapter 5), and a thin bentonite, unit 27, which is capped with an 18 inch thick, very hard, silica cemented, shaly, medium reddish gray sandstone, unit 28. This is the hardest sandstone in the section responding with a clear “ping” to the hammer. The sandstone contains

Figure 3.18: Detail photo of unit 22 at Highway 84.
Note silicified *Ophiomorpha* above hammer.

Figure 3.19: Bentonite, white, left of hammer handle is
unit 23 at Highway 84. Its age date is 93.12 Ma.

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, thus 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 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 the occasional burrowed very fine grained sandstone. 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.

Figure 3.20 is a stratigraphic column for the interval from 90 feet to the top of the section.

Units 32 to 36 comprise a shale/shaly sandstone section almost 30 feet thick containing a 6 inch, medium reddish 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 (Figure 3.21). 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

Figure 3.20: Stratigraphic column for interval from 90 feet to the top of the Dakota section at Highway 84.

Figure 3.21: Large-scale HCS near base of unit 36 at Highway 84. Note intense bioturbation in upper part of photograph. Walking staff is approximately four feet long.

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. 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 - 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 (Figure 3.5). 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 2 at Highway 84. The interval from S3 to the top of the section is part of Dakota Sequence 3.

Other Surfaces at Highway 84 - Units 24, 26 and 32 (Figure 3.6, 3.7, 3.17 and 3.20) 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 3.22):

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 bars and protected lagoons.
4. Development of tidal flats in the lagoon.
5. Rise in relative sea level.
6. Onshore movement of bars across the tidal flats.
7. Development of TSE across barrier bars in deepening water.
8. Deposition of deeper water shales and occasional storm beds.
9. Lowering of relative sea level.
10. Exposure and development of LSE, surface S2, top of Dakota Sequence 1.
11. Rise in relative sea level.
12. Deposition of offshore shales with occasional 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 Dakota Sequence 2.

Figure 3.22: 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 bentonite sample. Haq et al. (1987) show sea level spikes similar to those at S2 and S3 occurring at 93 Ma and 94 Ma. Numbers refer to discussion in text.

17. Deposition of lower foreshore sandstones.

18. Continuous rise in relative sea level to top of section resulting in deeper water shoreface deposition.

Gamma Ray Survey

In order to correlate the measured section to gamma ray logs in the subsurface, a gamma ray profile was generated for the measured interval. It is presented in Figure 3.23

Highway 84

Gamma Ray and Facies Column
with Stratigraphy

Figure 3.23: The stratigraphic column for Highway 84 with gamma-ray curve and facies.

Heron Dam Section

Figure 3.1 (map) 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 (Figure 3.24). A complete section of the Dakota Group is available at this exposure (Figure 2.25).

Figure 3.24: View of the outcrop on the north side of the Chama River at Heron Dam. The main section was measured on this face. Most of the Dakota (Kd) is visible, only the lowermost part is missing from the photograph. The supplemental section was measured to the left of this photo.

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

Figure 3.25: The main stratigraphic section at Heron Dam. Portions of this column are enlarged in the discussions that follow.

Formation and the K2 unconformity. Slope wash, unfortunately, obscures many of the details in parts of the interval in the main measured section.

The supplemental section is a partial Dakota section that 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. The location of the supplemental section is shown on Figure 3.26.

Description, Analysis and Interpretation

The section at Heron Dam has a measured thickness of about 280 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 stratigraphic column shown in Figure 3.25 as well as pertinent photographs. As before, stratigraphic units are numbered and the numbers key to both the graphic columns and the narrative descriptions in Appendix A. Thin section descriptions are in Appendix B. Appendix C contains tables of criteria used for determining depositional environments. All figures in this section are present on the CD-ROM inside the back cover.

Figure 3.26: 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 right 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 section and "SS" designates rock units in the supplemental section. Unit numbers tie to the discussions in this chapter and in Appendix A. The Dakota rests on the K2 unconformity and here it comprises proximal tidal flat gravelly shales, SS8, mixed sandstone and shale tidal flat sediments, MS 1-3, and a tidal channel, SS9-11, 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.

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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 (Figure 3.26).

Figure 3.27 is the first 90 feet of the main Dakota columnar section. Figure 3.28 is a correlation of the main and supplemental sections. The following discussion refers to both and abbreviates supplemental section as “SS” and main section as “MS.” The supplemental section ends about 7 feet above the interpreted S2 surface.

The K2 unconformity at Heron Dam (Figure 3.26) 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 3.28), at approximately 8 feet, 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 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, the previously mentioned pebbly sandstone, 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.

Figure 3.28: Correlation of main and supplemental sections at Heron Dam. See Figure 3.26 for a photograph that illustrates the relationships shown here.

They occupy a stratigraphic position similar to that of the mud/sand flat deposits at Highway 84 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 only two feet thick but it thickens to as much as 12 feet 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 crossbeds and two thinner zones in the upper part of the unit contain bidirectional to herringbone crossbeds. 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 until at the very top there are distinct ripples. The top of unit SS11 is sharp and overlain by a carbonaceous shale of unit SS12 (Figure 3.28).

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 gravelly shale of unit SS8 represents a coastal plain/proximal tidal flat marginal to the Cenomanian 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 3.26 and 3.28). What is particularly interesting is the succession represented in the main section by units MS1 through MS7E (Figure 3.27 and Appendix A).

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.

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. 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 (thin section and sample HD-23-09-5b) 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. Thin section HD-23-09-05b shows 30% intergranular clay in the bleached zone, which XRD analysis indicates is predominantly kaolinite (Appendix D). 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 charcoaled wood fragments (unit MS7E, Figure 3.29).

The top of unit MS7E is a ½ to 1 inch thick zone of concentrated charcoaled 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 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

Figure 3.29: Close-up of top of unit MS7E, Heron Dam Section. Arrow rests on kaolinitic section and points to charcoalized wood in uppermost part of unit. White arrow is approximately eight inches long.

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 (compare the sections shown in Figures 3.7 and 3.27). A correlation diagram for the two locations is provided in Chapter 4.

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 Highway 84 seaward of Heron Dam during the same time. In Chapter 2, it was mentioned that the depositional slope was $< 0.2^\circ$ during lowest Dakota deposition, 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 Dakota Sequence 1.

Interval S2 to S3 - Figure 3.30 is the interval from 90 to 180 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 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 about 115 stratigraphic feet 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

Figure 3.30: Stratigraphic interval from 90 to 180 feet at Heron Dam. Column on left is enlarged detail of the section immediately above surface S3.

intervals that are significant because they rest sharply on surface S2 and on facies C shaly sandstones higher in the section (Figures 3.27 and 3.30).

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 HCS (Figure 3.31). Unit 13 is the

Figure 3.31: Well defined HCS in Heron Dam unit 12 about 30 feet east of the measured line of section.

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 Dakota Sequence 2. The black shales in units 8, 13 and 16 (Figures 3.27 and 3.30) 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 Figure 3.30 and photo in Figure 3.32) 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 includes shale laminae that are nearly horizontal and contain large, horizontal to inclined, sand-filled burrows. The upper foot contains some poorly defined tabular/planar crossbeds 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 (thin section HD-24-09-01). 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

Figure 3.32: Units 19 through 26 at Heron Dam comprise a sharp based sandstone that is a cliff former in the middle of the valley. Four-foot scale is at right.

less well defined upward because of 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 (thin section HD-24-09-02).

Unit 21 is a 2 inch thick light gray, fine to medium-grained sandstone with ripple bedding and thin, wispy, carbonaceous shale laminae in horizontal to undulatory layers. Thin section HD-24-09-03 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 crossbeds and is heavily burrowed by *Ophiomorpha* and an indeterminant 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 (thin section HD-24-09-04), but there is no observable clay.

Unit 23 is a 2 inch thick interval of fine to medium grained, medium gray, shaly lenticular bedded to flaser bedded, heavily burrowed sandstone. The burrows are outlined by carbonaceous 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 (thin section (HD-24-09-05) in this interval.

Unit 24 is a thick, medium gray, shaly sandstone. It is remarkable for its extensive burrowing (Figure 3.33). 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 HD-24-09-06 shows that it, like the underlying sandstones, has interlocking quartz grains.

Unit 25 is a 1 foot medium gray, fine-grained, non-shaly sandstone with long period bidirectional trough crossbeds (Figure 3.34). The top of the unit grades into unit 26. Sorting and grain characteristics are similar to unit

Figure 3.33: Unit 24 at Heron Dam. Note extensive bioturbation and sharp contact with overlying sandstone, unit 25.

24. Thin section HD-24-09-07 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

Figure 3.34: Unit 25 at Heron Dam. Note cross-bedding and gradational contact into heavily bioturbated overlying sandstone interval. Arrow is about 8 inches long.

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 thick. Thin section HD-24-09-08 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 Appendix C, 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 (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 3.35 is the part of the Heron Dam stratigraphic column from 180 feet 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 above the base of the section and then the sandstones become increasingly 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 (Figure 3.36).

The interval from the top of unit 26 to unit 35 (Figure 3.36) 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 (see thin sections HD 24-09-5A, -5B, -5C, and HD 24-09-13 through -14C). 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 lies across the top of the highest Dakota sandstone on what is clearly a marine flooding surface. Except for a few scattered coarse quartz grains in the top quarter inch, there is little evidence from the outcrop

Figure 3.35: Stratigraphic interval from 180 feet to the top of the Dakota at Heron Dam.

that the topmost Dakota surface was ever exposed to subaerial erosion, but the quartz grains suggest that it may be a transgressive erosional surface. From a sequence stratigraphic standpoint, this could imply that the top of the Dakota event actually lies quite a bit higher in the section, perhaps even above the Greenhorn limestone or higher. However, subsurface maps and cross sections in Chapter 5 suggest that the uppermost surface in the Dakota, under the Graneros, is an unconformity. Therefore, here it is provisionally considered an LSE/TSE.

Figure 3.36: 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. Upper cliff (includes unit 35) is about 45 feet thick.

The interval between S2 and S3 is Sequence 2 at Heron Dam. The interval between S3 and the Graneros Shale is Sequence 3.

Other surfaces at Heron Dam - Units 8, 13 and 17 (Figures 3.27 and 3.30) contain black, thin bedded marine shales that include thin bentonites (Figure 3.37). 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 Vail et al. (1977).

Figure 3.37: Units 17 through 19 at Heron Dam. The bentonite, unit 17, was sampled for age dating and yielded no dateable K-spar. Paul Basinski of Burlington Resources for scale.

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 3.38):

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.

Figure 3.38: 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 93 Ma and 94 Ma (see Figure 3.22). Numbers refer to steps listed in the text.

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 Dakota Sequence 1.
9. Rise in relative sea level, marine flooding.
10. Deposition of offshore marine shales with occasional storm beds (units 8 through 10).
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 Dakota Sequence 2.
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

A gamma ray survey was run over the entire Heron Dam section and the result is presented in Figure 3.39. The section was constructed by measuring vertically and offsetting horizontally on suitable bedding planes. This was repeated several times along the access road to build the complete section. A better view of this figure is available on the enclosed CD-ROM.

Figure 3.39a: Upper part of the stratigraphic column at Heron Dam with facies and gamma-ray curve.

Reconnaissance Sections

During this study, four sections were visited but not described in detail. At North Gallina, for example, enough of the section is covered that even though measured, it did not add significant information to the study except for confirmation of the K2 unconformity. At West Gallina, only the very lowest Dakota was examined and the primary purpose was to look at what Aubrey (1988a) calls the Encinal Canyon Member of the Dakota. The sections at West Piedra and Holiday Acres, while beautifully exposed, were too steep to measure. Still, they provide much food for thought and are discussed below.

North Gallina Section

The North Gallina section is located on Gurule Mesa, north of the town of Gallina, New Mexico. It is a partial section that shows the K2 unconformity, the Burro Canyon Formation and the lowest part of the Dakota section. Because much of the section is covered, it is not particularly useful for environmental and sequence stratigraphic work in this study. However, it does give another point of reference for the nature of the lowest Dakota lithologies and how they sit on the regional K2 unconformity. See Appendix A for a detailed description and photographs.

West Gallina Section

The exposure at this location is on the south side of a small knoll on the north side of Highway 96 about 2 miles west of Gallina, New Mexico. Large shale ripups and apparent bank failure features give an indication that at this location, the lowest member of the Dakota underwent some high energy events. The most interesting thing about the outcrop is the amount of carbonaceous and coaly shale present. If this interval is correlative to the lowest Dakota at Highway 84 and Heron Dam, it implies that there was an area of paralic deposition to the west. The same types of lithologies are not present at North Gallina, so the paralic depositional area was apparently very local. Appendix A contains a complete description of the outcrop as well as photographs.

Holiday Acres Section

This outstanding exposure of the Dakota Group is complete from the Morrison Formation at the base of the outcrop to the Mancos Shale at the top (Figure 3.40). It is located on the east side of the San Juan River just south of Pagosa Springs, Colorado. Numbers on the figure correspond to numbers in the description in Appendix A.

As indicated in the detailed description in Appendix A, the outcrop contains the K1 unconformity at its base, K2 at the top of the Burro Canyon Formation and other stratigraphically higher surfaces. There is a pronounced marine flooding surface on top of unit 5, a possible scour surface above unit 6

Figure 3.40: The Dakota section at Holiday Acres. Numbrs refer to units mentioned in this discussion and in Appendix A. Surface K1 is at the base of the Cretaceous and marks the contact of the Burro Canyon Formation on the Morrison Formation.

and a coal interval in unit 8. It is impossible at this time to correlate these units with precision to the section at Heron Dam. However, the coal interval represents paralic conditions and its position suggests a possible relationship to the coal interval at West Piedra (see below), and to the lowstand marine sandstone at the base of Dakota Sequence 3 at Heron Dam.

With imagination, it is possible to assign the sandstones shown in Figure 3.40 to the classical divisions of the Dakota, but there are problems. If conventional thinking about the Dakota of the San Juan Basin is correct, this exposure is too far west for any but the lowest Dakota sandstones, in the Cubero interval, to be present. Most of the sandstones in the upper part of the outcrop are light gray, hard, silica cemented, fine grained, burrowed with *Ophiomorpha* and *Thalassinoides* and bioturbated. This character is consistent with all Dakota shorefaces, not just the Cubero. Carbonaceous material is present throughout, but is concentrated near the base of the section. Figure 3.40 shows that the sandstones become more resistant upward and stand out from the hillside. They are marine parasequences, and like the sandstones observed on outcrop at Heron Dam and Highway 84, they become less shaly upward rather than becoming coarser upward,. The key to their source may lie in the Dakota relationships to the northwest at Piedra River.

West Rio Piedra Section

The West Rio Piedra Section is located about 17 miles west of Pagosa Springs, Colorado on the west side of the Piedra River valley north of US Highway 160 (see map, Figure 3.1).

The most compelling feature at West Rio Piedra is the unconformity at the base of the Dakota Section (Figures 3.41 and 3.42). According to Aubrey (1988b) there is greater than 40 feet of relief on the surface. Because of its position at the base of the Dakota, the surface can be called K2. However, the Dakota section here appears thinner than elsewhere so if it is the K2 surface, then there must have been a period of non-deposition or erosion resulting in the observed thickness. The easiest way to explain it is to make this area topographically high during at least part of Dakota deposition.

Unit four on Figures 3.41 and 3.42 is a zone of thin sandstones, shales and coals that appears to become sandier, or “cleaner,” upward. Shale and coals suggest, as they did at Holiday Acres, a paralic environment. Most workers would argue that the Dakota shoreline was too far to the west for such rocks to exist at this location, but they are appropriate if the thick sandstone resting on the unconformity is a valley fill. It is possible that this interval is the shoreward equivalent of Dakota Sequence 3, above surface S3, at Heron Dam. If this is true, then it follows that the unconformity at the base of the West Rio Piedra Dakota section represents the same surface as the offshore marine erosion surface 60 miles to the south at Heron Dam. It also means there was a northern positive area that was incised by a river during Dakota Sequence 3 time. A northern positive feature would provide a

Figure 3.41: The north exposure at West Rio Piedra. Note truncated units under K2(?) unconformity. The Burro Canyon Formation is under the unconformity and the Jurassic Morrison Formation is in the lower right part of the photo. Numbers key to this discussion and to Appendix A.

Figure 3.42: The south exposure at West Rio Piedra. Note truncated units under K2(?) unconformity. The Burro Canyon Formation is under the unconformity. Relief on the unconformity is about 40 feet at this location. Numbers key to this discussion and to Appendix A.

shoreline for the north side of Seboyeta Bay proposed by Cobban and Hook (1984).

The Sub-Dakota Unconformity

Aubrey (1992) suggested that the “sub-Dakota unconformity is a major regional unconformity throughout the southeastern Colorado Plateau.” His “sub-Dakota unconformity” is what this dissertation has been calling the K2 unconformity. He goes on to state the “sub-Dakota unconformity” is part of

the same drainage system that created incised valleys between the Horsetooth and Fort Collins Members of the Dakota in the Colorado Front Range area, but he recognizes that the age of the surface is younger in the San Juan Basin than it is in central Colorado - latest Albian to the northeast and earliest Cenomanian in the San Juan Basin. There are two problems with making the “sub-Dakota unconformity” in the southeast part of the San Juan Basin equivalent to the unconformity under the Dakota at West Rio Piedra and Holiday Acres and equivalent to this project’s S3 to the south:

1) Based on an Ar/Ar date derived from a bentonite at Highway 84 (unit 23), the lower part of the Dakota in the study area is latest Cenomanian, perhaps earliest Turonian (Appendix E).

2) In a paper discussing the southeast part of the San Juan Basin, Aubrey (1988b) presents a cross section that everywhere shows the “sub-Dakota unconformity” as lying beneath the bentonite section that is in the classical Oak Canyon Member - the member that most workers consider the first Dakota marine unit and that is roughly equivalent to Dakota Sequence 2 of the present work. From previous evidence presented in this dissertation, it is clear that surface S3 is *above* the Oak Canyon bentonite section. If the unconformity under the Dakota at West Rio Piedra and Holiday Acres equates to the S3 surface to the south, then it is further evidence that the

“sub-Dakota unconformity” does not record a single, time significant erosional event.

Figure 3.43 diagrams a sequence of steps that could have led to the observed unconformities and sedimentation patterns in the study area. It offers the possibility that the unconformity at West Rio Piedra is not K2, rather it is a later unconformity, S3, that has removed the K2 surface. The “sub-Dakota unconformity” is, therefore, a composite surface that has regional extent, but is a result of at least two erosional episodes.

Depositional History of the Dakota from Outcrop Data

Figure 3.43 is a schematic rendering of the sequence of events during Dakota time that resulted in the outcrop patterns we see today. The interpretation requires three things to work: an overall rise in relative sea level, higher frequency fluctuations superimposed on the deepening trend, and a positive topographic area to the north. That these conditions are satisfied was demonstrated from the outcrop work at Highway 84 and Heron Dam and is illustrated in Figures 3.22 and 3.38.

There are several dynamics occurring at the same time during a flooding event such as the one that produced the Dakota. Sea level is rising, in the classical shelf model the depositional area is subsiding, sediment supply is varying and local tectonics affect all three. For this reason, the term

Figure 3.43: Diagrammatic cross section from Highway 84 on the south to West Rio Piedra 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. Sea level curves are from Figures 3-22 and 3-37 and the numbers on the curves refer to discussions related to those figures.

relative sea level has become popular. The sea level fluctuation curve that is included in Figure 3.43 relates the depositional events in the Dakota to cycles of relative sea level change.

Several authors, including Jervay (1988), Posamentier et al. (1988) and Posamentier et al. (1988), consider the rates of change of relative sea level as particularly important. In the sea level curve, the greatest rate of change occurs at the rising and falling inflection points. These are points of greatest horizontal water movement and are interpreted here as trigger points for TSE formation and initiation of marine flooding surfaces, during a relative sea level rise, and for LSE/RSE formation during relative sea level fall. This is in agreement with the literature, but it is simplified in the high shelf environment that existed during expansion of the Western Interior Cretaceous Seaway. The implication is that a depositional sequence is formed between successive falling inflection points. On that basis, Dakota Sequence 1 is between K2 and S2, and Dakota Sequence 2 is between S2 and S3. Surface S1 is a TSE that formed during a relative sea level rise. Dakota Sequence 3 is between surface S3 and the top of the uppermost parasequence.

Putting together all of the information presented on the preceding pages, it is possible to reconstruct a depositional history for the Dakota in the Chama Basin/eastern San Juan Basin. Much of this is summarized graphically in Figure 3.43. In the following listing, H84 is Highway 84, HD is Heron Dam, HA is Holiday Acres, and WRP is West Rio Piedra.

1. The K2 unconformity developed on top of the Burro Canyon Formation. Deposition of the Burro Canyon took place on an

alluvial plain and was characterized by coarse grained, braided stream deposition.

2. Rise in relative sea level.

3. Deposition of a thin transgressive sand, probably from reworking of the Burro Canyon (H84 unit 1). In the supratidal area, fines were partially removed from the fluvial Burro Canyon source sediments (HD supplemental section unit 8) and redistributed to intertidal mud flats (H84 unit 2, later unit 8, HD main unit 1). Depositional slope was less than 0.2°. Beginning of lower transgressive systems tract.

4. Development of tidal flats bounded on the basinward side by a barrier bar system (H84 unit 11). Breaches in the barriers allowed ebb and flood tidal deltas to develop. Flats were drained by tidal channels (H84 unit 8, HD units 1 to 3).

5. Rise in relative sea level increasing the sand content of mud flats (H84 unit 4 through 7, HD main section unit 2). Barrier bars overrode sand flats during transgression and eventually merged with the shoreface (Figure 3.14).

6. Continued rise in relative sea level moved shorefaces landward across barrier bar system (H84 units 13 to 15) creating a transgressive surface of erosion, TSE, surface S1

(Figure 3-14) at Highway 84. Deposition of offshore shales (H84 unit 16) on the TSE. TSE marks beginning of the upper transgressive systems tract.

7. Periodic deposition of thin sandstone storm beds (H84 units 17 and 18).

8. Drop in sea level, subaerial exposure in some areas (H84 unit 20BZ, HD unit 7). Formation of a lowstand surface of erosion, LSE, surface S2. This is the top of Dakota Sequence 1. Sequence 1 is composed of only a transgressive systems tract in the study area.

9. Rise in sea level forming a TSE and deposition of a thin transgressive sand in places (H84 units 20B and 20C). This is the base of Dakota Sequence 2.

10. Deposition of dark gray to black marine shales containing bentonites (H84 units 23, 24, 26, and 27). Each black shale marks a point of maximum onlap during a high frequency relative sea level cycle.

11. Continued storm bed deposition, and deposition of some thin delta front sands within the black shale sections (H84 units 22, 25, and 28, HD main section unit 8).

12. Deposition of shoreface sandstones as high frequency marine parasequences. There is one complete shoreface (H84 units 30 and 31) and an interrupted second shoreface (H84 units 36 to 41) at Highway 84, and two complete shorefaces (HD units 12, 14 and 15) and an interrupted third shoreface (HD unit 18) at Heron Dam. In both places, the highest parasequence in Dakota Sequence 2 is truncated by the next event.

13. Relative drop in sea level forming a marine regressive erosion surface (RSE) to the south and an unconformity to the north. This is surface S3. It is the top of Dakota Sequence 2 and lower boundary of Dakota Sequence 3. Sequence 2, like Sequence 1, contains only a transgressive systems tract but it is punctuated by the high frequency high stands that produced the included, prograding shorefaces mentioned in step 12.

14. Deposition of shorefaces to the south (H84 units 42 to the top of the section, HD units 19 through 26), and valley fill plus paralic coal deposits to the north (WRP units 3 and 4, HA unit 8). These are lowstand system tract components that rest on the sequence boundary, S3.

15. Relative rise in sea level evidenced by shoreface drowning to the south and shoreface transgression to the north. This is the transgressive systems tract (H84 units 42 to the top of the section, HD units 26 through 30, HA units 9 and 10, WRP units 5 and 6).

16. Relative stillstand in sea level causing final shoreface progradation (HD units 31 to the top of the section, HA unit 11, WRP, unit 7). Everywhere, the Dakota is overlain by the Graneros Shale. The surface is one of marine flooding and is likely a transgressive erosional surface. There is some evidence presented later from the subsurface that this surface is also a sequence boundary.

CHAPTER 4

OUTCROP TO SUBSURFACE CORRELATION

A primary objective of this study has been to correlate the observations made on outcrop to the subsurface. The benefit of so doing 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 chapter will start with comparison of the outcrop gamma ray curves and then tie the correlations to a well in the South Lindrith Field. In Chapter 5, a network of subsurface cross sections based on the outcrop calibration is developed and interpreted.

Method

Both the Highway 84 and Heron Dam sections were measured with a Scintrex model GRS-500 multispectral scintillation counter. Measurements were at one foot intervals and recorded as total (K, U, Th) counts per second.

At each measurement point, five readings were made and averaged for the final reading. The radius of investigation for this tool is 0.5 to 1 foot (Slatt et al., 1995) so each new measurement had virtually no overlap with the preceding. However, some intervals with very thin beds, e.g. less than 2 inches, that were not directly under the detector probably yielded a nonrepresentative total count because of interval averaging.

At both outcrop locations, the line of section was offset horizontally several times to allow a complete, albeit composite, measurement. At Heron Dam, most of the gamma ray readings were made as the section's stratigraphic detail was recorded resulting in a close correspondence between rock descriptions and gamma ray readings. At Highway 84, however, the gamma ray profile was made after recording the stratigraphic detail and took a slightly different path along the outcrop. The resulting curve was matched to the outcrop description through tie points. This resulted in a small to moderate amount of curve fitting to tie the gamma ray to lithology.

Theory

The three radioactive elements most common in sedimentary rocks are uranium, thorium and potassium. Uranium and thorium tend to concentrate in reducing chemical conditions that preserve organic matter. Potassium is commonly found in clay minerals, particularly in montmorillonite/bentonite and illite (Hilchie, 1982). Shale is typically high in both mineralogic clay and in clay sized particles, so it tends to have higher gamma ray counts than coarser grained, pure quartz sandstones. According to Schlumberger (1991),

the response of the typical gamma ray sonde used for well logging is nearly proportional to K_2O content in the rocks. Black shales typically have a high organic content and yield a high gamma ray reading. This is related to the concentration of uranium salts in the reducing chemical environment that typically accompanies organic-rich rocks. For this reason, the gamma ray log is commonly considered a good tool for measuring and differentiating the shale content of sedimentary formations.

Gamma Ray Scale Calibration

The Scintrex tool was checked daily with a supplied calibration source and adjusted as necessary. Care was taken when revisiting a previously measured point to ensure that the scale readings were the same. If not, the scintillator readings were adjusted to match.

The outcrop gamma ray profiles generated for this study are scaled from 0 to 800 counts per second (CPS). Typical wireline gamma ray logs are scaled from 0 to 200 API units. There does not appear to be a formal conversion factor between readings from a hand-held scintillator and a wire-line scintillation counter, but the principles are the same for both. Comparison of the curves generated on outcrop with subsurface logs shows that irrespective of count rate, correlations can be made using the log curve shapes.

Outcrop Gamma Ray Profiles and Their Correlations

Figures 3.23, 3.38a and 3.38b, in Chapter 3, are the gamma ray profiles at Highway 84 and Heron Dam respectively. Each log is presented with a stratigraphic profile and the facies assignments discussed in that chapter. In this chapter the logs are split within figures to make it easier to see the details. Please refer to the CD-ROM for full sized logs.

At Highway 84, Figure 4.1, the shallow-water facies F sediments at the bottom of the section have a low gamma ray count as expected from their larger grain sizes, higher quartz content and general lack of clay and organics. Above about 13 feet, there is good agreement between deeper water facies groups A and B and higher gamma ray counts upward to about 85 feet. However, the zone from about 85 feet to about 115 feet 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 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 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

Figure 4.1: Stratigraphic column, facies and gamma ray profile for the section at Highway 84.

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.

