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

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We are pleased that our paper stimulated the discussion by Bulnes and Poblet, who raise the type of issues that must be addressed to advance understanding of the geometry and kinematics of detachment folds. In the course of our work, we recognized most of the issues they raise and referred to them in general terms in our papers (Homza and Wallace, 1995, 1997). However, it was beyond the scope and space limitations of those papers to address them further, so we welcome the opportunity to do so here. To provide some context for our reply, we begin with some comments about models and their use.

APPLICATION OF CONCEPTUAL AND MATHEMATICAL MODELS TO NATURAL FOLDS

Bulnes and Poblet agree generally with the concepts we presented in our paper (Homza and Wallace, 1997), but they raise questions about the application to natural folds of the mathematical model we developed to explore those concepts. Our observations (Homza and Wallace, 1997) led to two major conclusions about the geometry and kinematics of natural detachment folds in the northeastern Brooks Range: (1) fold hinges remained fixed during fold growth and (2) the structural thickness of the incompetent unit varied during fold growth, resulting in change of detachment depth during folding. Simple models show that change in detachment depth is an expected consequence of fixed-hinge folding (e.g. Homza and Wallace, 1995; Poblet and McClay, 1996). Most models that have been proposed for detachment folds assume that detachment depth remains constant, but these models are inappropriate where changes of incompetent unit thickness are observed, as in the northeastern Brooks Range (Homza and Wallace, 1997) and other areas (e.g. Wiltschko and Chapple, 1977).

To address this problem, we have proposed the concept that detachment depth in detachment folds need not remain fixed, but can vary by structural thinning or thickening of the incompetent unit during folding (Homza and Wallace, 1995, 1997). This concept is very broad and can be represented by specific models that incorporate a wide variety of geometries and kinematics. We have explored the consequences of this concept using an idealized mathematical representation of a fold that includes simplifying assumptions to minimize variables and mathematical complexity. We obtained a closer match with the geometry of well-exposed natural detachment folds in the northeastern Brooks Range using our variable-depth model than with the constant-depth assumption (Homza and Wallace, 1997). This test provides a basis both to analyze fold processes and to judge which approach would yield better results where folds are not as well constrained. The natural folds are, of course, much more complex than our idealized mathematical model and uncertainties exist about the folds because of incomplete exposure of their geometry or unresolved questions about their kinematics.

The emphasis of our analysis was not to reconstruct in detail all the attributes of the natural folds, but rather to assess whether a constant-depth or variable-depth model for detachment folds better fits those natural examples. Although we found that our variable-depth model yielded a better approximation of the geometry of natural detachment folds in a region where detachment depth has varied, we do not claim that the model yields an exact reconstruction of natural folds nor that it applies to all folds. However, the conceptual model does not intrinsically require all of the simplifying assumptions of the mathematical model and can be adapted to take into account many details of natural folds. Nonetheless, the assumptions and limitations of this or any model must be recognized and accommodated if the model is used for reconstruction.

Bulnes and Poblet agree that detachment folds may form with fixed hinges and that detachment depth may vary during folding. Their comments mainly address

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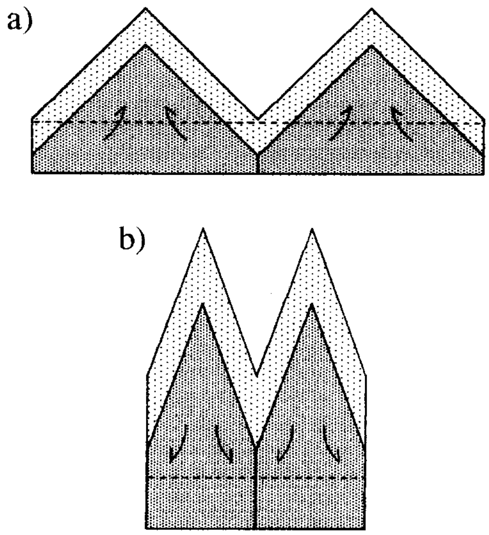

