PS 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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Bruce Trudgill, Colorado School of Mines

Regional Setting

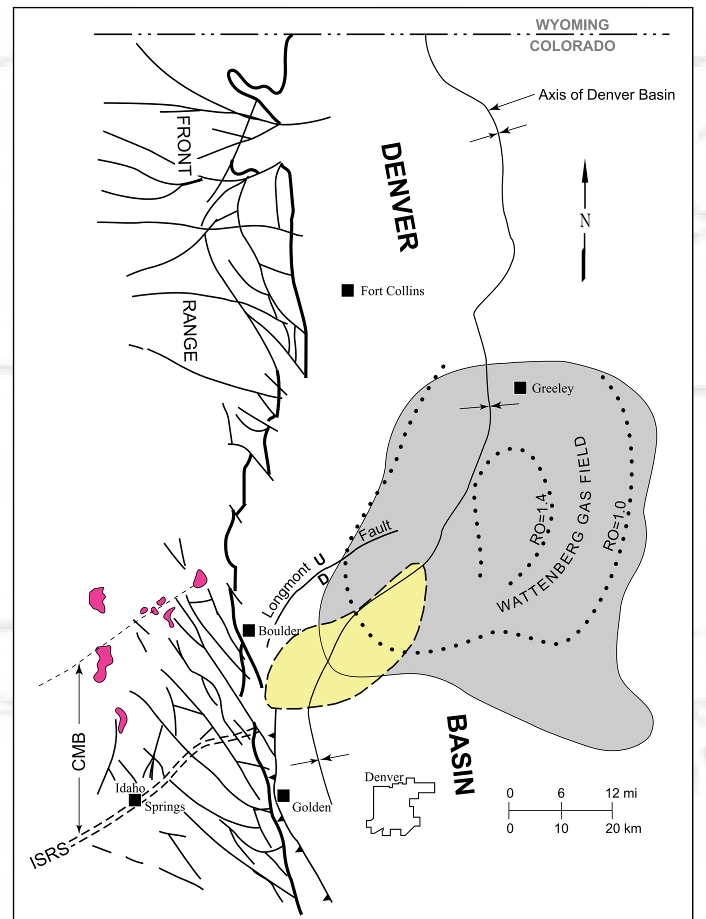


Figure 1. Simplified map of the northeastern margin of the Front Range and its intersection with the Colorado Mineral Belt (CMB). The location of the Boulder-Weld coal field is shown in yellow and the location of the huge Wattenberg gas field (gray) above a geothermal anomaly outlined by vitrinite reflectance values Ro = 1.0 and 1.4. Intrusives at the northeast end of the CMB are shown in red; ISRS—Idaho Springs–Ralston shear zone. After Chapin et al. (2014)

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 northward trend (Fig. 1) within ~10 km of the intersection. The Golden thrust is no longer mappable 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 loading 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 fron (Chapin et al., 2014).

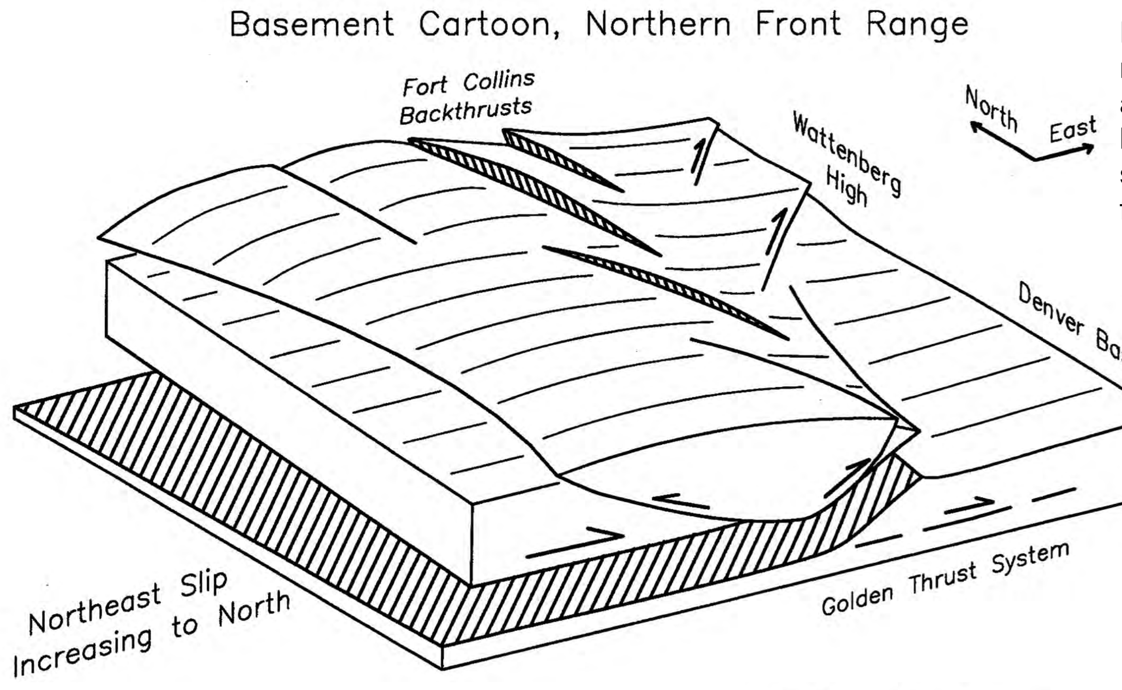


Figure 2A. Conceptual detachment model for the northern Front Range arch showing the relationships between thrust, backthrust, and strike-slip faulting along its eastern flank.(Erslev and Selvig, 1997)

