PERGAMON

Journal of Structural Geology 25 (2003) 1659–1673

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.com/locate/jsg

A unified kinematic model for the evolution of detachment folds

Shankar Mitra

School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019, USA

Received 15 October 2001; received in revised form 5 August 2002; accepted 11 November 2002

Abstract

Detachment folds represent a major structural element in a number of fold belts. They are common in the Jura Mountains, the Zagros fold belt, the Central Appalachian fold belt, the Wyoming fold-belt, the Brooks Range, the Parry Islands fold belt, and parts of the SubAndean belt. These structures form in stratigraphic packages with high competency contrasts among units. The competent upper units exhibit parallel fold geometries, whereas the weak lower unit displays disharmonic folding and significant penetrative deformation. Two distinct geometric types, disharmonic detachment folds, and lift-off folds have been recognized. However, these structures commonly represent different stages in the progressive evolution of detachment folds. The structures first form by symmetric or asymmetric folding, with the fold wavelength controlled by the thickness of the dominant units. Volumetric constraints require sinking of units in the synclines, and movement of the ductile unit from the synclines to the anticlines. Continuing deformation results in increasing fold amplitudes and tighter geometries resulting from both limb segment rotation and hinge migration. Initially, limb rotation occurs primarily by flexural slip folding, but in the late stages of deformation, the rotation may involve significant internal deformation of units between locked hinges. The folds eventually assume tight isoclinal geometries resembling lift-off folds. Variations in the geometry of detachment fold geometry, such as fold asymmetry, significant faulting, and fold associated with multiple detachments, are related to variations in the mechanical stratigraphy and pre-existing structure.

Keywords: Unified kinematic model; Detachment folds; Fold belts

1. Introduction

The structural styles of fold-thrust belts can be described in terms of systems of three main types of fault-related folds: fault-bend folds, fault-tip folds, and detachment folds. Fault-bend folds (Suppe, 1985) are formed by the movement of beds through bends in faults. Fault-tip folds (Elliott, 1977) constitute a class of structures in which a fold develops at the tip of a propagating fault. They include fault-propagation folds (Suppe, 1985; Suppe and Medwedeff, 1990; Jamison, 1987; Mitra, 1990; Chester and Chester, 1990; Erslev, 1991; Hardy and Ford, 1997; Almendinger, 1998), which are formed by the progressive transfer of slip from a fault to a fold developing at its tip, and faulted detachment folds (Mitra, 2002b), which form by the transition from detachment folding to progressive fault-propagation. Detachment folds (Dahlstrom (1990); Jamison, 1987; Mitra and Namson, 1989; Mitra, 1992; Homza and Wallace, 1995; Poblet and McClay, 1996) are characterized by the termination of a parallel fold at a basal detachment within a ductile unit.

Detachment folds form in sedimentary units with significant thickness and competency contrasts. The basal layer is usually an incompetent unit, such as shale or salt, and is overlain by thick competent units such as carbonates or sandstones. The fold geometry and evolution are strongly dependent on the mechanical stratigraphy, including the thickness, ductility, and stratigraphic sequence of the units (Currie et al., 1962; Davis and Engelder, 1985). Detachment folds are generally more symmetric than other fold forms in fold belts, particularly in the early stages of evolution. Unlike fault-bend and fault propagation folds, they commonly display opposite vergence both across and along fold trends. Faulting is usually secondary and occurs primarily to accommodate variations in strain with structural and stratigraphic position. A variety of

E-mail address: smitra@ou.edu (S. Mitra).

0191-8141/03/$ - see front matter © 2002 Elsevier Science Ltd. All rights reserved.
doi:10.1016/S0191-8141(02)00198-0

detachment folds have been documented from fold belts, including the Jura Mountains (Buxtorf, 1916; Laubscher, 1962), the Maritime Alps (Goguel, 1962), the Parry Islands fold belt (Harrison and Bally, 1988; Harrison, 1995), the Brooks Range (Namson and Wallace, 1986), the Central Appalachian Plateau (Gwinn, 1964; Wiltschko and Chapple, 1977), the Zagros fold belt (Stocklin, 1968; Hull and Warman, 1970), the SubAndean fold belt in Bolivia and Argentina Belotti et al. (1995)), and the Taiwan fold belt (Namson, 1981). The variety of documented structures can be grouped into two main geometric end-members: disharmonic detachment folds (De Sitter, 1964) and lift-off folds (Namson, 1981; Mitra and Namson, 1989). Despite detailed structural studies of these structures from all of these belts, the kinematic development of these structures, and related balancing of these structures remains controversial (De Sitter, 1964; Dahlstrom, 1990; Poblet and McClay, 1996; Poblet et al., 1997). The key questions relate to the relative importance of limb rotation and hinge migration in the formation of the folds, and the nature of deformation of the basal ductile units.

The objective of this paper is to present a unified kinematic model to explain a variety of detachment folds. The model is kinematically balanced, and relates the progressive development of the fold geometry to variations in the relative importance of different deformation mechanisms with time. Variations in structural geometry are primarily related to the mechanical stratigraphy and the amount of macroscopic strain. The model also proposes that although disharmonic detachment folds and lift-off folds are commonly described as discrete geometric and kinematic entities, they actually represent different stages of progressive detachment folding.

To develop the model, the characteristic features of detachment and faulted detachment folds from a variety of surface and subsurface structures at different stages of development are first examined. Other controlling characteristics, such as the mechanical stratigraphy are also considered. These observations are then integrated to develop an area balanced kinematic model. Variations from the basic kinematic model are also presented and compared with examples from a number of fold belts.

2. Geometry of detachment folds

Detachment folds can be classified into two main

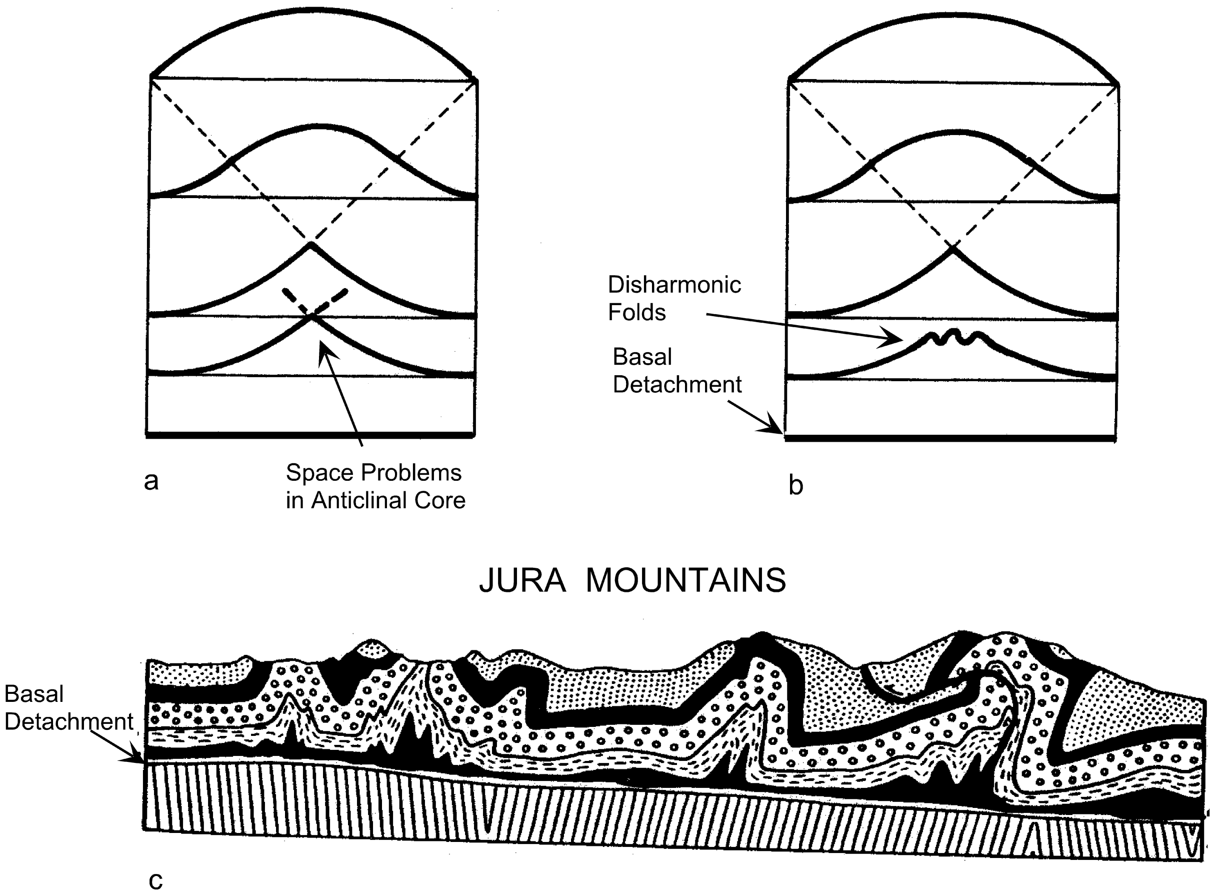

Fig. 1. Geometry of disharmonic detachment folds. a. Space problems in the core of a concentric fold resulting from convergence of radii of curvature to form cuspate geometry. b. Space problems resolved by the formation of disharmonic folds (modified from De Sitter, 1964). c. Example of disharmonic detachment folds from the Jura Mountains, Switzerland (modified from Buxtorf, 1916).

geometric types: disharmonic detachment folds, and lift-off folds. Disharmonic detachment folds are characterized by parallel geometries in the outer layers, and disharmonic and non-parallel geometries in the lower units (Dahlstrom, 1969), with the folds terminating in a detachment. Lift-off structures are characterized by tight isoclinal geometries of the upper units, and a weak lower unit, which is isoclinally folded in the core of the anticline.

