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Estimating extension and depth to detachment in simple rollover anticlines over listric normal faults

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Abstract: A number of geometrical techniques allow estimating amounts of horizontal extension and depth to detachment in simple rollover anticlines over listric normal faults given one or more horizons, the portion of the fault between the hanging wall and foot wall cut off points, and the depth to detachment (if the extension is to be estimated) or the extension (if the depth to detachment is to be estimated). These techniques assist in the construction and validation of sections across listric normal faults, but currently, it is unclear which ones predict correct amounts of horizontal extension and detachment depth and why is that. To sort this out, these techniques are evaluated using physical experiments and subsurface seismic examples of simple listric normal faults.

Keywords: listric normal fault, rollover anticline, extension, depth to detachment.

Resumen: En la literatura se han propuesto una serie de técnicas geométricas que permiten estimar la cantidad de extensión horizontal y la profundidad de despegue en anticlinales sencillos de tipo rollover desarrollados sobre fallas normales lístricas conociendo la geometría de uno o varios horizontes, la porción de falla situada entre los puntos de corte de bloque superior y de bloque inferior, y la profundidad de despegue (en el caso de cálculos de la extensión) o la extensión (en el caso de cálculos de la profundidad de despegue). Si bien estas técnicas facilitan la construcción y validación de cortes geológicos en regiones con fallas normales lístricas, se desconoce con precisión cuales de estos métodos predicen valores correctos de extensión horizontal y profundidades de despegue correctas. A fin de solventar esta situación, en este artículo se evalúan estas técnicas usando experimentos de laboratorio y ejemplos sísmicos de subsuelo de fallas normales lístricas sencillas.

Palabras clave: falla normal lístrica, anticlinal de rollover, extensión, profundidad de despegue.

Listric normal faults and their associated hanging wall rollover anticlines are common modes of crustal extension in different types of regions (e.g., Bally et al., 1981; Shelton, 1984). In these areas, a good knowledge of the structure, such as the depth to detachment and the amount of horizontal extension accommodated above the detachment, may be of crucial importance as it aids in interpretation of seismic profiles and provides control on structural and tectono-stratigraphic models. On seismic profiles, it is often possible to image the beds within fault blocks accurately, but little information on the slip vector and fault surface itself is obtained. To address this deficiency several geometrical methods are described in the literature for estimating the amount of horizontal extension and the depth to detachment.

There are two types of techniques to estimate the amount of horizontal extension accommodated by listric normal faults. The first group of techniques consists of constructing restored cross sections using appropriate restoration algorithms and comparing the length of a particular restored bed with that of the same bed in the balanced, deformed cross section (see user manuals of computer programs such as Restore by The University of Texas at Austin, Geosec by Paradigm Geophysical, 2D-3D Move by Midland Valley, Locace by the Institute Français du Pétrole, Gocad by the Ecole Nationale Supérieure de Géologie at Nancy, etc.).

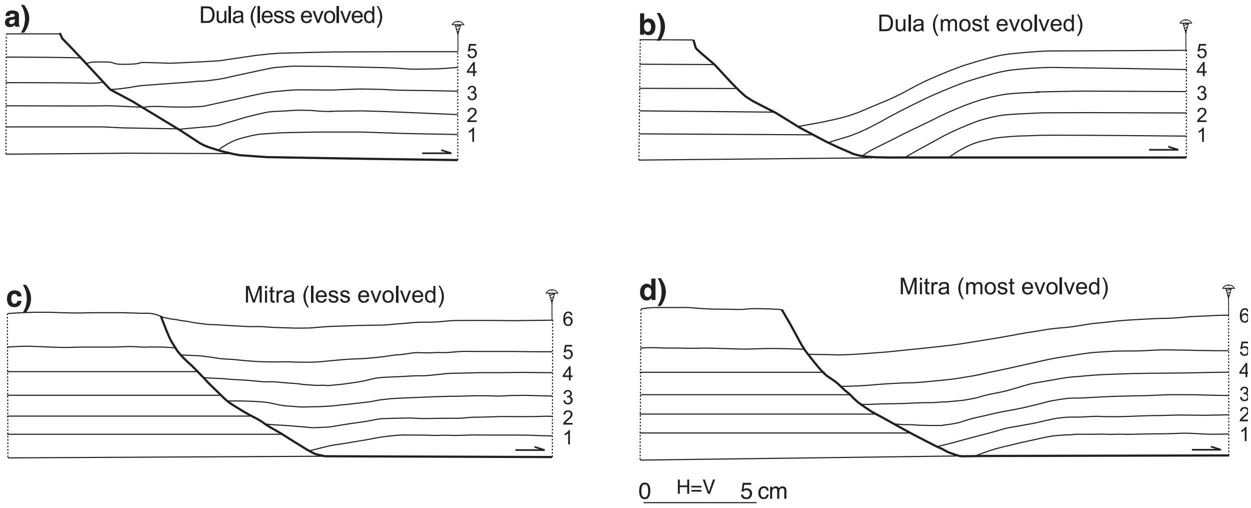


Figure 1. Line drawings of two stages of a physical experiment by Dula (1991) after 2 cm (a) and 6 cm (b) of extension, and a physical experiment by Mitra (1993) after 2 cm (c) and 4 cm (d) of extension. Beds 1 to 5 in the footwall of the Mitra (1993) experiment are not displayed in the original photographs of the experiment but have been constructed for measuring purposes assuming that they lay on the regional datum defined by the unfolded portion of the hangingwall. Small faults developed in the Mitra (1993) experiment have been omitted in the sake of clarity. The scale is the same for all the line drawings. After Poblet and Bulnes (2005) modified.