Figure 4.2 shows the details of the gamma ray profile at Heron Dam. Throughout, there is good agreement between the lithologies and the expected radioactivity readings. The gamma ray reveals subtle details that are not obvious in the lithologic descriptions. For example, starting at about 133 feet and going up to the S3 surface at about 148 feet (upper part of unit 18, Appendix A), 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. As mentioned in Chapter 3, 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 4.3 shows the correlation of the outcrop sections at Highway 84 and Heron Dam. Based on the surfaces and sequences identified in Chapter 3, 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 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 bar lithologies at Highway 84 are closer to the distal end of a protected shoreline than the more estuarine, 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

Figure 4.3: Correlation of the Heron Dam and Highway 84 outcrop sections using gamma ray, facies and lithologies. Note parasequence at Heron Dam that is present at Highway 84 only as a basal correlative shale section. The Heron Dam column has been reduced to the equivalent portion at Highway 84. Facies definitions are in Figure 4.1 and others.

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 northward through time. Support for a north moving shoreline was presented in Figure 3.41 and this correlation of the two outcrop sections supports the interpretation .

Correlation to the Subsurface

Figure 4.4 is a map of part of the study area that shows the locations of the South Lindrith Field, a subsurface well log and the two outcrop sections. Figure 4.5 shows the correlation of the outcrop profiles with the subsurface well logs.

There are no cores available within the South Lindrith field that can be used for log calibration. Those from nearby fields are very short and do little more than confirm that gamma ray values are low in sandstones. Formation picks from completion cards are available for all wells in the South Lindrith Field, but they use conventional Dakota nomenclature and are not useful in this study. Correlation within the field and to adjacent wells must be made with gamma ray curves supplemented with various resistivity and porosity logs. On outcrop, of course, there is only a gamma ray curve to work with. These limitations notwithstanding, the match in curve shapes from the Heron Dam outcrop to the subsurface is quite good, particularly below surface S3.

Figure 4.4: Map showing locations of outcrop measured sections and wells used in Figure 4.5.

Figure 4.5 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 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.

From the K2 unconformity upward, there is good agreement in the gamma ray curves despite the 44 miles from Heron Dam to South Lindrith. It is possible that the line of section is close to, but not on, depositional strike, thus there is little significant variation in the rocks. It was pointed out earlier that logs of sandstone/shale sequences can have remarkable similarity when there is no actual geologic correlation. In this example, however, 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. 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 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

Figure 4.5: Correlation from Heron Dam, on the right, to South Lindrith field, on the left. The Benson well is about halfway between the two locations.

Dakota is real. What the cross section shows is that above the S3 surface, the uppermost Dakota sandstone is thickening eastward. This is a trend seen in the subsurface and will be demonstrated in Chapter 5. It may represent a prograding highstand depositional system.

Conventional Dakota Terminology

Throughout this dissertation, there has been reference to conventional Dakota terminology. How does it compare to the sequence terminology developed during this study? Figure 4.6 shows the working subsurface nomenclature, carried by curve matching from the South Lindrith Field, applied to the outcrop at Heron Dam.

In general, Dakota Sequence 1 includes the Encinal Canyon Member. Sequence 2 encompasses the Oak Canyon Shale member and the sandstones of the Cubero Member. Sequence 3 begins with the Paguate Sandstone Member and finishes, at the top, with the Twowells Sandstone Member. In the classical way of naming this section, the Clay Mesa Shale Tongue of the Mancos Shale lies between the Cubero Sandstone and the Paguate Sandstone. The Whitewater Arroyo Shale Tongue lies between the Paguate Sandstone and the Twowells Sandstone.

This study shows that each of the shale to sandstone successions is a marine parasequence, or shoreface, prograding during high frequency relative sea level fluctuations. The Paguate of the subsurface is, at Heron Dam, related to a relative sea level lowstand and is not related to the

Figure 4.6: Conventional Dakota names applied to the section at Heron Dam. The symbol key and facies definitions are on Figures 3-38a and 3-38b.

underlying shaly section - the shale is part of a parasequence truncated by surface S3.

The problems with Dakota nomenclature relate to its transgressive depositional history. As the Western Interior Cretaceous Seaway expanded generally westward, the Dakota shoreline migrated along with it. However, the shoreline prograded generally eastward during times of high frequency relative sea level stillstands and lowstands, producing several vertically stacked eastward thinning parasequences - the classical Dakota “tongues.” Figure 2.12 illustrates the westward moving retrogradational parasequence stacking pattern that characterizes the Dakota interval. In the oil and gas fields within the project area, it appears that there is a tendency to name Dakota units from the top down in the order in which they are penetrated. In some instances, the first sandstone is called Twowells, in others it is called Paguate. The uncertainty about which part of the Dakota has been encountered is typical of strictly lithostratigraphic correlation.

Because of the excellent correlation from the subsurface to the outcrops, it is possible to refine the conventional Dakota member names in the study area and give them precise meaning in a sequence stratigraphic context. The first step is to correlate the unconformity surfaces and establish the individual sequence limits. Once done, the individual members become the following:

Dakota Sequence 3

Highstand systems tract: Twowells Sandstone Tongue

Transgressive systems tract: Whitewater Arroyo Shale Tongue

Lowstand systems Tract: Paguate Sandstone Tongue

Dakota Sequence 2

Transgressive systems tract:

Clay Mesa Shale

High Frequency Highstands:

Upper and Lower Cubero Sandstones.

Oak Canyon Shale

Lowstand systems tract: not named (unit 20B,C of this study)

Dakota Sequence 1

Highstand systems tract: Parts of Encinal Canyon Member

Transgressive systems tract: Parts of Encinal Canyon Member

Lowstand systems tract: Parts of Encinal Canyon Member

Using the conventional names requires only that they be related to the sequence in which they occur. For example, the lowstand sandstone at the base of Dakota Sequence 2 becomes the Paguate Sandstone by definition. Its name is determined chronostratigraphically in relationship to a significant surface rather than lithostratigraphically by stacking order.

The outcrop to outcrop and outcrop to subsurface correlations set the framework for subsurface correlation and interpretation in the South

Lindrith Field. Depositional strike appears to have been mostly west to east during formation of surfaces K2 and S2 and during Dakota Sequences 1 and 2. The shoreline trend changed and depositional strike became more north to south oriented during deposition of Dakota Sequence 3.

CHAPTER 5

GREATER SOUTH LINDRITH FIELD AREA

In the preceding chapters, the sequence stratigraphic framework of the Dakota has been developed and correlations have been made from the outcrop to the subsurface (Figures 4.1 and 4.2). In this chapter, wells in the South Lindrith field and part of the West Lindrith field to the northeast are correlated and the network thus established is tested against outcrop observations. The resulting well log cross sections and maps, both structure and isopach, show that the study area wells can be placed into the same stratigraphic sequences identified on outcrop. This is important because it calibrates the subsurface cross sections and because oil and gas production in the greater South Lindrith field area can be related to suspected compartments defined by a combination of sequence controlled lithology distribution and structure. Part of the reason for the present study was to evaluate the possibility of extending Dakota production in the area by examining the relationship between stratigraphy and structure.

The South Lindrith field is located on the south side of the San Juan Basin in sections 1 through 5, 8 through 16, 21 and 22 of Township 23 North, Range 4 West, and sections 27, 28, 33 and 34 of Township 24 North, Range 4 West in Rio Arriba and Sandoval Counties, New Mexico (Figure 1.2). This location is completely within the outline of the Jicarilla Apache Indian Reservation. The field includes approximately 125 wells from which production is comingled from the Dakota and Gallup Sandstones. The use of

“approximately” is made necessary because the legal definition of the Lindrith South Gallup-Dakota Pool includes more area than the geologic South Lindrith field as shown in Figure 1.2. The map in Figure 1.2 shows that about 70 wells of the 125 total produce from the Dakota. Wells are on 40 acre spacing and there are still locations available although many drillsites have been abandoned in recent years. Depth to the Gallup averages 6200 feet and to the Dakota 7200 feet.

Discovered in 1958, the South Lindrith field area has produced a cumulative total of approximately 85,000,000 barrels of oil and 190 billion cubic feet of natural gas as of December, 1998. At present, all wells in the field have reached the upper, flat part of their cumulative production curves, thus field totals are very close to the estimated ultimate reserves (EUR).

The subsurface study area is larger than the South Lindrith field. It includes parts of four townships: Townships 23 and 24 North, and Ranges 3 and 4 West, in Rio Arriba County and part of Sandoval County. Part of another Dakota field, West Lindrith, lies within the northeast quarter of the mapped area. Many of the West Lindrith wells were used to add mapping control and to extend the Dakota interpretation. Dakota well data become very sparse southwest of a northwest/southeast trending line on the southwest side of the South Lindrith field and this was the primary reason for including the area to the northeast. As will be shown, this choice of townships was fortuitous because much of the pertinent geology develops to the northeast of the South Lindrith field proper.

Well Log Correlation

In Chapter 4, a 44-mile cross section (Figure 4.5) showed that it is possible to correlate from the outcrop to the subsurface in the South Lindrith field area, particularly in the lower part of the Dakota section. The correlation allows identification of depositional sequences that can be applied to the well log cross sections.

One of the main benefits of outcrop to subsurface correlation is that gamma ray curves with similar shapes can be calibrated with respect to mineralogy, grain size, clay content, cements and diagenesis with good confidence. Cores are useful for the same purposes, but there are none within the South Lindrith field. Descriptions of two cored wells north and northeast of the field are in Appendix F.

To determine the sequence stratigraphy on outcrop, it was necessary to identify significant surfaces, plot them on the outcrop gamma ray profiles and then to pick out the parasequences in between (Chapter 3). Using a network of 28 cross sections (Figure 5.1), it is possible to do the same thing in the South Lindrith field. Each of the cross sections is presented as a full sized image on the enclosed CD-ROM. Portions of the sections that are particularly important to the interpretation are presented on pages that follow. The well that ties to the surface observations is the Chace Oil Company #6 Jicarilla Tribal, at the southwest end of the outcrop to subsurface correlation section (Figure 4.5), located in the southeast quarter of the northeast quarter of section 12 of T23N, R4W. This important tie well is number 8 on

Figure 5.1: Index maps showing the locations of cross sections in the South Lindrith Field area. Lettered northwest to southeast lines are indicated on the left, numbered southwest to northeast lines are indicated on the right. Green spots are wells with control at a particular horizon. Red spots are wells with no control for the same horizon. Gray lines represent the standard one-mile section grid. Most of the cross sections are included on the enclosed CD-ROM.

southwest/northeast trending cross section 14-14' of this dissertation (Figure 5.2).

Bentonites, a Caution

According to Kaufmann and Caldwell (1993), there are over 1300 known bentonites, altered volcanic ash beds, in the Late Albian to Maastrichtian section of the Rocky Mountain Cretaceous. Because they are related to very short term volcanic events, bentonites are good stratigraphic time markers. They contain clay-sized particles that tend to accumulate and to be preserved in fine grained, low energy aqueous environments such as offshore deep water marine environments that typically display dark gray to black shales on outcrop. Preserving a bentonite as a discrete layer in a sandy environment, on the other hand, requires that it be deposited in low energy, perhaps standing water and be protected from later high energy, erosional, conditions. Examples would be in meander cutoffs, marshes or lagoons. Such preservation will be more local than deposits in the deep water marine environment and, therefore, less valuable for correlation.

On well logs, bentonites typically have high gamma ray counts, extremely low resistivity and high apparent neutron porosity (Figure 5.3). They tend to be in thin beds and display thin bed response to the resistivity tool: a characteristic “cup” shape as shown in Figure 5.3. The enclosing dark gray to black shales also have high gamma ray, low resistivity and high apparent porosity, but particularly on the resistivity response, bentonites stand out. Because bentonites are so distinctive, they are commonly used for

Figure 5.2: Northeast end of stratigraphic cross section 14-14' showing the location of the Chace Oil Company #6 Jicarilla Tribal well (number 8 on the cross section). This well ties to the outcrop sections at Heron Dam and Highway 84. Kgr = Graneros Shale, Kgh = Greenhorn Limestone. Other abbreviations defined in text.

Figure 5.3: Chace Oil Company #28 Jicarilla Tribal 71 well showing distinctive bentonite log response.

chronostratigraphic correlation in the subsurface. This must be done with care.

The sequence stratigraphic significance of black shales is that they tend to mark condensed sections, sections that correlate onshore to maximum flooding conditions. As such, black shales mark maximum transgression - which is not necessarily recognized in the field as a formation boundary. Furthermore, according to the Exxon school of sequence stratigraphy (Van Wagoner et al., 1990) maximum floods happen between sequence boundaries with the boundaries defined as lowstand erosion surfaces. It should be noted that Galloway (1989, 1998) disagrees with this definition and specifies that a sequence is the interval between flooding surfaces. Galloway's approach is out of phase with the Exxon definition and is not used in this dissertation. In marine marginal conditions such as those during Dakota time in the San Juan Basin, a black shale is commonly the basal part of a continuously shallowing upward succession that culminates in a sandstone. This is the Exxon parasequence, a mappable unit that is bounded at the top and bottom by a flooding surface (Van Wagoner et al., 1990). In this dissertation, black marine shales comprise facies A and on the stratigraphic columns in Figures 3.21 and 3.37, it can be seen that they do, indeed, form part of a gradational system related to changes in relative sea level. Bentonite electric log response can help identify facies A environments, and the facies itself can be an important correlateable horizon.

Typically, formation boundaries identified on outcrop will correspond to mappable lithologic or fossil changes such as the top of a parasequence or the first appearance of a particular species. Shale color changes are too subtle

in most instances to make them useful. Bentonites tend to be very light gray to white on outcrop, but because they are thin and tend to weather, they are difficult to find, even in black shale sections. Picking formation boundaries on bentonites is impractical and, from the standpoint of the field geologist, unhelpful.

Because of the above, using bentonites to pick formation tops or formation members on subsurface logs can make it difficult to later place the sections into a sequence stratigraphic framework. Boundaries based on bentonites will obscure depositional sequences by artificially splitting them. Bentonites are good correlation markers, datums, for “hanging” sections because of their time significance, but they are not good formation or member divisions without supporting evidence. Nevertheless, it is apparent from analysis of completion cards that bentonites have been the basis for many subsurface “formation top” calls in the Dakota of the San Juan Basin and this has led to some confusion about stratigraphic relationships. In this dissertation, bentonites are used as correlation markers and are very useful for defining parts of the section that have been eroded, or “cut out,” by younger lithologic units. They mark “tops” only where it is clear that such use is appropriate.

Well Logs

There are approximately 125 wells in the South Lindrith field and most have well logs available. A few digital well log files within and near the South Lindrith field were supplied by Burlington Resources’ Farmington,

New Mexico, office as Canadian Well Logging Society (CWLS) Log ASCII Standard (LAS), version 2, files. The remainder were digitized using Terrasciences' TerraDigitizer program and exported as LAS files. The digitized files were loaded in the TerraSciences' TerraStation II software for correlation, mapping and analysis.

Correlation Method

The outcrop gamma ray log became the key to correlating along line of section 14-14' shown in Figure 5.2. From there, it was a matter of building intersecting sections and extending the correlations through all wells in the South Lindrith field as shown in Figure 5.1. All lines have several ties to others and in this way it was possible to cross check correlations as the work proceeded. The initial cross sections were built on paper and correlated to the outcrop log and to each other with the aid of a light table. After it was clear that the set of picked horizon tops was valid, the results were loaded into TerraStation II and the correlations were completed. Very careful attention was paid to marker bentonites, particularly to whether or not they were continuous across sections or had been eroded by younger units.

Cross Section Interpretation

Sequence and parasequence tops picked on the cross sections allowed accurate maps to be drawn for the greater South Lindrith field area. Because

the sections were constructed with the aid of TerraStation II, their exact locations are somewhat virtual, in the computer sense, because sections may be laid out, and redefined, quickly on any orientation. The value of the network shown in Figure 5.1 is that it forced multiple cross checks on correlated points. As work proceeded, many additional east/west and north/south lines were examined in the four township subsurface study area. The Dakota interpretation starts at the bottom of the section, at the K2 surface and works upward.

Cross Section Datum

Bentonites and flooding surfaces make good stratigraphic datums: bentonites because they are precise time markers and flooding surfaces because they tend to be overlain by coeval, fine grained, continuous lithologies with easy-to-pick log signatures - particularly if they are developed on sandstones. It is a working rule that when “hanging” a section on a datum that the datum should be as close as possible to the unit of primary interest.

Unconformities are generally not good datums because they represent erosional surfaces that can have significant topographic relief. See, for example, the K2 surface in Figure 3.10a, 3.10b and 3.10c. If a section were “hung” on the unconformity, it could misrepresent the stratigraphic relationships below.

A significant surface for this dissertation is S3 at the top of Dakota Sequence 2. There are two potential datums for examining S3: the top of uKdPS1, a flooding surface, and the bentonite beneath S3 that is colored red on the cross sections. Unfortunately, the bentonite is discontinuous. The flooding surface on uKdPS1 merges with the S3 unconformity. Because uKdPS1 has a flooding surface across its top and because it appears to fill in lows on the S3 surface, its upper surface is used as a datum in many of the stratigraphic cross sections. Other datums are used as necessary to illustrate particular points.

Dakota Sequence 1

The interval between K2 and S2 (Figure 5.2) is Dakota Sequence 1.

Surface K2 is unambiguous on gamma ray logs and is marked in some locations by a high resistivity value on the induction log (see, for example wells 6, 7 and 8 in Figure 5.2). The thin high-resistivity zone corresponds to a hard, weathered zone on outcrop and represents cementation due to reworking, exposure and subsequent drowning. If, as here, the zone of thin, high resistivity is associated with a weathered or reworked surface it is commonly referred to as a “transgressive spike.” Care must be exercised in using this term because other things such as calcite or silica cementation can exclude porosity and result in the same resistivity pattern. Hydrocarbon resistivity spikes, which can also look the same, will normally be associated with measurable porosity.

Surface S1, a transgressive surface of erosion, is not easy to correlate from the subsurface logs to the outcrop. Figure 4.5 in Chapter 4 (the outcrop to subsurface correlation) shows the S1 TSE surface at Highway 84 within a sandstone section overlain by dark-gray shale facies B. It is impossible to trace the same surface to Heron Dam based on lithologic similarities and there is only circumstantial basis for picking its correlative point on the gamma ray profile. However, because a transgressive surface is commonly overlain by deeper water sediments, black shales for example, the S1 surface is picked on well logs at the top of a thin sandstone overlying the K2 unconformity (Figure 5.2 wells 8 and 9) and beneath a thick shale section. On outcrop, dark colored shales correlate to high gamma ray count, so this correlation is reasonable. The interval between K2 and S1 on outcrop is in the tidal flat/lagoonal environment at Highway 84 and in the proximal tidal flat/tidal channel environment at Heron Dam. At both outcrop locations, the interval thickness is about 30 feet. In the subsurface study area, the corresponding interval is rarely more than 15 feet thick, probably reflecting that the field area was further offshore during that time.

Between surfaces S1 and S2, almost every log in the South Lindrith field area displays a high gamma ray count that resembles the same interval at Highway 84. The thick, shallow water, tidal facies F section below S2 at Heron Dam appears to correlate to a thin sandy interval between S1 and S2 in most logs in the South Lindrith field area (Figure 5.2) in which the gamma ray is commonly 40 API counts lower than in the underlying shale section. This seems to indicate that the oil field area is roughly on strike with the Highway 84 exposure, but is in a more southerly and seaward position than the time equivalent interval at Heron Dam. There is an implication here of a

west to east or southwest to northeast trending shoreline trend. Considering that surface S1 is a TSE, the continuity of the lower, shaly part of the S1 to S2 interval suggests that it is most likely a condensed section marking the maximum flood on the K2 unconformity.

Dakota Sequence 2

The interval between surfaces S2 and S3 is Dakota Sequence 2.

Surface S2, a combination LSE/TSE is a good pick on outcrop, but it, too, is somewhat difficult to tie to the subsurface. Figure 4.5 (the outcrop to subsurface correlation section in Chapter 4) locates S2 at the base of a gamma ray “kick” beneath the first parasequence labeled lKdPS1 (lower Dakota parasequence 1) on the cross sections. If this placement is correct, then the first parasequence overlying surface S2 represents the shallowing upward of a high frequency shoreline progradation. When positioned using the gamma ray “kick”, S2 is well defined on almost all wells in the project area (Figure 5.2). However, many wells in the South Lindrith field area do not penetrate to sufficient depth to include the surface.

Between S2 and the next unconformity, S3, there are three complete parasequences in the study area, each of which has decreasing gamma ray count upward and a characteristic funnel shape on the logs. They are labeled lKdPS1, -2 and -3 upward. Because each parasequence records an upward decrease in shaliness, and to a certain extent an upward coarsening, they

reflect intervals of short-term lowering of relative sea level and related shoreface progradation.

It is significant that from surface S2 upward, the gamma ray profile of each parasequence shifts more towards higher average count rates. This means that each stratigraphically higher parasequence was deposited in deeper water and is thinner and shalier, than the underlying. The pattern agrees with overall transgression during this part of the Dakota. The back-stepping parasequence stacking pattern is very important to recognize because it is the signature of a fluctuating transgressive shoreline (Van Wagoner et al., 1990). The three parasequences, IKdPS1, -2 and -3 comprise a transgressive parasequence set. The lower two parasequences in this interval are commonly referred to as the Cubero Sandstone on well completion cards. The upper, less well developed parasequence is commonly placed in the Paguate Sandstone interval. As mentioned several times in earlier discussions, such nomenclature obscures the actual depositional relationships. The interval from S2 to S3, is a single depositional sequence, not two separate events as conventional nomenclature would imply.

Parasequence IKdPS1, the lowest, is the least shaly and thickest of the three. In the South Lindrith field, the zone typically displays high resistivity and increased neutron and density porosity. Perforation data suggest that this is an important hydrocarbon producing sandstone unit in the field, and suppressed neutron porosity readings in some wells also suggest that the zone is mostly a gas producer.

Above parasequence lKdPS3, there is an interval of upward decreasing gamma ray that on some logs in the west and southwestern parts of the South Lindrith field would appear to be continuous all the way up to the top of uKdPS2 or higher if it were not for the presence of the marker bentonite (Figure 5.4). Careful correlation shows that the cleaning upward in these wells, and all others in the project area, is interrupted by a high gamma ray-count notch that represents surface S3. It is a subtle pick that in some wells would be overlooked if it were not for the correlation carried from the outcrop to the Chace Oil #6 Jicarilla Tribal (well 8 on Figure 5.2) and applied to all wells in the field. In the wells in which surface S3 has eroded the marker bentonite, such as wells 8 and 9 (Figure 5.2), there is no question that the interval above lKsPS3 does not continue upward beyond S3.

Dakota Sequence 3

It became obvious during the subsurface part of this study that there was one principal erosion surface in the Dakota interval that could be identified on logs simply by the disappearance of a marker bentonite. This is surface S3, good examples of which can be seen on cross sections F-F' (Figure 5.5a, -b, -c and -d) and 7-7' (CD-ROM). Surface S3 is the lower bounding surface of Dakota Sequence 3. On section F-F', note the bentonite cutoff between wells 10 and 11.

At both Heron Dam and Highway 84, the first sandstone above the S3 surface is distinctive because it shows a significant amount of shallower water depositional forms (facies D through F) and because it has a sharp

Figure 5.4: Chace #17Y Jicarilla Tribal 17 well showing typical log response in western part of the South Lindrith field. If the bentonite were not present and the gamma ray curve were flattened as at #1, it would appear that the interval above IKdPS3 would represent one parasequence (#2) continuing upward. However, the presence of surface S3 (#3) shows that there are at least two separate, correlatable events.

Figure 5.5a: This figure is stratigraphic cross section F-F' and it is in four parts, 5.5a, -b, -c, and -d. The full figure is on the enclosed CD-ROM. Kgr is the Graneros Shale, Kgh is the Greenhorn Limestone. All other unit identifiers are noted in the text. Datum is the top of uKdPS1/S3(U). This figure continues on Figure 5.5b.

Figure 5.5b: This figure is stratigraphic cross section F-F' and it is in four parts, 5.5a, -b, -c, and -d. The full figure is on the enclosed CD-ROM. Kgr is the Graneros Shale, Kgh is the Greenhorn Limestone. All other unit identifiers are noted in the text. Datum is the top of uKdPS1/S3(U). This figure continues on Figure 5.5a and Figure 5.5c.

Figure 5.5c: This figure is stratigraphic cross section F-F' and it is in four parts, 5.5a, -b, -c, and -d. The full figure is on the enclosed CD-ROM. Kgr is the Graneros Shale, Kgh is the Greenhorn Limestone. All other unit identifiers are noted in the text. Datum is the top of uKdPS1/S3(U). This figure continues on Figure 5.5b and Figure 5.5d.

Figure 5.5d: This figure is stratigraphic cross section F-F' and it is in four parts, 5.5a, -b, -c, and -d. The full figure is on the enclosed CD-ROM. Kgr is the Graneros Shale, Kgh is the Greenhorn Limestone. All other unit identifiers are noted in the text. Datum is the top of uKdPS1/S3(U). This figure continues on Figure 5.5c.

base. By carefully correlating the log at Heron Dam with the Chace #6 Jicarilla Tribal well in the South Lindrith field (well 12 on F-F'), it can be seen that the interval is thinner and has a different character west of the outcrop. It is designated uKdPS1 (upper Dakota parasequence 1). On the cross sections, the sandstone in this interval replaces, or cuts out, a bentonite. It will be shown later on an isopach map that there is a distinct northwest trend to the sandstone that adds additional strength to its being deposited on a lowstand surface. The direction of trend may reflect a shoreline direction that was predominantly southwest to northeast.

At Heron Dam, there is a bentonite about 35 feet below S3 (unit 17, Figure 3.37), but it is in the lower part of lower Dakota parasequence lKdPS3 and it does not correlate to the same position as the marker bentonite seen on the subsurface logs. If there was a bentonite at Heron Dam in the same position as the one in the subsurface, it was removed during deposition of uKdPS1.

On the outcrop, Dakota Sequence 3 is characterized by an interval that is increasingly less shaly and slightly coarser grained upward above uKdPS1. A gamma ray pattern in the upper part of unit 27 at Heron Dam (Figure 4.6) correlates to a gamma ray shoulder at about 7333 feet in the Chace #6 Jicarilla Tribal well and the interval between the pick and S3 is seen to become thinner from Heron Dam westward. Likewise, the top of the uppermost sandstone at Heron Dam appears to correlate to a gamma ray shoulder at about 7294 feet in the Chace well, and again, the interval is thinner if the correlation is valid. These two intervals are uKdPS2 and uKdPS3 on the cross sections.

In the subsurface, the very top of uKdPS3 is commonly associated with a thin high resistivity peak in the South Lindrith field (see wells 6 through 11 on F-F', Figure 5.5b and 5.5c). The peak generally corresponds to a thin low gamma ray zone that also has both neutron and density porosity. Perforation data indicate that this is a hydrocarbon producing zone. The neutron curve moves opposite the density. It is lower in some wells suggesting gas, rather than oil, production.

At the northeast end of cross section 14-14' (Figure 5.2, wells 6 through 9), and several others that parallel it, the interval between the top of the Dakota and the S3 surface thickens northeastward and does so by the stacking of additional parasequences above uKdPS3. These additional parasequences are uKdPS4 and uKdPS5 on the cross sections. The pattern exhibited is similar to that of a prograding shoreline related to a drop or stillstand in relative sea level. The sandstones, therefore, record a highstand systems tract in which the Dakota shoreline was moving in an eastward direction. It is important to note that this implies a basically north to south trending shoreline during this latest Dakota event. This means that during Dakota time, the shoreline orientation gradually changed direction, much as suggested by Cobban and Hook (1984).

Dakota Sequence 3 contains a lowstand systems tract (in the sense of Pemberton and MacEachern, 1995) equivalent, uKdPS1, transgressive systems tract, uKdPS2 and 3, and a highstand systems tract, uKdPS4 and 5. The very top of the Dakota is a flooding surface overlain by a dark gray to black shale called the Graneros Shale in the subsurface. On outcrop, the Dakota is overlain by undifferentiated Mancos Shale. At Heron Dam the

Greenhorn Limestone is about 115 feet above the top of the Dakota. The surface at the top of the Dakota does not display evidence of subaerial erosion on outcrop, but in the subsurface, there is a significant variation in the thickness of the Graneros Shale that implies an angular unconformity. For this reason, because of the abrupt change in facies and because of the clearly progradational relationship seen in the upper part of Dakota Sequence 3, the top of the Dakota is here considered a high frequency sequence boundary, as well as a flooding surface, that is overlain by the Greenhorn Limestone condensed section in the Mancos Shale.

