Pergamon

Journal of Structural Geology, Vol. 16, No. 5, pp. 613 to 618, 1994

0191-8141/94 $07.00+0.00

The role of strain in area-constant detachment folding

RICHARD H. GROSHONG, JR and JEAN-LUC EPARD*

Department of Geology, University of Alabama, Tuscaloosa, AL 35487-0338, U.S.A.

(*Received* 5 *January* 1993; *accepted in revised form* 5 *July* 1993)

Abstract—The classical constant-area relationship for balancing cross-sections is reformulated to accommodate layer-parallel strain leading to a general equation for the layer-parallel strain in a fold formed above a stratigraphically fixed detachment horizon. The strain required for area balance can be calculated from a knowledge of the fold shape and the depth to detachment. The strains predicted from a simple kinematic model are realistic, in the order of 10–30% layer-parallel shortening. The strain may be penetrative or occur as small-scale disharmonic folds and faults. The Tip Top anticline, a fold at the leading edge of the Wyoming thrust belt, is used to illustrate the applicability of this reformulation. The computed layer-parallel strains in the well-controlled upper portion of the structure are less than 5% because most of the shortening is accommodated by second-order folds and faults.

INTRODUCTION

A DETACHMENT fold forms above the region in which the displacement on the basal detachment dies out (Jamison 1987). In the first paper on balanced cross-sections, Chamberlin (1910) proposed a method for calculating the depth to the detachment based on the excess area, which is the area of material in a fold that is uplifted by deformation to a position above its original datum level (Fig. 1). The excess area is equal to the displacement times the depth to detachment. Chamberlin (1910) used this relationship with measurements of excess area and displacement as determined from fold width and bed length to find the depth to detachment. In many examples the calculation fails to produce the correct depth to detachment. This problem was first recognized by Bucher (1933) and more recently addressed by Jones (1987), Geiser (1988b), Mitra & Namson (1989) and Dahlstrom (1990). The excess area is equal to the area displaced above the detachment

$$S = Dh, \tag{1}$$

where S = excess area, D = displacement and h = depth to detachment (Fig. 1). To determine the detachment depth from this equation, the displacement must be known. Chamberlin (1910) assumed that the curved-bed length between the pin lines of a unit in the fold was the original bed length, L_0^*. The final length between the pin lines is the width of the fold at regional for that unit, W, so that the displacement is

$$D = L_0^* - W. \tag{2}$$

Equation (2) is substituted into (1) and solved for the depth to detachment to give

$$h = S/(L_0^* - W). \tag{3}$$

Two related problems arise from the use of equation (3). First, the calculated depth to detachment is often too deep. For example, Chamberlin (1910) applied his method to the central Appalachian fold–thrust belt and computed a detachment at a variable depth of from 9.2 to 52.6 km. It is now well known, however, that the basal detachment is planar and lies at a depth of about 8 km (Gwinn 1964, Herman 1984, Geiser 1988a, Mitra & Namson 1989). Second, a constant bed-length fold may be kinematically impossible above a stratigraphically fixed detachment horizon. A fold that decreases in width as it grows in amplitude while maintaining constant bed length (Fig. 2) implies a detachment that rises as the fold shortens. Yet, it seems more likely that the detachment horizon is stratigraphically fixed and remains constant throughout the deformation.

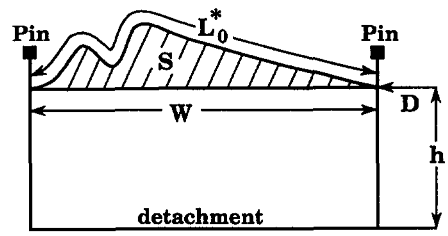

Fig. 1. The relationship between excess area (S) and depth to detachment (h) as formulated by Chamberlin (1910) and Bucher (1933). L_0^* = curved bed length, W = final width of fold, D = displacement.

Here we propose that layer-parallel strain, which has been neglected previously, is the key to resolving the depth-to-detachment problem and to developing a general kinematic model for detachment folding. The strains required for area balance will be shown to be realistically small. Use of the new formulation in the design and interpretation of a balanced cross-section is illustrated with the Tip Top anticline, a map-scale structure at the front of the Wyoming thrust belt.

STRAIN AND AREA BALANCE

The fundamental equation for area balance, equation (1), is unchanged from Chamberlin's (1910) concept.