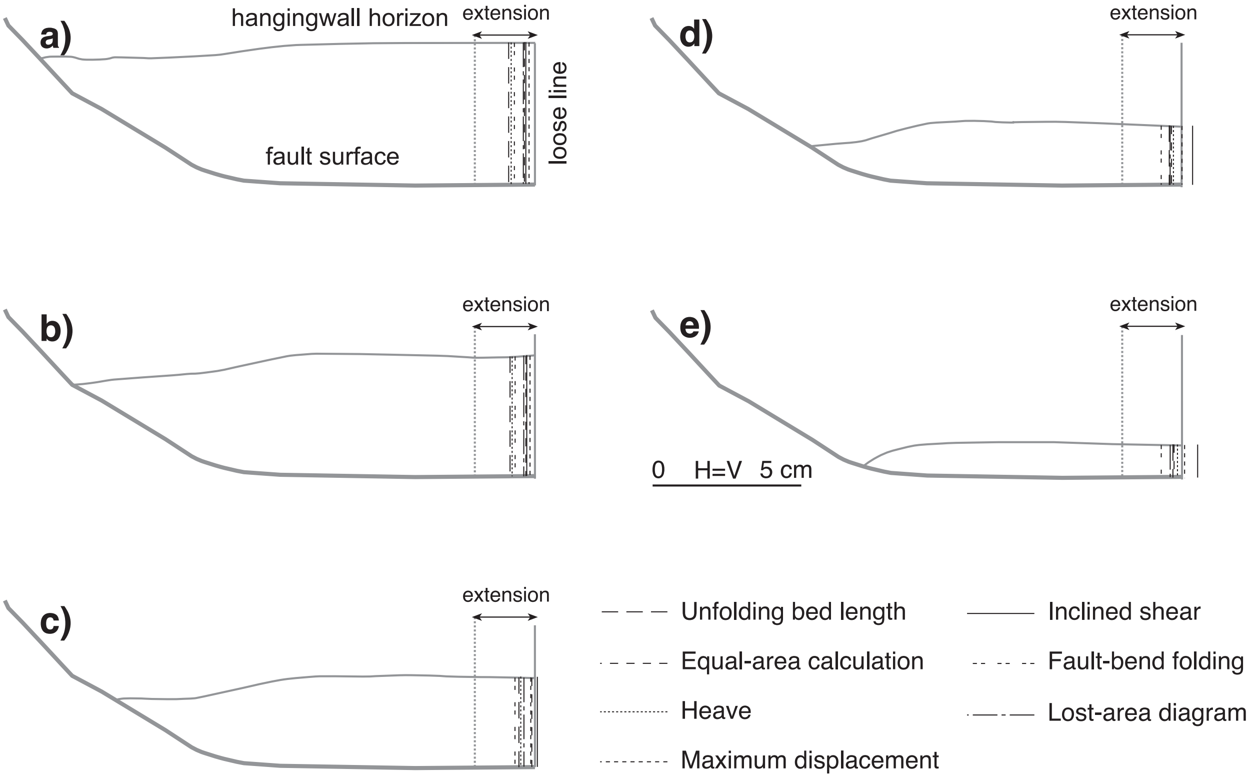


Figure 2. Estimations of the amount of extension using various techniques for different beds of the less evolved stage of the Dula (1991) experiment. To apply the inclined shear method (White et al., 1986) the following parameters measured by Dula (1991) have been used for the experiments: fault dip =45° and shear angle =20°. The scale is the same for all the line drawings.

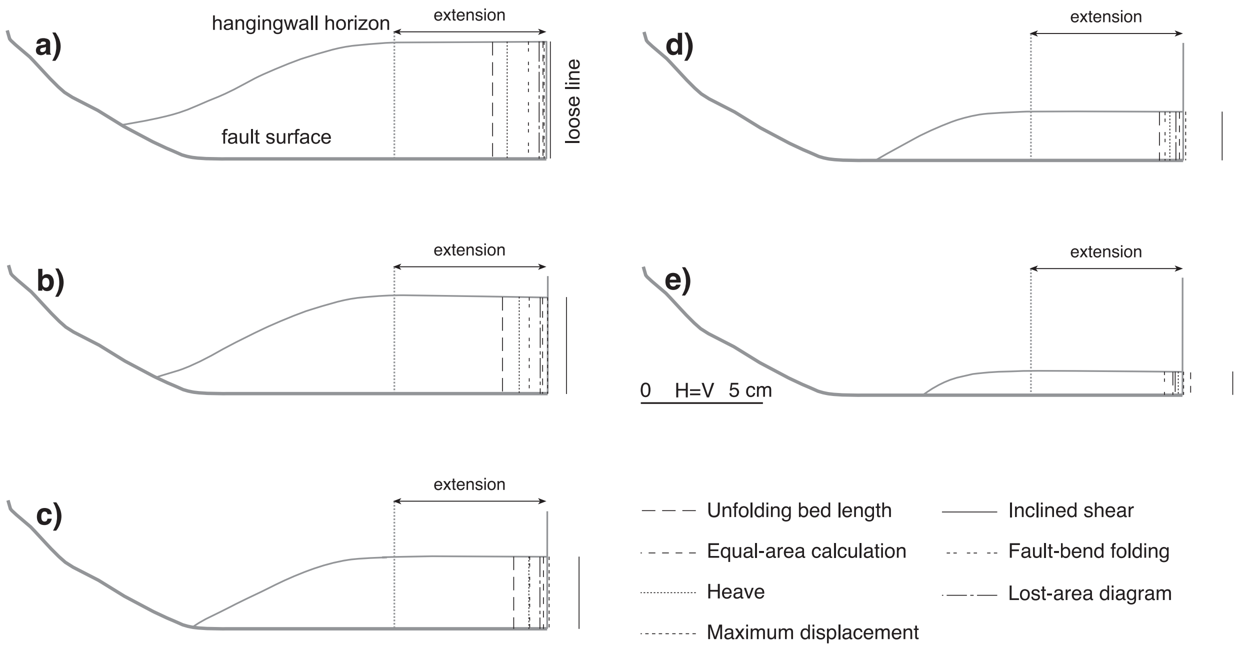


Figure 3. Estimations of the amount of extension using various techniques for different beds of the most evolved stage of the Dula (1991) experiment. To apply the inclined shear method (White et al., 1986) the following parameters measured by Dula (1991) have been used for the experiments: fault dip =45° and shear angle =20°. The scale is the same for all the line drawings.

Cross-section restoration, if carried out sequentially, also helps to decipher the original location, dip and geometry of the structures, their original angular relationships with bedding, timing of development, kinematics, etc. Unfortunately, restoring accurately sections is a time-consuming task. The second group of techniques enable to estimate specifically the amount of extension without restoring cross sections (e.g., Wernicke and Burchfiel, 1982; Ziegler, 1982; Gibbs, 1983; Chapman and Williams, 1984; Jackson and Galloway, 1984; White et al., 1986; White, 1987; Groshong, 1994, 1996; Xiao and Suppe, 1992). These specific techniques are faster and easier to apply than cross-section restoration, but do not supply additional information. Unfortunately, these specific techniques to estimate the amount of extension have not been applied to the same example to check whether estimates obtained from different methods yield similar or different results and how accurate the results are.

In the last decades, two different types of graphical/numerical methods developed enable to estimate the depth to detachment. The first group of techniques are designed to construct the entire geometry of listric normal faults, and therefore the detachment, based essentially on the shape of the hanging wall rollover (e.g., Verrall, 1981; Gibbs, 1985; Davison, 1986; White et al., 1986; Williams and Vann, 1987; Groshong, 1990; Morris and Ferrill, 1999). However, all these methods are related to different kinematical models of deformation, and therefore, if the kinematical model is not appropriate for the example analysed, a correct cross section may be considered to be invalid. In addition, the accurate construction of a complete fault surface is a laborious task. The second group of techniques allow estimating specifically the detachment depth without reconstructing the complete fault surface (e.g., Gibbs, 1983; Jackson and Galloway, 1984; White 1987; Williams and Vann, 1987; Moretti et al., 1988; Groshong, 1994, 1996). These specific techniques supply less information than the methods that predict the entire geometry of the faults at depth, but are quicker and easier to apply. Moreover, some of these specific methods to estimate the detachment depth have an additional advantage: they allow a cross section to be tested regardless of kinematical models on the basis of relationships between area and depth to detachment. The detachment depths estimated for particular examples using some of the above specific techniques to estimate the depth to detachment yield different results (e.g., Williams and Vann, 1987), however, not all the techniques have been tested on the same example to check their accuracy.