A lingering question remains about the northeastward thickening sandstones in Dakota Sequence 3. Was there a component of growth faulting or syndepositional faulting involved? This topic is addressed later under reservoir compartmentalization.

Structural Cross Sections

Six of the stratigraphic sections on the enclosed CD-ROM have a companion structural section (Figure 5.6), but the format of the structural sections is different. Structural sections are hung on a +250-foot datum and show only the gamma ray curve. The interval from the top of lKdPS1 downward to S3 is highlighted in yellow.

The structural cross sections show that trapping conditions within the South Lindrith field resulted from a combination of stratigraphy and structure. For example, northwest/southeast oriented structure section F-F'

Figure 5.6: Location of structural cross sections, in black, included in this dissertation. Green spots are wells with control at a particular horizon. Red spots are wells with no control for the same horizon. Gray lines represent the standard one-mile section grid.

(Figure 5.7), shows an anticlinal form that could guide subsurface fluid movements. Off the east flank of the anticlinal axis it can be seen that surface S3 cuts down and is filled by unit uKdPS1. On the section, it appears that there is a relationship between the anticline and erosion on S3. The structure shown, however, is present day structure and the anticline did not necessarily exist during erosion on S3 and deposition of uKdPS1. The zone of

Figure 5.7: Northwest to southeast structural cross section F-F'. Note zone of steep dip between wells 9 and 10 and the eastward thickening of uKdPS1. Gamma ray curve in green. No horizontal scale, see index map for well positions.

steep dip between wells 9 and 10 on this section may be an indicator of faulting. Additional evidence is presented and discussed later under structure mapping.

Figure 5-8 is structure section 14-14'. It, like most of the other southwest to northeast cross sections through the South Lindrith field, shows dip to the northeast into the San Juan Basin. This section shows that the anticlinal form seen on structural section F-F' is an anticlinal nose that does not have updip closure, and does not form a trap on the basis of structure alone. Figure 5.9 is structure 7-7' and it shows much the same structure dipping northeastward.

Cross section J-J' (Figure 5.10) runs from northwest to southeast along the southwest side of the South Lindrith field. Its most interesting feature is the up and down structural position of several adjacent wells. Some of this can be considered apparent structure because the cross section has even well spacing and the actual wells have variable spacing of between one half and two and a half miles. However, at least some of the apparent structure is real as shown later on maps.

Structural cross section I-I' runs northwest to southeast and is intermediate in position between sections F-F' and J'J'. It, too, has wells near the southeast end that are higher than the rest and suggest that there has either been anticlinal folding or fault control.

Structure section 3-3' shows only uniform dip into the basin center. It is not reproduced here, but is present on the enclosed CD-ROM.

Figure 5.8: Southwest to northeast structural cross section 14-14'. Gamma ray curve in green. Unit uKdPS1 highlighted in yellow. No horizontal scale, see index map for well positions.

Figure 5.9: Southwest to northeast structural cross section 7-7'. Gamma ray curve in green. No horizontal scale, see index map for well positions.

Figure 5.10: Northwest to southeast structural cross section J-J'. Gamma ray curve in green. Note that section appears to be aligned with strike, and that structural position of several wells is apparently fault controlled. No horizontal scale, see index map for well locations.

The five structural cross sections that are reproduced here (Figures 5.7 through 5.11) contain zones of apparent very steep dip that hint at faulting. Some of the oversteep dip is due to the sections not reflecting the actual well spacing. However, there are several places where the well spacing is almost uniform and the steep dip is a candidate for a fault zone designation. These include the zones between wells:

9-10, 13-14, section F-F' (Figure 5.7),
3-4, 5-6, section 14-14' (Figure 5.8),
1-2, 4-5, 6-7, 9-10, section 7-7' (Figure 5.9),
2-3, 3-4, 4-5, 5-6, 6-7 10-11, section J-J' (Figure 5.10),
7-8, section I-I' (Figure 5.11).

By plotting the candidates for faults on a base map and connecting the markers, the pattern in Figure 5.12 emerges. Four of the suspected faults can be projected through at least two of the cross section lines and they have a northwest/southeast, southwest/northeast orientation that fits with known fault patterns in the area (see the following section on structure mapping). The suspected fault labeled 1 on the map is very close to a line separating high from low oil and gas production volumes, so it may represent the edge of a structural compartment. This topic is discussed later under structural compartmentalization.

At first glance, the structural cross sections seem to show “layer cake” stratigraphy. But on close inspection, it can be seen that there has been differential movement, represented by changing interval thicknesses, between some of the wells. It is easier to see the variations on the

Figure 5.11: Northwest to southeast structural cross section 1-1'. Wells 8 and 9 are high and perhaps fault bounded. Note unit UKdPS1 thickening to east. Gamma ray curve in green. No horizontal scale, see index map for well locations.

Figure 5.12: Possible fault pattern in the South Lindrith field resulting mostly from postdepositional faulting. The circles and dots represent suspected fault positions on the structural cross sections. The black, numbered lines project through at least two suspected fault locations and are considered reasonable candidates for actual faults. Green spots are wells with control at a particular horizon. Red spots are wells with no control for the same horizon. Light gray squares represent the standard one-mile section grid. North is to the top.

stratigraphic sections. Those thickness changes may have been caused and enhanced by syndepositional faulting with the pattern later being modified by postdepositional structural activity. Structure and isopach maps provide much additional information.

Mapping and Map Interpretation

After all formation top picks were made, correlated and checked in the cross sections, they constituted a well information database that, combined with well names, locations and completion codes was mappable. Both isopach and structure maps were made to allow a more complete picture of the geology in the South Lindrith field area.

Computer Mapping Method

Base and contour mapping was done using TerraStation II software. The program uses a nearest neighbor search algorithm for gridding the data prior to contouring. As with most gridded datasets, contours do not always agree precisely with values at data points. The method produces a smoothed surface that fits the grid values and thus the result is a mathematical best fit. In contrast to hand contouring, which must honor all data points, computer contouring must honor calculated grid values unless there is a secondary processor to force data point honoring. The TerraStation software does a good job of honoring original data values if weighted *averaging* is used,

but some values may be slightly off-contour. In most instances, particularly for isopach mapping, the weighted *projection* grids are quite sufficient for showing surface to surface relationships.

One of the problems with computer mapping is that maps that look good commonly disregard original data values in favor of honoring grid values. It is possible by judicious selection of number of grid nodes, number of nearest neighbors used, contour interval and weighting exponent to force a computer to honor data values. Unfortunately, this commonly results in an unattractive, but nevertheless accurate, map. Another approach is to use Delaunay triangulation on the data points, then contour the resulting network. This method will honor every data point but most users do not like the edge effects such a process produces in areas where there is little control. A hybrid method that grids the resulting triangulated data reintroduces the problem of contours not honoring original data points. Slightly inaccurate contours are a fact of life for computer generated maps and the saving point is that the surface generated is a best fit according to the parameters used in its construction.

Isopach maps were gridded using a $1/\text{distance}$ ($1/d$) weighted *projection* with eight nearest neighbors. The contour interval was selected to match the thickness range of the data. Structure maps were gridded using a $1/\text{distance}^2$ ($1/d^2$) weighted *average* based on eight nearest neighbors. The contour interval on all structure maps is 10 feet. The width of the gridded area is approximately 12 miles and in the east/west direction the average well spacing is one third to one half mile. Setting a grid size of 75 by 75 points was

sufficient to allow just over two samples for each spacing increment, thus minimizing aliasing. The maps presented in the figures are slightly smaller than the full gridded area in an effort to lessen edge effects.

Structure Maps

All structure maps are reproduced on the enclosed CD-ROM. There is one map for each correlated surface picked. Only two of the maps are included here. The cluster of wells to the northeast and east of South Lindrith is part of the larger West Lindrith Gallup Dakota Field. Some wells from the southwest side of West Lindrith were digitized and used in this study to provide overall continuity.

There is remarkable similarity in the structure maps at all levels. For example, at every mapped level, there is a north-northeast trending anticlinal nose on the east side of the South Lindrith field (Figures 5.13 and 5.14) in sections 1, 12 and 14 of T23N, R4W. The central part of the field is in a synclinal depression that opens to the northeast and is bounded by the anticlinal nose on the southeast (sections 2, 3, 4, 9 and 10 of the same township). The west side of the field contains at least two northwest/southeast oriented structural steps that step downward to the northeast and are interrupted by narrow bands of steeper dip. Structural strike is northwest to southeast and there are several strike-parallel steep dip zones northeast of the field. At no structural level in the field is there significant closure. Single well closed contours are, for the most part, artifacts of the gridding and contouring process. It is obvious from the maps

Figure 5.13: Structure map on top of unit IKdPS3. The contour interval is 10 feet. The area of the South Lindrith field considered in this dissertation is outlined in green. Green spots are wells with control at the named horizon. Red spots are wells with no control for the same horizon. Gray squares represent the standard one-mile section grid.

Figure 5.14: Structure map on top of unit uKdPS1. The contour interval is 10 feet. The area of the South Lindrith field considered in this dissertation is outlined in green. Green spots are wells with control at the named horizon. Red spots are wells with no control for the same horizon. Gray squares represent the standard one-mile section grid.

that production in the field is not controlled by structural closure. In very general terms, the main producing area in the South Lindrith field is on a gently inclined shelf between steep dip zones. The steep dip zones may reflect faults, as discussed.

Because of the structural agreement at almost all levels within the Dakota section (Figure 5.15), it is likely that what the maps show is a result of post-Dakota structural activity, probably Laramide in age (Thadden and Zech, 1986). Proprietary seismic data northeast of the study area show that there are probable Laramide age basement faults with a wrench configuration within 30 miles of the study area.

Isopach Maps

Isopach maps of the intervals between each picked horizon in the South Lindrith field area show thickness variations that may be due to local, genetic unit thickness variations, syndepositional faulting or a combination of the two. In addition to those presented here, full sized copies of all isopach maps are on the enclosed CD-ROM.

Surface S3 is a natural division of the Dakota in the subsurface because it is an unconformity between Dakota Sequences 2 and 3. It also separates oil and gas producing zones associated with parasequences above and below. The lowest depositional sequence, Dakota Sequence 1 between surfaces K2 and S2, is not associated with oil and gas production, so it will not be discussed. Dakota Sequences 2 and 3, however, are perforated in the

Figure 5.15: Three dimensional representation of three horizons in the four township South Lindrith field area included in this study. Views are to the northwest at the elevation angles indicated. The field lies in a low behind the ridge in about the center of the surfaces. Note the exceptional surface form agreement at all levels. Surface Su is the top of the Dakota, surface IKdPS1 is in the lower part of the formation. The interval between Su and uKdPS2 is thickening eastward.

South Lindrith field area and it will be seen that production is associated with sequence-related lithology distribution. Structure, discussed later, helped localize production.

Dakota Sequence 2 - As mentioned earlier, Dakota Sequence 2 between surfaces S2 and S3, contains three parasequences that are stacked in a transgressive pattern. They will be discussed from the bottom up.

Thickness of the lowest of the three, IKdPS1, is shown in Figure 5.16. Note that most of the South Lindrith field is located southwest of a sudden change in thickness in IKdPS1. Within the field, the average thickness is about 50 feet, but northeast of the thickness change along the axis of the trend, the average is about 38 feet. The appearance on the map is that IKdPS1 was deposited on the southwest side of a northwest trending break in slope. The break in slope may be overemphasized by the computer adding closures in areas of low control, but the overall pattern is controlled by sufficient data to suggest that the slope break is real. Thickness on the northeast side of the thinner trend again increases but still averages about 10 feet thinner than within the South Lindrith field.

On the cross sections, for example line F-F' (Figure 5.5), it can be seen that the upper, less shaly part of IKdPS1 commonly displays high resistivity, eight to 10 percent porosity and some neutron gas effect. Interval IKdPS1 is perforated in many of the wells in the field. The position of this parasequence as the first significant sandstone above the S2 unconformity surface is significant: it shows a grain size and shaliness trend that developed in lower

Figure 5.16: Isopach of IKdPS1. Outline of the South Lindrith field in green. The wells northeast of the South Lindrith Field are part of the West Lindrith Field, the outlines of which extend well beyond the limits of this map. Green spots are wells with control at the named horizon. Red spots are wells with no control for the same horizon. Gray squares represent the standard one-mile section grid.

relative sea level, higher energy conditions. Regional mapping of the same isopach could reveal locations for additional Dakota production.

The isopach of IKdPS2, Figure 5.17, first appears to be very similar to that of IKdPS1, but it is not. There is a similar northwest/southeast oriented trend in the same position on the east side of the field, but in this example, it is a thick trend. Average thickness within the field is about 27 feet and average thickness in the trend is about 38 feet. Northeast of the axis of the thick trend, IKdPS2 is about the same thickness as it is in the field: 27 feet. A thick as seen here overlying a thin as seen in IKdPS1 suggests reciprocal sedimentation such as could occur during fault block movements that are syndepositional but changing in attitude with time.

The reservoir quality of IKdPS2 is lower than that of the underlying parasequence and this is reflected in its lower baseline resistivity, lower porosity and lower number of perforations.

The isopach of IKdPS3, Figure 5.18, features a slight thickening trend running northwest/southeast through the middle of the map area. In this example, there is an abrupt thinning on the west side of the South Lindrith field. This parasequence is thinner than the two below, has higher average gamma ray, lower resistivity and porosity. In some places, however, there is a three to four foot high resistivity spike at the very top of the interval that is included in the perforated interval in several wells.

Above IKdPD3, there is an interval in which gamma ray is decreasing and in which there is a bentonite marker noted on the cross sections.

Figure 5.17: Isopach of IKdPS2. Outline of the South Lindrith field in green. The wells northeast of the South Lindrith field are part of the West Lindrith Field, the outlines of which extend well beyond the limits of this map. Green spots are wells with control at the named horizon. Red spots are wells with no control for the same horizon. Gray squares represent the standard one-mile section grid.

Figure 5.18: Isopach of IKdPS3. Outline of the South Lindrieth field in green. The wells northeast of the South Lindrieth field are part of the West Lindrieth Field, the outlines of which extend well beyond the limits of this map. Green spots are wells with control at the named horizon. Red spots are wells with no control for the same horizon. Gray squares represent the standard one-mile section grid.

Nowhere does this zone show resistivity, porosity or gamma ray sufficient to be considered a hydrocarbon producing unit. Clearly, the most favorable reservoir in the lower part of the Dakota in the field area is lKdPS1, and the best zone within the parasequence is the upper 20 feet.

Dakota Sequence 3 - Surface S3 is the base of Dakota Sequence 3. From S3 to the top of the Dakota, there are as many as five identified parasequences in the study area. Parasequence uKdPS1, which lies on S3 in the eastern part of the study area, is a lowstand marine unit on outcrop. In the South Lindrith field area, it is notable in several ways.

Figure 5.19 shows that uKdPS1 is present in only one well in the South Lindrith field and that it is developed fully only to the north and east. Immediately east of South Lindrith, uKdPS1 thickens from one to 21 feet in a distance of about one-half mile. This represents a slope of a little more than one-quarter degree, but it is still the steepest gradient in the area. The one-foot contour interval on the map emphasizes the thickness change. Note that the axis of the thickest part of the trend runs northwest/southeast but takes an abrupt jog to the southwest, east of South Lindrith. It then realigns to the southeast. The contour pattern gives the southeast termination of the trend a fan appearance. There is sufficient well control to restrain the mapping algorithm, so there is a good probability that the pattern is accurate.

Interpretation of outcrop data suggested that uKdPS1 is a lowstand sandstone unit on a regressive erosion surface. On Figure 5.19 well controlled

Figure 5.19: Isopach of uKdPS1. Outline of the South Lindrith field in green. The wells northeast of the South Lindrith field are part of the West Lindrith Field, the outlines of which extend well beyond the limits of this map. Unit uKdPS1 looks very much like a channel: note thalweg and possible fan in southeast corner of map. Green spots are wells with control at the named horizon. Red spots are wells with no control for the same horizon. Gray squares represent the standard one-mile section grid.

contouring presents a picture of the deep part of a channel and, as mentioned above, a possible fan. These are characteristics that are compatible with the lowstand interpretation. Maximum relief on the channel is about 30 feet and average width of the 10 to 30 foot thick part is about 2 miles. The overall geometry suggests that uKdPS1 in the South Lindrith field area represents the distal part of a tide dominated estuary (see, for example, Reinson, 1992), a flooded valley. Its gamma ray readings in many places become higher upward as one would expect in a channel sandstone. Figure 5.20 is a color shaded representation of Figure 5.19 and it includes the entire study area in order to show the extent of the channel form of the sandstone interval. In some wells, notably in the least shaly, thickest part of the trend, resistivity and porosity increase and there is evidence of gas effect on the neutron log. Average porosity increases in the thickest part of the trend (see porosity section).

The map of uKdPS2 thickness, Figure 5.21, is unlike most of the others because it shows no clear trends. The total variation in thickness over the entire map area is only 23 feet. The thickness of this parasequence in the South Lindrith field is marginally thicker than it is in nearby areas. Nowhere in the study area does uKdPS2 display favorable reservoir characteristics.

Thickness data for uKdPS3, Figure 5.22, show the South Lindrith field on the northeast side of a northwest/southeast thickening trend in which the average thickness increases from about 15 feet to more than 40 feet on the northeast side of the field. The uppermost, least shaly part of this

Figure 5.20: Isopach of uKdPS1. Outline of the South Lindrith Field in green. The wells northeast of the South Lindrith Field are part of the West Lindrith Field, the outlines of which extend well beyond the limits of this map. Variable color shading on this map provides a suggestion that a northwest/southeast channel is present in this location.

Figure 5.21: Isopach of uKdPS2. Outline of the South Lindrith field in green. The wells northeast of the South Lindrith field are part of the West Lindrith Field, the outlines of which extend well beyond the limits of this map. Green spots are wells with control at the named horizon. Red spots are wells with no control for the same horizon. Gray squares represent the standard one-mile section grid.

Figure 5.22: Isopach of uKdPS3. Outline of the South Lindrith field in green. The wells northeast of the South Lindrith Field are part of the West Lindrith field, the outlines of which extend well beyond the limits of this map. Green spots are wells with control at the named horizon. Red spots are wells with no control for the same horizon. Gray squares represent the standard one-mile section grid.

parasequence has both high resistivity and more than five percent porosity. It is a commonly perforated zone than can be more than 15 feet thick.

The thickest part of uKdPS3, lies against the zone of abrupt thickening on the southwest side of South Lindrith. The interval gradually becomes thinner in the northeast part of the map area. There is a strong suggestion implied by this pattern: the zone of steep thickening may be related to syndepositional faulting.

On the map of uKdPS4, which is above uKdPS3, there is a similar zone of steep thickness increase that parallels the one in the underlying sandstone (Figure 5.23). It is, however, about 4.5 miles to the northeast. This is an area in which well control is sparse and the observed trend may be due to failure of the gridding and contouring algorithm, but close inspection shows that the machine-generated interpretation is reasonably accurate. Hand contouring may have smoothed out the gradient, but not by much. If the thickening is fault-related and if the fault extends through both IKdPS4 and IKdPS3, it is hard to imagine a geometry that would place the thicker sediments within the northeast footwall block of a fault dipping southwestward. If syndepositional growth faulting is involved, the faults must be wholly contained within individual sandstones and sole out to the northeast as listric faults. Isopach maps of the two intervals, Figures 5.22 and 5.23, do not show evidence of high angle throughgoing faults, so if faulting is involved, there is a maximum of about 20 feet of throw at a very low angle of less than one-quarter degree. This suggests that the thickening increase is apparently due primarily to northeastward progradation within the upper Dakota

Figure 5.23: Isopach of uKdPS4. Outline of the South Lindrith field in green. The wells northeast of the South Lindrith field are part of the West Lindrith Field, the outlines of which extend well beyond the limits of this map. Green spots are wells with control at the named horizon. Red spots are wells with no control for the same horizon. Gray squares represent the standard one-mile section grid.

sandstones. There is more on this topic under reservoir compartmentalization in the next section.

The isopach of uKdPS5, the uppermost specifically identified Dakota sandstone in this study, shows that it is present only along the northeast edge of the South Lindrith field and that it reaches maximum thickness on the east quarter of the mapped area (Figure 5.24). The thickest interval is aligned a little west of north and thins rapidly to the northeast. Steep contours bound the sandstone thick on the northeast and southwest sides suggesting that syndepositional faults helped control its deposition.

A final isopach interval is from the top of the Dakota to the top of uKdPS5 (Figure 5.25). By the time sandstones in this interval were deposited, the axis of thick sedimentation was farther to the northeast than in any of the underlying mapped units. There is, once again, a zone of abrupt thickening that is oriented north/south but slightly west of north. Only the easternmost wells in the South Lindrith field contain a very thin section of this parasequence.

In a sequence stratigraphic context, from surface S3 upward to the top of the Dakota, there is a complete depositional sequence, Dakota Sequence 3. The lowermost unit, uKdPS1 represents lowstand, and perhaps valley fill, deposits on a regressive surface of erosion. The next higher parasequence, uKdPS2, represents increasing water depth and the transgressive systems tract. From the base of uKdPS3 upward to the top of the Dakota, there is a steady shift of the zero isopach and the zone of steepest thickening to the northeast. This can be seen on the southwest/northeast oriented cross

Figure 5.24: Isopach of uKdPS5. Outline of the South Lindrith field in green. The wells northeast of the South Lindrith field are part of the West Lindrith field, the outlines of which extend well beyond the limits of this map. Lack of control in the South Lindrith Field area has resulted in the computer gridding and contouring algorithm being unrestrained in that area. Only wells on the northeast side of the field actually contain uKdPS5. Green spots are wells with control at the named horizon. Red spots are wells with no control for the same horizon. Gray squares represent the standard one-mile section grid.

Figure 5.25: Isopach of the upper surface of the Dakota to the top of uKdPS5. Outline of the South Lindrith field in green. The wells northeast of the South Lindrith field are part of the West Lindrith field, the outlines of which extend well beyond the limits of this map. Green spots are wells with control at the named horizon. Red spots are wells with no control for the same horizon. Gray squares represent the standard one-mile section grid.

sections as well. The pattern observed represents shoreline progradation and the highstand systems tract. Previous work (Franklin and Tieh, 1989) suggests that the sandstones of the uppermost Dakota are northwest/southeast trending offshore bar sands. As shown in the cross sections included in this dissertation, they do have thickness variations that could be interpreted as bar-like in section, but overall, each higher sand is a sigmoidal unit accreting northeastward on the face of the previous sandstone. They represent prograding regressive shorelines.

Porosity Maps

In an effort to identify reservoir quality, likely new reservoirs, or extensions of old ones in the Dakota, porosity maps were constructed for horizons of interest. The following method for deriving effective porosity is based on a V_{clay} calculation that uses the statistical distribution of gamma ray values within each well. The purpose of using V_{clay} is to include only reservoir quality sandstone in the calculation and to exclude shales, which tend to have high porosity values but low permeabilities

Calculating effective porosity, ϕ_e , involved several steps:

1. Calculation of V_{clay} using the gamma ray log. “Clean” sand was defined as less than 15% on the cumulative frequency curve superimposed on a gamma ray histogram. This typically corresponded to approximately 40 GR API units, but varied

according to the well. Without specific information of the types of clays in the reservoir, it is difficult to pick a correct “clean” value. The 15% figure is a working “rule of thumb” based on the idea that less than this amount of clay has little affect on the reservoir. Franklin and Tieh (1989) report that clays are important in Dakota diagenesis in the West Lindrith Field and there is little reason to believe that the situation is different in South Lindrith. “Dirty” was defined as greater than 85% on the cumulative frequency curve and this typically corresponded to about 120 GR API units, again depending upon the well.

2. Calculation of neutron/density crossplot porosity (ϕ_{nd}) in order to eliminate most of the gas effect. Most wells in the area have both logs. Those that do not typically have a density log and this was substituted for a working porosity value. Because of gas effect, neutron logs were not used by themselves as working porosity logs. Crossplot porosity is a root mean square average:

$$\phi_{ND} = ((\phi_N^2 + \phi_D^2)/2)^{1/2} \quad (5.1)$$

3. Calculation of ϕ_e as:

$$\phi_e = \phi_{ND} * (1 - V_{clay}) \quad (5.2)$$

The maps in Figures 5.26, 5.27, 5.28, 5.29 represent four horizons in the South Lindrith field area that are perforated in some wells. They were constructed by calculating feet of sandstone in each stratigraphic interval that contained more than five percent effective porosity as calculated above.

Analysis of these four porosity maps shows trends that align with isopach variations, but there is not always a correspondence between an isopach thick and greatest number of porosity-feet. Note on the porosity map of IKdPS1 (in Figure 5.30), for example, that there are two lines crossing at right angles and separating porosity ranges into quadrants of greater or less than 20 feet of porosity. The northwest/southeast trending porosity line has approximately the same alignment as the line separating isopach thicks and thins. The southwest/northeast trending line appears to run about parallel to the northwest side of the structural nose previously mentioned in the southeast part of the South Lindrith field. Unit IKdPS1 is a commonly perforated zone in the field, and northwest of the southwest/northeast trending porosity line, it appears to have greater than 50 feet of thickness of which more than 20 feet contain greater than five percent porosity.

The map of porosity-feet for unit IKdPS2 (in Figure 5.31) also has identifiable trends and they are approximately parallel to those for IKdPS1. Again, there is an area within South Lindrith field that has more than 20 feet of five percent or greater porosity, but it is confined to the center of the field. As in the previous example, the northwest/southeast trending line on the northeast side of the field separates areas in which there are more or less than 20 feet of effective porosity. The two southwest to northeast trending porosity lines through the South Lindrith field are subparallel to the trend of

Figure 5.26: Feet of porosity greater than 5% in IKdPS1. South Lindrith field outlined in green. Contours hachured on closed lows. Green spots are wells with porosity control. Red spots are wells with no control. Gray squares represent the standard one-mile section grid.

Figure 5.27: Feet of porosity greater than 5% in IKdPS2. South Lindrith field outlined in green. Contours hachured on closed lows. Green spots are wells with porosity data. Red spots are wells with no data. Gray squares represent the standard one-mile section grid.

Figure 5.28: Feet of porosity greater than 5% in uKdPS1. South Lindrith field outlined in green. Contours hachured on closed lows. Green spots are wells with porosity. Red spots are wells with no control. Gray squares represent the standard one-mile section grid.

Figure 5.29: Feet of porosity greater than 5% in uKdPS3. South Lindrith field outlined in green. Contours hachured on closed lows. Green spots are wells with porosity control. Red spots are wells with no control. Gray squares represent the standard one-mile section grid.

Figure 5.30: Fault trend analysis using structure, isopach and porosity maps for unit IkdpS1. These maps are reproduced in larger scale elsewhere in this dissertation. Trends are inferred mostly from steeper gradients in the maps. Green spots are wells with control at the named horizon. Red spots are wells with no control for the same horizon. Gray squares represent the standard one-mile section grid.

Figure 5.31: Fault trend analysis using structure, isopach and porosity maps for unit KdPS2. These maps are reproduced in larger scale elsewhere in this dissertation. Trends are inferred mostly from steeper gradients in the maps. Green spots are wells with control at the named horizon. Red spots are wells with no control for the same horizon. Gray squares represent the standard one-mile section grid.

the structural nose shown on the structure map. This unit is perforated in some wells in the field.

Figure 5.32 shows the structure, isopach and porosity maps for unit uKdPS1. Porosity trends are more difficult to pick out on this figure, but a line oriented southwest/northeast, as shown, aligns with the zero thickness line on the isopach map. The line is subparallel to the persistent structural nose on the structure map. The maps in the figure demonstrate that this unit is present only in the most northwest and southeast parts of the South Lindrith field.

