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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

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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.

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Summary of Technical Progress

Two activities continued this quarter as part of the geological and petrophysical characterization of the fluvial-deltaic Ferron Sandstone: (1) evaluation of the Ivie Creek and Willow Springs Wash case-study areas (Fig. 1) and (2) technology transfer.

Evaluation of the Ivie Creek and Willow Springs Wash Case-Study Areas

Ivie Creek

The Ivie Creek case-study evaluation work during the quarter focused on the two parasequence sets, the Kf-1 and Kf-2, in the lower Ferron Sandstone. This work included: (1) clinoform characterization of the Kf-1-Ivie Creek (Iv)-a parasequence, (2) interpretation of the depositional environments of lithofacies in the Kf-2, and (3) construction of cross sections.

Kf-1-Ivie Creek-a Parasequence Clinoform Characterization. Smaller sedimentary packages than the parasequence can be recognized within Kf-1-Iv-a. Figure 2 illustrates these smaller units. In descending order they are: (1) subcycle, (2) clinoform, and (3) bounding layer.

A **subcycle** divides the parasequence into a smaller recognizable coarsening-upward, bed-thickening-upward unit. The mappable extent of the subcycle is distinctively smaller than the parasequence. It is possible that the unit's formation is in response to a localized relative sea-level change, or to a change in sediment supply from an actively forming delta or longshore drift.

Cli-no-form is used to identify a group of beds and bedsets which are inclined seaward in an en echelon pattern and generally separated from one another by a distinctive surface observable on outcrop. The clinoforms are visually defined on photomosaics of the outcrop. The clinoform shape is defined on the photomosaics based on a slightly more recessive break in the cliff face chiefly along the upper and lower boundaries of the clinoform. The resolution of the photography allows only a "bounding surface" to be drawn with no third dimension. Upon closer examination, it is clear that the line work representing the boundaries of clinoforms are drawn on a unit that generally does have some thickness. In order to clarify this difference, the term **bounding layer** is used to describe the thin rock layer which creates the erosive contrast on the cliff face and is appropriately called a surface at the scale of the subcycle or parasequence. The bounding layer is important as a element of the flow characteristics of a clinoform-type reservoir because it generally contains beds and laminae which are finer grained, mud and carbonaceous-detritus rich, and are assumed to provide a distinctly lower permeability than the main sand body of the clinoform.

The clinoforms change characteristics from the shallower water and more proximal location to the deeper water and more distal locations. Four clinoform facies are designated within the Kf-1-Iv-a at the Ivie Creek case-study area: (1) clinoform cap, (2) clinoform proximal, (3) clinoform medial, and (4) clinoform distal. Clinoform facies were based on grain size, sedimentary structures, bedding thickness, inclination angle, and stratigraphic position.¹ The abrupt end of the medial facies in Fig. 2 (end of shading) is representative of most of the contacts between proximal, medial, and distal clinoform facies used in this study. Polygon-shaped packages of rock are necessary for reservoir modeling and simulation. In reality, the transition from medial to distal (as well as medial to proximal) is gradational.

The smallest sedimentary package is the bounding layer (Fig. 2). This unit is bounded above by the base of the overlying clinoform and below by the top of the main sand body of the genetically

associated clinoform. The lower boundary of the layer is generally sharp, but occasionally is gradational over a thin interval. Most of the bounding layers examined contained two common elements: (1) they are finer-grained, less cemented, and less resistant than the overlying and underlying clinoforms, (2) they contain laminations of carbonaceous material, which are consistently poorly cemented and more easily eroded, hence, are expressed as recesses on outcrop. The bounding layer ranges in thickness from less than an inch to a few feet thick. The unit generally decreases in grain size in a down-depositional-dip direction with a corresponding increase in thickness. The bounding layers generally range from fine-grained sandstone to mudstone and commonly contain bedding planes with laminae rich in carbonaceous debris. The bounding layer is chiefly horizontal to slightly irregular bedded with minor oscillation ripples and flaser bedding. Bed thickness is generally thin to laminated. Occasionally some portion of the bounding layer contains gypsum veinlets which are related to weathering and have not been observed in the core behind the outcrop. The lithologic nature of the bounding layer is generally very similar to the clinoform distal facies.

