PS Investigating Layer Parallel Diagenetic Shortening Using Field Data, Thin Section Analysis, and Analog Models*

Nicole Pierson[1] and Caroline M. Burberry[1]

Search and Discovery Article #41419 (2014)**
Posted August 18, 2014

*Adapted from poster presentation given at 2014 AAPG Annual Convention and Exhibition, Houston, Texas, April 6-9, 2014

[1]University of Nebraska-Lincoln, Lincoln, Nebraska, USA (npierson@huskers.unl.edu)

Abstract

Layer parallel shortening (LPS) is deformation that occurs in a compressive stress regime parallel to bedding, including both mechanical and chemical changes. Typically, this deformation is not incorporated into cross-section restoration, although an amount of bulk shortening can be calculated, because the amount and timing of increments of shortening is unknown. Previous research indicates that omitting this deformation can lead to error in palinspastic reconstructions and subsurface predictions up to 20%. A better understanding of when and where LPS deformation is accommodated can improve predictions important to the hydrocarbon industry such as fluid flow trajectories, trap volume, trap location, porosity and permeability. To address this issue, a combination of field measurements and thin section analysis calculated the amount of LPS across the central Colorado Front Range (CFR) system. Though the overarching goal of the research is to locate where and when LPS is accommodated during a deformation sequence, this contribution focuses on how much LPS is taken up by processes such as compaction and pressure solution. A transect of measurements across the central CFR was recorded, including attitude of foliations, bedding, fault planes, and stylolitic surfaces. Trend and plunge measurements of fold hinges and mineral lineations along fault planes were also recorded. Relative stylolite frequencies and fracture patterns were studied to assess variation in mechanical and chemical properties. Layer parallel structural diagenesis was assessed from these data as well as on the micro scale by examining directional grain dissolution and diagenetic histories in thin section. Analog sandbox models, scaled to be representative of the CFR, were deformed incrementally in accordance with Colorado's well-constrained tectonic history. Field data were compared to the model to test the robustness and applicability of the field measurements. Preliminary results indicate that layer parallel deformation occurs at the onset of each tectonic event before discrete structures are formed. LPS can be estimated at outcrop and precise calculations from thin section measurements corroborate the field data. These calculated LPS amounts fall within previously reported ranges. Whilst these results are specific to the CFR, a set of best practice recommendations, applicable to the general case, can be applied to future geomechanical models and cross-sections.

Investigating Layer Parallel Diagenetic Shortening Using Field Data, Thin Section Analysis, and Analog Models

Nicole Pierson[1] and Caroline M. Burberry, Department of Earth and Atmospheric Sciences, Lincoln, NE 68588
[1]npierson@huskers.unl.edu

I. Introduction

Layer parallel shortening (LPS) is deformation that occurs in a compressive stress regime parallel to bedding. This includes both mechanical and chemical changes. Like other strains, it can be transmitted great distances: up to 1200 kilometers away from an active plate margin (Craddock & van der Pluijm, 1989).Typically this deformation is not incorporated into cross-section restoration because, though an amount of bulk shortening can be calculated, the amount and timing of shortening increments are unknown. Though the overarching goal of the research is to locate where and when LPS is accommodated during a deformation sequence, this contribution focuses on how much LPS is taken up by processes such as compaction and pressure solution using both field data and analog models.

Previous research indicates that omitting this deformation can lead to error in palinspastic reconstructions and subsurface predictions up to 20%. A better understanding of when and where LPS deformation is accommodated can improve predictions important to the hydrocarbon industry such as fluid flow trajectories, trap volume, trap location, porosity and permeability.

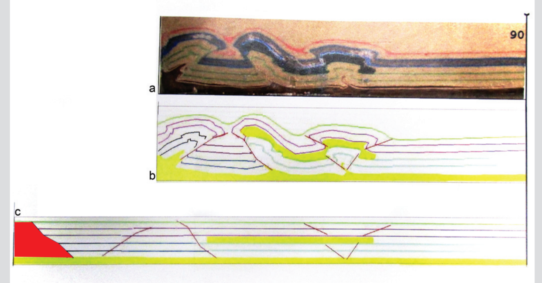


Figure 1. Without layer parallel shortening, restored layers of analog model cross-sections should measure original sandbox dimensions. They never do. Modified from Burberry (2008).
a. Photograph of sandbox analog model cross-section.
b. Computer-generated line drawing of image.
c. Restored cross-section showing the space problem shaded in red.

