DEPOSITIONAL SYSTEMS AND PERMEABILITY DISTRIBUTION
OF FLUVIAL-ALLUVIAL-EOLIAN DEPOSITS OF SIERRA
LADRONES FORMATION, APPLIED TO
PETROLEUM MIGRATION IN THE
ALBUQUERQUE BASIN
NEW MEXICO

by

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For my Mom, Dad, Brothers, Sisters, and Nunung
ABSTRACT

The Upper Sierra Ladrones Formation southwest of Bosque, New Mexico is located in southern half-graben of the Albuquerque Basin. The 21-30 meter thick deposits within my study area show fining-upward vertical sequences. The various types of lithofacies are produced by combinations of fluvial, alluvial, and eolian systems. These processes control the lateral and vertical geometry of each lithofacies. Some are more continuous than others. Vertical aggradation reflects decreasing stream power in channels, but also occurs on floodplains and in eolian settings. Some lithofacies interfinger and pinch-out. Different depositional processes may take place laterally at the same depositional level within the sequence.

Depositional systems control the permeability distribution in my study area, especially gravelly sandstones and sandstone lithofacies of channel-fill deposits. Gravelly sands have the biggest permeability value, followed by sandstone lithofacies derived from fluvial systems and finally sandy lithofacies from the eolian system. Their permeability values are reduced by increasing cementation and soil development and decreasing grain size distribution. Paleoflow in channels is determined by the sedimentary structures and is generally from a NW direction. Concretions and differential cementation are also oriented NW-SE.

Oil migration occur in layers having laterally continuous permeability distributions. The changes of permeability through time are caused by cementation. Such changes affect the direction of migration as well.
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CHAPTER 1 INTRODUCTION

Petroleum geologists are developing alternative techniques for increasing oil production while reducing costs of production. Two alternative ideas are to explore for new oil wells or stimulate oil production from formerly non-productive zones. In order to develop or to stimulate oil production, the permeability distribution and depositional model of the prospective area should be known. Therefore, geologic units within the site, the permeability patterns within the geologic units, and lateral correlation of permeability and lithofacies distribution are required to achieve this goal.

Hydrocarbons commonly migrate both laterally and vertically in the opposite direction of water movement (Braester et al., 1991). These lateral and vertical migration pathways are governed by temperature, capillary pressure, density of oil, and water buoyancy. The flows follow simple geometric rules, and therefore can be estimated. In most cases, vertical migration controls major hydrocarbon accumulation (Pratsch, 1991).

The purpose of this study is to achieve better understanding of relationships between the depositional system and permeability distribution applied to petroleum migration. This study classifies the deposits into lithofacies. The term "lithofacies" is defined as "a body of rock with certain specified attributes that distinguish it from other rock units" (Leeder, 1982). Conybeare, (1979) implies lithofacies is "a lateral change of rock type within a time-stratigraphic unit in response to a change in depositional environment". This change may reflect a change of climatic, paleogeographic, or other aspects. Depositional systems in the study area are interpreted from the lateral and vertical distribution of lithofacies. Both lateral and vertical lithofacies distribution govern the permeability behavior and distribution of petroleum. The lithologies are not always wide-spread; they may pinch out. Allen, (1974) determined that the sedimentology in alluvial-fluvial systems is controlled by autocyclic and allocyclic responses. Autocyclic adjustments control river movement as the result of changes in energy within a
sedimentary basin. Allocyclic responses, on the other hand, control the river as a result of climatic and tectonic changes. Because Allen's (1974) models for depositional shifts in river systems are good for distinguishing different kinds of depositional situations, results of this study will be compared to the models. Instead of merely describing the area with ten vertical measured sections, this study also measures the permeability value of each unconsolidated sandy lithofacies. The permeability distributions are determined by measuring the orientation of concretions.

Although previous workers in the study area utilized architectural elements for their classification, this study uses lithofacies. None-the-less direct comparisons may still be made between the present and past.

The field site chosen is approximately 1.3 km long and located southwest of Bosque, New Mexico, south of the areas studied by Davis, (1990,1993), Lohmann, (1992), and Gotkowitz (1993) (Figure 1.1). This study traces deposits of fluvial-alluvial-eolian systems continuing south of their mapped areas. This study concentrates on gravelly sands and sandstone lithofacies, because their permeability is measurable and continuous through out the mapped area. Interbedded sand-silt-clay and paleosols are not considered in as much detail in this study because they have lower permeability. This field site was chosen because of the presence of continuous sandstone and gravelly sand lithofacies that are generally bounded by clay-silt and paleosol lithofacies along the mapped area. This permeable and continuous lithofacies will represent a good example of reservoir lithofacies for estimating petroleum migration. Besides, there were several previous workers that had already done permeability measurements within Bosque site.
Figure 1.1. Site location of the Field area (black box)
CHAPTER 2 GEOLOGIC SITE

2.1 Site Location

The study area is located southwest of Bosque, Valencia County, central New Mexico. It is 48 - 60 km north of Socorro. The field site is in the south-central portion of Albuquerque Basin, along north-south trending eastern escarpment of the Llano de Albuquerque (Lozinsky 1988 ; figure 2.1). The site is bounded by latitudes 34° 32" 15' - 34° 33" 45' N and 106° 48" 00' - 106° 48" 30' W longitudes on the Veguita quadrangle map with scale of 1 : 24,000. The basin fill is exposed at the surface by down cutting of valleys rather than uplift of the basin center in Late Pleistocene (Lozinsky et al., 1991). The bluffs are 100 m high but I only studied the middle 30 m of exposures along 1.3 km.

2.2 Basin-Filling History of the Albuquerque Basin

Sediments within the mapped area are composed of fluvial-alluvial-eolian deposits (Davis, 1990,1993; Lohmann, 1992), which comprise the upper part of Sierra Ladrones Formation. Fluvial deposits are distributed by three major rivers, Rio Puerco, Rio Grande and Rio San Jose. The Rio Grande is the largest perennial river to traverse the Bosque site. The ancestral Rio Grande had braided character in the Albuquerque basin (Lozinsky, 1988). Both Rio Puerco and Rio San Jose were sometimes braided rivers (Stephens et al., 1988) flowed to the east, coalesced and fed the Rio Grande.

The Sierra Ladrones and Popatosa Formations are units that filled the Albuquerque Basin and form Santa Fe Group (Table 2.1). From Late Oligocene (30 Ma) until Late Miocene (5 Ma), the Albuquerque Basin formed by rifting in two major episodes (Chapin and Seager, 1975; Seager et al., 1984). The Popatosa Formation is the first deposit that accumulates in the basin during that time. This formation was deposited in a closed basin system.
Figure 2.1 Stratigraphic relationship of Popotosa and Sierra Ladrones Formations that form the Santa Fe Group (Lozinsky, 1991). Units 1 to 3 are specific to the Gabaldon badlands.

<table>
<thead>
<tr>
<th>Lithologic unit</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sierra Ladrones Formation</td>
<td>Pleistocene</td>
</tr>
<tr>
<td></td>
<td>Pliocene</td>
</tr>
<tr>
<td>Popotosa Formation</td>
<td></td>
</tr>
<tr>
<td>unit 3</td>
<td></td>
</tr>
<tr>
<td>unit 2</td>
<td>Miocene</td>
</tr>
<tr>
<td>unit 1</td>
<td></td>
</tr>
<tr>
<td>unit of Isleta #2 well</td>
<td>Oligocene</td>
</tr>
<tr>
<td>Baca Formation</td>
<td>Eocene</td>
</tr>
</tbody>
</table>

Figure 2.2. Position of field area in the South Albuquerque Basin half-graben systems (Lozinsky, 1988)
Sierra Ladrones Formation, on the other hand, began to be deposited when the Rio Grande flowed across the basin and deposited sediment on top of the basin floor facies of the Popatosa Formation (Lozinsky et al., 1991).

Based on outcrop and borehole analysis, there are three primary depositional facies which are: basin-margin alluvial fans, eolian facies, and playa facies at the center of the basin (Lozinsky, 1988). During Pliocene-Pleistocene time, alluvial - fluvial - eolian depositional facies of Sierra Ladrones Formation aggraded in the Albuquerque Basin. The Popatosa and Sierra Ladrones Formation are separated by a distinctive boundary of fluvial deposits along the axis of the basin. The sediments are now inclined about 1-2 m per 1 km southward. The aggradational system in Bosque site is dominated by several vertical sequences of fluvial-alluvial-eolian deposits and pedogenic overprints.

