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Sandstone geometry, porosity and permeability distribution, and fluid migration in eolian system reservoirs

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SANDSTONE GEOMETRY, POROSITY AND PERMEABILITY DISTRIBUTION AND FLUID MIGRATION IN EOLIAN SYSTEM RESERVOIRS

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ABSTRACT

Upper Paleozoic to Mesozoic eolian blanket sandstones of the Colorado Plateau and the Rocky Mountains of Colorado and southern Wyoming are texturally complex. As petroleum reservoirs they commonly have poor performance histories. They contain the sediments of a depositional system comprised of three closely associated depositional subenvironments: dune, interdune, and extradune. Sediments of each subenvironment have different textural properties which resulted from different depositional processes. Dune sediments are usually more porous and permeable than interdune or extradune sediments and may be better quality reservoirs than interdune or extradune sediments. Interdune sediments are here restricted to those nondune sediments deposited in the relatively flat areas between dunes. Extradune sediments (a new term) include all deposits adjacent to a dune field and are mainly subaqueous deposits. Dune sediments may be enveloped by extradune sediments as the depositional system evolves resulting in a texturally inhomogeneous reservoir having poor fluid migration properties.

This model of textural inhomogeneity in eolian blanket sandstones was applied to the Weber (Tensleep) Sandstone in Brady, Wertz, and Lost Soldier fields, Sweetwater County, Wyoming. Data were obtained from both outcrop and subsurface and included environmental interpretation, textural analysis, and plotting of the distribution of depositional subenvironments. As predicted from the model, the texture of dune sediments in Brady field differed markedly from interdune and extradune sediments. The predicted geometric distribution of subenvironments was confirmed in Lost Soldier and Wertz fields. However, secondary cementation and fracturing there has obscured the original porosity and permeability contrasts. The porosity and permeability distribution, a characteristic depending partly on depositional processes, could impede fluid migration in the reservoir and significantly reduce recovery of hydrocarbons.

INTRODUCTION

Many of the Upper Paleozoic to Mesozoic blanket sandstones of the Colorado Plateau and the Rocky Mountains of Colorado and southern Wyoming were deposited in eolian and closely associated noneolian environments. They are the reservoir rocks in many oil and gas fields. These sandstone units are widespread and of uniform thickness, and seem texturally homogeneous. There are, however, complex textural variations within the units that may affect porosity and permeability and be detrimental to their performance as reservoir rocks. These textural differences are related to environments of deposition and a conceptual model is proposed to explain them. The model will aid the geologist in evaluating porosity and permeability problems and result in significant savings in time and money.

The eolian depositional system contains three subenvironments which are related in time and by source: dune, interdune, and extradune. The term "dune" is applied in the classic geomorphic sense of Bagnold (1941). The term "interdune" is restricted to the description of the relatively flat area between the dunes of a dune complex. A new term "extradune" describes the area extending beyond the dune field, including some areas previously referred to as interdune. Interdune sediments probably were originally deposited by the same wind activity which built the dune (McKee and Moiola, 1975) and are commonly reworked by water or wind (Glennie, 1970). They are commonly preserved as the flay-lying sediments at the base of the crossbed sets of a dune sequence (fig. 1). Extradune sediments were probably deposited by processes independent of the dune-building process and involve sediments of diverse environments, such as alluvial fan, wadi, serir, stream, sebkha, playa, lake, beach, and tidal flat.

The new term "extradune" fulfills two purposes: (1) It has the specific purpose of describing a geomorphic area which has often been incorrectly termed interdune. (2) It has the broader purpose of a general term which could include a variety of subenvironments. It can be used in broad reference to various subenvironments or when identification of specific subenvironments is uncertain but stratigraphic relation to dune sediments is clear.

