Fractures in the Cardium and Normal Faults in Western Alberta

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Summary

Wrench-, reverse-, and normal fractures, are observed in outcrop of Cardium sandstones in Western Alberta. Kinematic indicators, fracture orientation and fracture morphology are used to determine the stress regime, timing and tectonic domains in which these fractures form. The strain expressed by the “orthogonal set” is compared to large scale stress fields, resulting faults and sedimentation patterns in the Alberta basin and the B.C. Cordillera.

Introduction

The proto-Pacific margin of the southern Canadian Rockies may have been formed as an extensional rift margin during the Precambrian to Cambrian (Bond and Kominz, 1984; Hansen et al., 1993). Rifting was succeeded by a period of contraction during the Antler orogeny (Brown, 1988), during which some neo-proterozoic normal faults inverted (Root, 2001). SW-NE contraction culminated in the Laramide orogeny, which resulted in km-scale reverse faults (Bally et al., 1966; Monger and Price, 1979; Price, 1981). A long history of convergence was interupted from about 50-20Ma ago during the Eocene, when NE-SW extension caused thermal collapse and normal faulting of the Cordillera (Price, 1965; Brown, 1981), after which the current compressive stress field was re-established (Constenius, 1996; Madsen, 2006). Because of this protracted tectonic history dominated by SW-NE compression, despite significant wrench component (Monger and Price, 1979), the prevailing mode I fracture direction in the Rocky Mountains of Canada and the West Central Alberta Basin is predicted to be SW-NE, which is confirmed by e.g. fractures in outcrop, core and borehole break-out data (Bell and Gough, 1979). The observation of sub-vertical SE-NW trending faults and fractures, at right angles (orthogonal) to the prevailing maximum horizontal stress direction ($S_H$max) is therefore, when not related to local extension during folding (Currie and Reik, 1977), remarkable.

Fractures in Cardium sandstone along the Bow and Ram Rivers

It was noted that some drill cuttings are covered on at least 2 sides with euhedral crystal druse. Parallel fracture surfaces are sometimes spaced at less than 1/3rd of a millimeter apart. These closely spaced open fracture surfaces inspired some work on druse coated fractures in the field. The Mohr circle and its failure envelope prescribe that fractures form either as a conjugate shear set, which form at an angle less then 45˚(~30°) to the maximum principal stress direction ($S_H$max), or normal to the minimum pricipal stress direction $S_H$min. 10km of Cardium outcrops straddle the Bow river in a SW-NE direction. They contain wrench-, reverse- and normal sets of fractures, representing all three Andersonian stress fields (Anderson, 1951; pp. 14-17). A conjugate set of vertical wrench shear fractures (Fig. 1; red) and a single vertical set of extensional fractures occupy two separate domains in the SW (7km) and the NE (3km) part of the outcrops, respectively (Muecke and Charlesworth, 1966). These 2 domains do not show significant differences in structure or stratigraphy. The shear fractures form a conjugate set with a dihedral angle, symetrically distributed around the maximum horizontal stress ($S_H$max) direction, i.e. parallel to the direction of thrusting and perpendicular to the fold axes. The dihedral angle fluctuates by up to 27° between stations, and decreases from 72° in the SW to 32° in the NE, where the angle disappears and a single, SW-NE trending, extensional set exists (Muecke and Charlesworth, 1966). This suggests that this shear set is conjugate and was formed in a single event, and not during two separate events.

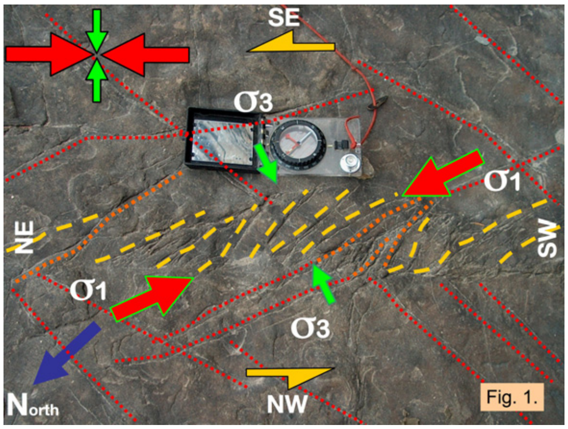

Figure 1, left: Mapview along strike of dm wide simple shear zone (sinistral / Riedel, yellow), striking as the bisectrix of the conjugate set of subvertical shear fractures (red). At least one of the conjugate sets abuts against the sinistral shear zone.

