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Detachment folds with fixed hinges and variable detachment depth, northeastern Brooks Range, Alaska: Discussion

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INTRODUCTION

The study of meso- and microstructures in hinges and limbs of a number of detachment anticlines from the northeastern Brooks Range, Alaska, led Homza and Wallace (1997) to propose that these folds grew with fixed hinges and rotating limbs (e.g. Hardy and Poblet, 1994). Homza and Wallace (1997) observed that the structural thickness of the ductile unit beneath some anticlines (detachment depth) varied from less than to greater than its stratigraphic thickness. They measured the detachment depth from field data and compared it with the detachment depth estimated using two methods: (1) a variable detachment-depth method (Homza and Wallace, 1995) that assumes variations of the ductile unit thickness beneath the anticline as it amplifies, and (2) the classical excess-area method (Chamberlin, 1910) which assumes constant depth. They concluded that the field observations were more consistent with the results estimated using Homza and Wallace (1995) method.

We agree with Homza and Wallace (1997) that the depth to detachment may vary during fold amplification (e.g. Wiltschko and Chapple, 1977; Dahlstrom, 1990; Butler, 1992; Groshong and Epard, 1994; Homza and Wallace, 1995), and in that sense, the use of their variable detachment-depth model is a notable improvement. However, we would like to discuss some drawbacks that arise from the application of this method, particularly to some of the natural examples from the northeastern Brooks Range used in Homza and Wallace (1997).

APPLICATION OF THE VARIABLE DETACHMENT-DEPTH MODEL TO THE NORTHEASTERN BROOKS RANGE

The Homza and Wallace (1997) method uses the assumption that no ductile material moves laterally through the anticline lower hinges in the plane of section (see fig. 7 in Homza and Wallace, 1997). As Homza and Wallace (1997) realized, this assumption implies that the detachment-depth variations predicted by their method are maximum estimates. We agree with this observation but we would like to contribute some ideas about it. According to the Homza and Wallace (1995) method, the pin and loose lines should be placed precisely in the anticline lower hinges, separating the anticline limbs from non-folded regions. The degree of accuracy when estimating the depth to detachment using this method strongly depends on the position of the pin and loose lines. To visualize differences in the detachment-depth estimations depending on the position of the pin and loose lines, we have constructed a graph that illustrates shortening vs depth to detachment for a single anticline formed with fixed hinges and rotating limbs (Fig. 1). The curves displayed in this graph have been obtained by increasing progressively the distance between the pin and loose lines. It appears that for a given amount of shortening, the detachment depth is different depending on the position of the pin and loose lines. The less the separation between the pin and loose lines, the greater the detachment-depth variations, and vice versa. Small differences in the position of the pin and loose lines cause noticeable differences in the detachment-depth estimations. Because natural detachment folds with rounded hinges are common (e.g. Wiltschko and Chapple, 1977; Poblet and Hardy, 1995), it is difficult to locate accurately the pin and loose lines, and therefore, the detachment-depth estimations can be variable. For instance, the lower left hinge of the Straight Creek anticline (see fig. 9 in Homza and Wallace, 1997) is relatively wide, which makes it difficult to place precisely the loose line. Homza and Wallace (1997) chose a loose line relatively close to the anticline core [see figs 9(b) & 10 in Homza and Wallace, 1997]. However, if they had chosen a loose line more to the left, away from the anticline core, the anticline core area would

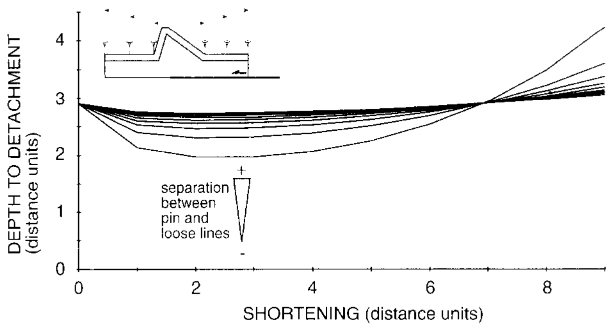

Fig. 1. Graph showing detachment-depth variations for a single detached anticline formed with fixed hinges and rotating limbs. The different curves resulted from increasing progressively the separation between the pin and loose lines. Fold amplification took place according to Homza and Wallace (1995), and Poblet and McClay (1996) equations. Both shortening and detachment-depth scales are arbitrary distance units.

have been greater, and therefore, the detachment depth estimated would have been different. This suggests that the detachment depth estimated for this anticline using the variable detachment-depth model of Homza and Wallace (1995) is only an approximate value.