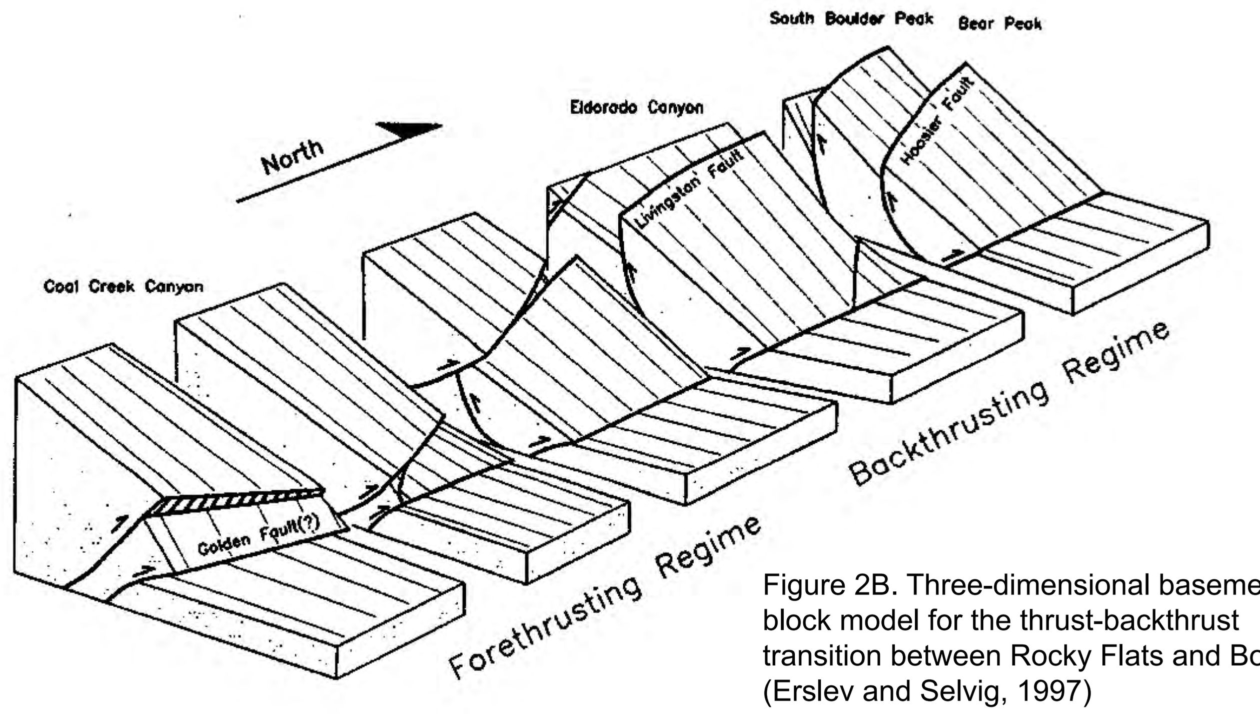
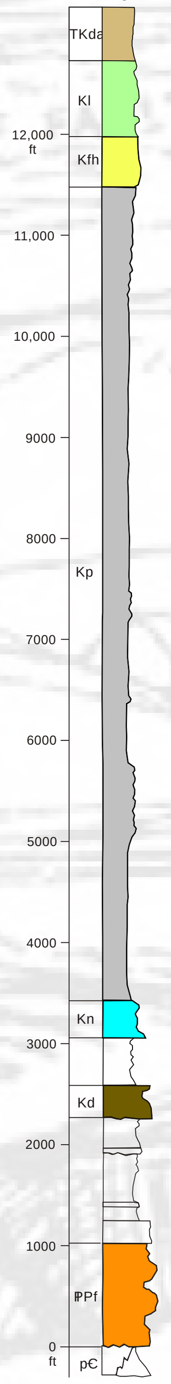
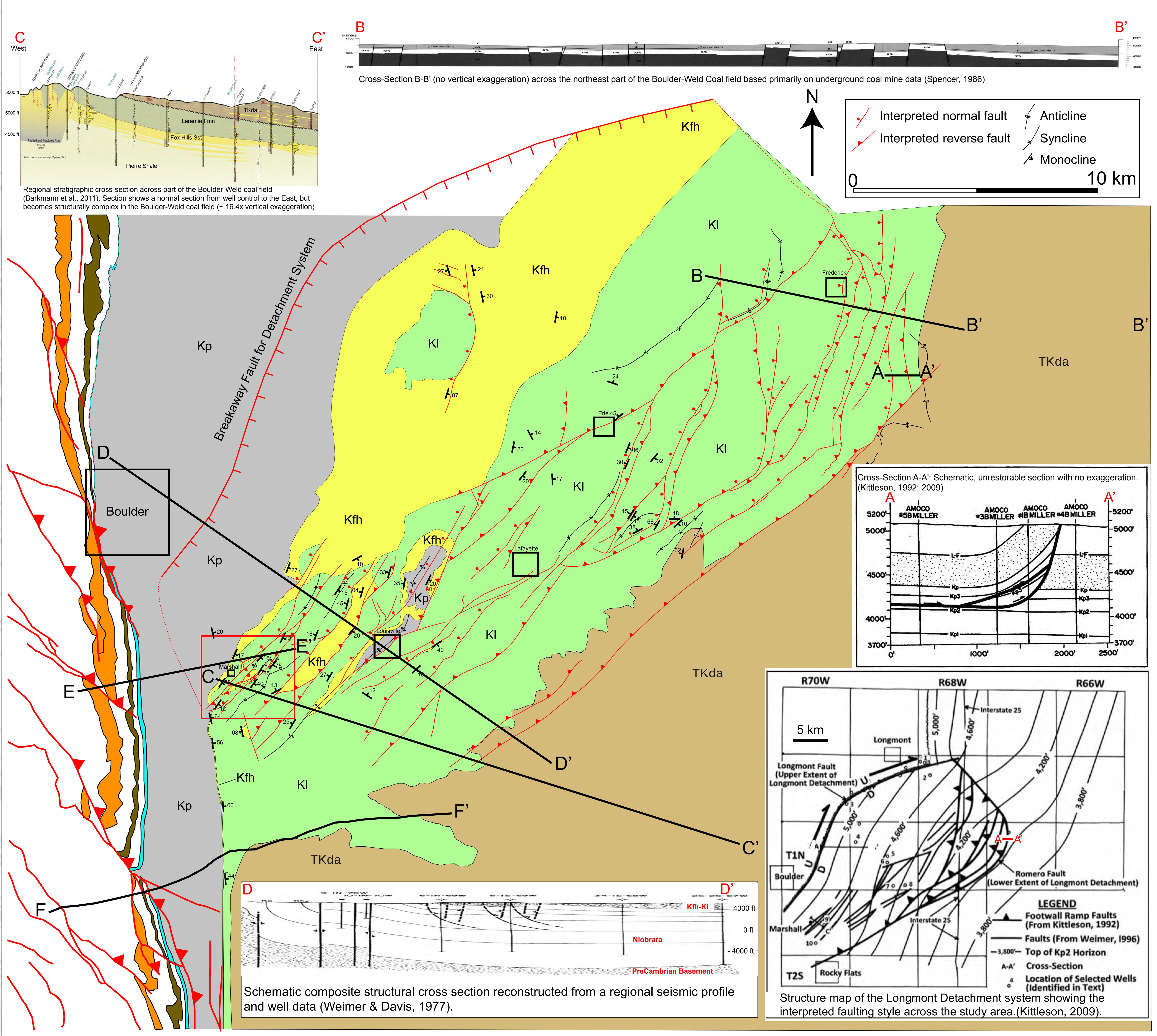


Figure 2B. Three-dimensional basement block model for the thrust-backthrust transition between Rocky Flats and Boulder (Erslev and Selvig, 1997)

Strat Column and Key





Regional stratigraphic cross-section across part of the Boulder-Weld coal field (Barkmann et al., 2011). Section shows a normal section from well control to the East, but becomes structurally complex in the Boulder-Weld coal field (~ 16.4x vertical exaggeration)

Cross-Section B-B' (no vertical exaggeration) across the northeast part of the Boulder-Weld Coal field based primarily on underground coal mine data (Spencer, 1986)

Cross-Section A-A': Schematic, unrestorable section with no exaggeration. (Kittleson, 1992; 2009)

Schematic composite structural cross section reconstructed from a regional seismic profile and well data (Weimer & Davis, 1977).

