Borehole Imagery Resolves Channel Trend*

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Introduction

Borehole imagery is one type of open-hole log that provides high-resolution data for improved reservoir characterization. Borehole images are used to:

- Characterize fracture and fault systems.
- Interpret stratigraphic discontinuities.
- Quantify pay in thin-bed packages.
- Interpret environments of deposition.
- Resolve sandstone-body geometry and paleocurrent orientation.

Borehole imaging tools have evolved from diplogs and dipmeters. Diplogs, which identify bedding orientations, have been most commonly applied to structural analyses. Over the past several years, borehole-imaging resolution, borehole coverage and interpretive capabilities have improved significantly. Instruments such as the Simultaneous Acoustic Resistivity Imager (STAR Imager^{SM}) provide a vertical resolution on the order of 0.4 inches (1 cm). One application of high-resolution borehole imagery is sedimentologic analysis of reservoir sandstone.

We present borehole images and core from the Frontier Formation on the Moxa Arch of southwest Wyoming. The core provides "ground truth" for sedimentary structure identification and gives us confidence in the technique of using borehole imagery to identify sedimentary structures. The borehole image also provides information about sedimentary strike and paleocurrent direction.

Geologic/Economic Context

The Frontier Formation contains both marine and non-marine gas reservoirs that make up multiple stratigraphic sequences. Frontier gas reserves on the Moxa Arch of southwestern Wyoming (Figure 1) exceed one trillion cubic feet of gas -- but due to reservoir heterogeneity, Frontier fields contain scattered dry holes and marginal producers.

In order to reduce drilling and completion risks, borehole imagery is being used to augment facies identification in a sequence-stratigraphic framework and to delineate sandstone-body geometries and paleo-transport orientations.

Our case study well (Figure 1) was drilled along the western limit of commercial Frontier gas production. Figure 2 shows a gamma ray log and environments of deposition interpreted using borehole imagery. This well produces gas from upper shoreface, foreshore and fluvial sandstones, but the primary reservoir (highlighted with a red bar) is a channel sandstone deposited on a lowstand event (LSE). The combination of core and high-resolution borehole imagery were used to better understand the reservoir geometry of this 15-foot thick reservoir.

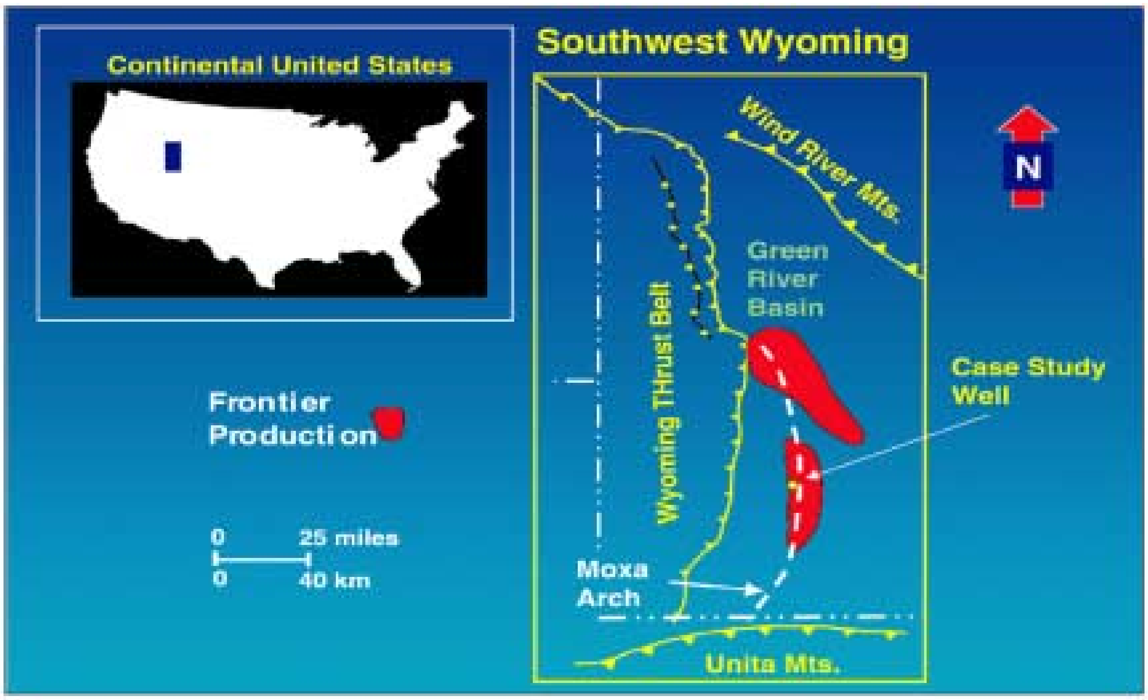

Figure 1. U.S. location map with regional setting and gas fields of the Green River Basin, Wyoming.