II. Field Data

A transect of field measurements across the central Colorado Front Range was recorded, including attitude of foliations, bedding, fault planes, and stylolitic surfaces. Trend and plunge measurements of fold hinges and mineral lineations along fault planes were also recorded. Relative stylolite frequencies and fracture patterns were studied to assess variation in mechanical and chemical properties.

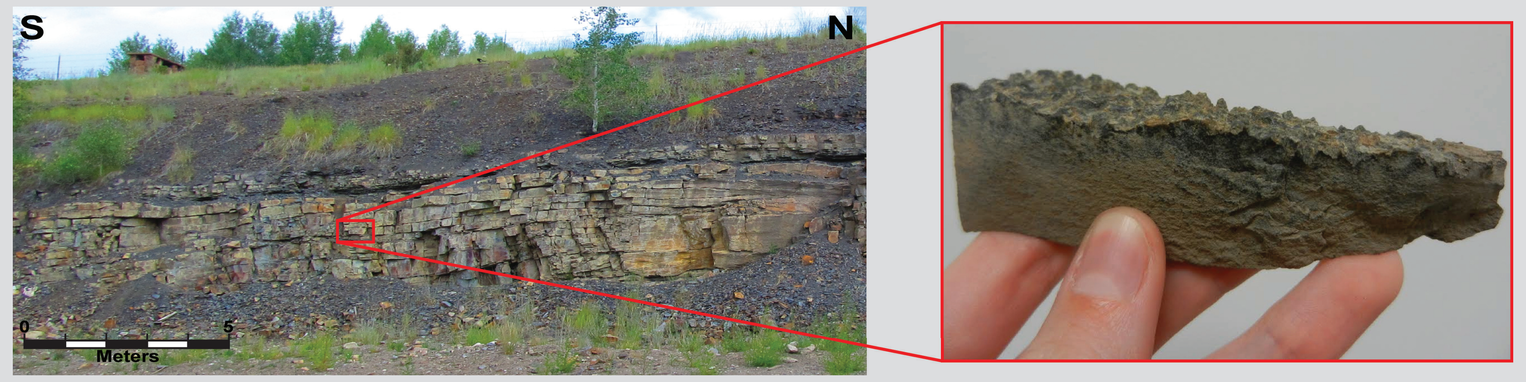


Figure 2. LPS seen in the field, outcrop near Dillon: pre-Cretaceous sedimentary section of central Colorado with a stylolite frequency of about one surface per foot of section. Apparent bedding planes seen in figure are all stylolitic surfaces. A combination of field measurements and thin section analysis calculated the amount of layer parallel structural diagenesis across the central Colorado Front Range system.

III. Thin Sections

Hand samples taken from the field also assessed layer parallel structural diagenesis via thin section by examining directional grain dissolution and diagenetic histories. One example of this type of measurement is shown here, calculating compressional grain dissolution. LPS calculated in thin section from grain boundaries used the Onasch (1993) method for calculating pressure solution shortening (PSS).

