Small-Scale Geologic Structures within Cedar Hills Red River B Field, Bowman and Slope Counties, North Dakota

by Paul E. Diehl

When most of the attention in the Williston Basin was focused on the record-breaking flow rates of the Lodgepole wells being completed near Dickinson, North Dakota, Burlington Resources Oil and Gas Co. (then Meridian Oil Co.) quietly completed the horizontally drilled discovery well for the Cedar Hills Red River B Field in the far southwest corner of North Dakota in August 1994 (Fig. 1). With little fanfare, Burlington Resources Oil and Gas Co. and Continental Resources, Inc. continued to drill and complete horizontal wells in the Red River B field. Over 200 horizontal wells have been completed thus far, mostly in Bowman County, and drilling continues in what is sure to become, by U.S. definition, a giant oil field. Cumulative oil production from 199 Red River B wells in Cedar Hills Field through September 2001 is over 25 million barrels with an estimated ultimate recovery of 155 million barrels.

Cedar Hills Field is developed in the B interval of porous dolostone within the Ordovician Red River Formation and is almost entirely made up of horizontally drilled wells. In the Cedar Hills area the B porosity interval occurs at an average of 40 feet from the top of the Red River Formation, has a modal thickness of 10 feet, and porosity ranging from about 13 to 23 percent with an average of 18 percent. It is immediately overlain by the thin B anhydrite and overlies a burrowed, non-porous, slightly dolomitic limestone which contains minor amounts of pore-filling anhydrite. The average thickness of the B limestone is 39 feet (Fig 2). Horizontal production from the Red River B continues to the northwest along the flank of the Cedar Creek Anticline into West Cedar Hills and East Lookout Butte Fields of Montana.

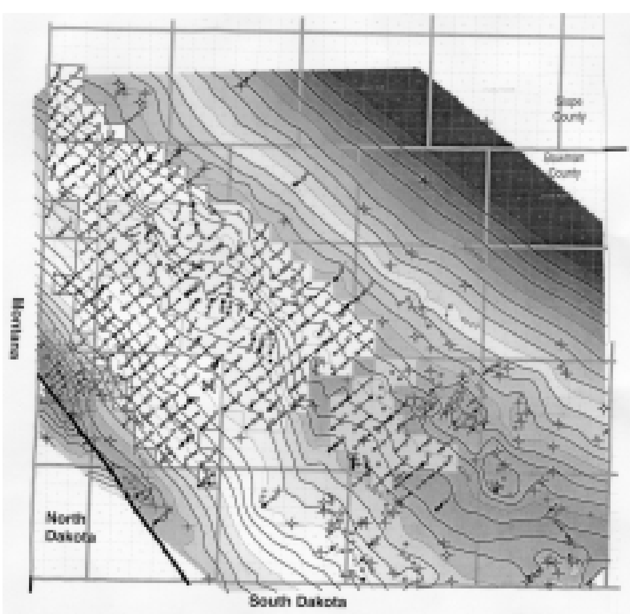

Figure 1. Structure map of the top of Red River B porosity zone showing the area discussed. Contour interval equals 50 feet.

One of several features that attracts attention to the Red River B interval in the Cedar Hills Field is its ability to produce oil in economic quantities from wells located more than 1000 feet down structural dip from the crest of the Cedar Creek Anticline. What controls this oil accumulation on the flank of a major anticline in an area with no significant structural closure has been the subject of many conversations and a few debates. Most geologists would agree that, to some extent, the heterogeneous permeability and down-dip groundwater movement within the B porosity interval is generally responsible for the trapping of commercial quantities of oil in the field. However, cumulative oil production, water-to-oil ratios, and API gravity, show considerable variation

