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# APPLICABLE CORRELATIONS AND OVERALL CHARACTERISTICS OF BARRIER ISLAND DEPOSYSTEMS

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## ABSTRACT

Five types of shoreline barriers (spits, shoals, barrier islands, barrier pennisulas, and barrier bars) and three basic genetic groups (aggradational, progradational, and transgressive) have been destinguished in modern and ancient barrier sediments. All the shoreline barriers are strongly affected by the dynamics of wave- or tide-dominated coasts. They differ significantly in their external dimensions, internal structures, sequence of facies, and thickness of sand bodies. Therefore, each genetic type of shoreline barrier may have different stroage capacity and flow unit distribution.

Diagenetic processes may strongly modify trends of sand composition, texture, and related petrophysical properties which are present at the time of deposition. Therefore, for valid comparison of barrier types, it is necessary to account for, in addition to the generic type of barrier, its diagenetic and subsidence history.

A correlation of petrophysical, petrographic, and production data at Bell Creek (MT) field indicates that clay content correlates with distance to the nearest fault, that clay content within the cleaner barrier island facies is a function of diagenesis, and that within the foreshore facies, permeability correlates with diagenetic clay content and initial production rate.

Three distinct log-defined groups of geological facies can be recognized at Bell Creek field. These include the "high productive" facies (high energy barrier island facies, foreshore, shoreface, upper part of middle shoreface, and washover); the "upper sand" facies identified as nonbarrier channel or valley fill deposits); and a "lower shoreface/lagoonal" facies (low energy barrier island/nonbarrier). The high productive facies is thickest in the central part of Unit 'A' and thins toward the lagoon and toward the basin, but remains thicker along the depositional strike of the barrier complex.

Reservoir quality is also highest along a NE-SW elongated zone in the central part of Unit 'A'. The sharp reduction of porosity and permeability due to the presence of diagenetic clay is most noticeable in the southwestern part of the Tertiary Incentive Project (TIP), in the southern half of the Unit.

The log crossplot technique used to define three major groups of facies at Bell Creek tends to be supported by high correlation cofficients between ultimate primary recovery (from a decline curve analysis) and storage capacity (from the crossplot data).

Based primarily on core-calibrated log analysis, it is concluded that the northern Pilot area was adversely affected by the higher amount of clay (either as matrix or cement) and by the higher degree of intercollation between high- and low- permeability strata.

## INTRODUCTION

This report represents the completion of milestone 6 including tasks 1 and 2 of project BE1 from the FY89 Annual Plan. The scope of work is related to continuing efforts to develop a more generalized model of barrier island hydrocarbon reservoirs which can be used to describe the internal structure, dimensions, and geometry of various facies.

This report is presented in two sections. The first describes the determination of characteristics required to construct a genetic classification of shoreline barrier types. At least three types of information are required to construct a generic classification of diverse types of shoreline barriers which include spits, shoals, barrier peninsulas, barrier islands, and barrier bars. The first type is the relative direction of growth or migration of the barrier (progradational, aggradational, or transgressive). Secondly, whether the shoreline is (or was) tide- or wave-dominated must be determined. Thirdly, the tidal range at the site of deposition must also be determined (microtidal, mesotidal, macrotical). Shoreline barriers generally do not form in macrotidal conditions. In microtidal and mesotidal conditions, barrier complexes form parallel or oblique to the coastline and have distinctive facies geometries and lateral extents. Only through comparisons and contrasts of truly analogous types of barrier deposits can a generalized model be constructed. This part of the report is largely based on a survey and analysis of the literature. The effects of diagenesis on parameters commonly used to define depositional facies, such as grain size or sorting, are also considered.

The second section describes methods for correlating petrophysical, petrographic, and production parameters within the barrier island section at Bell Creek field. In addition, lateral trends deliniated by various parameters such as clay content or permeability and trends which can be interpreted through the use of logs are described for the field.

## COMPARATIVE CHARACTERISTICS OF MODERN SHORELINE BARRIERS AND HYDROCARBON PRODUCTIVE ANCIENT ANALOGS

In this part of the comparative study leading to a generalization of external and internal geometries, dimensions, and petrophysical properties of barrier island deposystems, a broader relationship between recent and ancient shallow marine sandy shoreline barriers is addressed.

Before meaningful comparisons and conclusions regarding generalized features can be made, it is necessary (1) to define various shoreline barriers; (2) to determine how they are formed, by which depositional processes and in what setting; (3) to compare similarities and differences among various types; and (4) to compare similarities between various types.

### Types of Shoreline Barriers

Shoreline barrier island depositional settings encompass a variety of sandbody types. Shoals, spits, barrier peninsulas, barrier islands sensu stricto, and sandy barrier bars attached to the mainland at both ends are subtypes of shoreline barriers formed by long-shore currents and modified by wave and/or tidal action (fig. 1). They can be transformed from one to another during coastline evolution or even destroyed before their burial.

Most barrier bars are parallel or oblique to the coastline. Some may be attached to the shore at one end (spits, peninsulas), and others may be separated from the mainland and submerged (shoals) or emerged and breached by tidal channels (barrier islands). Strand plains, delta mouth bars, tidal sand ridges, and shelf ridges (offshore bars) are excluded from this discussion even though they may possess certain common features with nearshore barriers.

Generally, typical modern coastal barrier sand bodies are 10 to 25 miles long, 2 to 4 miles wide, and 30 to 50 feet thick.[1] The inner shelf shoals are typically 20 to 22 miles long, 1 to 6 miles wide, and 7 to 23 feet thick.[2]

## Information Required for a Genetic Classification of Shoreline Barriers

There are three major genetic groups of modern shoreline barriers: aggradational (build upward, sometimes called stationary); progradational (migrating seaward); and transgressive (migrating landward),[3] which differ

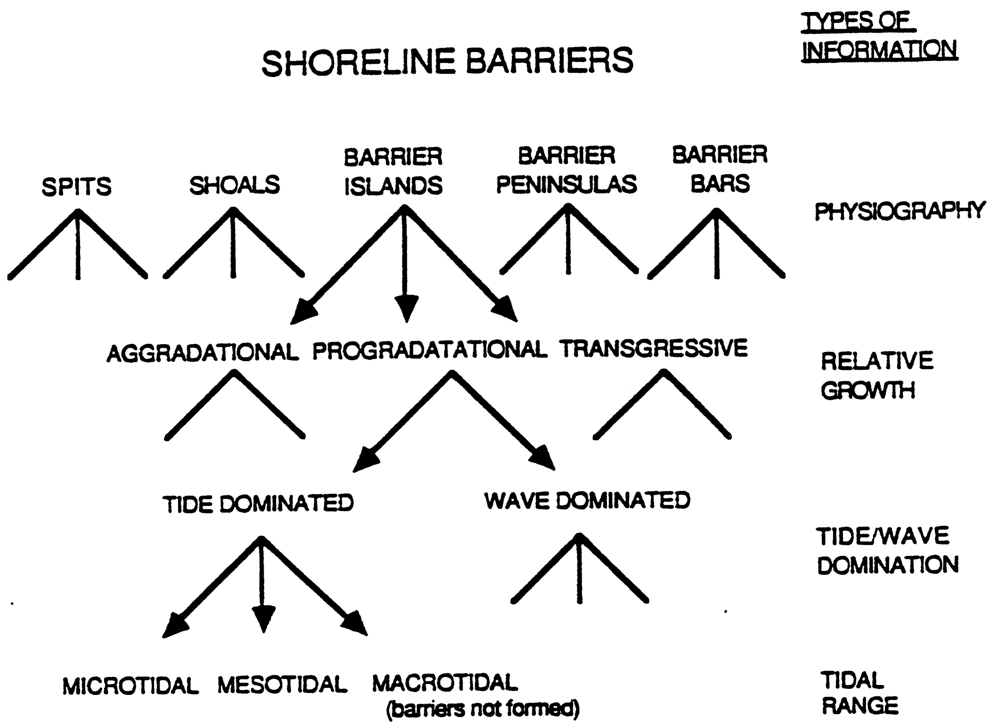


FIGURE 1. - Five major types of shoreline barriers may reveal different characteristics if formed in aggradational, progradational, or transgressive environments or if formed along tide- or wave-dominated coasts.

substantially in their external dimensions, internal structures, sequence of facies, and thickness of sand bodies (fig. 2). These types of barriers must be identified in the subsurface to ensure adequate predictions of reservoir geometry, petrophysical properties and distribution of facies in uncored

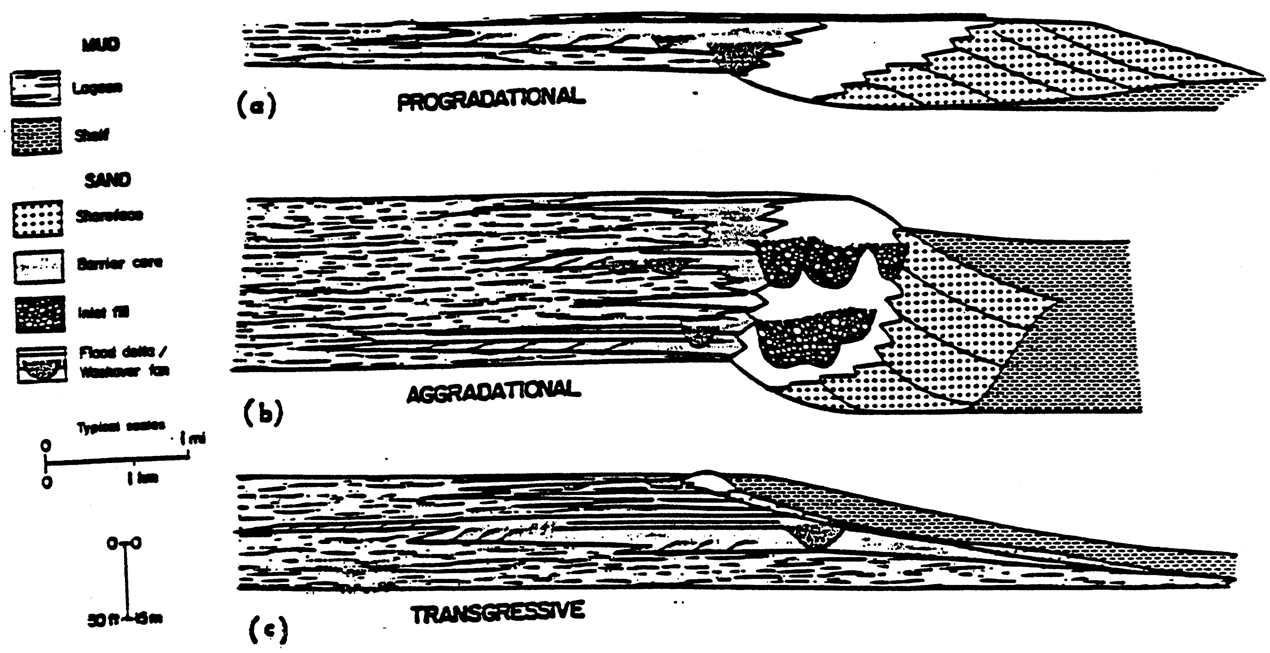


FIGURE 2. - Stratigraphy of (a) progradational, (b) aggradational, and (c) transgressive barrier island sand bodies (After Galloway, 1986).

areas, and for selection of optimum strategy for reservoir development. Modern transgressive barrier islands are 20 to 47 miles long, 1 to 1.5 miles wide, and only 7 to 16 feet thick.[4] An excellent description of evolutionary stages of the transgressive barrier shorelines of the Mississippi delta plain is given by Boyd and Pennland, 1984.[5] Fast marine transgression and rapid subsidence favors preservation of most barrier island sediments. Slow subsidence during transgressive periods results, however, in the reworking of most sequences, and only remnants of original facies have a chance to survive.[6] Numerous depositional models of shoreline barrier deposits indicate that continuity of sand bodies is usually excellent and petrophysical properties are relatively constant parallel to depositional strikes for all three major barrier types.[1] In the dip direction, however, the vertical profile is often disrupted, and petrophysical properties may vary greatly in aggradational and transgressive types (fig. 2).

For a generic classification of barrier type, two additional features which need to be defined are the paleodirection of shoreline currents which formed the reservoir body and determination of whether the paleocoast was tide- or wave-dominated. After these features are identified, a third major question must be addressed - whether the ancient shoreline was formed in a micro- or mesotidal environment. That the morphology of modern barrier islands and the type of sedimentation significantly differ in these two environments have been well documented.[7] In microtidal coasts (<1 m of tidal range) long, narrow barriers with numerous washovers and few inlets are formed. Padre Island, 110 miles long and 1/2 to 4 miles wide, which was aggradational for most of its history but which recently became transgressive[8] is a good example of a barrier island formed on a microtidal coast. Along mesotidal coasts; e.g., East Frisian Isles (1 to 3.5 m tidal range), the barrier islands are short in the direction of the depositional strike (rarely exceeding 10 miles length), wide in the dip direction, and are characterized by numerous inlets. In macrotidal coasts (>3.5 m tidal range), barriers are absent although shoals and supratidal islands perpendicular or oblique to the mainland can be formed (fig. 3).