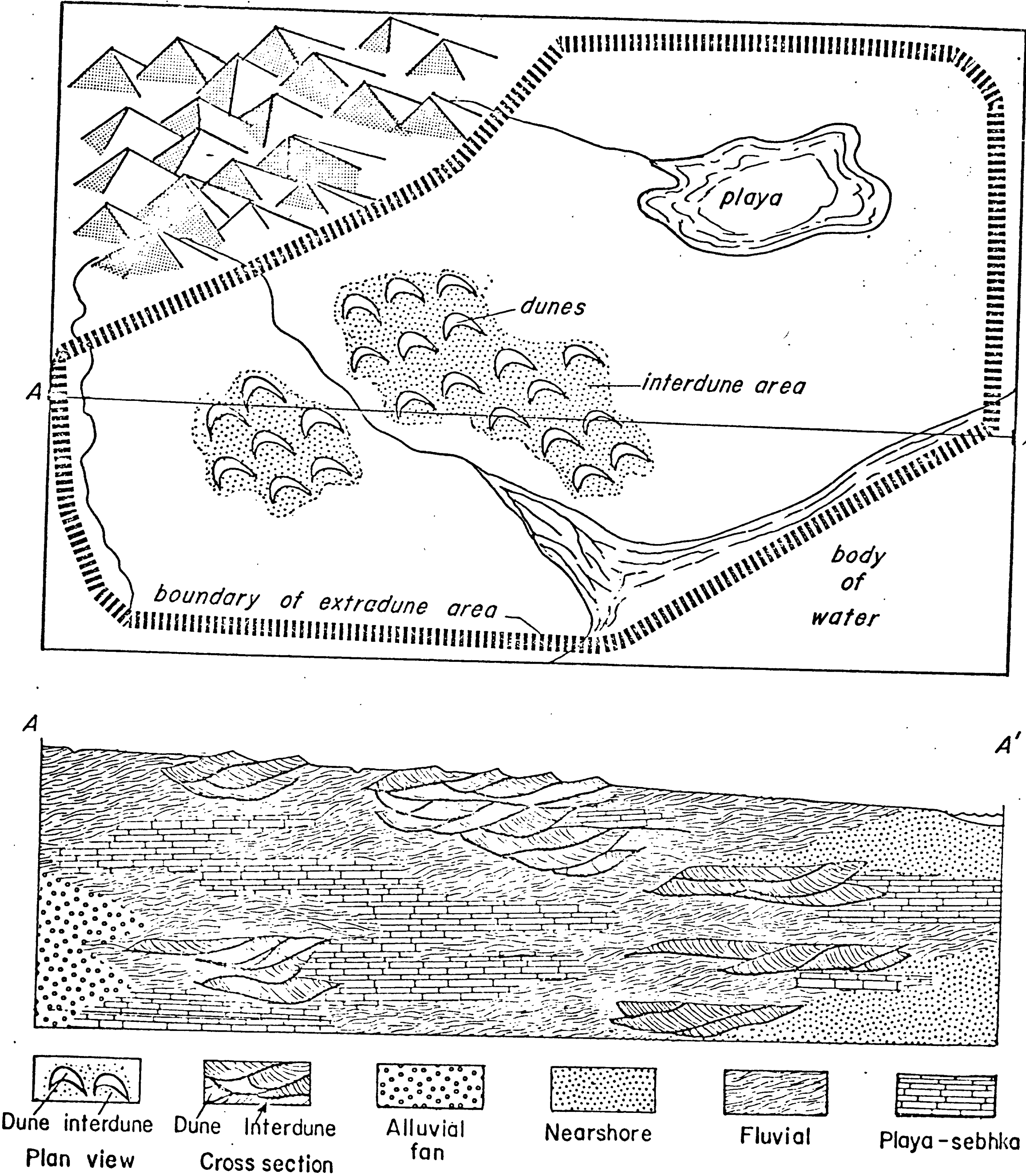


Figure 1.--(a) Schematic diagram of typical distribution of dune, interdune, extradune deposition; and (b) cross section illustrating evolution of a dune-extradune system, ending with the geographic configuration of (a). Subenvironments of the system migrate laterally as well as vertically, resulting in isolation of more porous and permeable dune sediments.

We particularly thank Amoco Production Company for support. We also thank Champlin Petroleum Company, operator of Brady field; Mountain Fuel Supply Company and Exxon USA, and other Brady field partners; and Hilliard Oil and Gas for permission to publish data in this report. Pasco, Inc. provided data for the Lost Soldier-Wertz field studies.

THE MODEL

The degree of textural contrast in dune, interdune and extradune sediments is a function of the texture of source material, of depositional processes, and of the spatial relations of subenvironments within the depositional system.

Dune sediments are relatively better sorted, better rounded, and more compositionally mature than sediments of most other depositional environments (Bagnold, 1941; Twenhofel, 1945; Kuenen, 1960; Kukal, 1971). Dune sand is generally more porous and more permeable than the source, interdune, or extradune sediments, because porosity and permeability in modern sediments are largely functions of particle size, shape, and sorting (Griffiths, 1967).

Extradune sediments are predominantly subaqueous, and, therefore, are usually more poorly sorted and less porous and permeable than dune sediments. Furthermore, porosity and permeability in these sediments could be further reduced because the topographically lower interdune and extradune areas are commonly the sites of early cementation (Glennie, 1972). Figure 2 shows porosity and permeability distribution of modern dune-interdune sediments; figure 3 illustrates porosity and permeability distribution for ancient dune-extradune sediments.