2.3 Previous Workers of the Upper Sierra Ladrones Formation

The Bosque site has been studied by Lohmann (1992), Gotkowitz (1993) and Davis, (1990; 1993). Their studies emphasized heterogeneity of the aquifer for hydrologic importance. Young et al. (1982) and Lozinsky et al. (1988; 1991) studied the Sierra Ladrones Formation. Although their area was not in my study area, they contributed valuable information. Young et al. (1982) determined that the pebbles along the Llano de Albuquerque escarpment were derived from three main rivers: Rio Grande, Rio Puerco, and Rio San Jose. Lozinsky et al. (1988 and 1991) described the general depositional system of the Albuquerque basin where sedimentation and rifting took place (Figure 2.2 and 2.3). Harris (1991) did point counts on coarse sand grains from three major distributary rivers, Rio Grande, Rio Puerco, and Rio San Jose as well as deposits from the Bosque site. Davis (1990,1993) separated the deposits within the Bosque site into seventeen elements. Lohmann (1992) described similar deposits by using
Figure 2.2 Hypothetical geometry of Albuquerque Basin during deposition of upper Sierra Ladrones Formation (Lozinsky, 1988) Arrows indicate source areas and clast types derived from those areas. PC = Precambrian, RS = Reworked sedimentary rocks, IV = intermediate volcanic rocks, BV = mafic volcanic rocks, ML = mixed lithologies, Approximate location of Bosque site is shown by black circle.
Davis' classification but he grouped the seventeen facies into four groups, CH I, CH II, OF and Paleosols. Both Davis (1990, 1993) and Lohmann (1992) utilized Miall's (1985, 1988) architectural element model (AEM; see Table 2.1). Facies presented in Table 2.1 basically are similar to the lithofacies in my study area, such as Gm, Gt, and Gms are the similar to Gs lithofacies in my classification; St, Sfl are similar with Ss1; Smb, Sr are similar to Ss2; Sl and Sm are similar to Ss3. Fr, Fm, Fsc are similar to paleosols lithofacies (P); Fr,Fm,Fsc and P are similar to ISS lithofacies. However, not all of the Davis' classification are found in my study area. Some of them are probably continuous or pinch-out. Therefore, I utilized different lithofacies with different symbol too.

Chapin and Cather (1995) determined the boundary between Popatosa Formation and Sierra Ladrones Formation as the onset of the through flowing arcestral Rio Grande. Mozley, (1995, in revision) discusses the paleocurrents of Upper Sierra Ladrones Formation based on distribution of the concretions within the Bosque site.
Table 2.1. Comparison of facies grouping for definition of Architectural Elements at Bosque Site (Mulyadi, 1995; Lohmann, 1992; modification from Davis 1990).

<table>
<thead>
<tr>
<th>Facies Present (Mulyadi, 1995)</th>
<th>Facies Present (Lohman, 1992)</th>
<th>Description / Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gs, Ss1, Ss2</td>
<td>Gm, Gt, Sp, St, Sl, Sgm (CH-1)</td>
<td>Channel element consists dominantly gravelly and coarse sand facies</td>
</tr>
<tr>
<td>Ss1, Ss2</td>
<td>Gms, St, Sp, Sfl, Sh, Sl, Smb, Fl, Fm, Fsc (CH-2)</td>
<td>Sand and sand-sized clay clasts dominate with local lag gravel deposits</td>
</tr>
<tr>
<td>Ss3, Ss4</td>
<td>---</td>
<td>Eolian deposits</td>
</tr>
<tr>
<td>P</td>
<td>P, Sm, Fsc (P)</td>
<td>Soil and Stacked Soils</td>
</tr>
<tr>
<td>ISS</td>
<td>Fr, Fm, Fsc, P (OF)</td>
<td>Overbank fines</td>
</tr>
</tbody>
</table>
CHAPTER 3 METHODOLOGY

As an extension of Lohmann's (1992), Davis' (1993) and Gotkowitz' (1993) field work, this study will also quantify the geologic features near Bosque, New Mexico, with the following methodology: i) lithofacies description and lateral mapping of geologic deposits, ii) measuring the permeability of individual coarse facies, iii) relate the observed sedimentary structures to depositional environment, iv) correlate the measured vertical sections to obtain a 2-D horizontal lithofacies distribution, and v) relate the depositional system to the permeability distribution. These last two are approached in the discussion section.

3.1 Lithofacies Description and Lateral Mapping

Consecutive vertical sections were measured and described using a jacob staff, shovel and 100 m tape. Even with ten vertical sections over 1.3 km of outcrop the depositional facies could not be correlated from section to section, therefore, horizontal tracing between the sections was done by walking to define the boundary geometry of each lithofacies.

Sections were located on a topographic base map (Veguita 7.5 minute quadrangle map). Areal photographs were also used for morphologic description and location of the outcrops. Three sections were done in 1993, and the rest finished during summer, 1994.

Based on the vertical sections, I classify the deposits into four lithofacies. Lithofacies and geometric description such as thickness, lateral distribution, and cross-sectional shapes of the deposits were determined during measuring sections. An "Apple Core" computer program was used after field data were collected for producing better plots of the vertical sections.
3.2 Permeability Measurement

A mini-airpermeameter (Davis et al., 1994) was used to obtain permeability values. This method is well-suited to obtaining in situ measurements on outcrops of dry sediment. First, I selected the permeable deposits such as sands and gravels, because the mini-airpermeameter cannot be applied to deposits of silt and clay due to their sizes. Before applying the mini-airpermeameter I cleaned a vertical surface and let the exposure dry for several days. The measurements were taken by putting the tip of the mini-airpermeameter directly to the outcrop surface. The permeameter measures the amount of time it takes to blow a volume of air into the outcrop. The value that I obtained was time (in seconds), so to convert these values to obtain real permeability I used the formula (from Davis et al., 1994):

\[
k = \frac{2 \mu q \Pi_1}{a G_0 (b_o) (\Pi_1^2 - \Pi_0^2)}
\]

Where \( k \) = permeability \([m^2]\); \( \mu \) = viscosity of air \([Pa \ s]\); \( q \) = volumetric flow rate \([m^3/s]\); \( \Pi_1 \) = pressure applied on tip seal / outcrop interface \([Pa]\); \( a \) = radius of tip seal orifice \([m]\); \( G_0 \) = geometric factor \([\text{dimensionless}]\); \( b_o \) = dimensionless tip seal radius \((b/a)\) \([\text{dimensionless}]\); \( b \) = outer radius of tip seal \([m]\); and \( a \) = inner radius of tip seal \([m]\).

All values except \( k \) and \( q \) are not known but the time is known, thus, \( q \) can be calculated and \( k \) can also be ultimately known. An example of calibration is shown in appendix IV.

3.3 Relation Between Sedimentary Structures and Depositional Environment

Sedimentary structures provide information about depositional mechanisms. From the depositional mechanisms, lateral distribution, and vertical sequence we can interpret the appropriate sedimentary environment. However, some of the structures are not
obvious. They might be obliterated by soil development or they might be locally absent, or they might be similar in many environments. For example, ripple stratification may form in fluvial and eolian environments. Therefore, instead of just comparing the orientation and geometry of sedimentary structures, vertical and lateral relationships are also applied to interpret an appropriate depositional environment (Table 3.1, 3.2 and 3.3).

The most common sedimentary structures in sandy gravel deposits at the Bosque site are (1) pebble imbrication, which is comprised of various orientations depending on depositional environment; (2) cross bedding, which is also has variety forms depending on depositional environment, such as: channel fill cross bedding, sand dunes cross bedding, micro delta cross bedding; (3) parallel lamination and (4) scour.
Table 3.1 Basic types of stratifications and mechanisms in eolian deposits (Hunter, 1977)

<table>
<thead>
<tr>
<th>Depositional process</th>
<th>Character of depositional surface</th>
<th>Type of stratification</th>
<th>Dip angle</th>
<th>Thickness of strata</th>
<th>Angularity of contacts</th>
<th>Separation of grain types</th>
<th>Packing</th>
<th>Form of surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rippled</td>
<td>Subsequently disturbed, transverse stratiations.</td>
<td>Stratification low (typically 0-10°), transition to high (up to 30°).</td>
<td>Typically 0-10°, maximum 30°.</td>
<td>Flat, smooth</td>
<td>Character should be in contact with</td>
<td>Close</td>
<td>Tablet, plane</td>
<td></td>
</tr>
<tr>
<td>Rippled</td>
<td>Subsequently disturbed, transverse stratiations.</td>
<td>Stratification low (typically 0-10°), transition to high (up to 30°).</td>
<td>Typically 0-10°, maximum 30°.</td>
<td>Flat, smooth</td>
<td>Character should be in contact with</td>
<td>Close</td>
<td>Tablet, plane</td>
<td></td>
</tr>
<tr>
<td>Rippled</td>
<td>Rippled, low-grade laminations.</td>
<td>Stratification low (typically 0-10°), transition to high (up to 30°).</td>
<td>Typically 0-10°, maximum 30°.</td>
<td>Flat, smooth</td>
<td>Character should be in contact with</td>
<td>Close</td>
<td>Tablet, plane</td>
<td></td>
</tr>
<tr>
<td>Smooth</td>
<td>Prismatic laminations.</td>
<td>Stratification low (typically 0-10°), transition to high (up to 30°).</td>
<td>Typically 0-10°, maximum 30°.</td>
<td>Flat, smooth</td>
<td>Character should be in contact with</td>
<td>Close</td>
<td>Tablet, plane</td>
<td></td>
</tr>
<tr>
<td>Smooth</td>
<td>Groove laminations.</td>
<td>Stratification low (typically 0-10°), transition to high (up to 30°).</td>
<td>Typically 0-10°, maximum 30°.</td>
<td>Flat, smooth</td>
<td>Character should be in contact with</td>
<td>Close</td>
<td>Tablet, plane</td>
<td></td>
</tr>
<tr>
<td>Convolute deposition</td>
<td>Marked by convolutions.</td>
<td>Stratification low (typically 0-10°), transition to high (up to 30°).</td>
<td>Typically 0-10°, maximum 30°.</td>
<td>Flat, smooth</td>
<td>Character should be in contact with</td>
<td>Close</td>
<td>Tablet, plane</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.2 Facies and characteristic structures of fluvial (Braided rivers; Mial, A. D., 1977)