## Examples of Reservoirs and Their Modern Analogs

Critical geological information such as genetic barrier type, dimension, geometry, petrophysical properties, trapping mechanism, depth of occurrence, and oil, gas, or condensate reserves has been tabulated for several hydrocarbon reservoirs producing from shoreline barrier deposits in different geologic settings of the United States. In some cases, reservoir characteristics are quite similar to their modern analogs. Identification of such genetic types with analogous facies dramatically improves understanding of reservoir behavior and facilitates improved predictions of reservoir properties for advanced stages of development. For example, the sedimentary pattern of the closely located group of south Texas oil fields producing from the Eocene Reklaw formation in Atkinson (barrier island), Hysaw, and Flax fields (distributary mouth bar prograding seaward) and Burnell, Hondo Creek, and Runge West fields (broad delta-front sheet sand deposited further downslope) reported by Bulling and Breyer[9] is similar to the modern sedimentary system of the Vistula barrier bar on the Baltic Coast, Poland, studied by Szpakiewicz.[10] Another example of a strong analogy with a modern

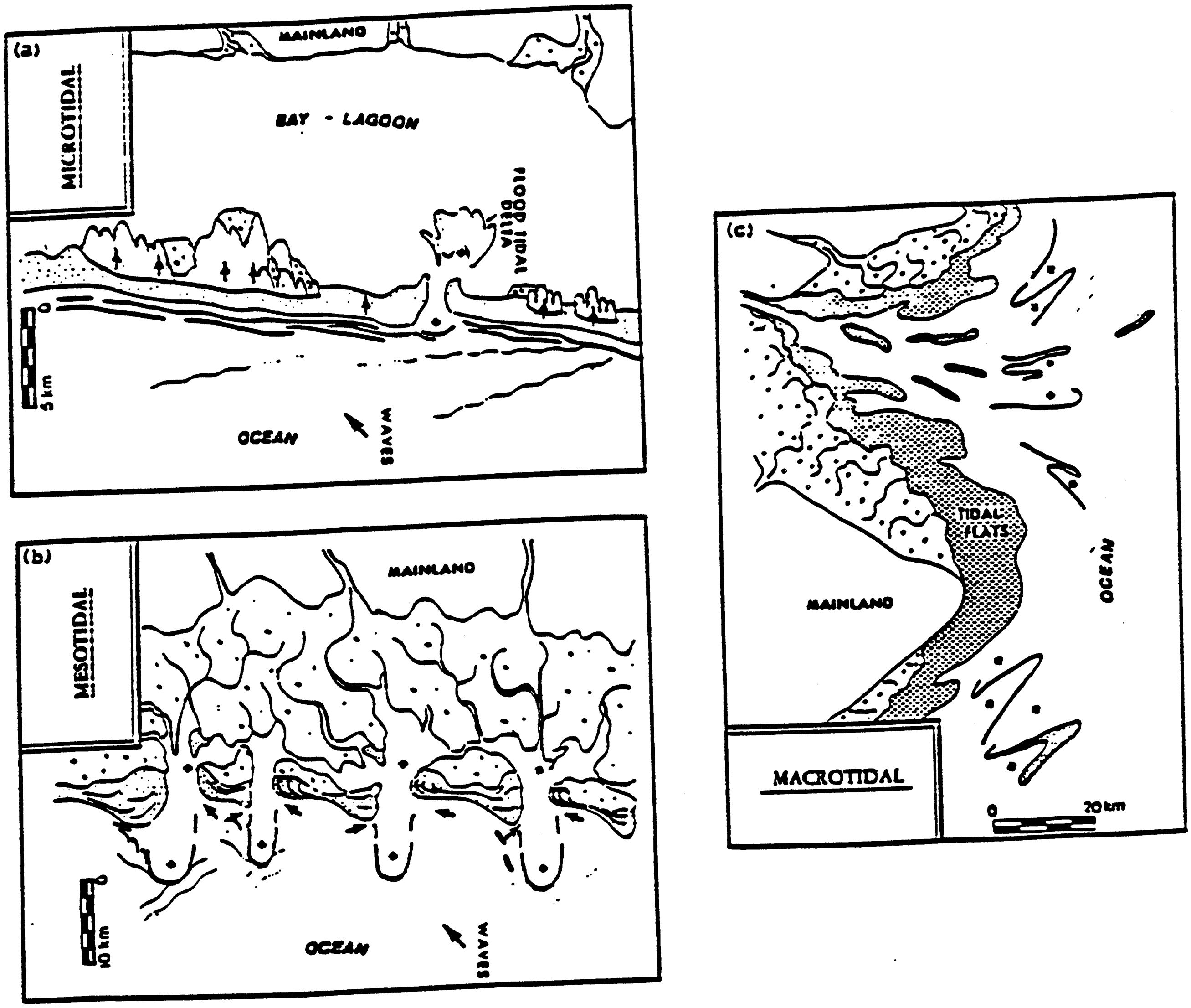


FIGURE 3. - Diagrams of Hayes' coastal morphology types. (a) Microtidal, showing long narrow barriers with numerous washovers and few inlets; (b) mesotidal, showing short, wide barriers with numerous inlets; and (c) macrotidal, on which barriers are absent (after Hayes, 1979; Galloway, 1986).

generic type of barrier comes from characteristics of the Pilot Sandstone reservoir of the Upper Cretaceous lower Tuscaloosa Group (Cenomanian) in South Carlton and Pollard fields of southwestern Alabama. The Pilot Sandstone is considered[11] to be similar to the transgressive shoreline barrier sands associated with the modern Mississippi River delta plain in Louisiana, as described by Penland (1985).[4]

West Ranch field, a prolific oil and gas field with multiple pay zones in the Frio formation barrier island/strand plain system (fig. 4), would provide a natural laboratory for comparative study of the three major types of barrier islands: (1) aggradational (Greta reservoir), (2) progradational (41-A reservoir), and (3) transgressive (Glasscock reservoir). Ward and 41-A reservoirs of West Ranch field represent the strand plain type of sedimentation.[3] The Glasscock reservoir is the thinnest of the three and contains the least oil-in-place. The progradation 41-A reservoir consists of barrier core, inlet fill, and flood tidal delta facies. The barrier core and inlet fill sediments are the best producers and occur in comparable proportions. The distribution of permeabilities, however, is very different in the two systems; in the barrier core, permeability increases upward and the highest permeabilities occur at the top of the section, whereas in the inlet fill, the highest permeabilities occur at the base and gradually decrease upward. The field may be considered for a more detailed comparison of nearshore marine reservoirs.

## Bell Creek Depositional Setting Compared

Characteristics of Bell Creek (MT) field resemble, to a much lesser degree, characteristics of progradational Galveston Island in Texas, that were suggested by previous workers.[12-13] Moslow[2] observed that an isopach map of Bell Creek sandstones is similar in morphology to that of a modern transgressive barrier island chain. The arcuate-shaped sandstone body that extends updip (paleo-landward) into lagoonal shales is interpreted as a series of transgressive storm washover deposits. Spontaneous potential log (SP) signatures from the Galveston Island barrier front, backbarrier, and across the tidal channel[14] are different from those of Bell Creek field; i.e., the SP is decreasing at the top of the Bell Creek barrier section but it is increasing at the top of the Galveston Island barrier.

In consideration of examples discussed here, a generalization of properties of shoreline barrier deposits, in their variety of forms, must be based on thorough comparative studies of numerous reservoirs, outcrops, and modern sediments. Only parameters from reservoirs that can be confidently

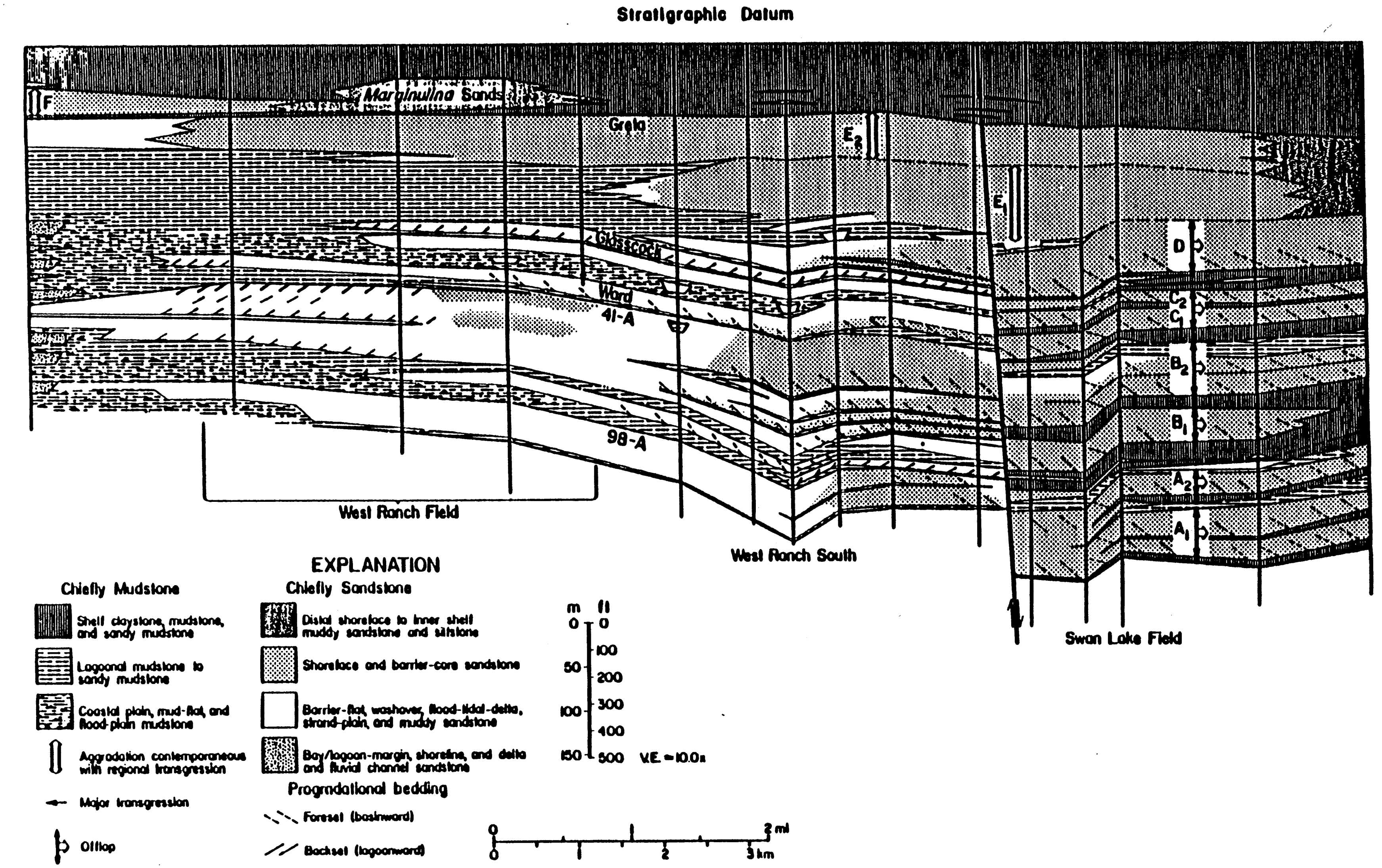


FIGURE 4. - Dip-oriented regional cross section through West Ranch field. West Ranch field lies updip of sand-rich axis of Greta/Carancahua barrier/strandplain system. Stratigraphic relationships indicate six cycles of progradation or aggradation (labeled A through F) separated by transgressive marine shales. Main producing reservoirs in West Ranch field are labeled (After Galloway, 1986). For genetic classification of Greta, Glasscock, Ward, 41-A, and 98-A reservoirs, refer to text.

assigned to a specific type of barrier should be used for such a comparison or generalization. For identification of genetic barrier type represented by Bell Creek reservoirs, comparative studies of cores from numerous parts of the field (different production units) is required.

## COMPARISON OF ROCK COMPOSITION AND TEXTURAL FACTORS

### Quartz Composition and Grain Size

Although the recognition of general rock type, vertical sequence, and distribution of major depositional facies used for field development are frequently based on log signatures alone, much more diagnostic information can be obtained if cores are also available. Facies characteristics, rock composition, textural parameters, and diagenetic history can only be calibrated with core or outcrop samples. Among these parameters, grain size and sorting are often valuable indicators of depositional environment because the detrital mineralogy and grain size distribution reflect the imprint of the environment of deposition. The sediments comprising shoreline barriers tend to be quartzose, and each detrital component has its own unique size distribution.[15] Therefore, grain size must be summarized only for the quartz fraction.