Here we pay attention to specific methods to estimate solely the amount of horizontal extension or the detachment depth. The validity and accuracy of the specific methods is tested through their application to

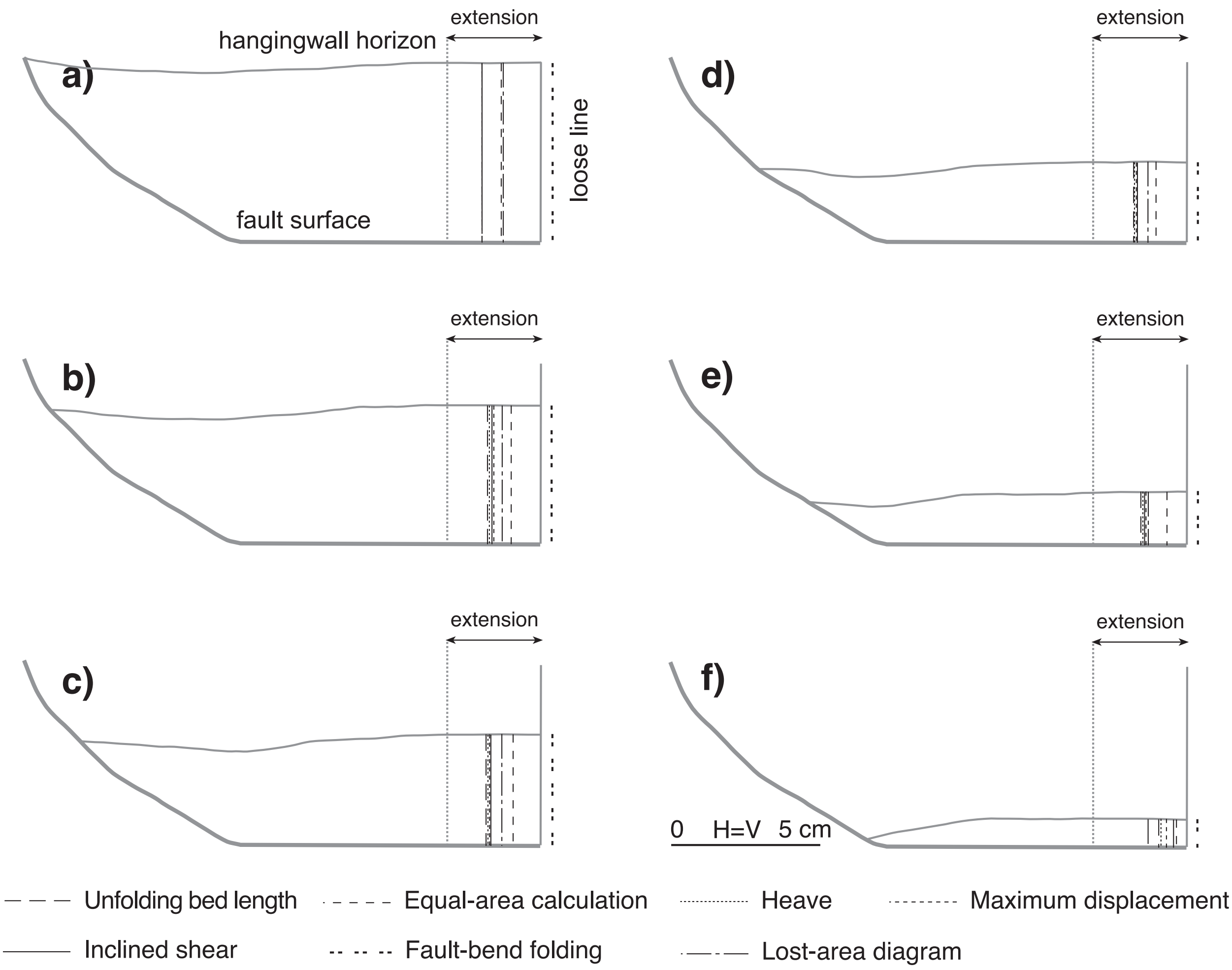


Figure 4. Estimations of the amount of extension using various techniques for different beds of the less evolved stage of the Mitra (1993) experiment. To apply the inclined shear method (White et al., 1986) the following parameters measured by Mitra (1993) have been used for the experiments: fault dip =45° and shear angle =20°. The scale is the same for all the line drawings.

four sections across two physical experiments and two sections across natural subsurface examples of rollover anticlines over listric normal faults.

Techniques to estimate the extension and depth to detachment

The two physical experiments selected are made up of clay and are presented in Dula (1991) and Mitra (1993) (Fig. 1). We refer the readers to Dula (1991) and Withjack et al. (1995) for specific details regarding the features of the modelling materials and experimental procedure in the case of the first experiment, and to Mitra (1993) in the case of the second experiment. The fault in the Dula (1991) experiment dips around 45° in the upper part and flattens approximately 5 cm below the upper fault tip. The fault in the Mitra (1993) experiment dips around 60° in the upper part and flattens around 6 cm below its upper tip. The natural examples are two faults along the Norwegian continental margin and in the Gulf Coast taken from Dula (1991). The Norwegian continental margin fault dips around 70° in the upper part and it is likely that detaches along a salt horizon located approximately 3 km below the upper fault tip. The Gulf Coast fault dips around 50° in the upper part and flattens around 2 km below its upper tip.

The physical experiments selected are sections across relatively simple rollover anticlines in which the true amounts of extension and detachment depth are known. The natural examples are geological interpretations of depth-converted seismic sections across relatively simple rollover anticlines in which the detachment depth may be approximately known. Unfortunately, the