Methodology and Sedimentology

All bedding structures were picked as dip vectors utilizing Vision™ software:

- The regional structural dip was determined.
- Bedding structures were interactively classified using DipInt interpretation software.
- Structural dips were rotated out for sedimentologic analyses.

The azimuths and dip angles of each vector population were then presented as dip-vector plots and rose-frequency diagrams so that the paleo-flow direction could be evaluated. Figure 3 provides an overview of the sedimentologic analysis. Three categories of color-coded dip vectors are shown. The vertical positions of borehole image/core displays presented as Figures 4, 5, and 6 are shown.

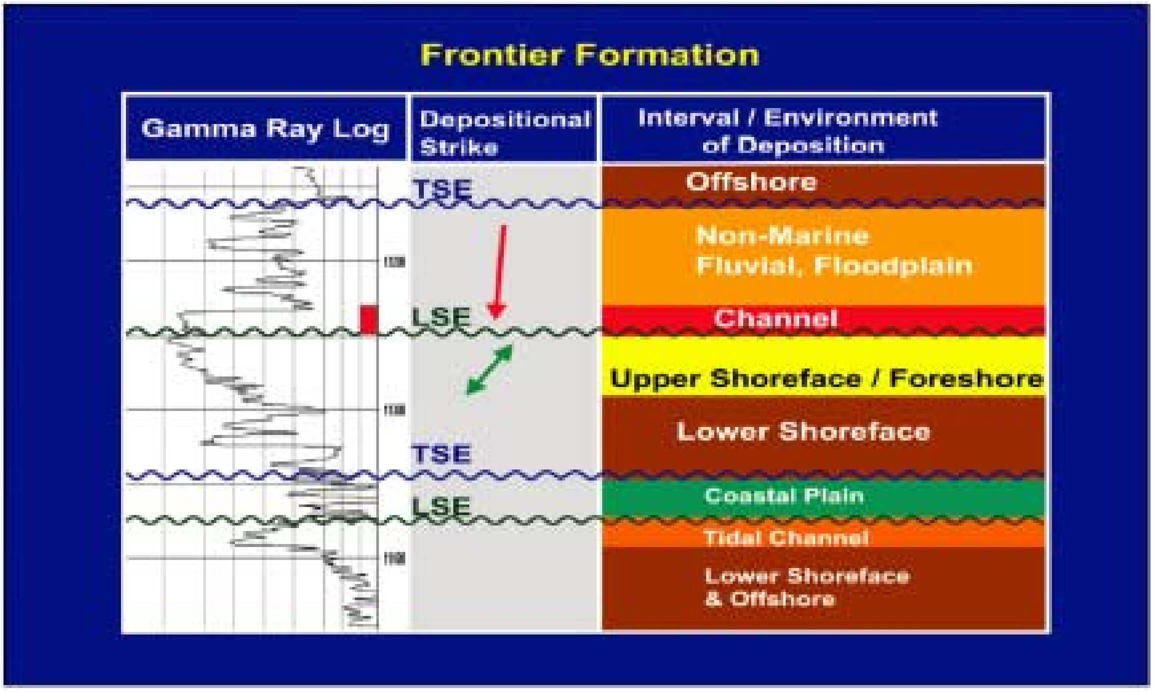

Figure 2. Sequence stratigraphic framework and environments of deposition interpreted using borehole imagery. Each transgressive surface of erosion (TSE) and lowstand surface of erosion (LSE) is a sequence boundary.