Cross plots of quartz size versus quartz content cannot generally be used to discriminate diverse environments of deposition.[16] However, compositional and textural data from samples collected within the same general environment and from within the same basin can be used to segregate subenvironments or facies as long as there is no change in source of the material and the diagenetic histories are identical. For example, bivariate plots of quartz size and quartz content collected from recent sediments along the Galveston barrier complex yield data that discriminate the major subenvironments (lagoon, lower shoreface, middle shoreface, upper shoreface-beach, and dune). A crossplot of quartz size and quartz content (fig. 5) shows a positive correlation with a reasonably high correlation coefficient (R = 0.71). Further, data for each facies tend to cluster in the expected order, with dune and upper shoreface-beach being the coarsest and having the greatest quartz content. In contrast, lagoonal and lower shoreface samples are the finest grained and contain the least quartz.

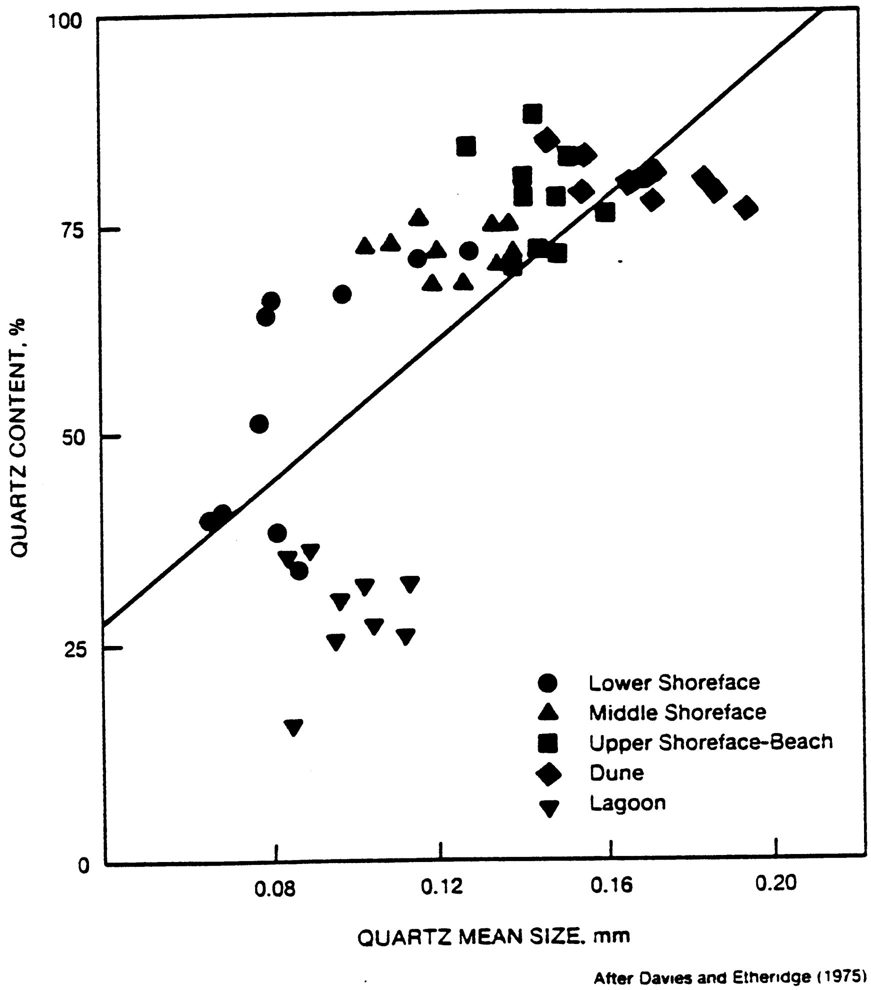


FIGURE 5. - Cross plot of quartz content and mean quartz size, Galveston barrier complex, TX. Correlation coefficient (R) for the regression line is 0.71. After Davies and Ehteridge (1975).

The close interdependence between quartz content and quartz grain size has also been reported[12,16] for samples from the Muddy formation of the Powder River Basin. The data by Davies and Etheridge[16] were not subdivided by facies. They concluded that an environmental identification must be made before any quantitative assessment of the interdependence between grain size and quartz content can be made. They reasoned that the positive relationship between grain size and quartz content reflects that those environments (or facies) characterized by the most winnowing are significantly enriched in quartz.

Berg and Davies[12] agreed that grain size is related closely to energy of depositional environment. Their plot of grain size and quartz content for samples from Bell Creek field showed a positive correlation, and the data were segregated into four distinct groups including beach and upper shoreface, middle shoreface, lagoon (with washover), and lower shoreface and lagoon.

Results of ongoing petrographic studies also indicate a visual relationship between quartz content and grain size; however, the correlation coefficient is not high (R = 0.51). In a crossplot of quartz content versus grain size (fig. 6), higher energy barrier facies show a tendency to be coarser grained, whereas lower energy barrier and lagoonal facies tend to be more fine grained. A major difference between our data and that of Berg and Davies [12] is the degree of scatter among the facies. A plot (fig. 6) of NIPER data clearly shows more scatter for individual facies and virtually no clear segregation of data into groups based on facies.

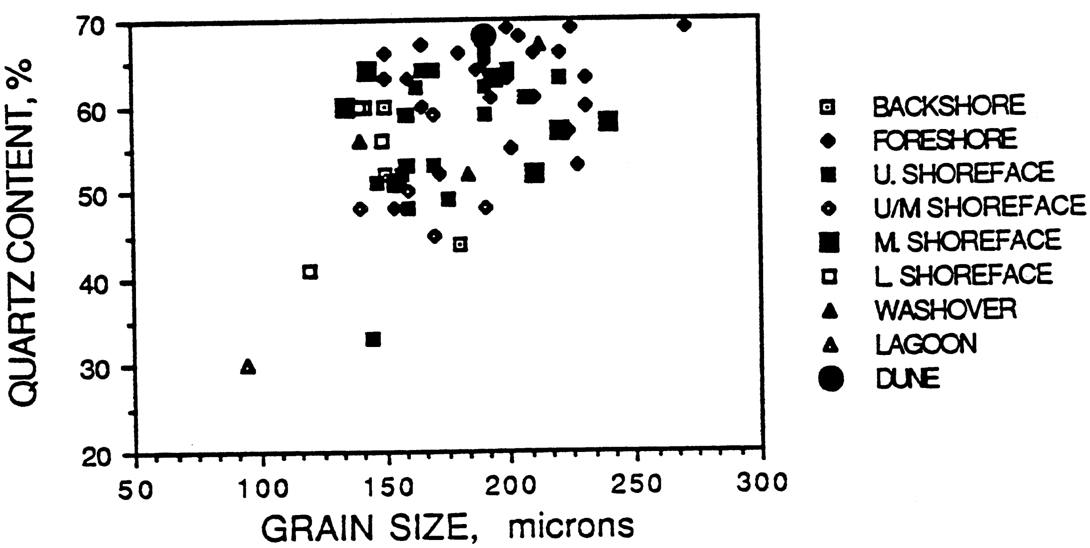


FIGURE 6. - Cross plot of quartz content and grain size, Unit 'A', Bell Creek (MT) field.

Discrepancies between our data and that of Berg and Davies may result from one or more of the following conditions.

1. Bell Creek data were selected from representative samples of each facies from cored intervals. As such, these data may be expected to illustrate more accurately the natural variability within each facies.

2. There may be some variation due to the spatial distribution of the data. NIPER data (fig. 6) are exclusively from wells within only four sections located within Unit 'A'. Berg and Davies data were selected from wells along the entire length of the field.

3. Great differences in rock composition, grain size, matrix, clay cement, and related petrophysical properties have been documented on a well by well basis in Unit 'A'. Such differences may indicate differing intensities of diagenetic processes. Plotting data from wells with divergent properties on the same chart would naturally lead to greater scatter, even for data from equivalent facies.

## Permeability and Grain Size

Permeabilities may be expected to vary according to grain size and sorting, therefore, according to depositional environment in recent settings. Berg and Davies[12] found a positive correlation for log permeability versus quartz grain size in their study of the Muddy formation at Bell Creek field but unfortunately did not report a correlation coefficient. In their figure 7, the finest grained samples have the lowest permeability and represent lower shoreface and lagoonal environments. Cleaner sandstones were segregated according to permeability so that four permeability-grain size categories were recognized: beach and upper shoreface, middle shoreface, lagoonal-washover, and lower shoreface-lagoonal. Although they found good environmental discrimination, Berg and Davies noted that segregation according to environment is not complete. They concluded that the principal type of variation in the permeability-grain size plot was caused by variations in the amount of matrix and cement.

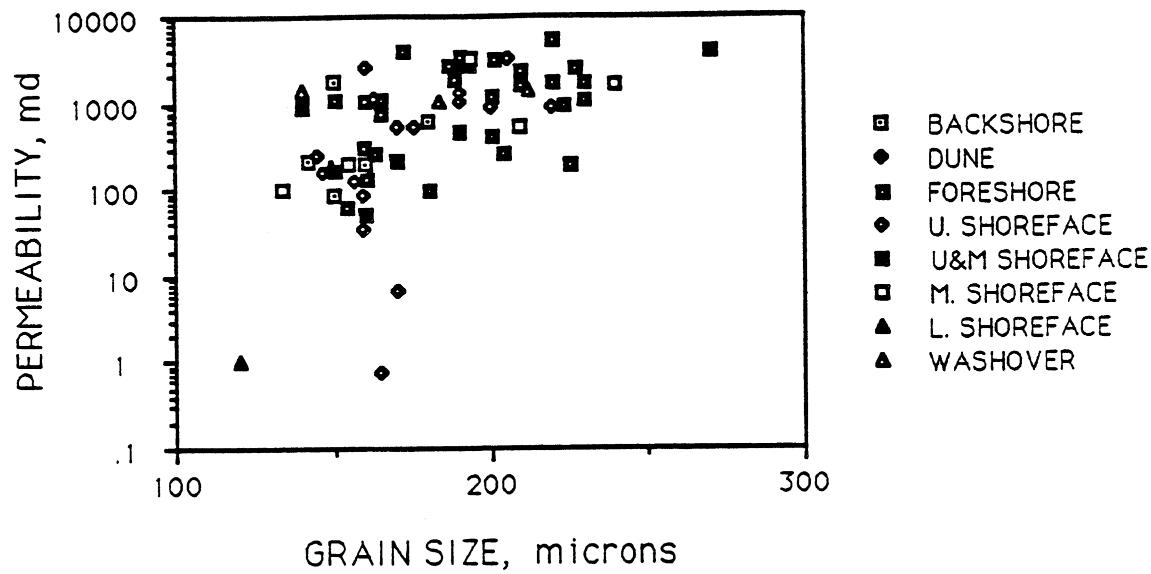


FIGURE 7. - Cross plot of permeability and grain size, Unit 'A', Bell Creek (MT) field.

NIPER data from the barrier island facies at Bell Creek field, Unit 'A' (fig. 7) indicates that there is no statistical correlation between permeability and grain size (R = 0.27).

Another way to look at the relationship between permeability and grain size is to consider a single mean value for each facies. This relationship, based on NIPER Bell Creek thin section data, is illustrated in figure 8. Although there is a general increase in grain size and permeability in the higher energy facies, the grain size and permeability are anomalously low for the dune facies. Finer mean detrital grain size from modern dune sediments has been reported at Mustang Island, TX.,[17] along the Atlantic Coast,[18] at New South Wales,[19] and at Padre Island, TX.[20] In contrast, coarser dune sediments have been reported at Galveston Island, TX.[16] The finer grained dune sediments recorded for the Muddy formation at Bell Creek (this report) are in line with most recorded modern settings.

