Estimating the detachment depth in cross sections involving detachment folds

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Abstract – This paper evaluates four different methods that have been proposed for the estimation of the detachment depth beneath detachment folds. Guidelines are presented in order to use the most suitable method in a particular region deformed by detachment folds. These guidelines are constructed considering the assumptions of each method, the influence of different parameters on the estimation of the detachment depth (folding mechanisms, cross-sectional area variations, position and orientation of the regional datum, number of stratigraphic horizons, bed length and thickness, dip and position of the bounding lines, initial thickness of the ductile unit, single anticlines or fold trains) and the available data (ductile unit thickness, regional datum, detachment depth). Moreover, a new, simple method based on two previous methods is presented. The advantages of this new method are that the calculations are extremely simple and it uses information from more than one stratigraphic horizon; therefore, it does not depend strongly on the accuracy of the data at one level. The precision of the proposed methods is tested by their application to a number of natural and experimental single anticlines and fold trains. It appears that better predictions are obtained when analysing a complete detachment fold train than when dealing with a single detachment anticline. The reason might be that ductile material flow beneath the folds along the cross-sectional plane is taken into account when dealing with a long-enough cross section. We also suggest some hypotheses concerning what the shape and dimensions of the detachment folds indicate about the detachment depth in those cases where insufficient data are available to apply the methods proposed.

1. Introduction

The detachment depth is an essential element when constructing, balancing and restoring cross sections across regions affected by different tectonic styles, such as fold and thrust belts or extensional terranes. Moreover, recognition of detachment depth is crucial in the assessment of the hydrocarbon-trapping potential of a fold.

Classically, the excess-area method derived by Chamberlin (1910, 1919) has been used to estimate the depth to detachment beneath a fold (e.g. Bucher, 1933; Goguel, 1962; Laubscher, 1962; Dahlstrom, 1969; Ramsay & Huber, 1987; Woodward, Boyer & Suppe, 1989). This method, based on the area-conservation principle, predicts that the detachment depth equals the excess area beneath a particular horizon uplifted above the regional divided by the shortening undergone by this horizon (Fig. 1). A number of papers point out that the application of this method to some particular examples of detachment anticlines gives inaccurate results (e.g. Bucher, 1933; Jones, 1987; Geiser, 1988; Mitra & Namson, 1989; Dahlstrom, 1990; Groshong & Epard, 1994; Homza & Wallace, 1995, 1997). In many cases, the failure of the detachment-depth prediction results from the fact that there is a discrepancy between the uplifted and displaced areas.

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Mitra & Namson (1989) suggested that interbed shear within detachment anticlines cause the discrepancy between the uplifted and displaced areas. To solve this area-balance problem, they modified the Chamberlin (1910) method to make it applicable to single detachment anticlines involving interbed shear (Fig. 2).

The discrepancy between the uplifted and displaced areas also appears to be related to the mechanism responsible for fold amplification. Thus, when sequentially restoring some individual detachment anticlines, it appears that in many amplification stages the uplifted area does not equal the displaced area (Fig. 3a, b) (Wiltschko & Chapple, 1977; Jones, 1987; Dahlstrom, 1990; Butler, 1992; Groshong & Epard, 1994; Homza & Wallace, 1995; Poblet & Hardy, 1995). Three numerical/kinematic solutions to this problem have been presented:

(1) Homza & Wallace (1995), Poblet & Hardy (1995) and Poblet & McClay (1996) developed a model, based on Dahlstrom's (1990) observations for single detachment anticlines that was area-balanced during any amplification stage (Fig. 3c). This model predicts that anticlines would form by a particular combination of limb rotation and hinge migration, keeping constant bed length and thickness in the upper, competent unit.

(2) Alternatively, in order to keep equal the uplifted and displaced areas during all the amplification stages,

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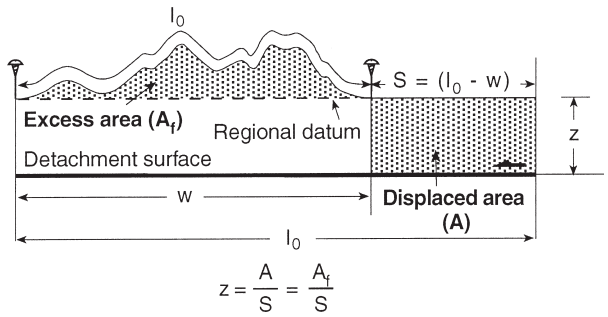


Figure 1. Relationship between excess area and depth to detachment according to the Chamberlin (1910) equation. Abbreviations: z, depth to detachment; S, shortening; l_0, initial bed length; w, fold width; A_f, uplifted area in the anticline core; and A, displaced area.

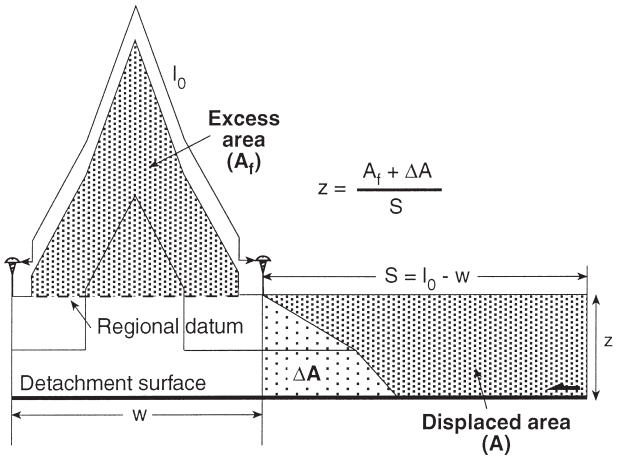


Figure 2. Relationship between excess area, area increment due to interbed shear, and depth to detachment beneath a single detachment anticline according to the Mitra & Namson (1989) method. Abbreviations: z, depth to detachment; S, shortening; l_0, initial bed length; w, fold width; A_f, uplifted area in the anticline core; A, displaced area; and ΔA, area increment due to interbed shear. Modified after Mitra & Namson (1989).

Groshong & Epard (1994) and Epard & Groshong (1995) presented a model for single detachment anticlines involving limb rotation or a combination of limb rotation and hinge migration coupled with layer-parallel strain (fig. 5 in Groshong & Epard, 1994; fig. 4 in Epard & Groshong, 1995).

(3) Another solution to make the uplifted area equal to the displaced area during all the amplification stages consists of assuming fluctuations in the detachment depth due to thickening or thinning of the lower, incompetent unit (Wiltschko & Chapple, 1977). Homza & Wallace (1995) created a model that allows detachment-depth variations, and these folds may grow by any amplification mechanism as long as bed length is preserved in the competent unit (figs 8, 10 in Homza & Wallace, 1995).

Epard & Groshong (1993) created a graphical technique to estimate the detachment depth for those individual detachment anticlines in which the uplifted area equals the displaced area during all the amplification stages and the detachment depth remains constant (i.e. solutions 1 and 2) (Fig. 4).

Homza & Wallace (1995) described a graphical/numerical method to estimate the detachment depth beneath individual detachment anticlines formed by

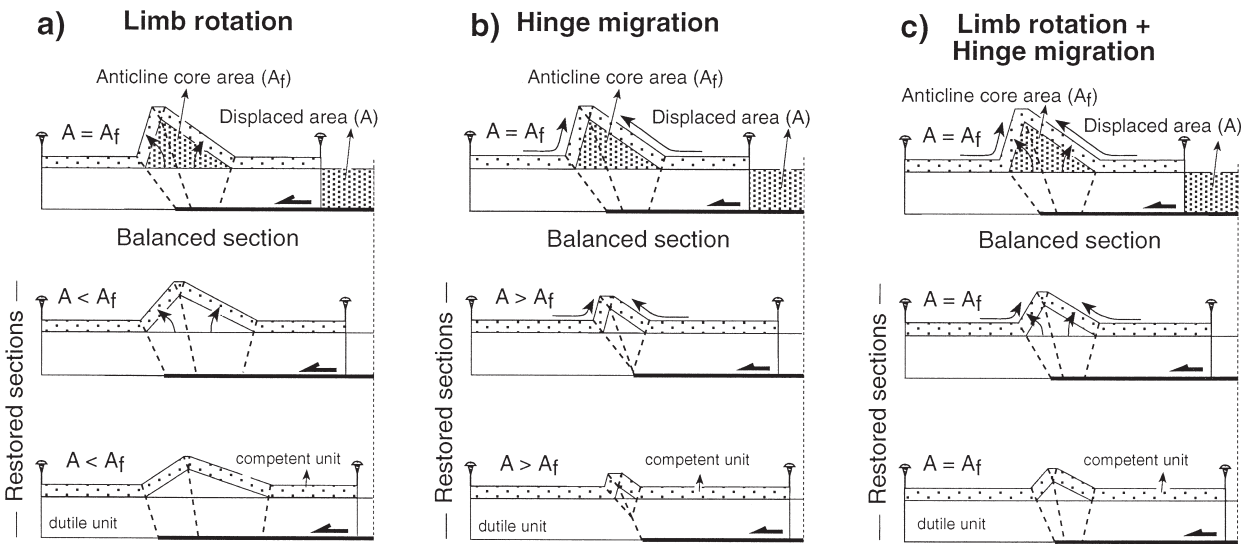


Figure 3. Balanced cross sections and restorations of single detachment anticlines developed by different amplification mechanisms: (a) limb rotation (De Sitter, 1956; Hardy & Poblet, 1994; Homza & Wallace, 1995; Poblet & Hardy, 1995; Poblet & McClay, 1996); (b) hinge migration (self-similar) (Suppe, 1983; Homza & Wallace, 1995; Poblet & McClay, 1996); and (c) combination of limb rotation and hinge migration (Dahlstrom, 1990; Homza & Wallace, 1995; Poblet & Hardy, 1995; Poblet & McClay, 1996).