2.1. Disharmonic Detachment Folds

Perhaps the best examples of disharmonic detachment folds have been documented from the Jura Mountains (Figure 1c; Buxtorf, 1916; Laubscher, 1962). Disharmonic detachment folds have a parallel geometry in the outer arc. The projection of the parallel fold form to depth results in a space problem, resulting in disharmonic and non-parallel geometries in the core of the anticline (Carey, 1960; Goguel, 1962; De Sitter, 1964; Dahlstrom, 1969). The disharmonic fold form eventually terminates in a basal detachment. It has also been pointed out that because concentric fold forms exhibit broad anticlines and narrow synclines in the upper units and broad synclines and narrow anticlines in the lower units, the fold form must also be bounded by an upper detachment (Dahlstrom, 1969). However, the upper detachment is absent in commonly emergent fold belts containing first order detachment folds.

2.2. Lift-Off Folds

Ideal lift-off folds are characterized by parallel geometries of most of the outer units and isoclinal folding of the basal detachment in the core of the anticline (Figure 2). A thin layer characterized by high shear strains occurs immediately above the basal detachment. Although the basal unit in a lift-off fold has a pseudo-parallel geometry at the macroscopic scale (Figure 2), suggesting a self-similar fold evolution by synclinal hinge migration (Dahlstrom, 1990), the deformation within these units is much more complex. Figure 3 shows an example of the core of a minor-scale detachment fold with an isoclinal lift-off geometry within the Formation in the Valley and Ridge. The highly

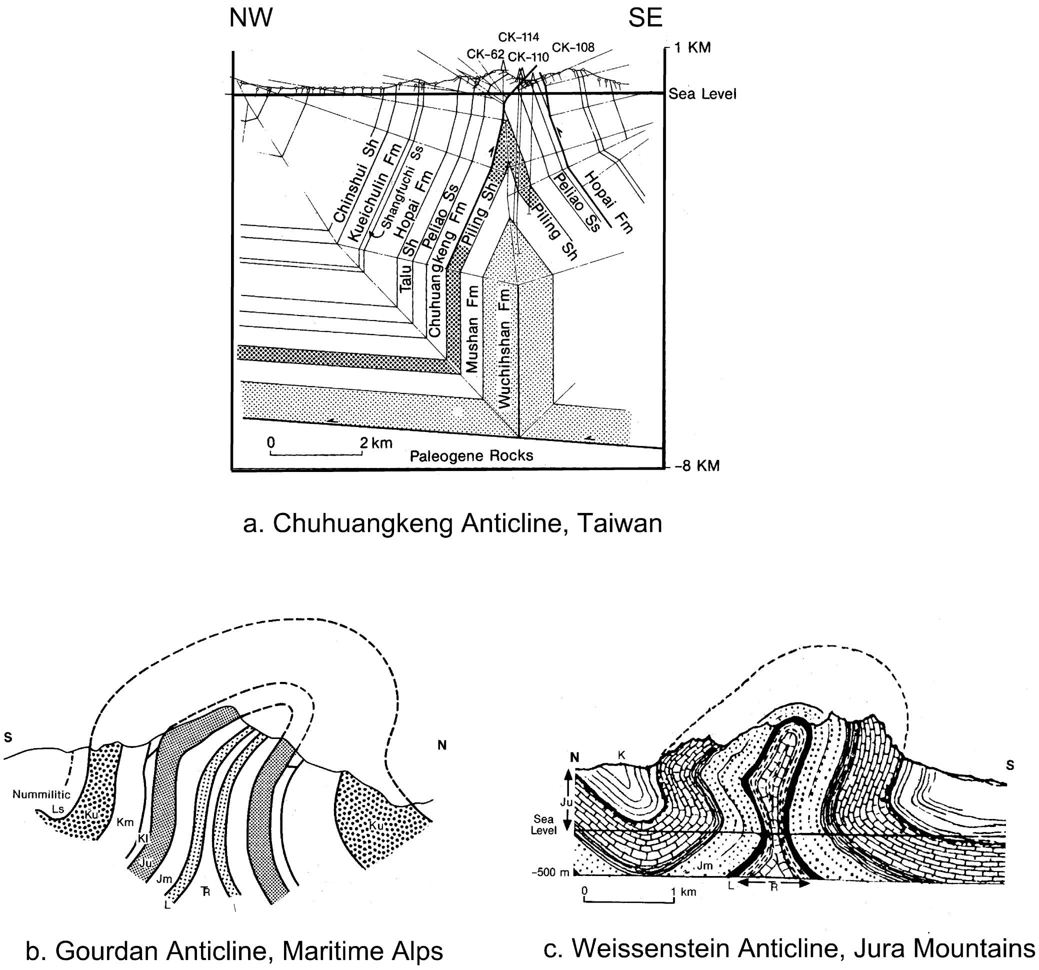

Fig. 2. Examples of lift-off folds from (a) the Taiwan belt (from Namson, 1981), (b) the Maritime Alps (Goguel, 1962), and (c) the Jura Mountains (Buxtorf, 1916).

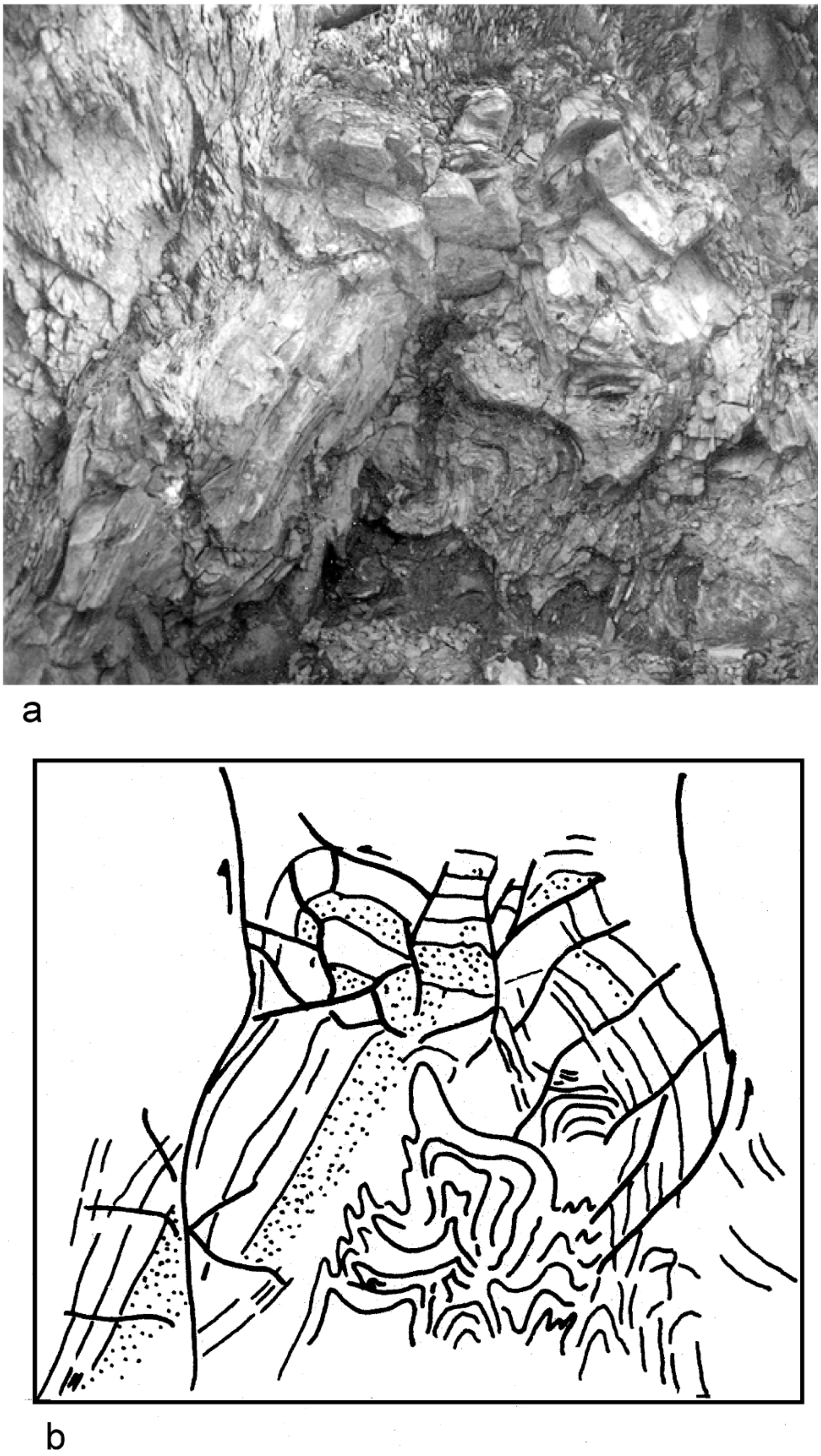

Fig. 3. Photograph (a) and sketch (b) of a lift-off detachment fold in the hinge zone of a second-order syncline in the Valley and Ridge near Mifflin, Pennsylvania. The very tight structure is cored by isoclinal folds within thin- bedded units. However, the core units display a strongly disharmonic geometry, and considerable internal deformation.

deformed nature of the core units is suggestive of the complex deformation history of these units.