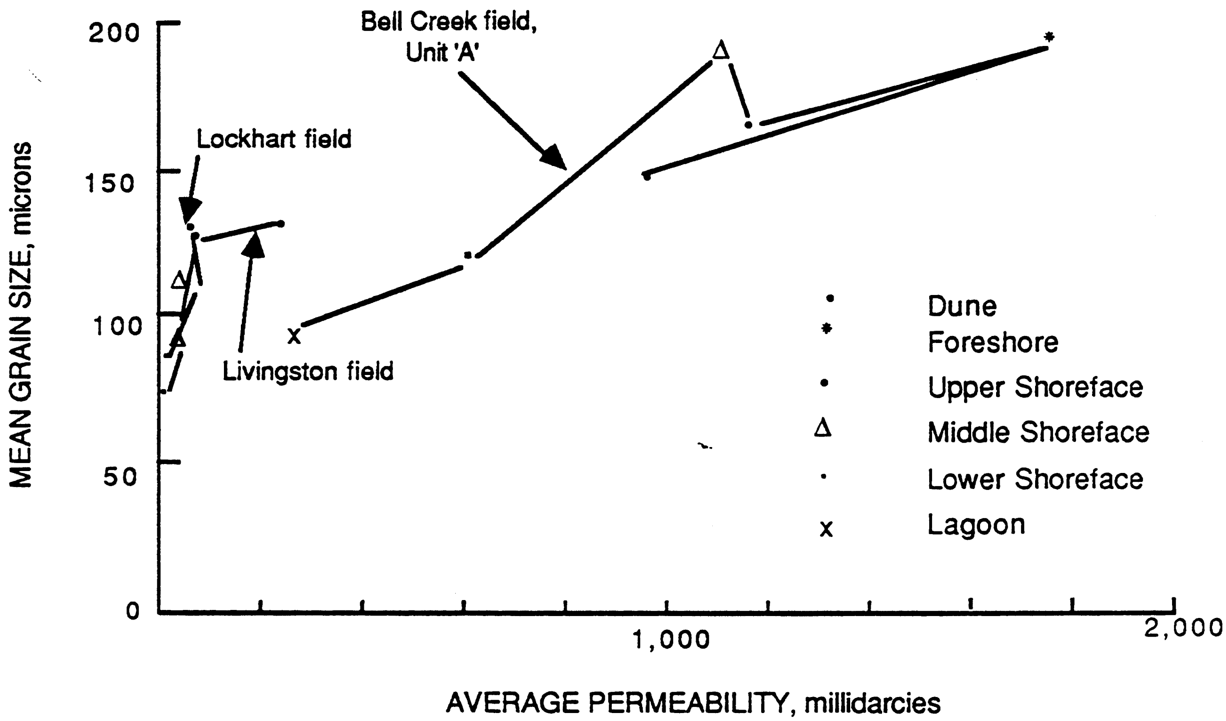


FIGURE 8. - Plot of mean grain size and average permeability for corresponding facies from Unit 'A', Bell Creek (MT) field, Lockhart (TX) field, and Livingston (TX) field. Data for the two Texas fields interpreted from Self et al., 1986.

The data in figure 8 also illustrate the danger of blindly comparing barrier island settings in terms of their petrophysical, textural, or compositional parameters. In addition to the data from Bell Creek, data from the literature are also presented in figure 8 for two other barrier island reservoirs. Note that the average grain size is distinctly different between Bell Creek and the two other fields and that permeability values do not overlap. Both Lockhart field and Livingston field, reservoirs in the Frio formation, Texas Gulf Coast, are at 10,000 ft, whereas Bell Creek is about 4,500 ft. The effect of increased depth is probably the most likely reason for the significantly lower permeabilities in the deep Gulf Coast reservoirs. Different diagenetic histories for two reservoirs could also produce equally dramatic differences.

## Composition and Sorting

Plots of mean grain size versus sorting are not adequate indicators of environment[21]; however, because quartz content is environmentally sensitive, plots of quartz content versus sorting should provide environmental discrimination for modern samples. As a test of this relationship for ancient settings, the available data (based on thin section analyses of Bell Creek samples) were plotted. The results (fig. 9) show no trend and no grouping of data by facies. Scattered data are most likely the result of strong diagenetic changes in the Bell Creek samples since the time of deposition. Furthermore, petrographic examination indicates that some wells have been diagenetically altered more than other wells. The effects of diagenesis can mask or destroy trends that were present within sediments at the time of deposition. The data in figure 9 serve as a warning not to make direct comparisons of parameters from barrier island reservoirs, or facies within the same reservoir, that have not been subjected to the same diagenetic history. Comparisons of average values from barrier island/strand plain reservoirs, such as those presented in table 1, may be of some comparative value, but can be misleading if both the genetic type of barrier and the diagenetic histories are not similar. Many of these properties may be related to the basin/age rather than to the depositional environment.

Rock, fluid, and reservoir properties from 67 barrier island/strand plain reservoirs were collected and analyzed. These reservoirs were mainly located in Texas,[27] and they were produced under various drive mechanisms such as solution gas, pressure maintenance, and/or water injection. Average reservoir properties of Unit 'A' of Bell Creek (MT) field, a barrier island reservoir, are listed for comparison with other barrier island reservoirs. Bell Creek field, Unit 'A' average properties consistently fell within the range of properties found in other reservoirs of the same environment of deposition.

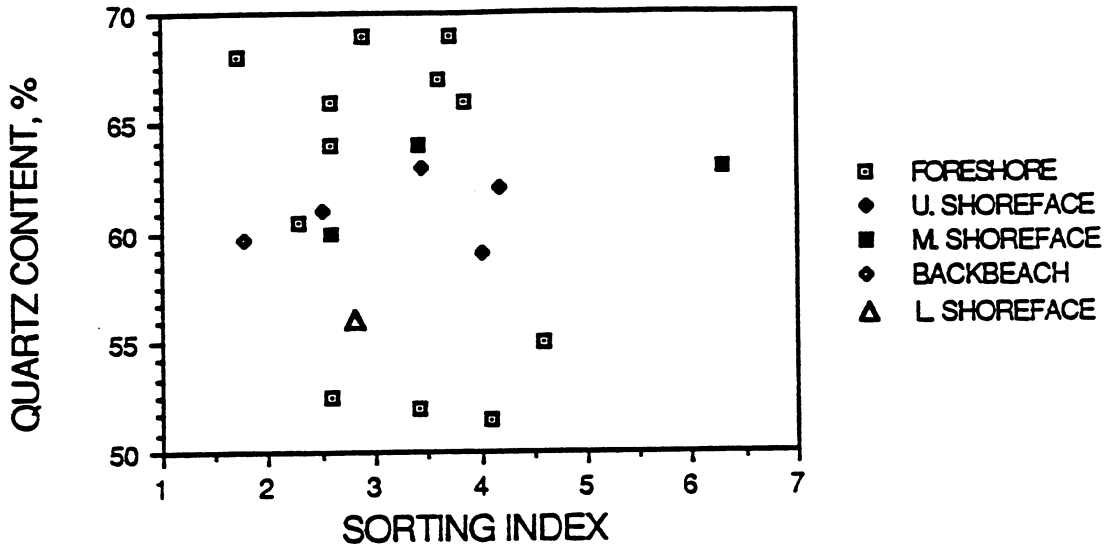


FIGURE 9. - Cross plot of quartz content and sorting index, Unit 'A', Bell Creek (MT) field.

TABLE 1. - Comparison of properties of 67 U.S. barrier island/strand plain reservoirs with those from Unit 'A' Bell Creek field

| Reservoir parameters | Texas reservoirs | | | Unit 'A' Bell Creek field, MT. |
|---|---|---|---|---|
| | Minimum | Maximum | Mean | |
| Depth, ft | 1,200 | 10,000 | 5,051 | 4,500 |
| Oil column thickness, ft | 10 | 300 | 75 | 210 |
| Absolute permeability, md | 164 | 4,500 | 1,006 | 2,250 |
| Porosity, % | 21.5 | 38 | 29.7 | 28.5 |
| Initial water saturation, % | 13 | 55 | 31 | 26 |
| Oil gravity, °API | 20 | 49 | 31 | 32.5 |
| Initial GOR, scf/stb | 40 | 6,000 | 613 | 200 |
| Initial pressure, psi | 575 | 4,658 | 2,184 | 1,204 |
| Reservoir temperature, °F | 100 | 236 | 154 | 110 |
| Residual oil saturation, % | 9 | 50 | 25.8 | 35 |
| Original oil-in-place, MM stb | 18 | 549 | 84.6 | 127 |
| Recovery factor, % | 23 | 73 | 49 | 54 |

## CORRELATIONS AND TRENDS OF PETROGRAPHIC, PETROPHYSICAL, AND PRODUCTION DATA AT BELL CREEK FIELD

Petrographic, petrophysical, and production data from Bell Creek (MT) field have been correlated and general trends in the data identified. This information will provide the basis for future comparative studies of barrier island types from different geological times and geographical locations with their ancient counterparts. This section is subdivided into two parts: a correlation of reservoir parameters indicated for the barrier island part of the reservoir at Unit 'A', Bell Creek field and a discussion of the recognized trends along and across the field.

### Correlation of Critical Parameters

Available petrophysical, petrographic, and production parameters have been correlated for data from the barrier island reservoir interval at Unit 'A', Bell Creek field (table 2). Although much of the data is from the four-section area encompassing the Tertiary Incentive Project (TIP), we feel that the correlations are generally applicable to the barrier island reservoir section at Bell Creek.

Results of correlations summarized in table 2 are presented as correlation coefficients (R values) between given sets of data. Correlation coefficients have been corrected in the sense that wild points in the cross plots of parameters have been eliminated from no more than one well for each correlation. For example, in the cross plot of diagenetic clay versus distance to the nearest fault, the data lie near a statistically determined regression line except for a single point. That point was ignored when the high coefficient (R = 0.812) for that correlation was determined.

Nineteen correlation coefficients from this data set are high (greater than 0.70). The most significant of these correlations includes relationships among the following:

1. Average total clay of the barrier island facies in a given well versus distance to the nearest fault (R = 0.850). This relationship may indicate a structural control on diagenesis.

TABLE 2. - Correlation coefficients for petrophysical, petrographic, and production data from Barrier Island facies Unit 'A', Bell Creek (MT) field.

| | Ft. nearest fault | Ave. diag. clay | Max. diag. clay | Ave. total clay | Vdp (foreshore) | Vdp (formation) | Initial production | 1980 ROS | Gross barrier sand | Shoreface k | Shoreface thickness | Foreshore k | Foreshore thickness | Shoreface kh |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ave. diagenetic clay | 0.434 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Max. diagenetic clay | [1]0.812 | [1]0.896 | - | - | - | - | - | - | - | - | - | - | - | - |
| Ave. total clay | [1]0.850 | 0.911 | [1]0.847 | - | - | - | - | - | - | - | - | - | - | - |
| Vdp [2] (foreshore only) | 0.662 | 0.581 | 0.378 | 0.498 | - | - | - | - | - | - | - | - | - | - |
| Vdp (entire formation) | 0.582 | 0.452 | 0.061 | 0.457 | 0.686 | - | - | - | - | - | - | - | - | - |
| Initial production | [1]0.715 | [1]0.632 | 0.015 | [1]0.712 | 0.371 | [1]0.772 | - | - | - | - | - | - | - | - |
| 1980 ROS [3] | 0.392 | 0.595 | 0.382 | [1]0.695 | 0.462 | 0.612 | 0.531 | - | - | - | - | - | - | - |
| Gross barrier sand | 0.341 | 0.393 | 0.497 | 0.159 | 0.749 | 0.087 | 0.303 | 0.082 | - | - | - | - | - | - |
| Shoreface perm | 0.645 | 0.531 | [1]0.798 | 0.402 | 0.329 | 0.306 | 0.509 | 0.430 | 0.136 | - | - | - | - | - |
| Shoreface thickness | 0.675 | 0.386 | 0.218 | 0.650 | 0.224 | 0.435 | 0.563 | 0.676 | 0.325 | 0.230 | - | - | - | - |
| Foreshore perm | 0.615 | [1]0.818 | [1]0.874 | [1]0.790 | [1]0.833 | 0.586 | [1]0.869 | 0.449 | 0.347 | 0.559 | 0.168 | - | - | - |
| Foreshore thickness | 0.461 | 0.108 | 0.072 | 0.107 | 0.165 | 0.265 | 0.479 | 0.393 | 0.393 | 0.358 | 0.409 | 0.525 | - | - |
| Shoreface kh [4] | 0.452 | [1]0.719 | 0.314 | 0.294 | 0.351 | 0.022 | 0.179 | 0.013 | 0.404 | 0.419 | 0.769 | 0.074 | 0.348 | - |
| Foreshore kh | 0.555 | 0.635 | 0.580 | 0.635 | 0.570 | 0.494 | [1]0.822 | 0.400 | 0.313 | 0.450 | 0.021 | 0.969 | 0.687 | 0.469 |

[1] Value has been increased by omitting a well.
[2] Vdp = Dykstra Parsons coefficient
[3] ROS = Residual oil separation
[4] kh = Permeability times thickness

2. Average total clay of the barrier island facies in a given well versus average diagenetic clay (R = -0.896). This relationship reflects that within the cleaner barrier island facies, total clay is a function of diagenesis, rather than depositional matrix.

3. Foreshore permeability versus maximum diagenetic clay (R = 0.874). This relationship basically reflects that the foreshore facies is very clean prior to diagenesis.

4. Foreshore permeability versus initial producton rate (R = 0.869). This relationship indicates that initial producton rate is related to permeability through depositional facies. Unfortunately, not all facies are as directly related to initial production as is the foreshore; e.g., shoreface permeability versus initial production has only R = 0.509.

Major generic groupings of geologically defined facies (such as valley fill, or the barrier island group consisting of foreshore, upper, and middle shoreface) provide the basis for a permeability layer model of the Bell Creek reservoir (table 3). Each of the layers has distinctive characteristics such as average permeability, variability of permeability (Dykstra-Parson's coefficient), and the ratio of vertical to horizontal permeability. This rather generalized permeability layer model is useful for forecasting field and well performance.