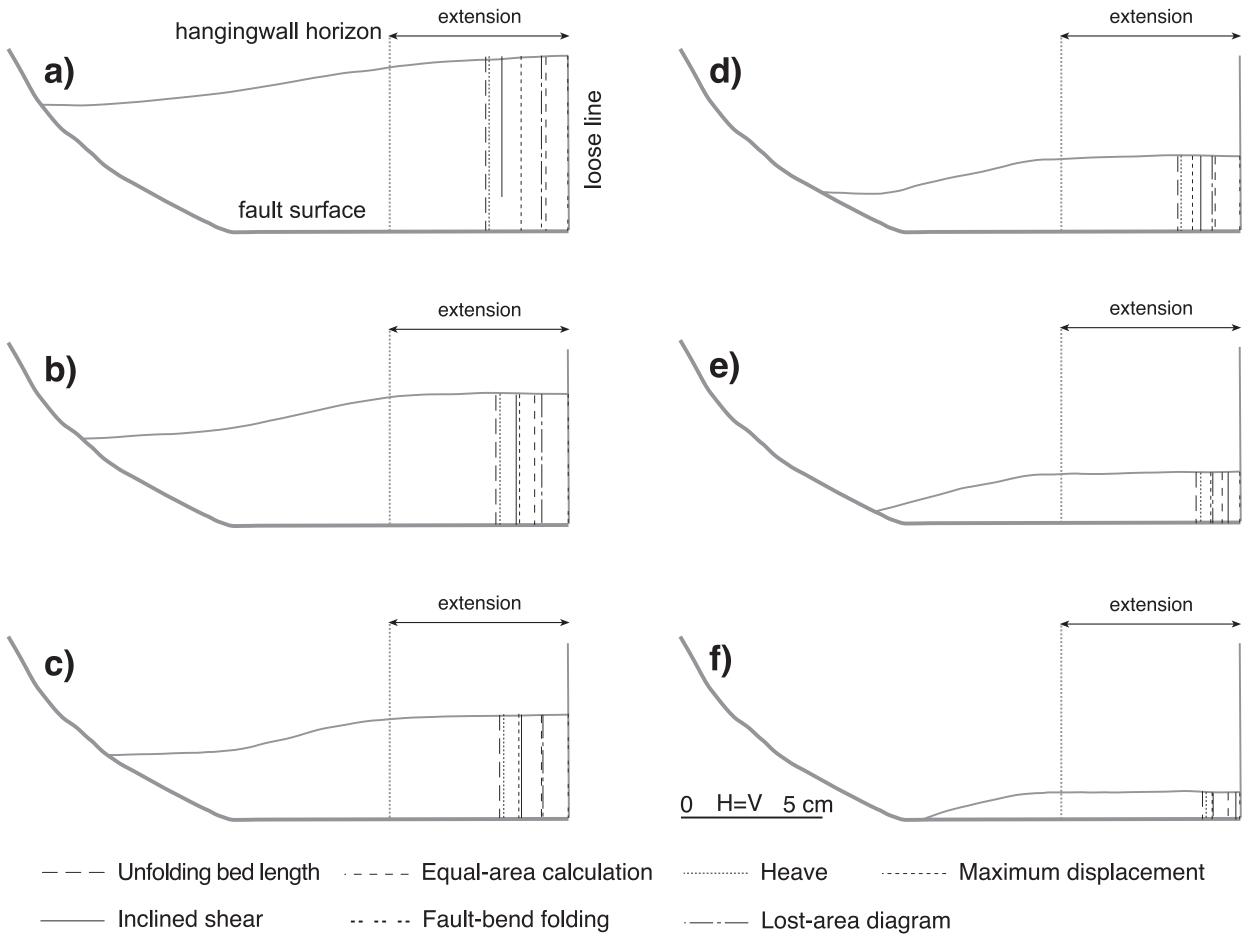


Figure 5. Estimations of the amount of extension using various techniques for different beds of the most evolved stage of the Mitra (1993) experiment. To apply the inclined shear method (White et al., 1986) the following parameters measured by Mitra (1993) have been used for the experiments: fault dip =45° and shear angle =20°. The scale is the same for all the line drawings.

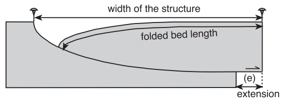
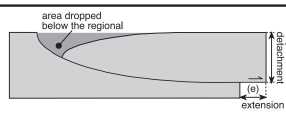
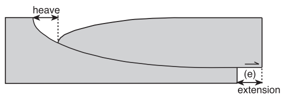
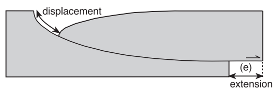
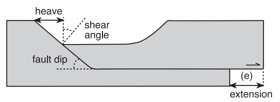
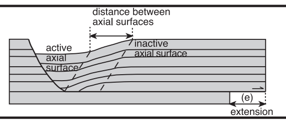
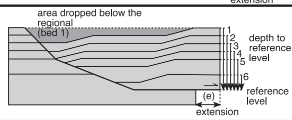
true amounts of extension are unknown and only one bed within the hanging wall has been interpreted, making some methods impossible to apply.

Estimating the amount of extension

The amount of extension accommodated by a fault block over a simple listric normal fault may be estimated using the following specific techniques: 1) unfolding sinuous bed length (Gwinn, 1970) applied to normal faults by Wernicke and Burchfiel (1982), Gibbs (1983) and Jackson and Galloway (1984) amongst others; 2) equal area calculation (Hossack, 1979); 3) fault heave (Ziegler, 1982; Jackson and Galloway, 1984); 4) maximum displacement on the fault (Chapman and Williams, 1984); 5) inclined shear method (White et al., 1986; White, 1987); 6) extensional fault-bend folding (Xiao and Suppe, 1992); and 7) lost-area diagram (Groshong, 1994, 1996). The data required and the procedures to apply these techniques are listed in Table I.

Figures 2, 3, 4 and 5 show the results obtained from the application of the techniques to estimate the extension accommodated by the physical experiments. The maximum displacement on the fault method (Chapman and Williams, 1984) yields the best estimates of extension for the Dula (1991) experiment, whereas it underestimates the extension for the Mitra (1993) experiment. The extensional fault-bend folding method (Xiao and Suppe, 1992) yields the best results for the Mitra (1993) experiment, whereas it underestimates the extension for the Dula (1991) experiment. The second best method for both experiments is the equal area calculation (Hossack, 1979), although it predicts amounts of extension slightly lesser than the true values. The unfolding sinuous bed length (Gwinn, 1970), fault heave (Ziegler, 1982) and lost-area diagram (Groshong,

Table I. Different methods employed to estimate the amount of extension (e) in simple rollover anticlines over listric normal faults. After Poblet and Bulnes (2005) modified.

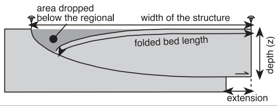
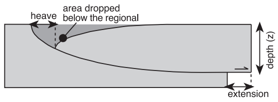
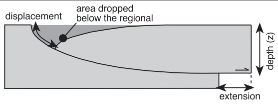
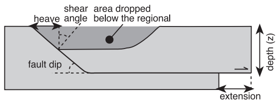
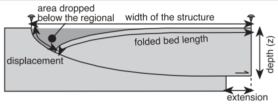
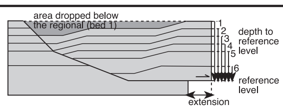
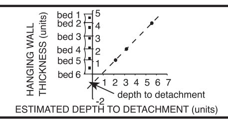
METHODS	DATA		PROCEDURE	REFERENCES
UNFOLDING SINOUS BED LENGTH	- structure width at regional - folded bed length of a horizon		e = structure width - folded bed-length	Gwinn (1970)
EQUAL-AREA CALCULATION	- area dropped below regional - detachment depth beneath a horizon		e = dropped area / detachment depth	Hossack (1979)
HEAVE	- heave of a horizon		e = heave	Ziegler (1982)
MAXIMUM DISPLACEMENT ON THE FAULT	- displacement of a horizon on fault surface		e = displacement on the fault	Chapman and Williams (1984)
INCLINED SHEAR	- heave of a horizon - fault dip - shear angle		e = heave * [1 + tan (fault dip) * tan (shear angle)]	White et al. (1986)
EXTENSIONAL FAULT-BEND FOLDING	- hanging-wall active and inactive axial surfaces across several horizons		e = distance between hanging-wall active and inactive axial surfaces along the lower flat	Xiao and Suppe (1992)
LOST-AREA DIAGRAM	- area dropped below regional - depth of several horizons to a reference level		e = slope of best-fit line across area versus depth of several horizons to a reference level	Groshong (1994)

1994) methods underestimate the extension. In general, the inclined shear method (White et al., 1986) overestimates the extension for the Dula (1991) experiment, whereas it underestimates the extension for the Mitra (1993) experiment.