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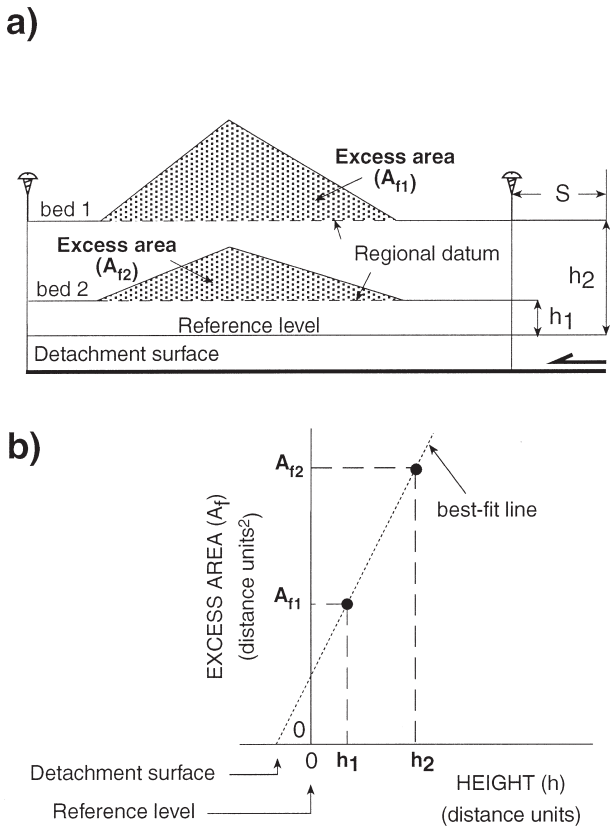


Figure 4. Graphical method proposed by Epard & Groshong (1993) to estimate the depth to detachment beneath single detachment anticlines. (a) Measurements on the fold profile. (b) Plot of excess area *v.* distance to a reference datum for the detachment fold illustrated above. Abbreviations: S, shortening; h_1 and h_2, distance from bed 1 and bed 2 to the reference level; and A_{f1} and A_{f2}, uplifted area beneath bed 1 and bed 2 in the anticline core. Modified after Epard & Groshong (1993).

any amplification mechanism and constant bed length in the competent unit (i.e. solutions 1 and 3) (Fig. 5).

This paper examines the influence of some parameters in the estimation of the detachment depth using the methods described above. In addition, we present a new method to estimate the detachment depth based on the Chamberlin (1910) and Epard & Groshong (1993) methods, which takes into account information at several stratigraphic horizons. As a result, we suggest some guidelines to estimate the detachment depths in regions involving detachment folding using the methods proposed to date. In addition, the reliability of the detachment-depth values obtained using these methods is assessed, taking into account the data available. The validity of these methods is tested through their application to the estimation of the detachment depth beneath some natural and experimental detachment folds. Finally, for those situations in which insufficient data were available to estimate the detachment depth, some general ideas are suggested about qualitative relationships between detachment depth and fold profiles.

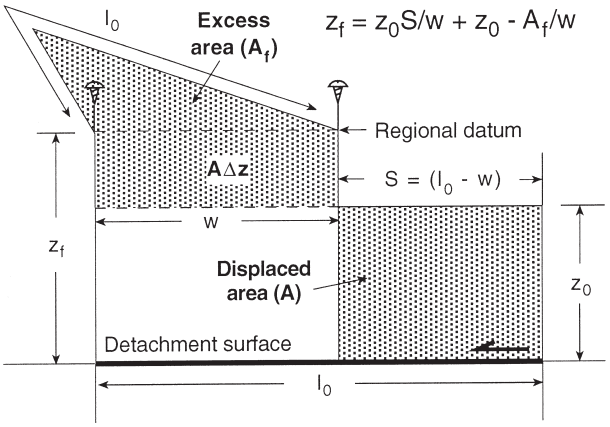


Figure 5. Homza & Wallace (1995) template to estimate the depth to detachment for single detachment anticlines. The Homza & Wallace (1995) equation is slightly modified. Abbreviations: z_0, initial depth to detachment (original thickness of the ductile unit); z_f, final depth to detachment; S, shortening; l_0, initial bed length; w, fold width; A_f, uplifted area in the anticline core; A, displaced area; and $A_{\Delta z}$, area variation beneath the anticline during deformation. Modified after Homza & Wallace (1995).

2. Parameters to consider when estimating the detachment depth beneath detachment folds

2.a. Types of fault-related folds and mechanisms of fold amplification

Before estimating the detachment depth using the methods outlined above, it is necessary to ensure that we are dealing with a detachment fold to avoid errors in the estimations. However, the methods proposed to estimate the detachment depth were developed for application in regions where the detachment surface and/or part of the structure are not exposed. In these regions, it may be difficult to distinguish between the different types of thrust-related folds (e.g. fault-bend, fault-propagation and detachment folds). In general, fault-bend folds usually have a relatively high interlimb angle, whereas, tight, upright folds are more apt to be detachment folds.

However, these three types of thrust-related folds may have identical geometry (e.g. Jamison, 1987) (Fig. 6), although they involve different kinematics (Fig. 7). (1) Fault-bend folds develop as a result of the movement of a thrust sheet over a thrust ramp, necessitating the bending of the rocks as they ride over a non-planar thrust surface (Suppe, 1983) (Figs 6a, b, c). Both fold limbs grow by hinge migration (self-similar growth): that is, the dip of the limbs is attained instantaneously during the initial amplification stage, and is kept constant during fold evolution (Suppe, 1983). (2) Fault-propagation folds develop at the tip of a thrust ramp simultaneously with ramp formation, so that the displacement along the thrust ramp diminishes progressively to zero beneath the fold (Mitra, 1990; Suppe & Medwedeff, 1990) (Fig. 6d). The backlimb amplifies

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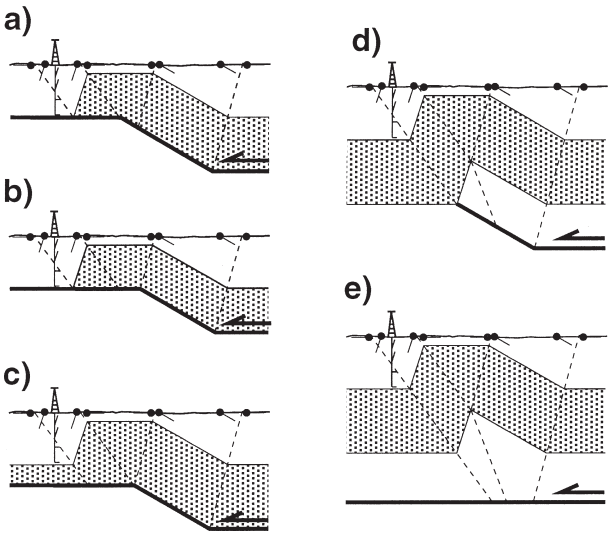


Figure 6. Various thrust-related fold interpretations using identical fold geometry derived from field and drill data: (a) simple-step fault-bend fold in the crestal uplift stage (minimum shortening); (b) simple-step fault-bend fold in the crestal broadening stage (maximum shortening); (c) simple-step fault-bend fold with the deepest thrust (intermediate shortening); (d) simple-step fault-propagation fold; and (e) detachment fold. Modified after Mitra (1990).

by hinge migration, whereas the forelimb may undergo hinge migration (Suppe, 1983) or limb rotation (De Sitter, 1956). (3) Detachment folds develop at the termination of a thrust, as displacement is transferred into folding above the leading edge of a flat region of a thrust, or within the interior of a flat region of a thrust where the fault displacement gradient changes abruptly (Groshong & Epard, 1994; Epard & Groshong, 1995; Homza & Wallace, 1995; Poblet & McClay, 1996) (Fig. 6e). Both the forelimb and the backlimb may amplify by hinge migration (Suppe, 1983), limb rotation (De Sitter, 1956), or a combination of both (Beutner & Diegel, 1985).

In addition, most of the methods developed to estimate detachment depth can only be applied to detachment folds formed by specific kinematic mechanisms. However, detachment folds formed by different kinematics (hinge migration, limb rotation or combination of both) (Fig. 7) can have identical geometry (e.g. Homza & Wallace, 1995; Poblet & McClay, 1996) (Fig. 3). Therefore, before estimating the detachment depth, it is necessary to determine the kinematics of the detachment fold analysed.

