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Unusual Natural Fracture Styles in the Lower Banff Formation Monarch Area, Southern Alberta

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Introduction

Recent big-dollar Crown land sales in southern Alberta have been attributed to the “Alberta Basin Bakken” play. This play apparently includes Devonian through Mississippian Big Valley, Exshaw and lower Banff strata; however, the majority of interesting historical oil shows occurred upon testing of naturally fractured deep-water Banff carbonates. Fracturing in these dark, siliceous mudstones to grainstones is dominated, in many wells, by an unusual style with secondary shears and extension fractures developed between closely spaced bedding parallel slickensided surfaces (slickensurfaces). Cores display great variation in the vertical frequency of slickensurfaces and intensity of associated fracturing. The mechanical origin of these bedding parallel faults is enigmatic, but may be constrained by the probable timing of fracture fill cements that include a pervasive solid bitumen phase.

Brief Geology of Exshaw-Banff Interval in Monarch Area

Figure 1 shows the study area, located approximately 80 km east of known involvement of Devonian-Mississippian strata in the “deformed belt”. Monarch is situated on the west flank of the Sweetgrass arch and displays a moderate westward dip interrupted by a series of northwest trending normal faults (Lemieux, 1999). Figure 1 displays interpreted faults derived from a map of structure on the top of Mississippian.

A regional depositional model for the Exshaw through Banff is well established (Richards, et al., 1999). Very briefly, following late Devonian emergence, the area was blanketed by marine organic shales of the Exshaw (= Bakken). The water depth during deposition of these shales is still debated but the overlying Banff is uniformly regarded as deep water with turbiditic facies including cross-bedded grainstones and siliceous spiculites and characterized by inferred slope failure scars and probable Waulsortian mounds. “Clinoforms” are documented in the Banff interval both seismically and through log correlations but no detailed published studies of the Monarch area could be found. Documentation of such is well beyond the scope of this paper but we found (via seismic and well log correlation) south dipping clinoforms in the Monarch area (and beyond). Figure 2 shows many of the cored wells used in this study positioned in a semi-schematic depositional dip section.

Interpretation of the Banff lithologies using a binocular microscope on slabbed or unslabbed core is very difficult due to a general dull, dark coloration and the presence of artifacts ranging from surface glaze to years of acid etching by geologists. We utilized some 55 thin sections to aid in logging and concluded that the Banff in this area consists of interbedded turbiditic and pelagic beds. Principal lithofacies are indicated on Figure 4. While slickensided surfaces and associated fractures are seen in many of the lithofacies, the details of fracture geometry do appear to be lithology dependent.

Banff Oil Shows in Monarch Area

Figure 1 highlights drill stem and production test shows of oil in the study area. The crude is generally sour, around 30 degree API, and of variable but high pour point. Completion reports for all wells were obtained from the ERCB and the following generalizations can be drawn:

- Reservoirs are generally overpressured;
- DST's commonly exhibit characteristics typical of "depletion";
- Production tests may show high initial rates but also evidence of rapid depletion; and
- Stimulations include acid fracs and propped gelled oil fracs of up to 100 tonne.

The best Banff producer in the area is 1-18-9-24 W4M. This well was put on production without stimulation after a shallow penetrating completion and went on to produce 31,000 bbls of oil. Most wells have produced much less. These characteristics are suggestive of a purely fractured reservoir with limited fracture volume or poor fracture connectivity.

Natural Fractures

During initial logging of these cores, natural fractures were described as chaotic with orientations varying from near vertical to near horizontal and, generally, of limited height. A dead oil stain was commonly observed, implying a certain extant fracture porosity even though much of the total fracture volume was seen to be infilled by calcite spar.

The cores were re-examined, mainly to clarify bulk lithofacies via thin section, but also to capture more detail regarding geometry of the fractures. It was at this point that the bedding-parallel slickensides were seen to be intimately related to the fractures and a probable shear origin for many of the fractures hypothesized. As shown on Figures 5 and 7, slickensided surfaces are planar to undulose and ornamented by patchy to linear calcite spar reflecting intersection with tension or shear fractures. Commonly, mineralization appears to nearly parallel a slickensurface, possibly due to shears intersecting at very low angle. Slickenfibers were not observed.