Structure map of the Longmont Detachment system showing the interpreted faulting style across the study area.(Kittleson, 2009).

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).

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

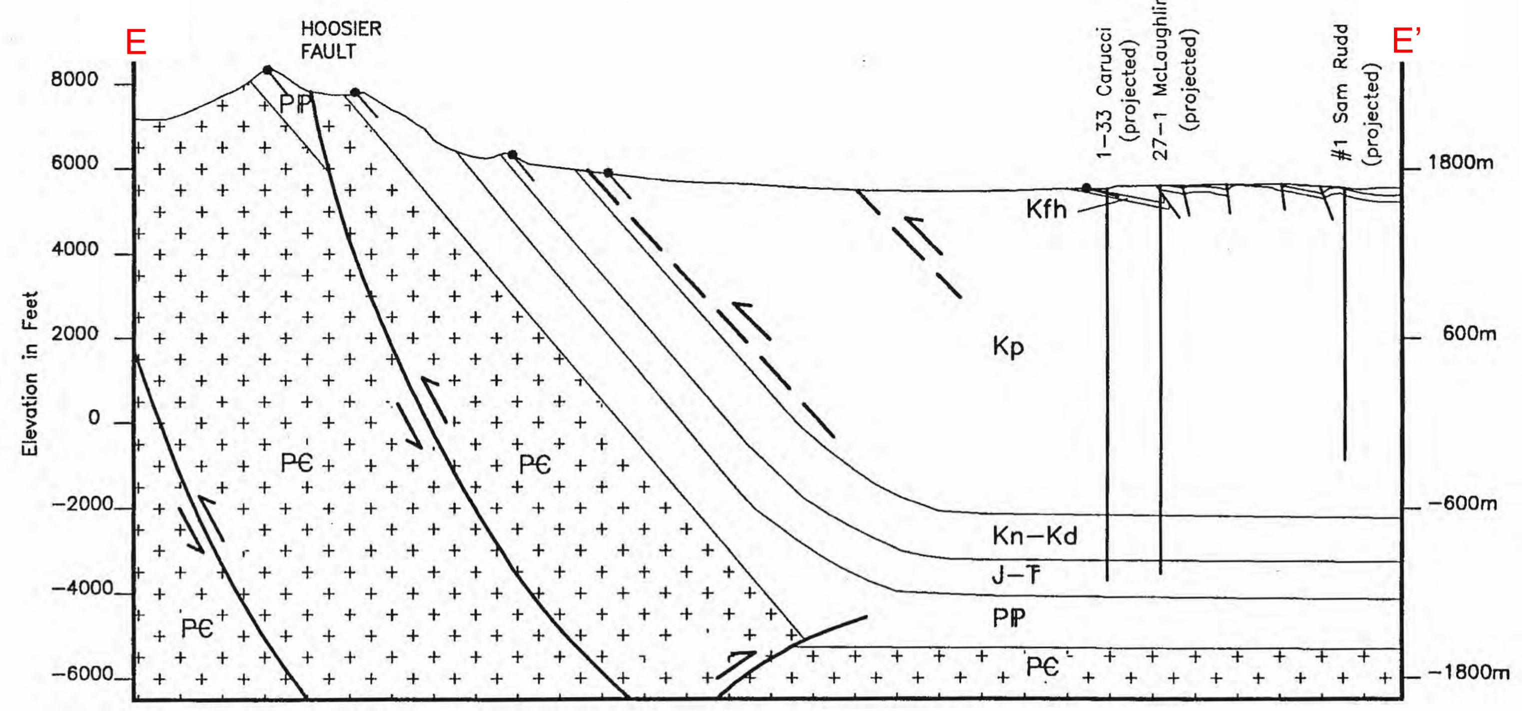


Figure 4. Cross section (see Fig. 3 for location) showing WSW directed back-thrusting along the eastern margin of the Front Range at Rocky Flats and interpreted NW directed thrusting in the Boulder-Weld fault zone (Erslev & Selvig, 1997)

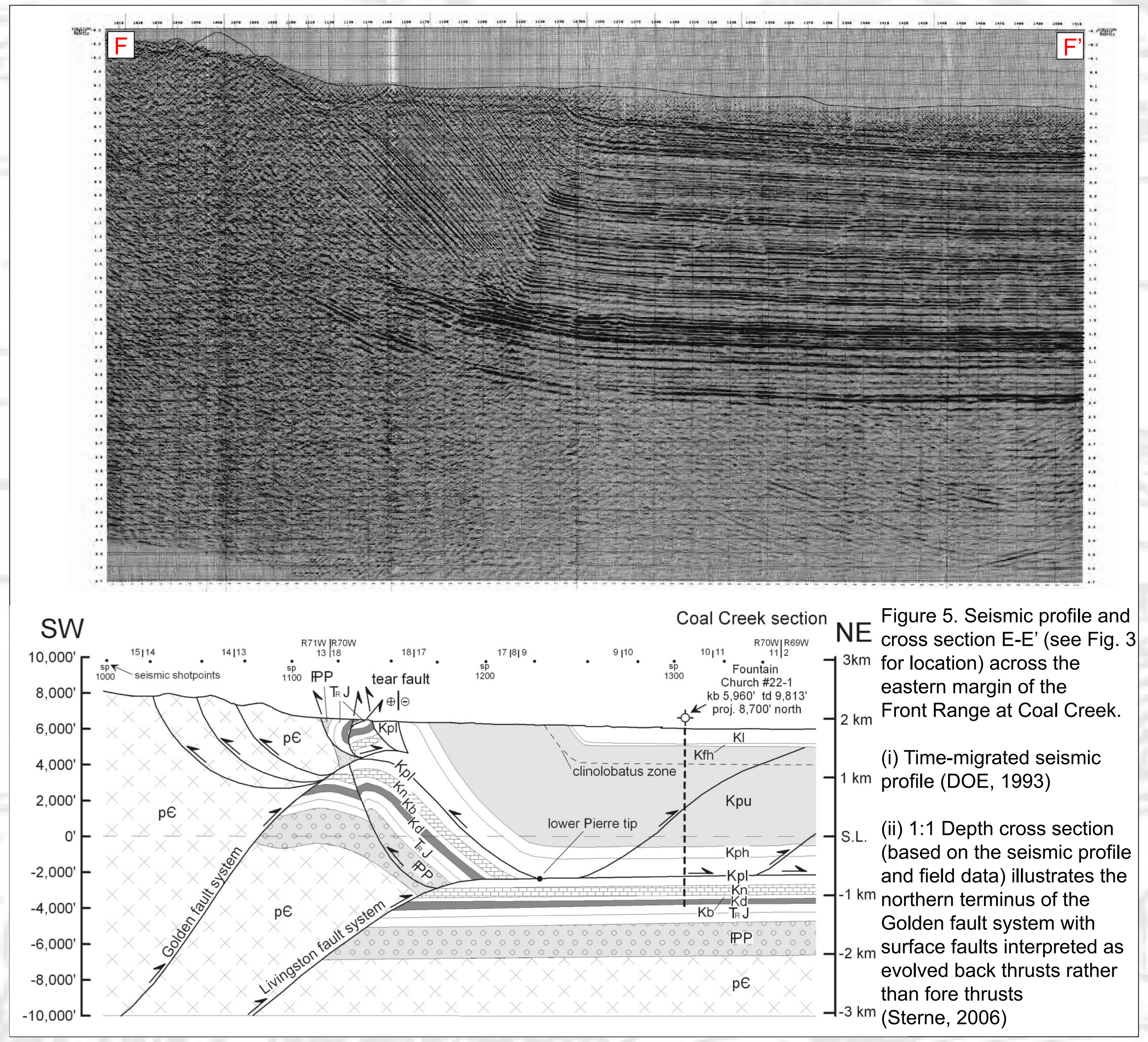


Figure 5. Seismic profile and cross section E-E' (see Fig. 3 for location) across the eastern margin of the Front Range at Coal Creek.

