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**GEOLOGICAL AND PETROPHYSICAL
CHARACTERIZATION OF THE FERRON SANDSTONE
FOR 3-D SIMULATION
OF A FLUVIAL-DELTAIC RESERVOIR
(Contract No. DE-AC22-93BC14896)**

TECHNICAL PROGRESS REPORT

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Program Manager: Thomas C. Chidsey, Jr.
Principal Investigator: M. Lee Allison**

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GEOLOGICAL AND PETROPHYSICAL CHARACTERIZATION OF THE FERRON SANDSTONE FOR 3-D SIMULATION OF A FLUVIAL-DELTAIC RESERVOIR

(Contract No. DE-AC22-93BC14896)

Utah Geological Survey (UGS), Salt Lake City, Utah 84114

Submitted: June 1996

Contract Date: September 29, 1993

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Government Award (fiscal year): \$ 633,650

Principal Investigator: M. Lee Allison, UGS

Program Manager: Thomas C. Chidsey, Jr., UGS

Contracting Officer's Representative: Robert Lemmon, Bartlesville Project Office

Reporting Period: January 1 - March 31, 1996

Objective

The objective of this project is to develop a comprehensive, interdisciplinary, and quantitative characterization of a fluvial-deltaic reservoir which will allow realistic inter-well and reservoir-scale modeling to be constructed for improved oil-field development in similar reservoirs world-wide. The geological and petrophysical properties of the Cretaceous Ferron Sandstone in east-central Utah will be quantitatively determined. Both new and existing data will be integrated into a three-dimensional representation of spatial variations in porosity, storativity, and tensorial rock permeability at a scale appropriate for inter-well to regional-scale reservoir simulation. Results could improve reservoir management through proper infill and extension drilling strategies, reduction of economic risks, increased recovery from existing oil fields, and more reliable reserve calculations. Transfer of the project results to the petroleum industry is an integral component of the project.

Summary of Technical Progress

Technical progress this quarter is divided into case-study evaluation, geostatistics, and technology transfer activities. The work focused on one parasequence set, referred to as the Kf-1, in the Willow Springs Wash and Ivie Creek case-study areas (Fig. 1). In the Ivie Creek case-study area the Kf-1 represents a river-dominated delta deposit which changes from proximal to distal from east to west. In the Willow Springs Wash case-study area the Kf-1 contains parasequences which represent river-dominated and wave-modified environments of deposition. Interpretations of lithofacies, bounding surfaces, and other geologic information are being used to determine reservoir architecture. Graphical interpretations of important flow boundaries in the case-study areas, identified on photomosaics, are being used to construct cross sections, paleogeographic maps, and reservoir models. Geostatistical analyses are being incorporated with the geological characterization to develop a three-dimensional model of the reservoirs for fluid-flow simulation. Technology transfer consisted of setting up a home page on the Internet and presenting project benefits to the public.

Case-Study Evaluation

Willow Springs Wash

Methods. Work during the quarter consisted of processing and interpreting the data collected from the Indian Canyon portion of the area during the previous field seasons. Particular attention was paid to developing depositional models for the Kf1-Indian Canyon-c and Kf1-Indian Canyon-d parasequences. This was done primarily by comparison of the collected data with models developed from non-barred and barred, wave-dominated shorelines and shorelines with varying amounts of tidal influence. Based on the conclusions from the aforementioned efforts, paleogeographic maps have been constructed that illustrate the evolution of depositional environments within the case-study area.

Interpretation. The Indian Canyon-c has been interpreted as a wave-modified shoreline. A tidal inlet developed during early deposition of the parasequence. Later, as longshore currents caused the inlet to migrate towards the southeast, deposition along a wave-dominated shoreline became the dominant process. Seaward of this tidal inlet, a thick section of dominantly seaward-oriented trough or tabular cross-stratification overlain by a thinner section of landward and more random oriented cross stratification implies that modification of this model might be warranted. Work on non-barred coasts by Clifton *et al.*¹ suggests that as waves approach a shoreline, the sequence of sedimentary structures that develops includes a section of landward-oriented cross-beds. This is the opposite of what is seen in Indian Canyon. Hunter *et al.*² described deposits of barred shorelines displaying a significant seaward-oriented, cross-bedded section. Seaward-oriented bedforms, in this case, represent deposition on rip-channel mouth bars or within longshore troughs. Evidence of repeated scour and fill, developed as rip-channels migrated along the shoreline, would help to confirm this. This type of scour and fill has not been observed.