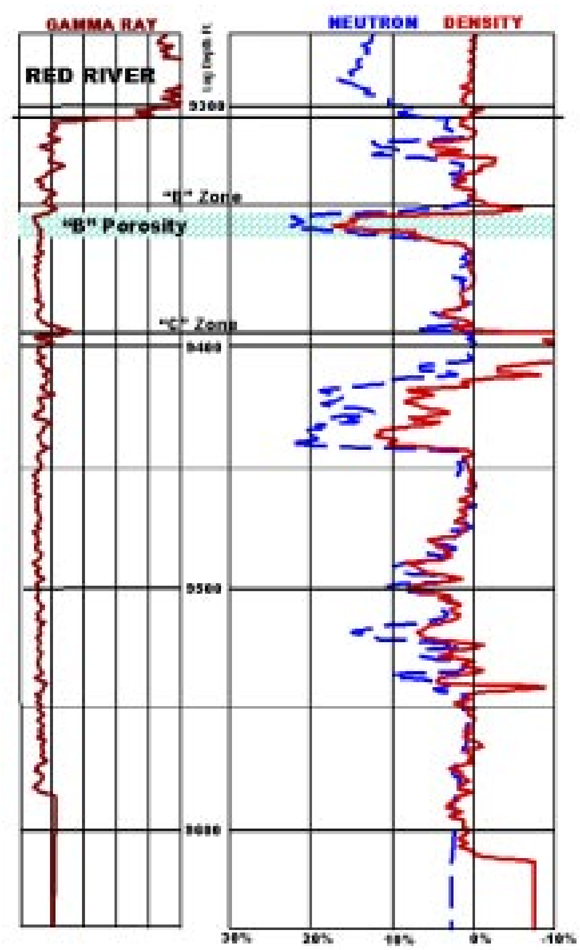

Figure 2. Type log (gamma ray-neutron-density) of the Red River Formation. The B porosity interval is indicated by a tilted-brick pattern.

within the field. All of these variables display a very similar and distinctive pattern. Is there something else, in combination with the varying permeability and hydrodynamic regime, that could influence the pattern seen within the Cedar Hills Field? This question led to the investigation of the small-scale geologic structures within the field. Because the productive B interval is only about 10 feet thick, it seemed reasonable that small folds (dip reversals) and faults could affect the amount of oil and water produced from individual wells within the field. I will provide a few examples of the small-scale geologic structures within the field, some of which are likely to influence the production pattern seen at Cedar Hills.

Geologic structures in the subsurface can be interpreted from well logs. If a borehole is drilled through a fault, the fault can sometimes be recognized on the log from that well. With some specific exceptions, when a vertical wellbore cuts a normal fault, the fault will be indicated on the well log by an interval of missing strata. The amount of missing section is equal to the relative stratigraphic displacement along the fault. If a reverse fault is cut by the wellbore, then part of the rock column affected by the fault will be repeated on the well log. When drilling wells that are intentionally deviated from the vertical, such as in the case of horizontal wells, directional surveys are conducted down hole at regular intervals while drilling. Directional surveys determine the depth measured along the drilled borehole (MD), the true vertical depth from the surface (TVD), the deviation of the borehole from vertical, and the azimuth (compass direction) of the borehole with reference to north. Combining the directional survey information with the rate of penetration (ROP: speed at which the hole is being drilled), the lithology or rock type being drilled as determined from cuttings samples, and the mudlog detection of variations in amount of hydrocarbons in the drilling fluid, geologists familiar with the drilling characteristics and lithology of the formations being penetrated are able to determine the part of the formation in which the hole is being drilled. From these data, a log is plotted that shows the location of the borehole in relation to the targeted formation; in this case the Red River B.

In the remainder of this paper, I will show examples of small–scale structures recognized in the Cedar Hills Field area, including a normal fault cut by a vertical well, a horizontal lateral hole in which a fold has reversed the regional dip on the flank of the Cedar Creek Anticline, a horizontal lateral hole which has cut a normal fault, and a normal fault located in an outcrop of Cretaceous strata southwest of Marmarth, North Dakota.