Figure 2, right: Vertical face view of a sub-vertical SE-NW striking hybrid (shear and extensional) fracture. Alternating dark domains of coated euhedral quartz druse and light vertically lineated slickenside, give the fracture face a mixed patchy to zebraesque appearance. Bedding dips 12° in the direction of view, which is southwest.

In the SW, 5 sets of vertical Riedel shear zones, at 6m spacing, form dm wide zones of open, druse coated, en echelon (sinistral) fractures (Fig. 1; yellow). The Riedel zones strike NW at 50°, sub-parallel to the bisectrix of the shear fractures ($S_H$max), and all show an anticlockwise sense of shear (Fig. 1). Several reverse faults, coated by a whitish striated slickenside, cut the outcrops and strike SE-NW, parallel to the trend of the mountains and dip at 10 to 30° SW. Striations on the slickensided surface trend SW-NE, in the direction of transport. Furthermore, a group of strike-parallel fractures and joints, oriented perpendicular to bedding and dipping steeply, strike parallel to the trend of the mountains (SE-NW). Most strike fractures have a textureless to plumose surface which is often coated by microscopic quartz druse. 7% of these fractures have slickensides with striations which all plunge subvertically. There is a conjugate set of wrench fractures symetrically disposed around the strike fractures, oriented at less then 30° angles with respect to vertical. These fractures may show a hybrid topography of alternating opening mode (euhedral quartz druse) and shear mode surfaces (lineated slickenside) (Fig. 2), similar to those observed in experiments on Carrara Marble (Ramsey and Chester, 2004; Rodrigues, 2005).

All wrench group of fractures carry slickensides with lineations parallel to the trace of bedding. Fracture orientation and kinematic indicators suggest wrench and extensional fractures were formed while the principal stress ($\sigma 1$) and minimum stress ($\sigma 3$) were horizontal, and the overburden stress was $\sigma 2$ (Muecke & Charlesworth, 1966; Fig. 7a). Within a thrust regime this condition is met at depth, e.g. in the footwall of a thrust or below an increased sedimentary pile in front of a thrust (Price and Cosgrove, 1990). A pre- to syn orogenic timing for wrench type fractures is furthermore arrived at by dating wrench fractures relative to folding (Barton, 1983). Deep shear to extensional fracturing is corroborated by fluid inclusion work on the Cardium in Ram River (Currie and Nwachukwu, 1974), the presence of pyrobitumen in shear fractures, and the observation of horizontal lineated shear fractures at 4km depth in core and vertical extensional fractures trending parallel to $S_H$max at depths of 2 to 3km. These are present depths below surface, and represent a minimum paleodepth of fracturing. However, because they display little lateral displacement, and in this case, occur associated with extensional fractures, the shear fractures are generally assumed to be a shallow feature formed by decompression during or after uplift and erosion (Muehlberger, 1961; Muecke & Charlesworth, 1966). However, it is now acknowledged that fluid pressures change the stresses in the crust to effective stresses, thus allowing extensional fractures to form at depth (Secor, 1965; Gretener, 1972; Cosgrove, 1995). High pore pressures can be achieved by telescoping of km scale thrust sheets (Hubbert and Rubey, 1959; Gretener, 1981), like the McConnell sheet just miles away to the west. The McConnell thrust moved over the dewatering Blairmore and Wapiabi shales and it is between these that the Cardium is situated. In conclusion, the above points towards a deep pre- to syn thrust timing for the generation of both these shear and extensional fractures, rather then them being of a shallow neo-tectonic origin.