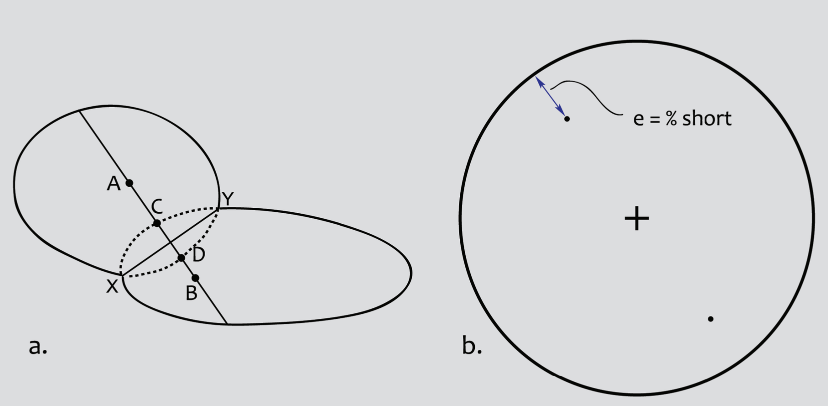
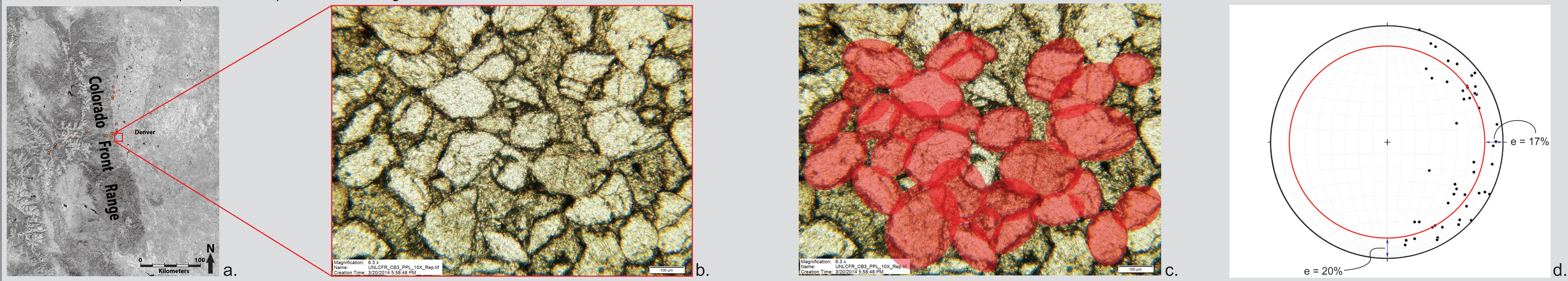


Figure 3.
a. Dashed lines are inferred grain boundaries. XY is the compromise boundary between the two ellipsis. A, B, C, and D are points along the line perpendicular to the compromise boundary. Modified from Onasch (1993).
e, or percent shortening,is calculated by the equation:

$$e = \frac{AB-(AB+CD)}{AB+CD} \cdot 100\%$$

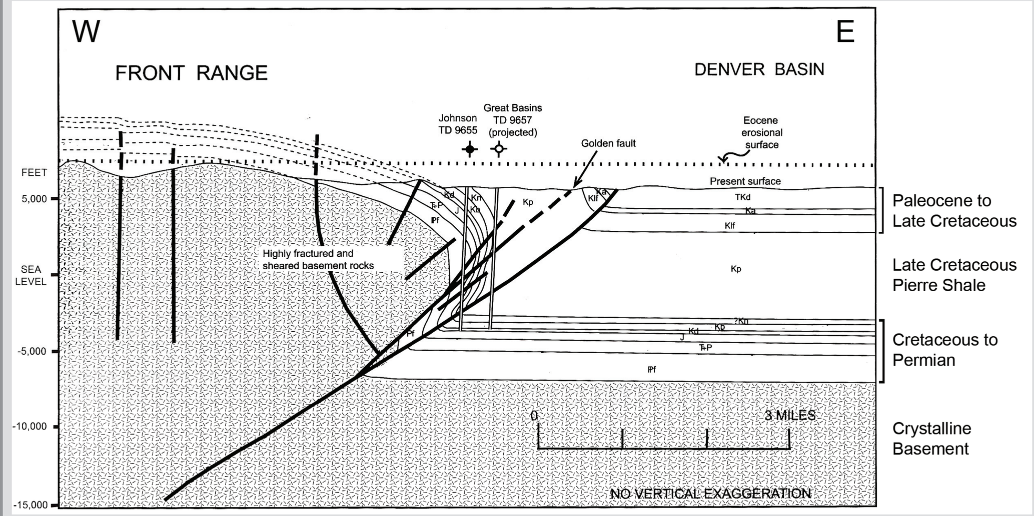
b. e is plotted with the orientation orthogonal to the compromise boundary on a stereonet, and used to calculate the percentage shortening by measuring the distance from the line to the edge of the stereonet. Modified from Onasch (1993).