The porosity map in Figure 5.33 shows two northwest/southeast oriented trends, the southwestern of which is coincident with a steepening in the isopach gradient. There is a less obvious trend at right angles to these two. At the level of uKdPS3, there is no apparent relationship between the structural nose and the trend of porosity. A few wells in the South Lindrith field produce from this interval.

The highest individually mapped sandstone in the Dakota is uKdPS5. It is a significant unit because of the agreement between its isopach (Figure 5.24), and gas production. This is illustrated and discussed later under Structural Compartmentalization.

A side value of this task was seeing the agreement between rock that was suspected to have good reservoir characteristics based on position within depositional sequences and rock that did have good reservoir characteristics. This was somewhat unexpected because conventional wisdom holds that the

Figure 5.32: Fault trend analysis using structure, isopach and porosity maps for unit UKdPS1. These maps are reproduced in larger scale elsewhere in this dissertation. Trends are inferred mostly from steeper gradients in the maps. Green spots are wells with control at the named horizon. Red spots are wells with no control for the same horizon. Gray squares represent the standard one-mile section grid.

Figure 5.33: Fault trend analysis using structure, isopach and porosity maps for unit ukdPS3. These maps are reproduced in larger scale elsewhere in this dissertation. Trends are inferred mostly from steeper gradients in the maps. Green spots are wells with control at the named horizon. Red spots are wells with no control for the same horizon. Gray squares represent the standard one-mile section grid.

Dakota of the San Juan Basin would not be productive if it were not for fractures.

Reservoir Compartmentalization

In his forward to the RMAG volume on Compartmentalized Reservoirs in the Rocky Mountains, Slatt (1998) states that "...oil and gas reservoirs are complex and often compartmentalized or segmented into discrete, isolated geologic units, sometimes with their own production characteristics." This is true in the South Lindrith field area, but it is not obvious on casual inspection.

This discussion begins a consideration of how to allocate production that is comingled from the Gallup and Dakota producing intervals. It then moves on to demonstrate possible structural and stratigraphic trapping mechanisms in the field and finishes with an analysis of possible compartmentalization. Weimer et al. (1998) recognized that compartmentalization can result from both structure and changes in sequence stratigraphic depositional units or a combination of both. A combination is working in the South Lindrith field area.

Production Comingling

There is a major problem when considering oil and gas production in the area of the South and West Lindrith fields: production is comingled from the Gallup and Dakota sandstones. According to the New Mexico Energy and

Minerals Department, the Dakota producing interval extends 400 feet below the base of the overlying Greenhorn Limestone (Franklin and Tieh, 1989). This definition includes the Graneros Shale Member of the Mancos Formation. In a like manner, the Gallup producing interval is defined as between the top of the Greenhorn Limestone and the base of the overlying Mesaverde Group. Without detailed formation test data, there is no way to ascertain specific contributions that each zone makes to total production. It is worthwhile, however, to have a general idea about the contributions made by Dakota and Gallup reservoir sandstones.

Matheny (1983) notes that the South Lindrith field discovery well, the Skelly #2 Jicarilla "D" in section 5, was completed from the Gallup for 36 barrels of oil per day (BOPD) and an unknown amount of gas. The Getty #3 Jicarilla "D", also in section 5, was perforated in the Gallup, Greenhorn and Dakota, yielding 2 BOPD from the Gallup and 50 thousand cubic feet of natural gas per day (MCFPD). On this basis, he attributes gas production to the Dakota and oil and gas production to the Gallup. Because many of the wells in the Dakota of the South Lindrith field show reduced neutron porosity while density porosity is increasing, the working assumption is that Dakota production is predominantly gas and Gallup production is predominantly oil.

The literature almost casually speaks of the Dakota source lying in the Mancos Shale. In this dissertation, it has been shown that what have previously been called tongues of the Mancos Shale are actually the shaly lower parts of Dakota parasequences that are becoming cleaner upward. The important point is that the shale to sandstone succession is all one genetic unit, it is not an interfingering of two discrete systems. A dark gray/black

shale sample from Highway 84 (unit 26) analyzed by Core Laboratories for total organic carbon (TOC) content contained 1.65% TOC. This is within the range for gas production and in the low end of the range for oil production, based strictly on TOC and disregarding original type of organic matter (Hunt, 1996, p. 487 - 491). The TOC result suggests that if the dark gray/black shales in the Dakota are source rocks, gas will be the most likely generated product. Northwest of the study area, the Basin Dakota Field is a gas field.

One well in the South Lindrith field produces only from the Gallup: the William Martin Associates #23 Martin Whittaker in section 7 of T23N, R4W. It is an oil well. This, again, suggests that the Dakota is primarily a gas producing zone.

Analysis of production data shows that as of December, 1998, every Dakota well in the nine township area centered on Township 23 North, Range 4 West, had reached or was very close to the upper, flat part of its cumulative production curve. Therefore, the cumulative totals for the study area are at or very near estimated ultimate reserves (EUR). Figures 5-34 and 5.35 show the oil and gas cumulative production and may be considered maps of EUR for the comingled producing zones.

Figure 5.34: Estimated ultimate oil production in the South Lindrith field area. Field outline in black. The fault pattern in northeast corner of map is from the West Lindrith field (Franklin and Tieh, 1989). The structure contours on Franklin and Tieh's map are on the Greenhorn Limestone, which is stratigraphically above the Dakota. The fault pattern in the South Lindrith field is inferred from contour patterns and gradients and closely matches that in the West Lindrith Field. Green spots are wells with oil production data. Red spots are wells with no data. Gray squares represent the standard one-mile section grid.

Figure 5.35: Estimated ultimate gas production in the South Lindrith field area. Field outline in green. Possible production controlling faults are indicated with lightweight black lines. See Figure 5-34 for a similar pattern in the West Lindrith field in the northeast part of this map. Green spots are wells with gas production data. Red spots are wells with no data. Gray squares represent the standard one-mile section grid.

Oil Production

The average well in South Lindrith field produces 2,330 barrels of oil per year over its lifetime, or just under 6.5 barrels per day. As can be seen on Figure 5.34, oil production is highest in the southeast half of the South Lindrith field. A production high in section 11 is indicated between two northeast trending gray lines on the map. There may be fault control localizing the production. Faults in the same direction as the lines that delineate oil production trends in the South Lindrith field are documented in the West Lindrith field about three miles to the northeast (Figure 5.34). In the South Lindrith field, further evidence for a similar fault pattern can be inferred from the porosity, structure and isopach maps (Figures 5.30, 5.31, 5.32 and 5.33).

Oil contributions from well to well show considerable production heterogeneity. The well in the southeast quarter of the northwest quarter of section 11 has produced in excess of 72,000 barrels and per well averages in this part of the South Lindrith field are greater than 50,000 barrels. In the northwest part of the field, per well averages are about 25,000 barrels.

The source of the oil is suspected to be the Gallup producing interval, as mentioned earlier. However, well log curves (e.g. cross section F-F', Figure 5.5) and completion card information suggest that oil production is also possible from Dakota units lKdPS1, lKsPS2, and uKdPS3.

Gas Production

The average well in the South Lindrith field produces 5.34 million cubic feet of gas per year over its lifetime, or about 14.6 thousand cubic feet per day.

Figure 5.35 is a map showing estimated ultimate gas production in the study area. It has a contour interval of 250,000 cubic feet (MCF). It is clear on this map that the best area gas production is in the West Lindrith field northeast of South Lindrith. Some wells along the axis of the highest production have produced more than a billion cubic feet over their lifetimes.

Figure 5.36 suggests that there is agreement between the thick part of the isopach of unit uKdPS1, the valley filling sandstone above surface S3, and highest gas production totals. The crossplot in Figure 5.37 shows that, unfortunately, there is no demonstrable relationship between thickness of uKdPD1 and gas production.

Figure 5.37 presents several graphs plotting unit thickness against estimated ultimate gas reserves. The figure shows that there may be a correlation between gas production and thickness only in unit uKdPS5. This is the uppermost mapped parasequence in the Dakota, and it thickens northeast of the South Lindrith field, reaching its greatest thickness in the maximum gas producing trend. Figure 5.38 is an overlay of gas production on the isopach of uKdPS5 that provides visual support for uKdPS5 providing gas to the combined Gallup/Dakota production. The charts in Figure 5.37 show that there is no gas production attributable to porosity in other

Figure 5.36: Map overlaying estimated ultimate gas production (cumulative production) on an isopach of unit uKdPS1 in the subsurface study area. Note how the trend of highest gas production aligns in part with the thickest sandstone. Green spots are wells with control. Red spots are wells with no control. Gray squares represent the standard one-mile section grid.

Figure 5.37: Thicknesses of six Dakota parasequences plotted against estimated ultimate gas production (cumulative production). The only unit that shows an identifiable trend is uKdPS5. Sandstone uKdPS5 thickens and produces northeast of the South Lindrith field. Comingling of Dakota and Gallup production may hide other trends present in these data. Green data points are in Dakota Sequence 2. Red data points are in Dakota Sequence 3.

Figure 5.38: Map overlaying estimated ultimate gas production (cumulative production) on the isopach of uKdPS5. The portion of uKdPS5 that appears to underlie the South Lindrith field is a contouring and gridding artifact resulting from lack of control in that area. A chart in Figure 5-37 shows that there is a moderate correlation between gas production and the thickness of uKdPS5 and this map adds visual confirmation that there is a relationship. Unit uKdPS5 is the highest Dakota parasequence and is the only one in which there is any indication of the production the Dakota contributes to the combined Gallup/Dakota total. Two possible inferred faults are shown. The one on the northeast side of the producing trend is most likely a zone of depositional parasequence thinning rather than a structural break. Green spots are wells with control. Red spots are wells with no control. Gray squares represent the standard one-mile section grid.

parasequences in Dakota Sequences 2 and 3. Gas production from those parasequences may be from fractures, rather than matrix porosity, in the Dakota.

Unit uKdPS1 may not show a thickness to production correlation in Figure 5.37, but it consistently has neutron/density crossover and high resistivity. Figure 5.39 is a well log from the gas producing trend illustrating crossover in both uKdPS5 and uKdPS1. The conclusion is that uKdPS5 *does* contribute to Dakota gas production and that uKdPS1 *may* contribute. It is important to note on Figure 5.35 that gas production figures in the South Lindrith field are considerably lower than those in the high production trend to the northeast.

Production figures strongly suggest that even though production is comingled from the Gallup and Dakota formations, gas production in the field is minor. Within the South Lindrith field outline shown in green on the various maps, it is likely that commercial production is oil from the Gallup formation.

From the distribution of production, it is clear that there is reservoir heterogeneity in the Dakota. There is little question that stratigraphy contributes a portion, and it will be seen that it is reasonable to expect a considerable structural component.

Figure 5.39: Log from the gas producing trend in Figure 5-35 showing gas indication from neutron/density curve crossover in uKdPS5 (#1) and uKdPS1 (#2).

Stratigraphic Compartmentalization

The Dakota of the study area includes three depositional sequences, the upper two of which contain mappable sandstones related to lowstand, transgressive and relative highstand events. Isopach maps (Figures 5.22, 5.23, 5.24, 5.25) of the highstand, progradational sandstones in the upper part of Dakota Sequence 3 show progressive northeast migration of the paleoshoreline and suggest that individual sandstone units represent potential stratigraphic compartments (Figure 5.40). The following discussion is confined to those Dakota sandstone units from which there is oil or gas production in the study area.

Figure 5.40: Diagrammatic cross section of a prograding shoreline in which the shaly facies on the basinward side of the sandy shoreface can separate the potential sandstone reservoirs into two stratigraphic compartments. This diagram has very high vertical exaggeration. On depositional slopes of a fraction of a degree, the sandstones will appear virtually horizontal and will be separated by shale sections that may be sealing.

Dakota Sequence 2 - Dakota Sequence 2 begins at surface S2 and extends upward to surface S3. The outcrop parasequence stacking patterns indicate that it was a time interval dominated by a relative rise in sea level and shoreline transgression. At times, there were short term, high frequency stillstands or relative sea level drops evidenced by shoreface progradation.

During a transgression, a transgressive surface of erosion (TSE) is formed. Intermittent high frequency stillstands will result in the erosion of a low relief, concave upward surface cut at fair weather wave base that will fill with shoreface sands (Figure 5.41, Pemberton and MacEachern, 1995). Renewed transgression results in preservation of part of the shoreface package and deposition of a subsequent shoreface above. Each sand package, from wave cut surface upward has the potential to form a stratigraphic compartment. Whether or not it does is related to its reservoir quality and the nature of any overlying, potentially sealing, shale section.

The lowest parasequence in Dakota Sequence 2, 1KdPS1, rests on an unconformity surface and is a sandstone with high porosity and resistivity in its uppermost “clean” part. It is bounded above by high gamma ray readings that on outcrop correlate to dark gray to black shales that rest on a flooding surface. The isopach map of the interval (Figure 5.16) shows that 1KdPS1 thins rapidly to the east, thus within the South Lindrith field, it is a candidate for a stratigraphic compartment. The contributing factors to compartmentalization are the presence of porous sandstone, reduced clay and an overlying shale seal.

Figure 5.41: Conceptual model of a transgressive shoreface system from Pemberton and MacEachern (1995). The lower sequence boundary (SB) is a regressive erosional surface. During relative stillstands, a low relief, concave upward erosional surface is cut by a high energy flooding surface (HE FS) upon which is deposited a stillstand shoreface that is part of the transgressive systems tract (TST). The authors recognize that each HE FS extends basinward to become a correlative low energy flooding surface (LE FS). The HE FS forms at or above fair weather wave base and the LE FS forms below. As transgression resumes, the HE FS can truncate the top of a stillstand shoreface and remove remnants of the backstepping shoreface seen on the left in this drawing. Modified from Pemberton and MacEachern (1995).

Parasequence lKdPS2 *thickens* to the northeast along a northwest/southeast oriented line that is coincident with the line of *thinning* in lKdPS1. Martinsen (1998) shows that in the Almond Formation of Wyoming, small-scale syndepositional, dip-slip faulting can change direction from faulting event to faulting event. If this is the cause of eastward thinning in lKdPS1 and eastward thickening in lKdPS2 in the South Lindrith field area, then we see an instance of reciprocal sedimentation in which the thickness of the two parasequences combined would change little and yet each parasequence is a stratigraphic compartment separated vertically by a marine shale and horizontally by a fault (Figure 5.42). If the fault is a sealing fault, one can imagine a situation in which it appears that an apparent single reservoir contains water over oil, when there are actually two compartments, only the lower of which contains hydrocarbons. This makes it imperative in studies of compartmentalization to define and isopach each sequence stratigraphic unit separately.

Dakota Sequence 3 - Sandstone uKdPS1 rests on surface S3 and is related to a relative sea level lowstand. It is separated from sandstones below by an erosional surface and a marine shale section (lKdPS1 represents the LST of Pemberton and MacEachern, 1995, as illustrated in Figure 5.41). Much detail about this sandstone unit is provided in Chapters 3 and 4. Its isopach indicates that it is a package bounded by a zone of thinning, a pinchout, on the southwest. Log characteristics (Figure 5.39) show that uKdPS1 contains gas and may be a sequence-related, stratigraphic reservoir compartment.

Figure 5.42: If a fault moves while sedimentation is in progress, it results in thickening on one side, as at Time 1 above. If it subsequently changes attitude, as at Time 2 above, it can result in later depositional units thickening on the opposite side. The total thickness for the two depositional units can be nearly the same as at A and B. This may explain thickness changes in lKdPS1 and lKdPS2 between wells 6 and 7 on Figure 5.2 and between wells 3 and 4 on Figure 5.5a. Inclined arrows represent gamma ray trend.

It was noted earlier that several of the sandstone parasequences in the upper part of the Dakota contain resistivity spikes in their uppermost parts. The spikes are commonly associated with low gamma ray and high porosity values. A calculation using the Archie equations (Asquith, 1982) and the previously derived effective porosity shows that the spike zones have low water saturations and represent hydrocarbons. Good examples of the resistivity spikes are present in unit uKdPS3 on dip oriented cross section 14-14' (Figure 5.2). The spikes develop northeastward then abruptly stop in well 8. Northeast of well 8, uKdPS3 thins, but the overlying parasequences thicken. In well 9, a resistivity spike develops at the top of uKdPS4. Based on outcrop descriptions, the least shaly sandstones are in the lower foreshore/upper shoreface, so as shoreline progradation proceeded, stepwise parasequences each provided petroleum trapping conditions. The seal between reservoirs was a shaly interval shown in the subsurface by increased gamma ray count and in outcrop by the presence of dark gray to black shales and bentonites. The pattern continues upward through uKdPS5 and, presumably, eastward to the limit of shoreface progradation.

The parasequences are prograding northeastward toward the present-day deepest part of the San Juan Basin (Figure 5.43 and previous structure and isopach maps) meaning that the shale seals are on the updip edges of individual depositional units. Structure clearly plays a part in hydrocarbon trapping.

Figure 5-43: View into a 3D volume representing the South Lindrith Field area. Note that north and south are intentionally reversed in this view in order to help visualization. The ceiling plot on the left gives orientation. The contact between the blue and green zones is the approximate position of surface S3, so the blue horizons represent the northeastward thickening parasequences in Dakota Sequence 3. A is the position of the South Lindrith field, B labels the northeastward thickening parasequences and C shows the locations of possible faults. The ends of the volume slices at D show artifacts resulting from poor control in that area. They are not faults. The blue parasequences are extracted from the 3D volume space and presented at the right.

Structural Compartmentalization

Each of the sandstone units mentioned above contains a sequence related reservoir compartment, but there is evidence in the structure maps that to some extent structural movement helped control the specific compartment shapes.

The stratigraphic cross sections used in this study show changes in the Dakota parasequences and erosional surfaces that could be judged sufficient to explain the production in the South and West Lindrith fields. Questions, however, remain. Specifically, is there a structural component in the observed stepwise east/northeastward progradation in the upper parasequences? As demonstrated in many previous pages, changes in relative sea level were a significant contributing factor, but it appears that the resulting depositional units were enhanced by syndepositional structural movements. Because of the lack of high resolution seismic information in the study area, most of the structural contribution must be inferred from maps.

Regional Structure - The present San Juan Basin is a Laramide feature. During Dakota time, the area was open to the east into the Western Interior Cretaceous Seaway. Nevertheless, basement structural elements such as the Nacimiento fault zone had been active for several tens of millions of years and continued to exert an influence. According to Woodward and Callendar (1977), faulting in the study area is related to right lateral movement along the Nacimiento fault zone, which bounds the west side of the Nacimiento

Uplift (Figure 3.2), southeast of the study area. Stevenson (1983) places the study area in the path of a regional northwest/southeast trending Precambrian basement structural element called the Farmington Segment of the Four Corners Lineament. Taylor and Huffman (1998) show a rectangular pattern of northwest/southeast, southwest/northeast trending basement faults in the study area (Figure 5.44). Note on Figure 5.44 two additional basement faults added from Burlington Resources proprietary seismic data that have a slightly different orientation. On the seismic lines these last two faults appear to affect sedimentation up through the Jurassic, perhaps into the Dakota, so they represent pre-Laramide or earlier basement fault movement. Thadden and Zech (1984) show present day structure on the base of the Dakota dips to the northeast at about 5 degrees (Figure 5.44). This is higher than the present study recognizes: in most of the study area, the average dip northeast into the basin is about 2 degrees except along sharp flexure zones where it can reach as high as 4 to 5 degrees. All these sources show that there is a rectilinear structural grain in the area and that it is basement related. As noted earlier, structure maps at all levels in the Dakota are remarkably similar, so the structural pattern displayed is most likely post Dakota, probably Laramide. However, the Laramide structural pattern may be an overprint based, in part, on earlier basement block movement.

Dakota Structural Compartments - Structural compartments are commonly defined using formation specific production data such as pressure tests, produced fluid analyses and gas to oil ratios. Most of these data have never been collected , or made public, in the study area and comingling would seriously limit their usefulness if they had been. The previous section on oil

Figure 5.44: San Juan Basin basement fault map of Taylor and Huffman (1998) overlaid on the Dakota structure map of Thadden and Zech (1984). Contours on the Dakota are at 500-foot intervals and the 0, or sea level, contour skirts the south edge of the South Lindrith field. Regional dip is to the northeast. A black, dashed line on the right marks the approximate position of the Dakota outcrop. Basements faults are in red and most were interpreted from seismic data. Two short faults shown in black in the north part of the map were interpreted from proprietary seismic data for the present study and are not part of Taylor and Huffman's work. The Nacimiento uplift is in the southeast corner of the map and is bounded on its west side by a thrust fault shown in red. Disagreement in the position of the township grid lines results from overlaying two maps produced on different bases.

and gas production in the South Lindrith field shows possible relationships between production and the thickness of only one Dakota parasequence, uKdPS5.

There are at least two kinds of structural involvement that can compartmentalize reservoirs: predepositional to syndepositional influence on the formation of stratigraphic reservoirs (e.g. Weimer et al., 1998, Martinsen, 1998) and post depositional faulting that can isolate blocks within the same stratigraphic unit (e.g. Warner, 1998). Both mechanisms apply to the study area. Predepositional to syndepositional structural enhancement can be inferred from contour patterns and sandstone distribution maps. Post depositional compartmentalization can be approximated using estimated ultimate production maps in conjunction with structure maps and cross sections. The similarity of the structure maps at all levels in the Dakota suggests that the present day structure was developed after the Dakota was deposited. It may be possible, therefore, to find structurally bounded compartments that control the combined production.

The isopach of uKdPS1 (Figures 5.19) resembles a channel deposited on erosional surface S3. Previous maps (Figure 5.32) strongly suggest that there are faults influencing the position of the channel. Figure 5.45 shows the uKdPS1 isopach with possible immediately predepositional to syndepositional faults that can be inferred from the contour pattern. This kind of relationship is very similar to that portrayed for the valley filling Horsetooth Member of the Muddy Sandstone in the Wattenberg Field north of Denver, Colorado (Weimer and Sonnenberg, 1982). The valley fill deposits form a stratigraphic compartment that was structurally influenced at the

Figure 5.45: Isopach map of unit uKdPS1 showing the possible fault pattern at the time of deposition. This type of control over the formation of a valley is similar to that described by Weimer and Sonnenberg (1982) in the Wattenberg Field north of Denver, Colorado. Outline of the South Lindrith field in Green. Location of the inferred thalweg in blue. Green spots are wells with control at the named horizon. Red spots are wells with no control for the same horizon. Gray squares represent the standard one-mile section grid.

time of deposition. Unfortunately, there are no production data available that are specific to uKdPS1, so it is only possible to infer structural involvement. The chart comparing thickness, which may be structurally influenced, to gas production in Figure 5.37 does not show a correlation.

The inferred fault on the southeast side of the South Lindrith field is present on all structure maps. Earlier, it was noted that a difference in oil production volumes exists on either side of a line oriented in the same direction. This gives further credence to the idea that faulting has helped form reservoir compartments in the Dakota. The faults shown on Figure 5.45 are based strictly on interpretation from the contours. They almost match but are rotated clockwise from the trend of a pair of faults mapped in the same township by Taylor and Huffman (1998) and shown in Figure 5.44.

Post-Dakota structural events also could lead to structural compartmentalization with vertical offsets measured in tens of feet and offset at all stratigraphic levels. Well 10 on structure cross section F-F' (figure 5.7) shows such offset above surface S3. On the K2 surface, Well 10 is 20 feet higher than Well 9. At the top of the Dakota, the upper surface is about 5 feet higher than in Well 9. The difference in offsets shows that even though the fault affects the entire Dakota section, there was syndepositional movement as well as possible later movement. This same kind of relationship can be seen between Wells 1 and 2 on cross section 8-8' (CD-ROM). When the offset increases with depth, it is possible that growth faulting (Weimer and Davis, 1977) or recurrent syndepositional faulting (Martinsen, 1998) is involved. Note on Figures 5.7 through 5.11 that much of the apparent movement seen on the structural cross sections is because the well spacing on the sections is

uniform and the well spacing in the field is not. For this reason, and because there is no seismic data available for the study area, the best confirmation of structural movement comes from the structure and isopach maps.

Structure maps represent present day structure. Isopach maps reflect changes in thickness related to original deposition plus any compactional changes that have happened with time. Considering the shaliness of the Dakota section in the San Juan Basin, compaction since the late Cretaceous may be significant, but it is not taken into account here. As noted above, the isopach maps contain zones of steep thickening that may be related to syndepositional faulting. A good example of this is found in the upper Dakota sandstone parasequences.

The isopach map of uKdPS3 (Figure 5.22) shows a northwest to southeast oriented zone of rapid thickening on the southwest side of the South Lindrith field and then gradual thinning to the northeast. Figure 5.46 is a diagrammatic representation of how this could have come about with either a listric normal growth fault or in a half graben environment. In situation 1, the isopach between formation tops stays the same, but an isopach of an included sandstone is thickest near the fault. Furthermore, it is possible that some gamma ray logs may show a high reading in a thin zone where the fault cuts through. This could be accompanied by high resistivity if the fault plane is compacted and has no porosity. The half graben, situation 2, results in the same thickening of a sandstone body near the fault, but it also increases the isopach between markers such as the tops of parasequences as shown in the figure. Because the vertical spacing between marker beds in the South Lindrith field area is only a few tens of feet at

Figure 5.46: Two possible mechanisms that lead to abrupt formation thickening and gradual thinning such as seen in the isopach map of unit uKdPS1 and others.

most, there is a problem with having room for a listric fault and then with a triggering mechanism for fault movement because of the extremely low gradient. Because there are differential offsets visible between several of the field area wells, the idea of a half or whole horst/graben model is much more appealing.

The isopach map of uKdPS4 (Figure 5.23) shows the same pattern as within uKdPS3, but shifted to the northeast about 4.5 miles. The next higher

map, that of uKdPS5 (Figure 5.24), is a special case that is discussed below. Finally, the isopach representing the thickness variation from the top of the uppermost sandstone to the top of uKdPS5 (Figure 5.25) shows a similarly oriented thickening zone moved to the northeast corner of the map. It is possible that each of these thickening episodes is associated with a half graben fault, but that would require northeast migrating, stepwise movement. It is not impossible, but it seems improbable.

Parasequence uKdPS5 is unlike the others because it is thickest in a northwest/southeast oriented trend that is bounded by zones of steep contours on both sides. The steep contour gradients can be interpreted as a pair of faults that define a full graben (Figure 5.47). This would require, however, that the northeastern fault have a direction of movement not seen at any other level in Dakota Sequence 3: down to the southwest. Therefore, it is more likely that the southwest fault bounds a half graben, as illustrated in Figure 5.46, and the zone of steep contours on the northeast side is due to depositional thinning.

The faults in Figure 5.47 are parallel to a trend in the same direction shown on Figure 5.34 in the West Lindrith field. However, because most of the northwest trending faults are offset by a northeast trending fault set in that illustration, the northwest set is older. Both sets of faults are apparently basement related, as shown in Figure 5.44. The offset fault relationships suggest that the two directions may show two different periods of activity.

Thickening of the upper Dakota parasequences to the northeast has been shown on the cross sections, maps and 3D illustrations. If the

Figure 5.47: Isopach map of uKdPS5 with locations of bounding faults inferred from zones of steep contours on either side of the isopach thick. Some of the contours extending into the South Lindrith field area are a gridding and contouring artifact created by lack of control in that area. Compare to Figure 5-38 to see how gas production aligns with the thick, and to Figure 5-37 to see a crossplot of thickness versus production that shows a correlation. Green spots are wells with control at the named horizon. Red spots are wells with no control for the same horizon. Gray squares represent the standard one-mile section grid.

thickening of uKdPS5 to the northeast is related to progradational shoreface accretion and is localized and enhanced by faulting, then both stratigraphy and structure play a role in positioning the sandstone. The defining fault on the southwest side is syndepositional and not visible on present day structure maps.

Compare Figure 5.47 to Figure 5.35 to see two inferred fault patterns, one from production data and one from isopach data. Figure 5.38 shows that there is a an apparent relationship between uKdPS5 thickness and gas production, and the crossplot of this interval in Figure 5.37 shows that there is correlation between the two. The well log in Figure 5.39 shows that uKdPS5 is capable of gas production. Because of the positive correlation of thickness to gas production and confirmation from well logs that the zone is capable of gas production, it is concluded that production from uKdPS5 is from a structurally and stratigraphically controlled compartment. Figure 5.48 illustrates these observations. This is the only demonstrable production compartment in the study area. Others may exist, and they are strongly suggested by wells logs, depositional patterns and structure, but they can not be confirmed with the data available.