<table>
<thead>
<tr>
<th>Facies identifier</th>
<th>Lithofacies</th>
<th>Sedimentary structures</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel</td>
<td>Gravel, massive or crudely bedded; minor sand, silt, or clay lenses.</td>
<td>Ripple marks, cross-strata in sand units, gravel imbrication.</td>
<td>Longitudinal bar channel deposits.</td>
</tr>
<tr>
<td>Gravel</td>
<td>Gravel, stratified</td>
<td>Broad, shallow trough cross-strata, imbrication.</td>
<td>Minor channel fills.</td>
</tr>
<tr>
<td>Gravel</td>
<td>Gravel, stratified</td>
<td>Planar cross-strata</td>
<td>Lenticular bar or dextral growths from older bar remnants.</td>
</tr>
<tr>
<td>Sand</td>
<td>Sand, medium to very coarse; may be pebbly</td>
<td>Solitary or grouped cross-strata</td>
<td>Dunes (lower-flow regime).</td>
</tr>
<tr>
<td>Sand</td>
<td>Sand, medium to very coarse; may be pebbly</td>
<td>Solitary or grouped planar cross-strata</td>
<td>Lenticular bar and waves (upper- and lower-flow regimes).</td>
</tr>
<tr>
<td>Sand</td>
<td>Sand, very fine to coarse; may be pebbly</td>
<td>Ripple marks of all types, including climbing ripples</td>
<td>Ripples (lower-flow regime).</td>
</tr>
<tr>
<td>Sand</td>
<td>Sand, very fine to coarse; may be pebbly</td>
<td>Horizontal lamination, parting or streaming lineation</td>
<td>Planar bed forms (lower- and upper-flow regimes).</td>
</tr>
<tr>
<td>Sand</td>
<td>Sand, very fine to coarse; may be pebbly</td>
<td>Broad, shallow scouring (including cross-stratification)</td>
<td>Minor channels or scour hollows.</td>
</tr>
<tr>
<td>Sand</td>
<td>Sand, very fine, silt, mud, interbedded</td>
<td>Ripple marks, undulatory bedding, bioturbation, plant rootlets, caliche.</td>
<td>Deposits of weaning floods, overbank deposits.</td>
</tr>
<tr>
<td>Sandy</td>
<td>Sandy, interbedded</td>
<td>Rootlets, desiccation cracks</td>
<td>Drape deposits formed in pools of standing water.</td>
</tr>
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</table>

Table 3.3 Classification of common primary sedimentary structures (Sam Boggs, JR., 1995)

<table>
<thead>
<tr>
<th>GENETIC CLASSIFICATION</th>
<th>Depositional structures</th>
<th>Erosional structures</th>
<th>Deformation structures</th>
<th>Biogenic structures</th>
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<td>MORPHOLOGICAL CLASSIFICATION</td>
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<td>STRATIFICATION AND BED-FORMS</td>
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<tr>
<td>Bedding and lamination</td>
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<td>X</td>
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<tr>
<td>Laminated bedding</td>
<td>X</td>
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<td></td>
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<tr>
<td>Massive (structureless) bedding</td>
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<td></td>
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<tr>
<td>Bedforms</td>
<td></td>
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</tr>
<tr>
<td>Ripples</td>
<td>X</td>
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<tr>
<td>Dunes</td>
<td>X</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Antidunes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross-lamination</td>
<td></td>
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<tr>
<td>Cross-bedding</td>
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<tr>
<td>Ripple cross-lamination</td>
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<td>Placer and ventricular bedding</td>
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<td>Hummocky cross-bedding</td>
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<td>Irregular stratification</td>
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<td>Convolute bedding and lamination</td>
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<td>Plane structures</td>
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<td>Bioturbate structures</td>
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<td>Synsedimentary folds and fans</td>
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<td>Dish and pillar structures</td>
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<td>Channels</td>
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<td>Scour- and-fill structures</td>
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<td>Meander bedding</td>
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<td>Stromatolites</td>
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<td>BEDDING-PLANE MARKINGS</td>
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<td>Groove casts: instructions: bounce, brush, prod, and roll marks</td>
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<td></td>
<td>X</td>
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<tr>
<td>Plunge casts</td>
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<td>Pitting lamination</td>
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<tr>
<td>Load casts</td>
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<tr>
<td>Tracks, trails, burrows</td>
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<tr>
<td>Mudcracks and syncretic cracks</td>
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<td>Pits and small impressions</td>
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<tr>
<td>Rill and swash marks</td>
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<tr>
<td>Sedimentary hills and dikes</td>
<td>X</td>
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</tbody>
</table>

*Not wholly stratification structures  Not wholly bedding-plane markings
Chapter 4 GEOLOGICAL RESULTS

4.1 Lithofacies Description

Sediments in my study area can be divided into four facies: gravelly sands (Gs), sands and sandstone (Ss1, Ss2, Ss3, and Ss4), interbedded sand-silt-clay (ISS), and paleosols (P). These lithofacies are distinguished from one to another by the color, texture and lateral and vertical geometry (Figure 4.1). Each lithofacies may be repeated in some sections, or may not even exist in one section. Detailed description of each vertical section is given in appendix 1. Measurement of each section began in lower gravelly sands (Gs). Two datums were used to tie sections together. First, for sections 1 to 6, the datum is the basal upper gravelly sands (known as "lower Fred"). Second, for the sections 6 to 10, the datum is the base of the slabby sands, where present at the middle of the section.

4.1.1 Gravelly Sands (Gs)

The studied section is restricted by two gravelly sands that occupy the base and the top of the mapped units. Both of them are commonly well cemented by calcite. These gravelly sands are light to medium gray, poorly sorted, traceable throughout the study area from north to south, and have variable thickness across the outcrop from 0.6 to more than 2.4 m. Sedimentary structures such as imbrication, scour, cross-bedding, and irregular graded bedding are well preserved in these beds (Figure 4.2, 4.3). Mud-balls within the gravelly sands range from 2 to 50 cm in diameter. Figure 4.2 shows the lower gravelly sands containing pebbles and cobbles that are fine upward. These beds are highly resistant to erosion. In some sections, the upper boundary of these gravels is irregular; and in other sections the gravels are graded. The lower boundary is commonly scoured.
Figure 4.1 General lithofacies sequences of my study area. They consist of four lithofacies that are present in my study area.
Figure 4.2. This figure shows several sets of fining upward of cemented cross bedded gravelly sands (Gs) and white calcite coatings around the grains in the lower gravelly sand. Lower boundary shows the mud balls with size range 2-10 cm. Scoured structures are obvious at the lower boundary. The upper boundary is flat and sometimes laminated. Location is between sections 3 - 4.
Figure 4.3. This figure shows two sets fineing upward of lower cemented gravelly sand that consists of mud-balls and imbrication structures. A) first set, B) second set.

This imbrication shows the flow direction is to S15E to S 35E.
Location is between section 2 and 3.
Figure 4.3 shows well preserved mud-balls and pebble imbrication in lower gravelly sands. General paleoflow from this imbrication is S 15 E to S 35 E. These sands are 1 - 1.5 m thick. In general these beds fine upward. The bottom gravelly sands overlie cemented coarse-grained sandstone at some places. At other places, bottom gravelly sands are interbedded with light gray, coarse, medium sorted, and orange, lower medium, well sorted sands. The top gravelly sands commonly overlie interbedded sand-silt-clay units and are continuous laterally to the south.

In the middle of some local sections (sections 2, 8), similar light gray, poorly sorted gravelly sands fine upward, but are thinner (60cm-90cm), structureless, not continuous, and not well cemented. The general appearance of these units is similar to the previous gravels with an undulous lower boundary and gentle slope (Figure 4.4). These layers are considered as the same as the bottom gravelly sands, as we called "lower Fred".

Outcrop morphology of the upper and lower gravelly sands is steep to clifty and remains largely the same laterally across the study area. In the middle of the map area the upper gravelly sands are less cemented. The local gravelly sands have a gentle slope due to non resistance to erosion.

4.1.2 Sandstones (Ss)

In my study area, there are four types of sandstones. Three of them have a light gray - tan color (10 YR 6/4). Generally, they are differentiated by texture and geometry. The fourth one is characterized by its orange-reddish color (5YR 6/6) and is described in more detail later in paleosols lithofacies. In most of the sections these types of sandstone beds are repeated, but these units are bordered by other types of sandstones, interbedded sand-silt-clay, or paleosol.

Type 1 sandstones (Ss1) are commonly continuous laterally across the outcrops and lie above gravelly sands (Gs) (Figure 4.5). Other type 1 sandstones also present as channels. Sedimentary structures in this typical lithofacies are not obvious. These beds are
**Figure 4.4.** This figure shows uncemented gravelly sands (Gs). This layer pinches out to the left. Morphology of this bed is flat-undulous at the base and nearly flat at the top. Location along section 2.
Figure 4.5 This figure shows type 1 (Ss1) of uncremented sandstone. This sandstone commonly overlies the gravelly sands with gentle slope. The same typical sandstone is repeated above this layer discontinuously. Location is in section 8.
easily distinguished by gentle slope, tan-gray color, and loose lower medium to upper coarse grained sands. Some places these beds are cemented by calcite as shown by concretions. A few pebbles commonly exist in these beds. The thickness ranges from 0.60 m to 2.25 m. The boundaries some of these beds are commonly undulous and graded at the base and irregular at the top. Some of them have scoured at the base.