A vertical well, the Shell Oil Co. Unit 41-13A-39, located in the NE ¼ of the NE ¼ of section 13 Range 130N Township 107W, completed in July 1963, was drilled through a normal fault. When comparing the logs of this well to logs of other wells in the area, careful examination reveals that a 12- to 14-foot interval is missing from the 41-13A-39 log. Figure 3 contains a log from the 41-13A-39 (log A) and a log from the Shell Oil Co. 21-13A-29 well (log B) located about 2500 feet to the west. Notice that the interval from the Stony Mountain Shale to the top of the Red River Formation is about equal in thickness on both logs. However, the interval from the top of the Red River Formation to the C anhydrite is about 15 feet shorter on log A than it is on log B. In this area, the thickness of these intervals is usually very consistent, thus the thickness difference seen by comparing these logs indicates something of geologic significance may have occurred. The difference in thickness might result from thinning of the beds seen on log A (all of the same beds are present in both wells but they are thinner in one well than they are in the other due to change in the depositional setting when these sediments were deposited). Alternatively, the change in thickness could be the result of the elimination of an interval by faulting of strata seen on log A. How can we determine which possibility may be correct? If all the beds are present on both logs but are thinner on log A, we should be able to correlate all the beds on one log to all of those on the other log. If an interval of beds is missing, the logs should correlate except for a normal stratigraphic interval present on the log from the well not faulted that does not exist on the log from the well which penetrated a fault. All the strata above and below the depth where the beds are missing should be recognized on both logs. By carefully matching the gamma ray curves on both logs in Figure 3, one sees that these beds correlate from the

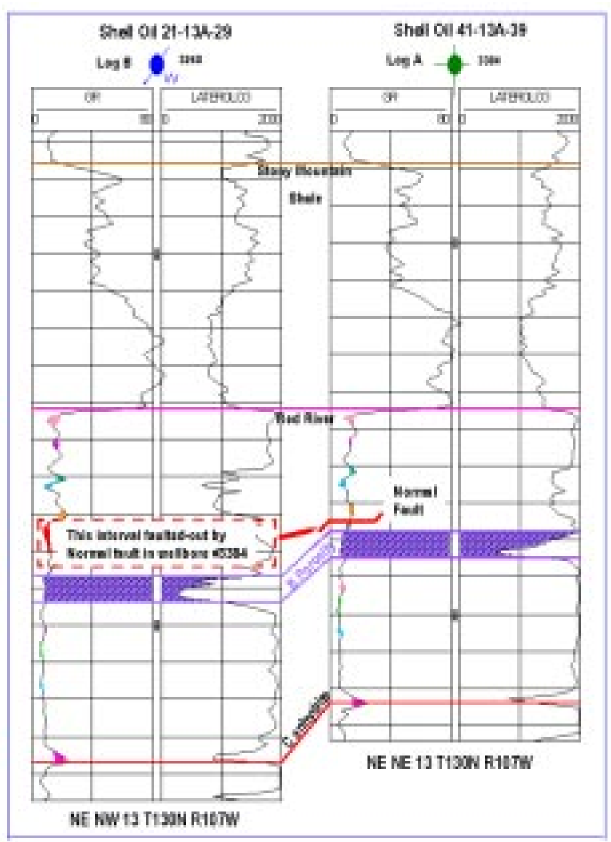

Figure 3. Well logs illustrating a normal fault cut by the wellbore of log A. Dashed-line box on log B indicates the section missing on log A. Stratigraphic displacement is approximately 12 to 14 feet.

top of the Red River Formation down to the line indicating the fault on log A. All the beds from the C anhydrite up to the fault marker correlate as well. However, the beds within the dashed-line box on log B are not present on log A. These missing beds indicate that the log A wellbore has been drilled through a normal fault that has approximately 12 to 14 feet of stratigraphic displacement. The orientation of this fault can not be determined from a single wellbore without the aid of oriented wireline logs. In this case, data from other logs in the area allowed us to determine that the fault has a northeast orientation with displacement down to the southeast.

In section 10 Range 131N Township 106W, the horizontal lateral for the Burlington Resources Oil and Gas Clark 41-10H well (#13987) demonstrates a fold structure in which the regional northeast dip of the strata is reversed to a southwest dip in a part of the lateral. Figure 4 illustrates the path of the wellbore in relation to the measured depth (the numbers across the top of the figure), the true vertical depth (the numbers at the left side of the figure), the Red River B porosity interval (UPR B and LWR B), and the wellbore path. At this location, the Red River B porosity interval is slightly less than 10 feet thick. The lateral was drilled to the southwest climbing up regional northeast dip, as was expected, until it reached about 11,900 feet MD. At that point the porous B beds began dipping to the southwest, opposite the regional dip, until the dip changed back to regional northeast dip at about 12,200 feet. By using the TVD measurements, it can be seen that there are about 17 feet from the top (anticline) to the bottom (syncline) of the dip reversal or "roll over." Hydrocarbons migrating up-dip could be preferentially trapped or concentrated in the anticlinal area of this reversal.