In all likelihood, therefore, a combination of structural movement combined with depositional progradation due to relative sea level change is the cause of the compartmentalization seen today in the study area. It is also possible, but difficult to quantify, that the zones of rapid thickness change are due completely to post-depositional compaction. Regardless of the underlying mechanism, each parasequence is suspected to be a reservoir compartment bounded on its updip side by rapid thinning. In the oil industry,

this type of relationship is called an “up-dip pinchout” and it is a common exploration target.

The triggering mechanism for syndepositional faulting could have been recurrent movement on basement fault blocks of the kind noted by Weimer (1980) in other parts of the Rockies. The fault orientations in the field are the same as postulated for the basement and there is evidence on seismic sections (Burlington Resources, proprietary) of recurrent movement. Furthermore, structure maps (for example, Figures 5.30 through 5.33) contain steep dip zones that align with a documented fault pattern in the West Lindrith field (Figure 5.34). For all these reasons, it is reasonable to expect a structural contribution to reservoir compartmentalization that enhances that due to sequence controlled lithologic variations.

Predicting Additional Compartments

The best way to find reservoir compartments is through a detailed integrated study involving, among other things, pressure tests in all wells. Comingled production and lack of hard engineering data have made it very difficult to be precise about internal South Lindrith field area production characteristics. The geology, however, suggests that additional production may be found along the trends of sequence stratigraphic units such as uKdPS5 that show some structural enhancement.

It is well known that there are basement faults in the study area and that they are common (e.g., Taylor and Huffman, 1998) . However, recent

seismic data suggest that the basement fault density is higher than presently mapped. The predictive tool mentioned in Chapter 1 is the ability to map Dakota sequences and their internal components. Where suitable sequence controlled lithologies intersect structural trends, there is a likelihood that additional Dakota producing compartments will be found.

Predicting additional Dakota compartments in the greater South Lindrith field area will involve several steps:

1. Correlate and map unconformities K2, S2 and S3.
2. Correlate and map the structure and thickness of parasequences and systems tracts between the unconformities.
3. Interpret syndepositional faults from steep gradient zones on isopach maps of the units mapped in step 2.
4. Map known and seismically interpreted basement faults that extend up through the Dakota section.
5. Overlay fault patterns on maps of the sequence controlled depositional units.
6. Examine the parasequence stacking pattern. If parasequences are stacked such that the shallier, lower parts of cleaning-upward parasequences overlies reservoir quality sandstones, there can be a vertical seal.

6. Candidates for compartments will be sandstones that show sequence related thickening bounded by faults that produce horizontal flow barriers and by overlying shales that produce vertical flow barriers.

Within producing field areas, comparing EUR or time-normalized production to the candidate compartments mapped in steps one through six may reveal sites for additional development wells. Between producing areas, the same approach provides a tool that may help identify potential new production.

CHAPTER 6

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

This study was undertaken to develop the sequence stratigraphy of the Dakota Formation in part of the eastern San Juan Basin, New Mexico, and then to see whether reservoir quality lithologies in depositional sequences could be related to structure and reservoir compartmentalization in the South Lindrith oil and gas field area. The goal was to develop a predictive tool.

Two sections were measured and described in the field: on the west side of US Highway 84, about 9 miles south of Cebolla, New Mexico, and near the spillway at Heron Dam, about 22 miles to the north. Four other outcrops were visited, but not described in detail. Discussions relating to all six outcrop areas are included in Appendix A.

The Dakota lies on the regional K2 unconformity. The unconformity represents a time interval of about seven million years in the study area. The Dakota is about 1.25 million years younger than its lithologic equivalents in the Raton Basin and about 2.5 million years younger than those in the Denver-Julesburg basin. Deposition of the entire Dakota interval took approximately two million years, making it a third order sequence.

Detailed analysis of the two main outcrop sections reveals that the Dakota contains three depositional sequences that record an overall transgressive event (Figure 4.6) with fourth and higher order fluctuations:

Dakota Sequence 1 is bounded below by the regional K2 unconformity and at the top by the S2 surface of this dissertation. The K2 unconformity separates the Early Cretaceous Burro Canyon Formation from the overlying Late Cretaceous Dakota Formation. The sediments within Dakota Sequence 1 are mostly tide-dominated shallow water sandstones and shales overlain by deeper water transgressive shales in the study area. Sequence 1 sediments are commonly called the Encinal Canyon Member of the Dakota.

Dakota Sequence 2 is bounded below by the S2 surface and above by the S3 surface. The S2 surface is a combination lowstand surface of erosion and transgressive surface of erosion underlain by kaolinitic sandstones (Appendix D). It is correlatable between the Highway 84 and Heron Dam outcrops. Sequence 2 records a transgressive interval that contains a transgressive shale commonly called the Oak Canyon Shale Member of the Dakota and a series of overlying shoreface successions that are commonly called the Upper and Lower Cubero Sandstone Tongues of the Dakota Formation and Clay Mesa Shale Tongue of the Mancos Shale. A bentonite sample from the Oak Canyon Shale interval yielded an age data of 93.12 ± 0.5 Ma (Appendix E), showing that the Dakota on the east side of the San Juan Basin is latest Cenomanian to earliest Turonian in age, making it younger than

most of the lithostratigraphically equivalent Dakota rocks to the north and east.

Dakota Sequence 3 is the section above the S3 surface up to the contact with the overlying Graneros Shale. The S3 surface is a regressive surface of erosion (in the sense of Pemberton and MacEachern, 1995) that is overlain by shallow marine sandstones that comprise a lowstand systems tract. The lowstand sandstone is commonly called the Paguate Sandstone Tongue of the Dakota Formation. The overlying transgressive systems tract contains a parasequence set that includes two or more shorefaces. The interval is commonly called the Whitewater Arroyo Shale Tongue of the Mancos Shale. The highstand systems tract includes a series of eastward prograding highstand shorefaces that are commonly called the Twowells Sandstone Tongue of the Dakota Formation. The upper surface, the contact with the overlying Graneros Shale, is a regional flooding surface that may be a transgressive surface of erosion. Variations in thickness of the Graneros Shale and truncations in the Dakota suggest that the upper surface is an unconformity as well.

The outcrop correlations show that each shale/sandstone couplet in the Dakota is a depositional parasequence that comprises one continuous depositional event. Previous correlations have shown the shaly intervals to be tongues of the Mancos Shale and sandy intervals to be tongues of the Dakota Sandstone. In the lithostratigraphic sense, depositional “tongues” imply two, separate depositional systems that interfinger. In the sequence stratigraphic sense, thicker sections near shore correlate to time equivalent

thinner sections, condensed sections, offshore. In both approaches, the controlling factor is fluctuation of relative sea level. The sequence stratigraphic approach, however, shows that the lower part of the Mancos Shale is time equivalent to the Dakota Sandstone and part of the same depositional system.

Twenty seven thin sections cut from samples at both Highway 84 and Heron Dam show that the average Dakota sandstone is fine to very fine grained with subangular to subrounded grains (Appendix B). The composition is mostly quartz with very minor feldspar, but there is substantial clay matrix in some sections. Silica cement predominates, but there is a small amount of calcite and hematite in some samples. There is a very small percentage of euhedral quartz overgrowths and a larger percentage of old quartz overgrowths within rounded grains. Dakota sandstones are interpreted, therefore, as second cycle or older.

The South Lindrith field, discovered in 1958, is located in Township 23 North, Range 4 West, about 44 miles southwest of the outcrop sections. Production in the field consists of both oil and gas and is comingled from the Gallup and Dakota Formations. Several lines of evidence suggest that the Dakota contributes mostly gas to the total production, and that the majority of the gas comes from Dakota Sequence 3, specifically parasequences uKdPS5 and uKdPS1. In lithostratigraphic terminology, these are the Twowells and Paguate Sandstone Tongues of the Dakota Formation, respectively (Figure 4.6 and the various cross sections).

Gamma ray profiles of the Highway 84 and Heron Dam sections were correlated to logs in the South Lindrith field and the observations made on outcrop were applied to the subsurface. Two cored wells near the field (Appendix F) show that the Dakota lithologies in the subsurface are virtually identical to those on outcrop.

Structure and stratigraphy in the South Lindrith field, and adjacent areas to the northeast in the West Lindrith Field, were mapped and analyzed using 214 digital well logs and TerraStation II software. The literature provided information on basement faults and on the fault pattern at Dakota level in the West Lindrith Field.

The result of computer analysis of the South Lindrith field is that the Dakota sequence stratigraphic framework established on outcrop is confirmed in the subsurface. Each of the primary surfaces, K2, S2 and S3 can be correlated to the outcrop gamma ray profiles over a distance greater than 42 miles. Surface S3 in the outcrop is subtle. In the subsurface, it is clearly a lowstand surface, or regressive surface of erosion, upon which were deposited reservoir quality sandstones (parasequence uKdPS1) that may account for some of the gas production in the Dakota section.

Structure maps were made using a contour interval of 10 feet. Isopach maps were made using contour intervals of 1 or 2 feet. The contour intervals made it possible to see zones of steep dip on the structure maps and zones of high gradient on isopach maps that align with regional structure trends. This helped identify the positions of both syndepositional faults and basement related faults that had postdepositional movement. The predominant trends

are northwest to southeast and southwest to northeast (Figure 5.34), and the intersections create blocks that can bound structural compartments. Faults are, therefore, mappable from well log information. They are important in creating reservoir compartments and in localizing Dakota production.

The trends of shore-parallel, sequence-related shoreline sandstones can be mapped to show the trends of higher porosity. On a regional basis, maps of each separate parasequence would tend to map out as more or less linear bands with local variations. On the South Lindrith field scale, shown in the various isopach maps, there are also mappable parasequences that play a role in stratigraphic compartmentalization, particularly in the progradational, highstand systems tract of Dakota Sequence 3.

Between unconformities K2 and S3, the shoreline trend was oriented mostly northeast to southwest and the resulting reservoir orientation is in a band trending in the same direction. Later, post S3, the shoreline became more north/south to slightly northwest/southeast oriented during transgression. Reservoir trends for the upper Dakota sandstones are aligned in that direction. This is confirmed in many regional studies in the area.

It is clear that the combination of structure and sequence related depositional units played an important role in localizing at least one Dakota reservoir in the study area (uKdPS5). Within the subsurface project area, uKdPS5 increases from zero thickness on the west southwest to more than 50 feet to the east northeast. Highstand progradational shoreface accretion thickened the unit over a very short distance to the northeast. Bounding syndepositional faults on its southwest and northeast sides helped localize

the northwest/southeast trending high-volume production area for this sandstone. The bounding fault or faults match regional trends, but they are not seen on present day structure maps and must be picked using isopach data. There is evidence that possible recurrent syndepositional faulting and Laramide post-depositional faulting may have compartmentalized other Dakota reservoir sandstones in the South Lindrith field as well.

An unexpected result of this study is that parasequence uKdPS5 produces from mappable porosity. In many places in the literature, the belief is stated that the Dakota could not produce unless it were fractured. That may be true in other areas, but it is not true in the South Lindrith field.

In the past, northwest/southeast aligned sandstone trends in the Dakota of the San Juan basin have been mapped as shore parallel, linear offshore bars that created simple stratigraphic traps. This study suggests that they are actually accreting shoreface wedges that are sigmoidal in cross section and that built to the east and northeast during relative sea level stillstands.

This study shows that the geologic reasons for Dakota production are much more complex than previously recognized. Defining structure is not enough to locate Dakota reservoirs because structural highs and structural closures may not correspond to the location of reservoir quality sands. The sequence stratigraphic relationships become the predictive tool mentioned in the goals for this dissertation. Only when the depositional framework is established and combined with structure, will additional Dakota production be found. Future exploration should first concentrate on defining sequence

stratigraphic depositional trends using very detailed well log correlation. This should be followed by analysis of the structural trends and the mapping of faults. Seismic data could be very useful for this purpose.

Recommendations

There are several topics in the geographic area of this dissertation that could become the basis for additional work.

1. Surface S3 is a fundamental division of the Dakota in the subsurface and regional mapping of this horizon would probably lead to discovering sandstones equivalent to uKdPS1 and the main gas producing interval, uKdPS5. This could yield additional Dakota drill sites and, ultimately, more production.

2. In this dissertation, it has been suggested that on a regional scale, the K2 unconformity may represent a composite of two or more erosional events. This is true if the basal Dakota unconformity at West Rio Piedra truncates the basal Dakota unconformity (K2) to the south at Heron Dam and Highway 84. It will take a significant mapping and correlation effort to determine the relationship between both surfaces. The benefit of such work will be increased understanding of the earliest Dakota paleogeography and the resulting trends of parasequences in Dakota Sequence 2 that are known hydrocarbon reservoirs.

3. The age date of 93.12 ± 0.5 Ma is based on a single bentonite sample from the Highway 84 section equivalent to the Oak Canyon Shale Member. The date is important because it shows the Dakota of the San Juan Basin to be significantly younger than it is in the eastern Rocky Mountain area to the north. Systematic sampling and age dating of more bentonites from the same stratigraphic level could further refine Dakota chronostratigraphy and better relate it to eustatic sea level changes.

4. A sample from the Oak Canyon Shale Member was submitted for total organic carbon analysis (TOC) and it yielded 1.65% TOC, an amount sufficient to produce gas. Using the approach of Curiale et al. (1992) a complete TOC profile through the Dakota interval would better define the sequence stratigraphic relationships and answer the question of whether or not the Dakota is self sourcing. It has been assumed for many years that the Mancos Shale is the source rock for Dakota hydrocarbons.

5. A study of the Gallup Formation that concentrates on the geographic area of this dissertation might yield a better way to differentiate Gallup and Dakota production contributions. In particular, it might show whether or not producing compartments stack vertically because of post Dakota basement faulting. Nummedal and Molenaar (1995) provide an excellent starting point for such a study, but their work concentrates on the southwestern part of the San Juan Basin. In addition, because their paper shows the northeastern seaward limit of the Gallup to be southwest of the dissertation study area, it raises the very interesting question of what is the nature of the Gallup producing zone in the South Lindrith field area?

6. A 3D multi-component seismic survey of the South Lindrith field area could yield definitive information about structure, and, to an extent, fluid distribution. If the estimated value of undiscovered reserves makes such a venture cost effective, then it should be done. Because of the structural and stratigraphic complexities of the field area, a funded research project using 3D methods would probably yield a valuable approach that could be applied to other areas within and outside of the San Juan Basin.

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APPENDIX A

FIELD OBSERVATIONS, DESCRIPTIONS,
AND MEASURED SECTIONS

This study includes four measured stratigraphic sections and three annotated photo sections covering the Dakota interval as exposed in northern New Mexico and southern Colorado. The term “Dakota” is useful as a name for the sedimentary interval of Cenomanian age lying between the underlying Burro Canyon Formation and the overlying Graneros Shale. It comprises several formal members including the Encinal Canyon Member, Oak Canyon Shale, Cubero Sandstone, Clay Mesa Shale, Paguate Sandstone, Whitewater Arroyo Shale and Twowells Sandstone, from the bottom up. The classical Dakota member names were used when outcrop study began and that use continues in this Appendix. Chapter 3 places the Dakota in a sequence stratigraphic framework and in so doing shows the danger of basing final interpretations on forced sandstone/shale relationships.

There are many descriptions of the Dakota interval in the literature. Four of the most useful for studies on the east side of the San Juan Basin include the several papers by Aubrey (1988, 1991, and 1992) and Owen and Siemers (1977). The unit names used by the authors follow the convention noted above. In this paper, use of conventional names helps place the described sections in a familiar context, but it is recognized that there is a danger in applying them. Lithostratigraphic correlations based strictly on the positions of sandy intervals in the Dakota are widely used. However, because

it is commonly difficult to trace a given sandstone from outcrop to outcrop, much less from the outcrop to the subsurface, such use can obscure important time related depositional details. This is particularly true in the uppermost part of the Dakota sequence. Where surfaces with sequence stratigraphic significance can be interpreted, they are shown on the following sections and these, when tied, may prove to have more genetic and, thus, predictive value than the more conventional correlations.

Two of the sections, *Highway 84* and *Heron Dam*, include gamma ray profiles as well as stratigraphic sections. Each unit in the measured sections is numbered and the numbers key to the gamma ray logs and the several photographs at each location. The gamma ray profiles are of sufficient quality to tie to the subsurface Dakota interval in the eastern part of the San Juan Basin. Gamma ray logging was performed following the guidelines in Slatt et al. (1995) with a Scintrex Model GRS-500 spectral scintillation counter set to measure a composite potassium-uranium-thorium signal. Measurements were made at one foot intervals and averaged over five readings. Because access roads cut at angles across the outcrops, it was necessary to laterally offset several times to construct a complete section and the offsets were made along appropriate marker beds.

Conventions Used in the Descriptions

In an effort to reduce the size of this appendix, a form of geologic shorthand is used in the descriptions.

Lithologies:

Ss - sandstone

Sh - shale

Slt - Siltstone

Slty - silty

CS - carbonaceous shale

Carb - carbonaceous

Chrt - chert

Colors:

Most colors are modified shades of gray.

gry - gray

rd - red

brn - brown

org - orange

yel - yellow

lt, md, dk - light, medium, dark

A typical description might be: lt → md yel gry, or, light to medium yellowish gray. A description without gry, e.g. rd, means the color is distinct enough to stand out on its own. The most common stand-alone colors in the following descriptions are red and orange.

Grain Sizes:

Cly, Slt, VF, F, M, C, VC, Cgl: clay, silt, very fine, fine, medium, coarse, very coarse, conglomerate.

A typical description may appear as: F → MG, meaning fine to medium grained.

Sorting:

VPS, PS, MWS, WS, VWS: very poorly sorted, poorly sorted, moderately well sorted, well sorted, very well sorted.

A typical notation might be: PS → MWS, or, poorly to moderately well sorted.

Angularity and Roundness:

A, SA, SR, R: angular, subangular, subrounded, rounded.

A typical description might be: SA → SR, or, subangular to subrounded.

Cements:

Calc - calcareous

sil - siliceous

fer - ferruginous

Bedding:

HCS - hummocky cross stratification.

SCS - swaley cross stratification.

xb, xbdd - crossbed, crossbedded.

BT - bioturbated

Description:

In general, a description is presented in order of: thickness, lithology, color fresh, color weathered, grain size, cement, angularity, and narrative description. Note that in the following descriptions, all footages are in feet with cumulative feet from the base of the section upward. Each described unit has a number and the numbers increase upward.

Formation Abbreviations:

Each of the formations and members of the Dakota have conventional abbreviations:

Kgh - Greenhorn Limestone

Kgr - Graneros Shale

Kd - Dakota interval

Kdtw - Twowells Sandstone

Kdp - Paguate Sandstone

Kdc - Cubero Sandstone

Kdoc - Oak Canyon Shale

Kdec - Encinal Canyon Member

Kbc - Burro Canyon Formation

Highway 84 Section

The outcrop location is about 8.5 miles south of Cebolla, New Mexico, on the west side of US highway 84. The highway cuts down to the south revealing the Dakota interval from the top of what most workers generally consider to be the Cubero sandstone down to the lower Cretaceous Burro Canyon and well into Jurassic sediments including the Todilto and Entrada Formations farther to the south. The Dakota is essentially flat at this location, although there is a very shallow east-west oriented syncline in the middle of the exposure. According to Owen (1998, personal communication), it is possible that the Paguate Sandstone is present north and east of the road cut section.

The measurement starts in a thin bedded, carbonaceous marine shale north of the Burro Canyon cliff on the west side of Highway 84, and steps by lateral offsets on correlative beds all the way to the north end of the exposure at the top of the highway cut. The base of the section is covered and buried downward, but appears to be a carbonaceous shale in the upper two feet. The cross-bedded sandstone above the carbonaceous shale weathers light yellowish gray and contains carbonized wood trunks on the cross-beds. The first occurrence of carbonaceous debris and the absence of reddish to greenish siltstone interbeds marks the base of the Dakota (Stokes, 1948). There is some question about whether the Encinal Canyon Member is present at this location. The sediments that are present appear similar to other Encinal Canyon exposures, but are much thinner. It is likely that the carbonaceous sandstone and shale noted here are actually within the Oak Canyon Member and mark the first marine transgression over the Burro Canyon.

This is a summary of observations made on 15 July, 22 to 24 September, 24 December, 1998, and 2 June, 22 and 23 September, 1999. The section is in normal stratigraphic order, base at bottom. Figures 3-6 and 3-21 present these descriptions as a stratigraphic columns with facies interpretations and a gamma ray profile. Because of their size, these figures are best viewed on-screen from the enclosed PC-formatted CD-ROM. The gamma ray log starts about 15 feet lower than the stratigraphic section and is appropriately correlated.

Top of section

Unit	Cumulative Thickness	Description
49.		Stream gravels, Qal, on pediment.
48.	158' 10"	2' Sh, md gry, evenly bedded.
47.	156' 10"	15' Ss, looks chaotic bedded on outcrop (Figure A.1), but there is internal organization. Unit is "slabby bedded" throughout, but still presents a vertical cliff face. The chaotic breaking pattern may be due to highway blasting. At the south end of the outcrop, the appearance is more like unit 45 below, but in thinner beds. These are the subunits in stratigraphic order:

Figure A.1: Unit 47 at Highway 84. Note bedding that is thoroughly bioturbated. Walking staff for scale.

2 - 3' Ss, variable thickness, lt yel gry weathering md yel gry, VFG, less shaly than below, BT, forms resistant cap on outcrop. Upper 6" bleached, likely from recent weathering.

10' Ss, VFG, as below but contains lenses of Ss, VFG, slightly less shaly, all BT, but there is some relict bidirectional crossbedding with master sets dipping north. 3' Ss, md gry weathering md yel gry, VFG, shaly to flaser bedded, thoroughly BT, crossbedded in trough set facing

north. Crossbed sets are a little less shaly and less BT, but they grade upward into BT, VFG Ss.

46. 141' 10" 1' Ss, lt gry weathering md yel gry, F → VFG, MWS, SR, clay coatings on grains. Thoroughly BT, bounded above and below by horizontal master bedding planes.
45. 140' 10" 15' Ss, lt gry weathering md yel gry, FG throughout, intensely BT with both horizontal and vertical burrows, some less burrowed zones up to 6" thick have beautiful *Ophiomorpha* that stand out in relief. Master bedding in horizontal 6" to 3' sets that show relict planar to trough crossbeds dipping uniformly north - it takes a correct sun angle to see the crossbeds. Friable on outcrop, but resistant weathering with rounded top. The top of this unit is a master bedding plane. The upper 2" becomes MG, WS, WR, no cement, friable. The sandstone presents a uniform, vertical cliff face.
44. 125' 10" 40" Ss, lt gry weathering md yel org, F → VFG, MWS, SR, in long sweeping trough crossbeds oriented south. Semihard, non-friable. In upper 12" BT has destroyed bedding. The troughs are tangential on the lower master bedding plane, the upper plane is sharp.

43. 122' 6" 6" Ss, lt gry weathering lt yel gry, MG, WS, SR, soft, weakly friable, in tabular to trough crossbeds dipping south, internal crossbed master planes thin in lenses laterally. Scattered vertical burrows through the sand, ½" shale at the base.
42. 122' 0" 18" Ss, lt gry weathering lt yel gry, MG, FWS, SR, in ¼" sweeping crossbeds oriented to the south, no internal cross cuts, very thin mud drapes on some crossbeds, ferruginous crossbed outlines. Sharp top and bottom.

RSE - Regressive surface of erosion based on facies relationships.

41. 120' 6" 3' Ss, lt gry weathering md yel org, FG, WR → SA, WS, soft, non-friable. In 2" to 6" horizontal beds, some shaly with ripple/flaser crossbeds, bioturbated in top 2". Some large U shaped burrows, 1½" by 1½" tall, ferruginous.
40. 117' 6" 10" Ss, like unit 37, VFG, soft, friable.
39. 116' 8" 1" Ss, like unit 37 but with no crossbeds, hard.
38. 116' 7" 10" Ss, md gry weathering md yel gry, VFG to upper silt range, shaly, wavy to flaser/rippled crossbedded with rare carbonized wood fragments. Becomes mottled and burrowed upward. Softer than unit 37.

- 37. 115' 9" 3" Ss, lt gry weathering md yel org, VFG, hard, planar to trough crossbeds facing south. (Note: the crossbedding is interpreted as large-scale HCS.) This unit is a 3" by 2.5' lens.
- 36. 115' 6" 2' Ss, md gry, FG → VFG, shaly, BT.
- 35. 113' 6" 12' Covered. Shale samples in float show interval becomes siltier and sandier upward.

(Figure A.2 is a photograph of units 20 - 34.)

- 34. 101' 6" 2' Sh, md gry, silty.
- 33. 99' 6" 6" Ss, md rd gry, VFG, WS, WR. Major scour surfaces with thin, horizontal laminated sandstones filling undulating surfaces, some with planar cross-bedding.
- 32. 99' 0" 15' Sh, drk gry → blk, no trace fossils. 1" bentonite 2' below top, several other very thin, discontinuous bentonites in interval.
- 31. 84' 0" 20' Ss, lt → md reddish gry weathering md gry, F → VFG, silica cemented, discontinuous disturbed bedding in ¼" to

Figure A.2: Units 20 through 34 at Highway 84. Note that most of unit 34 is covered by slope wash and slump.

2" layers, shaley to clean. Profile weathers back upward and this seems to reflect shaliness rather than sandstone grain size change, although there are some thin sandier layers within 6' of the top. Base of interval shows large scale HCS. Sandstone above HCS slightly more resistant than underlying sandstone.

- 30. 64' 0" 12' Ss, as above but with small scale HCS throughout, larger scale in middle of interval.

- 29. 52' 0" 4' Sh, md drk gry, scattered 1/16th" paired, vertical and inclined U shaped burrows (*Diplocraterion?*), platy and sulfurous in part.

- 28. 48' 0" 1'6" Ss, md rd gry weathering drk rd org, VFG, WS, very hard, silica cemented, very shaly sandstone with scattered shale "blebs," heavily BT in upper half and above base, abundant *Ophiomorpha*, *Thalassinoides* and other trace fossils, pronounced load casts or burrow casts at base. Faint, disturbed horizontal laminations throughout. Upper 1" is a sandstone, FG, WS, without burrows that appears to fill underlying vertical burrows. May represent sand deposition in pulses with burrowing in between. Two clean 2" stripes in the middle of the hard sandstone stopped the burrowers. This unit lies sharply on the upper of two bentonites and the bentonite is in a

very blk shale. The blk shale is on a gry shale and there is a similar sandstone about 7' lower.

- 27. 46' 6" 2" Bentonite, wht with iron stain.

- 26. 46' 4" 1' Sh, drk gry to blk, marine.

- 25. 45' 4" 1' Slt, shaly, md gry.

- 24. 44' 4" 4' Sh, as above but md gry with many U shaped burrows.

- 23. 40' 4" 3" Bentonite, wht, sampled for age dating. (See Figure 3-18.)

- 22. 40' 1" 2' Slt, md gry, shaley, discontinuous horizontal bedding, pronounced convoluted bedding seems to indicate rapid deposition (delta front turbidite?), Figure A.3. Very well preserved, silica cemented *Ophiomorpha*. This interval seems to thicken to about 10 feet to the south and replaces unit 21 below. At south end of the cliff outcrop, about 500 feet from the line of section, this unit is tentatively correlated to a SS, lt yel, F → MG, WS, WR with iron stain, semi blocky weathering. Within, it contains a SS, wht, "clean," cross-bedded with large *Terebellina* and *Ophiomorpha*. The "clean" interval shows

Figure A.3: Unit 22 at Highway 84 showing contorted bedding and silicified trace fossil *Ophiomorpha* (close-up of *Ophiomorpha* in Figure 3-17)

fractures that die out above and below where bioturbation increases (Figure A.4).

21. 38' 1" 8' Shly slt, md gry, contains *Terebellina*, *Diplocraterion*. Thins to north where it is sandy, poorly sorted with weathered "chert" clasts, wood fragments and shale clasts. At the top of this interval to the north there is a 1" highly ferruginous sandy shale. The grain size right at the top of the shale in the sandstone is VF → MG, PS with much woody debris.

