Fracture Systems in Folded and Faulted Carbonates: Surface and Subsurface Case Studies

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The Foothills and Front Ranges of western Canada provide an ideal natural laboratory for studying the character and distribution of fractures as a function of bed thickness, lithofacies, diagenetic versus tectonic vein-filling processes, and positions around folds and within thrust sheets in outcrops, cores, and image logs. The quantification of these controls on fracture length distribution, orientation, occlusion, density and spatial heterogeneity is required to accurately predict well performance in fractured reservoirs and provides insight into how the overall structure was initiated and developed over time.

In the case study areas described below, orientations of fractures, fold axes, bedding surfaces, stylolites, veins, and faults were measured and the lithologic, diagenetic and textural character of the rocks were determined. Fractures were characterized according to filling material, aperture, spacing and, where possible, trace length and outcrop-scale connectivity. Trace lengths, spacings, densities and intensities were determined using scanline or circle-window techniques. Orientation data were then analyzed to identify the main fracture sets in their present day configurations and relative to horizontal bedding (pre-folding). Corrections to the data included length weighting and removal of sample orientation bias. Orientation diagrams were compared to lineaments on air photographs, aeromagnetic and gravity data to identify possible deep-seated features that may have affected fracture development.

Livingstone Formation in the Foothills of Southwestern Alberta

Mississippian limestones are exposed in an east-verging anticline with an overturned forelimb in the hanging wall of the Turtle Mountain Thrust in Crowsnest Pass. As part of the Turtle Mountain Monitoring Project, a 61.3 m deep borehole was drilled on top of Turtle Mountain, 100 m from the

Frank Slide surface, and digital televiewer images were acquired to determine the nature and orientation of discontinuities beneath the surface. The goal was to identify fractures that potentially connect to the large open cracks observed at surface and statistically analyze the fracture population to determine which orientations are most likely to be involved in future mass wasting events. In the process, it was also possible to distinguish sets related to folding and faulting, and sets that remain open due to gravitational effects or *in situ* stresses.

Bedding was consistently oriented over the logged interval, with a mean dip direction and dip of 294°/37°, indicating that the borehole intersected only the west-dipping limb of the Turtle Mountain Anticline.

Several large open fractures with apertures of more than 1 cm are seen in the image logs and are potentially long enough (Vermilye and Scholz, 1995) to connect to fractures observed at the surface. The most frequent dip directions of the major fractures are to the northeast (toward the Frank Slide surface) and east, and most of the dips are steeper than 60°. One major fracture dips WNW, subparallel to bedding; another dips south along the ridge. 151 other fracture surfaces, with apertures <1 cm (commonly ≤1 mm), were also identified and measured in the image logs. Their orientations are more variable, but the larger sample size provides more statistically valid results. The three most frequently encountered orientations dip WNW (subparallel to bedding), ESE and ENE.

As the 40.5 m long borehole logs sampled only a limited portion of Turtle Mountain, the results were compared to surface data to determine that they are representative of a wider area than the borehole itself. Comparing the surface data to the borehole data indicates that the three most frequent orientations in both datasets are the NW-dipping steeper-than-bedding set, the set dipping steeply NE toward the Frank Slide surface, and the set that dips ~30°SE. The two main differences between the plots are: a) the lack of vertical beds measured in the borehole due to the low probability of intersecting surfaces sub-parallel to the borehole, and b) fewer azimuths represented in the surface data, which may be due to human bias, the tendancy to look for patterns and sets rather than measuring every orientation.

Fractures and cracks measured in outcrops on Turtle Mountain include Stearns' (1967) Type 1 and Type 2 extension and shear fractures, but several additional sets are observed. The variety is likely due to Turtle Mountain's position in the middle of the Crowsnest Deflection where surface structures trend N-S to the north and NW-SE to the south of the deflection, within the Vulcan Low on the aeromagnetic map of basement, and in an area of uncompensated topography on the isostatic residual gravity anomaly map. Type 1 dextral shears and Type 2 extension fractures are the most abundant, and there are significant numbers of fractures perpendicular to the local fold axis (*ac* fractures) and others sub-parallel to local bedding.

Turner Valley Formation in the Central Foothills of Alberta

Four main fracture sets oriented NE-SW, NW-SE, N-S and E-W are observed in outcrops and subsurface cores and image logs of Mississippian dolostones in the Foothills of central Alberta near Nordegg. They are present in all parts of the fault-bend and fault-propagation folds studied: the backlimbs, crests and forelimbs. The NW-SE (Stearns' Type 2) set is best developed in steep forelimbs, but the most open and abundant fractures in all structures studied are approximately perpendicular to bedding and strike NE-SW (Stearns' Type 1 fractures). Cross-cutting relationships indicate that the N-S fracture set is the oldest, followed by the NE-SW and NW-SE sets that developed simultaneously and show several stages of fracturing; the E-W trend appears to be the youngest. At surface the Elkton Member of the Turner Valley Formation had the lowest fracture densities and intensities, but in the subsurface it is more fractured than the Upper Porous and Middle Dense members (Baumeister, 2005).

Ksituan Member of the Belloy Formation in Monkman Pass, Northeast British Columbia

The Ksituan Member of the Pennsylvanian-Permian Belloy Formation contains three main lithofacies: dolomudstones, dolowackestones and dolopackstones. Out of the three studied, the dolowackestones have the best reservoir quality due to the interaction of fractures and matrix porosity, followed by the dolomudstone and dolopackstone lithofacies (Feltham, 2005).

Six main fracture orientations are observed at all fold positions in outcrop and subsurface data. The two dominant fracture orientations are orthogonal and directly related to *in situ* principal stresses that are slightly oblique to the structural trend of the area. The second most dominant sets consist of Stearns' regional Type 1 and fold-related Type 2 fractures. The remaining two sets have been interpreted as fractures related to a paleo-stress regime, perhaps basement normal faulting.

An optimal drilling direction can be determined through the use of occurrence (Joubert, 1998) and should target the crest of the structure at an orientation perpendicular to the regional compressive stress direction.

References

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