Type 2 sandstones (Ss2) look similar to type 1, because they are light gray - tan. Type 2 sandstones are lighter gray color, and are thicker and finer grained (Figure 4.6). Most of the type 2 sands occupy the middle of the measured sections. These beds are not continuous laterally throughout the mapped area, but they are traceable for a few hundred m. These beds are also repeated vertically. A few thin carbonate nodules exist in some local sections of these beds. Type 2 sandstones are distinguished from type 1 by very well cemented into tabular bodies and preserve low angle trough cross-bedding, horizontal lamination, cracks, and insects holes (Figure 4.7). The upper and lower boundaries for these beds are mostly irregular. Thickness varies from 30-60 cm. The type 2 sandstones form a continuous slabby sands from section 6 to section 10 in the middle of the section. Therefore, this typical sandstone is used as a base of the datum for section 6 to 10.

Type 3 sandstones (Ss3) are orange in color (5YR 6/6). In my mapped section, there are 3 or more layers of these beds (Figure 4.9). These beds are easily distinguished by their color from a distance. Some of them are not continuous, but at least one is continuous across the mapped area. The thickness of orange sandstones that are not continuous ranges approximately from 0.3 to 2 m. Type 3 sandstones also consist of uniform grain size from upper fine to lower medium sand. Carbonate nodules is another typical secondary structures that are also common in some of the local sections of type 3 sandstones. These sandstones are partially cemented, form steep slopes and locally have poorly preserved tangential cross bedding over several meters in their lower parts. These sands will be further discussed with paleosols lithofacies.
Figure 4.6. This figure shows type 2 (Ss2) of cemented sandstone lithofacies with undulous at lower boundary, low angle cross-bedding, and hammer as a scale.
Location is in between sections 2 and 3
Figure 4.7. This figure shows another sandstone type 2 (Ss2) with trough and ripple cross-bedding, and modern insect holes. Carbonate nodules are scattered throughout. Location is in between section 2 and 3.
Figure 4.8. This figure shows sandstones type 2 (Ss2) with horizontal lamination, climbing ripples, and burrows. In the middle of the section is a 2-3 cm thick unit with horizontal lamination. A scoured brown clay drape overlies this bed. Location is in between section 1 and 2.
Figure 4.9. A. Shows lithofacies (above). The intervening beds are sandy clay (Palosols-P), interbedded sand-silt-clay (ISS). Location is in between sections 9 and 10. B. Shows two beds (1 and 2) of well cemented orange sandstones (Ss3) and an intervening paleosol (P). Orange sandstone 2 has faint large dimension tangential cross-bedding that indicates eolian deposition. Location is in between sections 3 and 4.
Morphology of these units are commonly are steep to cliffy such as section 1 to 4 and section 7 to 10. 

Type 4 sandstone (Ss4) is characterized by light gray to tan color and upper fine to lower medium sands. These beds are not laterally continuous; for example, the thickest part of one unit in section 3 becomes thinner toward the south and north and pinches out near section 5. Horizontal lamination is the most common sedimentary structure in these beds. Climbing-ripple and low angle trough cross bedding are present only in local sections (Figure 4.8). In some sections sedimentary structures are not obvious. The thickness ranges from 0.2 m to 1.8 m. The upper and lower boundaries of these units are also irregular. Similar beds are also repeated vertically in some local sections (e.g. Section 6).

4.1.3 Interbedded sand-silt-clay (ISS)

Interbedded sand-silt-clay units are composed of dark brown clay, light gray to tan sand and tan silt with clay. These beds have variable total thickness from 0.45 to 2.7 m, in layers generally a few cm thick. The units occupy the top of sections (underlie gravelly sands) and the lower part of the section (above the type 2 sands). The ratio of sand-silt-clay thickness is variable. Most of the sections show the ratio of sand-silt-clay ranges from 4:1:3 to 5:1:2. Sands commonly are only 30 - 80 cm thick. Carbonate nodules commonly overlie the clay layers. Reddish-dark brown clay commonly underlies the lower part of these beds. In section 2 (Appendix II), the sand units are thicker and well cemented, but clay-silt units become thinner toward section 3. Between sections 4 and 5, the clay ratio increases and clay layers become darker (Figure 4.10).
Figure 4.10  This figure shows the two sets interbedded of sand-silt-clay lithofacies (1 and 2) overlying reddish-dark brown clay soil (P). Carbonate nodules overlie these beds. Thin horizontal laminations are common in the silt, boundary clay-silt and sand-silt. Location is in section 5.
Figure 4.11. This figure shows 45 cm interbedded sand-silt-clay lithofacies overlies the reddish-dark brown clay soil. A. A 10 cm thin horizontal lamination, B. A 32 cm laminated sand, and C. A 3 cm laminated silt.
Sedimentary structures such as thin horizontal lamination are common in between sandstone and silt, and clay and silt. Figure 4.11 shows the interbedded sand-silt-clay 45 cm thick. From the bottom, letter (A) indicates 10 cm dark brown clay with mud cracks and thin horizontal lamination. Letter (B) indicates a 30 cm tan churned sandy clay with horizontal lamination. Letter (C) is a 5 cm light tan well cemented sand-silt with thin horizontal lamination. Carbonate nodules are above the clay units.

4.1.4 Paleosols (P)

Paleosols are recognized by the absence of sedimentary structures, color, carbonate, and clay contents (Mack et al., 1993). Paleosols in the mapped area are comprised of two types: sand and clay paleosols. This section will briefly describe the soil lithofacies within the Bosque site.

Sandy paleosols appear as lower fine-upper medium sands, 0.9 - 3 meters thick, orange-red 5 YR 6/6 or 0.3-1.5-meter thick dark brown clayey sand. Sedimentary structures are poorly preserved and/or not obvious. The geometry of these soils are tabular or lens-shaped. These soils are commonly underlain by loose gravels at the bottom and overlain by clay paleosol or by laminated sand-silt-clay.

Most of the orange sand paleosols are cemented. Carbonate nodules within these beds are not well formed and are present locally. The carbonate nodules are spherical-elongated and distributed tabular (plane-sheet shape). The length is approximately 3 to 10 cm. The diameter is approximately 1 to 5 cm.

Clay paleosols are primarily composed of light tan silt and dark brown clay (7.5 YR 3/3). These units are distinguished by carbonate nodules within the beds, and churned, darker, and structureless compared to laminated sand-silt-clay units. The carbonate nodules that commonly are present peripherally at the boundary of sandstones typical 2, 3, 4, and interbedded sand-silt-clay. In most sections, these units are recognized by their dark
brown color and are continuous over hundreds of meters. In some places these beds are interbedded with silty clay, and have relict thin discontinuous horizontal lamination. These beds have gentle outcrop slope and commonly have more resistant sandstones at the bottom and the top. The thickness is variable from 0.3 - 1.6 meters. Original sedimentary structures are not obvious, and the clays have been churned (Figure 4.12).

Figure 4.12. This figure shows churned clay with relict silty-clay horizontal lamination. Elongated-spherical carbonate nodules are distributed peripherally at the boundary between sand and clay. Location: section 9.
4.1.5 Permeability Results

As previously described permeability calibration from field measurements is based on the formula given by Goggin et al., (1988; see Appendix IV herein for one example). Once variables within the formula have been established, permeability values are obtained by converting the "time" (Table 4.1) to darcies.

According to the Table 4.1, the highest permeability value is in gravelly sands (Gs) with a mean permeability value of 49 darcies. The lowest permeability value from measurements is the interbedded sand-silt-clay (ISS) facies, which has mean permeability value of 17.5 darcies. However, the lowest permeability value should be paleosol lithofacies due to clay enrichment.

In permeable lithofacies, on the other hand, cementation is the main factor reducing the permeability value. The reduction is indicated by the difference permeability value at the same lithofacies. For example, the permeability values of Ss4 in section 6 ranges from 22.90-24.13 darcies, but permeability value of Ss4 in section 10 ranges from 22.69-25.75 darcies. These lithofacies in section 6 and 10 have similar characteristic but different physical condition such as consolidation.
<table>
<thead>
<tr>
<th>Lithofacies (Units)</th>
<th>Time (Average) sec.</th>
<th>Grain size</th>
<th>Section</th>
<th>q $10^{-5}$</th>
<th>v $10^{-3}$</th>
<th>Ff</th>
<th>Fg</th>
<th>Pn</th>
<th>ΔP</th>
<th>P1</th>
<th>Permeability (k) $10^{11}$ [m²] [darcy]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Gravelly Sands (Gs)</td>
<td>2.88</td>
<td>very coarse-coarse</td>
<td>6</td>
<td>1.909</td>
<td>18.9</td>
<td>0.155</td>
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<td>108.447</td>
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<td>lower coarse-uc</td>
<td>6</td>
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<td>15.25</td>
<td>0.1360</td>
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<td>lower fine-upper med.</td>
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<td>lower fine-clay</td>
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<td>87.03</td>
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<td>1.351</td>
<td>13.37</td>
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<td>1538.86</td>
<td>62.13</td>
<td>1624.60</td>
<td>3.2339</td>
</tr>
<tr>
<td>12. Sandstone Type (Ss4)</td>
<td>5.56</td>
<td>lower fine-lower med.</td>
<td>10</td>
<td>0.989</td>
<td>9.794</td>
<td>0.148</td>
<td>1.744</td>
<td>1580.77</td>
<td>32.10</td>
<td>1666.39</td>
<td>2.308</td>
</tr>
<tr>
<td>13. Sandstone Type (Ss4)</td>
<td>5.70</td>
<td>upper fine-lower med.</td>
<td>10</td>
<td>0.965</td>
<td>9.55</td>
<td>0.1141</td>
<td>1.744</td>
<td>1583.78</td>
<td>30.08</td>
<td>1669.40</td>
<td>2.247</td>
</tr>
<tr>
<td>14. Sandstone Type (Ss2)</td>
<td>3.43</td>
<td>lower coarse-upper coarse</td>
<td>10</td>
<td>1.603</td>
<td>15.8</td>
<td>0.1386</td>
<td>1.744</td>
<td>1507.05</td>
<td>83.049</td>
<td>1592.67</td>
<td>3.914</td>
</tr>
</tbody>
</table>
CHAPTER 5 INTERPRETATION