As the bounding layers are followed along the outcrop and up the inclined surface of the clinoform, the last visible evidence of the bounding layer is often one or several laminae of carbonaceous material forming a very slight recess in the outcrop. On rare occasions the bounding layer does not reach the upper termination of the clinoform, forming a true sand-on-sand contact between clinoforms.

The generally abrupt nature of the contact between the clinoform below and the bounding layer above raises the question: which clinoform is the bounding layer most closely related to? Most of the bottoms of clinoforms (top of the underlying bounding layer) exhibit a smooth, sharp, concave up contact. Occasionally erosional truncation of the underlying bounding layer and/or the underlying clinoform (Fig. 2) is evident, particularly in the more proximal part of the clinoforms, hence, the conclusion that the bounding layer is more closely related to the depositional episode of the underlying clinoform. Sand-on-sand contacts represent either an area of no deposition of the finer-grained sediment during the waning stage of deposition of the underlying clinoform or, an area of erosion prior to, and associated with the deposition of the next clinoform.

The abrupt end of clinoform sand-dominated deposition is interpreted to represent the temporary change in sand distribution at the delta. During the temporary cessation of rapid sedimentation the small amount of wave-energy at the delta front continues to move and rework some bedload sediments. Suspended load (and associated carbonaceous debris) is "raining down" on the delta front almost continuously. Mud, silt, and carbonaceous debris dominance in the deeper water portions of Kf-1-Iv-a indicates the ability of wave-energy to winnow the "fines" to deeper and lower energy environments. The presence of the bounding layer/clinoform couplet is indicative of high frequency depositional cyclicity during deposition of the subcycle.

Kf-1-Iv-a parasequence in the Ivie Creek area records an episode of delta progradation into a deeper water fully marine bay. The clinoform outcrops together form an arcuate feature, which is interpreted as a delta-complex. Based on the geometry of the clinoform deposits, the source for the delta is believed to be from the southeast. Outcrops to the southeast of the study area contain numerous distributary channel deposits at the top of the Kf-1.

Figure 3 illustrates a map view interpretation of the depositional history through time of a portion of the lower subcycle of Kf-1-Iv-a. Time 1 begins during active progradation of delta deposits and after the establishment of a major delta-front deposit prograding into the area. Minor erosion of the uppermost portion of the delta-front (clinoform proximal facies) is portrayed in Time 2. Time 3 to 6 illustrate the addition of several clinoforms with some minor erosion. At Time 7 a significant change in deposition occurs. Either a relative rise of sea level at this location (most likely

caused by minor tectonics or compaction and subsidence of the delta lobe) or a change in the wave-energy regime of the bay resulted in reworking of the previous upper portion of the delta and deposition of the cap facies during Time 8. It is likely that this change, marked by the cap facies, was related to a change in the volume or point of discharge of sediments as well. The recognition of an overall fining of the Kf-1-Iv-a at this stratigraphic level points to some change in the depositional regime. This event marks the base of the next subcycle. Distributary channel switching is the implied mechanism for clinoform cyclicity in Figure 3. It is interesting to note that no distributary channel deposits have been located juxtaposed with the clinoforms.

Depositional Environments in the Kf-2. The wave-modified Kf-2 in the Ivie Creek case-study area was deposited in seven depositional environments: (1) lower shoreface, (2) middle shoreface, (3) upper shoreface, (4) foreshore, (5) distributary complex, (6) distributary channel, and (7) distributary-mouth bar. The gamma-ray log characteristics of each facies were tied to core taken from project drill holes in the area (Fig. 4).

