Estimate of Layer Parallel Shortening Using Deformed Mudcrack Polygons in a Leading Edge Fold of the Central Appalachians, Maryland

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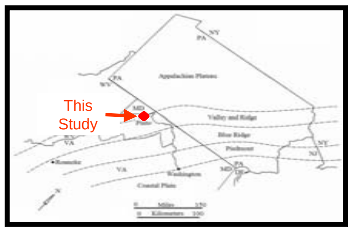
1. Abstract

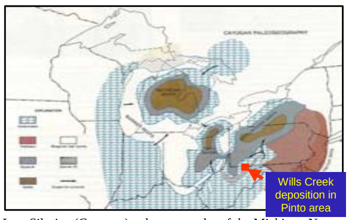
The Wills Mountain anticline is a large-scale, northwestward-vergent leading edge fold of the central Appalachian fold and thrust belt. This fold involves Silurian and Devonian strata which developed during the Alleghenian orogeny above a blind westward-vergent thrust and duplex system that involved Cambro-Ordovician rocks. Nearly vertical Silurian strata in the frontal limb of the Wills Mountain anticline are well exposed in a 0.5-km long outcrop in western Maryland near the town of Pinto. Unique bedding plane exposures of the Silurian Wills Creek Formation in this outcrop reveal deformed mudcrack polygons. The lengths and rakes of long and short axes were measured in 120 deformed polygons. The average ratio between the long and short axes is 1.70, representing 41% layer parallel shortening. Center-to-center analysis of the deformed polygons (n=348) produced an axial ratio of 1.57, corresponding to layer parallel shortening (LPS) of 36%. Restoring the rakes of the short axes of the polygons indicates a northwest-southeast direction for this episode of LPS. To ensure feasibility of a center-to-center analysis of deformed mudcrack polygons, an analysis of modern mudcracks was performed yielding an axial ratio of 1, showing that undeformed mudcrack polygons have an anticlustered distribution of centers. Previous total shortening estimates through this portion of the Appalachians range from 25-40%, based upon layer parallel features, cleavage, and solution loss, while measurements at the Pinto outcrop show approximately 36-41% shortening in layer parallel features alone. Published values of Alleghenian LPS in the Appalachian foreland (e.g. - plateau of northwestern Pennsylvania) range from 9% to 23% and in the hinterland (e.g. - the Blue Ridge of western Virginia) range from 55% to 68%. Our estimates of LPS are intermediate to these end members and reveal a systematic trend of decreasing LPS from the hinterland, through the fold and thrust belt, and into the foreland.

2. Introduction and Background

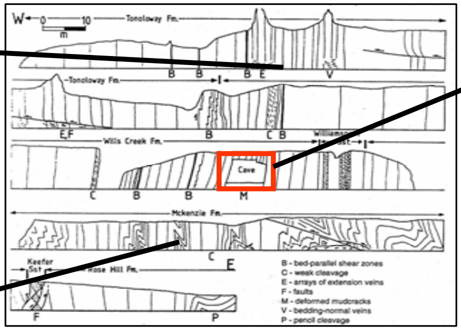
- This purpose of this study is to evaluate deformed mudcrack polygons as strain markers and as a record of layer parallel shortening.
- The study area includes an outcrop on the westward-vergent frontal limb of the Will's Mountain Anticline. This fold is at the leading edge of the Appalachian fold and thrust belt (Valley and Ridge Province).
- The deformed mudcrack polygons are found in the Late Silurian (Cayugan) Wills Creek Formation which consists of shale, calcareous mudrock, and subordinate limestone that was deposited in an evaporite basin.

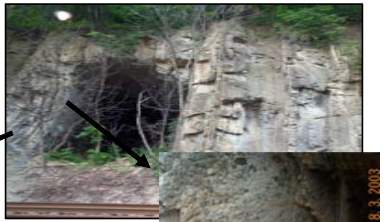


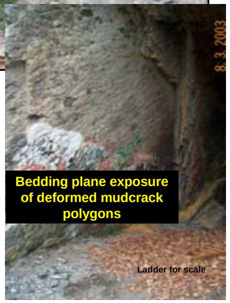
Regional map showing study area at Pinto (base map from Hatcher et. al, 1989).