The Homza & Wallace (1995) method can be

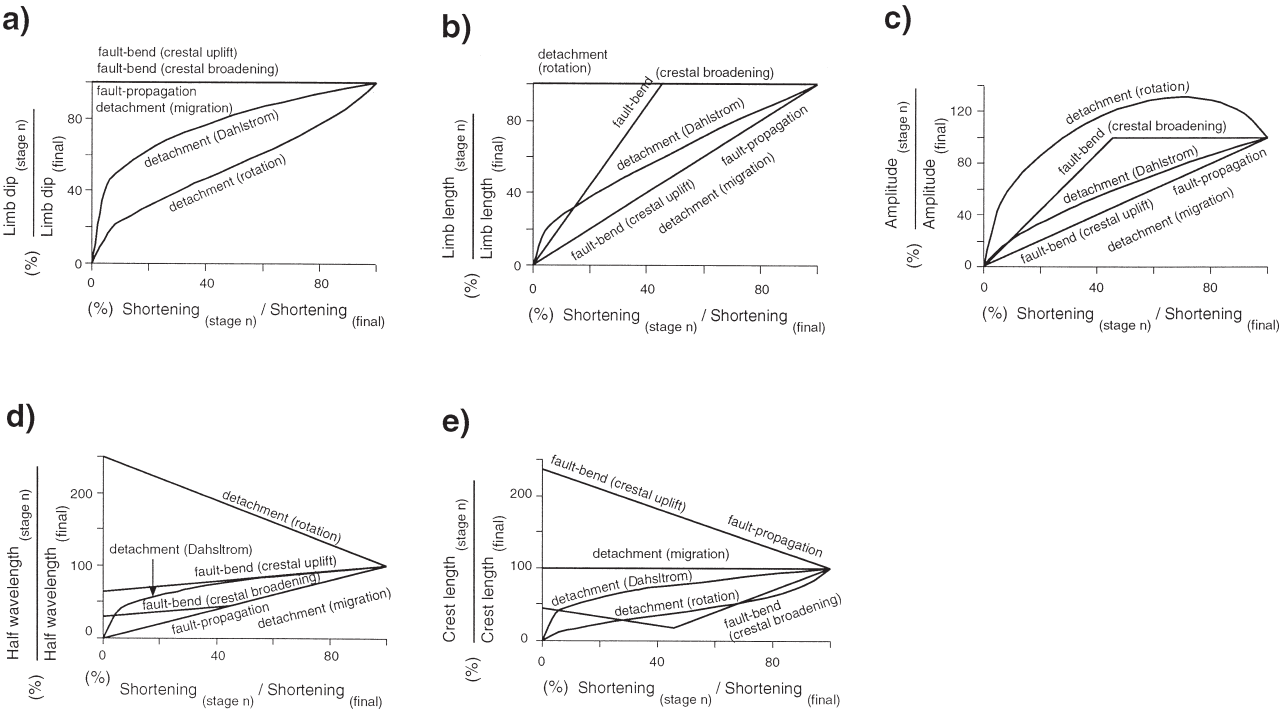


Figure 7. Graphs showing (a) limb dip, (b) limb length, (c) amplitude, (d) half wavelength, and (e) crest length versus shortening for six types of parallel folds related to thrusts: a simple-step fault-bend fold in the crestal uplift stage, formed according to equations in Suppe (1983) (hinge migration); a simple-step fault-bend fold in the crestal broadening stage, formed according to equations in Suppe (1983) (hinge migration); a simple-step fault-propagation fold formed according to equations in Suppe & Medwedeff (1990) (hinge migration); a detachment fold developed by hinge migration, formed according to equations in Homza & Wallace (1995) and Poblet & McClay (1996); a detachment fold developed by limb rotation, formed according to equations in Homza & Wallace (1995) and Poblet & McClay (1996); and a detachment fold developed by combination of hinge migration and limb rotation (Dahsltrom, 1990), formed according to equations in Homza & Wallace (1995) and Poblet & McClay (1996). Note the different kinematic path followed by each type of fold. To normalize the graphs, the value of each geometrical parameter, at a particular stage of fold growth, has been divided by the value attained at the final stage and multiplied by 100.

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applied to a single detachment anticline amplified by any mechanism, whereas the Chamberlin (1910), Mitra & Namson (1989) and Epard & Groshong (1993) methods can only be applied to folds amplified by certain mechanisms (solution 1 described in the introduction section in the case of the Chamberlin (1990) and Mitra & Namson (1989) methods, and solutions 1 and 2 in the case of the Epard & Groshong (1993) method). Therefore, with the exception of the Homza & Wallace (1995) method, it is important to determine the kinematic mechanism responsible for detachment fold amplification in order to carry out a detachment-depth estimation.

Fortunately, a number of methods have been described to distinguish between thrust-related folds formed by different kinematic mechanisms: analysis of syntectonic micro- and mesostructures developed in fold hinges and limbs (Beutner & Diegel, 1985; Fischer, Woodward & Mitchell, 1992; Fisher & Anastasio, 1994; Poblet & McClay, 1996; Anastasio *et al*. 1997); analysis of the fold geometry (Jamison, 1987); correspondence between fold wavelength and thickness of a dominant stratigraphic unit according to buckling equations, coupled with analysis of syntectonic mesostructures (Mitchell & Woodward, 1988); study of geometrical features, such as occurrence of sheared incompetent layers, volume change and fold core area, coupled with analysis of syntectonic micro- and mesostructures (Stewart & Alvarez, 1991; Homza & Wallace, 1995, 1997); study of the geometry of the syntectonic sediments (Suppe, Chou & Hook, 1992; Hardy & Poblet, 1995; Torrente & Kligfield, 1995; Hardy *et al*. 1996; Poblet *et al*. 1997; Storti & Poblet, 1997); and analysis of the presently observed spatial variations in fold geometry, assuming that they reflect temporal geometric evolution (Poblet *et al.* 1998).

2.b. Variations in the cross-sectional area

All the current methods to estimate the detachment depth assume no variations in the cross-sectional area during fold amplification. However, transfer of material in or out of the cross section may occur as a consequence of unexposed, additional faults between the folded surface and the detachment (Marshak & Woodward, 1988). Moreover, as detachment folds are often cored by ductile rocks (evaporites, shales, etc.), errors may arise because of flow of ductile material inside or outside the area enclosed within the bounding lines and/or along planes other than that of the cross section (Norris, 1971; Hossack, 1979; Jones, 1987; Butler, 1992). In addition, ductile rocks that have not undergone full compaction prior to deformation, may experience substantial decreases of the cross-sectional area due to compaction, and they often undergo internal deformation that may lead to increases or decreases of the cross-sectional area. Mitra & Namson (1989) introduced a correction factor in their equation to account for differential penetrative strain. However, this value can only be determined in those examples where the detachment depth is known. Therefore, if this factor is considered, then the Mitra & Namson (1989) method cannot be used to estimate the detachment depth. We conclude that these methods of depth determination may not be very precise because of this area-conservation simplification.

2.c. Position and orientation of the regional datum

In many detachment-depth estimations carried out previously, the regional datum (McClay, 1992) was placed at the base of the competent unit in the deepest synclines, implicitly assuming that the depth of these synclines did not change (e.g. Laubscher, 1962; Ramsay & Huber, 1987; Mitra & Namson, 1989; Epard & Groshong, 1993; Homza & Wallace, 1995, 1997). This may lead to inaccurate estimates because synclines may develop below the regional datum, as it has been documented in both field examples (Prucha, 1968; Frey, 1973; Wiltschko & Chapple, 1977) and physical models (Blay, Cosgrove & Summers, 1977; Abbassi & Mancktelow, 1992). In these cases we may overestimate the excess area, and consequently, the estimated detachment depth may be wrong. Therefore, it is recommended to establish the regional datum in regions where folds are not developed, rather than in synclinal areas in between anticlines (Billings, 1962; Jaroszewski, 1984).

All the methods require the detachment surface and the regional datum to be flat and parallel (Figs 1, 2, 4, 5). However, in some natural examples used to estimate the detachment depth, the synclinal hinges are located at different heights with respect to the detachment (Bulnes & Poblet, 1998). In these cases, if we assume that the regional datum is parallel to the detachment surface and is located at the base of the synclines, we are under- or overestimating the anticline core area and the shortening depending on the synclinal hinge selected to establish the regional datum. Alternatively, if the regional datum is obtained by joining both synclinal hinges, then it is not parallel to the detachment, and this makes it difficult to estimate the detachment depth. In addition, in some natural examples the detachment beneath the anticlines is not a flat surface (Mitra, 1992; Keller & Pinter, 1996; Bulnes & Poblet, 1998). This also makes it difficult to estimate the detachment depth using the methods described above.

2.d. Number of stratigraphic horizons required for the calculations

The Chamberlin (1910) and Homza & Wallace (1995) methods require only one stratigraphic horizon to esti-

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mate the detachment depth (Figs 1, 5). In the case of the Chamberlin (1910) method any stratigraphic horizon within the upper, competent succession can be used, whereas in the case of the Homza & Wallace (1995) method the base of the upper, competent unit must be used.

The Mitra & Namson (1989) and Epard & Groshong (1993) methods are only applicable if two or more stratigraphic horizons are available (Figs 2, 4). These two methods integrate geologic information at more than one stratigraphic level, and therefore, they do not depend strongly on the accuracy of the cross section and position of the regional datum at one level.

2.e. Bed length and thickness

To apply the Chamberlin (1910) and Homza & Wallace (1995) methods, folds must involve at least one competent bed unlikely to have undergone bed length and thickness changes, i.e. they should be parallel folds (class 1B according to Ramsay, 1967). The Mitra & Namson (1989) method also requires constant bed length, but some thickness variations are allowed (e.g. folds keeping constant thickness except for the hinge zone) (Fig. 2). The Epard & Groshong (1993) method can be applied to any fold, regardless of whether bed lengths and thicknesses remain constant (Fig. 4). However, in the case of folds with variable bed lengths and thicknesses, they should have formed according to the Groshong & Epard (1994) and Epard & Groshong (1995) mechanism. Folds formed by this mechanism show hinge thickening, and the curvature of the outer fold arc exceeds that of the inner fold arc, i. e. they are class 3 folds according to the Ramsay (1967) classification. Therefore, when applying these methods, we should pay attention to length and thickness changes around the detachment fold.

2.f. Dip and position of the bounding lines

The Chamberlin (1910), Epard & Groshong (1993) and Homza & Wallace (1995) methods require the bounding lines to be perpendicular to bedding (Figs 1, 4, 5), whereas in the case of the Mitra & Namson (1989) method one of the lines may be oblique to bedding due to interbed shear (Fig. 2). Errors in the dip of the bounding lines mean that some beds are longer or shorter than they should be, and this produces an apparent interbed shear. This may lead us to under- or overestimate the shortening at certain horizons, and consequently, to under- or overestimate the detachment depth when using methods in which the shortening is needed for the calculations (Chamberlin, 1910; Mitra & Namson, 1989; Homza & Wallace, 1995).