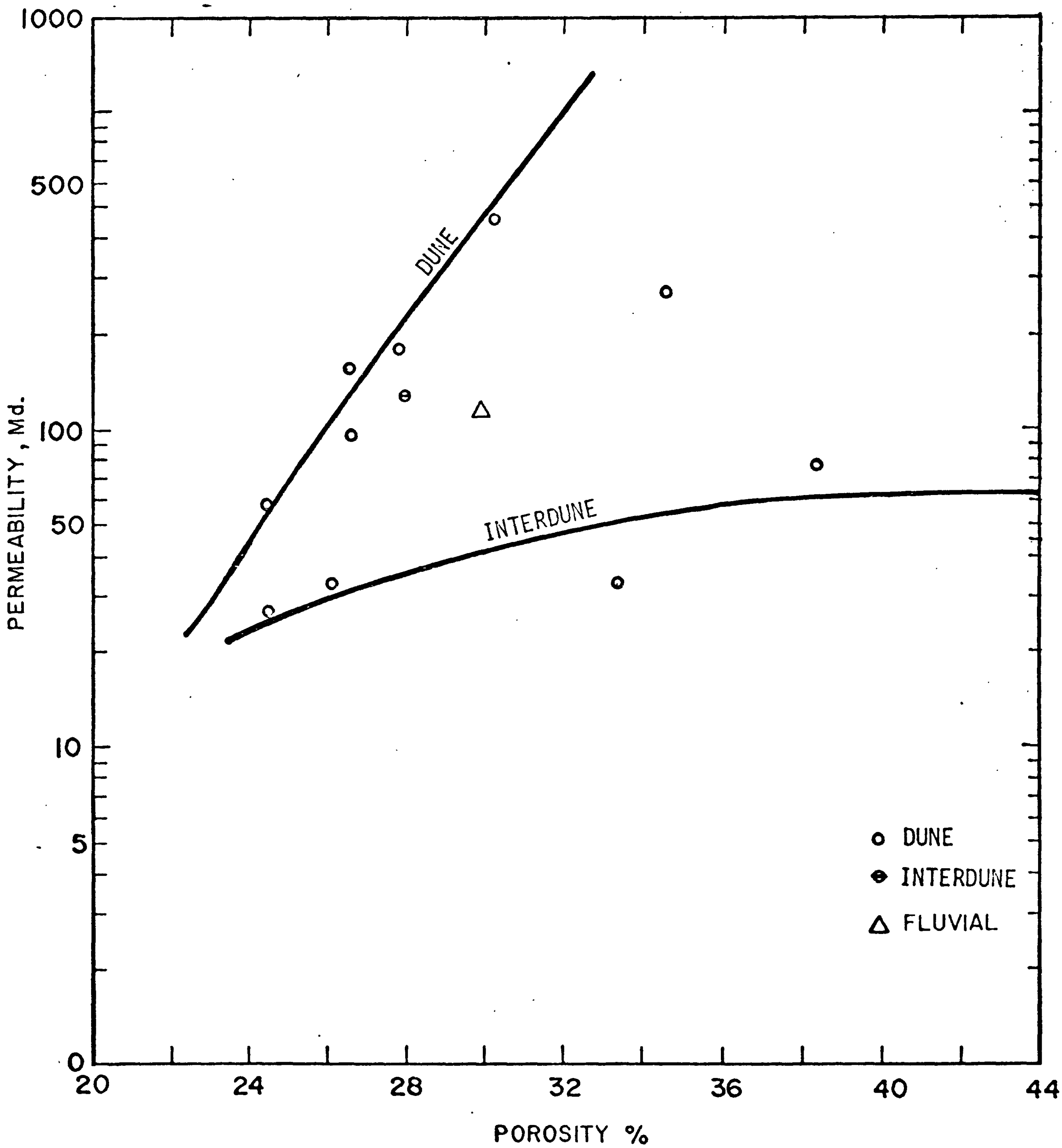


Figure 2.--Porosity and permeability distribution of dune and interdune sediments from cores, White Sands National Monument, New Mexico.