Late Silurian (Cayugan) paleogeography of the Michigan-New York-Ohio evaporite basin (Prothero and Dott, 2001)

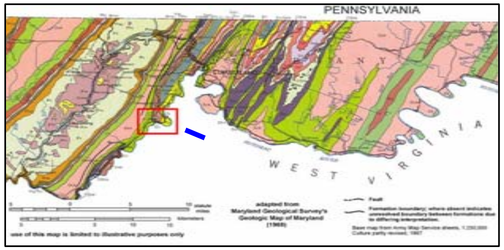




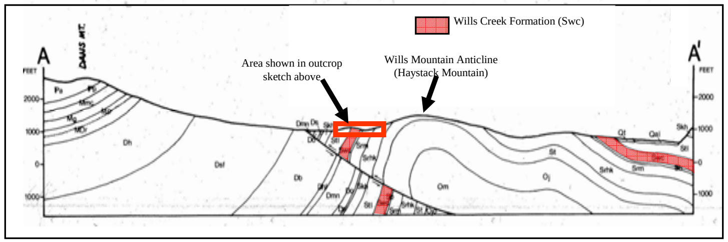


Photos by D. Wolf

Figure 5. Sketch of Pinto railroad outcrop (from Dunne, 1989) and photographs of selected features. Wills Creek Formation bedding plane exposure is found inside of cave in middle of outcrop.



Geologic map of Allegany County, MD. Pinto site location (red outline) along Potomac River just outside town of Pinto, Maryland. Blue line is approximate line of cross section shown at right.



Geologic cross section through the Wills Mountain anticline (Haystack Mountain) (cross section A-A' of Glaser, 1994)

3. Procedures

Field Work

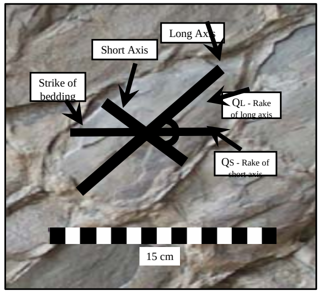
- Bedding surface divided into regions, mudcrack polygons numbered
- Measured length of long and short axes of deformed polygons
- Collected rake of long and short axes of deformed polygons
- Collected scaled digital photographs of outcrop face
- Collected oriented samples of mudcrack polygons

Bedding plane exposure of deformed mudcrack polygons.

Strain Analysis

- Fry center-to-center analysis of modern mudcracks and deformed mudcracks (to ensure feasibility of center-to-center technique on deformed mudcracks)
- Axial ratio determinations of deformed mudcracks

Oriented sample of two deformed mudcrack polygons



Measurements taken for each mudcrack polygon: length and rake of long and short axes.

Stereographic Analysis

- Stereonet analysis to restore deformed polygons to horizontal
- Direction of layer parallel shortening determined from restored short axis of deformed polygons

Literature Search

- Searched for other values of layer parallel shortening across central Appalachian region
- Axial ratios and percentage shortening for various geologic provinces were recorded

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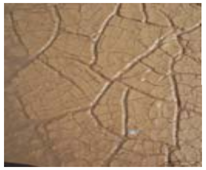
4. Results

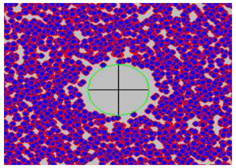
This study:

Center to Center Analysis

Undeformed Mudcrack Polygons

A control analysis was performed on modern undeformed mudcracks. The result indicates 0% shortening, and supports the application of Fry center to center analysis towards studying deformation in mudcrack polygons.

