Unraveling the Geometry and Origin of a Northeast-Southwest Striking Linked Fault Array at Marshall Mesa, Western Denver Basin: a (Possible) Solution through Integrated Digital Mapping*

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Abstract

An array of faults mapped at Marshall Mesa represents the southwestern exposure of a fault system interpreted as the result of either “listric growth faulting” or “decollement high-angle reverse faulting”. The faults crop out within the Late Cretaceous Fox Hills Sandstone and Laramie Formation in part of the Boulder-Weld coal field and have economic and environmental implications for sub-surface gas and coal reserves and the Laramie-Fox Hills aquifer in the Denver Basin. The listric growth-faulting model interprets high-angle normal faults at the surface as the products of growth faulting developed in the delta-front environment that deposited the upper Pierre Shale through the lower Laramie Formation. Listric normal faults observed in seismic data within the uppermost Cretaceous are also interpreted to have spatial a relationship with NE-SW striking deep basement-controlled faults on the northeast projection of the Ralston shear zone. NE-SW striking faults also compartmentalize reservoirs within the nearby Wattenberg gas field. The decollement high-angle reverse faulting model interprets sub-surface faults along strike to the northeast of the mapped array as representing the leading edge of deformation of the upper Cretaceous sedimentary rocks along a bedding plane decollement within the upper Pierre Shale. This deformation has uplifted the Laramie-Fox Hills aquifer and repeated sections within the aquifer, locally increasing its thickness by nearly 75 meters. Detailed, integrated digital mapping of the exposed fault array at Marshall Mesa reveals a series of complex structural relationships that indicate both normal faulting and subsequent shortening, marked by folding and locally reverse faulting, plus inversion of earlier normal faults. A history of extension and growth faulting linked to down-dip contraction, with localized inversion reconciles the competing earlier interpretations and illustrates the advantages of integrating digital data collection with detailed field mapping and cross section restorations.
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Regional Setting

An important change in structural style of the eastern margin of the Laramide Front Range occurs between Golden and Boulder, Colorado (Fig. 1). No major faults cross the margin of the Denver Basin to account for this change; however, the transition occurs across the trend of the northern Colorado Mineral Belt (CMB). The Front Range–Denver Basin margin changes from a north-northwest trend south of the CMB intersection to a northeast trend (Fig. 1) within ~10 km of the intersection. The Golden thrust is no longer mapable at the surface north of this zone. The structural style of the range front also changes from northeast vergent thrusts with triangle zones characteristic of the southern margin to northwest-trending, northeast-dipping, high-angle reverse faults (Erslev and Selvig, 1997; Sterne, 2006) north of the CMB intersection (Figs 2A and 2B). The axis of the Denver Basin is close to the range front south of the CMB due to buckling of the basin by overhanging northeast-vergent thrusts. Starting at the CMB intersection, the basin axis veers to the northeast to near Greeley, Colorado (Fig. 1); between Greeley and the Wyoming border the axis is ~ 40 km east of the range front (Chapin et al., 2014).

Sub-surface interpretations of the Front Range and Boulder-Weld Coal

Figure 4. Cross section (Fig. 3) for location showing (possible) directed back-thrusting along the eastern margin of the Front Range at Rocky Flats and interpreted (possible) directed buckling in the Boulder-Weld fault zone (Chapin, 1994).

Figure 5. Seismic profile and map for location across the eastern range of the Front Range at Coal Creek.

Figure 3. Geologic map of the eastern Front Range and northeastern part of the Denver Basin illustrating the mapped surface geology and interpreted sub-surface fault geometries based on a number of published cross sections. Detail area of field mapping at Marshall Mesa outlined by a red box (after Weimer & Davis, 1977; Spencer, 1961, 1986; Roberts et al., 2001; Kittleson, 2009; Barkmann et al. 2011).
Digital Field Mapping

An array of faults mapped at Marshall Mesa represent the southwestern exposure of a fault system previously interpreted as the result of either “listric growth faulting” or “decollement high-angle reverse faulting”. The faults crop out within the Late Cretaceous Fox Hills Sandstone and Laramie Formation in part of the Boulder-Weld coal field (see Figure 3) and have economic and environmental implications for sub-surface gas and coal reserves and the Laramie-Fox Hills aquifer in the Denver Basin.

The listric growth faulting model (Weimer and Davis, 1977) interprets high-angle normal faults at the surface as the products of growth faulting developed in the delta-front environment that deposited the upper Pierre Shale through the lower Laramie Formation.

The decollement high-angle reverse faulting model (Kittleson, 1992, 2009) interprets sub-surface faults along strike to the northeast of the mapped array as representing the leading edge of deformation of the upper Cretaceous sedimentary rocks along a bedding plane decollement within the upper Pierre Shale.