Another possible model for these deposits is an ebb-tidal delta. Ebb-tides would account for the seaward-oriented cross-beds present within Indian Canyon exposures. Additionally, a smaller

Fig 1. Location map of the Ferron Sandstone outcrop belt (cross-hatched), showing case-study areas (outlined in heavy dashed lines).

section of landward-oriented cross-beds present above this, and below the foreshore deposits, could be explained by the presence of swash bars associated with the ebb-tidal delta. This model implies generally higher tidal ranges for the Ferron Sandstone, however, Hays (verbal communication, 1996) has shown that tide ranges fluctuate due to coastal geomorphology and are accentuated within bights or embayments. Ryer and McPhillips³ have suggested that such a bight was present along the Ferron coastline at this time. Further, Walther's law requires that the spatial association of the seaward-oriented trough cross-stratification with a known tidal inlet be incorporated in the depositional model. An ebb-tidal delta model incorporates all of these constraints.

Preservation of ebb-tidal deltas is relatively low in modern environments. Some authors suggest that preservation of ebb-tidal deltas is higher along prograding shorelines (*e.g.* Heward⁴). It is certain that this shoreline prograded, and the upward- and seaward-stepping parasequence architecture suggests that sedimentation was overwhelming sea-level rise.

Realistically, a hybrid of both models may have produced the observed features in Indian Canyon. Slight differences in the depositional model may effect hydrocarbon reservoir potential, however, evidence to eliminate either model may be non-existent.

Ivie Creek

Methods. Work during the quarter consisted of applying lithofacies names to Kf-1-Ivie Creek-a parasequence in the amphitheatre area to be used for paleogeographic interpretation and the detailed reservoir modeling exercise. Scaled line work on photomosaics for this area show offlapping packages of beds referred to as clinoforms. Most of the clinoform boundary lines on the photomosaics were based on data from measured sections (that is unit boundaries) or changes in permeability as noted from the permeability transects. Where a visual (and qualitative) change in permeability is present corresponding to a line on the mosaic and a unit boundary in a measured section, the line was highlighted. If these conditions were not met the line was not highlighted. An estimated 80%+ of the lines on the interpreted mosaic were marked in yellow in the area of a measured section.

Two other higher order lines were also delineated. A line was marked where the tops of the clinoforms are truncated by erosional surfaces that extend for more than 300 ft laterally. These erosional surfaces drop stratigraphically through the Kf-1-Ivie Creek-a and the separate distal facies eventually become unrecognizable. The lines marking the tops of the clinoforms delineate larger packages of similar internal clinoform organization informally called subcycles.

Another highlighted line was used to designate a similar hierarchal package of rock or subcycle with a different upper bounding surface. In this case, the clinoforms do not appear to have been substantially eroded at the top. In the most proximal position, the bounding surface is overlain and underlain chiefly by sandstone. Progressing in a down-depositional direction, the lithology overlying the bounding surface becomes more shale dominated and a slope former on outcrop. In its most distal portion, this surface drops stratigraphically to a position within the lower third of bedding planes similar to the termination position of the other subcycle packages.

Interpretation. With the line work in place and an integration of measured sections, permeability data, and line work and associated annotations, the clinoform section of Kf-1-Ivie Creek-a parasequence was classified into four lithofacies: clinoform proximal (cp), clinoform medial (cm), clinoform distal (cd), and clinoform cap (cc). Lithofacies cp, cm, and cd are assigned to clinoforms

only, and lithofacies cc is a bounding facies above the clinoforms (Fig. 2).

Lithofacies cp is mostly fine- to medium-grained sandstone. The chief sedimentary structure is low-angle cross-stratification with minor horizontal and trough cross-stratification and rare hummocky bedding. The lithofacies is dominantly thick- to medium-bedded, well to moderately indurated, with permeabilities ranging from 2 to 600 md and a mean of about 10 md. The inclination of bed boundaries is generally greater than 10° . This lithofacies is interpreted to be the highest energy and most proximal to the sediment input point. The steep inclinations are interpreted to represent deposition into a relatively localized deep area in an open bay environment. The dominance of low-angle cross-stratification with inclinations within the bed or clinoforms in an up-depositional dip direction indicates the influence of on-shore wave energy.