Figure A.4: At the far south end of the Highway 84 outcrop, above the cliff in Figure 3-10, there is a possible correlative sandstone, shown here, to unit 22. Note how fractures are confined to the non-bioturbated interval in the center of the photograph.

20. 30' 1" 2'8" Ss in 3 beds, in stratigraphic order:
- 13" Ss, lt gry weathering md gry org, VFG, WS, WR, scattered plant debris, but much less than underlying sandstones. Most resistant of the three beds. Massive to wavy, indistinct horizontal beds. Plant fragments tend to align horizontally. Many vertical microfractures throughout the unit are iron stained and care must be

taken not to interpret the microfractures as roots. Weathering reveals two or three horizontal bedding planes in this unit. Persists to north, but splits into two sandstones with a medial shale.

10" Ss, md gry, VFG, many woody pieces and possible rootlets. Indistinct horizontal bedding, horizontal and vertical burrows, more resistant than underlying sandstone.

LSE or RSE - very low angle truncation to north (see Figure 3.15).

At the unconformity, the style of deposition changes from tidal flat with wave modifications below to stacked, marine parasequences above.

9" Ss, lt gry, VFG, WS, abundant woody material as small to 1/4" fragments commonly marked by iron stain aureoles. Some of these may be roots. Indistinct horizontal bedding - thoroughly disturbed, friable, least resistant of the three parts of this unit. This unit thickens laterally and appears to be a bleached sandstone that reaches 3' to 4' thick at the expense of the underlying shale. Possible unconformity as noted above. *Sample H84 20BZ* is the bleached zone.

Unit 20 forms a conspicuous low cliff break in slope and appears to be the lateral correlative of the truncating sandstone to the north. To the north, the section represented by unit 20 is much thinner.

Section to north (Figure A.5) is:

Top of offset to north measurement

3 - 4" Ss, variable thickness, It yel gry weathering to drk rd org, FG, hard with specular appearance, pinches and swells like a ripple set. Bidirectional tabular crossbeds, some ripple troughs filled with sandstone lenses, same description as preceding. This unit is laterally persistent.

Figure A.5: Unit 20 north of the main line of section. Note total thickness of unit is about 1 foot.

8" Ss, md gry weathering to drk rd gry, F to VFG, hard, sideritic (?) rosettes, white chert specks.

Scattered carbonized wood fragments. The sandstone appears to have no internal bedding but the 8" zone is in two bedsets with dividing plane sloping down to the south. No obvious trace fossils. Upper part grades to 6" sandy gry sh/shaly gry ss that shows some draped bidirectional crossbeds. The lower contact is sharp on the ferruginous zone in the shale below.

Base of offset to north measurement

19.	27' 5"	6' (estimated - slope too steep to climb) Sh, gry. Contact with overlying sandstone uneven and top of shale markedly lighter in color - bleached? - and has abundant oxidized woody material. It is white in stark contrast to overlying sandstone.
18.	21' 5"	20" Ss, lt gry weathering md rd gry, VFG, thin horizontal to wavy lamina at base and mud drapes. Becomes thinner bedded upward and maintains horizontal lamina. Laterally merges into thicker bed. Gradational into overlying shale at measured location.

17. 19' 9" 9" Ss, lt yel gry, FG → VFG, WS, WR, friable, contains very small-scale bidirectional cross stratification. Not heavily BT. Sandstone is base of fining upward interval. Unit pinches and swells laterally and continues to maintain small-scale cross-bed sets, mostly south dipping. The lowest 4" is more "massive" and contains a few small vertical burrows.
16. 19' 0" 2.5' Sh, md gry, uneven 1/8" bedding.
15. 16' 6" 18" Ss, md gry, F → VFG, WS, WR, in 6 approximately 3" beds with very thin gray shale partings between, faint horizontal to no internal structure, wavy contacts, BT. Sandstones coalesce and thicken north, middle part lenses out in same direction within 6' of measured location.
14. 15' 0" 3" Ss like unit 13 but with ripple cross lamination and reactivation surface at the top. Asymmetric ripples orient to the south, mud drapes on the south sides.
13. 14' 9" 14" Ss, F → VFG, uneven base, contains 1/4" to 1/2" mud clasts at lower contact. Iron stained in lower few inches. Unit thins to south. Contains tabular, planar cross-beds in middle 6" that dip south, otherwise bedding is faint horizontal. Burrowed and mottled.

There is a conspicuous break between units 12 and 13 to a mottled, burrowed marine sandstone above.

12.	13' 7"	15" Ss, like unit 11, but without conspicuous bedding and burrowing. It comprises alternating thin siltstone and CS units than can contain some FG sand, from bottom up: 1" CS - thickens to south, contains some clean, 1/2" by 3" FG sandstone lenses. 9" Ss 1" CS 3" Ss 1" CS
11.	12' 4"	4' 10" Ss, lt gry weathering med yel org, FG, WS, WR, friable with less than 5% porosity in four beds which are, from the base up, 6", 27", 20", and 5". All are mottled, vertically and horizontally burrowed with 1/8" to 1/4" indistinct, slightly uneven horizontal laminations. 27" bed thins to 0 within 50 feet to the south. 20" thickens to south. The 6" bed thickens to the north. All sandstones seem to reflect bidirectional currents on a large scale, but upper flow regime parallel laminations on the smaller, internal scale. There appear to be up to 2" high tidal bundle packages in the central portions of the 27" and 20" sandstones. The parallel internal laminations tend to dip

north, but the bundles dip south. In some places, the major visual bedding breaks that define the main sandstone units are separated by less than 1" partings of VFG to silty sandstone.

Unit 11 may be a subtidal sand wave or a barrier bar/tidal delta (see Figure 3-12).

10.	7' 6"	3" repeat of unit 9.
9.	7' 3"	5" Ss, md → lt gry, FG, WS, wispy horizontal bedding, 1/8" mud clasts and a hint of lenticular bedding. The unit is thin laminated in basal 1".
8.	6' 10"	3' 7" total for unit 8, 0 on line of section.

0 to 5' (in channel to right of main section with base buried to north) with contact erosional on underlying units. Bedding dips steeply to the north. Contains several lithologies which are, in stratigraphic order:

1/2" Ss, md rd org → drk rd org, FG, hard ground, abundant large carbonized wood clasts, weathered pebble clasts and uneven base. The 2" under this unit appear bleached.

6" Ss, lt → md gry, FG, carbonaceous, flaser bedded, low angle cross-beds dip to north and are topped by iron stain in some places. Vertical burrows up to 1/2" wide in places marked by iron stain.

12" Ss, lt → md gry, F → rarely CG averaging MG, becomes solidly MG in top 2", abundant carbonized wood fragments up to 1/2", mud drapes, flaser to lenticular bedded. May have some root zones. Dips to north.

1/2" Ss, as in 1" Ss below, but no flame structures at base.

1" Sh, as in 2" carbonaceous shale below.

1" Ss, md gry to rd org, FG, WS, hard, carbonaceous in part, faint wavy internal laminations, 1/4" flame structures at base pointing to the north.

2" Sh, carbonaceous to coaly, dips to north.

12" Sh, blk, uneven horizontal bedding, dips to north.

8" Ss, md → lt gry, F → VCG, clay coatings on grains, abundant carbonized wood and carbonaceous streaks. Oxidized chert clasts, semifriable. As unit thickens to

north, the contact at the base is a hard ironstone and the lower part of the unit contains mud clasts.

Unit 8 is erosional on the underlying (sandflat?) and may represent a tidal channel. It seems to laterally accrete to the north. Beds are in sandstone to shale, fining upward packages - graded - and this seems to indicate multiple depositional events. There is much internal cross cutting and possible multiple exposure surfaces marked by iron staining and carbonaceous debris. About 100 feet north of the section described above, the exposure is 4' 7" thick and has a somewhat different character, in stratigraphic order:

Top, offset section 100' to north (Figure A.6)

12" Ss, approx. thickness, md gry weathering md org gry, VFG, WS, WR, shaly lamina, blocky, hard, numerous 1/8th" by several inch burrows (*Scolithos*?). Mud lamina decrease upward. Indistinct horizontal lamina, some small-scale crossbeds dipping south. This unit becomes thinner bedded and shalier about 50' to the north where it is:

7" Ss, lt gry weathering md yel gry, VFG, WR, WS, shaly, very thin shale/mud drapes. Bidirectional

Figure A.6: Unit 8 about 100 feet north of the main line of section.

crossbeds. Two inches above the base are $1\frac{1}{2}$ " wide by $1\frac{1}{2}$ " deep depressions that contort the underlying sand/mud drapes. The top 3" above the crossbeds shows highly contorted bedding marked by shale drapes, but not BT. This interval looks like a slumped channel margin with soft sediment deformation.

3' Ss, lt yel gry weathering md yel gry, F $\rightarrow$ VFG in $\frac{1}{2}$ " to 2" bedsets with slightly wavy horizontal lamina showing abundant mud drapes. Most beds increase in finely laminated mud upward - graded beds. There are a few rippled surfaces and lenticular 2" sands. At the very top is a 2" laminated gry shale alternating with 2" VFG Ss and 1" gry shale. Surfaces in this unit have

abundant *Planolites*, other tracks and trails, some vertical burrows but little BT. The graded sand/mud layers suggest splay/spillover in surges - tidal? The deposition style is similar to unit 8 above.

Base, offset section 100' to north

7. 6' 10" 14" Ss, md → drk gry, FG, WS, shaly, lenticular bedded with ¼ by 3" ironstone lenses. Moderately hard. Mud drapes appear carbonaceous. Sorting in upper half becomes poor, M → FG, contains chert specks and abundant carbonized wood fragments. Very gently cross-bedded to south marked by an iron stain zone with minor internal bidirectional cross-beds to the north. Upper 2.5" marked by 1/2" very carbonaceous zone overlain by 2" Ss, md gry → blk with red, VFG → MG, PS ironstone pebbles up to 1/4" that seem pyritic in part. Extremely carbonaceous and looks like a lag under the next unit.

6. 5' 8" 3' Ss, lt gry weathers lt yel gry, M → FG, WS, planar and planar tabular cross-beds with main direction to south, but bidirectional. At least one scour (?) surface dipping north contains south-facing cross-beds. Tidal bundles in sets 2" to 6" high building south. Bedsets containing bundles and crossbeds are up to 10" thick. Unit appears

slightly but increasingly burrow mottled in upper ½.

Thin, carbonized wood zones near top. Thickens to north, but retains bidirectional crossbeds. Friable with clay coating on grains, about 10% porosity.

5. 2' 8" 7" Ss, lt → md gry, F → MG in cross-bed layers, herringbone crossbeds with mud drapes on south facing beds (the subordinate direction). Bounded above by a master bedding plane in the base of the next unit.
4. 2' 1" 11" Ss, md gry, MG, WS, WR, with clay coating on grains, scattered carbonaceous fragments. Lower 6" shows weak bedding, slightly wavy becoming 1/8" horizontal bedded in upper 5". Friable, perhaps 15 - 20% porosity.
3. 1' 2" 2" Ss, md gry → red, M → CG, hard, with weathered chert pebbles up to 1/4" and abundant carbonaceous debris. A TSE?
2. 1' 0" 4" Sh, blk, thin, even bedded in sharp contact on unit 1. Mud flat?
1. 0' 8" 8" Ss. lt → md gry, MG, WS, SR, with abundant carbonaceous streaks, pieces and layers, wavy bedded to horizontal, some weathered chert concentrated in lenses 2" wide by 1" tall.

K2 Unconformity

Unconformity (see Figures 3.7, 3.8 and 3.10) is undulatory on the underlying Kbc and comprises a ferruginous hardground. Hardground is iron cemented, MG, WS red → org Ss with up to 1/4" pebbles in places. Silica cemented, hard, in some places only the color change and hardness mark the change to the overlying formation. *Sample H84-21-09-02.*

Note: Many of the sandstones in this section are lt yel gry or lt yel org on fresh surface, but they appear md → drk gry on exposure because of slope wash from the overlying shales.

Total: 158' 10" measured

Base of Section in Burro Canyon Formation, covered.
Sample H84-21-09-01.

Description of Burro Canyon (Kbc)
on Cliff at South End of Outcrop

Sandstone, lt gry → wht, weathers lt yel brn, CG → Cgl, MWS, slightly calcareous, highly cross-bedded with pebble trains following the foresets (see Figure A.7). The unit looks like a braided stream deposit. It contains reddish, gray green siltstone lenses below conspicuous scour surfaces. The Kbc contains little clay but the white clay that is present contributes to the light gray to white color on outcrop. The formation is friable and contains high porosity and apparent high permeability.

Figure A.7: Early Cretaceous Burro Canyon Formation at the base of the Highway 84 outcrop. The Burro Canyon lies immediately below the K2 unconformity (see Figure 3.10).

Heron Dam Section

The Heron Dam location is about 12 miles west of US Highway 84, via New Mexico Highway 95 on the south side of Heron Reservoir (see Figure 3-1). The main Dakota exposure is on the north side of the Chama River east of the Heron Dam spillway (Figure A.8). The supplemental section is above the spillway north and west of the base main exposure (see Figures 3.22, 3.23 and 3.35). Access to both sections is by a gravel road signed “Rio Chama Trailhead” and a service road on the north side of the river just north of the trailhead and running downhill to the west.

Figure A.8: The Dakota section at Heron Dam. Access road leads downhill to the spillway and affords a complete view of the outcrop. The Chama River is to the left of the view included in this photo.

At this location, there is a complete Dakota section from what is commonly considered Encinal Canyon at the base to the top of the Twowells Sandstone and a bit of Mancos (Graneros) Shale at the canyon rim (see Figure 3.23) . At the base of the section, the Encinal Canyon Member rests with angular unconformity on the Burro Canyon Formation (see figure 3.24).

Figure 3-37 presents the section graphically and also includes the results of the gamma ray survey for this location. This is a summary of observations made on 6 August and 24 September, 1998 and 3 June, 17 August and 23 September, 1999.

Top of Main Section

Unit	Cumulative Thickness	Description
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Qal conglomerate rests on top of the Twowells Sandstone.

35.	277' 7"	22' Ss, md gry weathering md → lt yel gry, FG, burrowed, less shaly than below. Holds up steep, blocky weathering cliff. This is a horizontally bedded ss that seems uniform, top to bottom. Cleaner upward and upper 2" increases to MG, WS, silica cemented, lt gry on fresh surface, lt rd gry on weathered with abundant <i>Ophiomorpha</i> , <i>Scolithos</i> , <i>Planolites</i> and <i>Diplocraterion</i> . Upper 1' of sandstone has
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some very low angle crossbeds trending SE. Burrowing is visibly subtle, but the uppermost surface shows unmistakable paired burrows and other trace fossils. At the top of the road, there is one sweeping crossbed that cuts down about 5' and looks like a beach facet. *Sample HD-24-09-14a* at base, *14b* 5' above base, *14c* 10' above base, *14d* 15' above base, *14e* at very top.

34. 255' 7" 4' Ss, md gry weathering lt yel gry, FG, WR, WS, shaly but more sandstone than unit 2 or 4. Intensely burrowed horizontally and vertically but some indication of low angle crossbeds. Upper surface undulates perhaps from long period ripple bed forms.

33. 251' 7" 4'11" Ss, lt gry weathering lt yel gry, VFG in 5 beds that are thin and laterally continuous. The five units at the top of this interval are all FG, BT and have a 1" - 2" shalier bedded zone at the top. They may represent tidal pulsations. In stratigraphic order:

7" Ss, as below

20" Ss, as below.

8" Ss, as below, separations defined by shalier, wavy bedded intervals.

7" Ss, as below, separated by shale laminae.

6 to 7" Ss, VFG, bioturbated, shaly, disturbed horizontal to slightly inclined bedding. Wavy bottom fills undulating top of underlying sandstone. Increase in shale laminae separate this unit from next higher.

5" Ss, VFG, like unit below, remains clean, burrowed, long period ripple bedded, undulating top reflects ripples.

5" Ss, VFG, hard, clean with specular appearance. Some evidence of burrowing, becomes shalier and has bidirectional crossbeds in upper half.

32. 246' 8" 10' Ss, md gry weathering md yel gry, F → VFG, shaly, moderately burrowed, has some very long by ¼" vertical burrows and seems to have slightly higher sandstone content than unit 30. Contains poorly defined large planar crossbeds that dip SE with a minor set in the opposite direction. Burrowing hides bedding details. Minor increase in sandstone content upward except top 1" to 2" shalier and softer. Sharp contact with overlying sandstone.
31. 236' 8" 1" Ss, md → drk gry, VFG, very shaly, separates unit 30 from unit 32, may be gradational base of unit 32.

30. 236' 7" 5' Ss, md gry weathering md yel gry, FG, shaly, BT like base unit 29. Minor small-scale low angle crossbeds. Wavy bedded due to burrowing. Unit stays remarkably uniform over interval but can contain lenses 6 - 8" by several feet in upper half with increased sandstone content that are harder and stand out a bit from cliff face. Semirounded weathering.
29. 231' 7" 13' Ss, as below. Sandstone content increases upward and unit becomes "clean" in the upper 2". Grain size remains FG throughout. Upper 1' contains 1" by several inch sandy lenses. Rare *Ophiomorpha*. Bedding is mostly horizontal but there are minor low angle, small-scale crossbeds. Sharp bedding plane at the top marked by ferruginous stain. Rare clay pebbles and carbonized wood fragments in top ½". Semirounded weathering.
28. 218' 7" 21' Sh, md gry, heavily BT, burrows with FG sandstone weather out of slope. Lamsram with some low angle small-scale crossbeds at the top but mostly remnant horizontal bedding. Abundant *Ophiomorpha*, *Thalassinoides*, *Planolites*, *Scolithos* and similar forms, commonly approximately ¼ to ½ inch in diameter. Contact with overlying sandstone gradational, with shale content decreasing upward. Base of overlying unit is at a

prominent horizontal bedding plane above which the sandstone/shale is a little more durable (Figure A.9).

27. 197' 7" 28' Ss, VFG, md gry, or sandy shale, more resistant than

Figure A.9: Gradational base of the uppermost Dakota parasequence at Heron Dam. Numbers key to unit numbers in this discussion. Note hammer on right for scale.

overlying bed. Persistent horizontal lamina distorted by BT but clearly visible. Sandiness at base of interval gives way upward to 2" to 4" F → VFG sandstone stringers that come and go laterally over distance of 100 to 200 feet.

26. 169' 7" 5' Ss, md gry weathering lt gry, VF → FG, MWS, like unit 24 below, but fined grained. Burrowing intensity decreases in upper half, but throughout are back filled burrows as in 24. Shale content increases upward and becomes lenticular to flaser bedded at top. There is considerable horizontal variation in this unit and in places it forms a resistant ledge at the formation top. *Sample 24-09-08*. Figures 3-30 and 3-34 show units 19 through 26.
25. 164' 7" 1' 0" Ss, lt → md gry, FG, non-shaly, in long period horizontal to trough(?) bidirectional crossbeds - tidal bundles? Top of unit shows some shaly lamina and is uneven, grading into overlying BT sandstone.
24. 163' 7" 4' 6" Ss, md gry, FG, shaly, intensely burrowed with ½ by several inch, unlined horizontal and slightly inclined burrows. Fill in burrows appears to be in layers like back fill. Wavy horizontal bedding outlined by shaly wisps and layers. Pronounced horizontal bedding plane 1' from top above which is some poorly defined crossbedding for about 3", crossbeds fill large ripple depressions that come and go laterally. At the top, there are ¼" high current ripples and a sharp contact with the overlying unit.

23. 159' 1" 2" Ss, md gry, F → MG, shaly, lenticular bedded to flaser bedded, heavily burrowed, CS streaks outline burrows and bedding. Fills undulatory crest of unit 4.
22. 158' 11" 2' Ss, lt gry weathering lt yel gry → org, F → MG, relict horizontal bedding and tangential crossbeds, heavily burrowed with abundant *Ophiomorpha* as well as horizontal burrows. Clay coatings on grains and wispy shale laminae. This unit pinches and swells as a large wave form filling lows on unit 21 and it merges with 21 east of the line of section. Wavy upper surface that in places appears to contain thin bedded sandstone or shale. Becomes MG in upper half.
21. 156' 11" 2" Ss, lt gry weathering lt yel gry, F → MG, FWS, with ripple bedding, shaly with wispy, thin CS laminae. Horizontal to undulatory layers. Clay coatings on grains.
20. 156' 9" 2' Ss, lt gry weathering md gry, F → MG, hard, non-shaly with well defined tangential to planar crossbeds facing SE. Pronounced 2" crossbed set at base, but crossbedding becomes less well defined upward due to burrowing and abundant *Ophiomorpha*. The top of the sandstone is ripple modified.

19. 154' 9" 6' Ss, md gry weathering md yel org, M → CG in basal 2", FG above. Shaly, thoroughly horizontally and vertically BT. While there is no apparent bedding, there appears to be a remnant horizontal bedding plane 1 foot from the top. Basal 1" contains mud clasts and is ferruginous. There is 1" brn, very soft silty to sandy shale under the base CG sandstone. Top 6" includes shale laminae that are about horizontal with large horizontal to inclined, sand filled burrows. Still FG in upper 6" and very shaly. Laterally, there appears to be some poorly defined tabular planar SE facing crossbeds in upper 1'. Throughout, sandstone is hard to the hammer. *Sample HD-24-09-01* is from midway in this interval.

LSE or RSE

18. 148' 9" 37' Sh, md drk gry, thin horizontal laminations with minor bioturbation first five feet, becoming sandier and more burrowed upward *Ophiomorpha* near top, *Scolithos* (straight, vertical burrows) most common below.
17. 111' 9" 3" bentonite, sampled (see Figure 3.35).
16. 111' 6" 5' Sh, black, even, horizontal bedded.

15. 106' 6" 7' SS, FG, md gry, carbonaceous, shaly. Thoroughly BT. Grades upward to blk shale. Slope former.
14. 99' 6" 15' SS, md gry, VFG, WS, shaly, ferruginous. BT with faint distorted horizontal lamina. Four feet above base becomes hard and blocky, VFG, lt gry and ferruginous with horizontal laminations and suggestions of HCS.
13. 84' 6" 12' Sh, drk gry becoming md gry upward, thin horizontal laminations. 1" bentonite five feet above base marks color change from drk to md gry.
12. 72' 6" 21' SS, lt → md gry, F → VFG, WS, shaly. Average ¼" wavy to horizontal lamina. In some places has small cross-beds as scours. Carbonaceous and contains < 1/16th inch chert specks. Eleven feet above the base, there is a 2" ripple laminated zone that is F → MG, md gry and carbonaceous. Lower 10 feet is cliff former, but becomes rounded upward and cliff habit loses persistence to the east.
11. 51' 6" 10' Sh, md gry, sandy. Sandstone is VFG, hard, WS in 6" stringers. Shale contains abundant trace fossils that are mostly trails and horizontal burrows in every bedding surface.

10.	41' 6"	4' SS, FG, hard, silica cemented, ferruginous, BT in first 6". Grades up to VFG, WS, bioturbated. Upper part of sandstone has rounded weathering character that marks break in slope.
9.	37' 6"	9' Sh, as in unit 11, distinct sandy zone at base. Contains many thin, up to 1', horizontally discontinuous sandstones.
8.	28' 6"	7.5' Sh, black, even, horizontal beds. Two feet above base is a CS zone with wood fragments.

Unconformity

7a.	21' 0"	Marked by ½ to 2" zone of concentrated charcoaled wood fragments (Figure A10) in a matrix of Ss, md gry, shaly, F → MG, MWS on FG side, WR, in thin horizontal to wavy beds becoming short period, longitudinal crossbeds upward. Overlying unit contains abundant marine trace fossils.
7.	20' 11"	7' Ss, lt gry weathering very lt yel gry, almost white in 6 beds, whole interval appears bleached. This sandstone interval dips east and intersects the Kdec/Kdoc surface at about a 20 degree angle west of the measured section. It is important to note that the measured section would be

much different around the hill to the west. From the top down:

40" Ss, like 30" unit below. Soft weathers back. Upper contact wavy. In places, upper 6" is harder, more resistant.

6" Ss, like 4" unit below, but slightly coarser grained. Stands out from hillside, harder than units below. Contains one horizontal burrow where measured.

10" Ss, like 30" unit below but clearly FG. Wavy bedding suggests BT, but no signs of trace fossils.

4" Ss, VFG, harder, stands out from cliff. A lenticular unit that has some poorly developed ripple bedding.

30" Ss, F → MG, MWS on the finer end, SR → SA, soft, friable, no obvious bedding but appears wavy, becoming ripple (?) bedded at top. Contains some wispy shale lamina.

Note: Units 5 and 6 form a continuum from drk gry shale to drk gry shale through a contorted lt gry sandstone interval. Soft sediment deformation suggests rapid deposition, perhaps by bank failure. The middle

sandstone becomes much more pronounced, blockier and harder to the west on the nose of the hill. The combination of units becomes about a 5' lenticular channel.

6. 13' 5" 2'0" Ss, reverse of unit 5, grading back up to a drk gry, thin to platy bedded shale. Contact with overlying sandstone sharp.

5. 11' 5" 1'10" Ss, drk gry at base becoming lt gry at top, Slt at base to F → VFG at top. Base is thin, horizontal bedded, grading up through flaser to lenticular bedded, then inconspicuous horizontal to thoroughly distorted bedding outlined by shale drapes in the upper 8". A bedding plane below the contorted interval contains much carbonized plant debris.

4. 9' 7" 3'11" Ss, in several beds. In stratigraphic order they are:

Note: Units A and B probably represent pair of surges that grade from upper flow regime to lower flow regime. Both cycles grade to VFG upward. The top cycle is very shaly at the top and the upper contact is sharp.

B cycle

9'7" - 14" Ss, like 15" unit below.

8'5" - 12" Ss, like 6" unit below.

A cycle

15" Ss, lt gry, FG, thin horizontal to ripple bedded, soft, with shale flasers at the base grading up to FG, hard ripple bedded at top.

6" Ss, lt gry weathering md yel gry, FG, hard, indistinct horizontal bedding, appears mottled due to bioturbation.

3.	5' 8"	1'8" covered. Laterally appears to be a gry shale, like unit 1.
2.	4' 0"	1' Ss, lt gry weathering md yel org, FG, WS, WR, thin horizontal lamina with some paper thin shaly layers. Weathers very soft like unit 17 in the detailed "Encinal Canyon" section below.
1.	3' 0"	3' Sh, md gry, platy, hard.

K2 Unconformity

-- 0'0" 1" - 2" pebble lag (Figure A.10) on a 2' to 3' Ss, white weathering drk rd, F → MG, SA, WS, hard to friable.
Burro Canyon Formation. cross-bedded with pebble trains in cross-beds. Fluvial.

Total: 277' 7" measured.

Base of section in Burro Canyon Formation.

Figure A.10: View of the K2 unconformity just west of the main line of section. At this location, supplementary section unit 8 rests on the Burro Canyon Formation (Kbc). Note the presence of white, angular tripolitic chert concentrated on the surface.

Based on a hand-leveled measurement at the Los Ojos Day Use Area about one-half mile west of the spillway, the interval from the top of the measured section to the Greenhorn Limestone is approximately 110 feet thick. The interval is mostly covered, but appears to be a uniform gray, thin, even bedded shale.

Supplemental Dakota Section

This section through the lowest member of the Dakota is located in the cliff north of the lower spillway outlet of Heron Reservoir. The K2 is in the middle of the slope where lowest Kdec channel sandstone rests on Kbc - this is in the middle of a break in slope marked by a resistant sandstone. There is a color change from greenish yellow Kbc to yellower Kdec and a VCG to pebbly lag. Section starts in the top of the Kbc (Figures 3.23 and 3.25).

Note: The top of the measured section is well above the unconformity at the top of the S2 surface. In this interval there are a series of stacked lenticular sandstones separated by gry to drk gry shales. There does not appear to be any trace fossils. Contact between sandstones and shales appear sharp. There is an incredible amount of carbonized plant material in the gry shales above drk gry shales. The general sequence here is drk gry shales on sandstones grading up to gry shales over a small interval. From a distance, the sandstones are lenticular and appear to have some horizontal to inclined lamina. They may comprise a set of sand bars or waves becoming thinner upward as water deepened.