In the Chamberlin (1910), Mitra & Namson (1989) and Epard & Groshong (1993) methods, the two bounding lines can be placed anywhere outside the fold being analysed (Figs 1, 2, 4). In the case of the Homza & Wallace (1995) method the two bounding lines should be placed precisely in the anticline lower hinges at the base of the competent unit (Fig. 5). These authors realized that the position of their bounding lines implies that the detachment depths predicted by their method are maximum estimates. Bulnes & Poblet (1998) determined the influence of the bounding lines' position in the estimation of the detachment depth using the Homza & Wallace (1995) method. They concluded that the greater the separation between the bounding lines, the lesser the detachment-depth variations, and vice versa. Small differences in separation between the bounding lines lead to noticeable differences in the detachment-depth estimations. Because detachment folds with rounded hinges are common (e.g. Wiltschko & Chapple, 1977; Dahlstrom, 1969; Poblet & Hardy, 1995), this makes it difficult accurately to place the bounding lines, and therefore, the depth to detachment estimations using the Homza & Wallace (1995) method may be highly variable.

2.g. Thickness of the ductile unit

Only the Homza & Wallace (1995) method uses the thickness of the ductile unit to predict the detachment depth (Fig. 5). This method assumes that the ductile unit thickness corresponds to the initial detachment depth, and therefore that the detachment surface is located at the base of this unit. Two problems arise from this assumption (Bulnes & Poblet, 1998): (1) the detachment may not necessarily be located at the base of the ductile unit (e.g. Thompson, 1989), and (2) because the detachment depth may vary during fold amplification, the initial thickness of the ductile unit should be measured in non-deformed areas away from the folds, and therefore we must take into account lateral thickness changes due to sedimentary variations. However, sedimentary thickness variations may be difficult to predict.

Bulnes & Poblet (1998) analysed how errors in determination of the initial depth to detachment influenced the estimation of the final depth using the Homza & Wallace (1995) method. They showed that the deeper the initial detachment depth, the greater the depth to detachment variation. Thus, in areas with deep detachments, errors in the measurement of the initial thickness of the ductile unit may lead to significant variations in the depth to detachment estimations, whereas in areas with shallow detachments these errors are not so important in the depth to detachment calculations.

2.h. Single anticlines *v*. fold trains

Detachment folds usually develop in fold trains in many fold and thrust belts (e.g. Heim, 1919; Wiltschko

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& Chapple, 1977; Thompson, 1989); at the leading edge of salt sheets (e.g. Stewart & Coward, 1995; Rowan, 1997); in progradational deltas (e.g. Ferguson *et al.* 1997); and in experimental models (e.g. Dixon & Tirrul, 1991). In some physical experiments, detachment folds develop synchronously (e.g. Price & Cosgrove, 1990). Studies of syntectonic sediments associated with detachment fold trains show that they can grow simultaneously and sequentially (Millán, Aurell & Meléndez, 1994). In addition, palaeomagnetic tests of detachment fold trains show that there is a progression in the age of folding. However, some detachment folds can grow simultaneously (Stamatakos, Hirt & Lowrie, 1996). This suggests that amplification of an individual detachment fold may be somehow influenced by neighbouring folds.

In contrast, to solve the discrepancy between the uplifted and displaced areas observed in some single detachment anticlines, Wiltschko & Chapple (1977) presented an hypothesis based on interaction between adjacent detachment folds during fold amplification. According to these authors, single anticlines in which the uplifted and displaced areas are different may amplify due to shortening, along with ductile material flow from beneath adjacent synclines, to fill the anticline cores. As a result, the synclinal flanks and hinges would deepen (Billings, 1962) as the ductile material migrates. Thus, the uplifted area above the regional in the anticline cores minus the depressed area below the regional in the syncline cores would equal the displaced area. Ductile unit thinning beneath synclines leading to formation of synclines below the regional datum has been documented in natural examples (Prucha, 1968; Frey, 1973; Wiltschko & Chapple, 1977) and in physical experiments (Blay, Cosgrove & Summers, 1977; Abbassi & Mancktelow, 1992). If the Wiltschko & Chapple (1977) hypothesis is correct, then estimation of the detachment depth beneath some single detachment anticlines may fail because to equal the uplifted and displaced areas: (1) ductile material may enter and/or leave the ends of the cross section across the bounding lines, and (2) synclines below the regional datum may develop. Both problems could be substantially overcome if determination of the detachment depth is performed along a long-enough cross section involving a number of detachment folds. In addition, if the Wiltschko & Chapple (1977) hypothesis is true, the detachment depth estimated beneath a long-enough detachment fold train using the methods described above should be correct irrespective of the amplification mechanisms responsible for fold evolution. The Chamberlin (1910) method was created to be applied to both a single anticline and a fold train, whereas the Mitra & Namson (1989), Epard & Groshong (1993) and Homza & Wallace (1995) methods were designed to be applied to single anticlines. However, as we will show below, as long as the area is conserved, all the methods can be applied to single anticlines and to fold trains without modifying the basic equations.

3. Excess-area graphical method based on Chamberlin (1910) and Epard & Groshong (1993)

As mentioned above, one of the drawbacks of the Chamberlin (1910) method is that it only considers information derived from one horizon. Although based on the Chamberlin (1910) method, the simple technique described below includes some aspects from the Epard & Groshong (1910) method, so that it uses data from several stratigraphic horizons within a cross section. Thus, the following method may be used (Fig. 8), as long as the stratigraphic thickness, excess area and shortening with respect to a minimum of two levels can be measured.

The technique consists of estimating the detachment depth for several folded horizons using the Chamberlin (1910) method. Once the detachment depths have been calculated, we must plot the cumulative stratigraphic thickness (on the y axis) *v.* the detachment depth calculated for each horizon (on the x axis) using the same distance units for both. The results do not depend on which horizon is chosen to be $x = 0$. The next step consists of calculating a linear, best-fit line through the plotted points. The position of the detachment surface within the stratigraphic section lays at the point where the detachment-depth value (x axis) equals zero, i.e. the point where the best-fit line intersects the y axis. The depth to detachment can be directly determined from the graph: it is the distance measured along the y axis between each stratigraphic horizon and the detachment surface. Like the previous methods, this method can be applied to both single detachment anticlines and detachment fold trains. The parameters described in the previous section that influence the application of the Chamberlin (1910) method also affect this new method.

4. Guidelines to estimate the detachment depth

A guide consisting of one table and four figures is presented to: (1) determine which method or methods to estimate the detachment depth are more suitable for each particular case (Table 1), (2) indicate the easiest procedure to follow for each method depending on the available data (Figs 9, 10, 11, 12), and (3) assess the constraints that control the detachment values obtained (Figs 9, 10, 11, 12). These figures presuppose that an accurate cross section showing a detachment anticline or a detachment fold train is available.

5. Predicting the detachment depth beneath examples of detachment folds

In this section the methods proposed will be applied to six natural and three experimental detachment folds,

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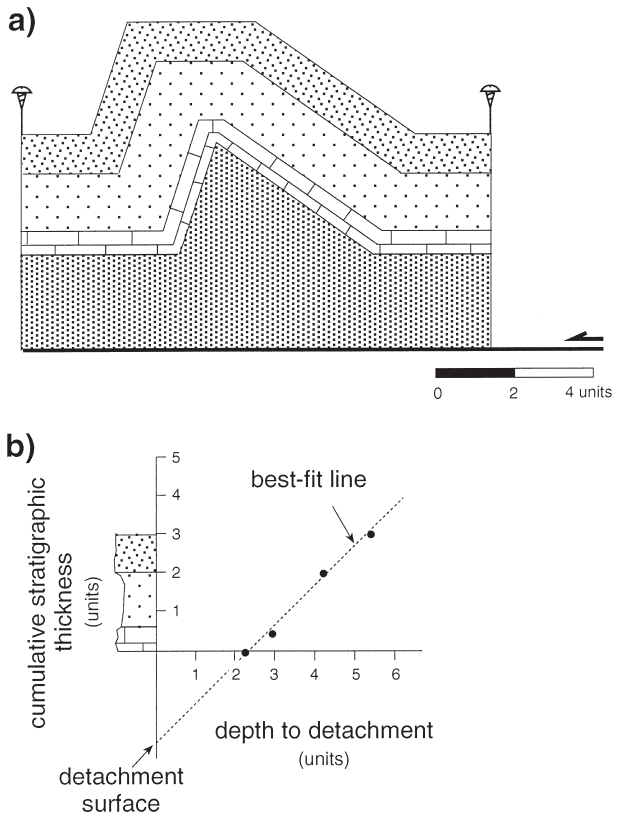


Figure 8. Graphical method to estimate the depth to detachment for a number of stratigraphic horizons. (a) Cross section of a theoretical detachment fold. (b) Plot of cumulative stratigraphic thickness *v*. estimated detachment depth (using the Chamberlin, 1910 method) for the detachment fold illustrated above. The slight dispersion of the measured points relative to the best-fit line is the result of measurement and drawing errors.

in which the location of the detachment is known. The comparison between the real and the estimated depths provides information on the reliability of the methods used in the estimation. These detachment folds have been obtained from previously published papers and no data on the amplification mechanisms responsible for them are available. For this reason we applied the five methods to all of them. Although most methods were created to be applied to single anticlines, we have used them to predict the detachment depth beneath both single folds and fold trains. The Chamberlin method has been applied to different horizons within the competent unit.

Figure 13 illustrates the results obtained from the analysis of individual anticlines, even if they belong to a fold train. In these examples, the line that joins the deepest part of the synclines for each horizon has been considered as its regional datum. Figure 14 corresponds to the analysis of portions of fold trains and Figure 15 displays the analysis of a complete fold train developed in a physical experiment. The observations derived from the sixteen sets of values obtained are listed below.