(i) Time-migrated seismic profile (DOE, 1993)

(ii) 1:1 Depth cross section (based on the seismic profile and field data) illustrates the northern terminus of the Golden fault system with surface faults interpreted as evolved back thrusts rather than fore thrusts (Sterne, 2006)

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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.

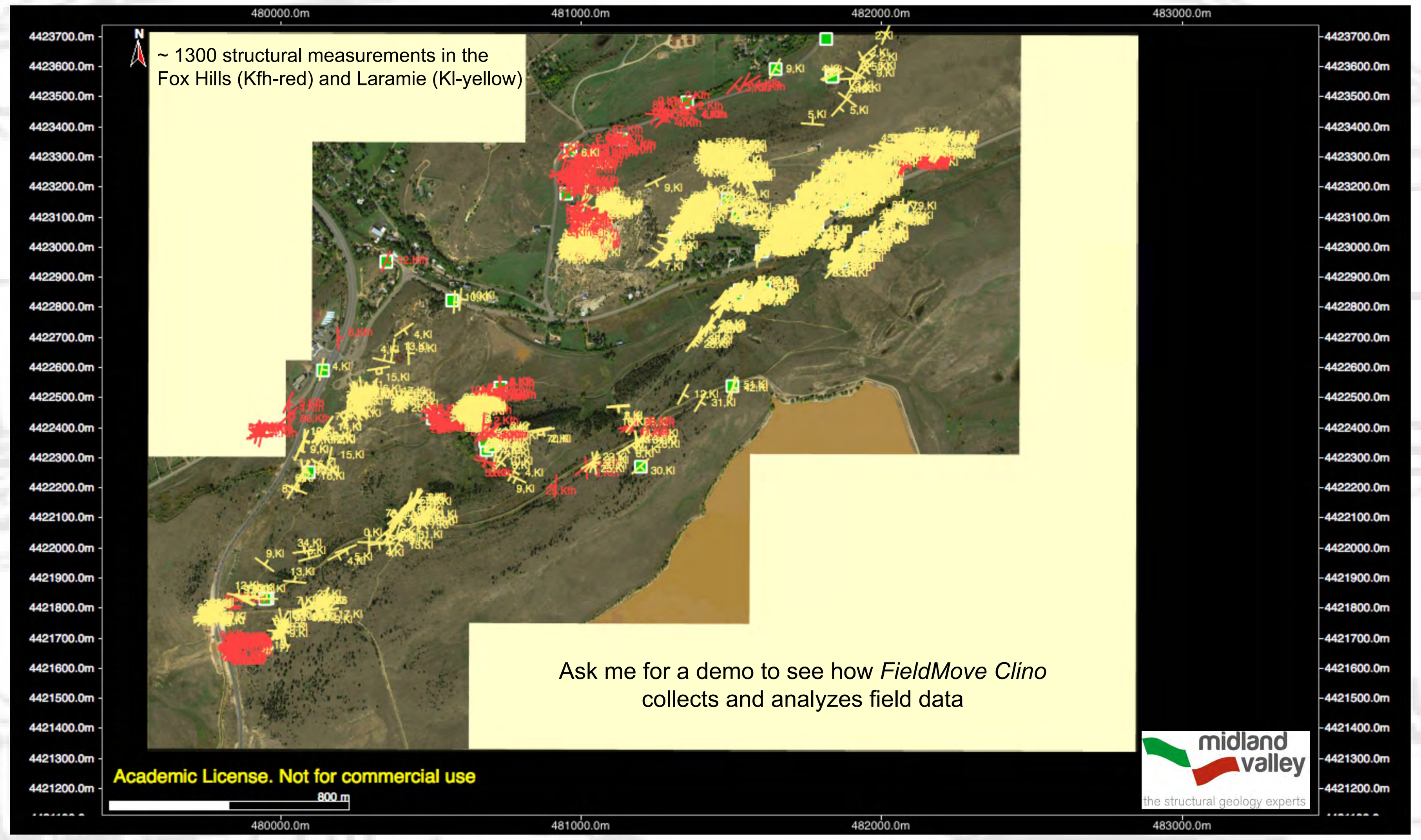

Figure 6. Map of collected field data from the Marshall Mesa area. ~ 1300 structural data points were collected over ~ 5 full days of mapping, along with geo-referenced photos and notes

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.