Lift-off folds have been interpreted using kink geometries as in the Chuhuangkeng anticline in the Taiwan thrust belt described by Namson (1981) (Figure 2a), and concentric geometries, as in the Weissenstein Kette structure in the Jura Mountains (Figure 2b) described by Heim (1921), and the Gourdan anticline in the Maritime Alps (Figure 2c) described by Goguel (1962). A number of perched lift-off folds are also present in the subAndean belt in Bolivia and Argentina (Belotti et al, 1995). These structures are characterized by folding of strata beneath the isoclinally folded detachment (Willis and Willis, 1934, p. 62), so that the fold form may continue to a deeper level.

A good example of an isoclinal lift-off fold is the Chuhuangkeng anticline (Figure 2a) in the Taiwan thrust belt (Namson, 1981). This structure is a nearly symmetrical upright fold with surface limb dips of 70°–80°. The detachment at the base of the Wuchihshan Formation is folded isoclinally in the core of the anticline. Namson (1981) analyzed the subsurface well data for the anticline and found no faults with significant stratigraphic throw. This evidence combined with the tight isoclinal geometry of the anticline was used to constrain the final interpretation. The structure is contains a number of minor uplimb thrusts. Namson (1981) chose the basal detachment for the Chuhuangkeng anticline to be at the base of the Wuchihshan Formation because it is documented as a zone of regional detachment in northern Taiwan.

3. Previous kinematic models

There is considerable controversy regarding the kinematic evolution of detachment folds, particularly with reference to the relative importance of hinge migration and limb rotation in the formation of these structures. De Sitter (1964) proposed that a fold develops its wavelength very early in its evolution and subsequently evolves primarily by limb rotation. The mechanism is similar to the buckling of a competent layer in an incompetent medium. A low amplitude and high wavelength fold forms in the early stages of folding. Increasing shortening results in tightening of the fold by limb rotation between fixed hinges.

De Sitter (1964) model was declared kinematically inadmissible by Dahlstrom (1990), because it presents an apparent balancing problem and an increase in detachment depth with progressive fold evolution. This contention was partly due to De Sitter (1964) depiction of the movement of material points relative to a fixed reference horizon coinciding with the synclinal hinges. Since De Sitter (1964) did not specify the location of an underlying detachment and whether the synclinal fold hinges are deflected below their regional position, it is difficult to assess whether the model is balanced.

On the other hand, Dahlstrom (1990) argued that detachment folds originate with small wavelengths and that hinge migration is the dominant deformation mechanism in their evolution. This model involves continuous movement of beds through the synclinal hinges and towards the anticlinal hinges. He proposed that concentric folds undergo some limb rotation with progressive deformation, whereas box folds develop their steep limb dips early in the folding history and grow entirely by synclinal hinge migration.

Poblet and McClay (1996) and Poblet et al. (1997) summarized some of the common models for detachment folding using three main kinematic end members.

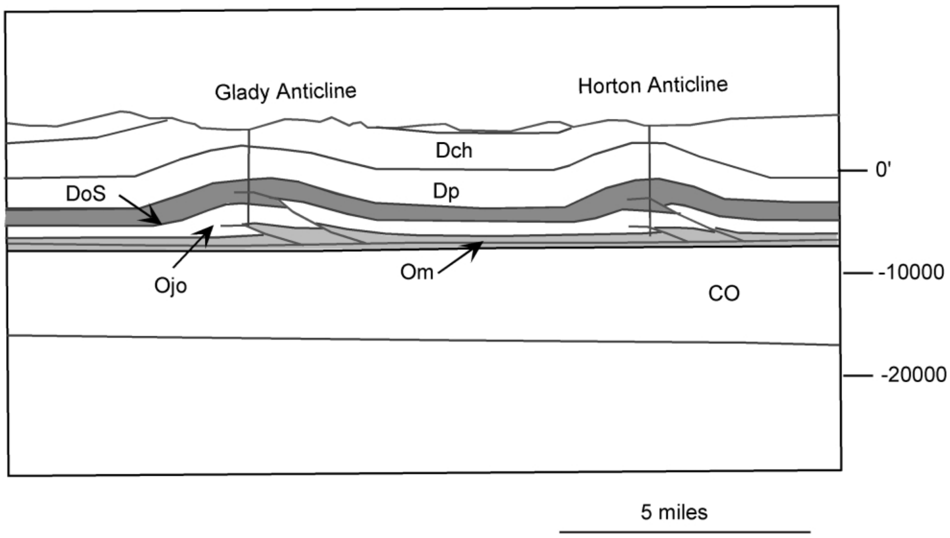

Fig. 4. Interpreted low-amplitude detachment folds in the Appalachian Plateau above a detachment in the Ordovician Matinsburg shales (after Gwinn, 1964). Note the relatively large wavelength/amplitude ratios of the folds. CO = Cambro-Ordovician; Om = Ordovician Martinsburg; Ojo = Ordovician Juniata to Oswego; DoS = Silurian to Devonian Oriskany; Dp = Devonian Portage; Dch = Devonian Chemung.

All models assume planar geometries of fold limbs, in which the beds return to the regional position outside the anticlinal area. Model 1 assumes a variable limb dip and constant limb length, so that limb rotation between fixed hinges is the primary deformation mechanism (De Sitter, 1964). Model 2 assumes constant limb dip and variable limb length, so that synclinal hinge migration is the dominant mechanism (Mitchell and Woodward, 1988; Dahlstrom, 1990). Area modeling of both of these models requires arbitrary and opposite variations in the depth to detachment, rendering them kinematically inadmissible. Model 3 assumes a variable limb dip and variable limb length, and involves both hinge migration and limb rotation. This model is area balanced and kinematically admissible, but requires a low amplitude fold in the early stages of development, and a specific sequence of wavelength–amplitude ratios during fold evolution.

The relative importance of limb rotation and hinge migration in the growth of detachment folds needs to be resolved. It is also important to establish whether the two distinctive geometric styles of detachment folds, disharmonic detachment folds and lift-off folds, form by different mechanisms, or represent end members of the same deformational evolution.

4. Characteristic geometric features

In order to develop kinematic models for detachment folds, we need to address a number of key questions that relate to the geometry of disharmonic detachment and lift-off folds. These are: (1) Do disharmonic detachment folds initiate with low or high wavelength– amplitude ratios? (2) Are low amplitude detachment folds flanked by corresponding evacuation synclines, or do the units return to their regional positions, as commonly invoked by existing models?, and (3) Do the two geometric types of detachment folds form by different mechanisms, or are they end members representing different stages of evolution?

4.1. Low-Amplitude Detachment Folds

In order to determine whether detachment folds always initiate with low wavelength–amplitude (w/a) ratios (Dahlstrom, 1990), or may have high w/a ratios (De Sitter, 1964), it is instructive to examine detachment fold belts with small amounts of contraction. A number of detachment fold-belts with small shortening, such as the Parry Islands fold belt (Fox, 1985; Harrison and Bally, 1988) and the Appalachian Plateau fold belt (Figure 4; Gwinn, 1964), consistently show relatively high wavelength–amplitude