Fig. 1. Neighboring fixed-hinge detachment folds joined at hinges, without an intervening non-folded panel. Light shading: competent unit. Dark shading: incompetent unit. Dashed horizontal line indicates original thickness of incompetent unit. Detachment depth, i.e. thickness of incompetent unit at synclinal hinges (vertical solid lines), must vary to accommodate changes in cross-sectional area of anticline as interlimb angle decreases. (a) Interlimb angle of 90°. Maximum cross-sectional area of anticline, minimum detachment depth. (b) Interlimb angle of 40°. Cross-sectional area of anticline has decreased significantly, resulting in increase in thickness of incompetent unit to greater than its original thickness. In this diagram, no incompetent material is assumed to have moved through boundaries at the synclinal hinges (vertical solid lines), although such movement could occur in nature. The variable detachment-depth model (Homza and Wallace, 1995, 1997) will yield the correct detachment depth for ideal folds of this type, but the conventional detachment-depth calculation (Chamberlin, 1910) will not because the synclines do not represent 'regional', the original elevation of the undeformed section.

uncertainties about the natural folds and related questions about the validity and application of some of our simplifying assumptions. Similar questions would arise in the application of any model to natural folds. Below, we address the issues that they raise, with emphasis on their general significance for detachment folds. The natural examples we observed apparently formed with fixed hinges (Homza and Wallace, 1997), so the emphasis of our discussion is on fixed-hinge folding.

ASSUMPTION OF NO FLOW THROUGH SYNCLINAL HINGES

In order to reconstruct thickness changes in the incompetent unit, an area must be defined within which the incompetent unit moves to accommodate changes in cross-sectional area of the fold during its growth. In order to allow a simple mathematical reconstruction, we assume no net movement of incompetent material through lines that are perpendicular to the basal detachment and are projected upward to the synclinal hinges that bound a fold (Homza and Wallace, 1995, 1997). These boundaries can be used both for fixed- and migrating-hinge folds. The hinges move with respect to the rock in migrating-hinge folds, but our mathematical model assumes that no material within the fold was derived from outside the final position of the synclinal hinges. The advantages of choosing these boundaries are that they are referenced to relatively well-defined geometric elements of the fold and their use provides an estimate of the maximum possible change in detachment depth. However, the actual bounds to movement of incompetent material are not well-defined in natural folds. If the synclinal hinges are not assumed as boundaries, no control exists on the distribution in time and space of the area within which incompetent material may move, so an infinite array of possibilities exists for movement of material through the hinges.

Our model considers only a single fold in isolation (e.g. fig. 7 of Homza and Wallace, 1997), but natural folds generally occur in trains of multiple folds that either meet at their synclinal hinges (Fig. 1) or are separated by non-folded panels (Fig. 2). Assuming fixed-hinge folds, the synclinal hinges provide the most reasonable choice of boundaries for folds that meet at those hinges (Fig. 1), although it is certainly possible to envision material flowing through these boundaries if, for example, the cross-sectional area of one fold decreases at the same time as the area of an adjacent fold increases. If our model or the approach used by Bulnes and Poblet in their fig. 1 is applied to fixed-hinge folds that are separated by non-folded panels, an unrealistic discontinuity is required between the area where the thickness of the incompetent unit has changed due to folding and the area where its thickness is unchanged. Instead, changes in thickness of the incompetent unit most likely are distributed smoothly outside the synclinal hinges (Fig. 2). In effect, this simply extends our model by adding a second pair of hinges to form the outer boundaries of the fold. By definition, the detachment depth at these outer boundaries remains constant, so this model combines attributes of the variable and constant depth models. However, this model can only be applied if the location and migration history of the outer hinges are known and planar limbs are assumed. Thickness changes like those required by this model probably can be documented in natural folds, and may be reflected by the multiple gentle hinges common in the limbs of detachment folds. However, it remains to be seen whether a model can be formulated to predict the distribution of these changes in time and space.

We agree with Bulnes and Poblet that the fold boundaries are difficult to place precisely in the Straight Creek anticline (fig. 9 of Homza and Wallace, 1997), and this leads to uncertainties in the application of any geometric model. For the purposes of analysis, we chose synclinal hinges based on the projected points of maximum curvature in the fold. Other boundaries could arguably be chosen, so our model-derived estimate of detachment depth is only approximate. However, using the same boundaries for each method, the variable-depth model yields a closer approximation to the observed depth to detachment than does the constant-depth model.