To apply the Homza and Wallace (1995) method, the detachment surface must be parallel to the line that joins the base of the competent unit at the anticline lower hinges (see fig. 7 in Homza and Wallace, 1997). In the case of the Straight Creek anticline, the lower hinges are located at different heights with respect to the detachment (see fig. 9 in Homza and Wallace, 1997). Homza and Wallace (1997) used the higher hinge [lower right hinge in fig. 9(b) in Homza and Wallace, 1997] to estimate the width and core area of the anticline. However, if they had chosen the lower hinge (lower left hinge), again the anticline core area would have been greater, and therefore, the detachment depth estimated would have been different. In addition, the detachment surface beneath the Straight Creek anticline is not flat, making it difficult to apply the Homza and Wallace (1995) method to this fold.

The Homza and Wallace (1995) method also uses the initial depth to detachment to predict the final depth. This model assumes that the detachment is at the base of the ductile unit, and that the initial detachment depth equals the thickness of the non-deformed ductile unit. Two problems arise from this assumption: (a) the detachment may not necessarily be at the base of the ductile unit (e.g. Thompson, 1989), and (b) because the depth to detachment may vary during fold amplification, we should measure the initial thickness of the ductile unit in non-deformed areas away from the folds, and take into account lateral thickness variations due to sedimentary reasons. The cross-sections in Homza and Wallace (1997) across the Brooks Range show that the core of the anticline is occupied by a ductile unit (Kayak Shale) and that the detachment is located at the base of this unit (see figs 9, 11, 12 & 13 in Homza and Wallace, 1997). However, the data indicate important thickness variations of this unit (50–1000 m) (see table 1 in Homza and Wallace, 1997). In addition, the detachment corresponds to the roof thrust of a kilometre-scale basement duplex [see fig. 12(a) in Homza and Wallace, 1997]. The detachment surface together with the Kayak Shale are folded due to underlying duplex stacking, and this might have caused thickness variations of the Kayak Shale (e.g. hinge and/or limb thickness variations due to non-parallel folding), even in "apparently non-deformed areas" in between detachment anticlines. Due to the thickness variations of the ductile unit, estimation of the detachment depth in this region should be better carried out using methods that do not need the initial thickness of the ductile unit. We would like to warn about the influence of the initial detachment depth in the estimation of the final detachment depth. The graph in Fig. 2 illustrates the variation of the depth to detachment vs shortening for a single anticline formed with fixed hinges and rotating limbs. The curves correspond to different initial depths to detachment (or initial thickness of the ductile unit when the detachment is located at the base of this unit), keeping constant the distance between the pin and loose lines. The graph shows that the deeper the initial detachment depth, the greater the detachment-depth variation. Therefore, errors in the measurement of the initial thickness of the ductile unit cause greater errors in the detachment-depth estimation when the ductile unit is thick than when the ductile unit is thin.

The variable detachment-depth model (Homza and Wallace, 1995) may be used to analyze different geometrical parameters of detachment anticlines; however, it was mainly developed to estimate the detachment depth in areas where the detachment surface does not outcrop or it cannot be identified using geophysical methods. When the detachment cannot be observed, it can be very difficult to differentiate detachment from fault-propagation folds because they can have identical geometry (e.g. Jamison, 1987; Mitchell and