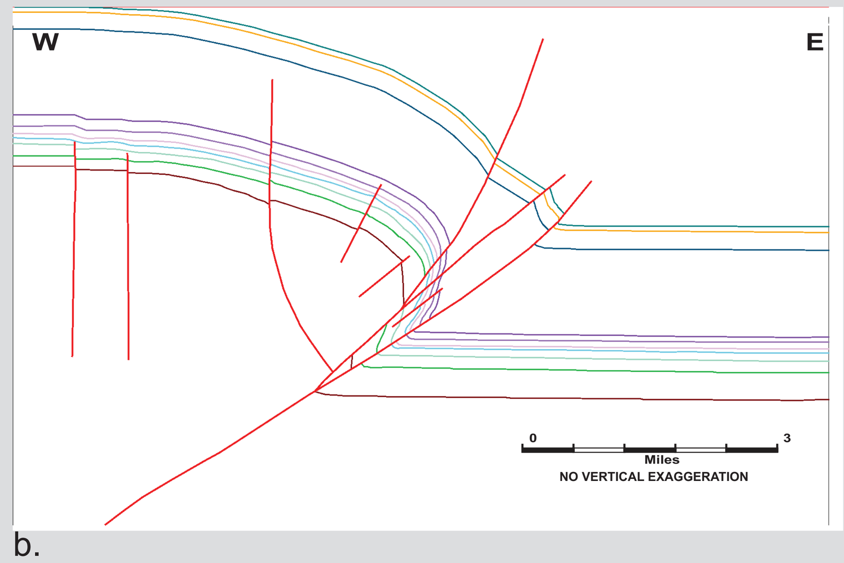
Figure 4.
a. Location map showing where the thin section's hand sample was collected.
b. Photomicrograph of Dakota Sandstone under plane polarized light with dip direction oriented left-right and compaction direction oriented up-down.
c. Photomicrograph showing ellipses used in the PSS method. Orientation of sample same as in 4b
d. Resultant stereonet from PSS calculations showing 20 percent compaction and 17 percent LPS. Stereonet is oriented so up-down is compaction and left-right is LPS, as before.



IV. Analog Modeling

Analog sandbox models, scaled to be representative of the Colorado Front Range, were deformed incrementally in accordance with Colorado's tectonic history. Field data were compared to the model to test the robustness and applicability of the field measurements.





Colorado Front Range

Segments of the Colorado Front Range were restored to gain insight into the deformation history and subsurface stratigraphic geometry. The restoration of the cross section, modified from Kellogg et al. (2004) (Figure 4a), revealed a minimum of two stages of deformation. These two deformation stages correspond to before and after the deposition of the Late Cretaceous Pierre Shale.

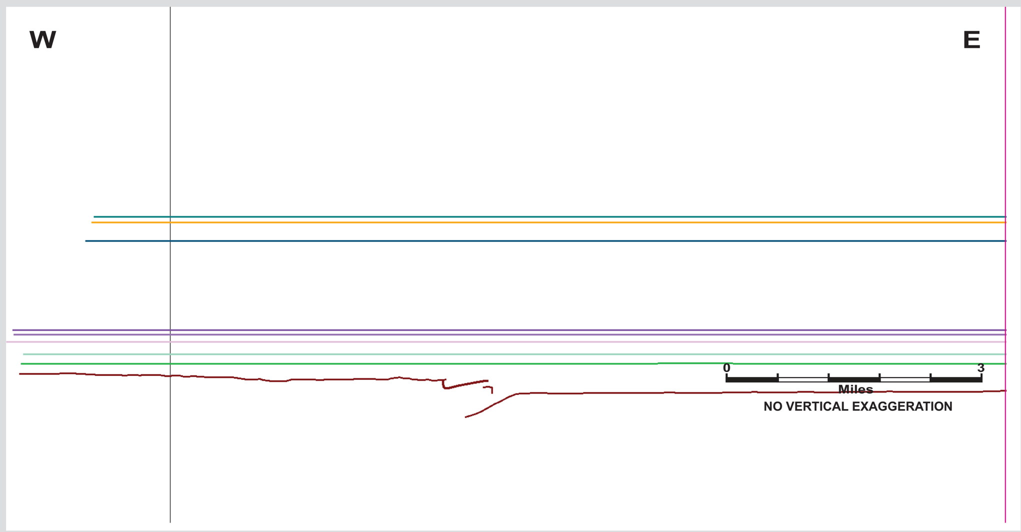


Figure 5.
a. Cross-section across the eastern margin of the Colorado Front Range near Golden, Colorado. Modified from Kellogg et al., (2004).
b. Line drawing of part a. projecting the Late Cretaceous to Paleocene horizons across the section.
c. Restoration of part b. The two main deformational phases can be seen, separated by the thick Pierre Shale. The irregular basal horizon represents the uneven basement terrain at the time of deposition of the Permian Fountain Formation. Minimum pre-Late Cretaceous shortening is calculated at 17.5% from this restoration, and minimum post-Cretaceous shortening is calculated to be 9.01%.