5.1 Lithofacies distribution

In this chapter, lithofacies interpretation emphasizes energy of the transport and depositional media, source, and environment of deposition. Gravelly sands and sandstone lithofacies are the two main interests, because their permeability is measurable and they are the most common constituents within the study area. Sedimentary textures and structures are the best indicators of the depositional mechanisms and depositional environments (Table 5.1).

5.1.1 Gravelly sands (Gs)

Gravelly sands (Gs) that bound the bottom and the top of the section indicate the mapped area has had at least two episodes of high stream competence. Poorly sorted gravel to coarse sands and sandy matrix present in gravelly sands can be interpreted as being deposited under high flow velocity (lower flow regime) from bed load, which forms large scale cross bedding (Figure 5.1, 5.2 and 5.3).

As the stream power decreases, lower plane bed results. With decreasing stream power, only smaller grains can be transported. In this condition, ripple cross and/or planar lamination structures may be formed.

Figure 5.1 General fining upward of gravelly sands (Gs) units in my study area.

Sands
(with lamination)
Sands
(with ripples)
Gravelly sands
(with large scale cross bedding)
Table 5.1  Summary of common lithofacies at the Bosque, New Mexico.

<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Units</th>
<th>Description</th>
<th>Sedimentary Structures</th>
<th>Paleocurrents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravelly sands (Gs)</td>
<td>Gravelly sands (Gs)</td>
<td>Light gray, very coarse sand-cobles, poorly sorted, well rounded, well cemented.</td>
<td>Imbrication, trough cross-bedding, hz. lamination, graded, scoured</td>
<td>S 15° E - S 35° E</td>
</tr>
<tr>
<td>Sandstone Type 1 (Ss-1)</td>
<td>Light gray, lower coarse-upper coarse sand with pebbles, well rounded, poorly sorted</td>
<td>Graded bedding</td>
<td>S 33° E - S 25° E</td>
<td></td>
</tr>
<tr>
<td>Sandstone Type 2 (Ss-2)</td>
<td>Light gray-tan, upper medium-lower coarse sand, well rounded, med.sorted, cemented</td>
<td>Climbing ripples, low angle cross bedding, parallel lamination</td>
<td>S 29° E - S 25° E</td>
<td></td>
</tr>
<tr>
<td>Sandstones (Ss)</td>
<td>Sandstone Type 3 (Ss-3)</td>
<td>Light gray-tan, upper fine-upper medium sand, well rounded, well sorted, concretions</td>
<td>Sand sheet, low angle trough cross bedding, climbing ripple</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Sandstone Type 4 (Ss-4)</td>
<td>Orange-reddish, upper fine-upper medium sand, well rounded, well sorted, med-well cemented, nodules</td>
<td>Relict tangential Cross-bedding</td>
<td></td>
</tr>
<tr>
<td>Interbedded Sand-Silt-Clay (ISS)</td>
<td>Interbedded Sand-Silt-Clay (ISS)</td>
<td>Dark brown - tan - whitish, upper fine sand-clay, well sorted and well rounded for ss.</td>
<td>Thin hz. lamination</td>
<td>N/A</td>
</tr>
<tr>
<td>Clayey Sands (P-1)</td>
<td>Brown - reddish, churned, mud balls</td>
<td></td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Paleosols (P)</td>
<td>Sandstone Type 4 (P2/Ss-4)</td>
<td>Orange-reddish, upper fine-lower medium sand, nodules</td>
<td>Local tangential cross-bedding</td>
<td>N/A</td>
</tr>
<tr>
<td>Clay (P-3)</td>
<td>Light brown - dark brown, red, churned, draping, nodules</td>
<td></td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>
Figure 5.2. The Hjulstørm diagram, as modified by Sundborg, showing the critical current velocity required to move quartz grains on a plane bed at a water depth of 1 m. (After Sunborg, A., 1956, The River Klaräven, a study of fluvial processes: Geografiska Annaler, Ser. A, v. 38, Fig. 16, pp. 197).

Figure 5.3. Relationship between stream power, median grain size, and bed form (From Simon, Richardson, and Nordin, 1965). Stream velocities shown at the right are approximate values for the grain size of 0.4 mm and extrapolated to 1 ft. flow depth.
The transition of gravelly sands at Bosque site to general thinning of the same gravelly sands toward the south, fining upward, plane and laminated at the upper boundary of these gravelly sands can be interpreted to show that the stream power decreases and/or decreasing the water depth toward south.

Thus, the general fining upward sequences of the gravelly sands without erosional surface between the bedforms is probably formed under waning flow in lower flow regime (Figure 5.3). The thicker gravelly sands at the center of my study area can be interpreted as local high energy flow and/or can be taken to mean flows of longer duration or short duration with high stream power condition.

Preserved imbrication and trough cross bedding in some gravelly sands shows that the paleocurrent depositing these beds trended southeast. They also indicate that these gravelly sands are derived northwest of my study area. Harris (1991, unpublished) also demonstrated that an ancestral Rio Puerco is the dominant source for the coarse Bosque sediments.

Based on the description above and geometry (in Figure 4.1), the consolidated gravelly sands are interpreted to have formed wide-spread braided channel systems. The streams moved back and forth, scoured, and reworked the previous deposits. According to the orientation of preserved imbrications, it is possible that the stream was the ancestral Rio Puerco (See Figure 2.2).
5.1.2 Sandstones (Ss)

Sandstones in the mapped area are comprised of four different kinds. Two of them are fluvial. Type 1 (Ss1) is characterized by lower fine - pebbly sands, medium sorted, rounded, with continuous and discontinuous horizontal lamination, graded bedding, and has no silt or clay. Position some of these beds above gravelly sands with graded bedding and thin horizontal laminations indicate that the energy of the stream decreased from gravelly sands to sandstones type 1. By relating vertically the graded boundary from these sandstones to the gravelly sands, it can be interpreted that the sands deposited with grade bedding within the same facies as gravelly sands in channel-fill deposits or channel-lag deposits as the discharge waned under lower-flow regime (Figure 5.3 and Table 3.2). Some Ss1 with undulous and scoured lower contact may be deposited under upper flow regime.

Sandstone type 2 (Ss2) is finer than sandstones type 1 and is characterized by light to dark gray, lower medium to upper coarse sandstone, well cemented, poor-medium sorted, with trough cross bedding, or ripple cross lamination. Some of these sandstone layers do not continue laterally, but form channels. Continuous layers commonly form tabular bodies. Based on the geometry and sedimentary structures, the type 2 sandstones can be interpreted as fluvial in origin. The type 2 sandstones formed as tabular bodies may be deposited on flood plains as crevasse splays under lower-flow regime. Sandstones type 2 with ripple cross laminations were deposited in narrow channels as a result of suspension load systems. Local sandstones type 2 that are isolated can be interpreted as arroyos because there is no fluvial systems during that time. However, they might also not as arroyos if the main fluvial systems are not located in the study area; they are still able to interpreted as crevasse splays. The source of type 2 beds is not known, because no petrology has been done, but trough cross beds suggest a
northwesterly source. If the discharge decreases at the Bosque site through time, the source could be the same as that for the gravelly sands.

The other two uniform upper fine-lower medium, well sorted, light gray-tan, well rounded sands are distinguished from sandstones type 1 and 2 by, geometry, better sorting and some typical sedimentary structures. Type 3 sandstones are characterized by uniform grain size and faint large-dimension tangential cross bedding (vertically 6-8 m), which is typical of eolian deposits (Rubin and Hunter, 1984), that has been followed by carbonate cement. Sandstones type 3 (Ss3) has been altered to become soil. Soil development is characterized by orange - reddish (5 YR, 6/6) color, lack of sedimentary structures, distribution of carbonate nodules within the bed, peripheral along the boundary (Surdam et al., 1993), or along the tangential cross-bedding. This red color derived from goethite or hematite shows the products of weathering (Berner, 1971; Walker, 1971).