5.a. General comments

Most of the predicted detachment depths deviate moderately or strongly from the correct values (Figs 13, 14, 15), and, in general, the worst results correspond to the estimations beneath individual anticlines (Fig. 13). Regarding the methods used, that of Mitra & Namson (1989) provides the deepest values. Usually, the results obtained from the application of the Chamberlin (1910) method to different horizons are similar, and in general, the closer the chosen bed and detachment surface, the more accurate the result. However, when the Chamberlin (1910) method is applied to the top of variable thickness beds, the resulting depths differ significantly from the real depth (Figs 13a, 13f, 14d, 14e, 15). Moreover, in the case of these variable thickness beds, the Epard & Groshong (1993) and Mitra & Namson (1989) methods, as well as the method proposed in this paper, give important errors in the detachment-depth estimation, as they include in their calculations parameters related to all the horizons.

5.b. Single anticlines

In the case of isolated anticlines, the Epard & Groshong (1993) method seems to give the best results, whereas the Mitra & Namson (1989) method gives the most deviated results (Figs 13b, 13c, 13g). The Homza & Wallace (1995) method provides the best results when analysing individual anticlines included in fold trains (Figs 13a, 13d, 13e, 13f).

Table1. Applicability of methods to estimate depth to detachment beneath detachment folds.

	Fold amplification mechanisms (single anticline)	Competent unit			Cross section H = V
		constant bed length	constant thickness	no. of horizons	
Chamberlin (1910)	Dahlstrom (1990)	yes	yes	1	yes
Mitra & Namson (1989)	Dahlstrom (1990) excess area = displaced area (including interbed shear)	yes	yes/no	2 or more	yes
Epard & Groshong (1993)	Dahlstrom (1990) Epard & Groshong (1995)	yes/no	yes/no	2 or more	yes/no
Homza & Wallace (1995)	Any	yes	yes	1 (base of the competent unit)	yes
This paper	Dahlstrom (1990)	yes	yes	2 or more	yes

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AVAILABLE DATA			ESTIMATION OF THE DETACHMENT DEPTH USING CHAMBERLIN (1910) METHOD	
Regional datum	Ductile unit thickness	Detachment depth	Procedure	Constraints
yes	no	no	1) estimate excess area and shortening 2) apply Chamberlin's equation	
no	yes	no	1) estimate shortening 2) assume detachment depth at the base of the ductile unit 3) displaced area = shortening * ductile unit thickness 4) place a regional datum so that displaced area = excess area 5) apply Chamberlin's equation	maximum detachment depth (the detachment is assumed to be at the base of the ductile unit)
			1) assume regional datum at the base of the deepest synclines 2) estimate excess area and shortening 3) apply Chamberlin's equation	the accuracy of the estimated detachment depth is a function of the distance between the regional datum considered and the real one amongst other parameters
no	no	yes	1) assume regional datum at the base of the deepest synclines 2) estimate excess area and shortening 3) apply Chamberlin's equation	if estimated detachment depth ≠ real detachment depth → cross-sectional area variation and/or → variable thickness of the ductile unit above the detachment and/or → regional datum is not at the base of the deepest synclines
yes	yes	no	1) estimate excess area and shortening 2) apply Chamberlin's equation	if estimated detachment depth ≠ ductile unit thickness → cross-sectional area variation and/or → variable thickness of the ductile unit above the detachment and/or → detachment is not located at the base of the ductile unit
yes	no	yes	1) check all over the cross section that the regional datum and the detachment are parallel 2) if yes, estimate excess area and shortening 3) apply Chamberlin's equation	if estimated detachment depth ≠ real detachment depth → cross sectional area variation
no	yes	yes	1) place the regional datum assuming that the detachment is located at the base of the dutile unit 2) estimate excess area and shortening 3) apply Chamberlin's equation	if estimated detachment depth ≠ real detachment depth → cross-sectional area variation and/or → variable thickness of the ductile unit above the detachment and/or → detachment is not located at the base of the ductile unit
			1) assume regional datum at the base of the deepest synclines 2) estimate excess area and shortening 3) apply Chamberlin's equation	if estimated detachment depth ≠ real detachment depth → cross-sectional area variation and/or → variable thickness of the ductile unit above the detachment and/or → regional datum is not at the base of the deepest synclines
yes	yes	yes	1) check all over the cross section that the regional datum and the detachment are parallel 2) if yes, estimate excess area and shortening 3) apply Chamberlin's equation	if estimated detachment depth ≠ real detachment depth → cross-sectional area variation
no	no	no	1) assume regional datum at the base of the deepest synclines 2) estimate excess area and shortening 3) apply Chamberlin's equation	the accuracy of the estimated detachment depth is a function of the distance between the regional datum considered and the real one amongst other parameters

Figure 9. Figure showing different sets of available data and the procedure to estimate the depth to detachment using the Chamberlin (1910) method and the method presented in this paper. This table is applicable to both a single anticline and a fold train. In the case of a single anticline the table has been constructed assuming that we are dealing with a Dahlstrom (1990) type fold. In the case of a fold train the table has been constructed assuming that Wiltschko & Chapple (1977) hypothesis is correct, that we are dealing with a long-enough cross section, and that we are not analysing minor folds belonging to a larger-scale structure.

5.c. Fold trains

The estimated depths in Figures 14e and 15 are excellent. Figure 14e corresponds to a fold-train portion made up of a large number of folds, in which non-deformed regions occur outside the area enclosed by the bounding lines. All the results, except for those derived from the application of the Chamberlin (1910) method to beds 2, 3 and 4, are located at the real detachment surface. Figure 15 corresponds to a complete fold train. The detachment predicted by the Homza & Wallace (1995) method is exactly located at the real detachment surface and the rest of estimated depths are close to the correct location. Finally, it

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AVAILABLE DATA			ESTIMATION OF THE DETACHMENT DEPTH USING MITRA & NAMSON (1989) METHOD	
Regional data	Ductile unit thickness	Detachment depth	Procedure	Constraints
yes	no	no		
no	yes	no	1) assume regional datum of the top of the ductile unit at the base of the deepest synclines 2) assume detachment depth at the base of the ductile unit 3) estimate excess area and shortening of each horizon 4) deduce interbed shear 5) apply Mitra & Namson's equation	— the accuracy of the estimated detachment depth is a function of the distance between the regional datum considered and the real one amongst other parameters
no	no	yes	1) assume regional data at the base of the deepest synclines 2) estimate excess area and shortening of each horizon 3) deduce interbed shear 4) apply Mitra & Namson's equation	— if estimated detachment depth ≠ real detachment depth → cross-sectional area variation and/or → variable thickness of the ductile unit above the detachment and/or → regional datum is not at the base of the deepest synclines
yes	yes	no	1) assume detachment at the base of the ductile unit 2) estimate excess area and shortening of each horizon 3) deduce interbed shear 4) apply Mitra & Namson's equation	— if estimated detachment depth ≠ ductile unit thickness → cross-sectional area variation and/or → variable thickness of the ductile unit above the detachment and/or → detachment is not located at the base of the ductile unit
yes	no	yes	1) check all over the cross section that the regional data and the detachment are parallel 2) if yes, estimate excess area and shortening of each horizon 3) deduce interbed shear 4) apply Mitra & Namson's equation	— if estimated detachment depth ≠ real detachment depth → cross-sectional area variation
no	yes	yes	1) place the regional data assuming that the detachment is located at the base of the ductile unit 2) estimate excess area and shortening of each horizon 4) apply Mitra & Namson's equation 3) deduce interbed shear	— if estimated detachment depth ≠ real detachment depth → cross-sectional area variation and/or → variable thickness of the ductile unit above the detachment and/or → detachment is not located at the base of the ductile unit
			1) assume regional data at the base of the deepest synclines 2) estimate excess area and shortening of each horizon 3) deduce interbed shear 4) apply Mitra & Namson's equation	— if estimated detachment depth ≠ real detachment depth → cross-sectional area variation and/or → variable thickness of the ductile unit above the detachment and/or → regional datum is not at the base of the deepest synclines
yes	yes	yes	1) check all over the cross section that the regional data and the detachment are parallel 2) if yes, estimate excess area and shortening of each horizon 3) deduce interbed shear 4) apply Mitra & Namson's equation	— if estimated detachment depth ≠ real detachment depth → cross-sectional area variation
no	no	no		

Figure 10. Figure showing different sets of available data and the procedure to estimate the depth to detachment using the Mitra & Namson (1989) method. This table is applicable to both a single anticline and a fold train. In the case of a single anticline the table has been constructed assuming that we are dealing with a Dahlstrom (1990) type fold or a fold including interbed shear in which the excess area equals the displaced area. In the case of a fold train the table has been constructed assuming that Wiltschko & Chapple (1977) hypothesis is correct, that we are dealing with a long-enough cross section, and that we are not analysing minor folds belonging to a larger-scale structure.

appears that the method proposed in this paper provides satisfactory results in the case of fold trains, except for the example in Figure 14d. In particular, it gives the best results in the fold trains illustrated in Figures 14a, 14c and 14e.