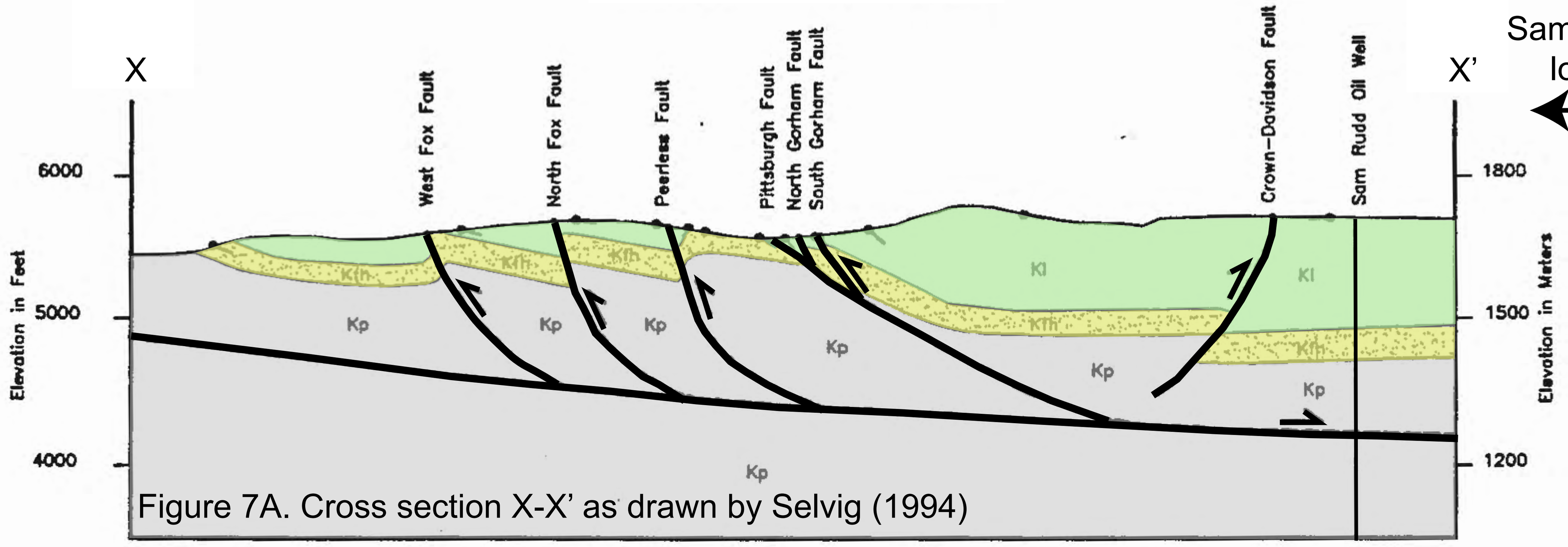

Figure 7A. Cross section X-X' as drawn by Selvig (1994)

