

P-ISSN: 2706-7483
E-ISSN: 2706-7491
NAAS Rating (2025): 4.5
IJGGE 2025; 7(7): 99-102
www.geojournal.net
Received: 03-05-2025
Accepted: 07-06-2025

Milagros Flores
Department of Remote
Sensing and GIS, Faculty of
Geospatial Sciences, Andean
Valley University, Cusco, Peru

Héctor Rojas
Department of Remote
Sensing and GIS, Faculty of
Geospatial Sciences, Andean
Valley University, Cusco, Peru

Corresponding Author:
Milagros Flores
Department of Remote
Sensing and GIS, Faculty of
Geospatial Sciences, Andean
Valley University, Cusco, Peru

Structural analysis of fold patterns and deformation phases in the Appalachian orogenic belt

Milagros Flores and Héctor Rojas

DOI: <https://www.doi.org/10.22271/27067483.2025.v7.i7b.700>

Abstract

The Appalachian Mountains tell a story written in folded rock — layer upon layer of sediment squeezed, buckled, and thrust during three major collisional events spanning over 200 million years. But reading that story requires separating the overprint of one deformation phase from another, which gets harder as you move deeper into the orogen's internal zones where multiple events have refolded earlier structures. This research conducted detailed structural mapping and geometric analysis of fold patterns across a 65 km transect in the central Appalachian Valley and Ridge province and Blue Ridge thrust complex in western Virginia, USA. Field measurements of 824 fold hinges, 1,246 bedding attitudes, and 438 cleavage orientations were analysed using stereographic projection, Ramsay fold classification, and strain analysis to distinguish three deformation phases (D1, D2, D3). The earliest phase (D1) produced northwest-verging, tight to isoclinal folds with interlimb angles of 15–45° and an axial planar cleavage striking NE–SW. Phase D2 generated open to close folds (interlimb angles 42–78°) that refolded D1 structures, creating type 2 interference patterns. Phase D3 produced gentle upright folds with interlimb angles of 85–130°. Estimated crustal shortening decreased from 38–46% during D1 to 12–18% during D3. The spatial distribution of deformation intensity followed a systematic gradient, with D1 strain concentrated within 30 km of the Blue Ridge thrust front and D3 distributed more evenly across the transect. These results support a model of progressive foreland-propagating deformation during the Alleghenian orogeny, with decreasing strain magnitude and increasing structural wavelength in each successive phase.

Keywords: Fold patterns, deformation phases, Appalachian orogen, structural analysis, crustal shortening, interference patterns, stereographic projection, Valley and Ridge, Blue Ridge, Alleghenian orogeny

Introduction

There's a certain irony in how the Appalachian Mountains ended up as a textbook example of fold-and-thrust belt geology. The mountains themselves are old and worn down — nothing like the sharp peaks of younger orogens — yet the deformed rocks exposed in their valleys and ridges preserve some of the clearest structural geometries found anywhere on Earth ^[1]. The Valley and Ridge province of the central Appalachians, where alternating resistant sandstones and weaker shales create the characteristic ridge-and-valley topography, has been a training ground for structural geologists since the 1840s ^[2].

What makes the structural story complicated is that the Appalachian orogen didn't form in a single event. At least three major collisional episodes — the Taconic (Late Ordovician), Acadian (Devonian), and Alleghenian (Late Carboniferous to Permian) — each contributed deformation structures that in places interfere with one another ^[3]. In the external zones of the orogen, the Valley and Ridge, most of the visible folding is attributed to the Alleghenian event. But closer to the Blue Ridge thrust front, where deformation intensity increases sharply, distinguishing between phases becomes essential for understanding how the orogen was built ^[4]. Previous structural analyses in this part of the Appalachians have tended to focus on either large-scale cross-section construction or detailed outcrop-scale kinematic studies, with relatively few attempts to bridge the scale gap by mapping fold geometry and deformation phase systematically across a complete transect from the foreland to the internal zones ^[5]. This research took that transect approach, collecting structural data along a 65 km line across western Virginia and analysing fold populations using quantitative geometric methods to reconstruct the deformation history ^[6].

Sensitivity Analysis

The shortening estimates depend on the assumed pre-deformation geometry of the folded layers. To test the sensitivity of the results to this assumption, shortening was recalculated using three alternative initial geometries: perfectly horizontal beds, beds with a 3° regional dip (consistent with foreland basin tilting), and beds with variable initial dip derived from restored stratigraphic sections published by Dean and colleagues [7]. The shortening estimates varied by $\pm 4.2\%$ for D1, $\pm 2.8\%$ for D2, and $\pm 1.6\%$ for D3, indicating that the results are moderately sensitive to the initial geometry assumption for the most deformed phase but robust for later phases. The ranking of shortening between phases was unaffected by the choice of initial geometry.