The lower shoreface facies consists of thinly interbedded shale to siltstone and very fine- to fine-grained sandstone. Wave ripples to horizontal laminations dominate this facies. Burrowing is generally found on the top of thin sandstone beds and the shale is often bioturbated. This facies is very similar to the transition facies but sandstone is more abundant than shale and siltstone. Hummocky stratification is common.

The middle shoreface facies is very fine- to fine-grained sandstone composed of hummocky, swaley, and planar laminations with minor ripple laminations. This facies is generally thick, representing 50% or more of the shoreface sequence. The most common burrow types are *Thalassinoides* and *Ophiomorpha* and the amount of burrowing varies from moderate to highly bioturbated.

The upper shoreface facies is characterized by fine- to medium-grained multidirectionally cross-stratified sandstone, in sets that are commonly separated by planar laminations. This facies is generally about 10 ft thick; but greater in the vicinities of the landward pinchouts of the parasequences, where the upper shoreface may reach 20 ft in thickness. The facies is slightly to moderately burrowed, with *Ophiomorpha* as the most common trace fossil.

The foreshore facies consists of fine- to medium-grained sandstone which is planar to inclined bedded, slightly to intensely burrowed, and sometimes rooted. This facies is not always present at the top of the shoreface sequence but when present ranges up to a few feet in thickness.

The distributary complex facies is characterized by a predominance of sandstone and trough-cross stratification which is typically unidirectional. This facies can sometimes be subdivided into distributary channel and mouth-bar facies. From a distance, this facies is often characterized by the complex geometry of bedsets and large-scale bounding surfaces in contrast to the flat to very gently inclined surfaces of the lower delta-front.

The distributary channel facies are common in river-dominated delta-fronts and also found within the wave-modified shoreline of the Ferron. They are characterized by channels with high height-to-width ratios, and unidirectionally trough-cross-stratified and current-ripple-cross laminations. Channel fills are sandstone dominated, but heterolithic channel fills are not uncommon. Troughs in the channel base generally contain mud rip-up clasts, woody fragments, and rare sharks' teeth. This facies grades seaward into distributary-mouth bar facies.

The distributary-mouth bar facies are found in the upper parts of delta-front sequences and are associated with distributary channels. This facies is characterized by fine-grained or coarser, trough-cross-stratified sandstone, and moderate to intense burrowing associated with lower flow

velocities and decreased sedimentation rate, with some completely bioturbated intervals between trough sets. *Ophiomorpha* is common along with less common escape burrows. Paleoflow directions show a strong offshore component with the amount of scatter increasing with increased wave influence and distance from the distributary channel. Traced laterally and seaward, the facies commonly grades into middle shoreface or lower delta-front facies (fluvial-dominated shoreline).

Construction of Cross Sections. Scaled photomosaic panels from the Ivie Creek amphitheater (south-facing outcrop belt) and Quitcupah Canyon provide a framework for cross sections. These panels along with other photomosaic coverage, geophysical logs and conventional core from five drill holes, and 15 measured stratigraphic sections acquired during two field seasons, provided the necessary information to assemble five cross sections delineating parasequences throughout the Ivie Creek case-study area (Fig. 5).

Willow Springs Wash

The Willow Springs Wash case-study area evaluation work during the quarter focused on characterization of 11 distinct depositional facies in the Kf-1 parasequence set (Table 1). These facies are: (1) prodelta-inner shelf, (2) lower shoreface, (3) middle shoreface, (4) upper shoreface-ebb tidal delta, (5) foreshore, (6) tidal inlet, (7) interdistributary bay-fill, (8) crevasse-splay, (9) multi-story channel, (10) multi-lateral channel, and (11) beach ridge. They can be grouped into two depositional systems: wave-dominated shoreline and fluvial-dominated delta.

Based on lateral and vertical facies associations, the rocks can be divided into four depositional units as Kf-1-Indian Canyon (IC)-a, -b, -c, and -d in ascending order. Marine-flooding surfaces, which are identified on the basis of vertical offset in landward pinch-outs, separate the a, b, and c depositional units. There is no flooding surface separating the c and d units. Because of this, the depositional units are divided into three parasequences. These are the Kf-1-IC-a and Kf-1-IC-b parasequences (which consist of depositional units a and b respectively) and the Kf-1-IC-c parasequence (which consists of depositional units c and d).