## Variogram Analysis of Permeability and Production

A sophisticated geostatistics software package recently acquired was used in computing variograms of average permeability and initial production rate per well.

Variogram analysis of average permeability per well indicates an isotropic, nested pattern consisting of two ranges of correlation lengths: 0.25 and 1.5 to 2.5 miles. The shorter range is about the distance between wells and reflects permeability variations within the flow unit. The longer range is on the order of the width of the sandstone body in Unit 'A'. This correlation range is consistent with the outcrop permeability variation observed, where similar permeability averages and vertical profiles extend over at least 1.6 miles.

The variogram of initial production rate potential also indicates an isotropic nested pattern with ranges in correlation lengths similar to those of average permeability. This similarity suggests a dominant control of permeability on initial production.

## LOG-DEFINED FACIES USED TO DESCRIBE LATERAL DISTRIBUTION OF PETROPHYSICAL PROPERTIES

The lithologic and petrophysical properties within each barrier island facies or a group of facies tend to be fairly distinct. Because of the relative uniformity of depositional processes in subenvironments, some uniformity in the distribution of petrophysical properties in these facies may be expected. The predictability of fluid production from barrier island reservoirs can, therefore, be augmented by an understanding of the spatial distribution of thicknesses and variations of petrophysical and fluid flow properties in each facies. Subsequent to deposition of sandstones, diagenesis or tectonic events may severely affect the distribution of flow properties in the different facies. Nevertheless, the distribution of depositional characteristics is frequently related to reservoir quality.

Two crossplot techniques based on interpretation of log data which can effectively distinguish some of the barrier island and associated nonbarrier island sandstone facies have been described.[22] From examinations of a large number of crossplots, it was concluded that barrier and nonbarrier sandstone deposits at Bell Creek could be grouped into three log facies which have similar petrophysical and fluid flow characteristics. Kolmogorov-Smirnoff (K-S) statistical, two-sample tests conducted on permeability and porosity data also indicate the presence of three distinct permeability distributions for the Muddy sandstone in the study area. The three log facies and the corresponding geological facies they represent may, therefore, be summarized as follows:

a. "high productive facies" consisting of foreshore, shoreface, the upper part of middle shoreface, and washover;
b. "upper sand facies" consisting of paralic facies of estuary, lagoon, or marsh, nonbarrier channel or valleyfill deposits; and
c. "lower shoreface/lagoonal facies" consisting of poorer reservoir quality sediments which include a and b.

## TABLE 3. - Permeability layer model characteristics

| Layer | Facies | Grain size (microns) | Number samples[1] | Permeability, md | | | Porosity, % | | kv/kh | Dykstra-Parksons coefficient | Cation-exchange capacity[2], meq/100g |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Arithmetic | Geometric | Range | mean | range | | | |
| 4 | Valley fill | 100-200 | 21 | 193 | 42 | 0.6-1320 | 23 | 15-33 | 0.5 (N=16)[3] | 0.90 | 3 (N=4)[3] |
| 3 | Paralic facies | 75-125 | 13 | 256 | 82 | 1.3-746 | 23 | 14-30 | 0.87 (N=4) | 0.93 | [4]24/7 (N-4/2) |
| 2 | Foreshore, upper and middle shoreface | 100-200 | 233 | 1662 | 859 | 0.01-7400 | 27 | 11-34 | 1 (N=26) | 0.59 | 0.8 (N=7) |
| 1 | Lower shoreface | 100-150 | 21 | 662 | 276 | 13-2694 | 23 | 9-30 | no data | 0.78 | 0.8 (N=1) |

[1] For permeability and porosity from conventional core anlaysis.
[2] N = number of samples.
[3] From 3 wells - P-1, W-7, W-16.
[4] From estuarine facies/lagoon facies.

In this investigation, variations in thickness and geometry of the different facies groups have been studied based on fieldwide log-derived facies maps. The distribution of other important properties critical to the determination of productivity of sandstones; i.e., porosity, permeability, water saturation, etc. in the various facies groups, was also investigated. Because clays have an important effect[22] on fluid production at Bell Creek, the distribution of total clays within different facies has also been investigated.

## DISTRIBUTION OF GEOMETRY AND PETROPHYSICAL PROPERTIES IN DIFFERENT LOG FACIES OF THE BARRIER ISLAND SANDSTONE AT BELL CREEK FIELD

### Facies Geometry Distribution

Based on porosity, resistivity, and the porosity, gamma ray cross,lots developed for facies discrimination, two stratigraphic cross sections, XX' and YY', one along the dip and the other along the strike direction of the barrier island deposit, were constructed (see fig. 10 for location). The variation in thicknesses of the different facies along the strike and the dip directions, the interfingering of facies, and the presence of valley cuts filled with low-permeability sediments, are shown in figures 11 and 12.

### Porosity Distributions

Good estimates of reservoir porosity may be obtained from interpretation of density logs from Bell Creek field. Included on the stratigraphic cross sections are density-log-calculated average porosities over vertical intervals having fairly uniform porosity values (figs. 11 and 12).

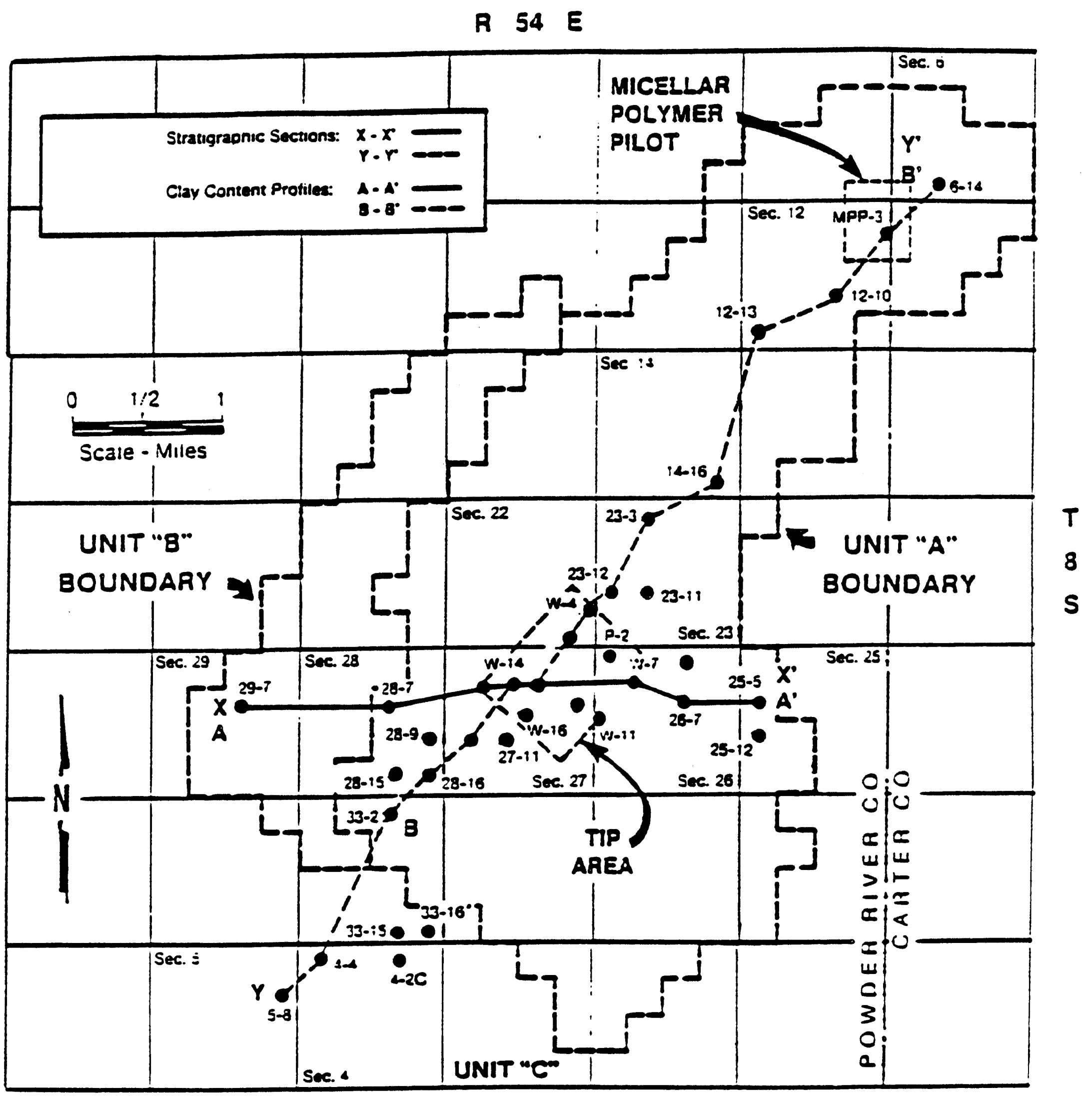


FIGURE 10. - The study area in Units 'A', 'B', and 'C' of Bell Creek (MT) field with locations of stratigraphic and clay content profiles.

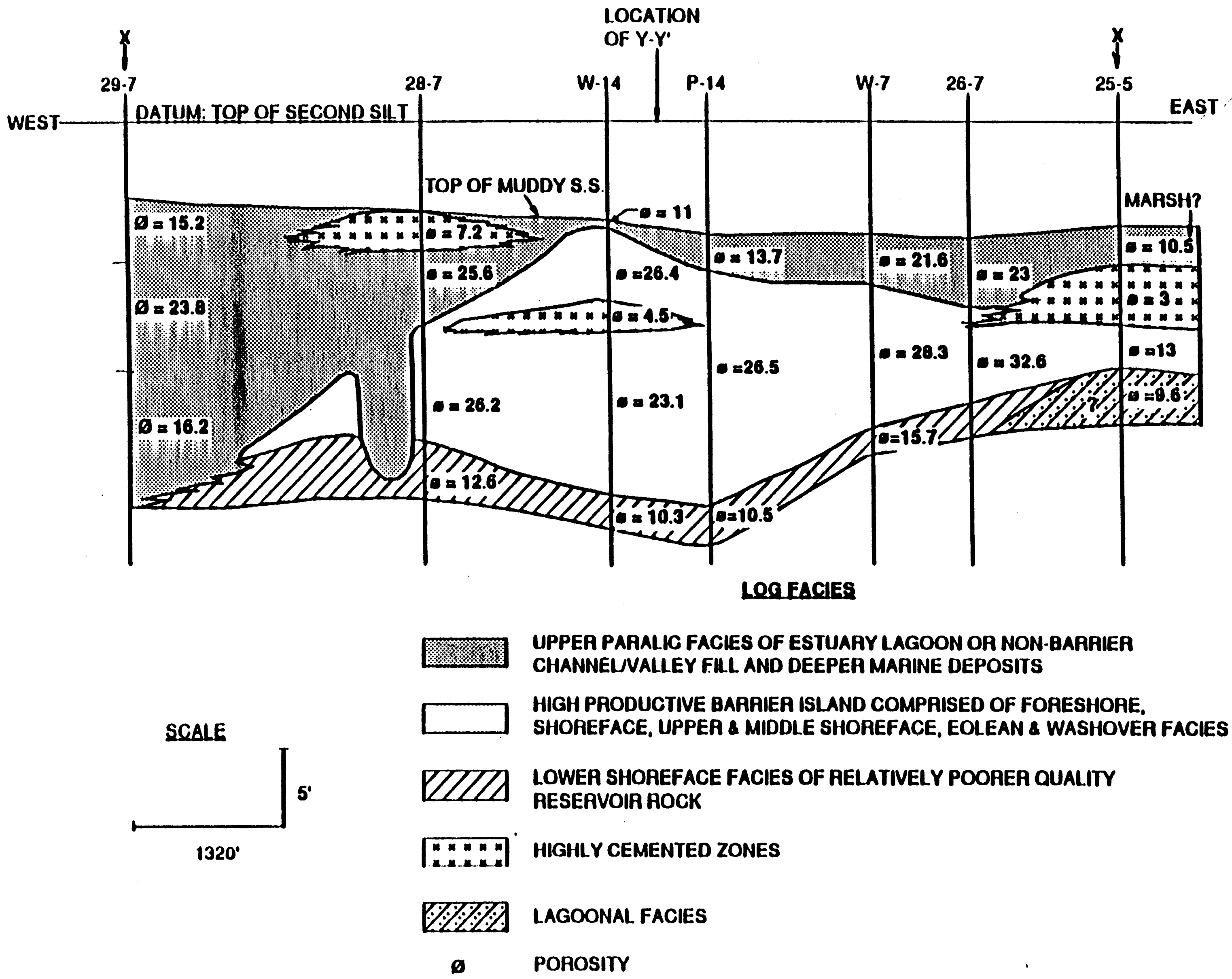


FIGURE 11. - Dip-oriented stratigraphic cross section XX' of the barrier island deposit at Bell Creek field obtained from log-based facies analysis.