There is a vast literature regarding fracturing in simple shear, much of it related to secondary shears in strike slip faults and in clay models of deforming cover above a strike slip fault (the so-called Riedel experiment). However, "Riedel arrays" are also noted in triaxial rock mechanics experiments, normal fault shear zones, and thrust fault shear zones. As per Arboleya and Engelder (1995), the proper notation of the various components of the Riedel array in the latter cases is shown in Figure 3. Very briefly, R1 and P are synthetic shears. R2 is an antithetic shear and T is an extension fracture. Y is a parallel shear usually seen in later stages of bulk strain. R2 and T are enhanced in dilative situations. We propose that much of the fracturing in the Banff at Monarch has resulted from movement on widely to closely spaced bedding parallel faults which has induced secondary shearing in the intervening slivers.
Figure 2 (gamma ray log section) highlights intervals with observed slickensurfaces and associated fracturing in the Monarch area. Figure 4 displays details in two wells: 16-35-9-24 W4M and 16-23-9-26 W4M. Figures 5, 6 and 7 contain core and thin section photos from these two wells.

Figure 5 displays examples of probable conjugate shears (R1 and R2) in hand sample and in thin section in massive, silty, bituminous marl. Note the fractures infilled with solid bitumen. These have the appearance of "pennant veins" (Coelho, et al., 2006) which form through continued deformation of sheared material.

Together with the presence of compacted earliest fractures, these observations are suggestive of a relatively ductile style of fracturing.

Figure 6 is an overview of a mainly grain-supported interval in 16-23-9-26 W4M exhibiting an extremely high density of slickensurfaces (not visible in the photo but up to 12 per box were observed). Note the common spar-filled en echelon fractures, which may terminate without thickness change at a slickensurface. These fractures may be (T) extension fractures that formed between initially widely spaced bedding plane faults and that were later broken as new (Y) shears evolved. Images in Figure 7 suggest that there may be a complex mix of different Riedel components within grainy intervals, including conjugate (R1 and R2) shears. Inferred synthetic (R1 and P) shears intersect slickensurfaces at a very low angle. In contrast to the bituminous marls, en echelon tension fractures may suggest a more brittle style of fracturing.

To summarize, in Monarch area Banff cores, natural fractures are commonly related to shearing between bedding plane (horizontal) faults. Details of fracture geometry appear to be controlled by lithofacies but all share a common cementation history: 1) calcite spar, 2) solid bitumen, 3) isotropic silica. The latest stage silica cement clearly indicates the bitumen was solid in-situ and that degradation of an earlier oil reservoir has dramatically reduced current fracture pore volume. Evidence of open fracture porosity is very limited in thin section and caution is indicated when interpreting porosity on core surfaces where the weak solid bitumen washes out.

Origins of Bedding Plane Faults

Based on a working knowledge of this area, we propose the following list of possible mechanisms capable of generating bedding plane faults in the Banff Fm.

1. Very early, (almost syndepositional) slumping in front of the prograding shelf margin.
2. Very early (again almost syndepositional) collapse above pre-Big Valley paleo-caves known to exist within the Stettler Formation in this area.
3. Extension of blind, Laramide-age thrusts east into Monarch area.
4. Laramide-age normal faults that have been documented in the Monarch area (Figure 1).

Number 1 (above) is an appealing solution as it could easily explain the widespread nature of the fracturing. However, it and Number 2 would seem to be precluded by the abundant solid bitumen, which suggests the fractures were open during post-Laramide oil generation. Number 3 is unlikely given the distance from the deformed belt, which leaves mechanism Number 4. Withjack, et al. (1990) present results of a modelling study wherein, with appropriate detachment surfaces built in, a forced fold above a basement fault requires a certain amount of bedding plane slip. This reference suggests the amount of slip (and hence subsidiary fracturing?) may vary across the structure in a predictable way. Thus, in the Monarch area, the key to finding economic fracture volumes may be to understand the normal faults. Figure 2 suggests that shear-related fractures may be most strongly developed in the basal Banff where bituminous marls (including the "Exshaw") offer potential detachment surfaces.