ASSUMPTION OF A PLANAR AND PARALLEL BASAL DETACHMENT

Another simplifying assumption we made in our mathematical model is that the basal detachment is planar and parallel to a line connecting the bounding synclinal hinges (Homza and Wallace, 1995, 1997). However, this is not an intrinsic requirement of our conceptual model. The natural examples we present show that detachment depth may vary between synclinal hinges and that the basal detachment may be nonplanar. If the geometry of the top of the incompetent unit and the basal detachment are sufficiently well constrained in such folds, the undeformed thickness of the incompetent unit can be calculated if constant cross-sectional area is assumed. A planar detachment, particularly one that remains horizontal, represents an ideal condition. No reason exists to assume that detachment folds form only above horizontal, planar detachments, and many probably form as a consequence of shortening that deforms the detachment surface.

As Bulnes and Poblet point out, the detachment surface beneath the Straight Creek anticline is neither perfectly planar nor exactly parallel to the 'base line' that joins the synclines (fig. 9 of Homza and Wallace, 1997). For the purposes of analysis, we chose a geometry that approximates parallelism between the base line and the detachment while honoring the general fold geometry. While this yields only an approximation of the detachment depth, it is a better approximation than the constant-depth model yields. Moreover, if the base line and detachment can be observed not to be parallel then, by definition, the detachment depth varies across the anticline and use of a constant-depth model is not appropriate.

ASSUMPTION OF A DETACHMENT FIXED AT THE BASE OF THE INCOMPETENT UNIT

Our variable detachment depth model requires only that initial or final detachment depth be specified, not that the detachment must be located at the base of the incompetent unit. Thus, our model yields identical results whether a particular initial detachment depth is assumed to be within (fig. 2 of Bulnes and Poblet) or at the base of an incompetent unit before folding. In our analysis of natural detachment folds, we assumed detachment at the base of the incompetent unit (Homza and Wallace, 1997). If the thickness of the incompetent unit before folding is known and the actual depth to detachment is not, then this assumption provides an estimate of maximum detachment depth.

Determining the position of the detachment within an incompetent unit may be very difficult in practice, particularly since incompetent units are generally poorly exposed. However, well-exposed deformation of competent interbeds indicates that the detachment was located near the base of the incompetent unit in at least two of the natural examples we documented (Straight Creek and Salisbury Creek). Deformation of the entire incompetent unit above a basal detachment is the most reasonable starting assumption in the absence of data to indicate otherwise.

THICKNESS OF THE INCOMPETENT UNIT BEFORE FOLDING

Our approach *requires* knowing (or assuming) either the initial or final depth to detachment because we do not assume that detachment depth remains constant. Initial or final depths are difficult to determine in natural folds because the incompetent unit is generally poorly exposed, and because the thickness of the incompetent unit can vary both stratigraphically and structurally. Bulnes and Poblet suggest that for these reasons detachment depth would be better estimated using methods that do not require knowing the initial thickness of the incompetent unit. However, where the detachment depth cannot be measured directly, the only method we are aware of to achieve this result is the conventional depth-to-detachment calculation, which relies entirely on uplifted fold area to determine detachment depth (e.g. Chamberlin, 1910). The fundamental problem is that this method requires that a constant detachment depth be assumed, an assumption that we have shown to be incorrect for at least some detachment folds in the northeastern Brooks Range and that has been shown to be incorrect for other natural detachment folds. The variable-depth model yields the same result as the constant-depth model for ideal folds that evolve with a constant detachment depth, but the constant-depth model yields a different result than the variable-depth model for ideal folds that evolve with a variable detachment depth. In other words, the variable-depth model is more likely to yield meaningful results when it is not known whether a fold evolved with a constant or variable detachment depth.