Top of Section

Unit	Cumulative Thickness	Description
18.	30' 3"	2' Ss, md gry weathering md brn gry, MG with much chert in M → CG clasts at base grading up to FG at top. Lenticular. Appears slightly crossbedded. Large carbonized wood fragments concentrated at top.
17.	28' 3"	12" Ss, md gry weathering white, MG, very soft and friable with abundant thin carbonaceous layers.
16.	27' 3"	4" Ss, md gry, F to MG, FWS, SR, shaly, flaser bedded.
15.	26' 11"	1'6" Ss, lt gry, FG, WS, WR, hard with no apparent bedding. Contains large carbonized plant remains. It is a lenticular sandstone that pinches out laterally over 6' in either direction.
14.	25' 5"	6" Ss, lt gry, FG, WS, WR, shaly grading upward to unit 15.
13.	24' 11"	2'0" Sh, lt gry, platy, hard.
12.	22' 11"	2" carbonaceous shale, black, soft.

Surface S2 in Heron Dam main section

11. 22' 9" 4' Ss, as below, but thinner bedded with ripples and lenticular sandstone layers. Has sharp top defined by a 4" muddier, platy weathering layer that correlates to Kdec/Kdoc surface. It is the weathering habit that defines the appearance of this unit. There are thin layers in the lower $\frac{1}{4}$, a massive middle $\frac{1}{2}$ and thin layered upper $\frac{1}{4}$. It forms a formidable cliff.

Note: Units 7, 8, 9 and 10 form a channel fill that grades laterally to zero thickness under the next unconformity in a SE direction. Unit 10 is a continuation of unit 9. The channel erodes into a gravely gry shale that has the look of an alluvial fan/braided stream deposit with spectacular grain size variations and sweeping trough crossbeds. The overlying/offsetting channel has marine affinities with herringbone crossbeds and lenticular bedding. Possible, this is a proximal tidal flat association.

10. 18' 9" 5' Ss, lt gry weathering md yel org, F → MG, WS, SR → SA, hard, in conspicuous tabular planar to longitudinal crossbed sets. A few large herringbone bidirectional sets. Scattered MG white chert specks in lower half. Scale of crossbeds decreases upward with more herringbone cross

stratification. Faint 1½" by 18" *Ophiomorpha* burrows near top.

9. 13' 9" 10" Ss, md gry weathering md yel org, FG, WS, WR, horizontal bedded with conspicuous master bedding plane at top. Angular weathering habit holds up base of cliff.
8. 12' 11" 2'0" Ss, lt gry weathering md yel org, M → CG, MWS, WR, abundant chert and other granules on planar tabular crossbeds facing east. Grades upward to unit 9.
7. 10' 11" 6" Ss, md brn gry, FG, WS, WR, planar crossbeds facing SE in horizontal sets, overlain gradationally by channel sandstone.
6. 10' 5" 2' Ss, lt gry, F → MG, WR, WS, platy, indistinct horizontal bedding, grades upward to unit 7. Units 6 and 7 thicken laterally and form a conspicuous larger-scale crossbedded unit in which crossbeds alternate in direction. Figure A.11 shows supplemental section units 2 through 6.
5. 8' 5" 2" Cgl, as below grading up into the overlying sandstone.
4. 8' 3" 2" Ss, md gry, MG, WR, MWS, with paper thin horizontal carbonaceous banding.

Figure A.11: Supplemental section units 2 through 6 at Heron Dam. The K2 unconformity is placed at the base of unit 3.

3.	8' 1"	5" Cgl, granule → FG, shaly with abundant punky white chert and carbonaceous fragments. This could be mistaken for the unconformity below except that it is above the first appearance of carbonaceous material.

Unconformity K2

2.	7' 8"	1'8" Ss, lt gry, MG, scattered wood fragments, soft, friable, 15 to 20% visible porosity, carbonaceous streaks with well

defined plant remains. Sharp contact on underlying sand.
No visible bedding, but appears to become very thin,
horizontal bedded at the top.

1. 6' 0" 6' Ss, thickness variable - channel, lt gry weathering md
yel org, FG → granule, crossbedded in sweeping crossbeds
oriented SE, becomes overall finer grained upward and
has horizontal lamina in top 6". Some trough crossbeds
defined by coarse grains in base. The coarse grains
contain much white chert, all of which is weathered and
punky.

- 0'0" 3" coarse pebble lag under strongly crossbedded
sandstone. FG to 3/16th" rounded pebbles: white chert
and rock fragments with clay cement. The unconformity is
in the middle of a sandstone and is fluvial on fluvial. The
sandstone below the unconformity is angular and blocky.
That above is more rounded weathering, but color change
is subtle.

Total: 30' 3" measured.

Base of section in Burro Canyon Formation,

Burro Canyon:

Ss, wht → lt gry weathering md grn yel, MG, about 20% visible porosity, friable, crossbedded, of variable thickness laterally, here channel sandstone is about 3' thick. Top of sandstone has whitish, bleached look.

Fractures

About ½ mile west of the spillway section, at the Los Ojos Day Use Area, the top of the Paguate is exposed as a resistant dip slope. In that location fractures are quite prominent forming a pronounced hummocky texture on the slope. There are two fracture directions:

The primary, very prominent fracture set runs N5E with variation of less than 5 degrees on either side. There are about 60 fractures per 100 feet in this set with average spacing of about 1' (range 2" to 2').

A secondary set that is almost invisible is oriented N50W, also with little variation. This set has about 30 fractures per 100' with an average spacing of about 2 to 3 feet.

Bisecting the small angle between the two fractures sets yields a direction of principal stress aligned N27.5W.

North Gallina

This outcrop on the top of Mesa Gurule north of Gallina (see map, Figure 3.1) features a good exposure of the Encinal Canyon and part of the overlying Cubero as well. Sandstones of the lower (?) Cubero are nicely exposed, but shale slopes above the Encinal Canyon are covered. The Highway 84 and Heron Dam sections show that good exposure of the shale sections is necessary for a complete understanding of the interval, so this section is of limited value. That notwithstanding, the outcrop features a good exposure of the unconformity at the base of the Encinal Canyon. This exposure is the closest accessible outcrop to the Lindrith Field in Township 23 North, Range 4 West.

At this location, the Encinal Canyon seems similar to that described by Aubrey (1988b) at Mesa Lagunitas and Gallina (on Old Gallina Road between Regina and Gallina).

To reach the outcrop, turn north from New Mexico Highway 96 two miles east of Gallina on Rio Arriba County Road 0422 (Forest Road 77). Go 3.6 miles to the Canyon Gurule sign at a road junction. Bear right on FR 77 and proceed 1.7 miles to the top of the hill. There is a very nice exposure of the Jurassic Entrada and Todilto along the way. Figure A.12 is a stratigraphic column for the outcrop. Location visited 23 September, 1998.

Figure A.12: The section at North Gallina. Numbers key to the discussion in this Appendix. Unconformity K2(?) may lie at the base of unit 1.

Top of Section

Unit Cumulative Description
Thickness

Red weathering, md yel, resistant sandstone at hilltop.

10.	137'	10' SS, md yl gry, FG, WS, horizontally bedded in 18" units with 12" MG, very friable, tabular cross-bedded unit in the middle. Many <i>Ophiomorpha</i> , but not bioturbated. Blocky weathering, friable.
9.	127'	9' SS, partly covered, VFG, shaly, <i>Ophiomorpha</i> . This interval is thoroughly covered on the north end of the outcrop and forms a pronounced slope between the two sandstones.
8.	118'	10' SS, as above, rounded weathering, forms small cliff at base of slope, highly bioturbated and uneven bedding, beds thin downward.
7.	108'	63' Covered, probable shale slope. Cubero sandstone above? Oak Canyon slope?
6.	45'	9' SS, lt yel gry, FG, WS, SA, scattered rich iron stain and apparent limonite cement, but most with clay cement.

Uneven horizontal laminations about 1 to 2" thick.

Swaley cross stratification. Much horizontal and vertical burrowing, *Ophiomorpha* and *Planolites(?)*. Unit weathers back at top. A marine sandstone?

5. 36' 5' SS, md yel gry → drk yl gry, VF → FG, WS, SR, friable with clay coatings on quartz grains, cross-bedded with beds concentrating CG to small granule trains. Except for CG trains, unit is similar to overlying sandstone but there is a distinct wavy surface separating the two and this unit has no marine trace fossils.
4. 31' 3' to 15' SS, md yel gry → drk yel gry, VF → FG, WS, SR, friable with clay coatings on quartz grains like sandstone above. About 3' is exposed. Tracing laterally sandstone becomes 12 to 15 feet thick and has indistinct tabular to planar cross-beds, there is little variation in the sandstone itself. Outcrop is discontinuous so the footages may be inaccurate. The sandstone weathers back at the top and 6" to 9" tabular cross-bed sets stand out.
3. 16' 2' Sh, md gry, to VFG SS, thin, even beds pinkish tint. Splay?

2. 14' 6' Ss, lt gry → lt gry yel, C → MG, becomes finer grained upward, PS, much lateral and vertical variability, cross-beds.

1. 8' 8' Ss, lt yel gry, M → CG, MS, WR, friable, cross-bedded to horizontal bedded with numerous pebbly zones. Appears to contain white, angular, devitrified chert, but no carbonaceous material. Sits on a possible exposure surface marked by 1 to 2 inch, hard ironstone layer in places. Pebbly zones clearly cut underlying layers. This unit grades into overlying unit. These appear to be fluvial sandstones. Figure A.13 is a photograph of the lower contact.

Total variable, 125 to 137 feet measured.

Base of Section in Burro Canyon.

West Gallina

The lowest unit in the Dakota interval, according to Aubrey (1988a), is the Encinal Canyon Formation. It lies unconformably on the Burro Canyon Formation, but the lower contact is not visible at this stop. This Encinal Canyon outcrop is on a knoll on the north side of Highway 96 about 2 miles west of Gallina (Figure A.14). The dip is about 30 degrees west reflecting faulting related to the Nacimiento Uplift to the south. The coaly and

Figure A.13: Possible K2 surface at the base of unit 1 at North Gallina. Unit 1 has many of the fluvial characteristics that Aubrey (1988a) describes in the Encinal Canyon Member of the Dakota. Unit 1 contains abundant white, angular chert unlike the underlying Burro Canyon Formation. However, it does not contain carbonaceous debris - a common identifier for the beginning of Dakota deposition.

carbonaceous shales at this location are similar to those noted by Aubrey (1988a). Here the interval is very close to the area where Aubrey mapped thickest Encinal Canyon: the maximum measured thickness is 160 feet at Regina (Aubrey, 1988a). Location: SE4, NE4, S11, R1W, T24N, west of Gallina (see location map, figure 3.1). Outcrop visited 16 August, 1999.

The outcrop contains alternating sandstones and shaly/coaly zones as shown in Figure A.14. The sandstones are F → VFG with some MG streaks,

Figure A.14: View of the exposure at West Gallina. This appears to be similar to the descriptions of the Encinal Canyon Member of the Dakota published by Aubrey (1988a). The section rests on the Early Cretaceous Burro Canyon Formation.

wht to lt gry, fluvial cross-beds with interbedded shale ripups (Figure A.15). Sandstones are separated by shaly/coaly beds that make up about one third of the total outcrop. The sandstones between contain carbonized wood fragments in some places, particularly near the contact with the shaly beds. All the shale beds are thin and even bedded with no signs of bioturbation.

The upper contact is obscured by slope wash, however, there is about a 15' md → lt gry, F → MG, MWS, indistinctly bedded sandstone on the Kdec. Rare ½ to ¾ inch vertical, smooth, branching burrows up to 2' long. Beach?

Above this sandstone is a poorly exposed 15' sand, F → VFG, MWS, md yel
gry → md yel rd with occasional ripple surfaces and zones of mud pebble

Figure A.15: Shale ripups in the exposure at West Gallina suggest high energy perhaps related to bank failure or severe storm conditions within a lagoonal area.

clasts. No trace fossils in this upper sand. Both sandstones are slightly to moderately carbonaceous. Sandstones may be in the lowest marine Dakota (classical Oak Canyon) and may correlate with those in Dakota Sequence 1 Highway 84.

Holiday Acres Section

Holiday Acres is a subdivision on the east side of the San Juan River south of Pagosa Springs (see map, Figure 3.1). It is located in the N½ Section 36, T35N, R2W. To reach the section, drive southeast from Pagosa Springs towards Chama on US Highway 84. About 2.72 miles south of the Highway 84/Highway 160 junction, turn west on Holiday Drive. The dirt road leads to the subdivision and gives access to the section at several places. The section is steep, rocky and dangerous. Private land blocks access and it is necessary to obtain permission from landowners to cross their property. The entire section from Morrison Formation to Greenhorn Limestone is available, but there are some questions about correlations above the Burro Canyon - as these notes will indicate. Figure 3.37, a photo taken from the northwest, shows the section.

Because of the difficulties imposed by steep cliffs and loose shale slopes, measuring a detailed stratigraphic section at this location proved to be impractical. The interval descriptions that follow are based on spot checks of accessible units and include estimated thicknesses. They key by number to Figure 3.37. This description is a composite from observations made on 16 and 17 July and 6 August, 1998.

Top of Section

Unit	Description
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12.	Lower part of Mancos Shale. Greenhorn Limestone is exposed along the road near the top of the hill, northeast of the exposure.
11.	SS, md gry → lt yel gry, lt gry on fresh surface, FG, shaly/bioturbated at base becoming blockier, more resistant, cliff former upward. Estimated thickness about 40 feet thick, but base is transitional. The lower bioturbated interval is rich in <i>Ophiomorpha</i> and <i>Thalassinoides</i> and includes what appear to be storm beds (HCS). There are horizontal as well as vertical trace fossils.
10.	Shaly sandstone/sandy shale slope, from base grades upward into overlying sand. Thin sandstones in interval (up to 18") are FG and laterally continuous, bed thickness increases upward. This, with unit 11 appears to be a shallowing, cleaning upward unit. Estimated thickness 35 feet.
9.	SS, md → lt gry, FG, WS, hard, silica cemented, trace carbonaceous material. Upper part includes approximate

3' shale break overlain by 3' hard, blocky sandstone, as above. Cliff former. Upper part of continuous interval comprising units 6 through 9. Estimated thickness 30 feet.

8. *Coal*, subbituminous or coaly, carbonaceous shale (Figure A.16). Estimated 2 to 3'.
7. SS, similar to unit 9. Estimated thickness 18 feet.

Possible scour surface

6. SS, FG, WS, lt gry, as unit 7, but pronounced color change. Hard, siliceous, blocky, cliff former at top. Few low angle cross-beds in upper blocky part. Base of interval is shale slope above unit 5 that becomes sandier upward. Estimated total thickness, shale and sandstone, 35 - 40 feet.

Marine Flooding Surface

5. SS, FG, WS, md gry weathering to lt yel gry, silica cement (quartzose), contains limonite rosettes under hand lens, cliff former, sharp contacts on underlying shale slope and at top. Carbonaceous. Strongly cross-bedded in 18" sets, gently to steeply inclined. No obvious trace fossils. Upper

Figure A.16: Coaly unit 8 on very hard unit 7 at Holiday Acres. Don Owen for scale.

contact gradational into lower shale slope of unit 6.

Estimated thickness 10 feet. Possible channel sandstone.

Possible channel cut surface

4. Ss, lt → md gry at base, FG → cgl, MWS, with much wood and carbonized wood as well as carbonaceous shale material both dispersed and as shale lenses. This sandier, harder lower part contains as many as three or four fluvial units containing crossbedded sandstone, conglomeratic in part. Weathers very drk gry → blk and is in sharp color contrast to underlying unit. Appears to have a scour contact with the underlying cliff forming sandstone. A 2 foot basal conglomerate, pebble lag and shale ripups mark the base of the unit in some places. Unit becomes shalier and bioturbated upward and contains alternating sandstone/shale intervals with sandstones becoming thinner upward. Carbonaceous shale zone at top under unit 5. Estimated total thickness about 30 feet.

K2 Unconformity

Units 1 through 3 are in the Burro Canyon Formation.

3. Ss, lt gry → med gry, conglomeratic, SA clasts, MWS but variable, cross-bedded with pebble trains on low angle cross-beds, contains green siltstone interbeds, some clay cement and kaolinite banding. Non-carbonaceous. Facies change within a few feet or tens of feet horizontally. One thin, hard, horizontally laminated quartz sandstone becomes a M → CG, cross-bedded sandstone within 50 feet horizontally. Estimated thickness about 20 feet.
2. Sh, shaly sandstone slope. Estimated thickness about 50 feet.
1. Ss, cliff forming, not examined. Estimated thickness 25 feet.

Base of section in Jurassic Morrison Formation

West Rio Piedra Section

The West Rio Piedra Section is exposed on the west side of the Piedra River north of US Highway 160 about 17 miles west of Pagosa Springs, Colorado (see map, Figure 3-1). The notes that follow were made from a distance because the way down the cliffs to the various lithologies has yet to reveal itself and the way up from the river is blocked by private property with a locked gate and a stern sign. Nonetheless, the outcrop can be

approached from the west by a 1.5 mile walk along an abandoned road leading east from a stock pond on First Notch Road. The Pond is about 3 miles north of Highway 160 and is located at a sharp north turn in the road. The turnoff from Highway 160 north onto First Notch Road is about ½ mile west of CR 168 on the west side of the Piedra River. From the rim, binoculars allow views of bedding details, angular relationships and at least one depositional sequence. A reasonable overview can also be had from the east side of the valley on First Fork Road (CR 166) from a point east of and above the Tres Piedras Ranch. A telescope is useful for enhancing the view. These outcrops were visited on 17 - 19 July, 7 August, 1998 and 4 and 5 July, 1999.

The views in Figures 3.38 and 3.39 are from the rim and look to the northwest. The horizontal distance between the two cliff exposures is about ½ mile. The most remarkable stratigraphic detail visible in both places is the distinct unconformity at the base of the Dakota Section. Look for the truncations of thin sandstones in the Burro Canyon. Numbers on the photographs are useful for comparing this section to others, particular to that described on the San Juan River. If we directly correlate the two coal sections, unit 8 at Holiday Acres and unit 4 (Figure 3.39) here, there is a similar sequence of beds above and below.

The following comments key to the numbers on the photographs.

Top of section

Unit	Description
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7.	Ss, cliff former, heavily iron stained in upper part. Grades upward from unit 6. Lower part thin horizontal to slightly wavy bedded becoming thicker bedded upward and blocky weathering at the top. Contains abundant <i>Ophiomorpha</i> at the top.
6.	Slope forming shale interval.
5.	Ss, cliff forming, in two distinct parts. Lower part is thin, horizontal to wavy bedded and in places appears to truncate the uppermost part of unit 4. The upper part is thin, horizontal bedded, appears highly bioturbated and has slight truncation of some of the wavy beds in the lower part. The very top of the interval has a thin shale break overlain by a thin sandstone.

Possible erosional surface

4.	Zone of thin sandstones, shales and <i>coals</i> that appears to become sandier, or cleaner upward. Base of the interval appears to be conformable with the top of unit 3. The top of the unit appears to be irregular beneath the lower sandstone of unit 5.

Note how unit 4 seems thinner in the south photo, Figure 3.39, and thicker in the north, Figure 3.38. Furthermore, a thin sandstone near the base of unit 4 seems to disappear to the south (arrow). See also Figure 3.28.

3. Thick, cliff forming sandstone. The base of this sandstone is erosional on the underlying shales. Through binoculars, it appears that the lowest 2 to 3 feet are cross-bedded and contain a coarse pebble conglomerate. The top of the unit becomes blockier than the base and appears to be horizontally laminated and highly bioturbated. Estimated thickness 70'.

Unconformity

2. Shale slope in Burro Canyon Formation. The red and green siltstones noted in unit 1 are here also, but they do not show up well in the photograph. Thin sandstones in this interval are cut out by the overlying sandstone (Figures 3.38 and 3.39).
1. Channel sandstone in the Burro Canyon Formation. Note red and green siltstones under the channel.

Base of Exposure in Jurassic Morrison Formation.

Significance of the Holiday Acres and West Rio Piedra Sections

Even though they could not be measured in detail, both Holiday Acres and West Rio Piedra are very important Dakota exposures having several characteristics in common that differentiate them from the sections to the south at Heron Dam and Highway 84.

1. Both sections have unconformities at the base and the units lying on the unconformities are cross-bedded sandstones with basal lag deposits that appear more fluvial than marine. At Heron Dam and at Highway 84, thin bedded shales, flaser bedding and bidirectional cross-beds in a vertical sequence suggest a tidal flat lay immediately above the unconformity.

2. Both sections contain coals. Because the coal, or coaly, units are in shales between sandstones displaying such marine characteristics as trace fossils, they represent paralic conditions. That is, they correlate to a time of protected marginal marine, probably estuarine, environments.

3. The unconformities represent lowstand. The fluvial deposits are lowstand deposits on the unconformities. The estuarine deposits formed during a the next transgression. Sandstones at the top of both sections may represent prograding highstand shorefaces.

APPENDIX B

THIN SECTION DESCRIPTIONS, EASTERN SAN JUAN BASIN DAKOTA STUDY

Section	Grain Size (mm), Wentworth	Range (mm)	Sorting	Roundness	Grain contacts	quartz	feld	clay	chert	Minerals calcite cements, other	Qtz extinction
HD 24-09-01	0.1, VFG		g		Touching, interlocking, old overgrowth, many filled grains	75	5	5	5	15 hematite cement, tr silica cement	sr
HD 24-09-02	0.3, MG		g		Interlocking, overgrowth, tr euhedral faces	80	10	10		silica cement	sr
HD 24-09-03	0.175, FG	0.1-0.25	f		Interlocking, overgrowth, eroded edges	90	5	5			sr
HD 24-09-04	0.25, F-MG		g		Interlocking, tr old overgrowth, tr euhedral overgrowth, some eroded edges	95		5		tr silica cement	sr - und (40%)
HD 24-09-05	0.2, FG	0.08-0.4	p		Interlocking, tr old overgrowth, some eroded edges	80	5	15		tr calcite	sr
HD 24-09-06	0.2, FG	0.1-0.3	f		Interlocking, tr old overgrowth, some eroded edges	95		5			sr - und (10%)
HD 24-09-07	0.1, VFG	0.08-0.25	f		Interlocking, tr old overgrowth, tr euhedral overgrowth, some eroded edges	85	5	10		tr calcite, tr silica cement	sr
HD 24-09-08	0.08, VFG		g		Interlocking, overgrowth, some eroded edges	80	10	10			sr
HD 24-09-09	0.15, FG	0.05-0.5	p		Touching, tr old overgrowth, tr euhedral overgrowth, few eroded edges	70	10	15	5	tr hematite cement, organics	sr
HD 24-09-10	0.125, VF-FG	0.1-0.2	f		Touching to interlocking, tr old overgrowth, some eroded edges	80	15	5		tr hematite cement, organics	sr
HD 24-09-11	0.125, VF-FG	0.05-0.2	p		Touching, silica cemented, tr old overgrowth, few eroded edges	95			5	tr silica cement	sr
HD 24-09-13	0.1, VFG		g		Touching to interlocking, eroded edges	85	5		10	tr calcite cement	sr-und (25%)
HD 24-09-14A	0.165, FG		g		Touching to interlocking, a few eroded edges	80	10	10		tr hematite cement	sr
HD 24-09-14B	0.2, FG		g		Penetrating, interlocking, overgrowth, tr euhedral penetrations	99		1		tr feldspar, silica cement	sr-und (20%)

Section	Grain Size (mm), Wentworth	Range (mm)	Sorting	Roundness	Grain contacts	quartz	feld	clay	chert	Minerals calcite cements, other	Qtz extinction
HD 24-09-14C	0.165, FG	0.125-0.75	f		Penetrating to touching, overgrowth, eroded edges	80		5	5	calcite, tr calcite	sr
HD 24-09-14D	0.15, FG		g		Touching to penetrating, eroded edges	95		5			sr-und (10%)
HD 24-09-14E	0.25, F-MG		g		Interlocking to penetrating, some euhedral overgrowth and penetrations	95		5		10% volcanic gr	sr-und (10%)
HD 24-09-15	0.1, VFG		g		Interlocking, touching to penetrating, some eroded edges	75	25			very shaly	sr-und (10%)
HD 24-09-2A	0.125, VF-FG	0.1-0.2	f		Interlocking, overgrowth, some eroded edges and a few euhedral penetrations	85		10	6	tr silica cement, some calcite streaks	sr-und (15%)
HD 24-09-2B	0.125, VF-FG		g		Interlocking, overgrowth, some eroded edges	80		10	10	tr silica cement	sr-und (50%)
HD 24-09-4C	0.125, VF-FG	0.1-0.165	f		Touching to interlocking, tr overgrowth, some eroded edges and a few euhedral penetrations	85	15	5		trace calcite, organics(?)	sr
HD 23-09-61	0.25, F-MG	10.0-0.125	vp		Touching, packed to interlocking, overgrowth, a few eroded edges	45		50	5	tr calcite cement, tr hematite	sr
HD 23-09-69	0.1, VFG		g		Tr old overgrowth, touching to interlocking, tr euhedral quartz grains	70		30		tr muscovite, clay is kaolinite (Appendix D)	sr-und (10%)
298Z	0.1, VFG	0.7-0.125	f		Touching, a few interlocking grains, tr euhedral faces	70	5	20	5	tr hematite cement, tr calcite, tr kaolinite (Append. D)	sr-und (10%)
H84-21-09-02	0.8, M-CG	5.0-0.1	vp		Touching, tr old overgrowth, well packed	80	15	15	10	tr hematite cement, tr calcite, tr rock fragments	sr-und (15%)
H84-21-09-11	0.1, VFG		g		Interlocking, tr old overgrowth, tr euhedral Qtz, tr penetrating quartz grains	85	5	10		tr silica cement	sr-und (20%)
H84-22-09-17	0.2, FG		g		Interlocking, tr old overgrowth, a few eroded edges	80		10	10	tr hematite cement, tr feldspar, tr silica cement	sr

Notes:
 Where there are euhedral quartz overgrowth, there is silica cement.
 Under "Cements, other" above, "tr" = trace.
 Framework grains in all samples are quartz.
 All samples have a clay matrix except HD 24-09-11, HD 24-09-14E and HD 24-09-5a which are silica cemented.