The type 4 sandstones (Ss4) look similar with sandstones type 3 (Ss3) in grain-size and sorting. They are distinguished by the color, in which sandstones type 3 is orange (see section between 5 and 6 in Figure 4.1), but type 4 is light gray to tan. Unlike sandstone type 3 with faint large-tangential cross bedding, sandstones type 4 have sedimentary structures such as low angle sand sheet and thin laminated structures. The lamination, climbing ripples structures can be formed either in fluvial or eolian deposits. In fluvial systems, lamination with upper fine-lower medium grain-sized may be formed under either lower or upper flow regimes (Figure 5.3). In upper flow regime, scoured lower boundaries are usually present. However, the lower contact of the type 3 and 4 sandstones are mostly flat. Therefore, these units could be fluvial lower flow regime. Climbing ripples are present in type 4 sandstones; cross bedding, on the other hand, is not present in type 4 sandstones. In eolian systems, climbing ripple structure can be formed in rainfall deposits on dunes (Fryberger et. al., 1979; Kocurek, 1981; Hunter, 1977; Rubin and Hunter, 1984; see Table 3.1). Similar well sorted beds and low angle sand sheets are interpreted to show wind velocity up to 1200 cm/sec (Fryberger et al., 1979). Some Ss4 are connected
laterally to Ss3 and distributed as relatively tabular sheets with flat boundary to the underlain beds (see Figure 4.1; between section 5-6). Some of Ss3 and Ss4 are overlain by Ss1 and Ss2. Some Ss3 and Ss4 are overlain by interbedded sand-silt-clay and paleosols. Laterally, some of Ss3 and Ss4 change to Ss1, Ss2, ISS, and paleosols. These vertical and lateral relationship may indicate the transition from fluvial to eolian. Although some sedimentary structures of these units are not unique to eolian origins, textures, stratigraphic relationships and geometries of type 3 and 4 sandstones can be used to interpreted that the type 3 and 4 sandstones are probably eolian deposits.

High permeability of these beds lets fluids (meteoric water) infiltrate and partially fill the pore space and then precipitate dissolved solids to produce concretions. In semiarid regions, atmospheric dust provides CaCO$_3$ to the soil which is remobilized by meteoric water (Gile et al., 1981). Resulting calcite cements formed in the sediments, where vertical permeability is less than horizontal (Raiswell, 1971; Guiyas, 1984).

The morphologies of concretions commonly follow the boundary of beds and have irregular elongated shapes. Organic matter and soil composition also influence calcite cement formation (Cerling, 1984; Quade, 1989; Pendlall and Amundson, 1990; Mora et al., 1991).

5.1.3 Interbedded sand-silt-clay (ISS)

The interbedded sand-silt-clay can be interpreted as overbank deposits in a package of flood and fining upward deposits of wide-spread suspension load depositional systems (Davis, 1990, 1993; Lohmann, 1992; Gotkowitz, 1993). This interpretation is supported by the association of these lithofacies with sandstone type 2 (For example, see Figure 4.1; between section 5 and 6). This association shows that the sandstones type 2 may be fining upward to the overbank sediments and/or interfingering with overbank sediments, where overbank sediments are commonly deposited. I envision that this
interbedded clay, silt, and sand are brought during large floods and settled as the discharge decreases. Horizontal lamination in silt-sands support decreasing intensity of discharge after large floods. Therefore, the possible depositional environment is overbank deposits.

5.2 Overall Depositional Sequences

General depositional sequences in the mapped area are similar to those mapped by Lohmann (1992) and Davis (1993), except the geometry of each differs locally. However, unlike the architectural elements that Lohmann (1992) and Davis (1993) used for describing the section, here I evaluate the section by lithofacies of the vertical sequences and lateral distribution of the deposits.

The stacking of each vertical section in my study area shows several sets of fining upward sequences (Gs-Ss-ISS-P). Generally my study area consists of 4 to 5 depositional sequences (Figure 5.4). Each sequence is commonly ended with soil at the top.

The first vertical sequence commonly consists of Gs-Ss1-Ss3-P-ISS-P, or Gs-Ss1-Ss3-P-Ss3-P. The second sequence is Ss2-Ss3-P-ISS-P, Ss2-ISS-P-ISS-P. The third sequences are dominated by fine-grained sands and clay such as, Ss4-ISS-Ss4-P, Ss2-Ss4-P-ISS-P, Ss2-Ss4-P1-ISS-Ss4-P. The fourth sequences are comprised of Ss4-ISS-Ss4-P, Ss1-ISS-Ss4-P, Ss2-Ss3-ISS-Ss4. The fifth sequence is similar to the fourth sequence, Ss4-ISS-P-Ss4-P, Ss4-ISS-P, but is thinner and discontinuous (see Figure 5.4 and Appendix II).

The whole sequence at the Bosque Site may be compared with Allen's (1974) facies models. Figure 5.5 shows the components of autocyclic and allocyclic depositional controls. Autocyclic controls on river movement are the results of changes in energy within the sedimentary basin, such as the results of channel avulsion, crevassing, and
channel migration and cut-off. Allocyclic controls, on the other hand, originate in energy changes outside the sedimentary basin, such as shifts in the climatic and tectonic regimes. Changes in allocyclic controls result in overall changes in the discharge, load and slope of the stream.

Figure 5.4 Graphical stacking of vertical sequences within my study area
(Numbers 1st, 2nd, 3rd, 4th and 5th indicate depositional sequences)

The first and fourth of Allen's six models are controlled by purely allocyclic factors, i.e. extreme climatic fluctuations (Figure 5.5). The second and third models are purely autocyclic, which are differentiated by the dominant of pattern of river movement.
(Figure 5.6). The second and third models are differentiated by the amount of river avulsion as caused by lateral river movements and pedogenesis development. The third model develops more river avulsion and pedogenesis. The fifth and sixth models are controlled by both autocyclic and allocyclic factors. According to Figure 2.2, the study area is controlled by autocyclic deposition that is dominantly influenced by avulsion and channel migration of Rio Puerco or/and Rio San Jose. The channels migration and avulsion in study area are shown by the lateral continuity of gravelly sands and some type 1 and 2 sandstones.

The stack of Allan’s model 3 deposits in the Figure 5.6 is similar to the stack of lithofacies within in my study area. Both of them are commonly end with soil development (pedogenesis). Vertical section in such models are often truncated due to large avulsive steps of the river and covered by eolian deposits. However, the meandering system in Allan’s model 3 is not obvious as well as in the middle section of my study area. It is because thick eolian deposits occupy predominantly in the middle section of my study area. Since the study area is comprised of fining upward sequences with thick overbank deposits, crevasse splays of sandstones type 2, and pedogenesis of eolian deposits (sandstones type 3) and sandy clay, therefore, the depositional systems in the mapped area can be similar to model 3 of Allen (1974). However, although depositional systems in the study area are controlled by autocyclic variations, climate also plays an important role as shown by soil development of orange eolian sands, calcite cements and carbonate nodules.

Imbrication in gravelly sands, trough cross-bedding in gravelly sands and sandstone type 2, and concretions in sandstone types 2 and 3 and in the boundary of sand-silt-clay found in the study area support the determination that the paleocurrent and depositional mechanisms are by fluvial systems derived from northwest of the study area.
Alluvial Sedimentary Controls

Allocyclic

Climate  Tectonics

Variations in:
Discharge
Load, and Slope

Autocyclic

Changing Energy Distribution in Basin

Channel
Migration
and
Cut-off

Crevassing
Avulsion

BOSQUE SITE DEPOSITS

Figure 5.5. Autocyclic and allocyclic controls on deposition (Modified from Allen, 1974).
Figure 5.6. Theoretical two dimensional vertical profile normal to mean paleocurrent direction to illustrate the fluvialite sedimentation generated using Model 3 (Allen, 1974).

☐ = approximate scale of Bosque site cross section.
Judging from description above, the Bosque sediments are deposited under several types of channels and wind blown sand facies. The large braided channels occupy the bottom and the top of the section. Above the large basal braided channels, the deposition is controlled by eolian systems, other channels systems (crevasse splays and arroyos), overbank deposits, and soil development. The presence of local crevasse splays and thick overbank deposits indicate that the stream flooded periodically, and the stream channels migrated as in the meandering system. Finally, the large braided channels covered the top of the Bosque sediments (Figure 4.1 and 5.6). This fining upward sequences can be interpreted as products of meandering system.

There is also at least one period of time when eolian deposition replaced the fluvial system, as shown by the thick continuous sandstone type 4 in the middle of the section of study area.

5.3 Controls on Permeability Distribution

The objective of this section is to discuss the depositional system and its relation to the permeability distribution, including lateral and vertical distributions applied to petroleum migration. In order to address this goal, additional data, such as concretions and permeability values from the field and from previous work are also utilized.

In terms of petroleum migration, permeability is the most important property that allows fluid to flow within the deposits. Generally, permeability values increase by increasing the porosity. However, the porosity and permeability values are dependent upon the depositional systems that produce lithofacies. Different facies have different thicknesses, sedimentary structures, and composition.
Figure 5.7. The interpretation of depositional environment of Bosque site deposits (Based on the lithofacies correlation).
5.3.1 Relation Depositional Systems and Permeability Distribution

As we described before (in Chapter 4), the mapped area consists of 4 lithofacies, gravelly sands, sandstones, interbedded sand-silt-clay, and paleosol, which were deposited originally from fluvial and eolian systems. Each lithofacies indicates each depositional system and shows different depositional mechanisms that work at the Bosque site. For example, gravelly sands and orange sandstones produced by fluvial and eolian processes respectively are distributed almost continuously along the mapped area from north to south with variable thickness. Some sandstones produced by fluvial processes form channel deposits, which are not distributed across the mapped area; some sandstones form tabular sands. This tabular sandstones are also not distributed continuously across the mapped area (Figure 4.1).