Same section location

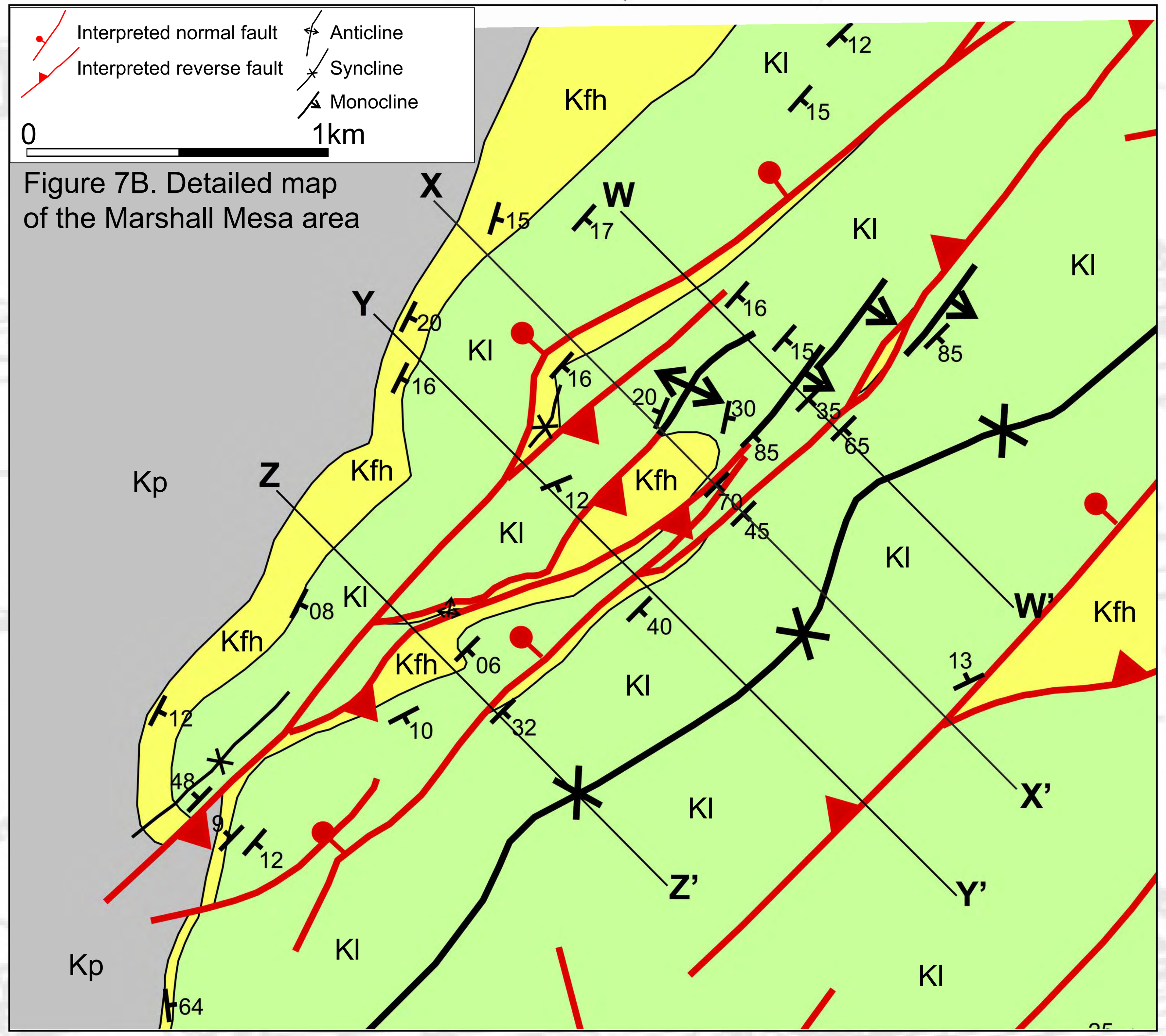

Figure 7B. Detailed map of the Marshall Mesa area

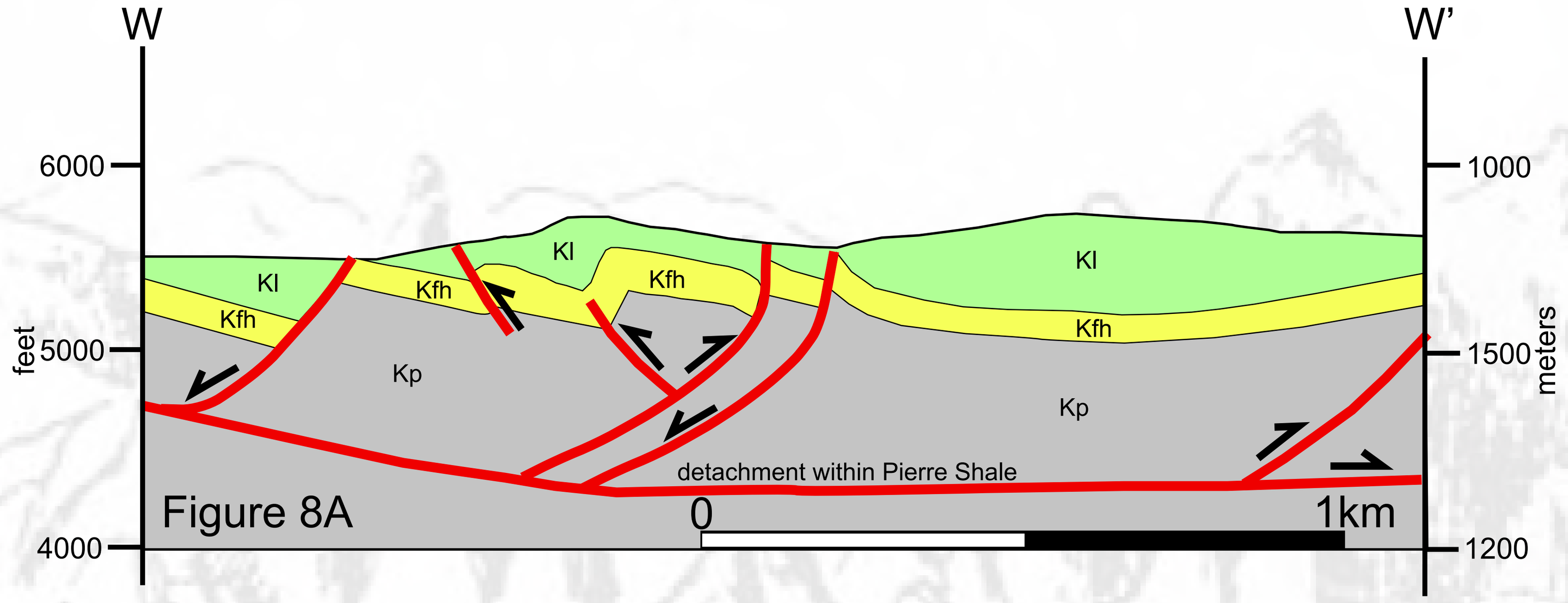

Figure 8A

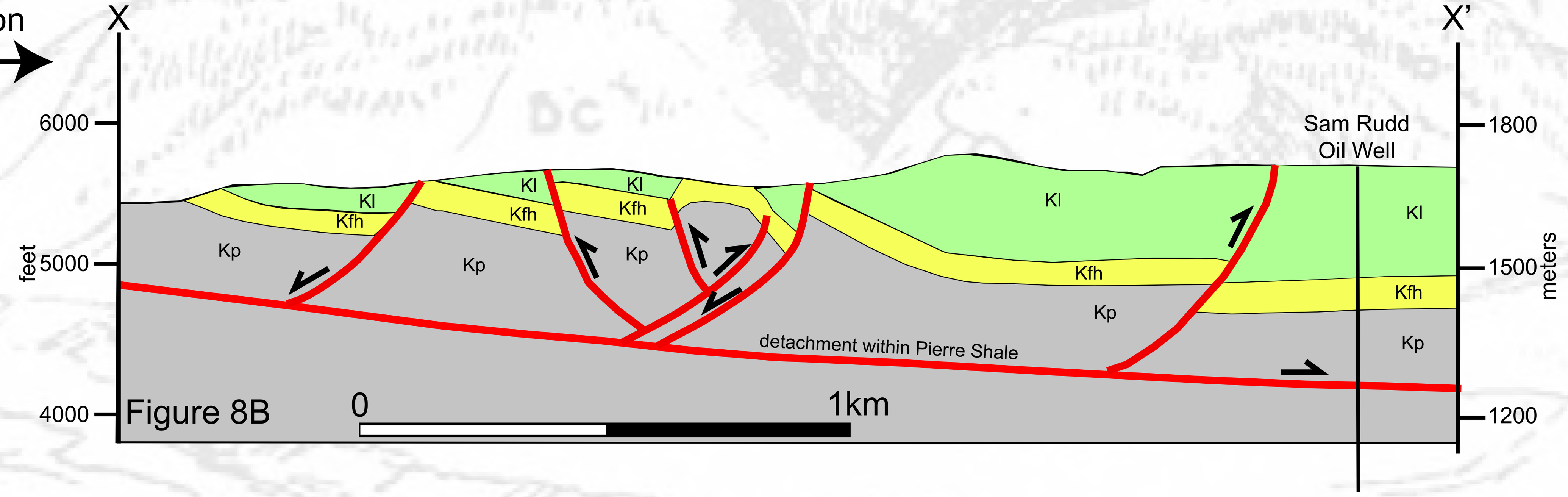

Figure 8B

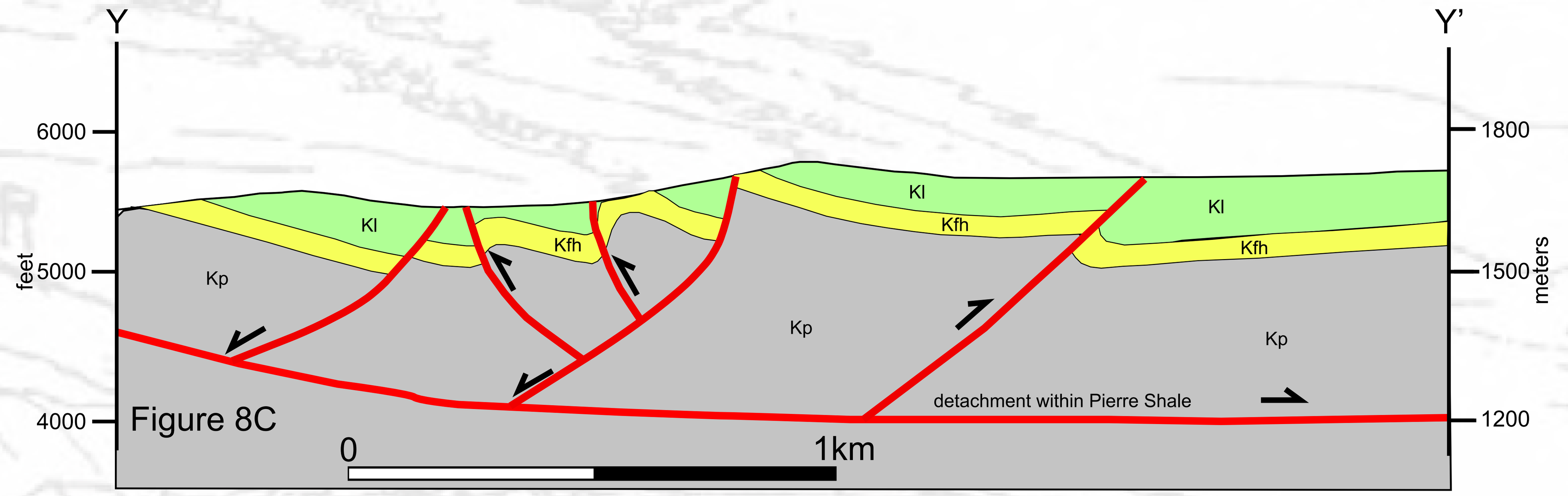

Figure 8C

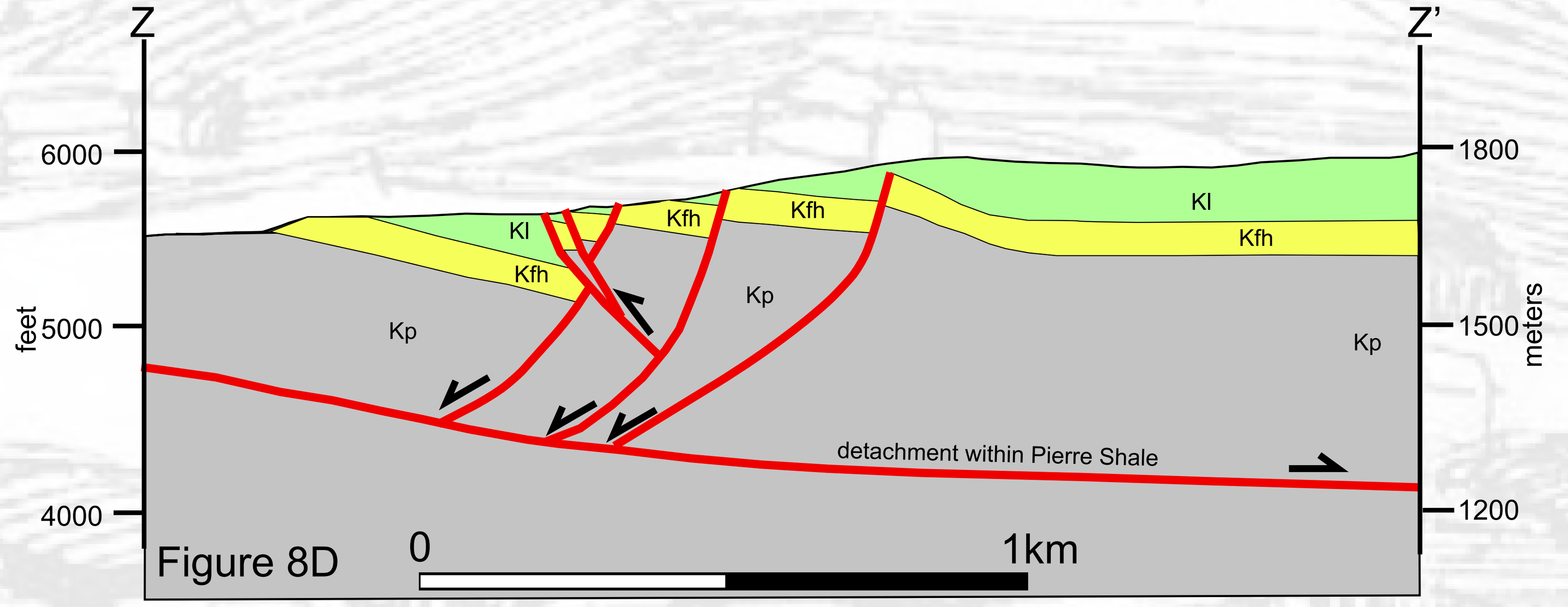

Figure 8D

NE

SW

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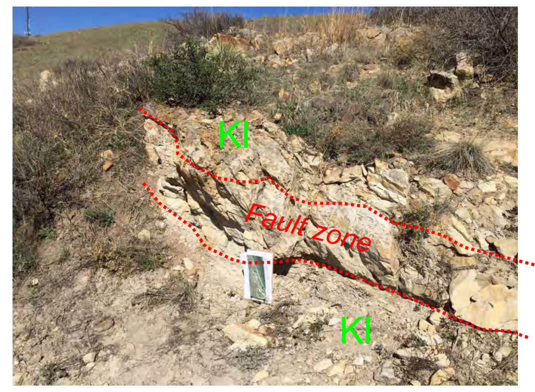
Preliminary Conclusions

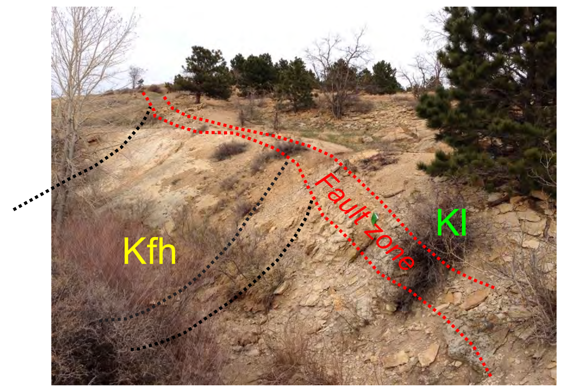
Detailed, integrated digital mapping of the exposed fault array at Marshall Mesa reveals a series of complex structural relationships (Figure 9A-D) indicating both normal faulting and subsequent shortening, marked by tight folding and locally reverse faulting, plus local strike-slip faulting. A history of extension and growth faulting linked to down-dip contraction, with localized inversion reconciles the competing earlier