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Section	Grain Size (mm), We-orth	Range (mm)	Sorting	Roundness	Grain contacts	quartz	feld	clay	chert	Minerals	cements, other	Qtz extinction
HD 24-09-01	0.1, VFG		g		Touching, interlocking, old overgrowths, many pitted grains	75		5	5		15 hematite cement, tr silica cement	sr
HD 24-09-02	0.3, MG		g		Interlocking, overgrowths, tr euhedral faces	80		10	10		silica cement	sr
HD 24-09-03	0.175, FG	0.1-0.25	f		Interlocking, overgrowths, eroded edges	90		5	5			sr
HD 24-09-04	0.25, F-MG		g		Interlocking, tr old overgrowths, tr euhedral overgrowths, some eroded edges	95			5		tr silica cement	sr - und (10%)
HD 24-09-05	0.2, FG	0.05-0.4	p		Interlocking, tr old overgrowths, some eroded edges	80		5	15		tr selenite	sr
HD 24-09-06	0.2, FG	0.1-0.3	f		Interlocking, tr old overgrowths, some eroded edges	85			5			sr - und (10%)
HD 24-09-07	0.1, VFG	0.05-0.25	f		Interlocking, tr old overgrowths, tr euhedral overgrowths, some eroded edges	85		5	10		tr selenite, tr silica cement	sr
HD 24-09-08	0.08, VFG		g		Interlocking, overgrowths, some eroded edges	80		10	10			sr
HD 24-09-09	0.15, FG	0.05-0.5	p		Touching, tr old overgrowths, tr euhedral overgrowths, few eroded edges	70		10	15		5 tr hematite cement, organics	sr
HD 24-09-10	0.125, VF-FG	0.1-0.2	f		Touching to interlocking, tr old overgrowths, some eroded edges	80		15	5		tr hematite cement, organics	sr
HD 24-09-11	0.125, VF-FG	0.08-0.2	p		Touching, silica cemented, tr old overgrowths, few eroded edges	85				5	tr silica cement	sr
HD 24-09-13	0.1, VFG		g		Touching to interlocking, eroded edges	85		5		10	tr calcite cement	sr-und (25%)
HD 24-09-14A	0.165, FG		g		Touching to interlocking, a few eroded edges	80		10	10		tr hematite cement	sr
HD 24-09-14B	0.2, FG		g		Penetrating, interlocking, overgrowths, tr euhedral penetrations	99			1		tr feldspar, silica cement	sr-und (20%)

Section	Grain Size (mm), We-orth	Range (mm)	Sorting	Roundness	Grain contacts	quartz	feld	clay	chert	Minerals	cements, other	Qtz extinction
HD 24-09-14C	0.165, FG	0.125-0.75	f		Penetrating to interlocking, overgrowths, eroded edges	90		5	5		tr calcite	sr
HD 24-09-14D	0.15, FG		g		Touching to penetrating, eroded edges	95			5			sr-und (10%)
HD 24-09-14E	0.25, F-MG		g		Interlocking to penetrating, some euhedral overgrowths and penetrations	95			5		10% volcanic qtz	sr-und (10%)
HD 24-09-15	0.1, VFG		g		Interlocking, touching to penetrating, some eroded edges	75		25			very shaly	sr-und (10%)
HD 24-09-5A	0.125, VF-FG	0.1-0.2	f		Interlocking, overgrowths, some eroded edges and a few euhedral penetrations	85		10		5	tr silica cement, some calcite streaks	sr-und (15%)
HD 24-09-5B	0.125, VF-FG		g		Interlocking, overgrowths, some eroded edges	80			10	10	tr silica cement	sr-und (50%)
HD 24-09-6C	0.125, VF-FG	0.1-0.165	f		Touching to interlocking, tr overgrowths, some eroded edges and a few euhedral penetrations	85		10	5		tr calcite, organics(?)	sr
HD 23-09-01	0.25, F-MG	10 0-0.125	vp		Touching, packed to interlocking, overgrowths, a few eroded edges	45			50	5	tr calcite cement, tr hematite	sr
HD 23-09-3B	0.1, VFG		g		Tr old overgrowths, touching to interlocking, tr euhedral quartz grains	70		30			tr muscovite, clay is kaolinite (Appendix D)	sr-und (10%)
200Z	0.1, VFG	0.7-0.125	f		Touching, a few interlocking grains, tr euhedral faces	70		5	20	5	tr hematite cement, tr calcite clay is kaolinite (Append. D)	sr-und (10%)
H84-21-09-02	0.3, M-CG	5 0-0.1	vp		Touching, tr old overgrowths, well packed	60		15	15	10	tr hematite cement, tr calcite, tr rock fragments	sr-und (15%)
H84-21-09-11	0.1, VFG		g		Interlocking, tr old overgrowths, tr euhedral qtz, tr penetrating quartz grains	85		5		10	tr silica cement	sr-und (20%)
H84-22-09-17	0.2, FG		g		Interlocking, tr old overgrowths, a few eroded edges	80		10	10		tr hematite cement, tr feldspar, tr silica cement	sr

Notes:
 Where there are euhedral quartz overgrowths, there is silica cement.
 Under "cements, other" above, "tr" = trace.
 Framework grains in all samples are quartz.
 All samples have a clay matrix except HD 24-09-11, HD 24-09-14E and HD 24-09-5a which are silica cemented.

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THIN SECTION DESCRIPTIONS, EASTERN SAN JUAN BASIN DAKOTA STUDY

Section	Grain Size (mm), Wentworth	Range (mm)	Sorting	Roundness	Grain contacts	quartz	feld	clay	chert	Minerals calcite	cements, other	Qtz extinction
HD 24-09-01	0.1, VFG		g		Touching, interlocking, old overgrowth, many pitted grains	75		5	5		15 hematite cement, tr silica cement	slr
HD 24-09-02	0.3, MG		g		Interlocking, overgrowth, tr euhedral faces	80		10	10		silica cement	slr
HD 24-09-03	0.175, FG	0.1-0.25	f		Interlocking, overgrowth, eroded edges	90		5	5			slr
HD 24-09-04	0.25, F-MG		g		Interlocking, tr old overgrowth, tr euhedral overgrowth, some eroded edges	90			5		tr silica cement	slr - und (40%)
HD 24-09-05	0.2, FG	.08-0.4	p		Interlocking, tr old overgrowth, some eroded edges	80		5	15		tr sericite	slr
HD 24-09-06	0.2, FG	0.1-0.3	f		Interlocking, tr old overgrowth, some eroded edges	95			5			slr - und (10%)
HD 24-09-07	0.1, VFG	0.09-0.25	f		Interlocking, tr old overgrowth, tr euhedral overgrowth, some eroded edges	85		5	10		tr sericite, tr silica cement	slr
HD 24-09-08	0.06, VFG		g		Interlocking, overgrowth, some eroded edges	80		10	10			slr
HD 24-09-09	0.15, FG	0.05-0.5	p		Touching, tr old overgrowth, tr euhedral overgrowth, few eroded edges	70		10	15	5	tr hematite cement, organics	slr
HD 24-09-10	0.125, VF-FG	0.1-0.2	f		Touching to interlocking, tr old overgrowth, some eroded edges	80		15	5		tr hematite cement, organics	slr
HD 24-09-11	0.125, VF-FG	0.09-0.2	g		Touching, silica cemented, tr old overgrowth, few eroded edges	95			5		tr siliceous cement	slr
HD 24-09-12	0.1, VFG		g		Touching to interlocking, eroded edges	85		5	10		tr calcite cement	slr-und (25%)
HD 24-09-14A	0.165, FG		g		Touching to interlocking, a few eroded edges	80		10	10		tr hematite cement	slr
HD 24-09-14B	0.2, FG		g		Penetrating, interlocking, overgrowth, tr euhedral penetrations	90			1		tr feldspar, silica cement	slr-und (10%)

Notes:
 Where there are euhedral quartz overgrowths, there is silica cement.
 Under "cements, other" above, "tr" = trace.
 Framework grains in all samples are quartz.
 All samples have a clay matrix except HD 24-09-11, HD 24-09-14E and HD 24-09-5a which are silica cemented.

Section	Grain Size (mm), Wentworth	Range (mm)	Sorting	Roundness	Grain contacts	quartz	feld	clay	chert	Minerals calcite	cements, other	Qtz extinction
HD 24-09-14C	0.165, FG	0.125-0.75	f		Penetrating to touching, overgrowth, eroded edges	90		5	5		tr calcite	slr
HD 24-09-14D	0.15, FG		g		Touching to penetrating, eroded edges	95			5			slr-und (10%)
HD 24-09-14E	0.25, F-MG		g		Interlocking to penetrating, some euhedral overgrowth and penetrations	95			5		10% volcanic Qtz	slr-und (10%)
HD 24-09-15	0.1, VFG		g		Interlocking, touching to penetrating, some eroded edges	75		25			very thin	slr-und (10%)
HD 24-09-5A	0.125, VF-FG	0.1-0.2	f		Interlocking, overgrowth, some eroded edges and a few euhedral penetrations	65			10	5	tr silica cement, some calcite appears	slr-und (15%)
HD 24-09-5B	0.125, VF-FG		g		Interlocking, overgrowth, some eroded edges	80			10	10	tr silica cement	slr-und (50%)
HD 24-09-5C	0.125, VF-FG	0.1-0.165	f		Touching to interlocking, tr overgrowth, some eroded edges and a few euhedral penetrations	65		10	5		tr calcite, organics(?)	slr
HD 24-09-01	0.25, F-MG	10.0-0.125	VD		Touching, packed to interlocking, overgrowth, a few eroded edges	45			50	5	tr calcite cement, tr hematite	slr
HD 24-09-08	0.1, VFG		g		Tr old overgrowth, touching to interlocking, tr euhedral quartz grains	70		30			tr muscovite, clay is kaolinite (Appendix D)	slr-und (10%)
2852	0.1, VFG	0.7-0.125	f		Touching, a few interlocking grains, tr euhedral faces	70	5	20	5		tr hematite cement, tr calcite clay is kaolinite (Append. D)	slr-und (10%)
H84-21-09-02	0.5, M-CG	6.0-0.1	VF		Touching, tr old overgrowth, well pitted	60	15	15	10		tr hematite cement, tr calcite, tr rock fragments	slr-und (15%)
H84-21-09-11	0.1, VFG		g		Interlocking, tr old overgrowth, tr euhedral Qtz, tr penetrating quartz grains	85	5		10		tr silica cement	slr-und (20%)
H84-22-09-17	0.2, FG		g		Interlocking, tr old overgrowth, a few eroded edges	80		10	10		tr hematite cement, tr feldspar, tr silica cement	slr

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Section	Grain Size (mm), Wentworth	Range (mm)	Sorting	Roundness	Grain contacts	quartz	feld	clay	chert	calcite	cements, other	Qtz extinction
HD 24-09-01	0.1, VFG		g		Touching, interlocking, old overgrowths, many silted grains	75		5			15 hematite cement, tr silica cement	str
HD 24-09-02	0.3, MG		g		Interlocking, overgrowths, tr euhedral faces	80		10	10		silica cement	str
HD 24-09-03	0.175, FG	0.1-0.25	f		Interlocking, overgrowths, eroded edges	90		5	5			str
HD 24-09-04	0.25, F-MG		g		Interlocking, tr old overgrowths, tr euhedral overgrowths, some eroded edges	95			5		tr silica cement	str-und (40%)
HD 24-09-05	0.2, FG	0.05-0.4	p		Interlocking, tr old overgrowths, some eroded edges	80		5	15		tr calcite	str
HD 24-09-06	0.2, FG	0.1-0.3	f		Interlocking, tr old overgrowths, some eroded edges	95			5			str-und (10%)
HD 24-09-07	0.1, VFG	0.05-0.25	f		Interlocking, tr old overgrowths, tr euhedral overgrowths, some eroded edges	85		5	10		tr calcite, tr silica cement	str
HD 24-09-08	0.08, VFG		g		Interlocking, overgrowths, some eroded edges	80		10	10			str
HD 24-09-09	0.15, FG	0.05-0.5	p		Touching, tr old overgrowths, tr euhedral overgrowths, few eroded edges	70		10	15	5	tr hematite cement, organics	str
HD 24-09-10	0.125, VF-FG	0.1-0.2	f		Touching to interlocking, tr old overgrowths, some eroded edges	80		15	5		tr hematite cement, organics	str
HD 24-09-11	0.125, VF-FG	0.05-0.2	p		Touching, silica cemented, tr old overgrowths, few eroded edges	95				5	tr silica cement	str
HD 24-09-13	0.1, VFG		g		Touching to interlocking, eroded edges	85		5		10	tr calcite cement	str-und (25%)
HD 24-09-14A	0.165, FG		g		Touching to interlocking, a few eroded edges	80		10	10		tr hematite cement	str
HD 24-09-14B	0.2, FG		g		Penetrating, interlocking, overgrowths, tr euhedral penitensions	98		1			tr kinktop, silica cement	str-und (20%)

Notes:

Where there are euhedral quartz overgrowths, there is silica cement.

Under "cements, other" above, "tr" = trace.

Framework grains in all samples are quartz.

All samples have a clay matrix except HD 24-09-11, HD 24-09-14B and HD 24-09-5a which are silica cemented.

Section	Grain Size (mm), Wentworth	Range (mm)	Sorting	Roundness	Grain contacts	quartz	feld	clay	chert	calcite	cements, other	Qtz extinction
HD 24-09-14C	0.165, FG	0.125-0.75	f		Penetrating to touching, overgrowths, eroded edges	90		5			tr calcite	str
HD 24-09-14D	0.15, FG		g		Touching to penetrating, eroded edges	95			5			str-und (10%)
HD 24-09-14E	0.25, F-MG		g		Interlocking to penetrating, some euhedral overgrowths and some eroded	85			5		10% volcanic qtz	str-und (10%)
HD 24-09-15	0.1, VFG		g		Interlocking, touching to penetrating, some eroded edges	75		25			very shaly	str-und (10%)
HD 24-09-5a	0.125, VF-FG	0.1-0.2	f		Interlocking, overgrowths, some eroded edges and a few euhedral penitensions	65		10	5		tr silica cement, some calcite streaks	str-und (15%)
HD 24-09-5B	0.125, VF-FG		g		Interlocking, overgrowths, some eroded edges	60			10	10	tr silica cement	str-und (50%)
HD 24-09-5C	0.125, VF-FG	0.1-0.185	f		Touching to interlocking, tr overgrowths, some eroded edges and a few euhedral penitensions	85		10	5		large calcite, organics(?)	str
HD 24-09-01	0.25, F-MG	0.05-0.125	vp		Touching, packed to interlocking, overgrowths, a few eroded edges	45			50	5	tr calcite cement, tr hematite	str
HD 24-09-5D	0.1, VFG		g		Tr old overgrowths, touching to interlocking, tr euhedral quartz grains	70		30			tr muscovite, clay is kaolinite (Appendix D)	str-und (10%)
20BZ	0.1, VFG	0.7-0.125	f		Touching, a few interlocking grains, tr euhedral faces	70		5	20	5	tr hematite cement, tr calcite clay is kaolinite (Append. D)	str-und (10%)
H84-21-49-07	0.5, M-CG	5.0-0.1	vp		Touching, tr old overgrowths, well packed	80		15	15	10	tr hematite cement, tr calcite, tr rock fragments	str-und (15%)
H84-21-49-11	0.1, VFG		g		Interlocking, tr old overgrowths, tr euhedral qtz, tr penetrating quartz grains	85		5		10	tr silica cement	str-und (20%)
H84-22-49-17	0.2, FG		g		Interlocking, tr old overgrowths, a few eroded edges	80			10	10	tr hematite cement, tr kinktop, tr silica cement	str

APPENDIX C

DEPOSITIONAL ENVIRONMENT TABLES

Tables C.1 and C.2 on the next two pages describe some of the defining characteristics of the depositional environments encountered in the study area.

Table C.1 -Tidal Flat Environment				
	Gravel Flat*	Mud Flat	Mixed Flat	Sand Flat
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, bidirectional 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 into clay drapes
Horizontal tidal oscillation	Very high to low - storm tides, spring tides	Low to high - upper normal tide zone	Low to moderate	Moderate, bidirectional
Boundaries	Sharp on underlying reworked beds	Gradational from underlying mixed flat	Gradational to scour	Gradational, much scour
Ichnofossils			<i>Skolithos</i> , <i>Planolites</i>	<i>Skolithos</i> , <i>Arenicolites</i> , <i>Diplocraterion</i>
Diversity		Low	Low	Moderate
Abundance		Rare	Low to moderate	Moderate
<p>* 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.</p> <p>References: Pemberton and Frey, 1992, MacEachern and Pemberton, 1992, Dalrymple, 1992, Sellwood, 1975, McKenzie, 1975</p>				

Table C.2 - Shoreline Environment

	Foreshore	Shoreface			Offshore
		Upper	Middle	Lower	
Bedding	Subparallel to low angle seaward dipping laminations - wedge sets	Subparallel to low angle seaward dipping wedge sets, multidirectional trough cross stratification, bidirectional 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	F → 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, swash zone, 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 fairweather wave base
Boundaries	Much scour and crossbedding		Gradational to sharp, erosive	Gradational to sharp, erosive	Gradational to sharp, erosive
Ichnofossils*	<i>Skolithos</i> , <i>Macaronichnus</i>	<i>Skolithos</i> ichnofacies	<i>Skolithos</i> ichnofacies	<i>Cruziana</i> ichnofacies	Restricted to full <i>Cruziana</i> 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, 1992

APPENDIX D

CLAY MINERAL ANALYSES

Sample H84 20BZ and sample HD 23-09-5B were submitted for x-ray diffraction analysis. On outcrop, the zones from which these sample were taken appeared to be just under a subaerially exposed erosion surface, but at locations about 22 miles apart. The purpose of the clay mineral analysis was to determine if the mineralogy of the zones was consistent with subaerial exposure.

Results

These are the analysis results as reported from the laboratory.

X-ray Fluorescence

Semi-Quantitative Elemental from X-ray Fluorescence (weight %)

	Si	Al	Fe	Ti	Cl	S	Mg	K	Zr
H84 BZ	71	23	2.1	1.2	0.8	0.5	0.3	0.3	0.2
23-09-5B	71	25	1.0	1.9		0.5	0.1	0.4	0.2

X-ray Diffraction: Whole Rock Mineralogy

Both samples appear similar, a mixture of quartz and clay. Based on the elemental above, there is sufficient aluminum available to yield up to 60 wt% kaolinite in the rocks. Some of the aluminum may be present in an

amorphous form, such as gibbsite. There is likely some trace zircon and pyrite.

X-ray Diffraction: Clay Mineralogy

Sample H84 BZ clay fraction contains well formed kaolinite.

Sample 23-09-5B clay fraction is a mixture of corrensite (mixed-layer clay, 50% chlorite:50% illite with long range ordering) and kaolinite. Relative estimates of the amount of each, based on external standards, is 60 wt% corrensite and 40 wt% kaolinite in the <2 micron fraction; 60:40 kaolinite: corrensite in the 2-8 micron fraction, and 80:20 kaolinite:corrensite in the 10 micron fraction. Thus, the mixed-layer clay, which has a small crystal habit, is concentrated in the finest fractions. A rough estimate of the bulk composition is 70% kaolinite:30% corrensite. The corrensite has strong odd order basal plane reflections (001, 003, 005) and weak even ordered reflections (002, 004). This intensity pattern is indicative of high iron chlorite in the corrensite mixed-layer clay, in both the octahedral layer and the hydroxide layer.

Analysis Procedures

Analysis involves both whole rock and clay mineral fractions.

Whole rock analysis

Rock samples were crushed in a Jaw Crusher” to ¼ inch grains and homogenized. One portion was transferred to a McCrone Micronizing mill and milled for 20 minutes under alcohol (IPA) to reduce average particle size to 5 microns. The slurry was air-dried and the powder mounted in a Siemens random powder holder. These preparations were then scanned in a Siemens D5000 x-ray diffractometer over the range of 2 to 70 degrees two-theta with a step size of 0.03 degrees.

A second portion of the sample was pressed into a powder pellet and analyzed on the Siemens SRS 303 x-ray spectrometer. A semi-quantitative program was employed that reports all elements from sodium to uranium at the 500 ppm level and greater.

Diffraction mineralogy and elemental chemistry data are jointly employed to calculate a semi-quantitative mineralogy, with typical errors on the order of plus or minus 15% of the amount of mineral reported.

Clay Mineralogy

The remainders of the crushed grains are chemically digested in a solution of sodium acetate buffered to a pH of 5.7 to remove cements. Acid applications are repeated until all cement is removed and fines are present in the suspension. The suspension is repeatedly washed with distilled water until all chloride ions are removed based on a test of precipitate forming from

silver nitrate additions. Next, two size fractions, less than 2 micron and 2 to 8 micron, of the deflocculated fines are collected by centrifugation. Oriented clay mounts are made from each size fraction. These mounts are scanned on the x-ray diffractometer over a range of 2 to 40 degrees two-theta with a step size 0.02 degrees per step. They are first scanned air-dried and then a second time after saturation with ethylene glycol vapors. If necessary, heat treatments may be necessary to identify some clay types. Semi-quantitative clay mineralogy is calculated from external standards run previously on the instrument.

Data Plots

X-ray diffraction data are plotted in figure D.1 and D.2

Figure D.1: Whole rock result. Intensity in counts vs. 2-Theta in degrees. Kaolinite and silicon oxide indicated.

Figure D.2: Clay mineral result. Intensity in counts vs. 2-Theta in degrees. Kaolinite peaks indicated

APPENDIX E

BENTONITE AGE DATING

The $^{40}\text{Ar}/^{39}\text{Ar}$ method is a relative dating technique based on a standard. The testing laboratory used a standard sanidine from the Fish Canyon Tuff. This standard is used by many labs, however the age of the standard is debated. The USGS uses an age of 27.55 Ma, they use 27.84, and Berkeley uses about 28.02 Ma. Therefore, based on the USGS calibration, the lab's 93.12 Ma age would be 92.15 Ma and based on Berkeley it would be 93.72 Ma. This is important because when $^{40}\text{Ar}/^{39}\text{Ar}$ data are taken to the absolute level for time-scale work, the age of the standard becomes an important issue (Matt Heizler, 1999, pers. comm).

The full Ar/Ar age date report is reproduced on the following pages.

Information: 505/835-5420
Publications: 505/835-5410
FAX: 505/835-6333
E-mail: bmrc@igis.unm.edu

New Mexico Bureau of Mines & Mineral Resources

A DIVISION OF
NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY
801 Leroy Place
Socorro, NM 87801-4796

Oct. 29, 1999

Peter J. Varney
5903 South Fairfield St.
Littleton, CO 80120

Dear Peter,

Enclosed is the report for the $^{40}\text{Ar}/^{39}\text{Ar}$ analysis of your bentonite sample. The sanidines yield straight-forward results and indicate an age of 93.12 ± 0.50 Ma for the bentonite.

Please don't hesitate to contact the lab if you have any questions regarding the age results. Also, we request notification of publication of the results prior to formal submission to a journal or elsewhere.

Sincerely,

A handwritten signature in black ink, appearing to read "M. Heizler", with a horizontal line extending to the right.

Dr. Matthew Heizler
Geochronologist

Introduction

Two bentonite samples from the Dakota Formation collected in the northeastern San Juan Basin were submitted for dating by Peter Varney. A sample at Heron Dam located in the Chama River canyon did not yield any sanidine, however sanidine was separated from an outcrop along highway 84. The sample was dated to determine if the ash is lower Cenomanian.

$^{40}\text{Ar}/^{39}\text{Ar}$ Analytical Methods and Results

Twelve sanidine single crystals were separated from H84 and analyzed by the laser total fusion method. Abbreviated analytical methods for the samples are given in Table 1, and details of the overall operation of the New Mexico Geochronology Research Laboratory are provided in the Appendix. The argon isotopic results are listed in Table 2.

The age results are presented on a probability distribution diagram (Figure 1). The ages are normally distributed about their errors ($\text{MSWD} = 1.2$) and the weighted mean of all analyses yields an age of 93.12 ± 0.50 Ma (Fig. 1; Table 2). Some analyses have radiogenic yields greater than 100% and undefined K/Ca ratios due to the inability to measure ^{36}Ar and ^{37}Ar , respectively (Table 2).

Discussion

The weighted mean age of 93.12 ± 0.50 Ma is interpreted to yield the deposition age of the ash. This age is consistent with the bentonite being Cenomanian.

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Figure 1. Probability distribution diagram for H84 sanidine single crystal analysis.

Table 1. Analytical methods.

Sample preparation and irradiation:

Mineral phases concentrated by dissolving glass and matrix from the crushed rock in 15% HF. K-feldspar separated with standard heavy liquid, Franz Magnetic and hand-picking techniques.

K-feldspars were loaded into a machined Al disc and irradiated for 7 hours in D-3 position, Nuclear Science Center, College Station, TX. Neutron flux monitor Fish Canyon Tuff sanidine (FC-1). Assigned age = 27.84 Ma (Deino and Potts, 1990) relative to Mmhb-1 at 520.4 Ma (Samson and Alexander, 1987).

Instrumentation:

Mass Analyzer Products 215-50 mass spectrometer on line with automated all-metal extraction system.

Single crystals were fused by a 50 watt Synrad CO₂ laser.

Reactive gases removed during a 2 minute reaction with 2 SAES GP-50 getters. 1 operated at -450°C and 1 at 20°C. Gas also exposed to a W filament operated at -2000°C and a cold finger operated at -140°C.

Analytical parameters:

Electron multiplier sensitivity averaged 1.75×10^{-16} moles/pA.

Total system blank and background averaged 525, 8, 2, 5, 6 $\times 10^{-10}$ moles

J-factors determined to a precision of $\pm 0.1\%$ by CO₂ laser-fusion of 4 single crystals from each of 4 radial positions around the irradiation tray.

Correction factors for interfering nuclear reactions were determined using K-glass and CaF₂ and are as follows:

$(^{40}\text{Ar}/^{39}\text{Ar})_k = 0.00020 \pm 0.0003$; $(^{39}\text{Ar}/^{39}\text{Ar})_{\text{Ca}} = 0.00028 \pm 0.00011$; and $(^{39}\text{Ar}/^{39}\text{Ar})_{\text{K}} = 0.00089 \pm 0.00003$.

Age calculations:

Weighted mean age calculated by weighting each age analysis by the inverse of the variance.

Weighted mean error calculated using the method of (Taylor, 1982).

MSWD values calculated for n-1 degrees of freedom.

Decay constants and isotopic abundances following Steiger and Jäger (1977).

All final errors reported at $\pm 2\sigma$, unless otherwise noted.

Table 2. Argon isoptic results.

ID	$^{40}\text{Ar}/^{39}\text{Ar}$	$^{37}\text{Ar}/^{39}\text{Ar}$	$^{38}\text{Ar}/^{39}\text{Ar}$	$^{36}\text{Ar}_K$	K/Ca	% $^{40}\text{Ar}^*$	Age	$\pm 1\sigma$
			($\times 10^{-3}$)	($\times 10^{-18}$ mol)			(Ma)	(Ma)
H84 sanidine, single crystal, J=0.0007996, NM-110, Lab#=50504								
15	65.29	0.0000	0.5333	1.93	-	99.8	91.6	1.5
12	65.83	0.0028	1.393	6.49	185.0	99.4	91.98	0.52
02	65.59	0.0029	0.4745	3.49	175.5	99.8	92.03	0.97
10	65.47	0.0525	-1.4537	2.65	9.7	100.7	92.6	1.1
09	65.00	0.0217	-3.3735	3.30	23.5	101.5	92.78	0.88
11	66.01	0.0031	-0.5704	3.46	163.4	100.3	93.03	0.87
07	66.33	0.0022	-0.5211	4.10	230.0	100.2	93.45	0.78
03	66.04	0.0000	-1.8307	2.94	-	100.8	93.6	1.1
13	67.62	0.0204	3.299	5.19	25.0	98.6	93.67	0.66
14	66.70	0.0102	-0.6039	2.75	50.2	100.3	94.0	1.1
08	67.21	0.0175	0.8865	5.79	29.2	99.6	94.08	0.55
06	65.94	0.0000	-3.5824	2.86	-	101.6	94.1	1.0
WM age		MSWD=1.20	n=12				93.12	0.50*

Notes:

n= number of analyses used for weighted mean calculation

Isotopic ratios corrected for blank, radioactive decay, and mass discrimination, not corrected for interfering reactions.

Individual analyses show analytical error only; weighed mean age error includes error in J and irradiation parameters.

K/Ca = molar ratio calculated from reactor produced $^{39}\text{Ar}_K$ and $^{37}\text{Ar}_{Ca}$.- no detectable ^{37}Ar .* 2 σ error

APPENDIX F

CORED WELLS NEAR THE SOUTH

LINDRITH FIELD

There are two wells near the South Lindrith Field that were cored in the Dakota interval. They confirm that observed outcrop lithologies continue into the subsurface. They are the:

Meridian #3 Arco Little Federal 32, NESW 32, T24N R3W

Cotton Petroleum #113 Apache, NWSE 1, T24N R4W

Figure F.1 and Figure F.2 are subsurface logs of the two wells with a lithology column and core description. Of the two, the Meridian well is closest, being approximately 4.5 miles northeast of the South Lindrith Field. Only part of the original cored interval, as reported on completion cards, is available for description.

In the Meridian well, the cored interval includes uKdPS4 and uKdPS5 at the top of the Dakota and uKd PS1 on the S3 surface. Unit uKdPS1 contains some medium-grained sand grains and shell fragments. This supports the higher energy environment noted in this unit on outcrop.

A third nearby cored well, Southland Royalty #7 Medio Canyon in section 35

Figure F.2: Portion of the Meridian (Odessa Natural) #3 ARCO Little Federal 32 well with core description.

of T24N R4W had only sidewall cores reported on the completion card. The cores do not appear to be available.