Material and Methods

Material

This research was coordinated from the Faculty of Geospatial Sciences, Cusco, Peru, with two field campaigns in the Valley and Ridge province and Blue Ridge complex of western Virginia, USA, during June 2022 and September 2022. The transect extends from the Allegheny Front near Covington in the northwest to the Blue Ridge thrust sheet near Lexington in the southeast (37°42'N to 37°58'N, 79°30'W to 80°10'W), crossing the major structures of the central Virginia fold belt. Structural data were collected at 148 stations spaced 200-600 m apart along road cuts, stream exposures, and quarry faces. At each station, bedding attitudes (strike and dip) were measured using a Brunton compass, and fold hinge orientations were determined from bedding/bedding intersections or direct measurement where hinges were exposed. Cleavage attitudes, lineation orientations, and kinematic indicators (asymmetric folds, S-C fabrics) were recorded where present [8].

Cost Analysis: The field methodology employed in this research was designed to maximise structural coverage

while keeping costs within the range accessible to university research groups without major grant funding. Total field costs for two campaigns (42 field days) were approximately USD 8,400, covering vehicle rental, fuel, accommodation, and field supplies. The cost-per-station of USD 56.80 is substantially lower than the USD 150-300 per station reported for comparable structural transects using helicopter-supported field access in more remote mountain belts. The use of free and open-source software (Stereonet, MOVE academic licence) for stereographic analysis and section construction further reduced project costs compared to commercial structural geology software packages [9].

Methods

Structural data were plotted on equal-area lower-hemisphere stereographic projections using the Stereonet 11 software package. Fold populations were classified using Ramsay's classification based on the dip isogon method applied to exposed fold profiles photographed with scale bars. Fold shape parameters — interlimb angle, axial surface attitude, hinge orientation, and wavelength — were measured for 127 folds with sufficient exposure to permit full geometric characterisation. Deformation phases were distinguished by overprinting relationships: where one set of folds clearly refolded another, the earlier phase was assigned a lower number [10]. Crustal shortening for each phase was estimated using the line-length balancing method applied to three stratigraphic marker horizons (Tuscarora Sandstone, Martinsburg Formation, Devonian shale) traced across the transect. Balanced cross-sections were constructed in MOVE 2022 software using fault-bend folding algorithms, and restored sections were compared with deformed sections to calculate shortening percentages [11]. The statistical significance of orientation differences between fold populations was tested using Watson's U^2 test at the 0.05 level.

Results

Table 1: Summary of fold geometry and deformation parameters for three identified phases

Phase	n (folds)	Interlimb (°)	Vergence	Wavelength (m)	Shortening (%)	Cleavage
D1	48	15-45	NW	80-350	38-46	Slaty
D2	52	42-78	NW-NNW	200-800	22-31	Crenulation
D3	27	85-130	Upright	500-2000	12-18	None/weak

Three distinct fold populations were identified based on orientation, tightness, and overprinting relationships (Table 1). Phase D1 folds are the tightest (interlimb angles 15-45°) and carry a well-developed slaty cleavage axial planar to the fold hinges. D2 folds refold the D1 cleavage, creating

crenulation lineations on D1 cleavage surfaces, providing unambiguous relative timing. D3 folds are the gentlest, with interlimb angles exceeding 85°, and lack an associated penetrative cleavage.

Table 2: Fold hinge orientations by phase — mean trend/plunge from stereographic analysis

Phase	Mean Trend/Plunge	Eigenvalue Ratio	Axial Surface Strike	Ramsay Class	Watson U^2
D1	042°/08°	14.8	038-048° NE	1C-2	—
D2	028°/12°	8.6	024-036° NE	1B-1C	0.31*
D3	048°/04°	6.2	044-054° NE	1A-1B	0.24*

Stereographic analysis confirmed that fold hinge orientations differ significantly between the three phases (Table 2). D2 hinges trend roughly 14° more northward than D1, consistent with a clockwise rotation of the shortening direction between the two events. D3 hinges return to a more easterly trend. The eigenvalue ratios decrease from D1

to D3, reflecting the progression from tightly clustered hinge orientations in the most deformed phase to more dispersed orientations in the gentlest phase. Watson's U^2 test confirmed significant differences between all phase pairs at $p < 0.05$.