The amounts of extension obtained from the application of all these methods to the physical experiments, except for the extensional fault-bend folding method, are more accurate in the case of the Dula (1991) experiment than in the case of the Mitra (1993) experiment. As the fault dip is greater and the detachment is deeper in the Mitra (1993) experiment than in the Dula (1991) experiment, we believe that the results may depend on one or both geometric parameters. In the case of the unfolding sinuous bed length, fault heave, inclined shear and extensional fault-bend folding methods, the extension estimated also depends on the true amount of extension undergone by the experiments. For instance, the values obtained for the unfolding sinuous bed length, fault heave and inclined shear methods are more deviated from the true amount of extension in the most evolved stages of both experiments than in the less evolved stages. The position of the chosen horizon to perform the calculations influences the results when using the unfolding sinuous bed length, equal-area calculation, fault heave, maximum displacement on the fault and inclined shear methods. In general, the extension estimated is greater and closer to the true value for deeper horizons than for shallower ones. It must be emphasised that many methods to estimate the amount of extension include kinematic assumptions (e.g., flexural slip, inclined/vertical shear) which are directly related to the mechanical properties of the rocks, and therefore, it is likely that the results obtained depend not only on the geometry of the faults, amount of extension or position of the horizons but on the rheological properties of the rocks.

Figure 6 shows the results derived from the application of different techniques to estimate the amount of extension accommodated by the natural listric faults selected from Dula (1991). Unfortunately, the true amounts of extension are unknown, and therefore, it is not possible to asses which are the most accurate techniques. Different techniques yield extremely different results. Thus, in the case of the Norwegian margin fault (Fig. 6a), the maximum amount of extension obtained is 616 m

Table II. Different methods employed to estimate the depth to detachment (z) in simple rollover anticlines over listric normal faults. After Poblet and Bulnes (2005) modified.

METHODS	DATA		PROCEDURE	REFERENCES
EXCESS/LOST-AREA (BED LENGTH)	- area dropped below regional - structure width at regional - folded length of a horizon		z = area / (width - folded bed length)	Chamberlin (1910) Gibbs (1983)
EXCESS/LOST-AREA (HEAVE)	- area dropped below regional - heave of a horizon		z = area / heave	Chamberlin (1910) Gibbs (1983)
EXCESS/LOST-AREA (DISPLACEMENT)	- area dropped below regional - displacement of a horizon on the fault		z = area / displacement on the fault	Chamberlin (1910) Williams and Vann (1987)
INCLINED SHEAR METHOD	- area dropped below regional - heave of a horizon - fault dip and shear angle		z = area / [heave * (1 + tan (fault dip) * tan (shear angle))]	White (1987)
BED-LENGTH AND DISPLACEMENT CONSERVATION	- area dropped below regional, - structure width at regional - folded length of a horizon - displacement of a horizon		z = area / [(displacement on the fault + width - folded bed length) / 2]	Williams and Vann (1987)
LOST-AREA DIAGRAM	- area dropped below regional - depth of several horizons to a reference level		point where best-fit line across area versus depth of several horizons crosses the x axis	Groshong (1994)
BEST-FIT DETACHMENT DEPTH GRAPH	- beds' thickness - detachment depths beneath several horizons estimated using other methods		point where best-fit line across thickness versus detachment depths crosses the y axis	Bulnes and Poblet (1999)

using the inclined shear method (White et al., 1986), whereas the minimum amount is 131 m using the unfolding sinuous bed length method (Gwinn, 1970), being the difference between both methods of 485 m (almost four times the extension predicted by the unfolding sinuous bed length method). In the case of the Gulf Coast fault (Fig. 6b), the maximum amount of extension obtained is 791 m using the maximum displacement on the fault method (Chapman and Williams, 1984), whereas the minimum value is 421 m using the unfolding sinuous bed length method (Gwinn, 1970), being the difference between both methods of 370 m (almost the value predicted by the unfolding sinuous bed length method). In both natural examples, the equal area calculation (Hossack, 1979), the maximum displacement on the fault (Chapman and Williams, 1984) and the inclined shear (White et al., 1986) methods yield the greatest amounts of extension, whereas the unfolding sinuous bed length (Gwinn, 1970) and the fault heave (Ziegler, 1982) methods give the lesser amounts of extension.

Comparing the results obtained from the physical experiments (Figs. 2, 3, 4 and 5) and the results obtained from the natural examples (Fig. 6) furnishes important information. In general, the values of extension obtained from the application of the unfolding sinuous bed length and the fault heave methods to the natural examples are lesser than the values obtained from the application of the other methods. In the case of the physical experiments, where the true amount of extension is known, these two methods provide the worst estimations. Assuming that the natural examples and the physical experiments behave in a similar manner, the values obtained from the application of these two methods to the natural examples, significantly lesser than the results from other methods, do not correspond to the extension accommodated by the natural faults.

Estimating the depth to detachment

The detachment depth in simple listric normal faults may be estimated using the following specific methods: 1) the excess/lost area method (Chamberlin, 1910) using: a) the difference between the sinuous and unfolded bed lengths as input for the amount of extension, applied to normal faults by Gibbs (1983) and Williams and Vann (1987); b)