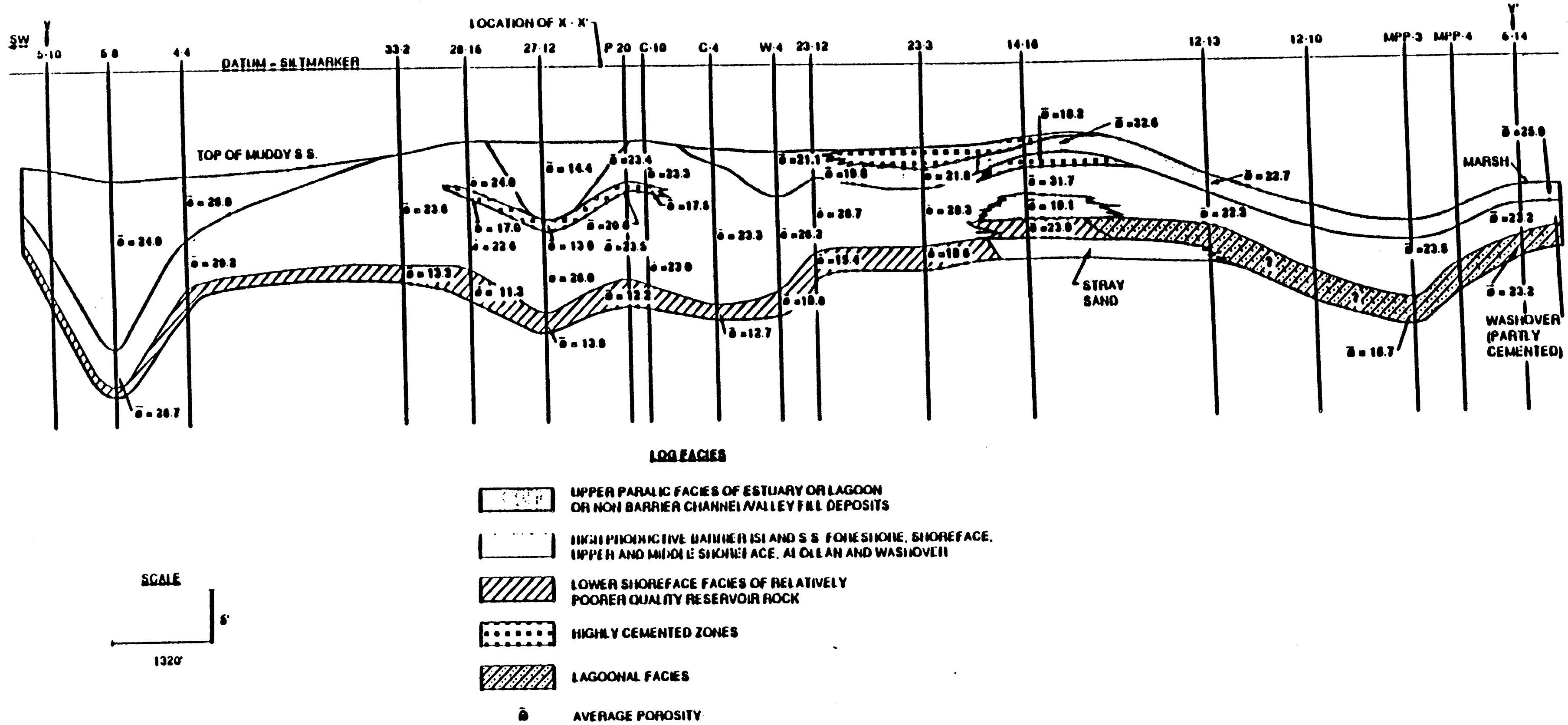


FIGURE 12. - Strike-oriented stratigraphic cross section YY' of the barrier island deposit at Bell Creek (MT) field obtained from log-based facies analysis.

## Distribution of Total Clays

A reasonably good estimate of clay content ($V_{CL}$) can be determined from interpretations of density and sonic log data from the following relationships:[23]

$$V_{CL} = \frac{\phi_s - \phi_d}{\phi_{ssh} - \phi_{dsh}} \qquad (1)$$

where $\phi_s$ = porosity from sonic log, corrected for compaction

$\phi_d$ = porosity from density log

$\phi_{ssh}$ = apparent sonic porosity in shale, corrected for compaction

$\phi_{dsh}$ = apparent density porosity in shale

The average total clay content in each facies was plotted at different well locations along profiles AA' and BB', coincident with the dip and strike stratigraphic cross sections (figs. 13 and 14). The east-west dip profile AA' (fig. 13) shows a sharp increase in clay content in all three facies in the southwestern part of the TIP area which is believed to be due to an increase in diagenetic clays, as indicated by detailed thin-section studies conducted in the area. From the central part, the average total clay content along profile AA' decreases in either direction. In the lagoonal side, in the eastern extremity of the profile AA', there is a 5.4% increase in average clay content in the higher productive (washover) facies. In the NE-SW profile BB' (Fig. 14), the effect of diagenetic clays is noticeable in the southwestern part of the TIP area. The clay contents in all the three facies of this profile exhibit much less variation toward the northeast.

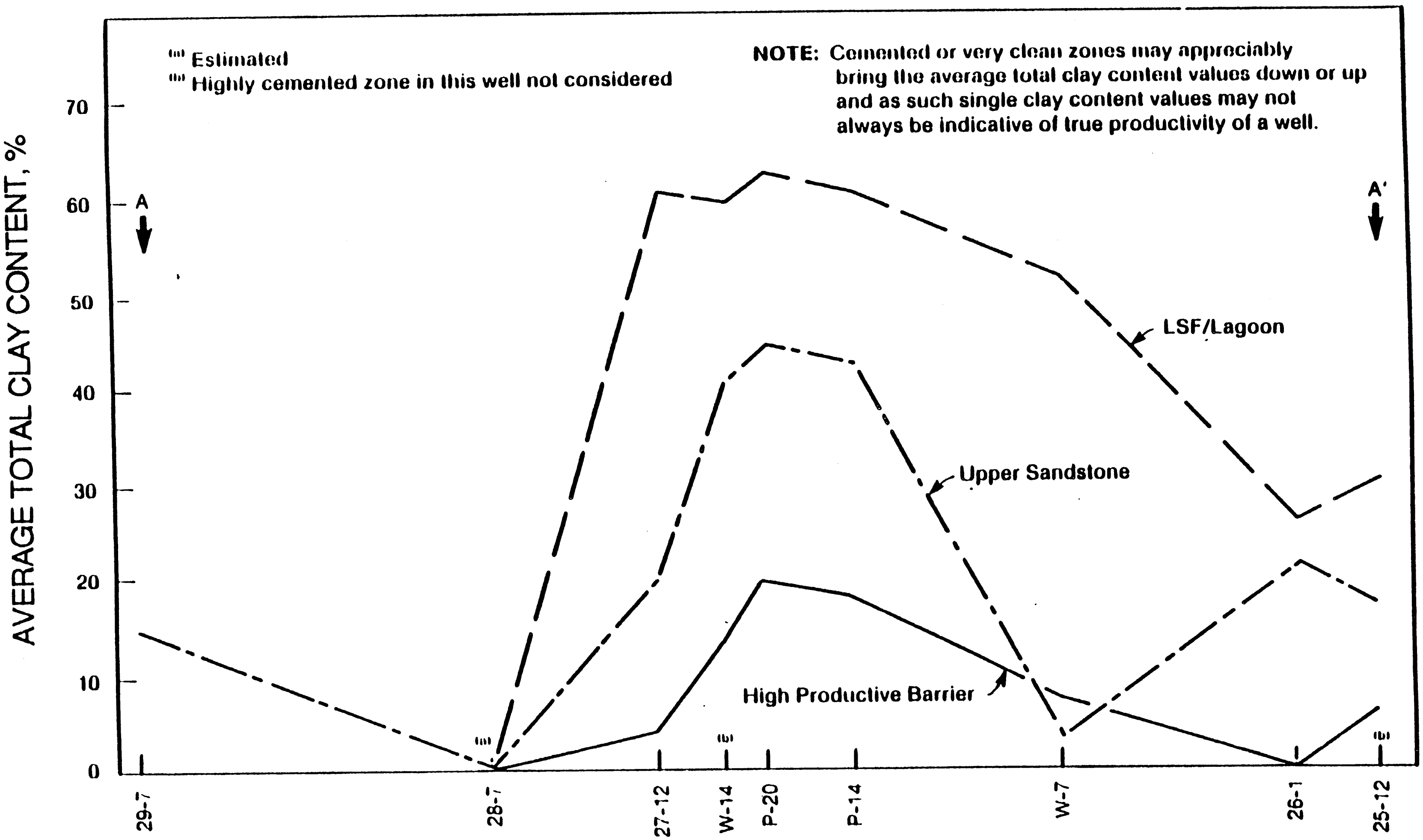


FIGURE 13. - Distribution of average total clay content in the three log-derived facies along dip section AA'.

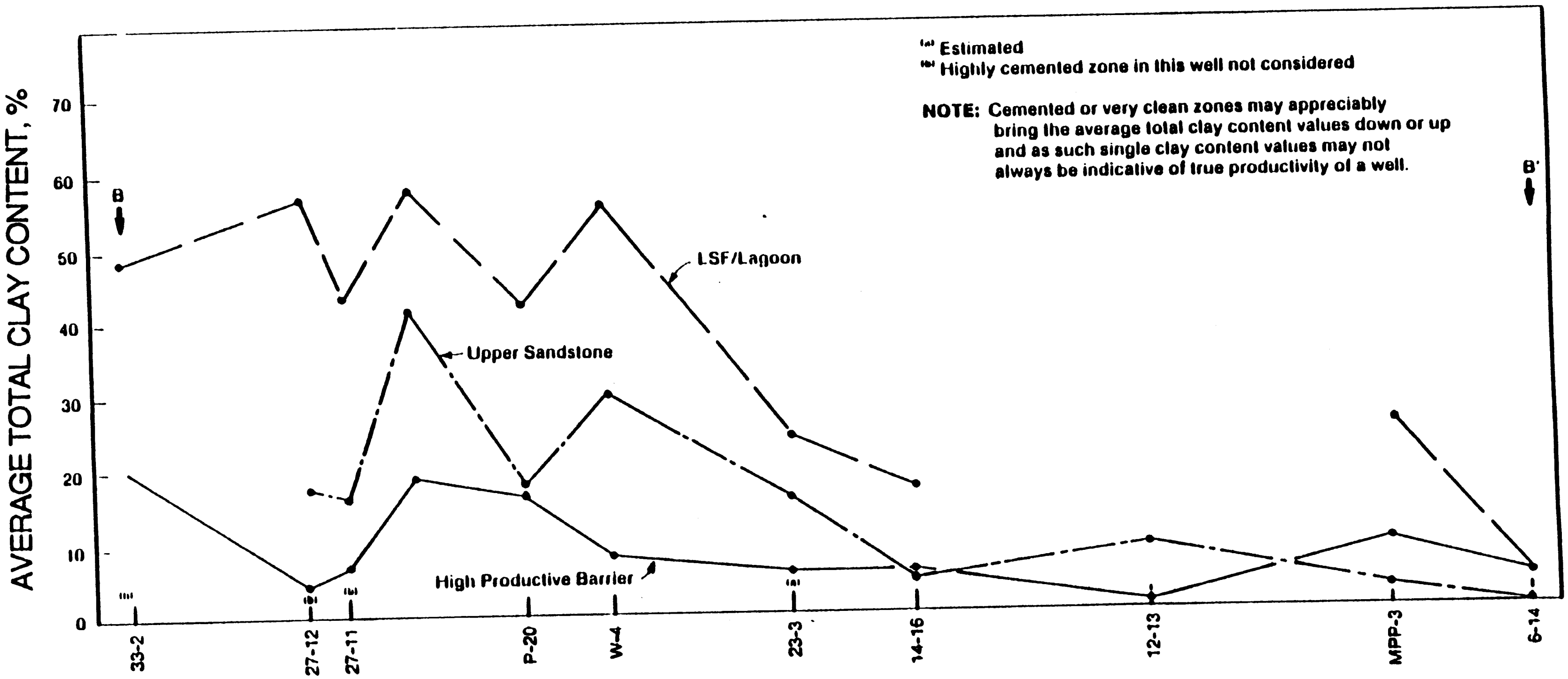


FIGURE 14. - Distribution of average total clay content in the three log-derived facies along strike section BB'.

## Distribution of Air Permeabilities

Lateral distributions of geometric means of air permeability in two barrier island sandstone facies (upper-sand and high-productive facies) in wells along the dip and strike directions of the deposit are shown in figures 15 and 16. Sufficient data were not available for calculation of geometric means of permeability for the lower shoreface/lagoonal facies. The sharp reduction in permeability of high productive facies in the diagenetically effected southwestern part of the TIP area (around wells W-16, W-14, and C-4) is clearly indicated in the two permeability profiles. The low-permeability values in the upper sand facies, around well W-7 (fig. 16), are due to low porosity and clayey deposits in swamp and/or estuary. This trend is also noticed in the strike profile near well 23-11.