*Present address: Institut de Géologie et Paléontologie, Université de Lausanne, BFSH2, CH-1015 Lausanne, Switzerland.

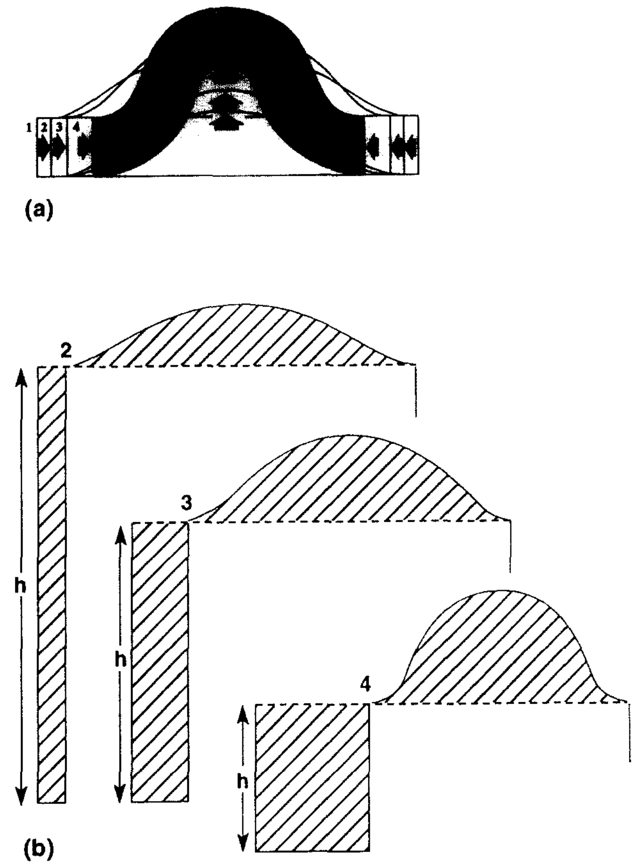

Fig. 2. Constant bed-length folding and change in depth to detachment, redrawn from Jones (1987). (a) Evolution of constant bed-length fold from deSitter (1956). (b) Calculated depths to detachment (equation 3) for the three stages of folding.

The new formulation arises from the recognition that the curved-bed length observed on the deformed-state cross-section (L_0^* on Fig. 1), is the deformed length, L_1, (Fig. 3) and not necessarily the original bed length. The original bed length (Fig. 3) is

$$L_0 = W + D, \tag{4}$$

where L_0 = original bed length, W = width of the fold at regional for the stratigraphic unit of interest and D = displacement. The layer-parallel strain is calculated from

$$e = (L_1 - L_0)/L_0. \tag{5}$$

Solving (1) for D, substituting this into (4) and the result into (5) gives the strain in terms of quantities that can be directly measured on a cross-section

$$e = (L_1 h/(hW + S)) - 1. \tag{6}$$

The value of e calculated from equation (6) is here termed the *requisite* strain. It is the amount of layer-parallel strain required for the given cross-section to be area constant.

Layer-parallel strain is not required for area balance in all beds or in all folds. If bed length is constant ($L_1 = L_0$), then $e = 0$ and

$$L_1 = (hW + S)/h. \tag{7}$$

This equation must be satisfied by any unit for which the bed length remains constant. In this instance alone, equation (3) gives the correct depth to detachment.

Finding the requisite strain requires knowing the geometry of the bed between where it departs from and returns to regional, and also knowing the depth to detachment. If the detachment depth is not known from direct observation, it should be determined from an excess-area graph (Groshong & Epard 1992, Epard & Groshong 1993). An excess-area graph is a plot of the excess areas of several horizons in the fold vs depth. For an area-constant detachment fold, the relationship is a straight line that intersects zero on the excess-area axis at the detachment. The method will be illustrated in the later example from the Tip Top anticline.

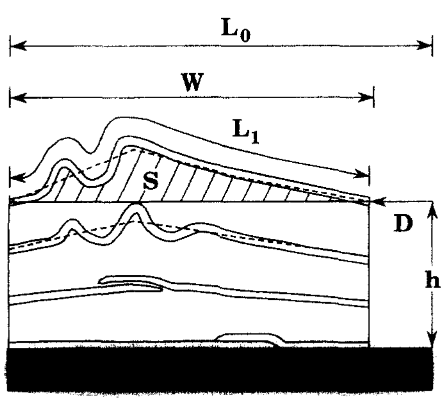

Fig. 3. The relationship between excess area (S) and depth to detachment (h) allowing the final bed length (L_1) to be different than the original (L_0). W = width of the fold, D = displacement. The dashed lines show the positions of homogeneously strained beds enclosing the same excess area as the constant-length, solid-line beds.