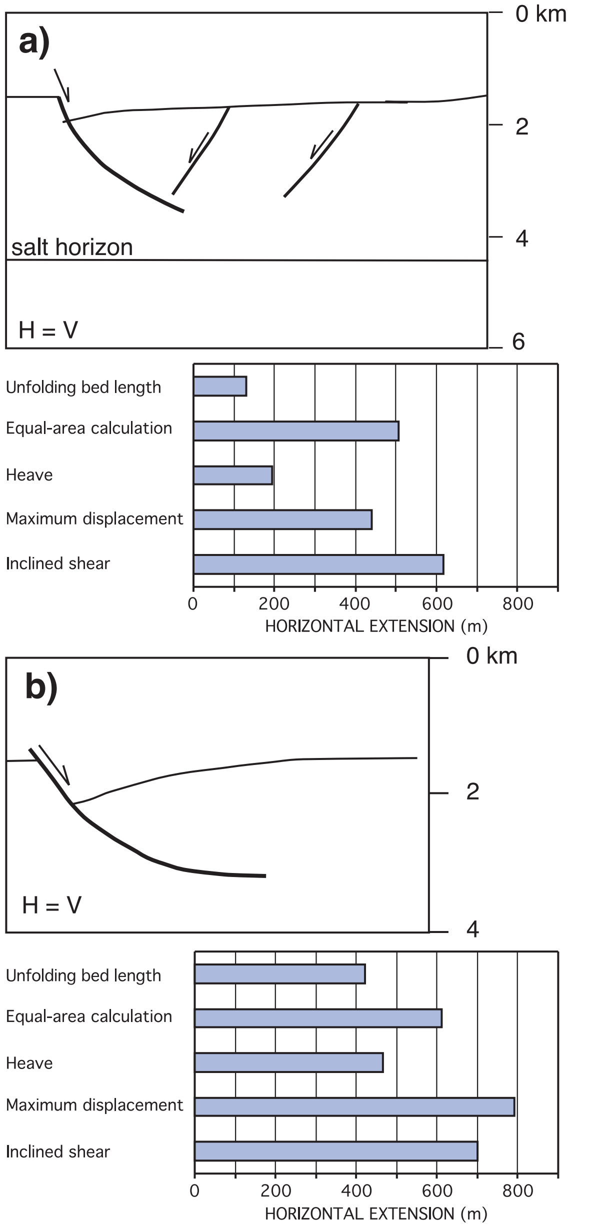


Figure 6. Estimations of the amount of extension using various techniques for the bed displayed in the section across a listric normal fault in the Norwegian continental margin (a) and for the bed displayed in the section across a listric normal fault in the Gulf Coast (b). The cross sections are modified from Dula (1991). The values of fault shear and dip of the fault employed to apply the inclined shear method (White et al., 1986) are 40° and 69° respectively for the Norwegian margin fault and 20° and 54° for the Gulf Coast fault. The shear angles have been taken from Dula (1991), whereas the fault dips have been measured using the portion of the fault between the hanging wall and foot wall cut off points of the marker horizons. The extensional fault-bend folding method (Xiao and Suppe, 1992) and lost-area diagram (Groshong, 1994) have not been tested in the natural examples because they require several horizons.

the fault heave as input for the amount of extension, applied to normal faults by Gibbs (1983) and Jackson and Galloway (1984); and c) the displacement as input for the amount of extension, applied to normal faults by Williams and Vann (1987); 2) the inclined shear method (White, 1987); 3) the bed-length and displacement conservation method (Williams and Vann, 1987); 4) the block rotation model along circular faults (Moretti et al., 1988); 5) the lost-area diagram (Groshong, 1994, 1996); 6) the requisite strain equation (Groshong, 1994, 1996); and 7) the best-fit detachment-depth graph (Bulnes and Poblet, 1999) that can be applied to normal faults using data from previous methods. The Moretti et al. (1988) method can only be used in the case of circular faults and rollover anticlines of constant dip, and therefore, the applicability of this method is limited as listric faults may be modelled as a circular arc only locally. The requisite strain equation (Groshong, 1994, 1996) uses the amount of layer-parallel strain to estimate the detachment depth and this makes it difficult to be used because the strain is unknown in many natural cases. Neither the block rotation method along circular faults, nor the requisite strain equation have been applied to the examples analysed here. The data required and the procedures to apply these techniques, with the exception of the block rotation model and the requisite strain equation, are listed in Table II.

Figures 7, 8, 9, 10, 11 and 12 illustrate the detachment depths obtained from the application of the above techniques to the Dula (1991) and Mitra (1993) experiments. The best method to estimate the detachment depth for both experiments is the lost-area diagram (Groshong, 1994). The second best method is the excess/lost area method (Chamberlin, 1910) using the displacement of both single beds (Figs. 7, 8, 10 and 11) and several horizons (Figs. 9 and 12) as input for the amount of extension. In the case of the less evolved stage of the Dula (1991) experiment, the bed length and displacement conservation method (Williams and Vann, 1987) yields results comparable to the excess/lost area method (Chamberlin, 1910) using the displacement. The excess/lost area method (Chamberlin, 1910) using the bed length and the fault heave, and the bed length and displacement conservation method (Williams and Vann, 1987) predict depths below the true detachment depth of both experiments. The inclined shear method (White, 1987) underestimates the detachment depth in the case of the Dula (1991) experiment, whereas it overestimates the detachment depth in the case of the Mitra (1993) experiment. The best-fit detachment-depth graph using data from other methods (Bulnes and Poblet, 1999) underestimates the detachment depth for both experiments.