An estimate of the degree of permeability stratification in the different facies may be determined from the distribution of normalized standard deviations of air permeability values in different wells located along the dip and the strike profiles (figs. 17 and 18). In homogeneous sandstones with little or no stratification, normalized standard deviations will assume low values. As the permeability stratification increases, due either to depositional or diagenetic causes, normalized standard deviations will also increase. Figures 17 and 18 indicate a higher degree of permeability stratification in the high-permeability facies toward the lagoon, toward the basin, and also in diagenetically affected regions. There is a greater degree of intercollations between high- and low-permeability strata in the upper sand facies, and in certain parts (around wells W-7 and 23-11) the degree of stratification is quite extreme. These phenomena are believed to be the result of deposition of clay-rich, low-permeability, swamp, or estuarian sediments along a north-south linear trend.

## Water Saturation in Different Facies

By application of Simandoux and Fertl's shaley sand models,[22-23] initial water saturations were calculated for each foot of pay thickness in wells 5-8, 23-3, 27-12, 27-1, 26-4, 14-16, and 6-14. The average initial water saturation in the high productive facies in these wells ranged between 15 and 40%. In the upper sand (mainly valley or channel fill deposits), the average calculated water saturation ranged between 25 and 60%, and water saturation was highest in the lower shoreface facies (around 30 to 75%).

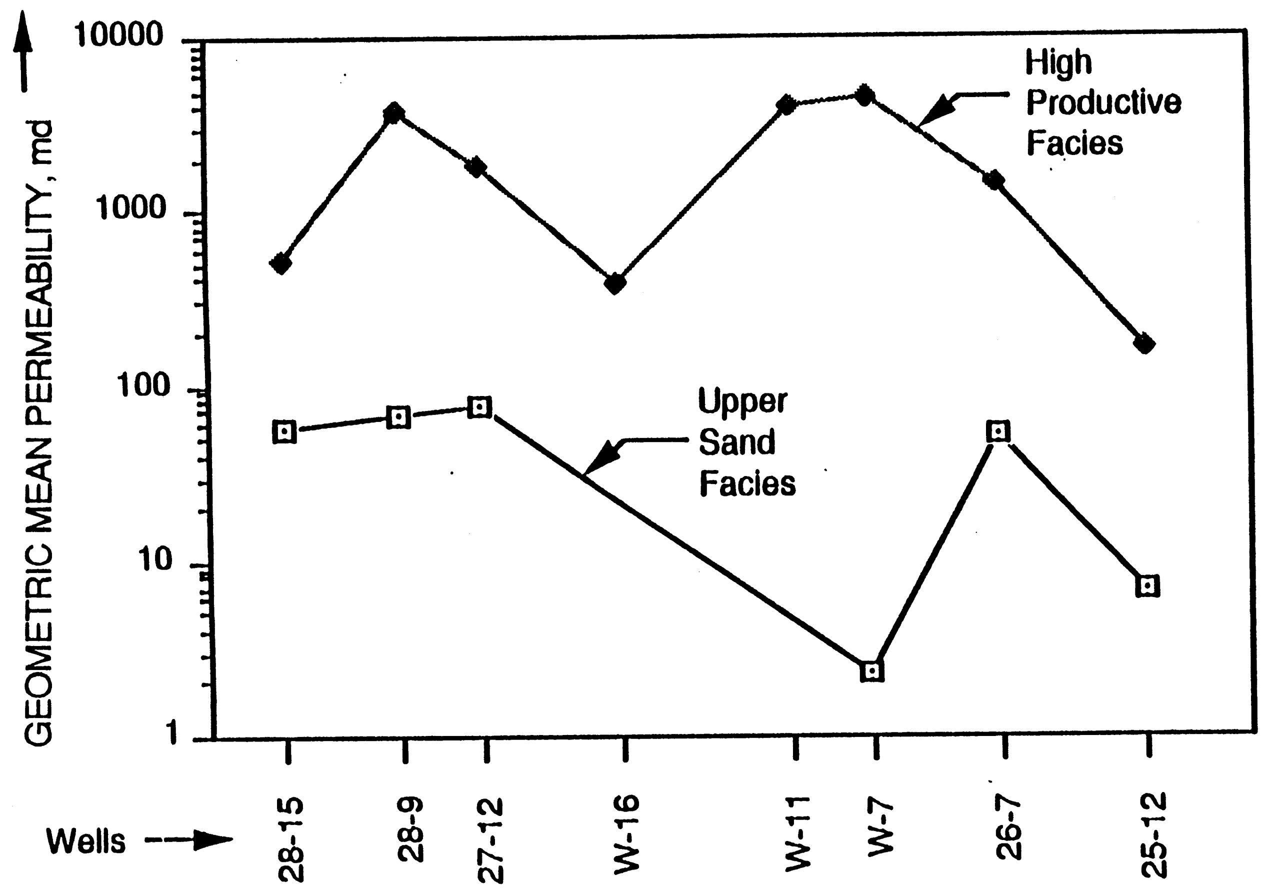


FIGURE 15. - Distribution of geometric means of air permeability in the dip direction, Unit 'A', Bell Creek (MT) field. See figure 10 for location of wells.

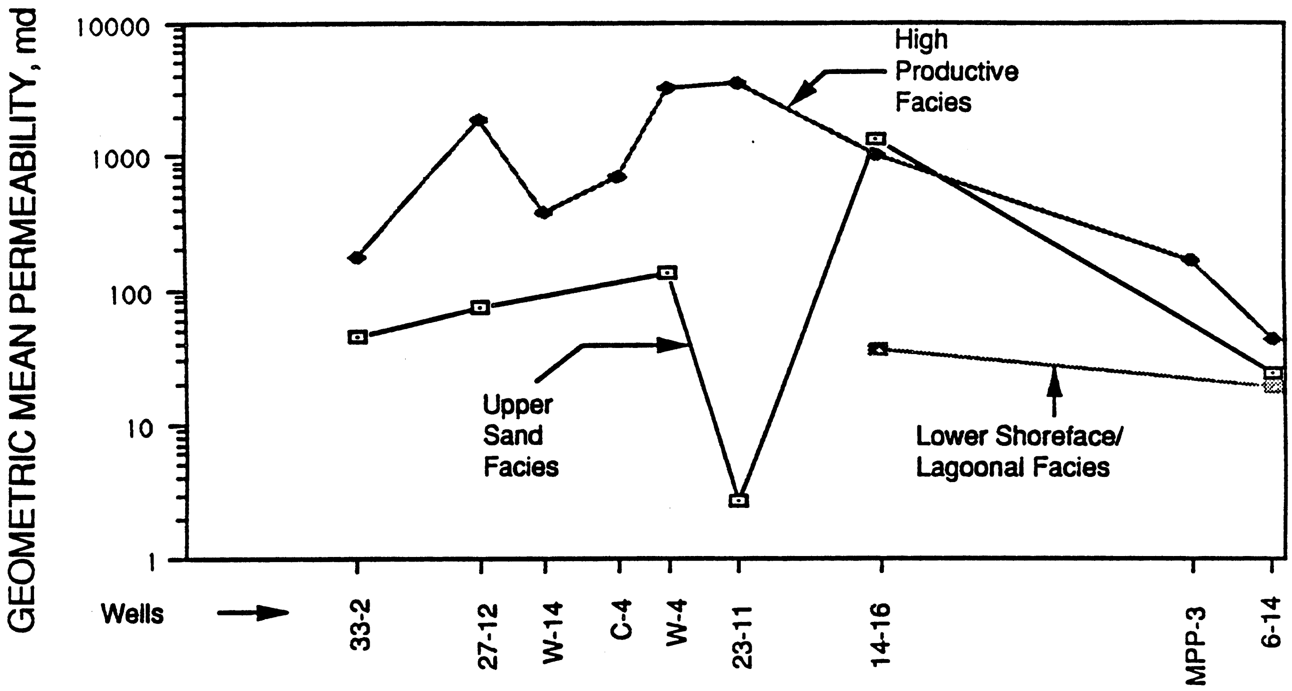


FIGURE 16. - Distribution of geometric means of air permeability in the strike direction, Unit 'A', Bell Creek (MT) field. See figure 10 for location of wells.

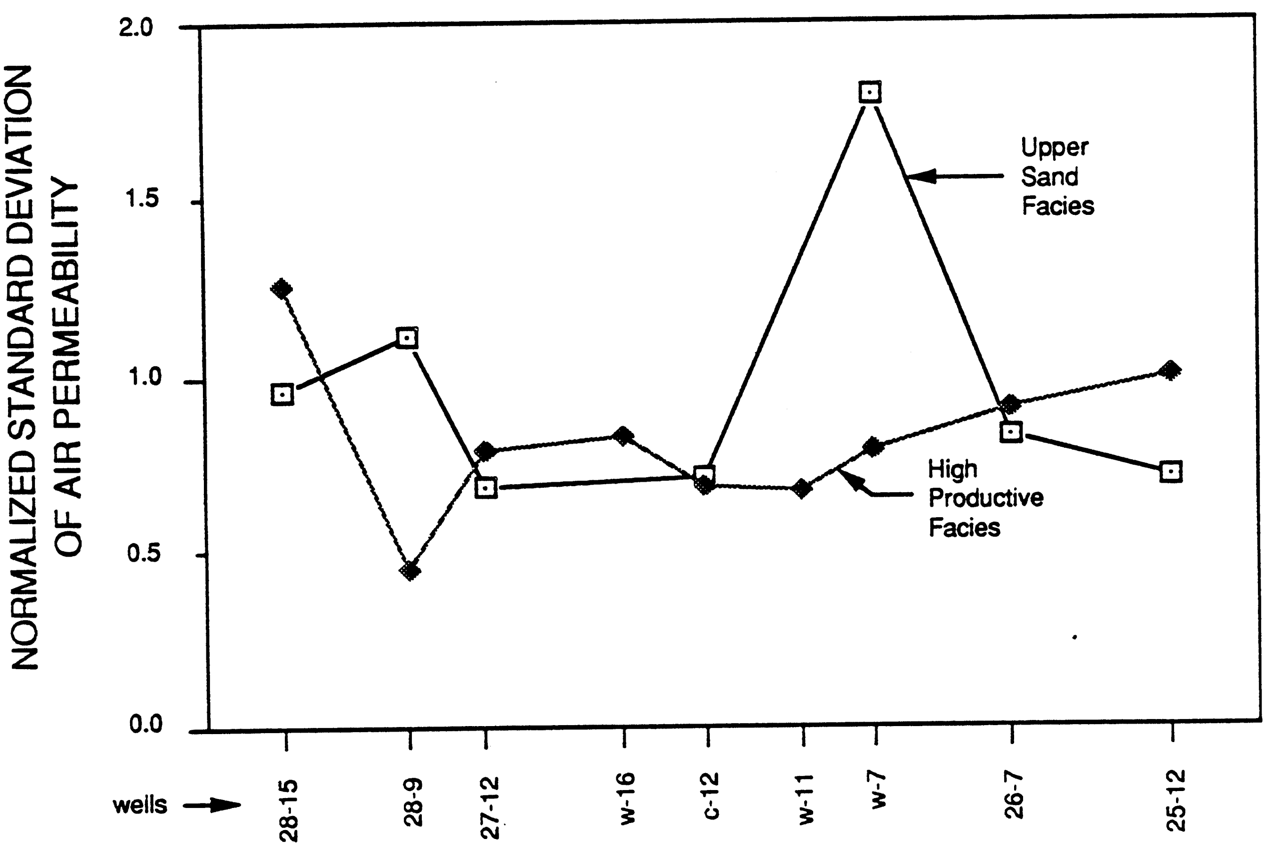


FIGURE 17. - Degree of permeability stratification in Unit 'A', Bell Creek (MT) field from the distribution of normalized standard deviation of air permeability along the dip profile AA' indicated in figure 10. Higher standard deviations indicate more extensive layering.