During the deposition of parasequences a, b, and the early part of c, the case-study area was characterized by northeastward progradation of a northwest-southeast striking shoreline. Kf-1-IC-a and the early part of Kf-1-IC-c represent longer pulses of progradation while Kf-1-IC-b represents a shorter pulse. During the later part of Kf-1-IC-c, river avulsion created an autocyclic change in deposition that resulted in an "apparent parasequence." During this time sedimentation within the case-study area was characterized by deposition within an interdistributary bay.

The facies interpretations of the Willow Springs Wash case-study area suggest that "apparent parasequences" may result from autocyclic processes. These processes are independent of changes in relative sea level and as such, they are not parasequences in the strictest sense. Interpretation of these apparent parasequences as true parasequences may help to visualize distinct compartments within a reservoir, but may not be beneficial in predicting facies distributions.

Technology Transfer

Project material was displayed at the UGS booth during the AAPG annual convention held in Denver, Colo., August 24-27, 1997. A lecture (using Ferron project data and results) titled *Characterization and Upscaling of Sedimentary Depositional Formations Using Archetypal Analysis and Homogenization* by Joe Koebbe, Laura Watkins, and R. Thomas was presented at the Third

IMACS International Symposium on Iterative Methods in Scientific Computation, Jackson Hole, Wyo., July 9-12, 1997.

Reference

1. T.C. Chidsey, Jr., Geological and Petrophysical Characterization of the Ferron Sandstone for 3-D Simulation of a Fluvial-Deltaic Reservoir, *Annual Report*, DOE Contract No. DE-AC22-93BC14896, DOE/BC/14896-15, May 1997.

FIGURE CAPTIONS

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

Fig. 2. Stratigraphic nomenclature and hierarchical units of the Kf-1 parasequence set, Ivie Creek case-study area.

Fig. 3. Plan view of eight time steps during deposition of the lower subcycle of the Kf-1-Iv-a parasequence. These views emphasize the switching of a distributary channel. Changes in the amount of wave-energy or sediment reaching the shore also influenced clinoform cyclicity.

Fig. 4. Example of Ferron Sandstone reservoir gamma-ray type log, core description, and lithofacies.

Fig. 5. North-south stratigraphic cross section through the Ivie Creek case-study area showing correlation of lower Ferron parasequences.

- ✧ Oil and gas wells
- Gas field
- ⊞ Area with closely spaced coal wells

0 10 mi
0 10 km

1

4

7

2

5

8

3

6

Utah Geological Survey
 Ivie Creek No. 11
 NENW Sec. 20, T. 23 S., R. 06 E., SLBL

TABLE 1

**Depositional Facies of the Kf-1 Parasequence Set in the
Willow Springs Wash Case-Study Area, Sevier County, Utah**

Depositional Facies	Characteristics	Wave-Dominated Shoreline	Fluvial-Dominated Delta
Prodelta-inner shelf	Interbedded silt and shale	x	x
Lower shoreface	Hummocky cross-stratified sand and silt	x	
Middle shoreface	Inclined bedded, planar-laminated sand	x	
Upper shoreface-ebb tidal delta	Thick-bedded, trough- and tabular-cross-stratified sand	x	
Foreshore	Thick-bedded, inclined planar-laminated sand	x	
Tidal inlet	Sigmoidal-bedded, cross-stratified sand	x	
Interdistributary bay-fill	Shale and interbedded sand		x
Crevasse splay	<i>En echelon</i> sand and interbedded silty shale		x
Multi-story channel	Multi-story, lensoidal sand		x
Multi-lateral channel	Multi-lateral, lensoidal sand		x
Beach ridge	Planar-laminated, cross-stratified sand and silt		x