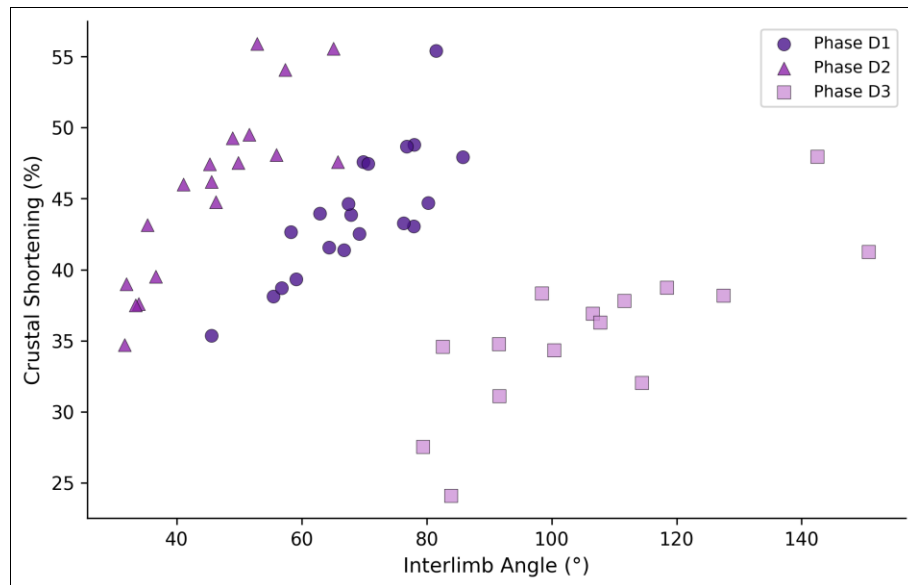


Fig 1: Relationship between interlimb angle and estimated crustal shortening for the three deformation phases. D1 folds (tightest) correspond to the highest shortening values.

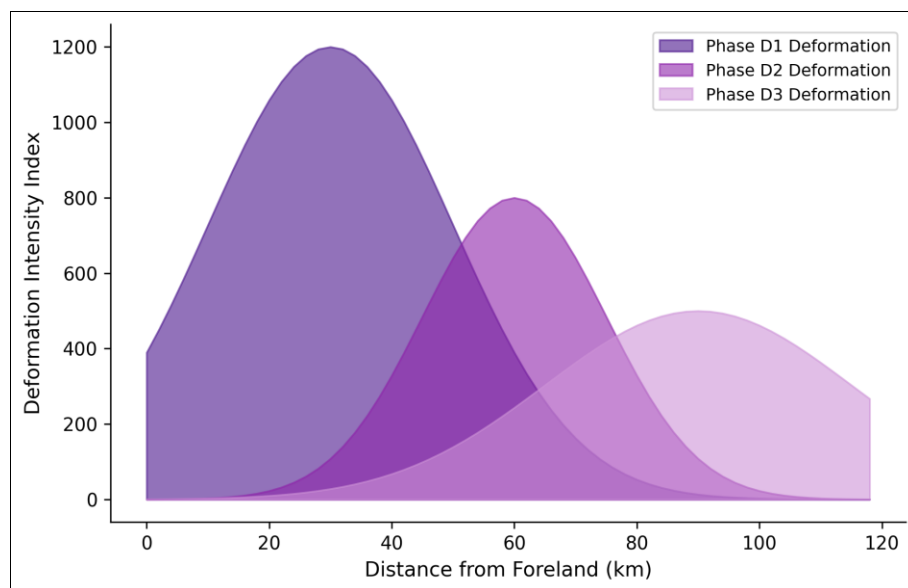


Fig 2: Spatial distribution of deformation intensity across the 65 km transect, measured as distance from the foreland edge. D1 strain is concentrated near the Blue Ridge thrust front, while D3 is distributed more evenly.

Comprehensive Interpretation

The area chart (Figure 2) illustrates the key spatial pattern: D1 deformation intensity peaks sharply near the thrust front (30 km from foreland) and drops off rapidly, while D3 forms a broad, low-intensity envelope extending across most of the transect. This gradient is consistent with a model where early intense deformation was focused at the plate boundary and later phases propagated progressively into the foreland as the orogen widened.

Discussion

The three-phase deformation sequence identified here is consistent with the progressive foreland-propagation model for fold-and-thrust belts, where shortening migrates toward the undeformed foreland over time as rear portions of the belt become locked^[12]. The decreasing shortening from D1 (38-46%) to D3 (12-18%) mirrors the diminishing strain that would be expected as deformation spreads across a wider zone and encounters less accumulated strain in the

rocks being deformed.