interpretations for the Boulder-Weld Fault Zone and illustrates the advantages of integrating digital data collection with detailed field mapping and cross section construction.

Figure 9

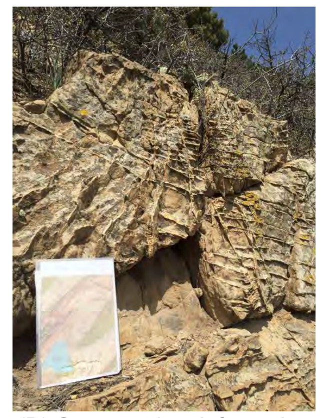


(A) Northwest dipping fault zone in the Laramie showing both reverse and strike-slip lineations within the fault zone

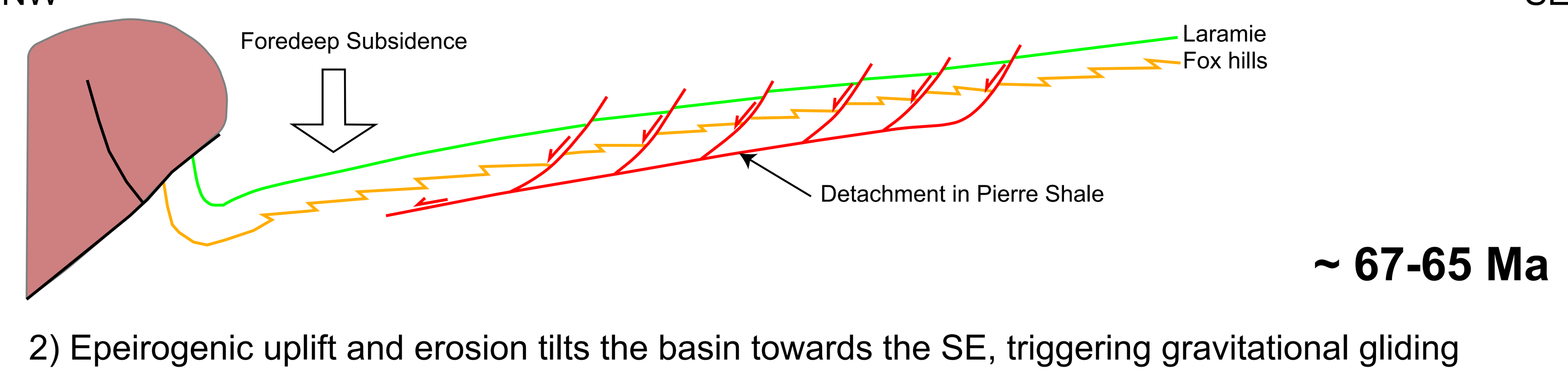

(C) Sub-vertical bedding in Laramie sandstones above an interpreted underlying fault-tip



(B) Southeast dipping fault zone between Fox Hills (Kfh) and Laramie (Kl) with steep upturn in Kfh


(D) Cross-cutting deformation bands in Laramie sandstones

1) Laramide basement-involved thrusting and uplift generates a foredeep in the western part of the Denver foreland basin, and inititiates NW directed normal faulting in the Fox Hills/Laramie driven by flexure and/or gravity gliding above a detachment in the upper Pierre Shale.