Analog Model Setup

The University of Nebraska-Lincoln Earth and Atmospheric Sciences Department Deformation Research Group uses a "sandbox" analog model with a straight, rigid moving wall. Deformation occurs at about 10 millimeters per hour. A basement fault was cut parallel to the deformation front into the basal two layers, representing a reactivated Precambrian fault. Those layers were deformed 7.85% during deformation sequence 1, based on a comparison to Colorado Front Range deformation geometry. A silicone polymer was then deposited, along with the uppermost brittle fine sand layer, representing the Late Cretaceous Pierre Shale succession and overlying units. The model was then deformed in deformation sequence 2 to a total of 17.55% bulk shortening.

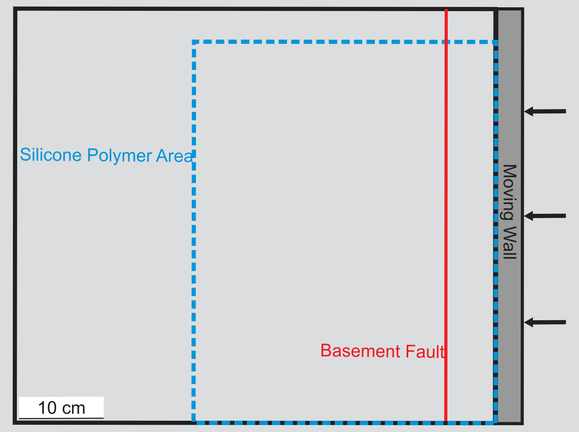


Figure 6. Post-Late Cretaceous model configuration showing the extent of the silicone polymer and the location of the cut basement fault

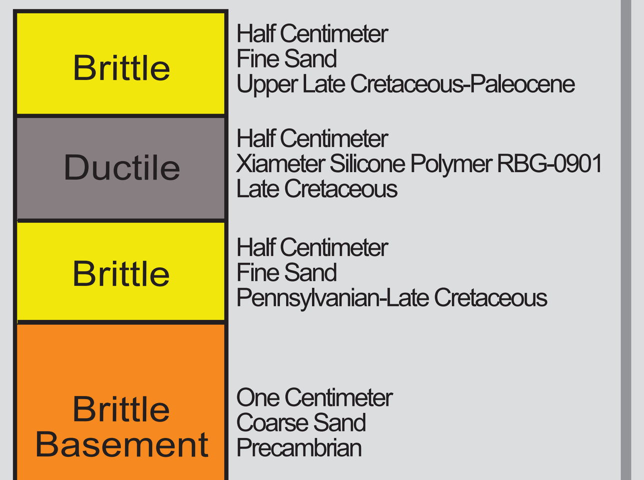


Figure 7. Simplified sedimentary sequence across the Colorado Front Range.

Analog Model Results

The analog model underestimates the layer parallel shortening in the area based on the Front Range cross-section and thin sections. This is not unexpected on both fronts. The location of the thin section's hand sample is outboard of the main thrust. That is, any deformation expressed in the undeformed side of the thrust is likely to be taken up in pressure solution shortening. Both the geologic and modelled cross-section have significant deformation taken up by thrusting. Shortening calculated from the restoration was combined with the total bulk shortening value to calculate model LPS, which ranges from 7.71-10.54%.