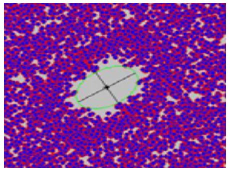




Fry Plot of modern mudcrack polygons
Rs = 1.000, n = 283

Deformed Mudcrack Polygons

Center to center analysis of deformed mudcrack polygons in the Wills Creek Formation indicate 36% shortening.



Fry Plot of deformed mudcrack polygons
Rs = 1.567, n = ###

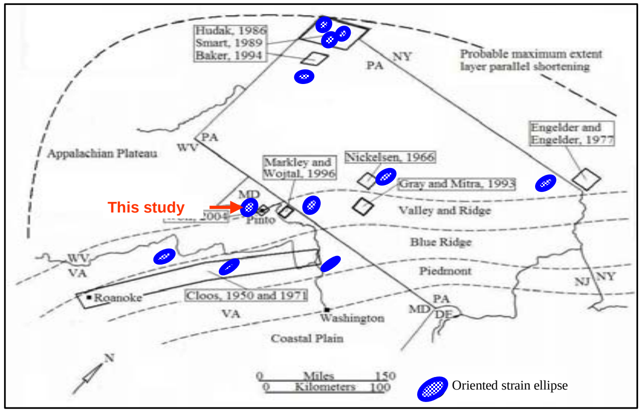
Axial Ratio Determination

The average axial ratio of 120 deformed mudcrack polygons is ####, indicating ##% shortening.

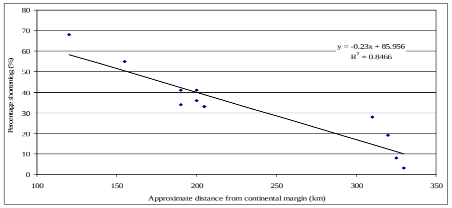
		Strike	Dip	Polygon Long Axis (n=20 per row)	Polygon Short Axis (n=20 per row)	Axial Ratio	Rake Angle of Polygon Long Axis	Rake Angle of Polygon Short Axis
PCW	A	170	75 W	18.79	10.57	1.777	52	39
	B	170	73 W	15.81	9.71	1.629	43	47
	C	172	78 W	19.35	11.16	1.734	48	42
PCE	A	171	77 W	18.14	10.22	1.776	51	39
	B	171	77 W	17.79	10.72	1.660	45	45
	C	171	78 W	18.79	11.44	1.642	42	48

Brief text on results – amount of shortening determined with each method

Regional context:



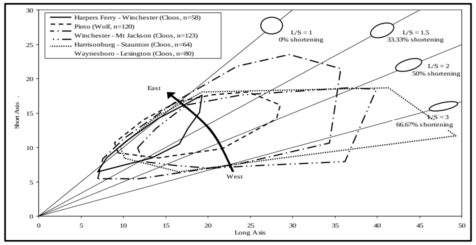
Iso-strain map of Pennsylvania, Maryland, Virginia and West Virginia.



Correlation between distance from continental margin and percentage shortening across central Appalachians.

Table 2. Summary of strain analysis across the central Appalachians

Site Location	Author, Date	Distance From Continental Margin	Average Percentage Shortening	Average Axial Ratios	Restored Short Axis Orientation	Unit Age
Appalachian Plateau	Hudak, 1986	~310-330 km	3% - 8%	1.03 - 1.09	N43W	Devonian and Mississippian
	Smart, 1989		19%	1.23	N43W	
	Baker, 1994		28%	1.386	N7W	
	Nickelsen, 1966	~200-210 km	33%	1.49	N32W	
	Engelder and Engelder, 1977					
Valley and Ridge	Wolf, 2004	~190-200 km	36% - 41%	1.567-1.703	N52W	Silurian
	Markley and Wojtal, 1996		25-40%	1.16-1.67	N50W - N68W	
	Gray and Mitra, 1993	~130 km	Not collected	Not collected	N23W - N50W	
	Cloos, 1950 and 1971	~120-190 km	41%	1.69	N25W	Devonian – Precambrian
Blue Ridge			55% - 68%	2.25 - 3.15		