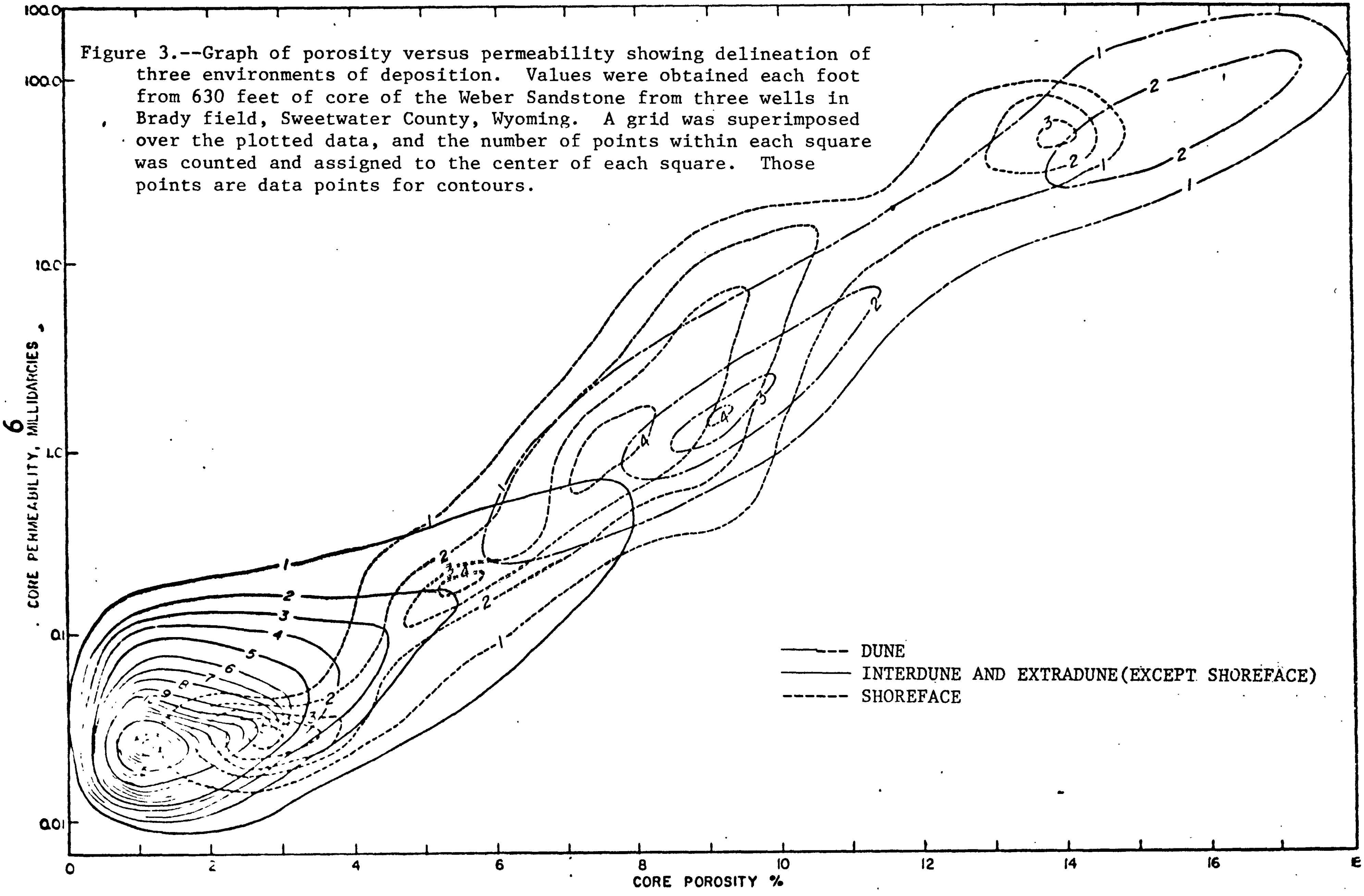


Figure 3.--Graph of porosity versus permeability showing delineation of three environments of deposition. Values were obtained each foot from 630 feet of core of the Weber Sandstone from three wells in Brady field, Sweetwater County, Wyoming. A grid was superimposed over the plotted data, and the number of points within each square was counted and assigned to the center of each square. Those points are data points for contours.

Dune and extradune sediments abut laterally, and successive dune-extradune depositional systems may overlie one another, with dune sands either in vertical contact with other dune sands or with extradune sediments (fig. 1). Dune sand bodies may become isolated from one another, with the degree of isolation dependent on the original distance between dune complexes and the way in which succeeding depositional systems overlie one another. Movement of fluid would be affected by this distribution of sand bodies of different porosity and permeability. Furthermore, the porosity and permeability contrast may be enhanced by the effects of burial (Rittenhouse, 1971).

THE MODEL AND THE SUBSURFACE SITUATION

Extending the dune-extradune model for eolian blanket sands to the subsurface has potential value for the petroleum industry. Two preliminary steps are required: First, recognition of sedimentary environments from conventional well bore data; and second, recognition of the relations between depositional environments and the distribution of porosity and permeability, as described above. Then the size and distribution of various subenvironments must be determined. In some cases the spatial relations of subenvironments can only be approximated from outcrop and(or) subsurface information. Outcrop data may not resemble the actual subsurface situation and subsurface data may not be geographically dense enough to give a complete picture.

On the other hand, subsurface information can provide accurate quantitative data for the model. Porosity and commonly permeability are routine log analyses. Cores can provide not only porosity and permeability data but also environmental information. However, environmental information can also be obtained from electric logs if they are periodically calibrated with core data.