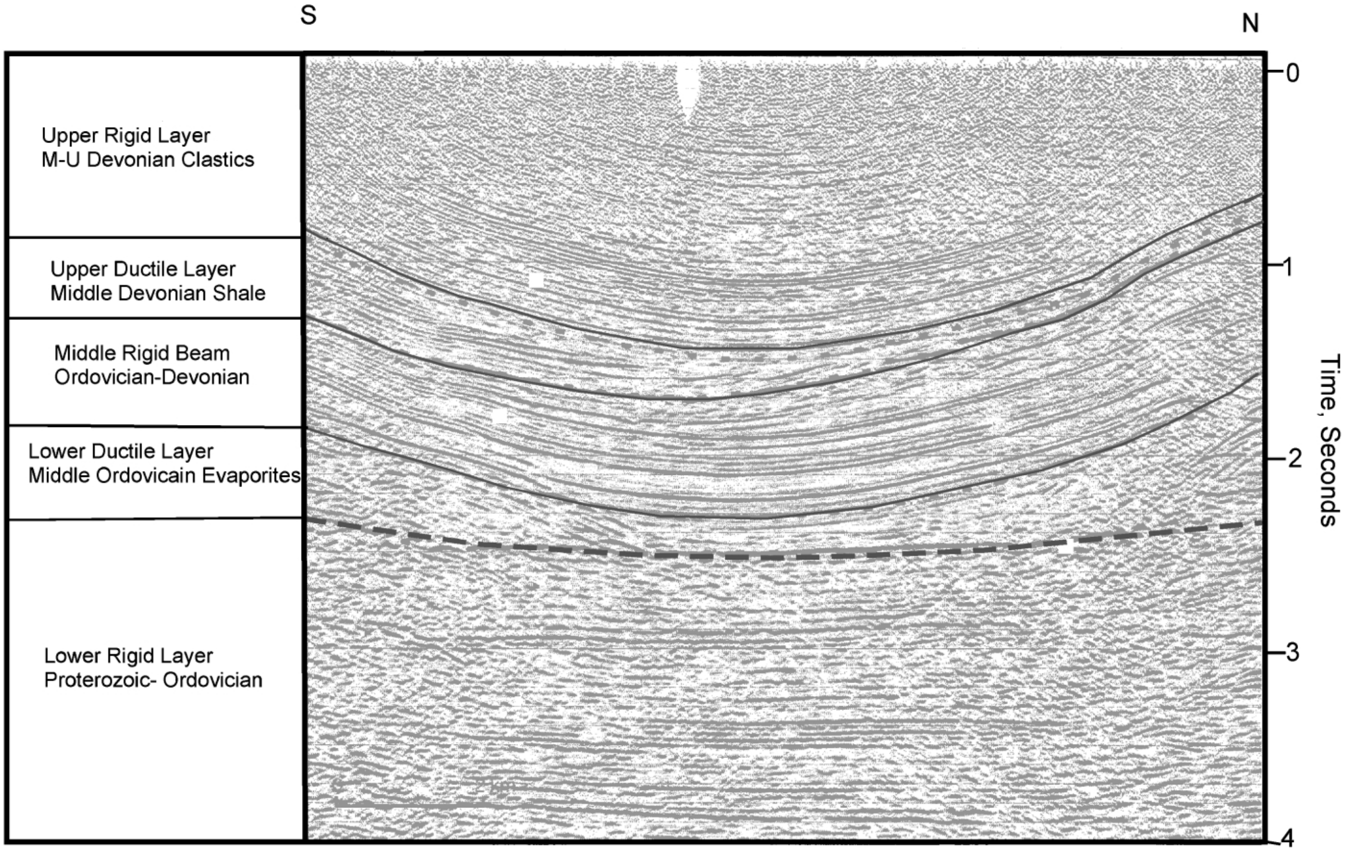

Fig. 5. Synclinal sinking of units below their regional datum in the Parry Islands fold belt (modified from Harrison, 1995). The middle rigid beam (Ordovician to Devonian) sinks into the lower ductile layer (Middle Ordovician evaporites), which is thinned in the trough of the syncline.

ratios. This suggests that for many fold belts, disharmonic detachment folds initiate as high wavelength structures, or rapidly acquire this geometry in the early stages of fold growth. These folds are then are progressively tightened by limb rotation, and also undergo additional increase in the fold wavelength by hinge migration.

Examination of detachment folds with high wavelength–amplitude ratios in their early stage of development also reveals that all units sink below their regional levels within the synclines flanking the anticlines. This phenomenon was first proposed for Appalachian Plateau folds on the basis of detailed cross sections of macroscopic structures (Wiltschko and Chapple, 1977; Gwinn, 1964; Prucha, 1968; and Frey, 1973). It is also supported by data from physical experiments (Blay et al., 1977; Abassi and Mancktelow, 1992). Furthermore, seismic data from the Parry Islands fold belt (Harrison and Bally, 1988), clearly illustrate that the units sink below their regional positions within the synclines (Figure 5). Synclinal sinking is commonly unrecognized, because the downward deflection is usually small and occurs over a very broad region. Furthermore, it is usually difficult to determine the original regional position of the units.

4.2. Geometric Progression From Disharmonic Detachment To Lift-Off Folds

Fold belts which contain structures with different amounts of shortening, such as the Jura Mountains (Figure 6; Buxtorf, 1916), the Zagros fold belt (Stocklin, 1968; Hull and Warman, 1970), and the Brooks Range (Namson and Wallace, 1986; Homza and Wallace, 1995), exhibit a complete range of structures from low-amplitude disharmonic detachment folds to box or lift-off folds.

The Jura Mountains fold belt presents a classic example of detachment folds at various stages of development. The fold belt has been studied by numerous workers, but the most

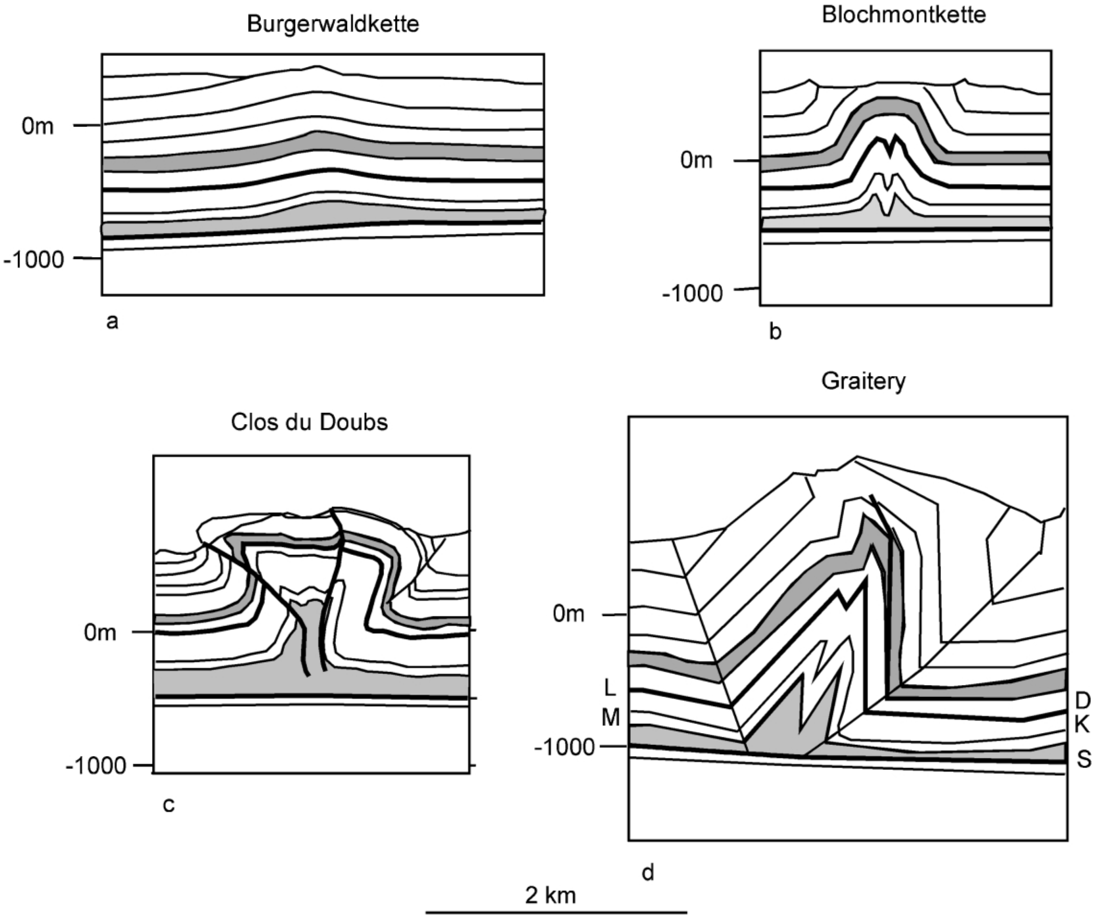

Fig. 6. Examples of detachment folds which have undergone different amounts of shortening from the Jura Mountains, Switzerland (modified from Buxtorf, 1916, and Laubscher, 1962). a. Low amplitude and relatively large wavelength fold. b. Disharmonic detachment fold with moderate amplitude. c. Box fold, transitional between disharmonic detachment fold and lift-off geometries. d. Tight high amplitude lift-off fold. S = Salzton. M = Muschelkalk. K = Keuper. L = Lias. D = Dogger. The occurrence of these different geometric types in the same stratigraphic package, and deformed under the same conditions suggests that they represent different stages in the evolution of detachment folds.

comprehensive accounts are provided in the works of Buxtorf (1916) and Laubscher (1962), who constructed numerous cross sections through the belt. Buxtorf used a concentric fold style to depict the geometry of the Jura fold belt, whereas Laubscher (1962) used kink-band geometries in his interpretations. In either case, the parallel geometry of outer units and disharmonic folding in the core is clearly demonstrated.

The stratigraphy within the Jura Mountains is ideal for the development of disharmonic detachment folds. The Jurassic Dogger and higher units exhibit parallel geometries ranging to concentric to kink or box forms. These units are underlain by disharmonic folds of the Lias, Keuper and the Muschelkalk, with the detachment located in the basal evaporite units.