A normal fault was also detected in the laterals of horizontal wells located in sections 24 and 14 Range 131N Township 107W. The fault in section 24, illustrated in Figure 5, can be seen in the lateral hole of the Continental Resources, Inc. Misty 1-24F well (#14017). In addition to the TVD, MD, upper B porosity, and wellbore path as shown on Figure 4, a rate of penetration (ROP) plot is shown across the top of the figure, and a lithology plot is shown across the lower half of the figure. As in the previous example, the lateral hole was drilled in a southwest direction up the regional dip, as illustrated on the left half of the figure. At approximately 10,700 feet MD the wellbore drilled out of the B porosity zone into the low porosity and low permeability (tight) Red River A limestone. Evidence that the borehole left the porous rocks of the B zone is indicated by the decrease in ROP with an accompanying change in lithology of the cuttings samples from B porosity dolomite to that of the A zone limestone. As shown on the lithology log, the wellbore went directly from the B porosity beds into the tight limestone of the A zone. The A limestone occurs immediately above the B anhydrite in the normal vertical stratigraphic sequence. The wellbore did not first drill through the B anhydrite; which would normally be found between the A limestone and the B porosity interval. The hole being located in the A limestone indicated to the wellsite geologists and other persons responsible for steering the hole and keeping it in the B porosity reservoir, that the wellbore quite likely crossed a fault with the southwest side of the fault down-dropped relative to the northeast block. If this interpretation were correct, the B porosity beds should

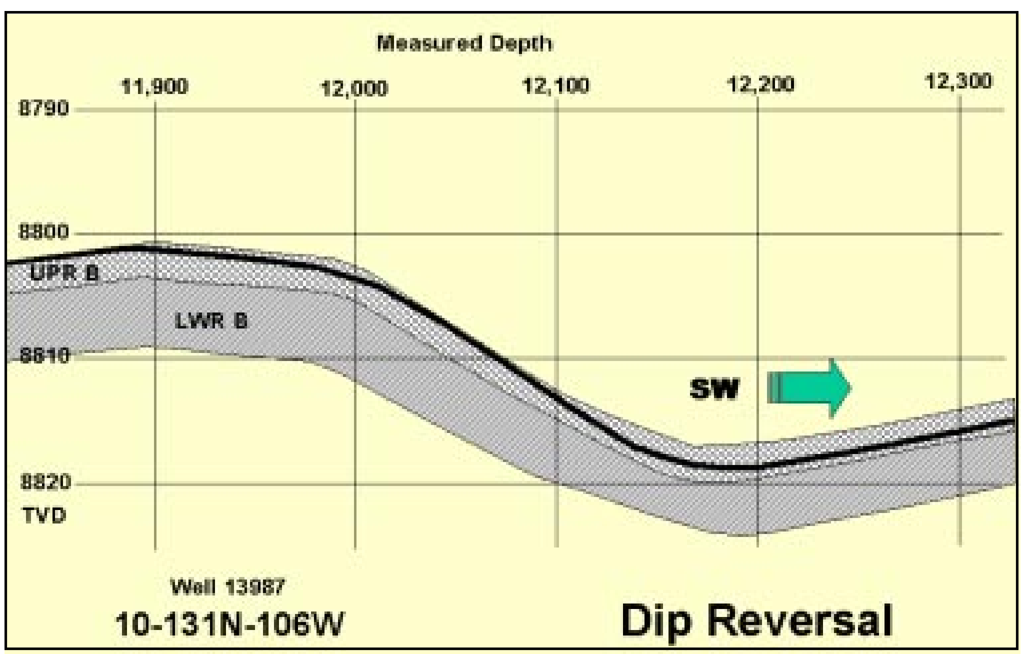

Figure 4. Reversal of dip in the horizontal lateral of the Burlington Resources Oil and Gas Co. Clark 41-10H. Lateral was drilled from the northeast to the southwest, up regional dip. Rollover is approximately 17 feet.