Acknowledgements

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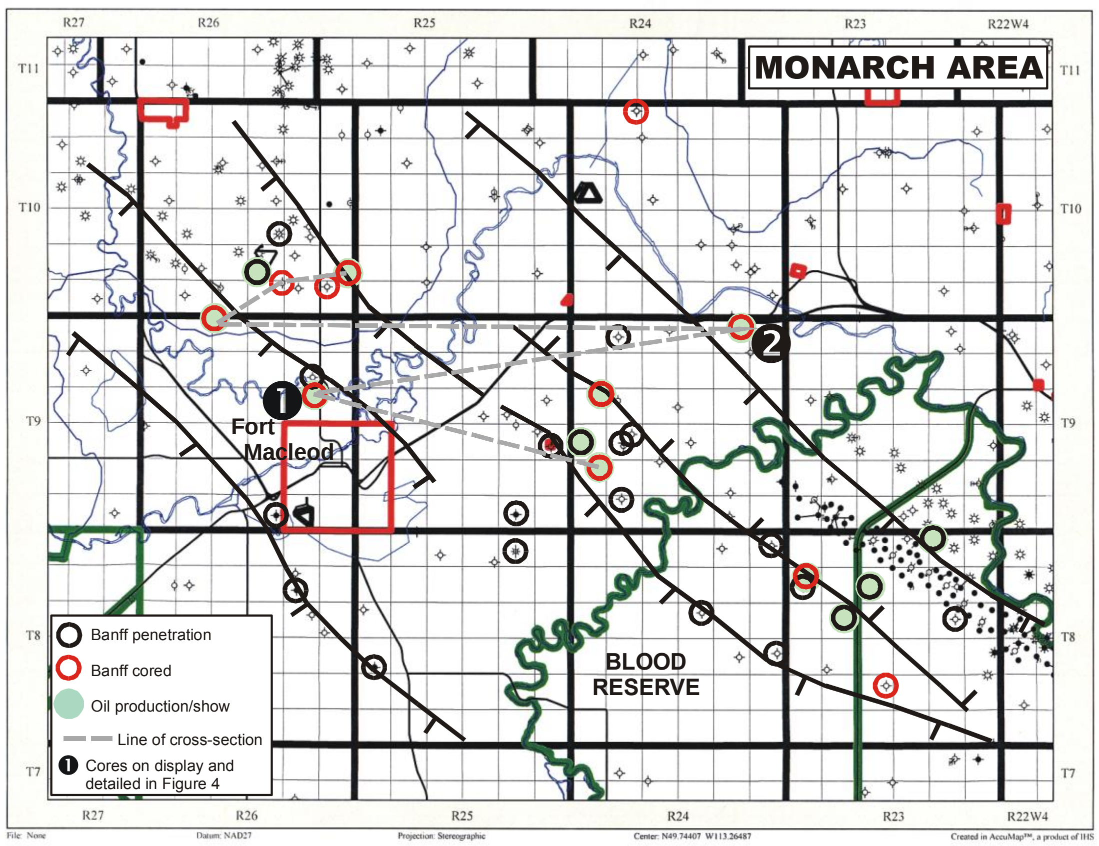


FIGURE 1. Index map.