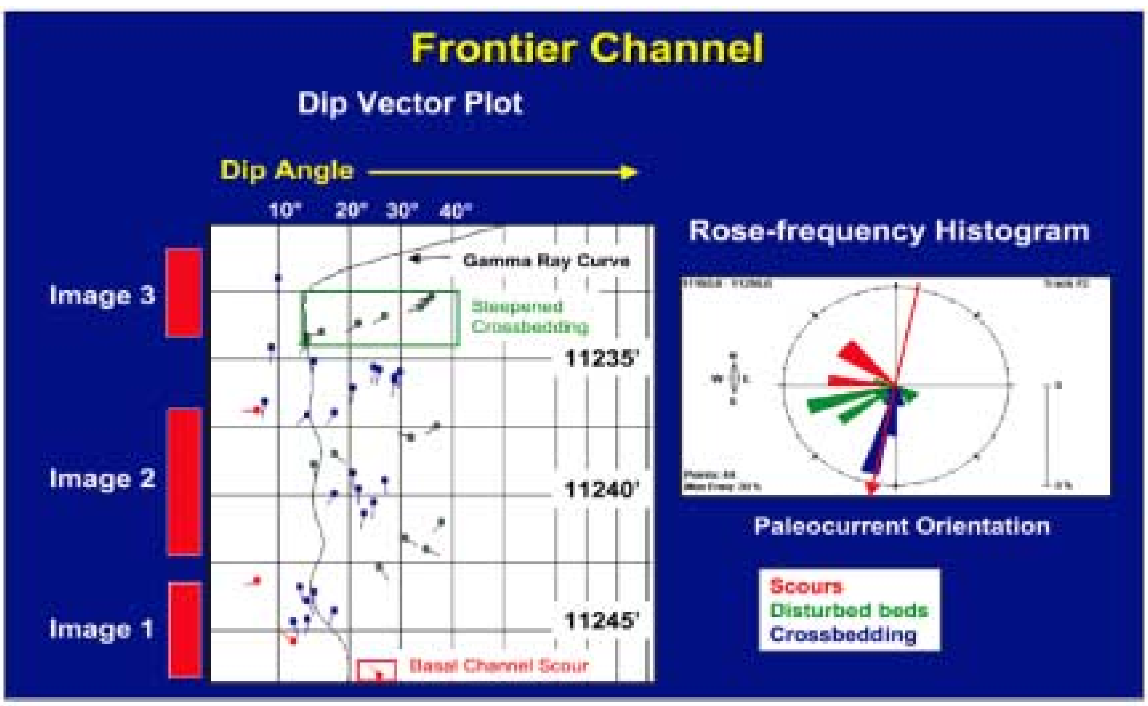

Figure 3. A dip-vector plot and rose frequency diagram illustrate how sedimentary structures are used to interpret sandstone-body geology and paleocurrent flow direction.

Figures 4, 5, and 6 present core and interpreted "dynamic" borehole images of the channel reservoir. Borehole microresistivity data can be displayed as either static or dynamic images. Dynamic images have variable contrast applied to the data in a small moving window in order to show subtle details more clearly.

Dynamic images are presented here because they were found to be more useful for identifying bedding features characterized by a limited resistivity contrast. On borehole images, planar bedding features that intersect the borehole are manifest as sine waves. Sine-wave amplitude is a function of bedding dip, such that steeper bedding dip angles correspond to steeper sine waves.

Figure 4 shows a channel lag deposit overlying a basal channel scour. Referring back to Figure 3, we see that the basal scour dips at an angle of approximately 25 degrees. The pebbly nature of the channel lag is discernable from both the core and the borehole image.

Figure 5 shows an image and core of carbonaceous material, crossbedding and a water-escape feature, all features characteristic of channel facies. In Figure 6, the core photo shows non-planar crossbedding, a channel lag deposit and upper mottled shale. The corresponding borehole image shows steeply dipping crossbeds, a channel scour, an overlying channel lag deposit and mottled shale. The steeply dipping crossbedding is also highlighted on Figure 3.