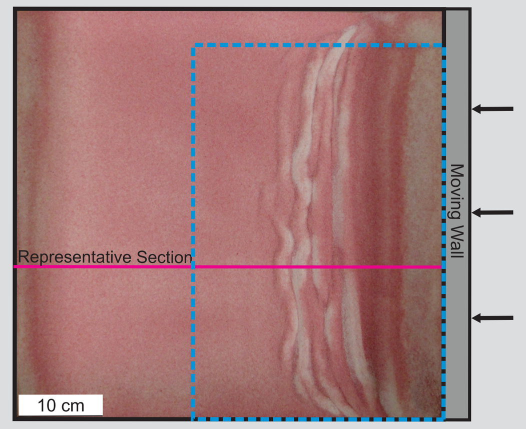


Figure 8. Map view photograph of shortened model with the final location of the silicone layer in blue, and the trace for the representative cross-section (Figure 10a) in pink.

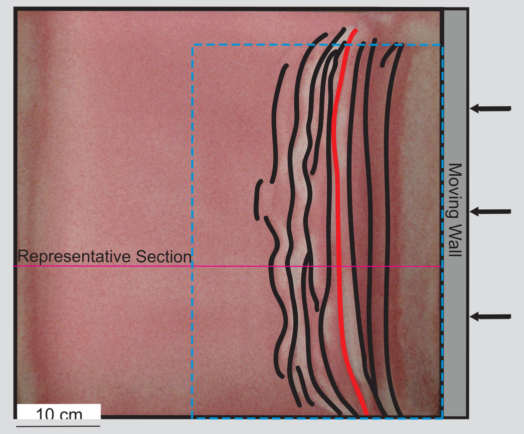


Figure 9. With fault traces interpreted. The expression of the basement fault is in red.

Horizon	Shortening Calculated from Restoration	Deformation Timeframe	Layer Parallel Shortening
Purple	1.06%	Stage 2	8.64%
Green	7.01%	Stage 1 & 2	10.54%
Blue	9.84%	Stage 1 & 2	7.71%

Table 1.

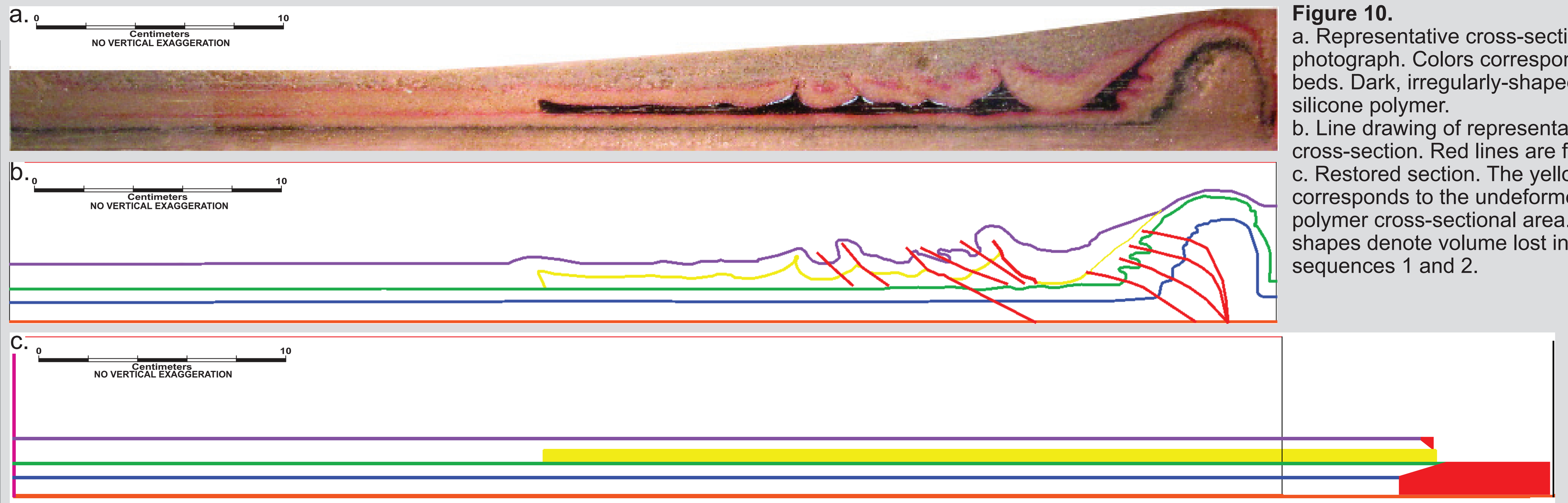


Figure 10.
a. Representative cross-section photograph. Colors correspond to marker beds. Dark, irregularly-shaped unit is the silicone polymer.
b. Line drawing of representative cross-section. Red lines are faults.
c. Restored section. The yellow corresponds to the undeformed silicone polymer cross-sectional area. The red shapes denote volume lost in deformation sequences 1 and 2.