Low-amplitude detachment folding, with flow of the incompetent units from the syncline to the anticline is depicted by the frontal folds, such as Burgerwaldkette (Figure 6a). Tighter folding and the development of disharmonic folds in the core is depicted by the Blochmontette (Figure 6b), Buebergkette, Movelierkette, and Vorburgkette. Further

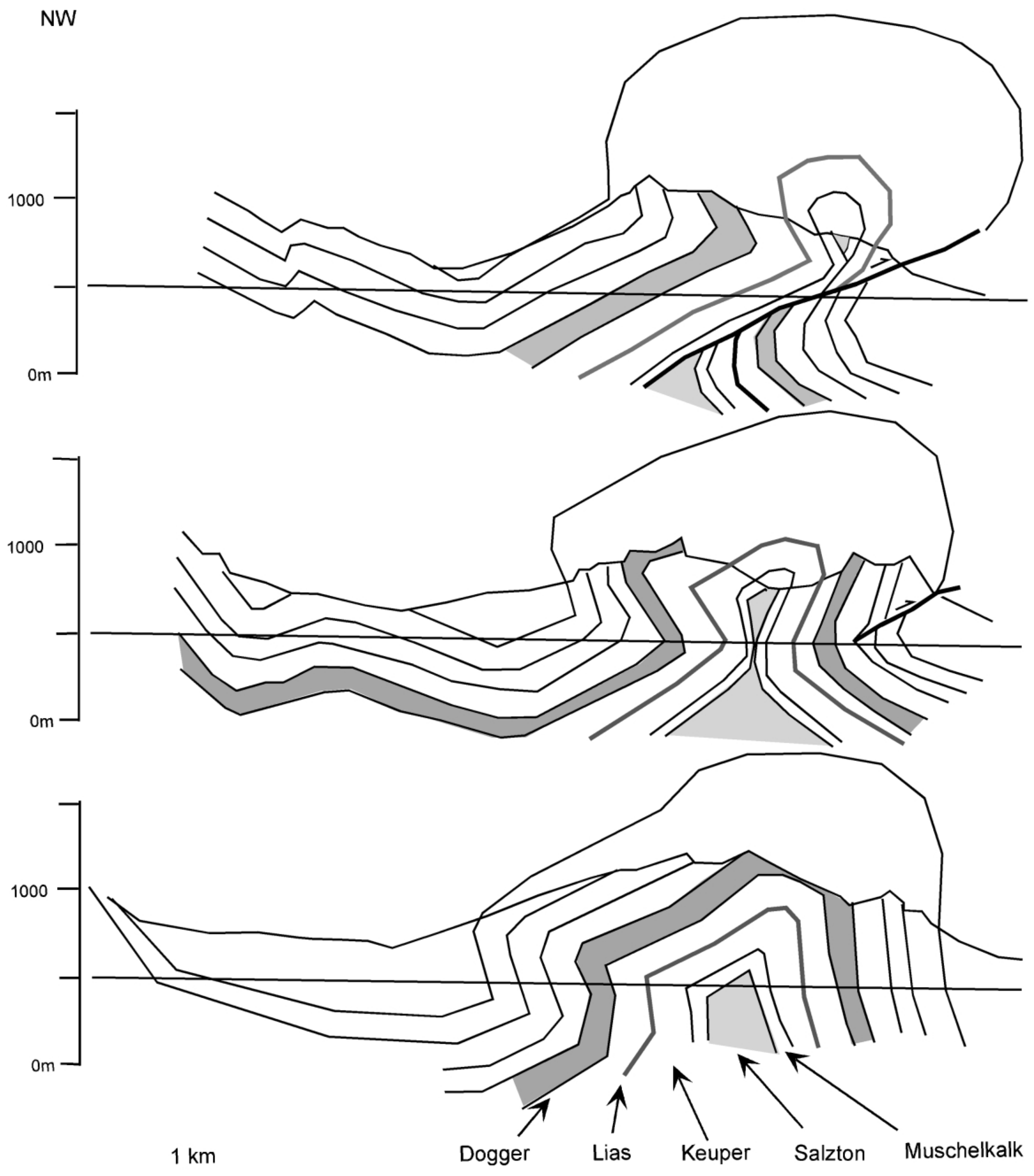

Fig. 7. Serial cross sections through the Weissenstein structure, Jura Mountains (modified from Heim, 1921). The structure shows a transition in geometry from a box-shaped lift-off fold to one with a separating bulb and the shearing of the bulb along a thrust fault. These three cross sections depict the evolution of lift-off structures from disharmonic detachment folds.

tightening of the structure results in box-shaped folds such as the Clos du Doubs anticline (Figure 6c), and the development of tight isoclinal lift-off folds and related faults, such as in the Graitery (Figure 6d), and the Grenchenberg structures. Layer-parallel stretching in the late stages of folding results in isoclinal folds with bulbous heads and pinched-off necks, as depicted in the Weissenstein kette structure (Figure 2c).

A three-dimensional study of the Weissenstein structure (from Heim, 1921) shows the progressive evolution of the structure from a disharmonic box fold to an isoclinal structure with bulbous hinge to a complex faulted asymmetric structure (Figure 7). The occurrence of such a wide variety of structures within the same stratigraphic column, and in the same deformational environment, suggests that the disharmonic and lift-off structures represent different stages of development of the same folding process.

A smaller-scale example of a detachment fold train containing folds at different stages of development has been documented from the Reed Wash area, on the west flank of the San Rafael swell, Utah (Royse, 1996). The folds have formed within a gypsiferous interval within the Middle Jurassic Carmel Formation. All shapes of fold forms, ranging from open, concentric folds to box and lift off folds are present within the fold train. The spectrum of observed fold geometries suggests that the folds have formed by both hinge migration and limb rotation.

The characteristic features of disharmonic detachment folds and lift-off folds listed above are all suggestive of the fact that the two types of structures represent different stages of the same evolutionary sequence, and that the simple parallel geometries of lift-off folds observed at the macroscopic scale belie a more complex history.

5. Unified kinematic model

A unified kinematic model for the development of detachment folds is presented below (Figure 8). The model is consistent with observed characteristic features of natural detachment folds, and is geometrically and kinematically balanced. It also proposes that disharmonic detachment folds and lift-off folds represent different stages of the same evolutionary process. The model assumes a mechanical

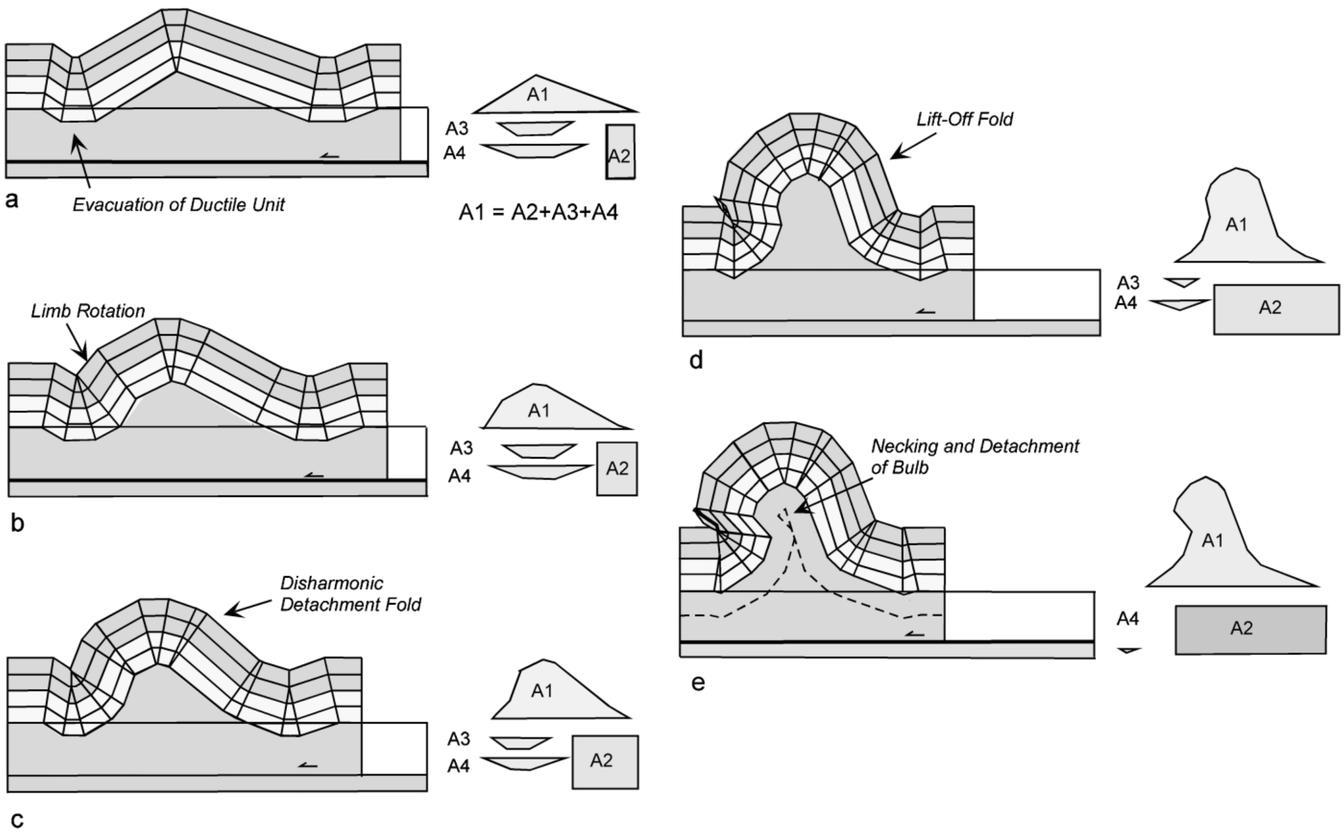

Fig. 8. Model for the evolution of a symmetric detachment fold involving a competency contrast between the basal and cover units. a. Initial development of a low amplitude detachment fold. Area balancing requires that the excess area (A2) is equal to the difference between the anticlinal area (A1) above the regional position, and the synclinal areas (A3 and A4) below regional. b–d. Growth of fold from a disharmonic detachment fold to a lift-off fold by rotation of limb segments and migration of material from the synclinal area to the fold limbs. The limb rotation may initially occur without appreciable internal deformation, and subsequently by shear between fixed hinges. e. Late stage deformation results in overturning and necking of beds and the formation of a detached bulb.

stratigraphy consisting of a highly incompetent unit at the base, overlain by a thick sequence of competent units, which deform by flexural slip folding accompanied by some fracturing and faulting. Implicit in the use of this mechanical stratigraphy is significant variation in the deformational behavior of the two units.

