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Fractal strain distribution and its implications for cross-section balancing: Discussion

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INTRODUCTION

Wu (1993) makes three major points in his paper: (a) Deformation at the outcrop- and microscale is important when assessing shortening of rock sequences during the construction of regional balanced cross-sections. (b) Shortening at different scales has a fractal relationship. (c) The cover or roof sequence above the Cacapon Mountain duplex in the central Appalachians locally compensated the emplacement of this blind thrust system. We wholeheartedly agree with the first point. A balanced cross-section does not truly achieve that status until smaller scale deformation is demonstrated to be insignificant or is included from direct measurement (e.g. Herman 1984, Herman & Geiser 1985). Our concerns center on the methodology and the resulting conclusion that the roof sequence locally compensated blind thrusting.

APPLICATION OF FRACTAL ANALYSIS

Wu states at the top of p. 1504 that D (fractal dimension) = 1.001 for the Cambro–Ordovician carbonates, meaning that "not much deformation has occurred on smaller scales" in this rock unit. Just to the southeast, the carbonates have essentially the same duplex geometries and profile shapes within the North Mountain thrust sheet (Evans 1989). They should yield almost exactly the same D, and as a result, would also be interpreted to lack significant smaller scale deformation. They actually experienced a total shortening of 10–15% at the microscale, which exceeds 30% locally (Cloos 1971, Dean & Kulander 1972, Evans & Dunne 1991). The present methodology fails to detect this microscale deformation because the analysis depends on a fractal dimension that describes the amount of a plane covered by a one-dimensional curve, or in essence, describes the complexity of curve shape. If deformation does not produce long complex profile shapes from pre-existing marker lines, D is small and shortening below the initial measurement scale is calculated as small. The profile curves or preferably layers should be analyzed as two-dimensional objects that account for changes in curve width and length, as well as complexity of curve shape. Conceivably, a fractal analysis that examines all scales for a one-dimensional object should acquire the strain from microscale deformations, but this methodology fails because it depends only on complexity of curve shape.

Another example of this problem concerns the profile shape at the top of the Silurian Tuscarora Sandstone (St in fig. 4 of Wu 1993), which is part of the roof sequence below the chosen marker at the base of the Silurian Bloomsburg Formation (base of DS in fig. 4 of Wu 1993). More thrusts and folds deform the St profile at section scale than the DS profile, and therefore, St has 4.36 km more section-scale shortening (fig. 5 in Wu 1993). The greater complexity of curve shape should mean that the St profile has a greater fractal dimension (D) than the DS profile, indicating greater complexity of structure along the St profile for increasing resolution (r). Yet, studies of microscale deformation reveal that the Tuscarora Sandstone has equivalent rather than greater deformation (Ferrill & Dunne 1989, Onasch 1994). Also, outcrop-scale investigations demonstrate that the Tuscarora Sandstone has much less mesoscale structural complexity than rocks in the DS unit (Cloos 1951, Dennison 1955, Perry 1971, Dunne & Schultz 1986, Ferrill & Dunne 1989, Scott & Dunne 1990, Adamson 1992). These direct observations are inconsistent with predictions from this type of fractal analysis.

A key assumption for Wu's analysis is that the base of the DS, which corresponds to the base of the Bloomsburg Formation, has a profile shape that is representative of the entire roof sequence from the roof detachment in Ordovician rocks to the youngest Devonian rocks at the surface. The base of the DS was chosen because it has a limited number of faults and overturned folds, which means that the profile should mostly yield single y values for the Fourier transform calculation. The base of the DS is not representative of the majority of the overlying Devonian sequence, which lacks thrusts and has much less folding than the DS profile (fig. 4 in Wu 1993). Further, the DS is not representative of the underlying rock units of the Silurian Tuscarora Sandstone to Ordovician Oswego Formation (St, Oj, Oo in fig. 4 of Wu 1993) because those units have more faults and folds than the DS with 4.36 km more shortening (fig. 5 in Wu 1993). Thus, a fractal analysis of the profile shape for the base of the DS is not representative of the entire roof sequence. In the context of the analysis, the fractal dimension (D) should be noticeably smaller for the younger Devonian units, and larger for the older Silurian to Ordovician units. These differences in fractal dimension should also mean that the Devonian units are much less deformed at scales smaller than the section, whereas the older units are more deformed. These scale-dependent differences in deformation by stratigraphic unit are not found (Cloos 1951, Ferrill & Dunne 1989, Schultz in press).