The values we used for the undeformed thickness of the incompetent unit (Kayak Shale) were determined from the nearest places where the top and bottom of the unit were planar and parallel over significant distances (Homza and Wallace, 1997). These values are reasonably constant within a local area and we are confident that they are reasonable estimates of the

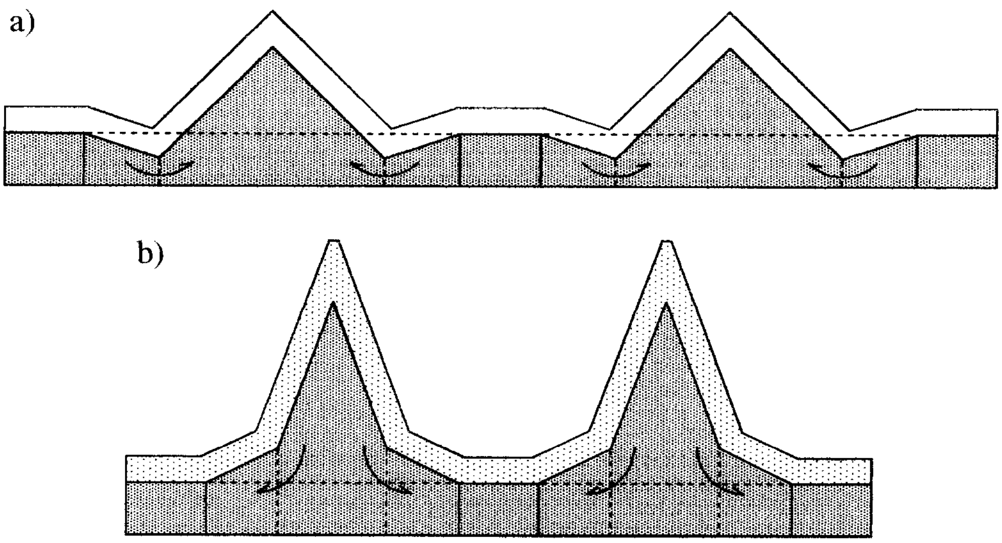

Fig. 2. Neighboring fixed-hinge detachment folds separated by an intervening non-folded panel. Light shading: competent unit. Dark shading: incompetent unit. Dashed horizontal line indicates original thickness of incompetent unit. As interlimb angle decreases, changes in cross-sectional area of anticline are accommodated by movement of incompetent material through the inner synclinal hinges (vertical dashed lines). Resulting changes in cross-sectional area outside of the inner synclinal hinges are distributed evenly beneath outer fold limbs. The outer hinges have a constant detachment depth equal to the original thickness of the incompetent unit and define outer boundaries of the fold (vertical solid lines) through which no net movement of incompetent material has occurred. (a) Interlimb angle of 90°. Maximum cross-sectional area of anticline, minimum detachment depth as measured at inner synclinal hinges. Increase in anticline area has been accommodated by movement of incompetent material inward through inner synclinal hinges. (b) Interlimb angle of 40°. Cross-sectional area of anticline has decreased significantly, resulting in movement of incompetent material outward through inner synclinal hinges. Thickness of incompetent unit is greater than its original thickness everywhere between outer hinges. In this diagram, the outer hinges are assumed to be fixed at an arbitrary constant limb length from the inner synclinal hinges. Uncertainties in nature include whether the outer hinges are fixed and their distance from the inner synclinal hinges. The conventional detachment-depth calculation (Chamberlin, 1910) will yield the correct detachment depth for ideal folds of this type provided that 'regional' is correctly identified. However, the calculation will be incorrect if the inner synclinal hinges are taken to represent regional, an assumption that is likely to be made where they are the structurally lowest points, as in (a), or if the dip of the outer limb is very gentle. If the inner synclines are used as the fold boundaries, the variable detachment-depth model (Homza and Wallace, 1995, 1997) will yield a value for detachment depth that represents the maximum possible departure from the original thickness of the incompetent unit.

thickness of the incompetent unit before folding. The wide range of thicknesses cited in our table 1 represents a range of thicknesses reported throughout the northeastern Brooks Range, with the extremes reflecting areas of local depositional thinning or structural thickening. Most areas do not display these extremes of variation in stratigraphic thickness nor in structural thickness outside of anticlinal cores.