Normal group fractures show steeply pitching slickenside striations. Relating the accute bisectrix of the conjugate set of normal fracures to the principal stress axes (Anderson, 1951), suggests that these were formed while $\sigma 1$ was the overburden stress, and that the SW-NE directed stress, formerly $\sigma 1$, had decreased to become $\sigma 3$ (Muecke & Charlesworth, 1966; Fig. 7b). This means that either, they are related to a different stress field then the shear fractures, or they could be anti- or syncline crest normal fractures. According to Currie and Reik (1977) the orientation of the normal sets is regional, and therefore not related to local folding. Moreover, normal type fractures strike parallel to normal faults in the region and normal fractures and faults cut through, and are therefore younger than exposed small-scale Laramide thrusts (Barton, 1983). In contrast to outward rotation of the fracture plane, as observed on joints in the Monkshood anticline (Jamison, 1997), the bisector of the hybrid normal fracture set rotates slightly opposite, towards the vertical. This all suggests that normal type fractures may not be formed by anti- or syncline crest fracturing (outer arc), but rather that they were formed by regional, NE-SW directed, horizontal extension (Price, 1965) after thrusting and folding. Kinematic indicators, geometry and intersection relationships suggest that shear fractures formed first, before the reverse faults and normal fractures formed last, after the reverse faults. Despite this kinematic analysis it is still not possible to rule out that, because of km scale transport of the Cardium on undulating thrust planes and underlying reverse faults (e.g. Hart et al., 2007), wrench-, reverse- and normal fractures were produced at alternating times, rather then in any specific order.

SE-NW oriented normal faults in the Alberta basin

On a much larger scale there are many examples of inferred and observed SE-NW striking faults, (e.g. Workman, 1968; Murray et al., 1994; Lemieux, 1999; Saller et al. 2001; Green and Mountjoy, 2005 and Warren, 2007). Starting in the Devonian, the Rosevear structure and the Kaybob field are two SE-NW trending structures of what Ross (1991) describes as “the sudden appearance of a mosaic of reefs” possibly influenced by underlying basement structures. The SE-NW normal faults, observed in seismic by Warren (2007) form an orthogonal pattern with the SW-NE trending facies belts in the Mississippian which have been interpreted as “piano keys” (Brandley et al., 1996). Furthermore, the lower Manville map of Cant and Abrahamson (1996), is an example of an orthogonal isopach pattern in the Cretaceous, similar to that observed further south by Zaitlin et al. (2002), and further north by Nodwell and Hart (2006). Because the present pacific margin is near parallel to the Cambrian margin of ancestral western Canada (Powell et al., 2006), stresses, both extensional and compressional, have had a (S)W-(N)E direction for ½ a billion years, which may be reflected in a coincidence of isopachs, facies trends and fault directions. This could well be caused by repeated reactivation of an underlying orthogonal pattern of rift and transcurrent faults (e.g. Hansen et al., 1993) rooted in the Cambrian or even before (Kanasewich et al., 1969). High angle normal faults are reactivated relatively easy, compared to wrench- or reverse faults (Sibson, 1974).

Summary

The Cardium along the Bow is fractured in directions relating to all three Andersonian stress fields: wrench-, reverse-, and normal fractures all occur within one outcrop. Early shear and extensional fracture patterns however, occur in two adjacent 7km and 3km regions. This km-scale spatial distribution suggests that both domains were fractured by a regional increase of hydraulic pressure in the footwall of the McConnell thrust, corroborating the role of fluid pressure in the mechanics of thrusting in general (Hubbert and Rubey, 1959) and the McConnell in specific (Gretener, 1972 and 1981). Hydraulic fracturing may further result in closely spaced fracture surfaces as observed in cuttings. An orthogonal pattern of shear (dip) fractures and normal (strike) fractures is oriented parallel to a much larger scale pattern of SW-NE directed facies trends and SE-NW directed (reactivated) faults of possible (Pre)Cambrian origin. The normal fractures may have formed in the foothills while pre-existing normal faults in the basin were re-activated, due to Laramide compression and / or Eocene extension.

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