The generation of fractal descriptors does not necessitate a fractal behavior for the modified rocks. Two different measures (spectral method and compass method) of fractal dimension yield internally consistent results, which is a successful test of model applicability. Yet, this consistency does not sufficiently demonstrate that fractals provide a uniquely correct description of deformation in the roof sequence. Structural geologists since at least Pumpelly (1918) knew that small structures are useful indicators of morphology for larger structures, but such relationships are not necessarily fractal. The applicability of a fractal approach would be more convincing if other possibilities such as stochastic or deterministic systems were also considered and successfully discounted.

NECESSITY OF LOCAL COMPENSATION

Wu states (pp. 1498–1499) that the roof sequence requires another response besides forethrusting because the behavior necessitates the accommodation of 10's to 100's of km of blind thrust displacement as shortening in the Appalachian Plateau. As Wu correctly states, the Appalachian Plateau lacks this intensity of deformation. However, this requirement is not valid because the necessity of intense shortening in the Plateau is incorrect. The potential sources of the greater than 100 km of blind thrust displacement are the Wills Mountain duplex (WMD, Fig. 1), Cacapon Mountain duplex (CMD, Fig. 1), and the North Mountain thrust sheet (Fig. 1). First, Evans (1989, 1990) has cogently shown that the North Mountain thrust sheet did not transfer +60 km of displacement under the Valley and Ridge province along a roof thrust in the Ordovician Martinsburg Formation (dashed line, Fig. 1). This displacement was transferred along the North Mountain thrust (NMT, Fig. 1). Second, strain and map-scale fault and fold intensities of the roof sequence increase across the Broadtop synclinorium (BTS, Fig. 1) toward the Cacapon Mountain anticlinorium and underlying duplex (Jacobeen & Kanes 1974, Nair *et al.* 1991; Schultz in press). This increasing deformation intensity in the roof sequence toward an underlying blind duplex is consistent with forethrusting (Dunne & Ferrill 1988, Geiser 1988), where displacement is not rigidly transferred forward as supposed by Wu, but instead is accommodated by deformation forelandward of the leading branch line of the blind duplex. Thus, the roof sequence has accommodated up to 20 km of displacement from the Cacapon Mountain duplex by deformation in the roof sequence of the Broadtop Synclinorium. As a result, the remaining 20 km of displacement from the Wills Mountain duplex is all that the Plateau rocks must accommodate. Such an amount is not unreasonable because microscale deformation alone accommodates about 15 km in the Plateau of Pennsylvania and New York (Engelder & Geiser 1979, Engelder 1979). Thus, the displacements from all blind duplexes in the Cambro-Ordovician carbonates do not accrue in the Plateau, and forethrusting would be the dominant kinematic response.

Wu states (p. 1504 bottom left) that "the shortening produced by these structures (i.e. fourth- and fifth-order folds) in this scale range is estimated to be about 10%". This 10% is also the local shortening imbalance between duplex and roof sequence that micro- and mapscale shortenings do not accommodate. If present, this intermediate scale of deformation would eliminate the imbalance. Yet, the existence and magnitude of this intermediate scale of deformation are stated but never documented, except for one piece of anecdotal evidence (fig. 10 in Wu 1993). This figure illustrates fifth-order folds in a sequence with well-developed cleavage. Small-scale folds and faults are common in stiff interbeds without cleavage in sequences dominated by fine-grained lithologies that deformed by cleavage formation (Cloos 1951, Ferrill & Dunne 1989). For example, cleavage-related strain in limestones was calibrated from shortening of stiff interbeds by contraction faults (Alvarez *et al.* 1978). Most fifth-order folds in Cacapon Mountain anticlinorium also formed in stiff uncleaved layers while cleavage developed in thick less competent interbeds (Ferrill 1987, 1989, Ferrill & Dunne 1989). Thus, the shortening contribution of the fifth-order folds is already in the measured microscale component of deformation that includes cleavage formation (Ferrill & Dunne 1989). Consequently, the 10% shortening estimate for intermediate scale deformation is unsupported by any direct evidence. Yet, this estimate is crucial to Wu's conclusion that "the cover sequence has a comparable shortening to that in the underlying blind thrust sheet". Lack of proof for the estimate implies that the related conclusion is not validated.