Detailed (in places meter-scale), integrated digital mapping of the exposed fault array at Marshall Mesa, SE of Boulder, CO reveals a series of complex structural relationships that potentially indicate both normal faulting and subsequent shortening, marked by folding and locally reverse faulting, plus inversion of earlier normal faults. A history of extension and growth faulting linked to down-dip contraction, with localized inversion (and possible strike-slip motion) reconciles the competing earlier interpretations and illustrates the advantages of integrating digital data collection with detailed field mapping and cross section construction.

Structural Map and Cross Sections

A detailed geological map of the Marshall Mesa area (Fig. 7B), and four structural cross sections (Fig. 8) illustrate the interpreted structural style across the mapped area. Selvig (1994) also drew 4 cross sections across the mapped area and his version of X-X’ is shown in Figure 7A for comparison with X-X’ in Figure 8B. Both sections have an interpreted detachment surface in the Pierre Shale (Kp) after Kittleson (2009). However, the sections drawn by Selvig (1994) show primarily a series of NW directed thrusts whilst here, a combination of early normal faults, reverse faults and inverted normal faults are interpreted. Steep surface dips (up to 85-90°) are interpreted as fault tip monoclines above buried (inverted?) fault tips. Note that field-collected fault-slip data indicate a significant number of low angle slip lineations across the area, indicating the possibility of strike slip motion across the fault zone.

Figure 6. Map of collected field data from the Marshall Mesa area. ~ 1300 structural data points were collected over ~ 5 full days of mapping, along with geo-referenced photos and notes.

Figure 7A. Cross section X-X’ as drawn by Selvig (1994)

Figure 7B. Detailed map of the Marshall Mesa area

Figure 8A. Same section location

Figure 8B. Same section location

Figure 8C. Same section location

Figure 8D. Same section location

Ask me for a demo to see how FieldMove Clino collects and analyzes field data.
Preliminary Conclusions

Detailed, integrated digital mapping of the exposed fault array at Marshall Mesa reveals a series of complex structural relationships (Figure 9A-D) indicating both normal faulting and subsequent shortening, marked by tight folding and locally reverse faulting, plus some strike-slip faulting. A history of extension and growth faulting linked to down-dip extension, and subsequent shortening, marked by tight folding and locally reverse faulting, plus some strike-slip faulting, is documented. This suggests a series of complex structural relationships (Figure 9A-D) indicating both normal faulting and subsequent shortening, marked by tight folding and locally reverse faulting, plus some strike-slip faulting. Detailed, integrated digital mapping of the exposed fault array at Marshall Mesa reveals a series of complex structural relationships (Figure 9A-D) indicating both normal faulting and subsequent shortening, marked by tight folding and locally reverse faulting, plus some strike-slip faulting.

Arthur Lakes in 1889. Note how the complexity of some of the contact relationships is captured by Lakes, well in advance of any digital mapping techniques!

Figure 11. A new (very preliminary!) hypothesis for the generation both early normal faulting and later thrusting/inversion in the Boulder/Weld coal field fault zone.

Further Work

- Additional analysis of field-gathered fault-slip data, deformation bands and detailed mapping of fault zone structures is required to confidently interpret fault zone geometries.
- Restitution of structural cross sections in order to test this new hypothesis.
- More detailed mapping of isolated outcrops outside of Marshall Mesa to build a better regional structural framework.
- Re-evaluation of published coal mine data for information on fault orientations in the subsurface.
- Evaluate all available seismic and well data for better regional control.

Acknowledgements

Some Thoughts on Digital Mapping Using Smart Phones

midland valley's Facebook choir (and other digital mapping tools) are excellent tools for collecting GPS referenced structural data in the field. Ideal conditions, data collection is up to 30% faster than using a standard compass/clinometer!

You must be sure to carefully calibrate your device frequently against a traditional compass/clinometer and make sure the GPS location updates BEFORE you take a reading. Battery life is a serious hurdle and you have a backup power source you will probably run out of juice over the course of an 8 hour field day......

The GPS functionality is affected (like any GPS) by cliff faces etc that can block the satellite connection, so in areas with complex topography you MUST be able to read your topographic-map and air photo to determine where you are.

Mapping tools for drawing contacts are not easy to use (for me!) on a smartphone screen, so a combination of geo-referenced air photos and topo maps is better for field mapping.

Boulder-Weld Fault Zone References


Figure 9

(A) Northwest dipping fault zone in the Laramie lineations within the fault zone
(B) Southeast dipping fault zone between Fox Hills and Claymont sandstone
(C) Sub-vertical bedding in Laramie sandstone above an interpreted detachment
(D) Cross-cutting deformation underling fault-tip to NW-SE thrusting/inversion in the Boulder/Weld coal field fault zone.