Figure 4 is an example in which conventional logs were used to interpret environments of deposition. The dipmeter is the most effective tool for describing sedimentary environments (Gilbreath and Maricelli, 1964; Campbell, 1968); but the resistivity curve of modern electric logs may also provide the same data. In figure 4 the dipmeter log accurately recorded the high-angle dune crossbed sets and the flat-lying interdune and extradune beds. The resistivity curve of the Dual Induction Laterolog also responded to the same sedimentary structures. The resistivity curve responded to porosity differences (lower porosity, higher resistivity). In this case the porosity contrast resulted from porosity differences of sediments deposited in different sedimentary environments: More porous dune sediments versus less porous interdune and extradune sediments. Hence, the most basic suite of logs not only may provide the quantitative data for the construction of a model, but they also may be used to discriminate subenvironments in blanket eolian sandstones if secondary cementation has not obscured the original porosity distribution. The savings of time and money could be significant.

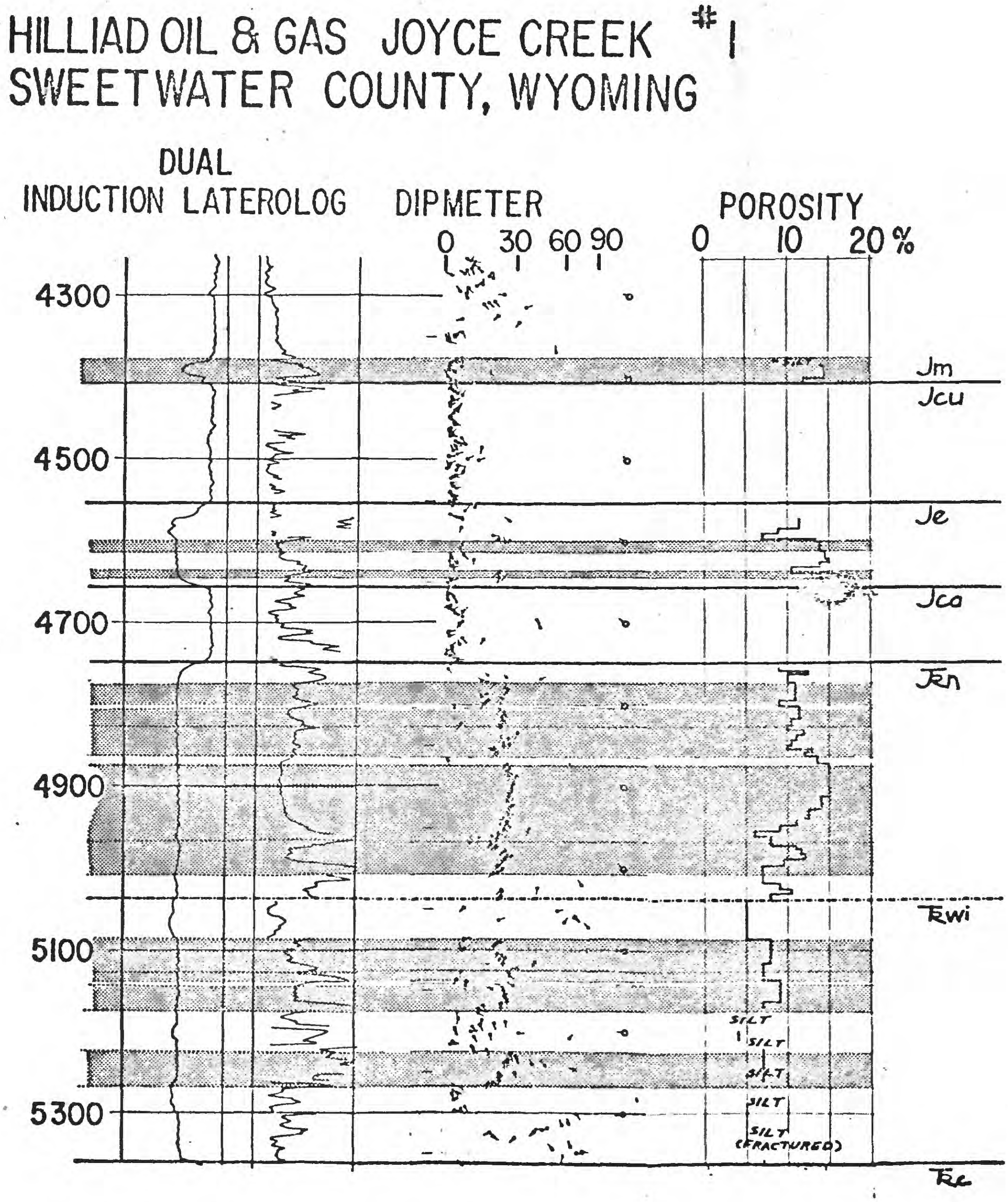


Figure 4.--Recognition of sedimentary structures and depositional environments from electric logs (Hilliard Oil and Gas, Joyce Creek 1, Sweetwater County, Wyoming). Both the dipmeter and resistivity curve of the Dual Induction Laterolog distinguish between dune, interdune, and extradune sediments. Note correlation of porosity with sedimentary structures--that is, with depositional environment.