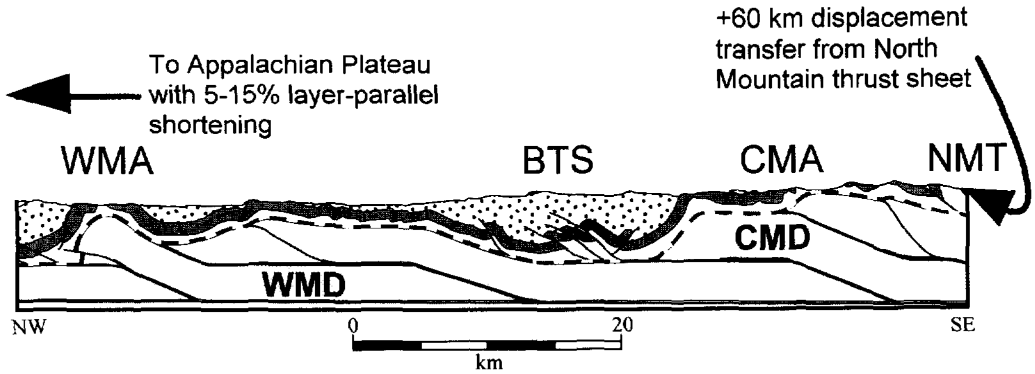

Fig. 1. Regional cross-section across the Valley and Ridge province of the central Appalachians. BTS—Broadtop synclinorium, CMA—Cacapon Mountain anticlinorium, CMD—Cacapon Mountain duplex, NMT—North Mountain thrust, WMA—Wills Mountain anticlinorium, WMD—Wills Mountain duplex. Light grey shading—Cambro-Ordovician carbonates; dark grey—upper Ordovician to lower Devonian rocks of the roof sequence; spots—lower Devonian to Mississippian rocks of the roof sequence; thick dashed line—roof detachment for blind duplex in Ordovician Martinsburg Formation.

CONCLUSIONS

While Wu correctly considers deformation at all scales when balancing regional cross-sections, this particular attempt does not succeed because: (1) The methodology does not detect penetrative deformations that do not complicate the shape of reference curves. (2) One of the two profile markers (base of DS) is not representative. (3) The analysis has some internal consistency but is not demonstrated to be uniquely correct. (4) A constraint that requires local compensation of blind thrusting is incorrect. (5) An 'estimate' for intermediate-scale deformation is undocumented and the presented anecdotal evidence is misinterpreted.

REFERENCES

Adamson, G. W. 1992. Fold development in the cover enveloping the Broadtop Horse. Unpublished M.S. thesis, West Virginia University.

Alvarez, W., Engelder, T. & Geiser, P. A. 1978. Classification of solution cleavage in pelagic sediments. *Geology* **6**, 263–266.

Cloos, E. 1951. Structural geology of Washington County. In: *The physical features of Washington County: Maryland Department of Geology, Mines, and Water Resources Report* **14**, 124–163.

Cloos, E. 1971. *Microtectonics along the Western Edge of the Blue Ridge, Maryland and Virginia*. John Hopkins University Press, Baltimore.

Currie, N. B., Patnode, M. W. & Trump, R. P. 1962. Development of folds in sedimentary strata. *Bull. geol. Soc. Am.* **73**, 655–674.

Dean, S. L. & Kulander, B. R. 1972. Oolite deformation associated with faulting in the northern Shenandoah Valley. In: *Appalachian Structure, Origin, Evolution and Possible Potential for New Exploration Frontiers* (edited by Lessing, P., Hayhurst, R. I., Barlow, J. A. & Woodfork, L. D.). West Virginia Geological and Economic Survey, Morgantown, West Virginia, 103–139.