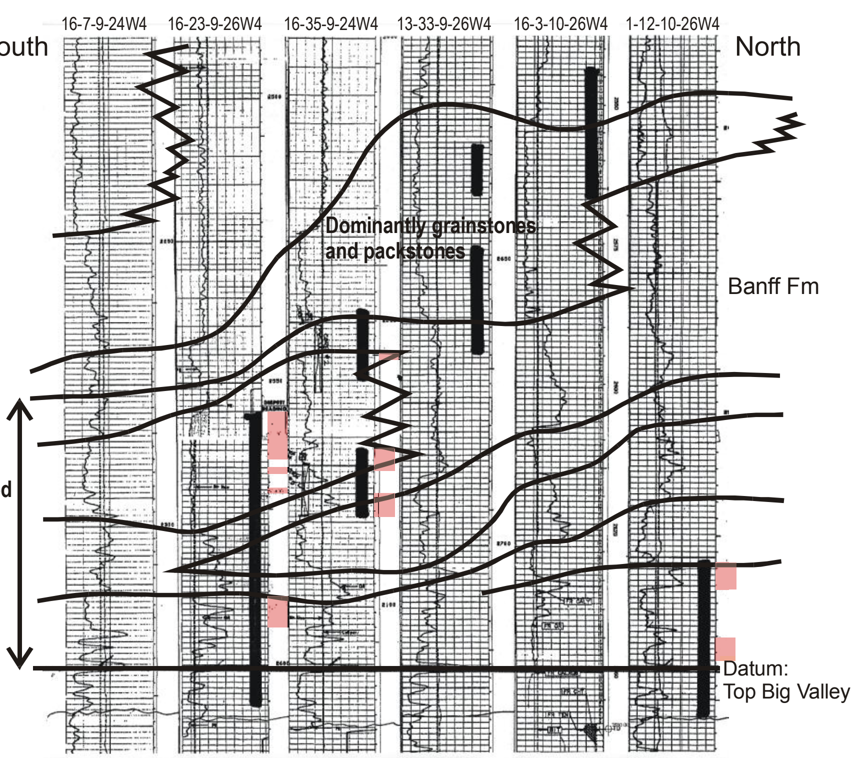


FIGURE 2. Gamma Ray cross-section. Depositional dip section of cored wells showing apparent clinoforms.

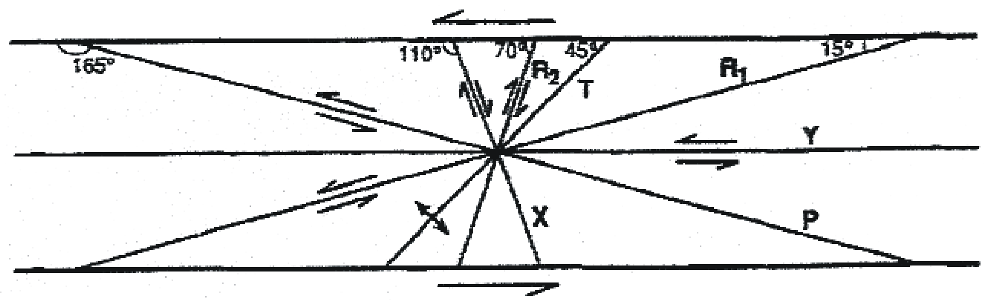


FIGURE 3. Schematic of Riedel shear array, with annotations for triaxial stress (from Arboleya and Engelder, 1995).