KINEMATIC MODEL

A representative kinematic model for the evolution of a detachment anticline is given here to illustrate the type of geometric and strain history that is possible above a stratigraphically fixed detachment horizon. The model is representative in the sense that a number of different model geometries and different evolutionary histories tend to give similar results in terms of strain magnitude and strain history (Epard & Groshong in preparation).

Assume that the fold has planar limbs, a vertical axial

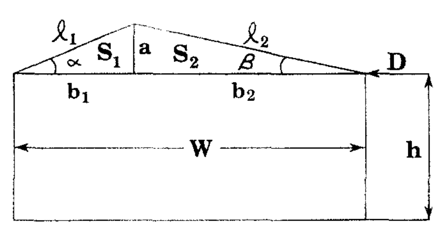

Fig. 4. Area balance of a single horizon above a fixed detachment, assuming planar fold limbs. The limb dips are α and β. The anticline is divided into two triangles of amplitude a with bases b_1 and b_2, bed lengths l_1 and l_2, and areas S_1 and S_2. D is displacement and h is depth to detachment.

surface, vertical pin-line boundaries and that the excess area takes the form of two right triangles (Fig. 4). The excess area is

$$S = S_1 + S_2 = (a/2)(b_1 + b_2), \quad (8)$$

where a is the amplitude of the fold and b_1 and b_2 are the widths of the short and long limbs, respectively. The fold amplitude as a function of displacement and the original bed length in the fold is found by substituting (1) and (4) into (8) and noting that $b_1 + b_2 = W$, to give

$$a = 2\,Dh/(L_0 - D). \quad (9)$$

The limb-dips, α and β, are found from their widths and the fold amplitude as

$$\tan\alpha = a/b_1 \quad (10a)$$

$$\tan\beta = a/b_2, \quad (10b)$$

and the limb lengths l_1 and l_2 are

$$l_1 = b_1/\cos\alpha \quad (11a)$$

$$l_2 = b_2/\cos\beta. \quad (11b)$$

The final bed length in the fold is

$$L_1 = l_1 + l_2 = (b_1/\cos\alpha) + (b_2/\cos\beta), \quad (12)$$

from which the layer-parallel strain can be calculated using equation (6). The strain is a function of the relative limb lengths, although the variation is small unless one limb is nearly vertical (Epard & Groshong in preparation).

As an example, a representative asymmetric anticline is defined by setting b_2 equal to $2b_1$ so that from (8)

$$a = 2S/3b_1. \quad (13)$$

The geometries in Fig. 5 are calculated for specified original lengths and displacements, using equations (1), (10), (11) and (13). The requisite strain is from equation (6).

At each stage of displacement, the amplitude of the fold decreases downward toward the detachment (Fig. 5). The requisite strain, here shown as an homogeneous layer-parallel shortening, increases downward to a maximum just above the detachment. As the displacement increases, the amplitude at every level increases. In most beds the strain increases with displacement, but at large displacement the upper bed undergoes incremental extension (Fig. 5c), so that the total shortening strain decreases.

An important result of the model is that the requisite strains are comparatively small. The calculated layer-parallel shortening strains range from 7 to 29%. The longer the bed length enclosing a given excess area, the smaller will be the requisite strain. Because straight beds have the shortest possible lengths, the model overestimates rather than underestimates the expected requisite strain in natural folds that have more complex limb shapes.

The shortening required in a detachment fold need not be penetrative strain. Instead, the shortening may be accommodated by smaller-scale folds and faults (Fig. 3).