Most of the observations presented above are preliminary because a greater number of examples need to be analysed. In addition, at the present state, most observations are difficult to interpret. K. McClay (pers. comm. 1999) suggested that in some cases, detachment may occur at some distance above the detachment surface because of frictional 'drag' effects along the basal detachment. This would explain why some calculated detachments lie above the detachment

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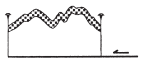
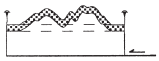
AVAILABLE DATA			ESTIMATION OF THE DETACHMENT DEPTH USING EPARD & GROSHONG (1993) METHOD	
Regional data	Detachment depth		Procedure	Constraints
yes	no		1) define reference level 2) estimate height and excess area of each horizon 3) plot data on Epard and Groshong's graph	
no	yes		1) assume regional data at the base of the deepest synclines 2) define reference level 3) estimate height and excess area of each horizon 4) plot data on Epard & Groshong's graph	—— if estimated detachment depth ≠ real detachment depth → cross-sectional area variation and/or → variable thickness of the unit above the detachment and/or → the regional data is not at the base of the deepest synclines
yes	yes		1) check all over the cross section that the regional data and the detachment are parallel 2) if yes, define reference level 3) estimate height and excess area of each horizon 4) plot data on Epard and Groshong's graph	—— if estimated detachment depth ≠ real detachment depth → cross-sectional area variation
no	no		1) assume regional data at the base of the deepest synclines 2) define reference level 3) estimate height and excess area of each horizon 4) plot data on Epard & Groshong's graph	—— the accuracy of the estimated detachment depth is a function of the distance between the regional data considered and the real ones amongst other parameters

Figure 11. Figure showing different sets of available data and the procedure to estimate the depth to detachment using the Epard & Groshong (1993) method. This table is applicable to both a single anticline and a fold train. In the case of a single anticline the table has been constructed assuming that we are dealing with a Dahlstrom (1990) type fold or an Epard & Groshong (1995) type fold. In the case of a fold train the table has been constructed assuming that Wiltschko & Chapple (1977) hypothesis is correct, that we are dealing with a long-enough cross section, and that we are not analysing minor folds belonging to a larger-scale structure.

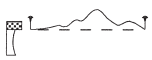
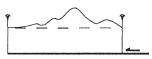
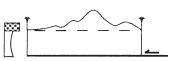
AVAILABLE DATA			ESTIMATION OF THE DEPTH TO DETACHMENT USING HOMZA & WALLACE (1995) METHOD	
Initial detachment depth	Final detachment depth		Procedure	Constraints
yes	no		1) estimate shortening, fold width and excess area 2) apply Homza and Wallace's equation	—— the accuracy of the estimated final detachment depth is a function of the distance between the detachment and the base of the ductile unit amongst other parameters
no	yes		1) check all over the cross section that the regional datum and the detachment are parallel 2) if yes, estimate shortening, fold width and excess area 3) assume that initial detachment depth = final detachment depth 4) apply Homza and Wallace's equation	—— if estimated detachment depth ≠ real detachment depth → cross-sectional area variation and/or → regional datum is not at the base of the deepest synclines and/or → ductile unit thickness does not equal the detachment depth
yes	yes		1) check all over the cross section that the regional datum and the detachment are parallel 2) if yes, estimate shortening, fold width and excess area 3) apply Homza and Wallace's equation	—— if estimated detachment depth ≠ real detachment depth → cross-sectional area variation and/or → regional datum is not at the base of the deepest synclines and/or → detachment is not located at the base of the ductile unit
no	no			

Figure 12. Figure showing different sets of available data and the procedure to estimate the depth to detachment using the Homza & Wallace (1995) method. In this method, if an anticline profile is available, then the regional datum is automatically established at the base of the competent unit in the adjacent syncline hinges. This table is applicable to both a single anticline and a fold train irrespective of the formation mechanisms. When using the Homza & Wallace (1995) method to analyse a fold train, we are considering average detachment-depth fluctuations at the scale of the fold train, but not individual fluctuations for each single fold.

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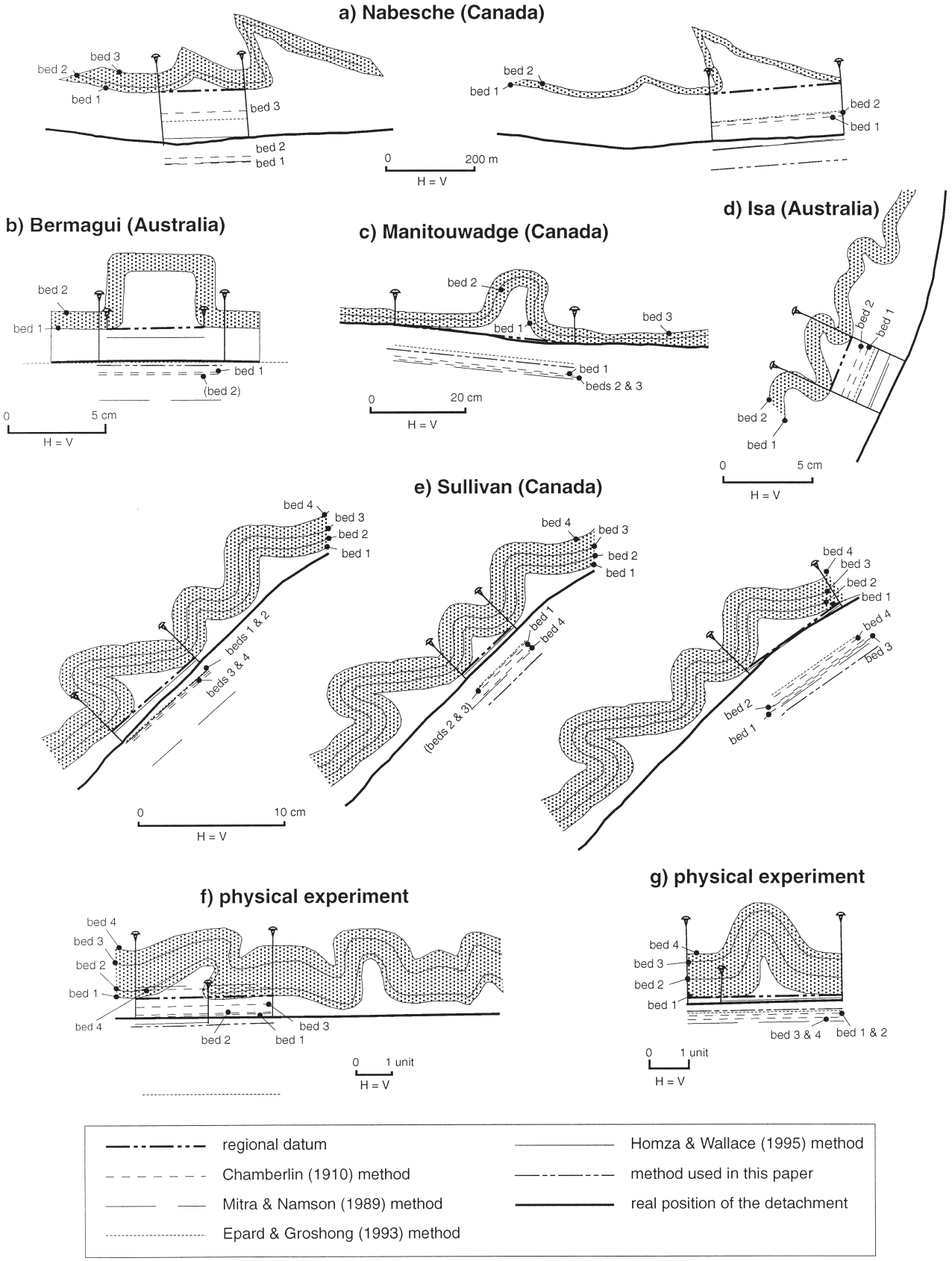


Figure 13. Estimation of the detachment depth beneath single detachment anticlines drawn after photographs using the Chamberlin (1910), Mitra & Namson (1989), Epard & Groshong (1993), Homza & Wallace (1995) methods and the method presented in this paper. (a) Folded limestones and shales, Nabesche, Canada (fig. 6 in Fitzgerald & Braun, 1965; fig 8 in Jamison, 1987; fig. 1a in Poblet & McClay, 1996); (b) folded sandstones and shales, Bermagui, Australia (fig. 4.17a in Hobbs, Means & Williams, 1976); (c) folded lacustrine siltstones, Manitouwadge, Canada (fig. 160 in Whitten, 1966); (d) folded siltstones with galena matrix and shales, Mount Isa, Australia (fig. 4.20b in Hobbs, Means & Williams, 1976); (e) folded sedimentary rocks with sulfides, Sullivan Mine, Canada (photograph courtesy of K. McClay); (f) experimental folds in a gelatine multilayer (plate 5d in Blay, Cosgrove & Summers, 1977); and (g) experimental fold (fig. 4 in Kuznetsova, 1965)