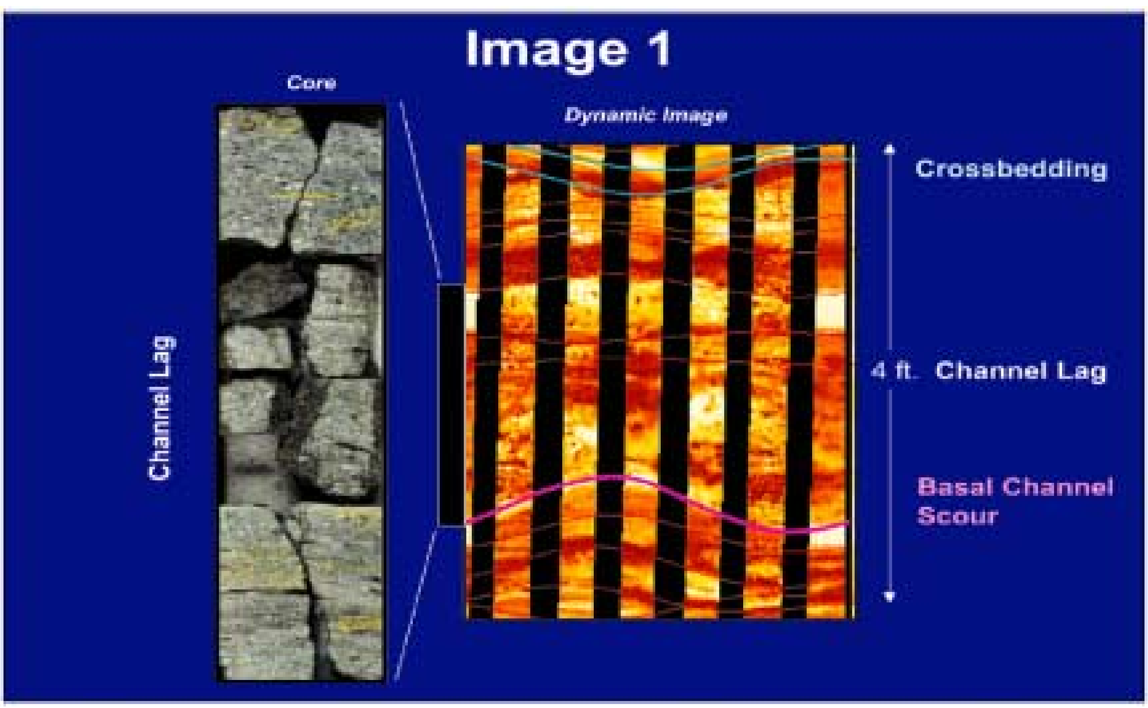

Figure 4. Core and a borehole image of lowermost channel deposits referenced in Figure 3.

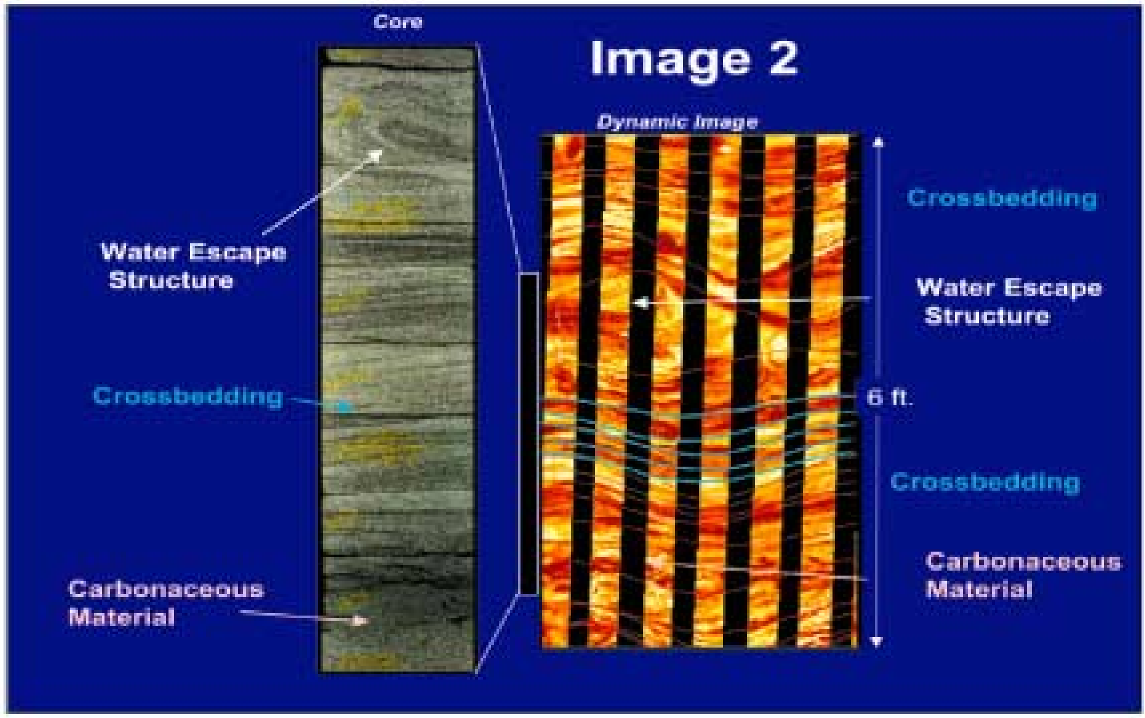

Figure 5. Core and borehole image of middle channel deposits referenced in Figure 3.