Axial ratio clusters across the central Appalachian orogen. Data compiled from Cloos (1950 and 1971) and Wolf (2004) → LIST ALL DATA SOURCES

Regional Comparison of Finite Strain

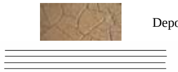
- The amount of shortening in response to the Alleghenian orogeny progressively decreases across the central Appalachians from the Blue Ridge, into the Valley and Ridge, and extending into the Plateau.
- Oriented strain ellipses show a consistent orientation of the primary shortening direction through the region along a northwest – southeast azimuth

5. Conclusions

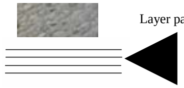
Deformed mudcrack polygons can be used as quantitative strain markers to determine amounts of layer parallel shortening.

The Wills Creek Formation in the frontal limb of the Wills Mountain anticline experienced ~40% layer parallel shortening that preceded regional folding.

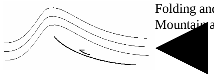
The phases of deformation recorded in the Wills Mountain anticline include:



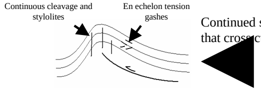
Deposition of Wills Creek Formation.



Layer parallel shortening with $S_{H\ MAX}$ oriented ~128°.



Folding and faulting forming the northwestward vergent leading edge fold (Wills Mountain anticline) of the Appalachian orogen.



Continued shortening with slaty cleavage, stylolites, and tension gashes that crosscut folded beds.

Bulk shortening estimates for the Wills Mountain anticline are 28% north of the Pinto area (Glasser, 1994) and 42% south of the Pinto area (Cleaves et al., 1968). These estimates are based on regional folding and do not include estimates for internal deformation. By including the amount of layer parallel shortening recorded in the deformed mudcrack polygons in the Wills Creek Formation, we estimate between about 60 and 80% total shortening for rocks in the Wills Mountain anticline.

The amount and direction of layer parallel shortening recorded in this study is consistent with a clear trend of decreased Alleghenian deformation from east to west across the central Appalachian orogen.

These features need to be considered when constructing geologic cross sections, attempting cross section restorations, or developing geologic modes of rock behavior.

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Kinematics of Wills Creek Deformation

•Horizontal beds compressed from the East – Southeast, creating layer parallel shortening features such as stylolites, dissolution, solution cleavage and deformation of the layer parallel mudcrack polygons

•Continued compression caused folding and faulting of the unit, reorienting the deformed mudcrack polygons and other bed parallel features

•Another series of layer parallel shortening occurred creating more stylolites, solution cleavage planes, and tension gashes in the unit

The unit experienced multiple phases of deformation, each phase recorded by different rock responses

Site Location	Author, Date	Distance From Continental Margin	Average Percentage Shortening	Average Axial Ratios	Restored Short Axis Orientation	Unit Age	Possible Orogenies		
							Taconian	Acadian	Alleghenian
Appalachian Plateau	Hudak, 1986	~310-330 km	3% - 8%	1.03 - 1.09	N43W	Devonian and Mississippian			×
	Smart, 1989		19%	1.23	N43W				×
	Baker, 1994		28%	1.386	N7W				×
	Nickelsen, 1966	~200-210 km	33%	1.49	N32W				×
	Engelder and Engelder, 1977								×
Valley and Ridge	Wolf, 2004	~190-200 km	36% - 41%	1.567-1.703	N52W	Silurian			×
	Markley and Wojtal, 1996		25-40%	1.16-1.67	N50W - N68W				×
	Gray and Mitra, 1993	~130 km	Not collected	Not collected	N23W - N50W				×
	Cloos, 1950 and 1971	~120-190 km	41%	1.69	N25W	Devonian – Precambrian	×		×
Blue Ridge			55% - 68%	2.25 - 3.15					