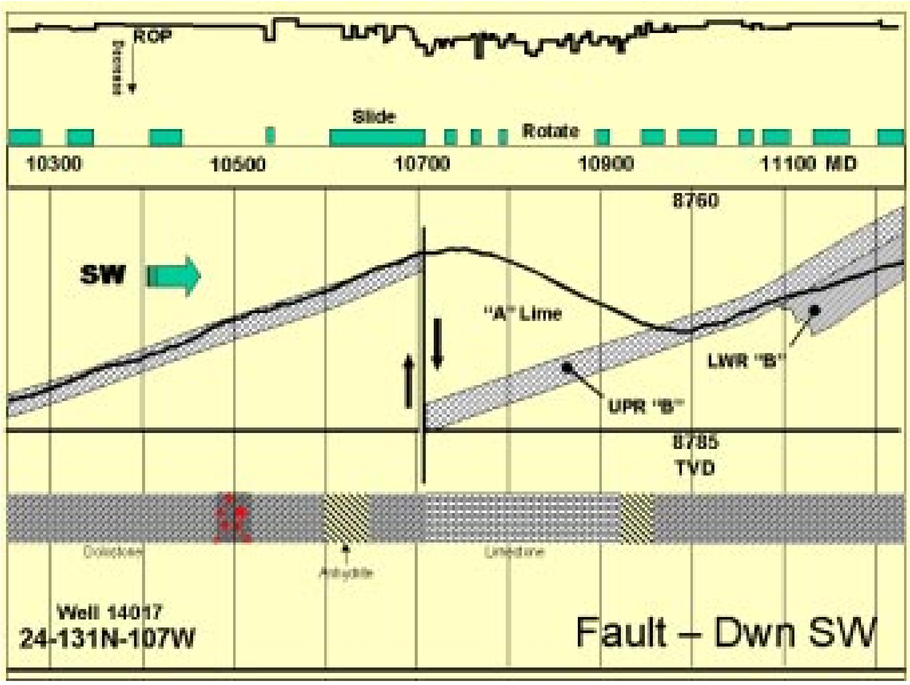

Figure 5. A normal fault in the horizontal lateral of Continental Resources, Inc. Misty 1-24F well. Lateral was drilled up regional dip to the southwest. Stratigraphic displacement is about 16 feet.

again be penetrated by steering the borehole deeper. As is illustrated in Figure 5, the well path was steered downward and the B porosity zone was intersected again at about 10,950 feet MD. After the wellbore entered the B porosity beds, the hole remained in the B porosity zone as it was steered updip to the southwest, indicating the down to the northeast fault interpretation was correct. Displacement on this fault is about 16 feet; enough to block the movement of fluids in the B porosity zone from crossing the fault.

The last example of small-scale geologic structures is a normal fault found in an outcrop of Cretaceous strata (Figure 6) southwest of Marmarth, North Dakota, within the Cedar Hills Field area. The bluff near the center of the photo provides a cross-section view of the fault trace between the two arrows (Figure 6). The fault can be most easily recognized by noting, the down to the left (southwest) offset of the thin darker bed just below the upper of the two arrows. In plan view, the erosion-resistant, iron-rich sandstone preserves the fault plane which can be seen dipping to the southwest within the circle in Figure 6. With the enhancement of the fault plane provided by the iron-rich sediment, the trace of the fault plane can be easily followed for about one-half mile to the southeast. This normal fault strikes 140 degrees and dips 55 to 65 degrees southwest. Stratigraphic displacement on this fault is about 13 feet. Interestingly, the orientation and magnitude of displacement of this surface fault is similar to many of the small-scale structures found in the subsurface within the Cedar Hills Field.

A few examples of the small-scale geologic structures that occur within the Cedar Hills Field, both in outcrop and in the subsurface, have been illustrated in this article. In some instances it can be shown that these subsurface features affected and may still be affecting the movement of oil and water through the Red River B reservoir. Although structures of this scale are probably not responsible for the existence of the field, it is likely that they do influence where the better, as well as the poorer quality, Red River B wells are found within the Cedar Hills Field.

Figure 6. Photograph of faulting in Cretaceous strata southwest of Marmarth, North Dakota. Sectional view of the fault trace is exposed on the side of the bluff (between arrows). The fault plane is seen in relief within the circle.