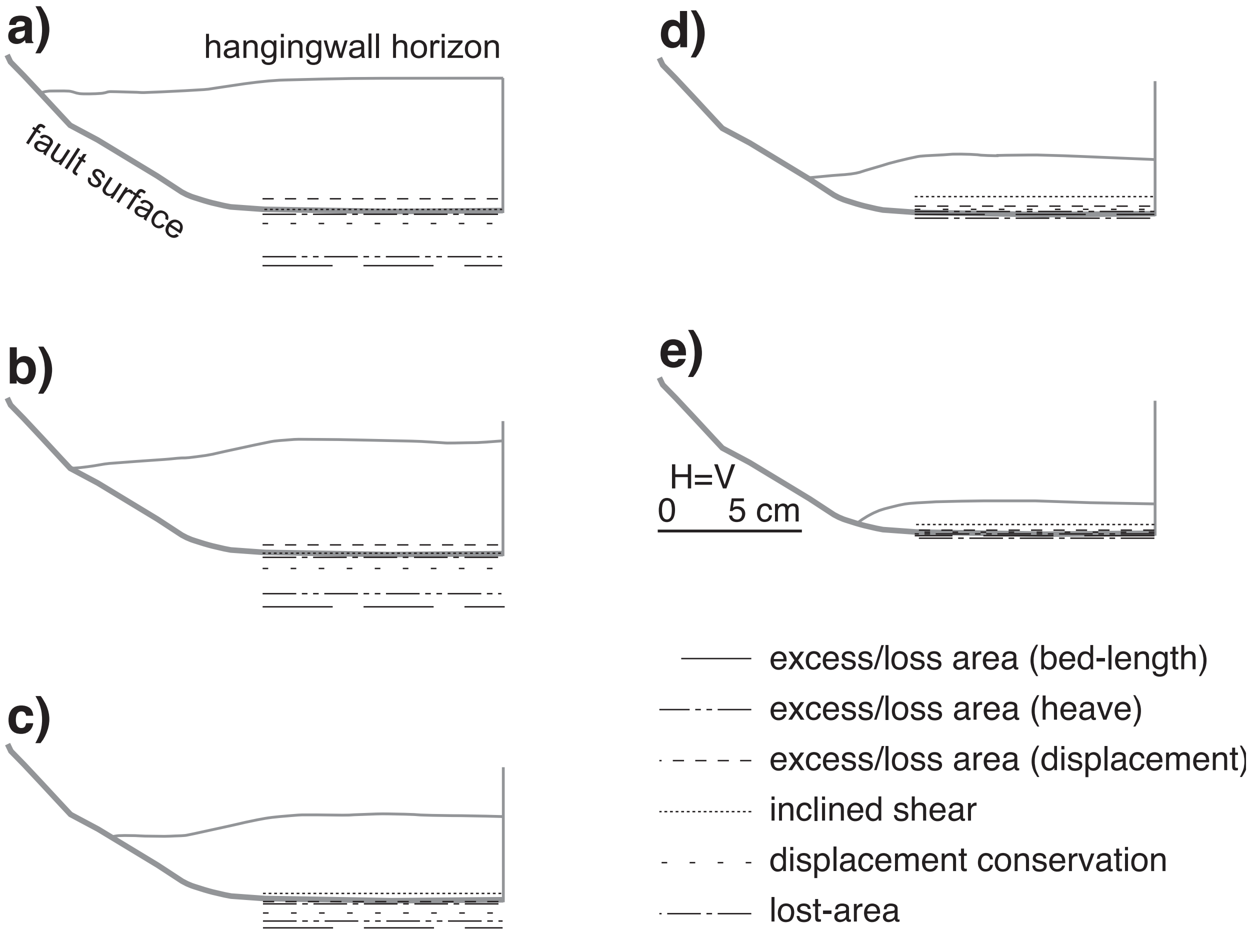


Figure 7. Estimations of the detachment depths using various techniques for different beds of the less evolved stage of the Dula (1991) experiment. The scale is the same for all the line drawings.

The comparison of the results obtained from the application of the different methods to both physical experiments suggest that the depths to detachment estimated for the Dula (1991) experiment are closer to the true value than those estimated for the Mitra (1993) experiment. Since both the fault dip and the detachment depth are greater in the Mitra (1993) experiment than in the Dula (1991) experiment, it is likely that the results are strongly influenced by one or both geometrical parameters. The accuracy of the depths to detachment obtained for both stages of the Dula (1991) experiment are similar, however, the depths to detachment obtained for the most extended stage of the Mitra (1993) experiment are more accurate than those estimated for the less extended stage of this experiment. The height of the horizon chosen to carry out the calculations with respect to the detachment also seems to influence the results. Thus, for both experiments, the deeper the horizon chosen, the more accurate the depths to detachment obtained. In both physical experiments, the depths to detachment estimated using methods that involve more than a single horizon are not as close to the true values than those estimated using deep horizons, but they are much better than those estimated using shallow horizons. Similarly to the estimations of the amount of extension, a number of methods to calculate the detachment depth involve kinematic assumptions which are strongly related to the mechanical properties of the rocks, and therefore, it is possible that the accuracy of the results is related not only to the fault geometry, amount of extension, position and number of the horizons used but to the rheological properties of the rocks.

Figure 13 illustrates the depths to detachment obtained by applying the above techniques to the natural examples taken from Dula (1991). Assuming that the Norwegian margin fault detaches along the salt horizon, the excess/lost area method (Chamberlin, 1910) using

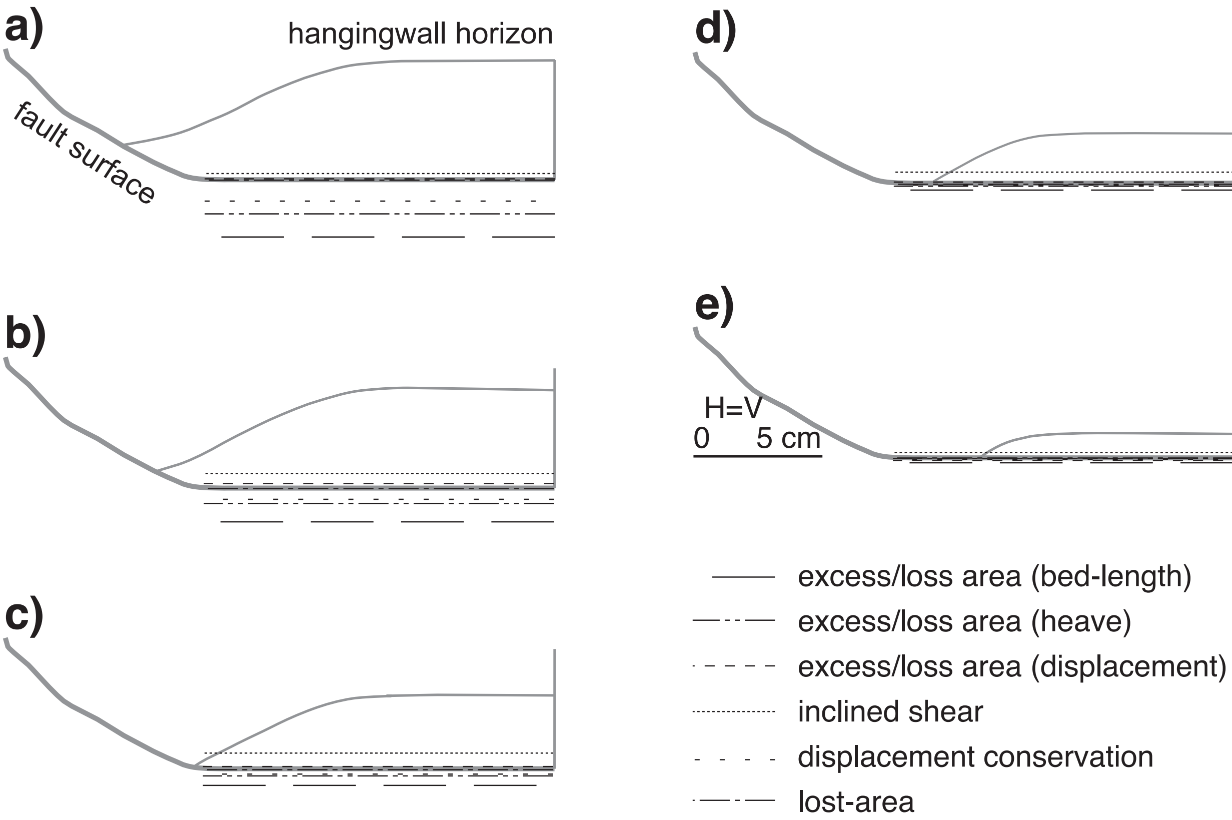


Figure 8. Estimations of the detachment depths using various techniques for different beds of the most evolved stage of the Dula (1991) experiment. The scale is the same for all the line drawings.

the displacement yields the best results in the case of this fault (Fig. 13a), although it slightly overestimates the detachment depth. In the case of the Gulf Coast fault (Fig. 13b), the detachment depth obtained using the bed-length and displacement conservation method (Williams and Vann, 1987) coincides with the true detachment depth. The second best method is the inclined shear method (White, 1987) that slightly underestimates the detachment depth of both natural examples . The bed length and displacement conservation method (Williams and Vann, 1987) overestimates the detachment depth in the case of the Norwegian margin fault, and the excess/lost area method (Chamberlin, 1910) using the displacement underestimates the detachment depth in the case of the Gulf Coast fault. In both natural examples, the detachment depth obtained using the excess/lost area method (Chamberlin, 1910) using bed lengths and fault heaves substantially overestimate the detachment depth.