According to the Figure 5.8, the gravelly sands (Gs) of channel deposits have the highest permeability value followed by Ss2 of channels, Ss4 of eolian sands and ISS of overbank deposits respectively. Soils and clay deposits should have lower permeability.

Channel lithofacies Gs1, Ss1, Ss2 are categorized as high permeability (k > 30 darcies). Both eolian and overbank lithofacies (Ss3, Ss4, and ISS) have medium permeability (1 < k < 30 darcies). Clay-rich paleosols are categorized as low permeability (k < 1 darcies) (Figure 5.9). Although the general permeability distribution is easily recognized due to the partial cementation, discontinuity of vertical and lateral lithofacies distribution, and the heterogeneity of the deposits, the exact permeability distribution is variable (Table 5.2). In deposits partly cemented, for example, permeability measured now probably is different from the original permeability and probably will not useful for determining the permeability distribution in the future. If the arid condition keep continuing, the pore spaces will be completely cemented and/or influenced by ongoing diagenetic processes in the future as the atmospheric dust with high CaCO₃, keep dissolved by meteoric water. As a result, the permeability value can be either bigger or smaller.
Therefore, permeability distribution is controlled by depositional systems and post depositional processes.

5.3.2 Relation between Permeability Distribution and Petroleum Migration.

Hydrocarbon (oil and gas) is commonly controlled by its contact with surrounding water within rocks of variable permeability. This control is described by Hubbert's (1953) hydrodynamic equation:

\[
\frac{\delta z_o}{\delta x} = \frac{\rho_w}{\rho_w - \rho_o} \frac{\delta h}{\delta x}
\]

where \(\delta z_o/\delta x\) = tilt of oil-water interface, \(\delta h/\delta x\) = potentiometric surface gradient, \(\rho_w\) = density of water (g/cm\(^3\)), and \(\rho_o\) = density of oil (g/cm\(^3\)), and Hubbert's equation 41:

\[
E_o = g + \frac{\rho_w}{\rho_o} (E_w - g)
\]

where \(E_o\) = driving force of the oil (dynes), \(g\) = gravitational acceleration (cm/sec\(^2\)), and \(E_w\) = driving force of the water (dynes). Equation 4.1 shows that if density of water is the same as density of oil, the driving force of the oil will be equal with driving force of water. However, such a case is seldom found. Commonly density of oil is lighter than water. As a result, oil will be driven by driving force of water. Combination of these two equation indicate that besides permeability distribution, other parameters such as gradient is also significant to predict oil migration.

Paleoflow directions of the fluvial lithofacies are generally oriented S15\(^\circ\)E - S35\(^\circ\)E. Previous workers (Davis, 1991,1993; Lohmann, 1992) found that the permeability distribution at the north end of my study area is similar, S30\(^\circ\)E. This direction is indicative of the gradient for water in these underformed beds, especially under steady state flow, which is parallel to the potentiometric surface gradient (Davis, 1987).
Relationship
Permability Value and Lithofacies
\[ \begin{align*}
\text{6} & = \text{High Permeability} \\
\text{0} & = \text{Medium Permeability} \\
\text{3} & = \text{Low Permeability}
\end{align*} \quad (k > 30 \text{ darcy}) \quad (1 < k < 30 \text{ darcy}) \quad (k < 1 \text{ darcy})
\]

**Figure 5.9.** Interpretation of Permeability Distribution within Study Area

Arrows indicate the possible pathways of oil migration. These pathways are made with assumption of water drive.
<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Units</th>
<th>Description</th>
<th>Sedimentary Structures</th>
<th>Permeability (darcy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravelly sands (Gs)</td>
<td>Gravelly sands (Gs)</td>
<td>Light gray, very coarse sand-cobles, poorly sorted, well rounded, well cemented.</td>
<td>Imbrication, trough cross-bedding, hz.</td>
<td>48.32</td>
</tr>
<tr>
<td>Sandstone Type 1 (Ss-1)</td>
<td>Light gray, lower coarse-upper coarse sand with pebbles, well rounded, poorly sorted</td>
<td>Lamination, graded, scoured.</td>
<td>Graded bedding</td>
<td>N/A</td>
</tr>
<tr>
<td>Sandstone Type 2 (Ss-2)</td>
<td>Light gray-tan, upper medium-lower coarse sand, well rounded, med.sorted, cemented</td>
<td>Climbing ripples, low angle cross beding, parallel lamination</td>
<td>N/A</td>
<td>32.65 - 40.89</td>
</tr>
<tr>
<td>Sandstones (Ss)</td>
<td>Sandstone Type 3 (Ss-3)</td>
<td>Light gray-tan, upper fine-upper medium sand, well rounded well sorted, concretions</td>
<td>Low angle trough cross bedding, climbing ripples, sand sheet</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Sandstone Type 4 (Ss-4)</td>
<td>Orange-reddish, upper fine-upper medium sand, well rounded, well sorted, med-well cemented, nodules</td>
<td>Relict tangential cross-bedding</td>
<td>22.69 - 25.90</td>
</tr>
<tr>
<td>Interbedded Sand-Silt-Clay (ISS)</td>
<td>Dark brown - tan - whitish, upper fine-sand-clay, well sorted and well rounded for sands.</td>
<td>Thin hz. lamination</td>
<td>N/A</td>
<td>17.17</td>
</tr>
<tr>
<td>Clayey Sands (P-1)</td>
<td>Brown - reddish, churned, mud balls</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Paleosols (P)</td>
<td>Sandstone Type 4 (P2/Ss-4)</td>
<td>Orange-reddish, upper fine-lower medium sand, nodules</td>
<td>Local faint tangential cross-bedding</td>
<td>22.69 - 25.90</td>
</tr>
<tr>
<td>Clay (P-3)</td>
<td>Light brown - dark brown, red, churned, draping, nodules</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>
Depositional sequences in Figure 4.1 and permeability distribution in Figure 5.9 show that there is a possibility that permeability might change direction due to lateral and/or vertical changes in lithofacies distribution. In terms of migration, light density of oil will always migrate to and accumulate at the highest point following the lithofacies pattern. Water having heavier density than oil, on the other hand, will always migrate downward and accumulate at the lowest point. Here, we need the overall inclination of the deposits. Once we know the regional inclination and permeability patterns, we can predict the direction of migration. Since the oil has a lighter density than water, oil will migrate in an opposite direction. Furthermore, the oil will migrate to the highest point. For example, in Figure 5.9, assuming units are undeformed as shown and under water drive, petroleum migrates upward from below through the permeability zones. (See the possible pathways of oil migration in Figure 5.9). The oil will migrate from high permeability to lesser permeability following the gradient of permeable zones. According to Figure 5.9, the change of oil to be accumulated in the trapping zones (place where reservoir zone is covered by impermeable zones or seal so oil are not able to move again) is very small and not prospective because the trapping zones are very small. As the result, oil keeps migrating through the leaking zone (area where oil are still able to move) out of the study area. Because this study performs only 2-D lateral and vertical distributions, the exact permeability patterns beyond this area (to the west) are hardly known.
CHAPTER 6  CONCLUSIONS

Based on lithofacies distribution and depositional environments interpretation, sedimentation processes in the Bosque site are controlled by meandering systems of Rio Puerco. Both fluvial and eolian processes aggrade the area in various sequences, such as stacked fluvial channels, eolian, and fluvial overbank-eolian deposition. The base and the top of the mapped area is controlled by an aggrading braided channel system.

Both allocyclic and autotyc factors control the study area. Gravelly sands is the best indicator of autotyc factors (channel avulsion and migration); continuous eolian sandstones are the best indicator for allocyclic factor (especially climatic) as the transition from fluvial to eolian systems in arid region. Discontinuity of other lithofacies show that local depositional energy and depositional mechanisms play an important role in aggradational processes at the Bosque site.

Fluvial channel and eolian lithofacies are the most significant units in estimating the permeability distribution. Paleoflow obtained from fluvial sedimentary structures and previous permeability measurements show that the general permeability distribution ranges from $S15^\circ E$ - $S35^\circ E$. The opposite direction of this value can be used as the general trend of oil migration under present conditions.

Lateral permeability values of eolian sandstone lithofacies have relatively similar values at each of different sections from south to north in my study area. The small difference in permeability values is probably caused by heterogeneous texture of the lithofacies during sedimentation and the different intensity of local diagenetic processes.