APPLICATION

A study of the Pennsylvanian Weber Sandstone in Brady field and its correlative 90 miles (150 km) to the northeast, the Tensleep Sandstone, in Lost Soldier and Wertz fields, Sweetwater County, Wyoming, tested the application of the dune-extradune model and the prediction of reservoir complexities. The Weber (Tensleep) was ideal for three reasons: (1) It was considered to be an eolian blanket sandstone. (2) It had a history of requiring an unpredictably large number of closely spaced wells to drain the field. At Rangely field, Colorado, for example, Chevron Oil Company is developing the field on 10-acre spacing because of poor fluid migration (Western Oil Reporter, December 10, 1973). The cause of the poor fluid migration was unknown. Emmett, Beaver, and McCaleb (1972) described a similar situation in the Tensleep of Little Buffalo Basin field, northwest Wyoming. They attributed the poor fluid migration to reservoir heterogeneity. The possibility of similar reservoir performance in the Weber Sandstone in Brady or other deep fields, where drilling is costly, made the question an economic one. (3) Much exploration activity is currently underway in the Weber (Tensleep) Sandstone and although a study of the Weber Sandstone at Brady field is still in progress, a similar porosity and permeability problem is anticipated.

The study of the Brady, Lost Soldier, and Wertz fields was based largely on core examination. Four thousand five hundred feet of core from 45 wells in Lost Soldier and Wertz fields were studied by M. W. Reynolds, T. S. Ahlbrandt, J. C. Fox, and P. W. Lambert. Six hundred and fifty feet of core from three wells in Brady field were examined by Robert Lupe. In addition, core porosity and permeability were measured, and Weber Sandstone outcrops in the Uinta Mountains 175 miles (280 km) southwest of Brady field were examined.

Depositional environments were interpreted from cores of selected wells in these fields. The Weber (Tensleep) Sandstone is dune-extradune system composed of mixed nearshore marine and eolian sediments (fig. 5). Dune sandstones were preserved only in Wertz and Brady fields where they are isolated by foreshore, shoreface, tidal flat, supratidal, or sebhka, extradune sediments, and, to a lesser degree, interdune deposits. Furthermore, dune sandstones were preserved in upward-thinning, transgressive and regressive depositional cycles, which are normally bounded by intraformational unconformities.