2) Epeirogenic uplift and erosion tilts the basin towards the SE, triggering gravitational gliding towards the SE with updip extension, inversion of earlier normal faults and down-dip shortening in the form of toe-thrusts.

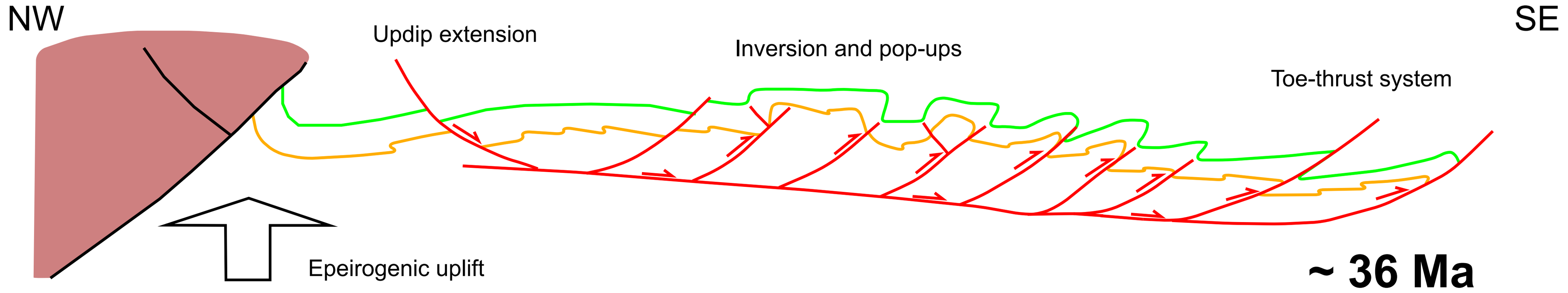


Figure 11. A new (very preliminary!) hypothesis for the generation both early normal faulting and later thrusting/inversion in the Boulder/Weld coal field fault zone.

Sketch credit: Colorado School of Mines

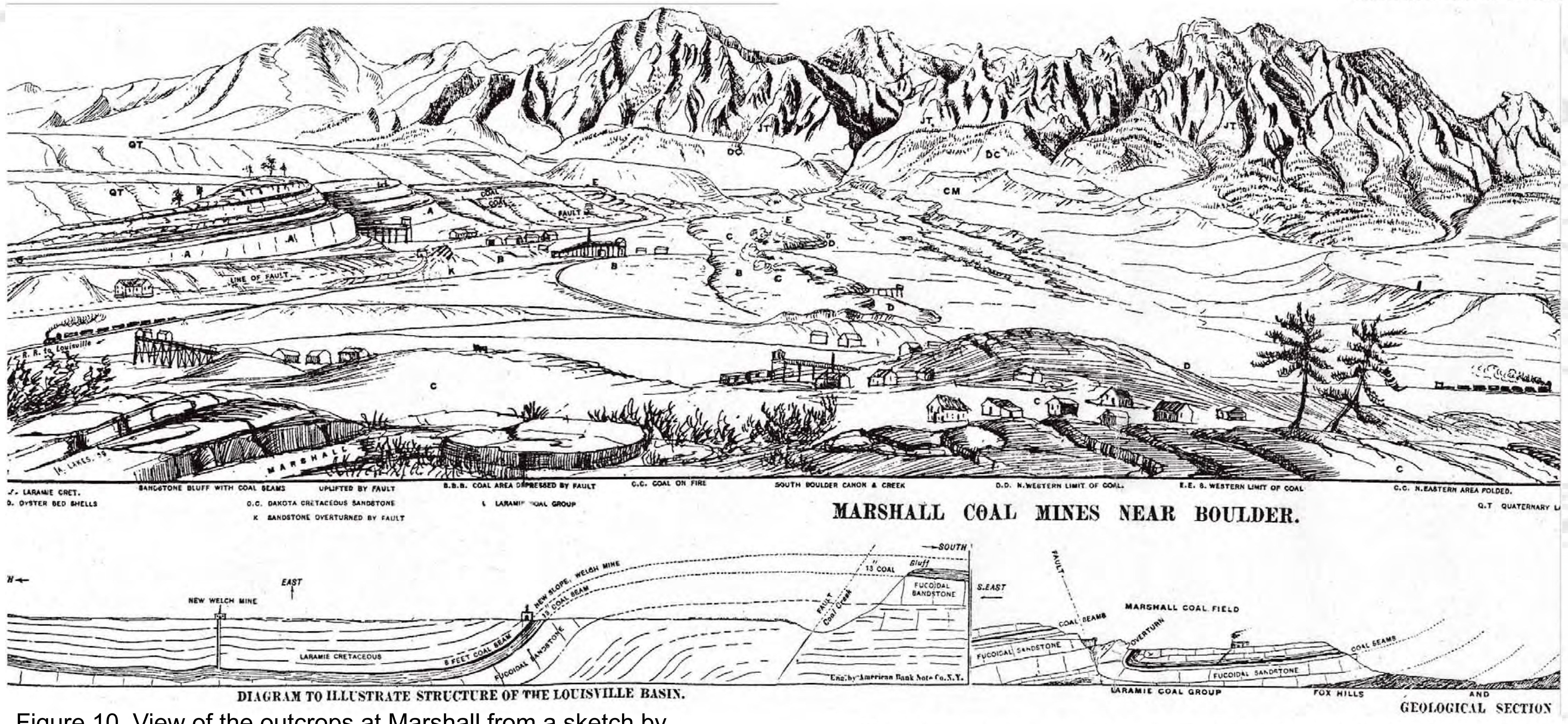


Figure 10. View of the outcrops at Marshall from a sketch by Arthur Lakes in 1889. Note how the complexity of some of the contact relationships is captured by Lakes, well in advance of any digital mapping techniques!

The sketch Professor Arthur Lakes made of Marshall in 1889. The library at the Colorado School of Mines in Golden is named for him, and his watercolors of dinosaurs and geological formations are on display in the entrance hall of the building.

Further Work

- Additional analysis of field-gathered fault-slip data, deformation bands and detailed mapping of fault zones is required to confidently interpret fault zone geometries.
- Restoration 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.

Some Thoughts on Digital Mapping Using Smart Phones

Midland Valley's *FieldMove Clino* (and other digital mapping tools) are excellent tools for collecting GPS referenced structural data in the field. In ideal conditions, data collection is up to 10x faster than using a standard compass/clinometer!

You must be sure to carefully calibrate your devise frequently against a traditional compass and make sure the GPS location updates BEFORE you take a reading.

Battery life is a serious issue and unless 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 with geo-referenced air photos and topo maps is better for field mapping.

Boulder-Weld Fault Zone References

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This poster is dedicated to the inspiration and memory of Chuck Kluth

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