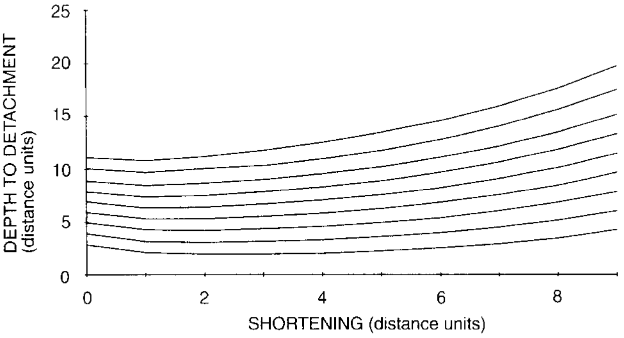

Fig. 2. Graph showing detachment-depth variations for a single detached anticline formed with fixed hinges and rotating limbs. The different curves resulted from increasing progressively the initial depth to detachment. Fold amplification took place according to Homza and Wallace (1995), and Poblet and McClay (1996) equations. Both shortening and detachment-depth scales are arbitrary distance units.

Woodward, 1988; Mitra, 1990; Storti and Poblet, 1997). Therefore, we must ensure that the fold we are analysing is a detachment fold before applying the Homza and Wallace (1995) method. In the West Fork transect, the detachment surface is not exposed except for the left side of the cross-section [see fig. 12(a) in Homza and Wallace, 1997]. Homza and Wallace (1997) state that the West Fork anticline and adjacent structures are clearly detachment folds since the Kayak Shale is thickened in the core of each fold. This statement may not be necessarily correct because natural examples of fault-propagation folds with thickened hinges have been documented (e.g. Alonso and Marcos, 1992; Bulnes, 1995). According to Homza and Wallace (1997), to the south and west of the West Fork transect, thrusts are observed to cut up-section from the basement and through the fold's forelimb. To explain these observations, Homza and Wallace (1997) suggested an evolutionary model for this region in which thrusts may cut through detachment folds at any stage of their history. However, it is also possible that the West Fork anticline and adjacent structures are fault-propagation folds. Such an interpretation presupposes that a thrust should be located in the core of the West Fork anticline in the West Fork transect. This interpretation is consistent with the observations of Homza and Wallace (1997) regarding the occurrence of a folded and thrusted, competent limestone bed within the Kayak Shale in the core of the West Fork anticline. Bulnes (1995) documented natural examples of fault-propagation folds in which shortening was accommodated not only by a major thrust and a fold, but minor structures such as imbricated thrusts and folds related to them. If the West Fork anticline were a fault-propagation fold, then constant detachment-depth methods (Chamberlin, 1910; Mitra and Namson, 1989; Epard and Groshong, 1993) would be more appropriate to estimate the detachment depth, because amplification of a fault-propagation fold does not involve detachment-depth variations (e.g. Mitra, 1990; Suppe and Medwedeff, 1990).

CONCLUSIONS

1. One of the lower hinges of the Straight Creek anticline is relatively wide, which makes it difficult to place precisely the loose line. The detachment depth estimated using the variable detachment-depth model of Homza and Wallace (1995) strongly depends on the position of the pin and loose lines. Therefore, the detachment depth estimated by Homza and Wallace (1997) for the Straight Creek anticline is only approximate.
2. The detachment surface is not parallel to the line that joins the base of the competent unit at the lower hinges of the Straight Creek anticline. In addition, the detachment beneath this anticline is not a flat surface. One of the most important requirements of the variable detachment-depth model of Homza and Wallace (1995) is that the detachment surface must be flat and parallel to the line that joins the base of the competent unit at the anticline lower hinges. This makes it difficult to estimate the detachment depth beneath the Straight Creek anticline using the Homza and Wallace (1995) method.
3. Tectonic thickness variations are likely to occur in the Kayak Shale due to its structural position above a folded roof thrust of a regional-scale duplex. Moreover, extrapolation of the original Kayak Shale thickness measured in regions far from the studied cross sections is not recommended due to important sedimentary thickness variations. The Homza and Wallace (1995) method uses the stratigraphic thickness of the ductile unit to determine the detachment depth, but it assumes that this thickness is constant beneath the studied fold. In our opinion, methods in which the detachment depth could be estimated irrespective of the initial thickness of the ductile unit are more appropriate for the Brooks Range anticlines.
4. Although the West Fork anticline is interpreted as a detachment fold by Homza and Wallace (1997), the anticline features described by these authors also fit the fault-propagation fold models. Fault-propagation folds do not undergo detachment-depth variations during their amplification. Therefore, if the West Fork anticline is a fault-propagation fold, the detachment depth should be better estimated using constant detachment-depth methods instead of the variable detachment-depth method of Homza and Wallace (1995).