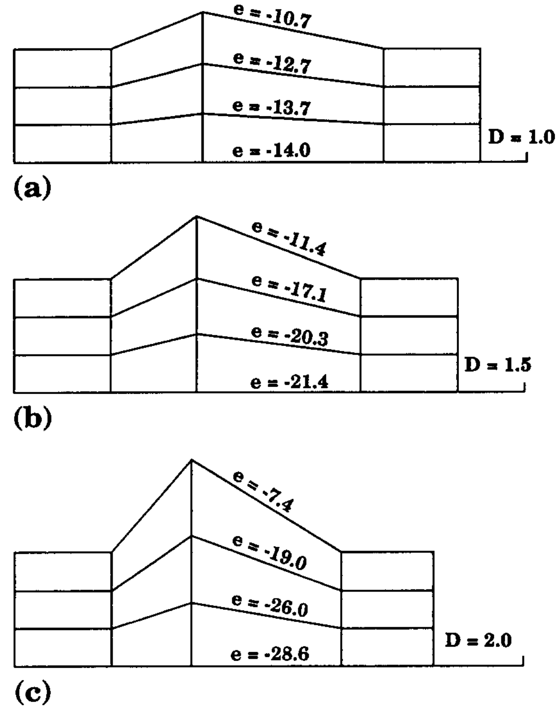

Fig. 5. Kinematic evolution of a detachment anticline assuming homogeneous strain within the anticline and no strain outside the anticline. The strain, e, is in percent. Displacements are scaled to thickness. (a) Scaled displacement = 1.0. (b) Scaled displacement = 1.5. (c) Scaled displacement = 2.0.

The solid-line units in Fig. 3 are the constant-length beds that enclose the same area as the straight beds (dashed lines) in Fig. 5(a). The requisite strain for the solid-line units in Fig. 3 is zero. A wide variety of other internal geometries can satisfy the area balance and shortening requirements in the model. For example, Fig. 3 could have been drawn with fold shortening in the lower two beds and fault shortening in the upper two, or the faults could have been shown with transport in the opposite direction.

The kinematic model (Fig. 5) illustrates that area-balanced detachment folding is possible over a stratigraphically fixed detachment horizon but that, in general, layer-parallel strain is required. The area-balanced model of Fig. 3 shows that if beds maintain constant lengths, they must develop small-scale folds or faults in order to shorten appropriately at the scale of the whole detachment fold. The requisite strain is the layer-parallel strain at a scale smaller than the cross-section that is required for a given bed to satisfy the requirements of area balance within the whole fold. We will now illustrate how these concepts can be used in the design and interpretation of the cross-section of a natural, map-scale detachment fold.

TIP TOP ANTICLINE

The Tip Top anticline is a detachment-fold oil field at the leading edge of the Wyoming thrust belt. The original cross-section by Webel (1977, 1987) (Fig. 6) is controlled by eight wells that extend as deep as the