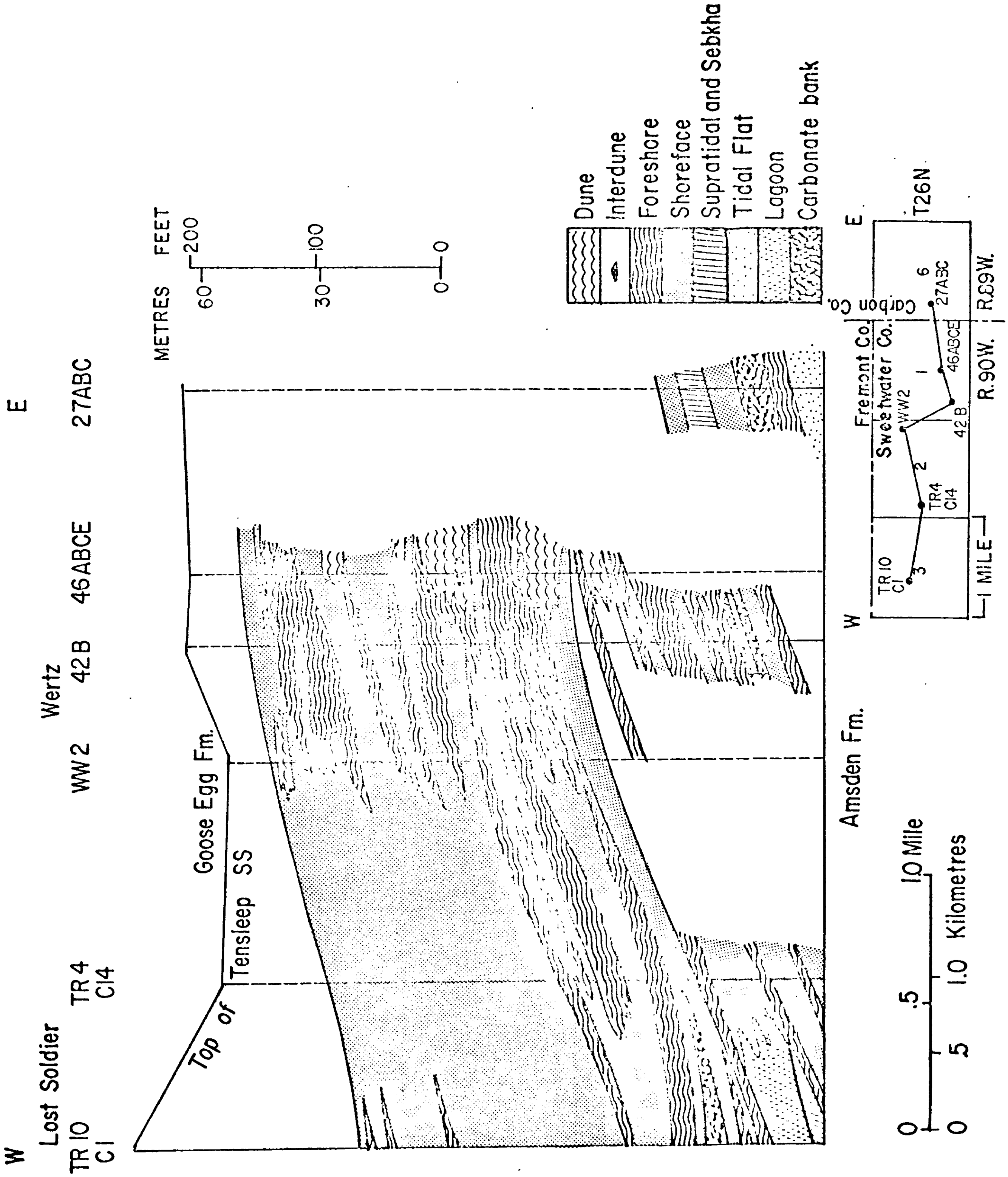


Figure 5.--Cross section of depositional environments interpreted from cores of the Tensleep Sandstone in the Lost Soldier and Wertz oil fields, Sweetwater County, Wyoming. The top of the Amsden Formation is used as a horizontal datum.

Dune sandstones were recognized by thick bedding; even and relatively continuous parallel laminae, which commonly dip at high angles; and lack of burrowing. These sandstones are very fine to fine grained, are well to very well sorted and contain frosted grains. Interdune deposits separate dune sandstones and are relatively thin (less than 10 ft (3 m)) and horizontally bedded. They contain poorly sorted, bimodal sandstones with frosted grains and evaporite cements, commonly anhydrite. Flaser bedding and adhesion ripples were observed in some interdune sediments.

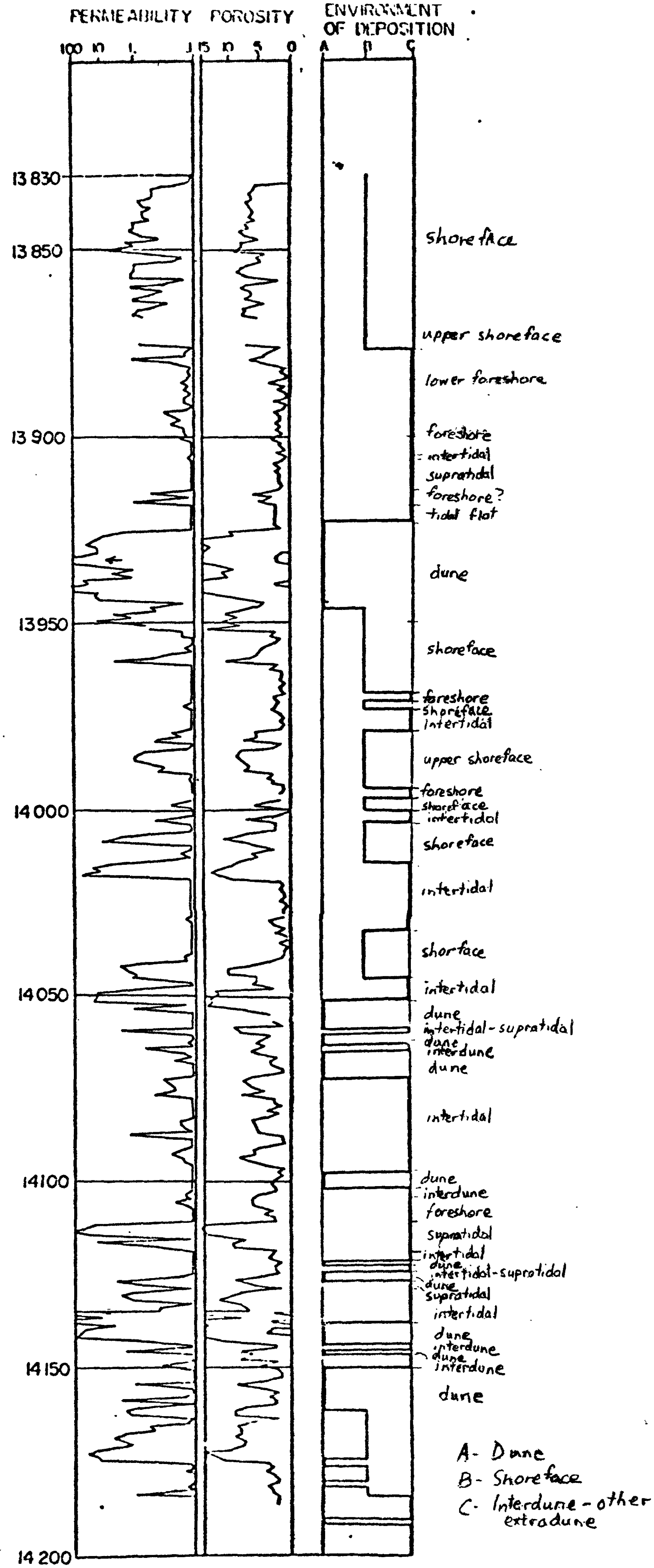
The general criteria used to differentiate extradune subenvironments included many described by Campbell (1971). Foreshore sandstones contain relatively discontinuous, even-parallel to wavy-parallel laminations which dip less than 10° and contain a few burrows and scour-and-fill structures. These sandstones are moderately to well sorted. Tidal flat deposits have discontinuous, wavy, nonparallel laminae and algal structures, all of which are horizontally bedded and commonly burrowed. Shoreface deposits are extensively burrowed and contain contorted, slumped, and discontinuous wavy, nonparallel to parallel relict laminae with maximum dips of 20°. Symmetric wave ripples were occasionally observed in the relict laminae. The shoreface deposits are also distinctly finer grained than juxtaposed foreshore deposits. Supratidal and sebhka deposits contain rip-up clasts, flaser bedding, adhesion ripples, and abundant precipitates such as anhydrite and dolomite with birdseye structures and desiccation features.