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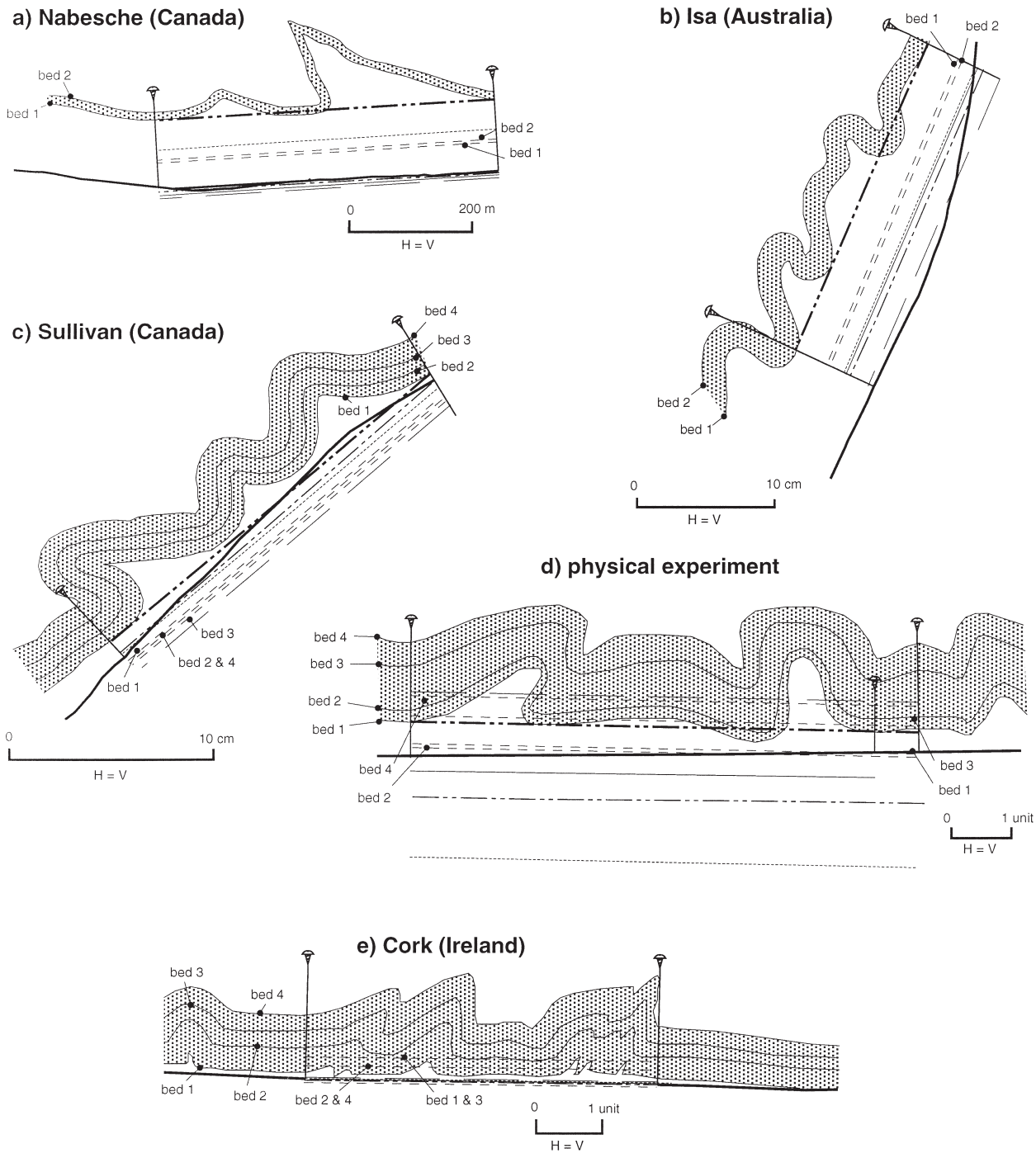


Figure 14. Estimation of the detachment depth beneath parts of detachment fold trains drawn after photographs using the Chamberlin (1910), Mitra & Namson (1989), Epard & Groshong (1993), Homza & Wallace (1995) methods and the method presented in this paper. (a) Folded limestones and shales, Nabesche, Canada (fig. 6 in Fitzgerald & Braun, 1965; fig 8 in Jamison, 1987; fig. 1a in Poblet & McClay, 1996); (b) folded siltstones with galena matrix and shales, Mount Isa, Australia (Fig. 4.20b in Hobbs, Means & Williams, 1976); (c) folded sedimentary rocks with sulfides, Sullivan Mine, Canada (photograph courtesy of K. McClay); (d) experimental folds in gelatine multilayer (plate 5d in Blay, Cosgrove & Summers, 1977); and (e) folded sedimentary rocks, West Cork, Ireland (fig. 7.125 in Ramsay, 1967).

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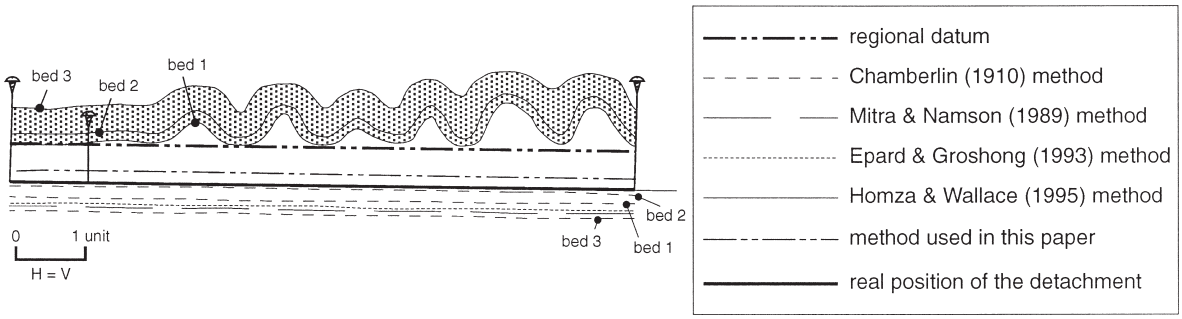


Figure 15. Estimation of the detachment depth beneath a complete, experimental, detachment fold train in a gelatine multilayer drawn after a photograph (plate 3a in Blay, Cosgrove & Summers, 1977) using the Chamberlin (1910), Mitra & Namson (1989), Epard & Groshong (1993), Homza & Wallace (1995) methods and the method presented in this paper.

a)

	DIMENSIONS/TIGHTNESS	ASYMMETRY	SHAPE
LIMB ROTATION ANTICLINE	*limbs + crest length*	***limbs length ratio*** backlimb length / forelimb length = 1 → symmetrical fold backlimb length / forelimb length > 1 → asymmetrical fold	***crest length*** crest length = 0 → kink/chevron fold crest length > 0 → box fold
HINGE MIGRATION ANTICLINE	*interlimb angle*	***limbs dip ratio*** sin (backlimb dip) / sin (forelimb dip) = 1 → symmetrical fold sin (backlimb dip) / sin (forelimb dip) ≠ 1 → asymmetrical fold	***crest length*** crest length = 0 → kink/chevron fold crest length > 0 → box fold

b)

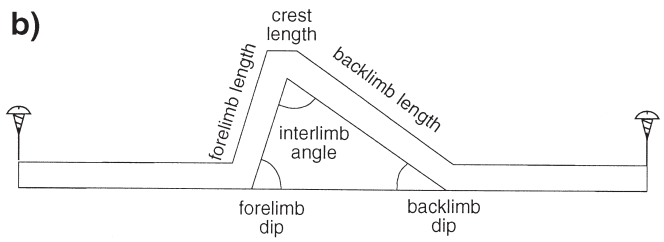


Figure 16. (a) Parameters that control the fold core area in single detachment anticlines formed by limb rotation and by hinge migration; (b) geometrical elements of a single detachment anticline.

surfaces. Such an effect may be less in large examples of detachment folds, but unfortunately we have not been able to find larger-scale detachment folds in which the detachment surface is exposed.

One of the most significant conclusions is that the estimations beneath single anticlines include greater errors than the estimations beneath fold trains. This might be explained by migration of material inside or outside the area enclosed within the bounding lines, so that the precision of the estimations would depend on the amount of material flow, and on whether the cross section is long enough to account for flow or not. In this sense, two areas are the subject of our ongoing research: (1) to look for more examples of detachment folds in the literature and in nature to test the proposed methods, and (2) to design a detachment-depth method that includes a three-dimensional fold analysis to account for flow along strike.

6. Inferences on the detachment depth from the fold dimensions, tightness, asymmetry and shape

In many cases the estimation of the detachment depth using the methods described above is not possible either due to insufficient data, or because the folds do not satisfy the conditions necessary to apply those methods. However, in these cases, if ductile material flow is not significant, the area in the fold core beneath the upper competent unit may help us to determine which folds require deep detachments and which folds require shallow detachments. For instance, the larger the fold core area the thicker the ductile unit required to fill this area, and therefore, the deeper the detachment. The fold core area depends on the following geometrical parameters: (1) fold dimensions (limbs + crest length), (2) fold tightness (interlimb angle), (3) asymmetry degree (limb lengths ratio or

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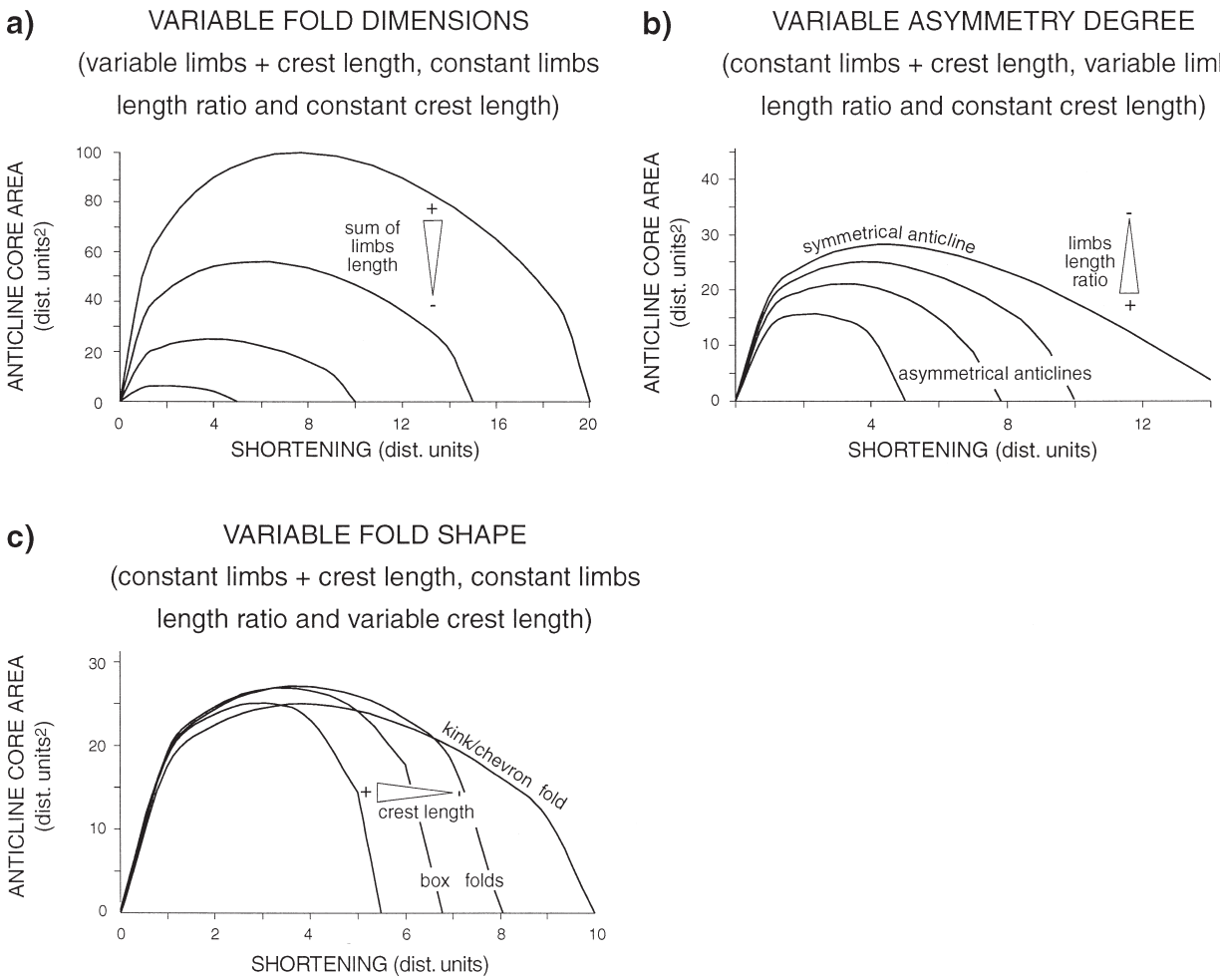