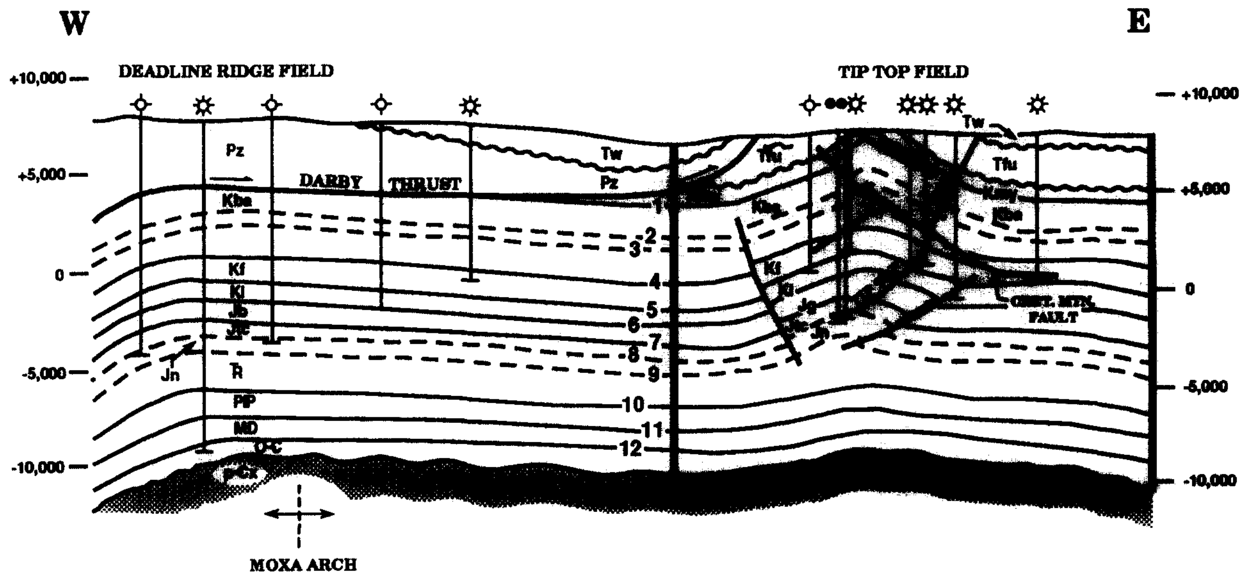

Fig. 6. Tip Top anticline, Wyoming (from Webel 1977, 1987). Regional transport is to the east. Symbols: Tw = Wasatch, Tfu = Fort Union, Kmv = Mesaverde, Kba = Baxter–Hilliard, Kf = Frontier, Kl = Aspen and Bear River, Jb = Beckwith-Gannett, Jtc = Twin Creek, Jn = Nugget, ₮ = Triassic, PP = Permian and Pennsylvanian, MD = Mississipian and Devonian, OE = Ordovician to Cambrian, Pz = Paleozoic, p€x = Precambrian cystalline basement (shaded). Wavy lines are unconformities. The thick lines mark the boundary of the enlarged cross-section in Fig. 7(a).

Jurassic Nugget Formation (Jn). The surface geology (Edman & Cook 1992) together with the wells show that the anticline contains both forward (eastward-directed) and back thrusts. Published seismic lines do not further solve the internal structure of the anticline but do show that the Precambrian crystalline basement is not involved in this structure (Edman & Cook 1992). The fold does not match the geometry of any simple fault-bend or fault-propagation fold model (compare Suppe 1983, 1985, Jamison 1987, Mitra 1990, Suppe & Medwedeff 1990).

A preliminary plot of excess area vs depth for this fold by Epard & Groshong (1993) gave a straight-line best fit that projected to zero excess-area at the top of the basement, which is thus the detachment horizon. Consequently, here we have slightly modified the original cross-section to show the basement as being uninvolved, produce a better fit to the excess-area line and to ensure that the requisite strains are reasonable. The revision (Fig. 7a) honors all the well data, the surface geology and the regional dip of each horizon as determined by a straight line connecting opposite sides of the section. It results in a very good fit to a straight line on the excess-area diagram (Fig. 7b). The slope of the line is the displacement that caused the fold, 0.53 km.

The required requisite layer-parallel strains (equation 6) in the original cross-section (Fig. 6 and Table 1) range from −4.9% (shortening) to +7.7% (extension). These magnitudes are quite small and thus reasonable for a structure in a foreland thrust belt. Rocks with strains less than 10% generally appear undeformed to the naked eye. For example, strains of up to 15% have been measured from twinned calcite in foreland thrust belts and cratonic structures (Groshong *et al.* 1984a,b) in rocks that appear to be undeformed in hand sample.

An alternative interpretation of the requisite strain is

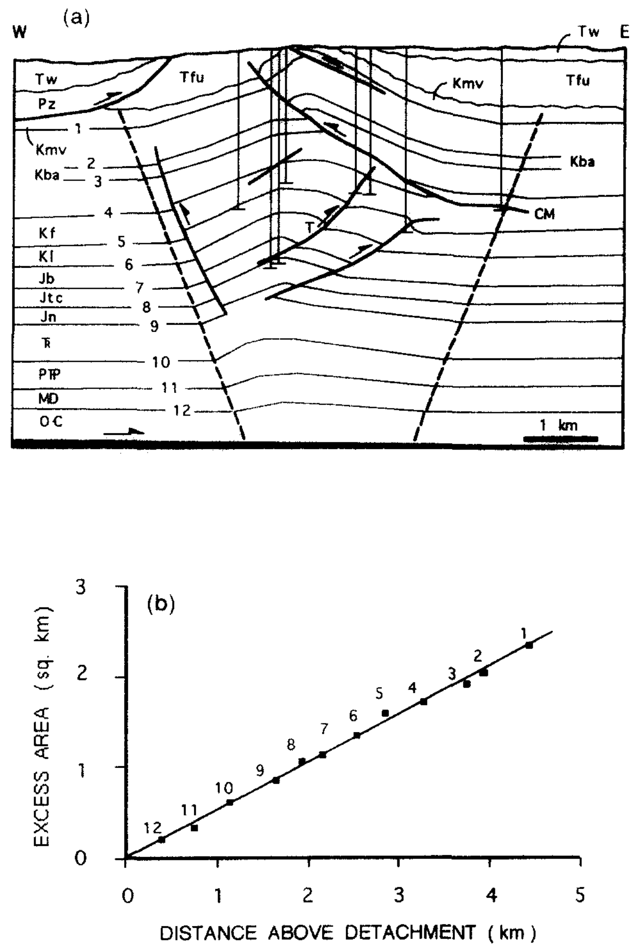

Fig. 7. Revised cross-section of the Tip Top anticline. (a) Cross-section with measured horizons numbered. Formation names given in Fig. 6. Fault T is the Tip Top thrust and CM is the Cretaceous Mountain fault. The base of the section is the crystalline basement. The heavy dashed lines are the approximate boundaries of where the fold is elevated above regional dip. (b) Excess-area diagram for the cross-section in (a).