Lithofacies cm is dominantly sandstone with about 5% shale. The sandstone is primarily fine-grained with slightly more fine- to very-fine-grained than fine- to medium-grained. Horizontal beds dominate with some rippled, trough and low-angle cross-stratification. Bed thicknesses range from laminated to very thick, but most are medium. The beds are generally well to moderately indurated, but are occasionally friable. The permeability values range from non-detectable to 100 md with the mean about 3 md. Inclination on the clinoform boundaries is between 2 and 10° . Lithofacies cm is generally transitional between lithofacies cp and cd, but occasionally is present at the erosional truncation or offlapping boundary of the clinoforms, with no visible connection to lithofacies cp.

Lithofacies cd is sandstone (sometimes silty) with about 10% shale. The sandstone grain size is dominantly fine- to very-fine-grained, with considerable variation. Sedimentary structures in this lithofacies are chiefly horizontal laminations and ripples in medium to thin beds. Induration of the beds ranges from well to friable. Average lithofacies cd permeability is just at the detection limit of 2 md, but ranges up to 80 md. This lithofacies is gradational with lithofacies cm and represents the deepest water and lowest energy deposition within the clinoform. It can be traced distally into prodelta to offshore.

Lithofacies cc consists of very-fine- to fine-grained, thick- to medium-bedded sandstone. The beds are horizontal, with some trough and low-angle cross-stratification. Burrowing is rare. The sandstone is mostly well indurated, with permeabilities ranging from non-detectable to 100 millidarcies (md) and a mean of about 2 md. This lithofacies is present stratigraphically above the truncated clinoforms near the top of the parasequence and where bed boundaries show little to no inclination. The cc lithofacies is interpreted to represent an eroded and reworked delta top.

Figure 3 is a paleogeographic interpretation of the third step of the five depositional time steps of parasequence Kf-1-Ivie Creek-a. The main delta lobe was located to the east and northeast. That delta lobe allowed a protected embayment to develop in the northwest part of the case-study area. The clinoforms observed in section 16 (Fig. 2) represent deposition into the embayment fed by river channels to the southeast. The shoreface/delta front, shallow marine, and deep marine environments produced the clinoform proximal, medial, and distal lithofacies respectively.

Geostatistics

Geostatistical work this quarter was devoted to investigating statistical relationships between geologic features and permeability data, and among various geologic features. The analyses thus far have included only data for the Kf-1-Ivie Creek-a parasequence in the Ivie Creek case-study area.

Explanation

clinoform-cap		clinoform-medial
clinoform-proximal		clinoform-distal

Fig. 2. Scaled cross section, based on a portion of the Ivie Creek photomosaic, showing clinoform lithofacies assigned to the Kf-1-Ivie Creek-a parasequence. Vertical lines represent permeability transect locations.

Explanation

Deep Marine

River Channels

Shallow Marine

Abandoned Channel System

Shoreface/Delta Front

Coastal/Delta Plain

● core hole location

Fig. 3. Paleogeographic interpretation of the third of five time steps of the Kf-1-Ivie Creek-a parasequence. River channels flowing from the south and southeast deposited sands into a protected embayment in the northwest part of the area.

Permeability values exhibit log-normal distributions with respect to sedimentary structure and grain size, and a less clear relationship with respect to bed size and induration. When grouped by clinoform lithofacies, permeability values exhibit a log-normal distribution where mean permeability value decreases with decreasing depositional energy (Fig. 4). Each clinoform lithofacies is characterized by a particular suite of geologic features as shown in the summary plots of Figure 5. There are distinct relationships between depositional energy, sedimentary structure, average grain size, and lithology, weaker correlations exist for induration and bed size. The relative frequency of sedimentary structures was calculated for the four lithofacies (Fig. 5A). Horizontal bedding is the most common sedimentary structure in all lithofacies. Ripple cross-laminated beds are most common in the clinoform distal lithofacies (cd). Low-angle and trough-cross-stratified beds are common only in the clinoform proximal lithofacies (cp). The grain-size distributions (based on megascopic observations) were also calculated for the four lithofacies (Fig. 5B). As one might expect, the clinoform proximal lithofacies contains the coarsest material and the clinoform distal lithofacies the finest. The proximal sandstones also contained the greatest variations in grain sizes.