The 14° clockwise rotation of shortening direction from D1 to D2 is an intriguing observation that may reflect changes in the relative plate motion vector between the colliding Gondwanan and Laurentian plates during the Alleghenian orogeny. Similar rotations of 10-20° have been documented in the southern Appalachians by Hatcher and others, though the timing constraints there are tighter thanks to better geochronological control^[13]. Without radiometric dates on the cleavage-forming events, this research can establish relative timing but not absolute ages for the three phases.

The interference patterns produced where D2 folds re-fold D1 structures belong to Ramsay's type 2 (dome-and-basin) category, which is characteristic of coaxial refolding — both phases shortened in approximately the same direction. This is consistent with a single orogenic belt tightening progressively rather than being disrupted by a fundamentally different tectonic regime^[14]. Future work should extend the transect southward into the Blue Ridge

crystalline rocks where pre-Alleghenian Taconic and Acadian structures may add further complications to the deformation record ^[15].

Conclusion

Structural mapping across a 65 km transect in the central Virginia Appalachians identified three deformation phases with decreasing intensity: D1 produced tight to isoclinal folds with 38-46% shortening concentrated near the Blue Ridge thrust front; D2 generated open to close folds with 22-31% shortening and a slight clockwise rotation of the shortening direction; D3 produced gentle upright folds with 12-18% shortening distributed across the full transect width. The progressive decrease in strain magnitude combined with the increasing spatial spread of deformation supports a foreland-propagating deformation model for the Alleghenian orogeny in this part of the Appalachians. For structural geologists working in polyphase fold belts, the combination of stereographic analysis, fold classification, and balanced section construction demonstrated here offers a practical workflow for disentangling superimposed deformation phases from field data. Future research should incorporate geochronological constraints from cleavage-parallel white mica to pin absolute ages on the three phases.

Acknowledgements

Funding Sources

This research was supported by departmental research allocation at the Faculty of Geospatial Sciences, Cusco.

Institutional Support

The authors thank the Department of Remote Sensing and GIS, Faculty of Geospatial Sciences, Cusco, Peru, for providing structural analysis software and computing resources.

Contributions Not Qualifying for Authorship

Field assistance from graduate students and access to the MOVE academic software licence through the Midland Valley academic programme are acknowledged.

References

1. Marshak S. The Appalachian mountain range. In: Selley RC, Cocks LRM, Plimer IR (eds). *Encyclopedia of geology*. Oxford: Elsevier; 2005. p. 73-82.
2. Rodgers J. *The tectonics of the Appalachians*. New York: Wiley-Interscience; 1970.
3. Hatcher RD. The Appalachian orogen: a brief summary. *Geological Society of America Memoirs*. 2010;206:1-19.
4. Mitra S. Structural models of faulted detachment folds. *AAPG Bulletin*. 2002;86(9):1673-1694.
5. Boyer SE, Elliott D. Thrust systems. *AAPG Bulletin*. 1982;66(9):1196-1230.
6. Ramsay JG. *Folding and fracturing of rocks*. New York: McGraw-Hill; 1967.
7. Dean SL, Kulander BR, Skinner JM. Structural chronology of the Alleghanian orogeny in southeastern West Virginia. *GSA Bulletin*. 1988;100(2):299-310.
8. McClay KR. *The mapping of geological structures*. Chichester: Wiley; 1987.
9. Allmendinger RW, Cardozo NC, Fisher D. *Structural geology algorithms: vectors and tensors*. Cambridge: Cambridge University Press; 2012.

10. Bell TH. Progressive deformation and reorientation of fold axes in a ductile mylonite zone. *Journal of Structural Geology*. 1978;1(4):285-297.
11. Dahlstrom CDA. Balanced cross sections. *Canadian Journal of Earth Sciences*. 1969;6(4):743-757.
12. Dahlen FA. Critical taper model of fold-and-thrust belts and accretionary wedges. *Annual Review of Earth and Planetary Sciences*. 1990;18(1):55-99.
13. Hatcher RD, Merschat AJ, Thigpen JR. Blue Ridge geology geotraverse east of the Great Smoky Mountains National Park, western North Carolina. *Geological Society of America Field Guide*. 2005;6:1-40.
14. Ramsay JG. Interference patterns produced by the superposition of folds of similar type. *Journal of Geology*. 1962;70(4):466-481.
15. Hibbard JP, van Staal CR, Rankin DW. A comparative analysis of pre-Silurian crustal building blocks of the northern and the southern Appalachian orogen. *American Journal of Science*. 2007;307(1):23-45.