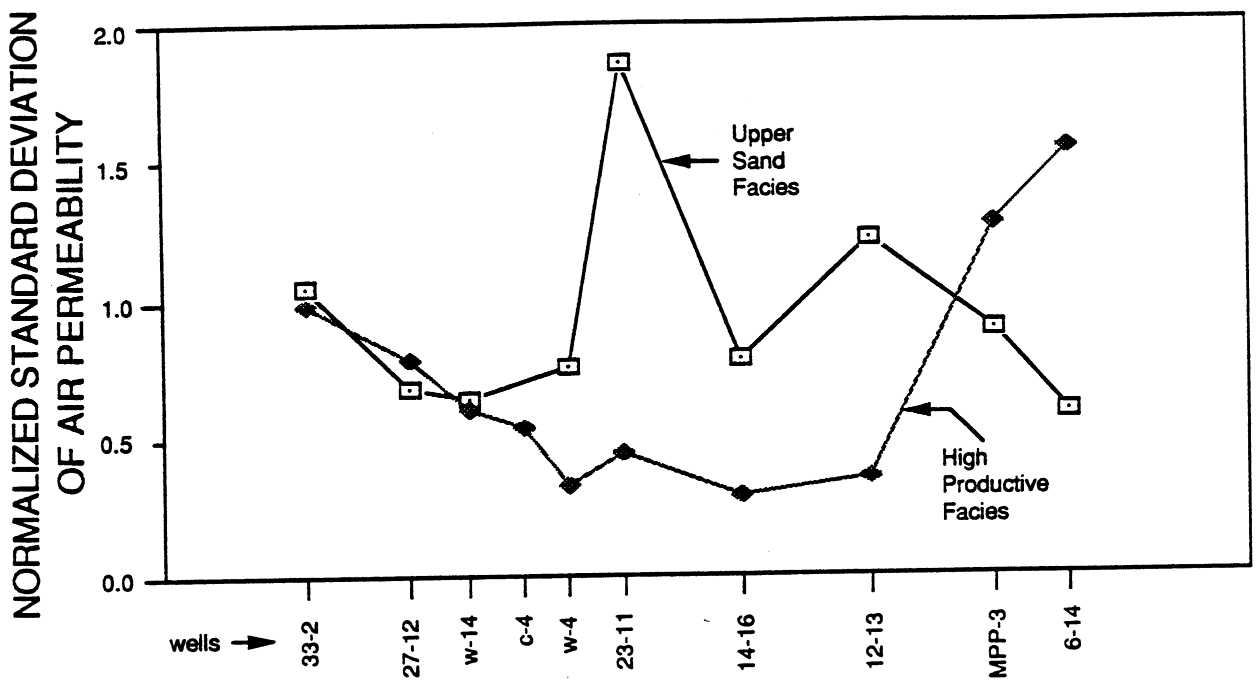


FIGURE 18. - Degree of permeability stratification in Unit 'A', Bell Creek (MT) field. Facies are from the distribution of normalized standard stand deviations of air permeability along strike profile BB' indicated in figure 10.

## PRODUCTIVITY OF BARRIER ISLAND AND NONBARRIER SANDSTONES

### Primary Production From Different Facies

Based on decline-curve analysis of primary production data, primary reserves were calculated for the wells indicated on the stratigraphic sections (figs. 11 and 12). A plot of primary reserves against storage capacity (product of porosity and thickness) was made from the crossplot data for each well. Fig. 19 indicates a strong correlation between primary reserves and storage capacity (correlation coefficient, R = 0.91). This result is an indirect confirmation of the effectiveness of the crossplot technique in subdividing the producing Muddy sandstones into different units.

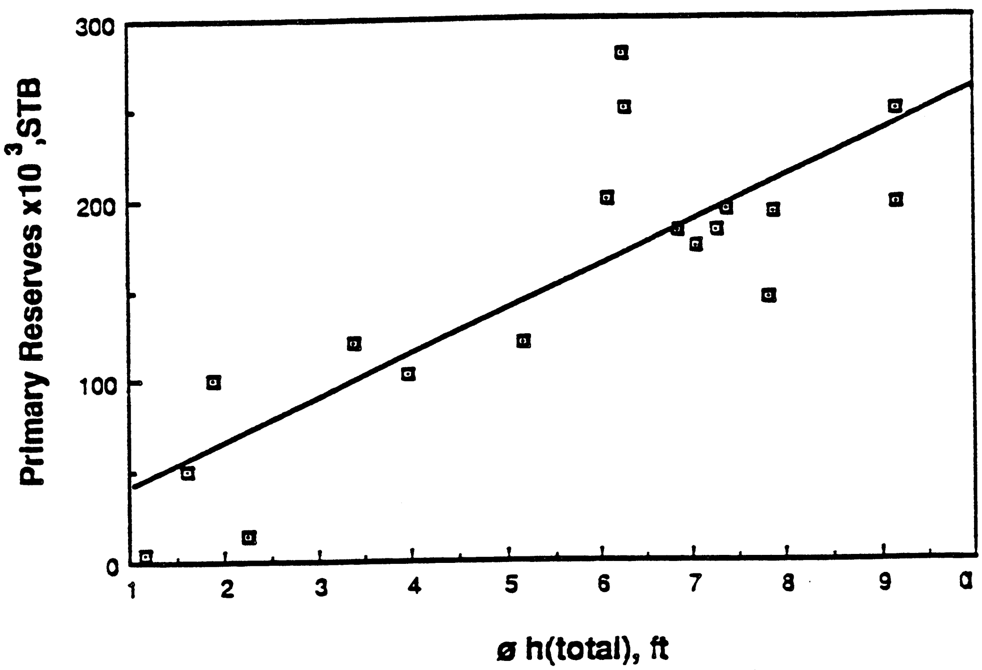


FIGURE 19. - Plot of primary reserves against stroage capacity.

## Areal Distribution of Productivity of Barrier Island Sandstones

The initial production rate map (fig. 20) constructed from production data from Bell Creek field indicates that the highest production comes from the central part of Bell Creek field where there is thickest development of the high productive facies (figs. 11 and 12). The initial production, which is strongly dependent upon the flow capacity, kh, and initial oil saturation, $S_{oi}$, should be related to the distribution of the three log-derived reservoir facies. In the northeastern part of Bell Creek field, the high productive log facies have been eroded and are overlain by the low-porosity, low-permeability brackish marine and alluvial sediments with poorer reservoir properties. This accounts for the comparatively lower productivity of the area, as indicated in figure 20. The highest initial production rate generally comes from where the log-defined high productive facies is cleanest and thickest.

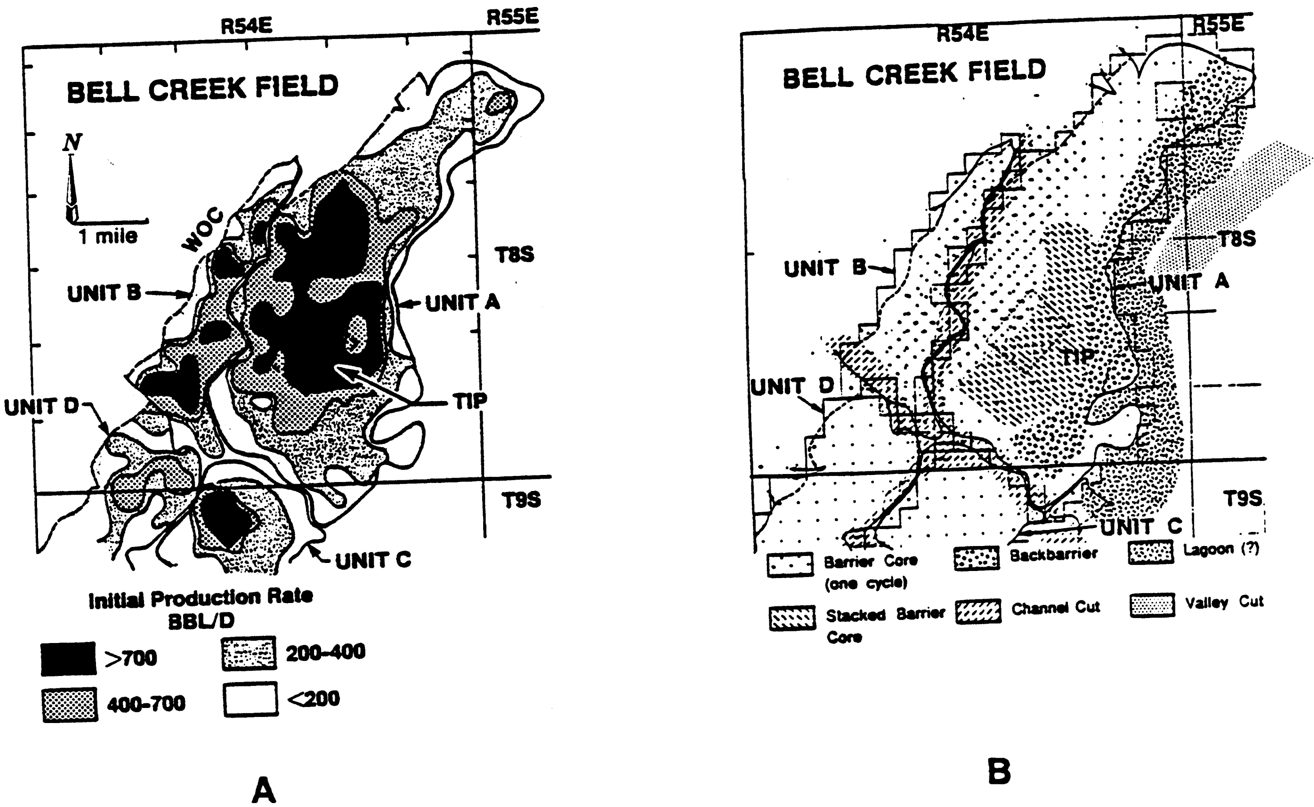


FIGURE 20. - Initial oil production rate map for Units 'A' and 'C' of Bell Creek (MT) field. (a) Compared with the depositional pattern (b) for the same area.

## CONCLUSIONS

Based on these studies and a survey of the literature the following conclusions have been made:

1. Shoreline barriers include spits, shoals, barrier peninsulas, barrier islands, and barrier bars. Although geologically similar, barrier island settings must be distinguished for a valid comparison of analogous reservoir deposits.

2. To make meaningful comparisons of barrier islands, three types of information must be known: (1) the direction of growth or migration (aggradational, progradational, or transgressive); (2) whether the shoreline is wave or tide-dominated; and (3) the tidal range at the site of deposition (microtidal, mesotidal, or macrotidal). Only by knowing which depositional processes created specific types of barriers can similarities and differences

among and between them be compared and the scale and configuration of major reservoir sandbodies predicted.

3. The geometry of shoreline barriers is a function of their generic type. For example, typical modern coastal barrier sandbodies are 10 to 25 miles long, 2 to 4 miles wide, and 30 to 50 ft thick. Modern transgressive barrier islands, however, are 20 to 47 miles long, 1 to 1.5 miles wide, and only 7 to 16 ft thick. Inner shelf shoals, in contrast, are generally 20 to 22 miles long, 1 to 6 miles wide, and 7 to 23 ft thick.

4. Composition rather than grain size may provide first-order environmental discriminators for facies in a barrier island deposystem. At the time of deposition, each subenvironment leaves a strong imprint on the detrital mineralogy.

5. Composition, texture, and related petrophysical parameters inherent in barrier island subenvironments may be strongly altered through geological time by diagenetic processes. These changes can mask or completely destroy trends present at the time of deposition, even between closely spaced wells. Therefore, for valid comparisons between various generic types of barrier island reservoirs, it is necessary to account for the diagenetic history, to understand possible differences in original detrital mineralogy, to understand the subsidence history of the reservoir, and to know the final depth of burial.

6. At Bell Creek field along the dip direction, the high-productive sandstones have maximum development in the central part and taper off toward the open sea and lagoonal directions. Thickness distributions in the upper sand are highly variable because of deep valley incisions in several areas. In the lower shoreface, the thickness variation is very small. In the strike directions, the thickness gradually reduces in all three facies groups, both in open sea directions and the lagoonal side.

7. The distributions of petrophysical properties (permeability, porosity, intial, and postwaterflood oil saturations) in the high-productive facies at Bell Creek field, excepting in diagenetically affected regions, have the highest values along a zone in the central part of the deposit and decrease in all directions from central high areas. The decrease in properties is more gradual in the strike direction compared to that in the dip direction of the deposit.

8. In addition to grain size, both depositional and diagenetic clays had a dominant control on the distribution of porosity, permeability, and initial and postwaterflood oil saturations in the three log-defined facies groups at Bell Creek field. Sharp reductions in porosity and permeability due to diagenetic clays are most noticeable in the southwestern part of the TIP area.

9. Because of the varying effects of cementation, certain zones of the high-productive facies (like a part of washover facies in well 6-14) may be tight, and because of textural and diagenetic differences, part of lower shoreface/lagoonal deposits (like the storm deposit sequence in well 25-12) may have appreciable porosity and permeability.

10. The high correlation coefficient between ultimate primary recovery determined from decline curve analysis and storage capacity determined from analysis of Bell Creek crossplot data indirectly confirms the usefulness of subdividing barrier island sandstones into three major groups with distinct porosities for finding the storage capacity of various pay thickness. The initial production rate map agrees with the distribution of sandstone geometry, petrophysical properties, and clay content in different parts of the sandbody, as determined from this study. Compared to the second chemical flood project in the TIP area, the postwaterflood oil saturation in the first pilot was comparatively much lower, the amount of clays in the sandstone pore spaces was much higher, and the degree of intercollations between high- and low-permeability strata was much higher in the area of the first pilot. These factors adversely affected the chemical flood in the first pilot and account for the low oil recovery from the first pilot.

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