Table 1. Requisite strain

Horizon	Original section (Fig. 6) e in %	Revised section (Fig. 7) e in %
1	−0.6	0.0
2	+5.5	0.0
3	+7.7	0.0
4	+1.9	0.0
5	−4.9	−4.8
6	−3.8	−3.8
7	−0.7	+0.6
8	−0.6	+2.7
9	−3.8	−1.6
10	—	−11.3
11	—	−14.0
12	—	−15.1

that it is a measure of the error in an approximately constant bed-length cross-section. With this in mind, the revised cross-section (Fig. 7a) was drawn to minimize the requisite strains to the extent possible. The requisite strain in the top four layers is zero in the revised section (Table 1). The major change in the cross-section is in horizon 3 where a small fault wedge was deleted and the requisite strain reduced from +7.7% to zero. On the revised section, fault segments that have offsets too small to be visible at the scale of the cross-section are omitted. Horizons 5 and 6, although not identical in the two cross-sections, have nearly the same requisite strains. The strains in the lowest three units (10–12) were not computed from the original cross-section because their geometries were not controlled by the data and, as shown, were not consistent with the interpretation of a detachment at the top of basement. In the revised cross-section, these units are shown as smooth curves and consequently the requisite strains are large, ranging from −11% to −15%. Some or all of this shortening is probably accommodated by small folds and faults. They would be analogous to those in units higher in the fold, resulting in smaller requisite strains, as in the units above.

The revised cross-section (Fig. 7a) illustrates that the strain theory gives a reasonable result in a complex natural example. The overall geometry of the anticline is similar to that of Fig. 5(a) for which the requisite strains in the upper beds are −11 to −13%. Zero requisite strain in the upper beds of the Tip Top anticline constitutes excellent agreement with the model because the shortening is on visible structures as in Fig. 3. The requisite strains in other beds may be the values that would be measured at the thin-section scale, or, especially for the larger values in the three deeper horizons, probably represent strains due to outcrop-scale folds and faults that are not visible at the scale of the cross-section. It should be noted that although specific horizons are interpreted to have maintained constant bed length (zero requisite strain) the units between these horizons may change thickness. This effect is also illustrated in Fig. 3 where the units change thickness between the four beds having constant bed length and bed thickness.

DISCUSSION

Outcrop-scale fold and fault structures are abundant in fold-thrust belts worldwide and have been documented in innumerable publications. Yet in the balancing of map-scale cross-sections across the fold–thrust belts, the strain represented by these structures is rarely taken into account. A primary value of the requisite strain concept in the area balancing of cross-sections is that it provides a simple means to include the deformation at all scales and at all locations within the map-scale structures. The requisite strain is the amount of strain at a scale smaller than that visible on the cross-section that is required for the section, as shown, to area balance. In the Tip Top anticline, the data are good enough in the upper 9 beds for most of the shortening to be seen as second-order folds and faults. In the lower three units only the general observation can be made that −11% to −15% shortening is required for the section to balance with a detachment at the top of the basement.

The kinematic model of a detachment fold (Fig. 5) has significant implications for the growth of the Tip Top anticline as well as for other detachment anticlines. For the growing anticline to remain area balanced above a stratigraphically fixed detachment, the appropriate amounts of shortening must accumulate simultaneously at all levels within the structure. All the second-order folds and faults within the Tip Top anticline should have been growing simultaneously. The first-order fold could not grow as a detachment anticline without the shortening contributed by these smaller-scale structures. Thus it is a virtual requirement that the internal structure of a detachment anticline will be complex, with many overlapping but linked internal structures, all growing at the same time as the anticline as a whole.