The results of core examinations are illustrated in figures 5 and 6.

Although the original environments of deposition and textures of the Weber (Tensleep) Sandstone in the Brady and Lost Soldier-Wertz fields were virtually identical, the present porosity and permeability characteristics of the two areas are significantly different. The Tensleep in Lost Soldier-Wertz has been tightly cemented to an average intergranular porosity of 5 percent, and production is from complexly fractured strata. In Brady field, however, much original porosity and permeability remains; production is from strata having intergranular porosity of a maximum 15-20 percent.

The combination of the studies of the two fields creates a nearly complete picture of dune-extradune geometry, of the original distribution of porosity and permeability, and of the potential influence that it may have on fluid migration. The close control in Lost Soldier-Wertz (fig. 5), combined with the porosity-permeability contrasts resulting from the same depositional processes which are preserved in Brady (fig. 6), provides a subsurface example of the dune-extradune model. Relatively more porous and permeable dune sand is isolated by generally less porous and permeable extradune sediment at Brady field and fluid migration may be influenced.

Figure 6.--Diagram of core permeability and porosity and environment of deposition in the Weber Sandstone, Champlin Petroleum Company Brady Unit 2, Sweetwater County, Wyoming.



SUMMARY

From study of the Weber Sandstone and examination of the Jurassic Nugget Sandstone and correlative Navajo Sandstone in the Colorado Plateau and southern Wyoming, we conclude that dune-extradune systems, such as the Weber (Tensleep), present greater reservoir problems than dune-interdune types, such as the Nugget. Dune-interdune systems present less of a problem because (1) interdune sediments are usually thinner than extradune sediments, and, therefore, present less of a porosity and permeability barrier; and (2) interdune sediments are commonly lenticular, a condition which would allow communication between dune bodies. Furthermore, judged from production histories, porosity-permeability problems in dune-interdune reservoirs are apparently not common.

Effective fluid movement between well bores is influenced by the complex permeability barriers that resulted from dune-extradune depositional processes. In cases where fluid movement between well bores is critical as in retrograde reservoirs where reservoir pressure maintenance is essential, the efficient recovery of hydrocarbons requires knowledge of the distribution of depositional environments and the resultant porosity and permeability characteristics.

DEFINITIONS

Dune-extradune depositional system--A system that contains the sediments of a dune complex, that is, dune and interdune sediments, as well as associated extradune sediments, such as alluvial fan, wadi, serir, stream, sebkha, playa, lake, beach, and tidal flat.

Dune-interdune depositional system--A system that contains only the sediments of a dune complex, that is, dune and interdune sediments.

Extradune--The area marginal to a dune field which contains sediments related to dune sediments in time and by source.

Interdune--The relatively flat area between the dunes of a dune complex.

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