The fold initiates with, or rapidly develops, a high wavelength amplitude ratio, with the fold wavelength determined by the thickness of the competent unit (Currie et al., 1962). This initial geometry is based on the observation described in an earlier section that fold belts characterized by disharmonic detachment folding and small shortening commonly exhibit high wavelength–amplitude ratios. Moreover, fold belts which contain structures with a wide range of shortening values, all exhibit some structures with relatively large wavelength–amplitude ratios. Currie et al., 1962 predicted that the ratio of initial wavelength to thickness is about 20:1. However, consideration of a composite package of competent units probably results in a lower ratio. Folds in the Appalachian Plateau, typically have restored wavelength to thickness rations of 6 to 8:1, whereas Rowan (1993) found an arc length to thickness ratio of about 4:1 for folds in the Wildhorn nappe. The model

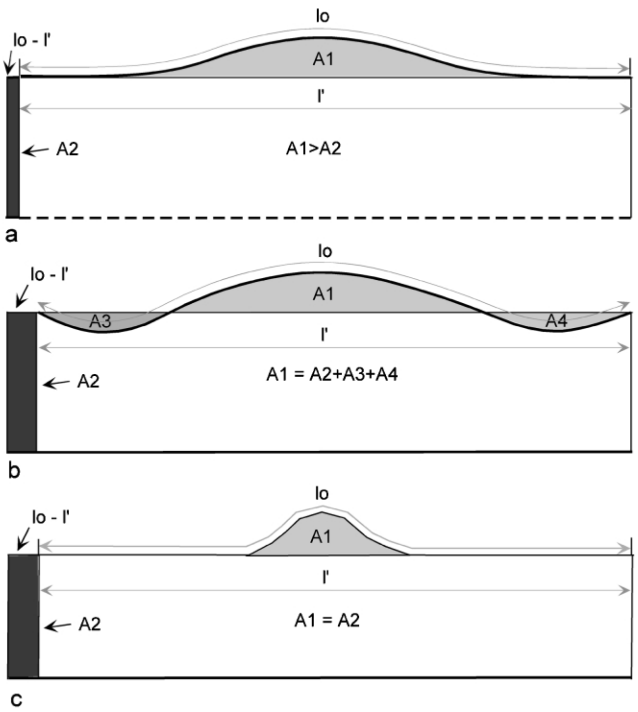

Fig. 9. a. Problem of developing a low amplitude and large wavelength fold above a regional datum. Excess area above regional datum (A1) is too high compared to the shortened area (A2). Application of conventional depth to detachment calculation incorrectly predicts a deep detachment. b. Problem is resolved if units sink below their regional position in the adjacent synclines, so that A1 = A2 + A3 + A4. c. Synclinal deflection may be absent for low amplitude folds that initiate with low wavelength–amplitude ratios.

shown in Figure 8 has a slightly asymmetric form, although a perfectly symmetric geometry is also possible.

The formation of such a fold typically results in a large anticlinal area (Figure 9a), which is greater than the shortened area. This apparent balancing problem alluded to by Dahlstrom (1990) is resolved by the fact that the folding of a competent unit surrounded by an incompetent unit results in an upward deflection of the anticlinal hinges and a corresponding downward deflection of the synclinal hinges, relative to the original position of the competent units (Figure 9b). The folded competent units are surrounded by a zone of influence within which the deformation is affected by the folding. The detachment within the zone of influence results in damping out of these folds. Therefore, the synclines are flattened and have lower amplitudes compared to the anticlines. The downward deflection of the syncline below the regional position of the unit results in movement of an area of the underlying incompetent unit into the anticlinal core. This phenomenon is supported by outcrop and seismic data from macroscopic structures and by experimental modeling, described earlier.

The extent of synclinal deflection depends on the initial wavelength–amplitude (w/a) ratio, which in turn is related to the thickness of the competent unit and the viscosity contrast between the competent and incompetent units. For folds with low w/a values, the synclinal depression may be small or absent (Figure 9c). The deflection is also dependent on the thickness and ductility of the basal unit. A thin, incompetent basal unit may be completely evacuated from the synclinal hinges, resulting in grounding of the overlying units. On the other hand, a thick incompetent unit may result in folding with a relatively small component of hinge migration, for a significant part of the folding history. In most instances, the downward deflection of the beds is usually broad, and of low amplitude.

Continued growth of the fold occurs by limb lengthening, involving the migration of hinges through beds, and limb rotation (Figure 10b and c). Both of these mechanisms may operate simultaneously and in different proportions at different stages of fold growth. Rotation of bed segments to steeper dips may occur in two ways (Mitra, 2002b): (1) rotation of a segment of the limb to a steeper dip without any internal deformation of the beds (Figure 10d), requiring the migration of beds through one or both of the outer hinges; (2) rotation of a limb segment to a steeper dip by internal shear, between fixed hinges, which may not involve the migration of the outer hinges (Figure 10e).

In the early stages of fold tightening (Figure 8b), the upper competent units are deformed primarily by hinge migration without appreciable internal deformation (Figure 10d). This requires migration of beds through the synclinal hinge onto the limbs, resulting in a reduced synclinal area and an increased anticlinal area. Continued deformation (Figure 8c and d) results in progressive reduction of the synclinal area through hinge migration, so that in the late stages of deformation, the units may return to their regional

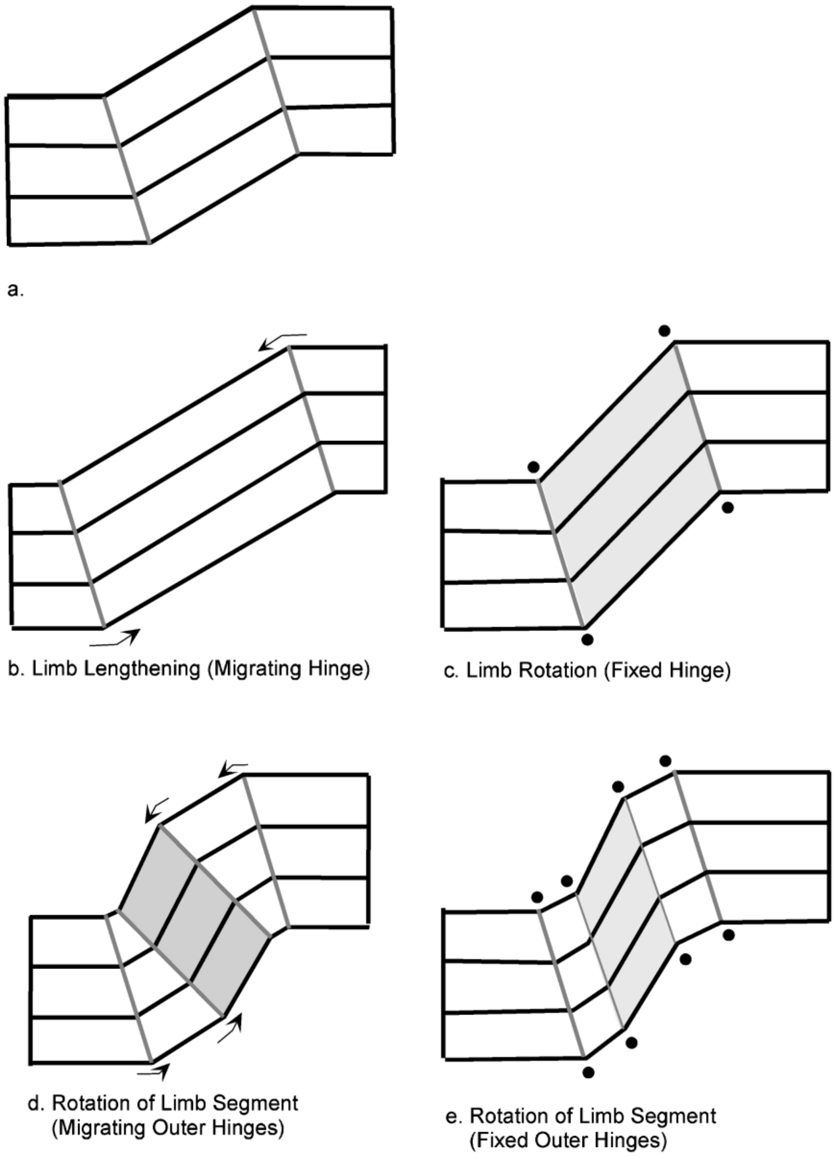

Fig. 10. Mechanisms of fold growth (from Mitra, 2002b). a. Pre-exisiting fold. b and c represent the commonly cited mechanisms of fold growth. b. Fold growth by migration of beds through hinges (migrating hinge model). Beds within the kink band maintain their original thickness. c. Fold growth by rotation of beds between fixed hinges. This involves internal shear of beds within the kink band. d and e. Alternative mechanisms of fold growth. d. Rotation of limb segment to a steeper dip with constant bed thickness. This requires migration of beds through one or both of the outer hinges. e. Rotation of limb segment along a pair of fixed hinges. This involves internal shear of beds and does not require migration through the outer hinges. Both d and e are expected to occur at different stages in the evolution of detachment folds.