REFERENCES

Alonso, J. L. and Marcos, A. (1992) Nuevos datos sobre la estratigrafía y la estructura de la sierra del Pedrosu (Zona Cantábrica, NW de España): implicaciones tectónicas. *Revista de la Sociedad Geológica de España* **5**, 81–88.

Bulnes, M. (1995) Estructura geológica del Valle del Río Trubia (Zona Cantábrica, NO de España). Unpublished Ph.D. thesis. Universidad de Oviedo, Oviedo.

Butler, R. W. H. (1992) Evolution of Alpine fold-thrust complexes: a linked kinematic approach. In *Structural geology of folds and thrust belts*, eds S. Mitra and W. Fisher, pp. 29–44. The John Hopkins University Press, Baltimore.

Chamberlin, R. T. (1910) The Appalachian folds of central Pennsylvania. *Journal of Geology* **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. *Bulletin of the American Association of Petroleum Geologists* **74**, 336–344.

Epard, J.-L. and Groshong, R. H., Jr (1993) Excess area and depth to detachment. *Bulletin of the American Association of Petroleum Geologists* **77**, 1291–1302.

Groshong, R. H., Jr and Epard, J.-L. (1994) The role of strain in area-constant detachment folding. *Journal of Structural Geology* **16**, 613–618.

Hardy, S. and Poblet, J. (1994) Geometric and numerical model of progressive limb rotation in detachment folds. *Geology* **22**, 371–374.

Homza, T. X. and Wallace, W. K. (1995) Geometric and kinematic models for detachment folds with fixed and variable detachment depths. *Journal of Structural Geology* **17**, 575–588.

Homza, T. X. and Wallace, W. K. (1997) Detachment folds with fixed hinges and variable detachment depths, northeastern Brooks Range, Alaska. *Journal of Structural Geology* **19**, 337–354.

Jamison, W. R. (1987) Geometric analysis of fold development in overthrust terranes. *Journal of Structural Geology* **9**, 207–219.

Mitchell, M. M. and Woodward, N. B. (1988) Kink detachment fold in the southwest Montana fold and thrust belt. *Geology* **16**, 162–165.

Mitra, S. (1990) Fault-propagation folds: geometry, kinematics and hydrocarbon traps. *Bulletin of the American Association of Petroleum Geologists* **74**, 536–554.

Mitra, S. and Namson, J. (1989) Equal area balancing. *American Journal of Science* **289**, 563–599.

Poblet, J. and Hardy, S. (1995) Reverse modelling of detachment folds; application to the Pico del Aguila anticline in the South Central Pyrenees (Spain). *Journal of Structural Geology* **17**, 1707–1724.

Poblet, J. and McClay, K. R. (1996) Geometry and kinematics of single-layer detachment folds. *Bulletin of the American Association of Petroleum Geologists* **80**, 1085–1109.

Storti, F. and Poblet, J. (1997) Growth stratal architectures associated to decollement folds and fault-propagation folds. Inferences on fold kinematics. *Tectonophysics* **282**, 353–373.

Suppe, J. and Medwedeff, D. A. (1990) Geometry and kinematics of fault-propagation folding. *Eclogae Geologicae Helvetiae* **83**, 409–454.

Thompson, R. I. (1989) Stratigraphy, tectonic evolution and structural analysis of the Halfway River Map area (94B), northern Rocky Mountains, British Columbia. *Geological Survey of Canada Memoirs* **425**, 1–119.

Wiltschko, D. V. and Chapple, W. M. (1977) Flow of weak rocks in Appalachian Plateau folds. *Bulletin of the American Association of Petroleum Geologists* **61**, 653–670.