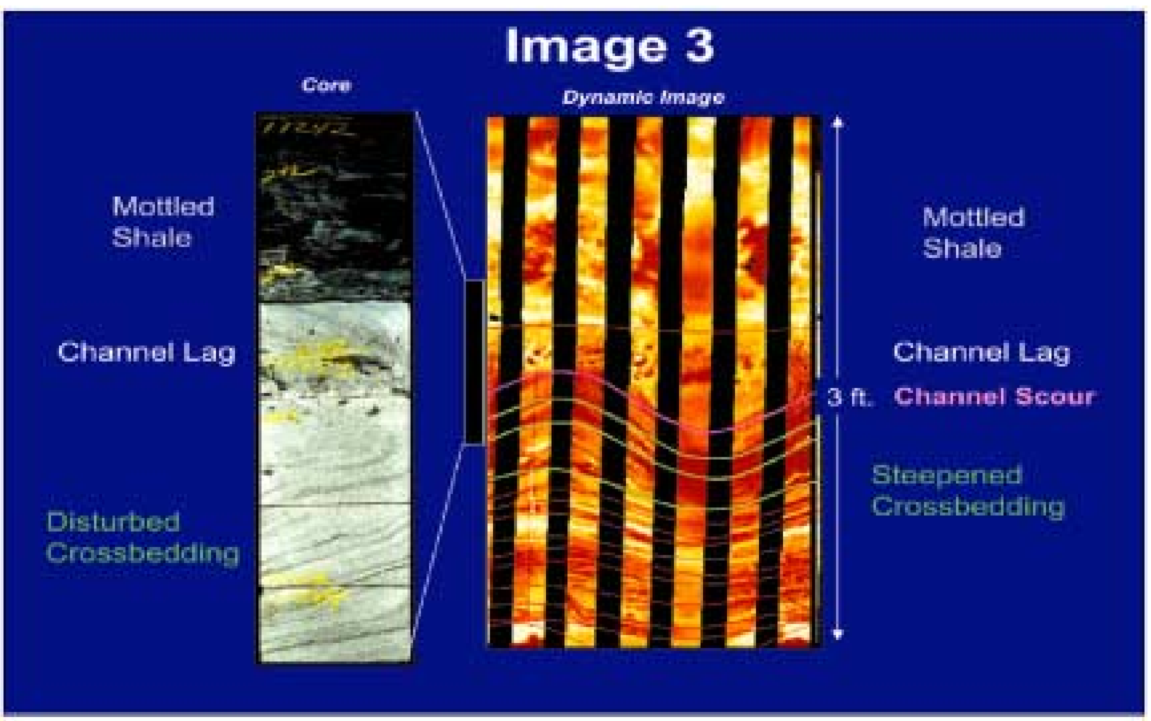

Figure 6. Core and borehole image of upper channel deposits referenced in Figure 3.

Collectively all of these sedimentary structures are used to interpret paleocurrent flow direction -- but crossbedding dips are the best paleocurrent direction indicators. The rose-frequency histogram in Figure 3 shows that crossbeds dip to the south-southwest. Disturbed beds and channel scours dip generally perpendicular to the paleocurrent flow direction. The over-steepened crossbeds referenced earlier, which dip perpendicular to the crossbed dip direction, are interpreted as slumped material from cut-bank failure. In general, a southern paleo-flow direction is interpreted at this location.

Based on outcrop studies and other oriented well data, the overall regional Frontier paleo-flow direction has been interpreted to be from west to east. A southward flowing Frontier channel system at this location is significant, because it may represent an isolated depositional system that is yet not drained by existing development wells. Borehole imagery will be used in this portion of the field to further evaluate reservoir geometry and extent.

Summary

High-resolution borehole imagery can be used to identify sedimentary structures and for defining paleocurrent trends. Sedimentary structures visible in Frontier core are clearly evident on new high-resolution borehole images.

In our case study well, a southerly flow direction is interpreted that predicts an unexpected trend of local Frontier reservoir facies. Interpretation results will help identify future infill drilling locations to improve reservoir drainage.