positions in the synclines. If the anticlines are originally separated by very broad and shallow synclines, only the flanks of the synclines will return to regional, and a large-wavelength and low-amplitude syncline may be present in the late stages of folding.

Crowding of the units in the synclinal region may also result in the development of out-of-syncline thrusts (Mitra, 2002a). In the late stages of evolution, limb rotation may occur between fixed hinges (Figure 10e), so that the beds are internally deformed and possibly faulted in some of the rotated limb segments.

The fold form finally assumes an isoclinal geometry commonly observed in lift-off folds (Figure 8d). Earlier-formed out-of syncline thrusts are now rotated to vertical or very steep dips, as seen in the Graitery (Figure 6d) and Chuhuangkeng (Figure 2a) structures. Continued tightening may result in thinning and necking of the ductile unit to the point that a part of the structure is detached as a separate bulb (Figure 8e). This type of geometry is observed in the Weissenstein Kette structure (Figure 2c and 7).

Interpreted macroscopic geometries of lift-off folds commonly display approximately parallel geometries of all units. This observation has led to the suggestion that lift-off folds form by a self-similar mechanism involving synclinal hinge migration (Dahlstrom, 1990; Rowan et al., 2000); however, the detailed geometry (Figure 3) and evolution of these folds is usually more complex. According to the model proposed here, the basal ductile unit may be first thinned under the synclines and thickened under the anticlines. In the late stages of deformation, the reduction of the synclinal area may result in the basal unit reverting to its original thickness. At the same time, the unit is stretched parallel to the axial plane in the anticlinal core, so that the basal unit exhibits a pseudo-parallel geometry in its final form.

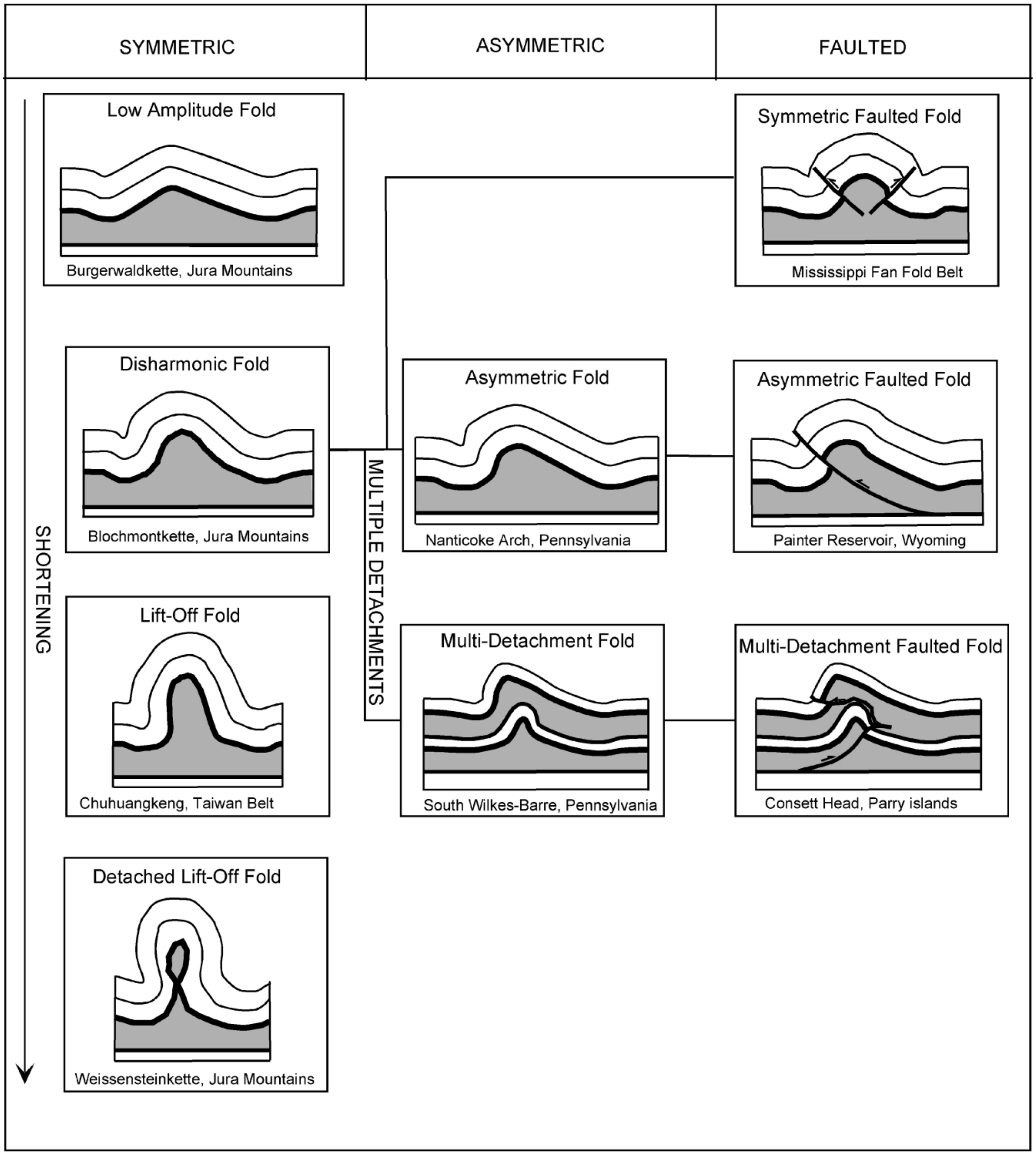

Fig. 11. Variations in structural styles of detachment folds related to magnitude of shortening, asymmetry, faulting, and the occurrence of multiple detachments. One interpreted example of each type of structure is cited.

6. Area balancing of detachment folds

Area balancing of detachment folds requires that the anticlinal area above the regional position of each unit minus the sum of the synclinal areas must equal the area lost in the shortening associated with the formation of the structure.

The original depth to detachment equation for detachment folds was developed by Chamberlin (1910), and has been modified by a number of authors since (Mitra, 1990; Epard and Groshong, 1995; Homza and Wallace, 1995). Chamberlin's equation assumes that the area resulting from the shortening of the units above the basal detachment (A) is uplifted as an excess area above the regional level, and that all units deform entirely by parallel folding. This yields the depth (z) to detachment relationship

$$z = A/(lo - l') = A/(lo - l') \quad (1)$$

The transfer of material from the synclinal to the anticlinal area proposed in this paper requires that

$$A2 = A1 - (A3 + A4) \quad (2)$$

The depth to detachment (z) is therefore given by:

$$z = A/(lo - l') = [A1 - (A3 + A4)]/(lo - l') \quad (3)$$

In Figure 8, the variation in the anticlinal, synclinal, and shortened areas with time is shown for each stage of evolution. For mature detachment folds and lift-off folds, the synclinal area is small to absent. A common observation in a number of fold belts is that using the conventional depth to detachment calculation, low amplitude folds yield a greater depth to detachment than high amplitude folds. In the early stages of folding, the anticlinal area (A1) is significantly higher than the area of shortening (A2), so that the structure must be balanced by subtraction of the synclinal areas A3 and A4. In the late stages of folding, the anticlinal area (A1) is approximately equal to the shortened area (A2), so that the units return to their regional positions in the synclines. Therefore, the modification to the depth to detachment method proposed here alleviates the problem of variable detachment depths and results in a more uniform depth to detachment for structures of different wavelength–amplitude ratios in a single fold belt.

7. Variations in Structural geometry

The most common variations in the geometry and evolution of detachment folds from the model shown in Figure 8 are (1) an asymmetric geometry, (2) faulting of limbs to form faulted detachment folds, and (3) complex fold and fault geometries resulting from multiple detachment horizons (Figure 11).