Technology Transfer

The Utah Geological Survey (UGS) presented a brief overview of the geology and development activity of the Ferron Sandstone coalbed methane fairway at a public information meeting, March 5, 1996 in the Emery County Courthouse at the request of the Emery County Planning Commission. A lecture, entitled *Geology and Gas Potential of Utah's Ferron Sandstone*, was also presented to the Association of Petroleum & Mining Landmen on January 4, 1996 in Salt Lake City.

The UGS has established a home page on the Internet. The address is <http://utstdpwww.state.ut.us/~ugs/>. The site includes a page the heading Utah's *Petroleum Resources*, describing the UGS/DOE cooperative studies (Ferron Sandstone, Bluebell field, and Paradox basin) and *Petroleum News*.

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1. H. E. Clifton, R. E. Hunter, and R. L. Phillips, Depositional Structures in the Non-Barred High-Energy Nearshore, *J. Sed. Pet.*, 41: 651-670 (1971).
2. R. E. Hunter, H. E. Clifton, and R. L. Phillips, Depositional Processes, Sedimentary Structures, and Predicted Vertical Sequence in Barred Nearshore Systems, Southern Oregon Coast: *J. Sed. Pet.*, 49: 711-726 (1979).
3. T. A. Ryer, and Maureen McPhillips, Early Late Cretaceous Paleogeography of East-Central Utah: in W. M. Reynolds, and E. D. Dolly, eds., Mesozoic Paleogeography of the West-Central United States, *Rocky Mountain Section SEPM, Rocky Mountain Paleogeography Symposium 2*: 253-272 (1983).
4. A. P. Heward, A Review of Wave-Dominated Clastic Shoreline Deposits, *Earth Science Reviews*, 17, 223-276 (1981).

Fig. 4. Statistical analyses of Kf-1-Ivie Creek-a parasequence in the Ivie Creek case-study area showing cumulative percent of the four clinoform lithofacies versus permeability.

Fig. 5. Statistical analyses of the clinoform lithofacies from the Kf-1-Ivie Creek-a parasequence: (A) histogram showing relative frequency of sedimentary structure versus lithofacies, and (B) histogram showing grain-size distributions (megascopic observations) in each lithofacies (SH = shale, ST = silt, VFG = very fine grain, FVF = fine to very fine grain, FIN = fine grain, MFG = medium to fine grain, and MED = medium grain).

NEXT QUARTER PLANNED ACTIVITIES

Activities planned for the next quarter include:

1. Continue plotting locations of measured sections, paleocurrent sites, and gamma-ray and mini-permeameter transects on base maps. Post paleocurrent rose diagrams on the digital base maps.
2. Complete graphical log displays of gamma-ray measurements taken from outcrops in the Ivie Creek case-study area.
3. Enter 1995 measured section data and core descriptions into the revised UGS database.
4. Continue petrophysical analysis of samples from the 1995 core-plugging program.
5. Complete gridded cross sections as a basis for constructing digital fence diagrams. Simulate two-dimensional cross sections mapped by the project field team.
6. Continue quantifying sedimentary and petrophysical data to develop statistical models.
7. Publish as a UGS contract report, the computer codes describing the method in intuitive terms and how to use the codes. Modify TETRAD, the modeling program provided by Mobil, to test the homogenization methods in real oil industry simulators. The modifications require the inclusion of full tensor permeabilities.
8. Begin production of cross sections and lithofacies maps for the case-study areas.
9. Scale measured sections (1 in = 40 ft) to be used in regional cross sections. Input regional measured sections made during the 1995 field season into graphic software. Prepare a base map of the region, locating all measured sections and transects by their latitude and longitude.
10. Set up project page within the UGS Internet home page. Release the latest issue of UGS *Petroleum News*.
11. Present a talk entitled *Flow Based Scale-Up of Heterogeneous Porous Media using Homogenization and Wavelet Representation* by Joe Koebbe to the Second International Symposium on Spatial Accuracy Assessment in Natural Resources and Environmental Sciences, May 21-23, 1996, Colorado State University, Fort Collins, Colorado.