CONCLUSIONS

The presence of layer-parallel strain allows a detachment fold to form above a stratigraphically fixed detachment horizon. The strain requisite for constant area is a function of the excess area, observed bed length, width of the fold and depth to detachment. A simple kinematic model shows that the requisite strains are of a reasonable order of magnitude. Application to the Tip Top anticline, a first-order detachment fold in the Wyoming thrust belt, shows that where adequate control exists to document the internal geometry of the fold, nearly all of the required shortening occurs by the formation of second-order folds and faults. The requisite strain remaining is quite small and could occur as third-order structures or as homogeneous strain at the thin-section scale.

Acknowledgements—Jean-Luc Epard acknowledges support of grants from the Swiss National Science Foundation (Bourse de Jeune Chercheur, project No. 21-31082.91), the "Fondation du 450^e anniversaire de l'Université de Lausanne" and the "Societe Academique Vaudoise". We thank Bryan Cherry for his review of an early version of this manuscript and Bill Dunne for his helpful comments.

REFERENCES

Bucher, W. H. 1933. *Deformation of the Earth's Crust*. Princeton University Press, Princeton, New Jersey.

Chamberlin, R. T. 1910. The Appalachian folds of central Pennsylvania. *J. Geol.* **18**, 228–251.

Dahlstrom, C. D. A. 1990. Geometric constraints derived from the law of conservation of volume and applied to evolutionary models for detachment folding. *Bull. Am. Ass. Petrol. Geol.* **74**, 336–344.

deSitter, L. U. 1956. *Structural Geology*. McGraw-Hill, New York.

Edman, J. D. & Cook, L. 1992. Tip-Top field–U.S.A., Wyoming–Utah–Idaho overthrust belt, Wyoming. In: *Structural Traps VII, Treatise of Petroleum Geology* (edited by Beaumont, E. A. & Foster, N. H.). American Association of Petroleum Geology, Tulsa, 1–27.

Epard, J.-L. & Groshong, R. H., Jr. 1993. Excess area and depth to detachment. *Bull. Am. Ass. Petrol. Geol.* **77**, 1291–1302.

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

Geiser, P. A. 1988b. The role of kinematics in the construction and analysis of geological cross-sections in deformed terranes. *Spec. Pap. geol. Soc. Am.* **222**, 47–76.

Groshong, R. H., Jr & Epard, J.-L. 1992. New excess-area/depth-to-detachment relationship for fold-thrust structures. *Am. Ass. Petrol. Geol. Ann. Conv. Prog.* 49.

Groshong, R. H., Jr, Pfiffner, O. A. & Pringle, L. R. 1984a. Strain partitioning in the Helvetic thrust belt of eastern Switzerland from the leading edge to the internal zone. *J. Struct. Geol.* **6**, 5–18.

Groshong, R. H., Jr, Teufel, L. W. & Gasteiger, C. 1984b. Precision and accuracy of the calcite strain-gage technique. *Bull. geol. Soc. Am.* **95**, 357–363.

Gwinn, V. E. 1964. Thin-skinned tectonics in the Plateau and northwestern Valley and Ridge provinces of the Central Appalachians. *Bull. geol. Soc. Am.* **75**, 863–900.

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.

Jamison, W. R. 1987. Geometric analysis of fold development in overthrust terranes. *J. Struct. Geol.* **9**, 207–219.

Jones, P. B. 1987. Quantitative geometry of thrust and fold belt structures. In: *Methods in Exploration Series No. 6*. American Association of Petroleum Geology, Tulsa.

Mitra, S. 1990. Fault-propagation folds: geometry, kinematic evolution and hydrocarbon traps. *Bull. Am. Ass. Petrol. Geol.* **74**, 921–945.

Mitra, S. & Namson, J. 1989. Equal-area balancing. *Am. J. Sci.* **289**, 563–599.

Suppe, J. 1983. Geometry and kinematics of fault-bend folding. *Am. J. Sci.* **283**, 684–721.

Suppe, J. 1985. *Principles of Structural Geology*. Prentice-Hall, Englewood Cliffs, New Jersey.

Suppe, J. & Medwedeff, D. A. 1990. Geometry and kinematics of fault-propagation folding. *Eclog. geol. Helv.* **83**, 409–454.

Webel, S. 1977. Some new perspectives on the old Nugget oil fields of the LaBarge platform. In: *Twenty-Ninth Annual Field Conference—*1977. Wyoming Geological Association Guidebook, 665–671.

Webel, S. 1987. Significance of backthrusting in the Rocky Mountain thrust belt. In: *Thirty-Eighth Field Conference*—1987. Wyoming Geological Association Guidebook, 37–53.