Asymmetric fold geometries are quite common for detachment folds. Davis and Engelder (1985) suggested that fold belts with a weak and subhorizontal detachment are usually characterized by folds and thrust faults with opposite vergence. The low taper angle of these belts, defined by the sum of the topographic slope and the slope of the basal detachment, results in the two potential slip planes being symmetrically aligned to the direction of maximum principal compressive stress, so that maximum shear along either or both of these orientations is possible. Therefore, folds or faults may develop along local discontinuities or perturbations on the basal detachment, such as pre-exisiting normal faults or areas of change in the dip of the underlying basement. The local discontinuities may act as focal points for the initiation of folding, and also control the vergence of the folds. Detachment folds are therefore more likely to exhibit variable vergence than other fold types.

Faulting of fold limbs and the development of faulted detachment folds (Mitra, 2002b), usually occurs due to high strains on the fold limbs during limb rotation. The faults may develop on the forelimbs of asymmetric folds, or on both limbs of symmetric folds. Faulting is encouraged by reduced flexural slip efficiency of the upper competent units, a lower ductility contrast between the units, and grounding of the competent units due to complete evacuation of a thin basal ductile unit.

Stratigraphic packages characterized by more than one major detachment, exhibit more complex fold forms. Individual packages may develop different fold forms and even a different sense of vergence. In the latter case, complex fault systems, including the fish-tail structures described by Harrison and Bally (1988), may develop.

8. Conclusions

Detachment folds form in stratigraphic packages with high competency contrasts among units. The competent upper units exhibit parallel fold geometries, whereas the weak lower unit displays disharmonic folding. They are typically more symmetrical and more likely to display opposite senses of vergence than other fault-related folds.

Two distinct geometric types, disharmonic detachment folds, and lift-off folds are recognized. These structural geometries usually represent different stages in the evolution of detachment folds.

The structures first form by symmetric or asymmetric folding, with the fold wavelength controlled by the thickness of the dominant units. The ductile basal unit flows from the synclines to the anticlines in the early stages of folding. Increasing fold amplitude and wavelength involves both limb segment rotation and hinge migration.

Initially, limb rotation occurs primarily by flexural slip folding, but in the late stages of deformation, the rotation may involve significant internal deformation of units between locked hinges. Tight lift-off geometries and detached bulbs typically form in the late stages of deformation.

Variations in the geometry of detachment fold geometry, such as fold asymmetry, significant faulting, and fold associated with multiple detachments, are related to variations in the initial mechanical stratigraphy and pre-existing structure.

References

Abbassi, M.R., Mancktelow, N.S., 1992. Single layer buckle folding in non-linear materials. I. Experimental study of development from an isolated initial perturbation. Journal of Structural Geology 14, 85–104.

Almendinger, R., 1998. Inverse and forward numerical modeling of trishear fault propagation folds. Tectonics 17, 640–656.

Belotti, H.J., Saccavino, L.L., Schachner, G.A., 1995. Structural styles and petroleum occurrence in the sub-Andean fold and thrust belt of northern Argentina. In: Tankard, A.J., Suarez, R., Welsink, H.J. (Eds.), Petroleum basins of South America, 62. American Association of Petroleum Geologists Memoir, pp. 545–555.

Blay, P., Cosgrove, J.W., Summers, J.M., 1977. An experimental investigation of the development of structures in multilayers under the influence of gravity. Journal of the Geological Society of London 133, 329–342.

Buxtorf, A., 1916. Prognosen und befunde beim Hauensteinbasis-und Grenchenberg-tunnel und die Bedeutung der letzeren fur die geologie des Juragebirges. Verhandlungen der Naturforschenden Gesellschaft in Basel 27, 184–205.

Carey, S.W., 1962. Folding. Journal of Alberta Society of Petroleum Geologists 10, 95–144.

Chamberlin, R.T., 1910. The Appalachian folds of central Pennsylvania. Journal of Geology 18, 228–251.

Chester, J.S., Chester, F.M., 1990. Fault-propagation folds above thrusts with constant dip. Journal of Structural Geology 12, 903–910.

Currie, J.B., Patnode, H.W., Trump, R.P., 1962. Developments of folds in sedimentary strata. Geological Society of America Bulletin 73, 655–674.

Dahlstrom, C.D.A., 1969. Balanced cross sections. Canadian Journal of Earth Sciences 6, 743–757.

Dahlstrom, C.D.A., 1990. Geometric constraints derived from the law of conservation of volume and applied to evolutionary models of detachment folding. American Association of Petroleum Geologists Bulletin 74, 336–344.

Davis, D.M., Engelder, T., 1985. The role of salt in fold-and-thrust belts. Tectonophysics 119, 67–88.

De Sitter, L.U., 1964. Structural Geology, Second edition, McGraw-Hill, New York, p. 551.

Elliott, D., 1977. Some aspects of the geometry and mechanics of thrust belts: Parts 1 and 2. 8th Annual Seminar Canadian Society Petroleum Geology, University Calgary.

Epard, J-L., Groshong, R.H., 1995. Kinematic models of detachment folding including limb rotation, fixed hinges, and layer parallel shortening. Journal of Structural Geology 247, 85–103.

Erslev, E.A., 1991. Trishear fault propagation folding. Geology 19, 617–620.

Goguel, J., 1962. Tectonics, Freeman, San Francisco, p. 348.

Fox, F.G., 1985. Structural Geology of the Parry Islands Fold Belt. Bulletin of Canadian Petroleum Geology 33, 306–340.

Frey, M.G., 1973. Influence of Salina salt on structure in New York-Pennsylvania part of the Appalachian Plateau. American Association of Petroleum Geologists Bulletin 57, 1027–1037.

Gwinn, V.E., 1964. Thin-skinned tectonics in the Plateau and northwestern Valley and Ridge provinces of the central Appalachians. Geological Society of America Bulletin 75, 863–900.

Hardy, S., Ford, M., 1997. Numerical modeling of trishear fault-propagation folding and associated growth strata. Tectonics 16, 841–854.

Harrison, J.C., 1995. Tectonics and kinematics of a foreland folded belt influenced by salt, Arctic Canada. In: Jackson, M.P.A., Roberts, D.G., Snelson, S. (Eds.), Salt tectonics: A global perspective, American Association of Petroleum Geologists Memoir 65, pp. 379–412.

Harrison, J.C., Bally, A.W., 1988. Cross sections of the Parry Islands fold belt on Melville Island. Canadian Petroleum Geology Bulletin 36, 311–332.

Heim, A., 1921. Geologie der Schweitz. Leipzig, C.H. Tranchnitz, 704 p.

Homza, T.X., Wallace, W.K., 1995. Geometric and kinematic models for detachment folds with fixed and variable detachment depths. Journal of Structural Geology 17, 475–488.

Hull, C.E., and Warman, H.R., 1970, Asmari oil fields of Iran. In Geology of giant petroleum fields, American Association of Petroleum Geologists Memoir 14, pp. 428-437.

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

Laubscher, H.P., 1962. Die Zweiphasenhypothese der Jurafaltung. Ecogae Geol. Helvetiae 55, 1–22.

Mitchell, M.M., 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, kinematic evolution, and hydrocarbon traps. American Association of Petroleum Geologists Bulletin, v. 74, 921–945.

Mitra, S., 2002a. Fold-accommodation faults. American Association of Petroleum Geologists Bulletin 86, 671–693.

Mitra, S., 2002, Structural geometry of faulted detachment folds, American Association of Petroleum Geologists Bulletin (in press).

Mitra, S., and Namson, J.S., 1989. Equal-area balancing. American Journal of Science, 289, 563- 599.

Namson, J.S., 1981. Detailed structural analysis of the western foothills belt in the Miaoli–Hsinchu area. Taiwan: I. Southern part. Petroleum Geology of Taiwan 18, 31–51.

Namson, J.S., Wallace, W.K., 1986. A structural transect across the Brooks Range. Alaska, Geological Society of America Abstracts with Programs 16, 163.

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

Poblet, J., McClay, K., Storti, F., Munoz, J.A., 1997. Geometries of syntectonic sediments associated with single-layer detachment folds. Journal of Structural Geology 19, 369–381.

Prucha, J.J., 1968. Salt deformation and decollement in the Fir Tree Point anticline of central New York. Tectonophysics 6, 273–299.

Rowan, M.G., 1993. Structural geometry of the Wildhorn nappe between the Aar massif and the Brienzer See. Eclogae Geol. Helvetiae 86, 87–119.

Rowan, M.G., Trudgill, B.D., and Fiduk, J. C., 2000. Deep-water salt-cored foldbelts: Lessons from the Mississippi fan and Perdido fold belts, northern Gulf of Mexico, p. 173-191. In Atlantic Rifts and Continental Margins, Geophysical Monograph 115, American Geophysical Union.

Royse, F., 1996, Detachment fold train, Reed Wash area, west flank San Rafael swell, Utah: An example of a limb lengthening, roll-through folding process on the eastern margin of the Sevier thrust belt, The Mountain Geologist, v. 33, p.45-64.

Stocklin, J., 1968. Structural history and tectonics of Iran: A review.

American Association of Petroleum Geologists Bulletin 52, 1229–1258.

Suppe, J., 1985. Principles of Structural Geology. Prentice Hall, Englewood Cliffs, New Jersey, 537p.

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

Willis, B., and Willis, R., 1934. Geologic Structures. McGraw Hill, New York, 544p.

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