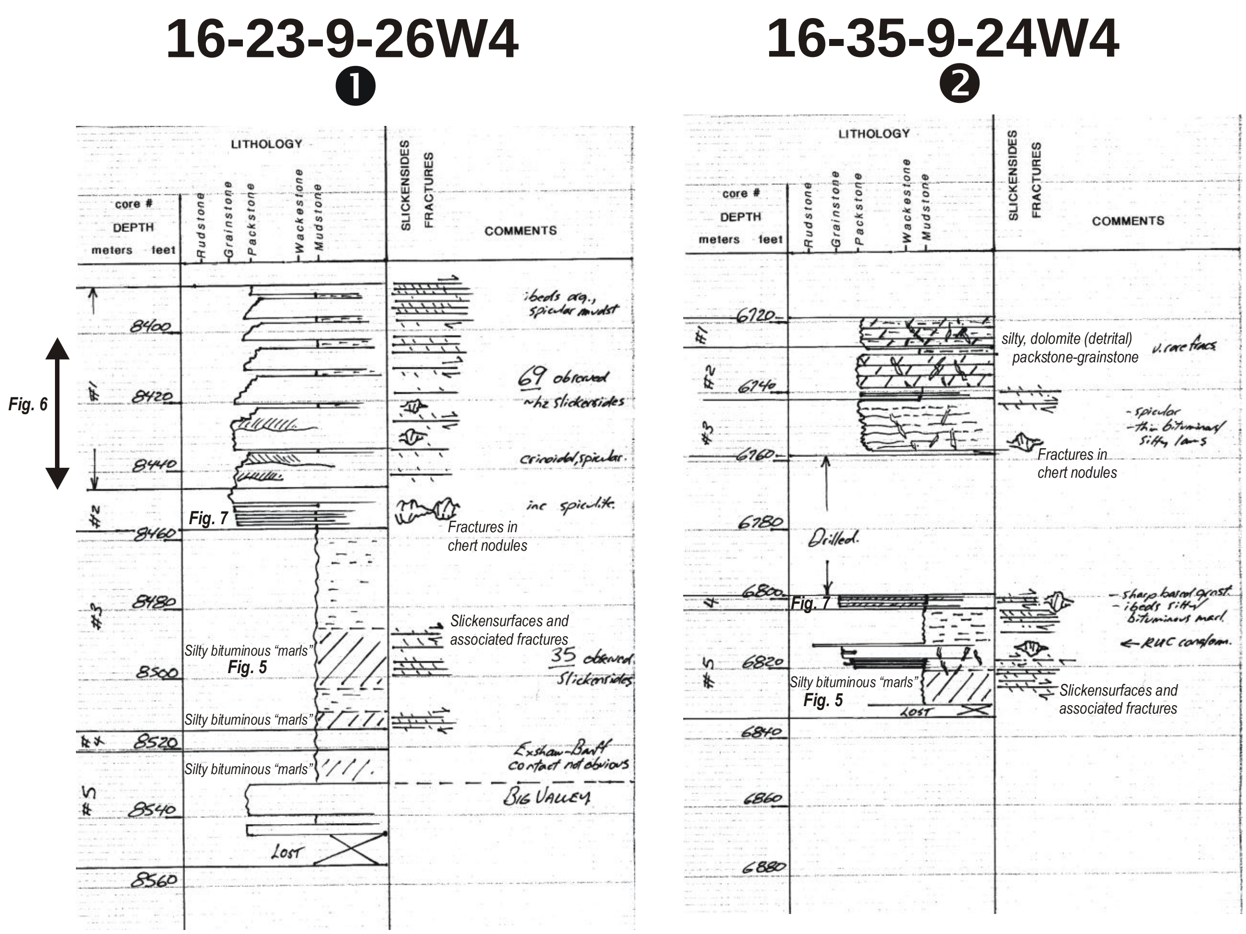
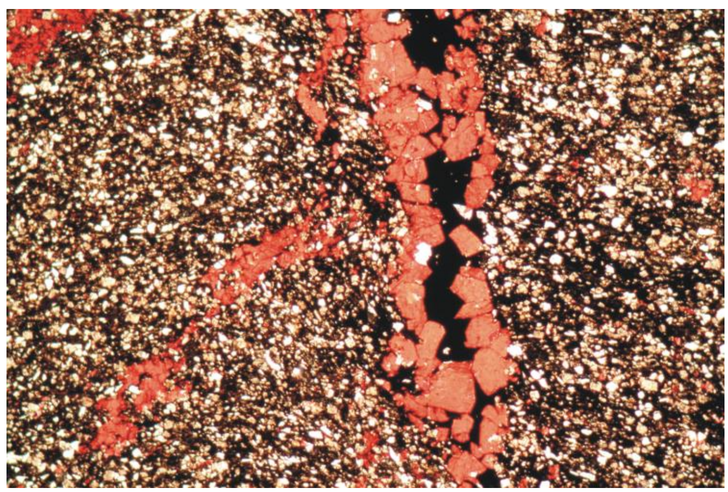


FIGURE 4. Descriptions of two Banff cores containing examples of concentrated slickensurfaces and associated secondary fracture development.

Three views of probable conjugate shears at 6826 ft (2080.7m) in 16-35-9-24W4.



Thin-section image of fracture-fill phases at 8496.7 ft (2589.84m) in 16-23-9-26W4. Plain light at 25X magnification.

FIGURE 5. Examples of slickensides and fractures in the silty bituminous marls of the Lower Banff Formation

FIGURE 6. Overview of a portion of Core 1 (see Fig. 2) in 16-23-9-26W4. Note frequent, wide calcite-cemented en echelon tension fractures. Slickensides are not visible in this plate, but up to 12 per box were documented.

16-35-9-24W4 ~2073m
Possible conjugate shears?

16-35-9-24W4 ~2073m Mineralization intersecting slickensurface at very low angle - possible shear?

16-23-9-26W4 2581.3m Tension fracture terminating abruptly at slickensurface.

16-23-9-26W4W4 2560.4m
En echelon tension fractures?

Figure 7. Examples of slickensides, fractures and fracture cement fills in the "grainy" (packstone-grainstone) facies of the Lower Banff Formation. In contrast to the bituminous marly facies (Fig. 5), many of these appear to be simple en echelon tension fractures, although there are possible examples of conjugate shear fractures.