Although there is no indication of oil in the study area, this study provides useful information for petroleum geologists who are developing or stimulating oil production in similar basinal settings about how depositional systems control the permeability distribution. However, since this study only describes lithofacies in 2-D, further study of
permeability distributions to the west will produce better predictions regarding possible oil migration.
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APPENDICES
APPENDIX I

MEASURED GEOLOGIC SECTIONS
sandy clay with mud ball, clay more brown

overbank deposits
with thin interbedded sand, silt and clay

clay, brown

sands, very fine, pale brown, sands, ripple and overbank silt and

combining grey clay and silt.
July 20/91

LH - UF cs, tan, well sorted, very well cemented, interbedded with silty clay, dark brown nodules

LH - UF cs, tan, well sorted, very well cemented

Sandy clay, dark brown

Sandstone, orange, well sorted, well rounded, well cemented

LM - UM cs, orange, well sorted, poorly sorted, well cemented

Overhorde deposits of sands, silty clay, silty clay, dark brown, thin

Sandy clay, brown, reddish, orangeish

Gravelly silt, light, brown grey, poorly sorted

CS

LM - UM cs, orange, well sorted, well rounded, well cemented

Sandy clay, dark brown, clayey

Overhord windows

Sandy clay, dark brown, clayey
course grained sands with mud ball

medium grained cemented sands
fine grained wind blown sand

coarse silt with mud ball

cemented sand - clay

medium grained sand - laminated

fine - medium sand - light grey - reddish

cemented sand

coarse sand with pebble

pebbly sand with mud ball

Brown clay

wind blown sands

Brown clay

silt & clay

silt & clay

fine grained wind blown sand

clay + silt + sand - clumped

Wind blown sands

sandy clay - soil

fine - medium sand with mud ball (clay expert), light grey - reddish
Section 3:

- Fine grained wind blown sands, tan (brownish)
  - Well cemented fine sands
  - Fine, wind blown silt, cemented

- Fine grained silt, well laminated, orange, reddish
  - Brown clay
  - Sandy clay
  - Sandy silt, churned, orange-redish
  - Fine, well grained, silt
  - Fine, well grained with mud ball, reddish
1. **Sedimentation**
   - Calcium carbonate
   - Clay & gravel

2. **Soil Characteristics**
   - Light grey, sandy, loamy
   - Loam, gravelly, with pebbles, large sand, rounded vs. well rounded

3. **Soil Layers**
   - Brown silt and clay, brown, dominated
   - Pale brown soil and gravel

4. **Geological Formation**
   - calcium carbonate
   - Silts & clays

5. **Topographic Features**
   - Elevation
   - Basal gravel
   - Topographically low line

6. **Hydrological Considerations**
   - Meander channel
   - Valley floor
U fine, L med, orange sandy soil

Clay, brown, compacted

Brown clay, compacted

Light gray, U med, light gray

Carbonate (calcite)

Loam, U med, light gray

Sand, U med, light gray
sandy clay, dark brown, churned

U1: LM ss, tan, well sorted, well rounded

5

U1: LM ss, orange, well sorted, well rounded, mud cemented

5

 UM: coarse ss, light grey - orangish with mud clast
   with pebbles, mildly sorted

sandy clay, orange, brown

U1: LM ss, orange, well sorted, well cemented

5

(2)

Overbank deposits

1. Light grey + silt - silty clay
2. Tan, sandy silt
3. Brown, sandy clay, churned
July 18/84

Overbank deposits, silt, sand, clay, shelly, sandy clay, clumped. 6D, upper part is clayey.
Feb 19, 1991

- Overbank deposit: sandy and clay in horizontal
- Tan soil and fine orange silty clay and laminated clay
- Light brown clay
- Brown shelly clay
- Brown clay with nodules at the top
- Mixture of reddish clay and mud
- Fine wind blown silt and clay interbedded laminated
- Wine, brown, orange colored with sand lenses on the top
- Well spread
Quano J/97
Section 7

- Fine - mid sand - light brown - laminated (or a channel)
- Fine - mid sand - light brown
- Dark brown clay - interbedded sand - carbonate
- Coarse - ground sand - grey - brownish parallel lamination
- 
- No pebble or nodules
- Sandy carbonate (compacted cemented whitish)
- No pebble or nodules
- No pebble or nodules
- Carbonates while laminated, ground cemented
- Light sand - redish orange
- Locally with pebble and nodules carbonate
- Brown clay
- Carbonate (white)
- White sand (pale brown - mid. fine) & clay (dark in
- Pale sand - pale brown, which bleeds through
L mid sands, orange-red, well sorted

Gravelly sands, light gray, poorly sorted

L mid coarse sands, tan, laminated, cemented

S

L mid - L coarse sands, orange-red, well sorted, partially cemented

S

L mid - L coarse sands, orange-red, well sorted with carbonate nodules, well sorted, partially cemented

S

L med - orange, well sorted

S

Sandy clay, churned, dark brown
July 5/84

- Purple sands end up interting with clay southward & northward.

Lower Tred:

- s: tan, well cemented, well sorted

- Silty clay, laminated, dark brown

- Sandy clay, dark brown

- Linseed ss, tan, well sorted, well cemented

- Lt: Uf 13, light gray, well sorted, (wind blown sands?)

- Sandy clay, sill, cement brown (purple)

- Silty clay, light brown

- Carbonate layer
Silty clay, silt

Sandy silt + clay, brown

Sandy silt, well sorted, mud exhibited

Overbank deposit consists of mudwall, carbonate nodule

U. coarse ss, redish, pebbly, poorly sorted, well cemented, light gray, laminated

Lm ss, light gray, laminated, well cemented, tan

Brown clay + silt

Gravelly ss, brownish, poorly sorted

Rbly ss, well cemented, poorly sorted, laminated, light gray

Mm ss, light gray, sandstone

U. coarse ss, light gray, well pebble-gravel, poorly sorted

Brown clay + silt

Overbank deposit (interbedded clay, sand, silt)

Branth tan

Tan

Brown clay + silt

Overbank deposit, brown

Clay, sand, silt

Brown clay + silt
July 1/94

10 - 30:

5


Brown clay, sandstone, carbonates nodule.

10

10 - 80:

20

Uf: quartz, well sorted, well cemented, light brown. Vertically laminated

Lm: light grey, well sorted, wind-blown sand.

8

Uf: well sorted, tan

Clay, light tan-brown

S

Sandy clay with pebbly, rounded, poorly sorted pebbles, laminated, poorly sorted, well cemented, light grey

10 - 30:

Gravely s.s. with mud clasts, light grey, clayish.

IM - L.I. (s.) light grey, well sorted.
July 1/99

- Lined 65, tan, well sorted, wind-blown sands, with concretions
- Lined 60, tan, well sorted, wind-blown sands, with concretions
- Lined 50, orange, well
- Sandy clay, brown
- Sandy clay, tan, churned with carbonate nodules
- Clay silts, brown
- Sandy clay, churned, tan
- Lined 40, light gray, well sorted, laminated, wind-blown sands
Sandy clay brown - light red

Carb. nodule - mud clast

Cgb. well cemented, light grey

Cgy. well cemented, light grey

UPL. Limestone, light grey - tan, well cemented, well sorted

UPL. Limestone, light grey, well sorted, mud clast

UPL. Limestone, light grey, well sorted, laminated, mud clast

UPL. Limestone, light grey - tan, well sorted, well cemented
overbank deposit, (clay-rich)

purple - brown, contain 6 coarse laminae, dark and carbonate nodules

Sandy clay, tannish brown

Sandy clay, dark brown - tan

Laminated - orange, very well cemented, well sorted, with carbonate nodules

Sandy clay, very well cemented, cross-laminated, well sorted

Sandy clay, light grey - tan, laminated, well sorted
APPENDIX II

LITHOFACIES CORRELATION
APPENDIX III

Example of Mini AirPermeameter Calibration
\[ 2 \mu q \ L1 \]

Formula \( k = \frac{\mu \text{Go(bD)}}{r_0^2 - \rho_0^2} \)

- \( \mu \) = Viscosity of air [Pa·s] = 1.745 x 10^{-5}
- \( q \) = Vol. Flow Rate [m³/s] = volume/time = 5.5 x 10^{-5} / time
- \( P1 \) = Press. at Tip [Pa] = \( P1 = P0 + Pn \), where \( Pn \) is the net pressure.
- \( P0 \) = Atm. Press. [Pa] = 85.622
- \( \rho \) = Radius of Tip [m] = 0.002 m
- \( \text{Go bD} \) = Geometric Factor = 4.5
- \( m \) = Mass piston = 0.178 kg
- \( A \) = Area piston = 0.00101 m²

\[ P_g = \frac{F_g}{A} = \frac{mg}{A} \]

\[ F_r = \beta v^2 = 0.1 + 155 v^2 \]

\( v = \frac{q}{A} \)

\[ q = \text{Vol.} / \text{time} \]

\[ \Delta P = \alpha q - b \]

\( P1 = P0 + Pn \), where \( Pn \) is the net pressure.

\[ P_n = \frac{F_g}{A} + \Delta P = \frac{mg}{A} - \alpha q - b \]

Example:

For Gravelly sands (GR1) sec. 6

Time = 2.88 sec.

\( q = 5.5 \times 10^{-5} / 2.88 = 1.909 \times 10^{-5} \)

\( \frac{F_r}{0.1 + 155 v^2} = 0.1 + 155 x 0.0189^2 = 0.155 \)

\( \Delta P = (8.3 \times 10^4 \times 1.909 \times 10^{-3}) - 50 = 108.447 \)

\( \frac{F_g}{mg} = 0.178 \times 9.8 = 1.7444 \)

\( \frac{F_n}{(0.155/0.00101) + (1.7444/0.00101) - 108.447} = 1464.8 \)

\[ P1 = 85.622 + 1464.8 = 1550.42 \]

\( 2 \times 1.745 \times 10^{-5} \times 1550.42 \)

\[ k = \frac{4.7848 \times 10^{-11} \text{ m}^3}{0.002 \times 4.5 \times (1550.42^2 - 85.622^2)} \]