Dennison, J. M. 1955. Geology of the Keyser and part of the Lonaconing 7.5-minute topographic quadrangles. Unpublished M.S. thesis, West Virginia University.

Dunne, W. M. & Ferrill, D. A. 1988. Blind thrust systems. *Geology* **16**, 33–36.

Dunne, W. M. & Schultz, D. P. 1986. A mesoscopic thrust system in West Virginia: Its deformation history and regional importance. *Southeastern Geology* **26**, 131–139.

Engelder, T. 1979. Mechanisms for strain within the upper Devonian clastic sequence of the Appalachian Plateau, western New York. *Am. J. Sci.* **279**, 527–542.

Engelder, T. & Geiser, P. 1979. The relationship between pencil cleavage and lateral shortening within the Devonian section of the Appalachian Plateau, New York. *Geology* **7**, 460–464.

Evans, M. A. 1989. The structural geology and evolution of foreland thrust systems, northern Virginia. *Bull. geol. Soc. Am.* **101**, 359–354.

Evans, M. A. 1990. Reply to "The structural geometry and evolution of foreland thrust systems, northern Virginia: Alternative interpretation and reply". *Bull. geol. Soc. Am.* **102**, 1444–1445.

Evans, M. A. & Dunne, W. M. 1991. Strain factorization and partitioning in the North Mountain thrust sheet, central Appalachians, U.S.A. *J. Struct. Geol.* **13**, 21–35.

Ferrill, D. A. 1987. Analysis of shortening across Cacapon Mountain anticlinorium in the central Appalachians of West Virginia. Unpublished M.S. thesis, West Virginia University.

Ferrill, D. A. 1989. Primary crenulation pencil cleavage. *J. Struct. Geol.* **11**, 457–461.

Ferrill, D. A. & Dunne, W. M. 1989. Cover deformation above a blind duplex: an example from West Virginia, U.S.A. *J. Struct. Geol.* **11**, 421–431.

Geiser, P. A. 1988a. Mechanisms of thrust propagation: some examples and implications for the analysis of overthrust terranes. *J. Struct. Geol.* **10**, 829–845.

Herman, G. C. 1984. A structural analysis of a portion of the Valley and Ridge province of Pennsylvania. Unpublished M.S. thesis, University of Connecticut.

Herman, G. C. & Geiser, P. A. 1985. A "passive roof duplex" solution for the Juniata Culmination; central Pennsylvania. *Geol. Soc. Am. Abs. w Prog.* **17**, 24.

Jacobeen, F., Jr. & Kanes, W. H. 1974. Structure of Broadtop synclinorium and its implications for Appalachian structural style. *Bull. Am. Ass. Petrol. Geol.* **58**, 362–375.

Nair, N., Dean, S. L., Kulander, B. R. & Lessing, P. 1991. Crinoid deformation in the Valley and Ridge of eastern West Virginia and northwestern Virginia. *Geol. Soc. Am. Abs. w Prog.* **23**, A108.

Nickelsen, R. P. 1963. Fold patterns and continuous deformation mechanisms of the central Pennsylvania folded Appalachians. In: *Tectonics and Cambrian-Ordovician Stratigraphy in the Central Appalachians of Pennsylvania: Pittsburgh Geological Society and Appalachian Geological Society Guidebook*, 13–29.

Onasch, C. M. 1994. Assessing brittle volume-gain and pressure solution volume-loss processes in quartz arenite. *J. Struct. Geol.* **16**, 519–530.

Perry, W. J. Jr. 1971. Structural development of the Nittany anticlinorium, Pendleton County, West Virginia. Unpublished Ph.D. dissertation, Yale University.

Pumpelly, R. 1918. *My Reminiscences.* Henry Holt & Co., New York.
Schultz, A. In press. Geology of the Broadtop synclinorium within the Winchester 30′ by 60′ quadrangle. *Bull. U.S. geol. Surv.*
Scott, P. B. & Dunne, W. M. 1990. Deformation history of an outcrop-scale fault system in the central Appalachians. *Southeastern Geology*, **31**, 93–107.
Wu, S. 1993. Fractal strain distribution and its implication for cross-section balancing. *J. Struct. Geol.* **15**, 1497–1507.