V. Implications and Future Work

Preliminary results indicate that layer parallel deformation occurs at the onset of each tectonic event before discrete structures are formed. LPS can be estimated at outcrop and precise calculations from thin section measurements corroborate the field data. These calculated LPS amounts fall within previously reported ranges (See Table 2). Whilst these results are specific to the Colorado Front Range, a set of best practice recommendations, applicable to the general case, can be applied to future geomechanical models and cross-sections.

Table 2. Layer Parallel Shortening Percentages Reported

Amount	Citation
5–15%	Weil and Yonkee (2009)
2–10%	Wiltschko et al. (1985)
6%	Craddock and van der Pluijm (1989)
10%	Engelder and Engelder (1977)
9–14%	Whitaker and Bartholomew (1999)
10–14%	Engelder (1979)
15–23%	Sans et al. (2003); Koyi et al. (2004)
18.6–19%	Baseline Lab Models

VI. References Cited and Acknowledgements

Burberry, C.M., 2008, Dynamic and kinematic evolution of a fold-thrust belt with emphasis on the evolution of deformation front structures, Doctoral Dissertation, Imperial College, London, 169 p.
Craddock, J.P., and van der Pluijm, B.A., 1989, Late Paleozoic deformation of the cratonic carbonate cover of eastern North America, Geology, v. 17, no. 5, p. 416-419.
Engelder, T., 1979, The nature of deformation within the outer limits of the central Appalachian foreland fold and thrust belt in New York state, Tectonophysics, v. 3-4, p. 289-310.
Engelder, T., and Engelder, R., 1977, Fossil distortion and décollment tectonics of the Appalachian plateau, Geology, v. 5, no. 8, p. 457-460.
Kellogg, K.S., Bryant, B., and Reed, Jr., J.C., 2004, The Colorado Front Range—anatomy of a Laramide uplift, in Nelson, E.P., and Erslev, E.A., eds., Field trips in the southern Rocky Mountains, USA: Boulder, Geological Society of America, Field Guide 5, p. 89-108.
Koyi, H.A., Sans, M., Teixell, A., Cotton, J., and Zeyen, H., 2004, The significance of penetrative strain in the restoration of shortened layers—insights from sand models and the Spanish Pyrenees, in McClay, K.R., editor, Thrust tectonics and hydrocarbon systems, American Association of Petroleum Geologists Memoir 82, p. 207-222. Onasch, C.M., 1993, Determination of pressure solution shortening in sandstones, Tectonophysics, v. 227, p. 145-159.
Sans, M., Vergés, J., Gomis, E., Parés, J.M., Schiattarella, M., Travé, A., Cavlet, F., Santanach, P., and Doulcet, A., 2003, Layer parallel shortening in salt-detached folds: constraint on cross-section restoration, Tectonophysics, v., 372, p. 85-104.
Weil, A.B., and Yonkee, A., 2009, Anisotropy of magnetic susceptibility in weakly deformed red beds from the Wyoming salient, sevier thrust belt: relations to layer-parallel shortening and orogenic curvature, Lithosphere, v. 1, no. 4, p. 235-256.
Whitaker, A.E., and Bartholomew, M.J., 1999, Layer parallel shortening: a mechanism for determining deformation timing at the junction of the central and southern Appalachians, American journal of science, v. 299, p. 238-254.
Wiltschko, D.V., Medwedeff, D.A., and Millson, H.E., 1985, Distribution and mechanisms of strain within rocks on the northwest ramp of Pine Mountain block, southern Appalachian foreland: a field test of theory, Geological Society of America Bulletin, v. 96, p. 426-435.

I would like to thank Matthew Peppers and Paula Leek for their assistance in thin section preparation. I would also like to thank my field assistant Shelby Chandler, Steven Odom for graphic support, the University of Nebraska-Lincoln Department of Earth and Atmospheric Sciences for financial support, and Midland Valley Ltd. for an academic license for the MOVE software.