DETACHMENT FOLDS VS FAULT-PROPAGATION FOLDS

Bulnes and Poblet caution that we must be sure that a fold is in fact a detachment fold before applying our model to it. We agree completely and add that this caution is not specific to our particular model or even to detachment folds! It is important to establish the fold type before applying any model, and to be sure that the specific model used is appropriate to the observations. Rather than assuming that a fold is a particular type when the evidence is not definitive, the uncertainties and assumptions should be specified so that alternatives can be considered.

Bulnes and Poblet suggest that one of the examples we present, the West Fork anticline (fig. 12 of Homza and Wallace, 1997), could be a fault-propagation fold rather than a detachment fold. We cannot completely rule out the possibility that the West Fork anticline is a fault-propagation fold because neither its geometry nor its kinematics are completely known. [Ironically, we suggest for the same reasons that many map-scale folds that have been interpreted as fault-propagation folds could instead be interpreted as detachment folds (Wallace and Homza, 1996, 1997).] Several lines of evidence support our interpretation of the West Fork anticline as a detachment fold. Fault-propagation folds are not characteristic of the structural style of the region (Wallace and Hanks, 1990; Wallace, 1993). Detachment folds with characteristics similar to the West Fork anticline are exposed in the same stratigraphic interval throughout the northeastern Brooks Range and typically display anticlinal cores in which the incompetent unit is thickened by internal deformation. These folds are not typically cut by thrust faults, and certainly do not contain the well-defined ramps required in a fault-propagation fold. The only probable fault-propagation folds identified in the northeastern Brooks Range are where the incompetent unit is depositionally thin to absent and faults have propagated up-section from basement that is unusually competent. The West Fork anticline is not located over a ramp that cuts up-section from basement, although such faults are present nearby. Instead, the anticline is separated from basement by a flat. The exposures do not rule out the possibility of a ramp within the structurally thickened incompetent unit, but the overlying competent unit certainly is not penetrated by a thrust. The regional structural style, the internal thickening of the incompetent unit in the anticlinal core, and the lack of ramps in the underlying and overlying competent units all support our interpretation of this fold as a detachment fold.

Bulnes and Poblet state that some fault-propagation folds display structurally thickened hinges. However, this implies a geometry and mechanism different from the familiar fault-propagation fold models that they cite (Mitra, 1990; Suppe and Medwedeff, 1990). Significant internal thickening within the fold core suggests processes similar to those in detachment folds, perhaps reflecting folds that are a hybrid of fault-propagation and detachment folds. In this case, a variable-depth interpretation should not be excluded unless geometric and/or kinematic data require a constant-depth interpretation.

CONCLUSIONS

We emphasize two fundamental results of our work (Homza and Wallace, 1995, 1997):

1. Change in fold area with fixed-hinge growth of detachment folds requires a change in incompetent unit thickness as measured at synclinal hinges (Figs 1 & 2);
2. Natural detachment folds in the northeastern Brooks Range apparently grew with fixed hinges and display variable detachment depths.

These results indicate that constant detachment depth should not automatically be assumed for natural detachment folds, particularly if they may have formed with fixed hinges. We found that a better fit to natural detachment folds in the northeastern Brooks Range is attained with our variable-depth model than with the constant-depth model (Homza and Wallace, 1997). Our mathematical model was useful both for analyzing fold processes and assessing which approach would yield better results where folds are not as well constrained, but it is idealized and was not designed to reconstruct folds in detail. The model is simply a mathematical representation of area balancing beneath a line of constant length, with the assumption of constant detachment depth removed. Our conceptual model is more flexible and can be applied and extended by using the same balancing approach in more detail to accommodate additional assumptions or data on natural folds.

Bulnes and Poblet accept our major conclusions conceptually, but point out limitations and questions about the application of our mathematical model to natural folds. Their points draw attention to specific issues that must be considered in using this, or any, model to reconstruct folds in detail and they identify questions of the type that must be addressed in order to understand fold processes better. These points highlight areas of uncertainty and directions for future work, but they do not alter our conclusions.

We expect and hope that our variable-depth model will be refined and augmented, and perhaps eventually superseded, as more is learned about natural folds. If the model helps to define questions that must be answered to understand how natural folds work, and so stimulates the testing of assumptions and the collection of data to answer those questions, then it will have served its purpose.

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