Figure 17. Graphs showing fold core area *v*. shortening for a single detached anticline formed by limb rotation: (a) variable fold dimensions (sum of limbs length); (b) variable asymmetry degree (limbs length ratio); and (c) variable fold shape (crest length).

limbs dip ratio), and (4) fold shape (crest length) (Fig. 16a).

In this section we will study the influence of these parameters in single detachment anticlines with straight limbs and infinite curvature at hinges, but variable asymmetry and shape from kink to chevron to box folds (Fig. 16b). To carry out this analysis we will use the equations derived by Poblet & McClay (1996) for detachment anticlines in which the competent unit maintains bed length and thickness during fold amplification. Two end members are considered: anticlines formed by limb rotation, and anticlines formed by hinge migration (Figs 3a, 3b). Any intermediate case will necessary fall between these two.

To investigate the detachment depth required by a single anticline, we have plotted the anticline core area *v*. shortening for different anticlines keeping constant all the geometrical parameters except for one. In the case of anticlines formed by limb rotation, it appears that the greater the limbs length, the greater the fold core area (Fig. 17a), and therefore, the deeper the detachment. In addition, the greater the asymmetry degree, the shallower the detachment (Fig. 17b). Box folds require deeper detachments than kink/chevron folds (Fig. 18c) at least in the first stages of growth (Fig. 17c). In the case of anticlines formed by hinge migration, the greater the interlimb angle, the deeper the detachment (Fig. 18a), and the greater the asymmetry degree, the deeper the detachment (Fig. 18b).

The ideas obtained from the study of single detachment anticlines can be hardly extrapolated to fold trains, because of the large number of geometrical parameters to consider. An accurate study of the parameters controlling the amount of uplifted area in the case of a detachment fold train requires more complex algorithms, and is beyond the scope of the present study.

7. Conclusions

Four methods have been proposed to estimate the detachment depth beneath natural or experimental examples of detachment folds (Chamberlin, 1910; Mitra & Namson, 1989; Epard & Groshong, 1993; Homza & Wallace, 1995). Only in two cases is it appropriate to apply the four methods: (1) an isolated detachment anticline that maintained constant bed length and thickness, and the base of the adjacent

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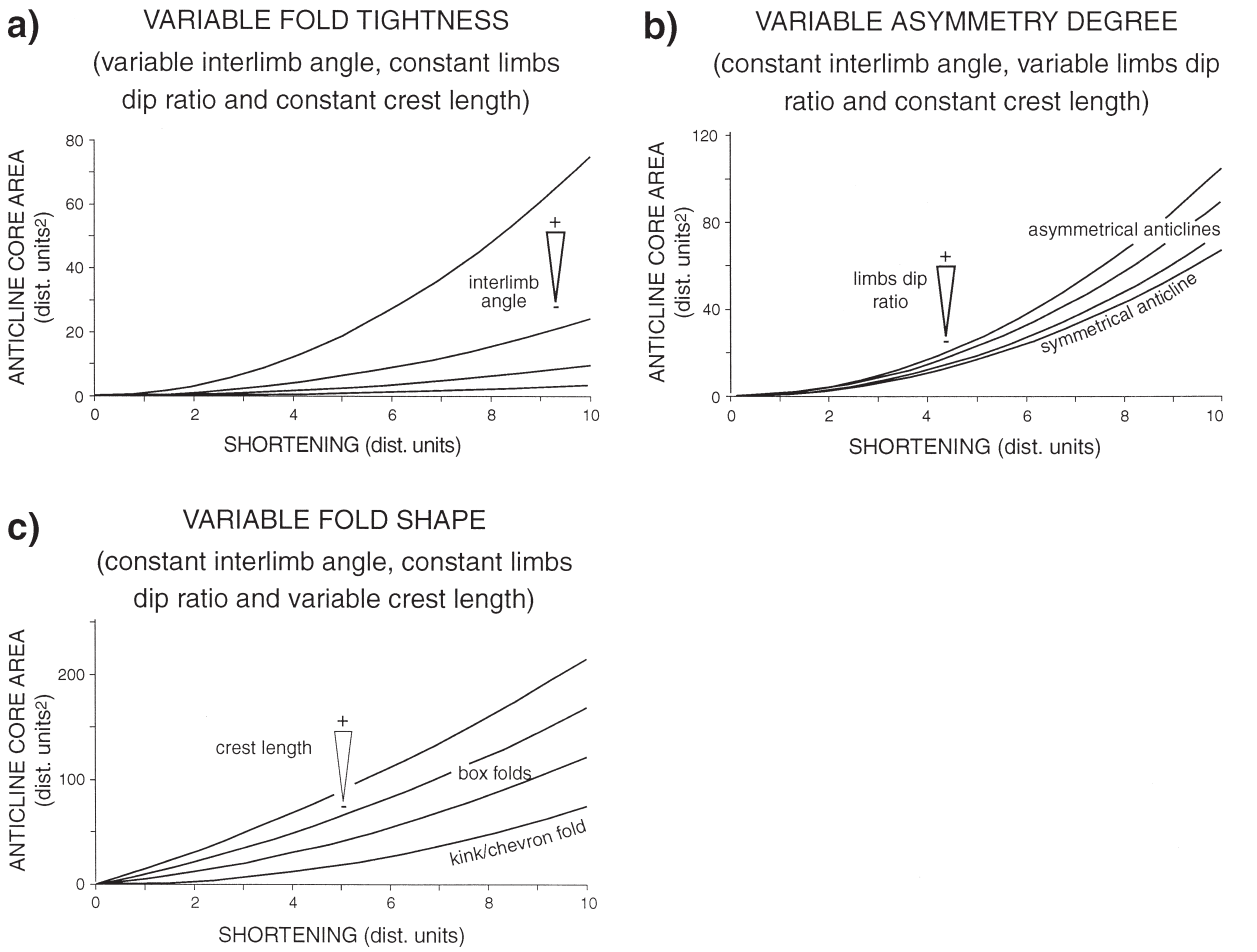


Figure 18. Graphs showing fold core area *v.* shortening for a single detached anticline formed by hinge migration. (a) variable fold tightness (interlimb angle), (b) variable asymmetry degree (limbs dip ratio), and (c) variable fold shape (crest length).

synclines remained on the regional datum (an isolated detachment anticline with these features must area-balance and amplify according to Dahlstrom's (1990) mechanism); and (2) a complete detachment fold train in which folds maintained constant bed length and thickness. Except for these two cases, some methods are more appropriate than others to predict the detachment depth depending on the fold features and the available data.

A number of factors should be taken into account when choosing the best method for each situation: (1) these methods can only be applied to folds amplified by certain mechanisms; (2) deformation may cause cross-sectional area variation due to transfer of material inside or outside the area enclosed by the bounding lines, and/or along planes other than that of the cross section; (3) the regional datum must be established in non-folded areas and must be parallel to the detachment; (4) some methods are applicable only if two or more horizons are available, whereas others only need one horizon; (5) some methods require the bed length and thickness to be maintained during deformation, whereas others do not; (6) in some methods the bounding lines should be perpendicular to bedding and/or they need to be located in a specific position, whereas in others it is not necessary; (7) although the thickness of the ductile unit is only necessary in the Homza & Wallace (1995) method, our results show that it might be a useful element when using the Chamberlin (1910) and Mitra & Namson (1989) methods; (8) the Mitra & Namson (1989), Epard & Groshong (1993) and Homza & Wallace (1995) methods were initially created to be applied to single anticlines, but our study shows that can be equally applied to detachment fold trains without modifying their basic equations.

A new simple method is proposed to predict the detachment depth. It consists of estimating the detachment depth for several horizons using the simplest equation (Chamberlin, 1910), and relating the results using a graph similar to that of Epard & Groshong (1993). This method enables us to obtain an estimated depth that takes into account data from more than a single stratigraphic horizon. The validity of this method is demonstrated through its application to a number of detachment fold examples.

The application of the methods to a number of examples indicate that more accurate results are

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obtained when estimating the detachment depth beneath fold trains and regional-scale cross sections rather than individual structures. This may be due to migration of material along the cross-sectional plane. Thus, material flow is taken into account when analysing a whole fold train, whereas it is not considered when analysing a single detachment anticline.

In those cases where not enough data are available, the fold geometry may suggest which anticlines require deeper detachment surfaces than others. Our results show that for single anticlines, the greater the limb length, the interlimb angle, the asymmetry degree and the crest length, the deeper the detachment.

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