Conclusions

The best method to estimate the amount of extension differs depending on the physical experiment considered; it is the maximum displacement on the fault (Chapman and Williams, 1984) for one of the experiments and the extensional fault-bend folding (Xiao and Suppe, 1992) for the other. The equal-area calculation (Hossack, 1979) is the second best method to estimate the amount of extension in both physical experiments. The results obtained depend, not only on the method employed, but on parameters such as dip of the master fault, depth to detachment, amount of extension undergone by the experiment and height of the horizon chosen with respect to the detachment. Thus the lesser the fault dip, the depth to detachment, the amount of extension and/or the vertical distance between the horizon chosen and the detachment, the more accurate the results. It is likely that the accuracy of the results obtained using different methods is also dependent on the rheology of the modelling materials employed.

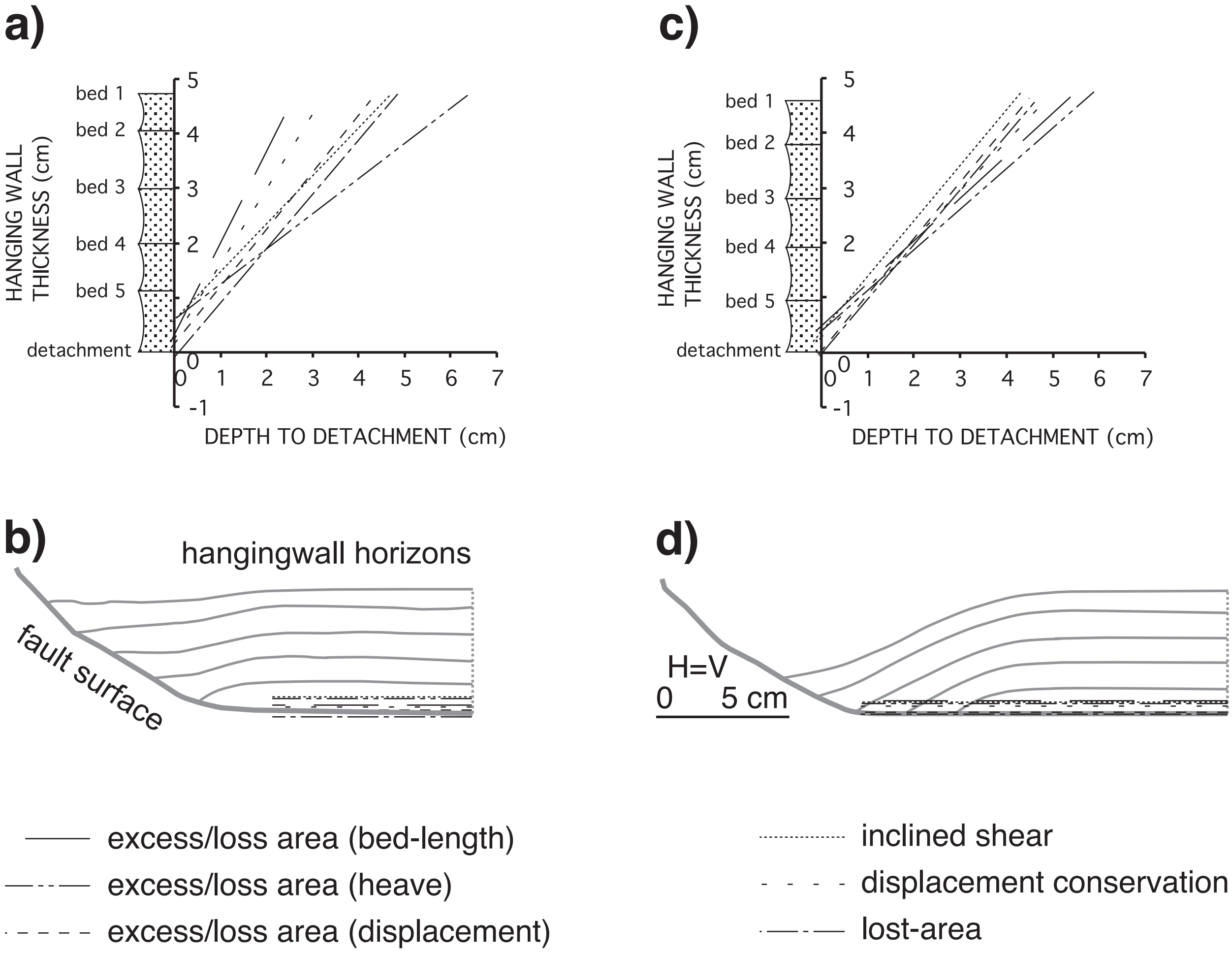


Figure 9. Graphs to estimate the depth to detachment according to the technique by Bulnes and Poblet (1999) using data from all the other methods for both the less evolved (a and b) and the most evolved (c and d) stages of the Dula (1991) experiment. The scale is the same for all the line drawings.

The results differ dramatically in the case of the natural examples. Unfortunately, our conclusions regarding the different techniques to estimate the extension and the detachment depth in natural examples are preliminary due to two crucial constraints: the true amount of extension is unknown and we have not been able to test these methods using information from more than a single horizon. This prevents us to fully compare the results obtained from physical experiments and natural examples. Nevertheless, it is possible that the unfolding sinuous bed length and the fault heave methods are less accurate than the rest of methods. Thus, the equal area calculation method (Hossack, 1979), the maximum displacement on the fault (Chapman and Williams, 1984) and the inclined shear method (White et al., 1986) yield the greater amounts of extension, whereas the unfolding sinuous bed length method (Gwinn, 1970) and the fault heave method (Ziegler, 1982) give the lesser amounts of extension.

The lost-area diagram (Groshong, 1994), followed by the excess/lost area method (Chamberlin, 1910) using the displacement for both single and several horizons (Bulnes and Poblet, 1999), are the best methods to estimate the detachment depth in physical experiments. The dip of the listric fault, the depth to detachment and the stratigraphic position of the horizon chosen to perform the calculations seem to influence the final results. Thus, reasonable estimations of the detachment depth are obtained in those experiments where the fault dip, the detachment depth and/or the height of the horizon chosen above the detachment are small. It is unclear whether the amount of extension undergone by the experiment influences the results; thus, in the first experiment the accuracy of the depths to detachment estimated is similar irrespective of the amount of extension, whereas in the second experiment, better results are obtained for the highly extended stage. The

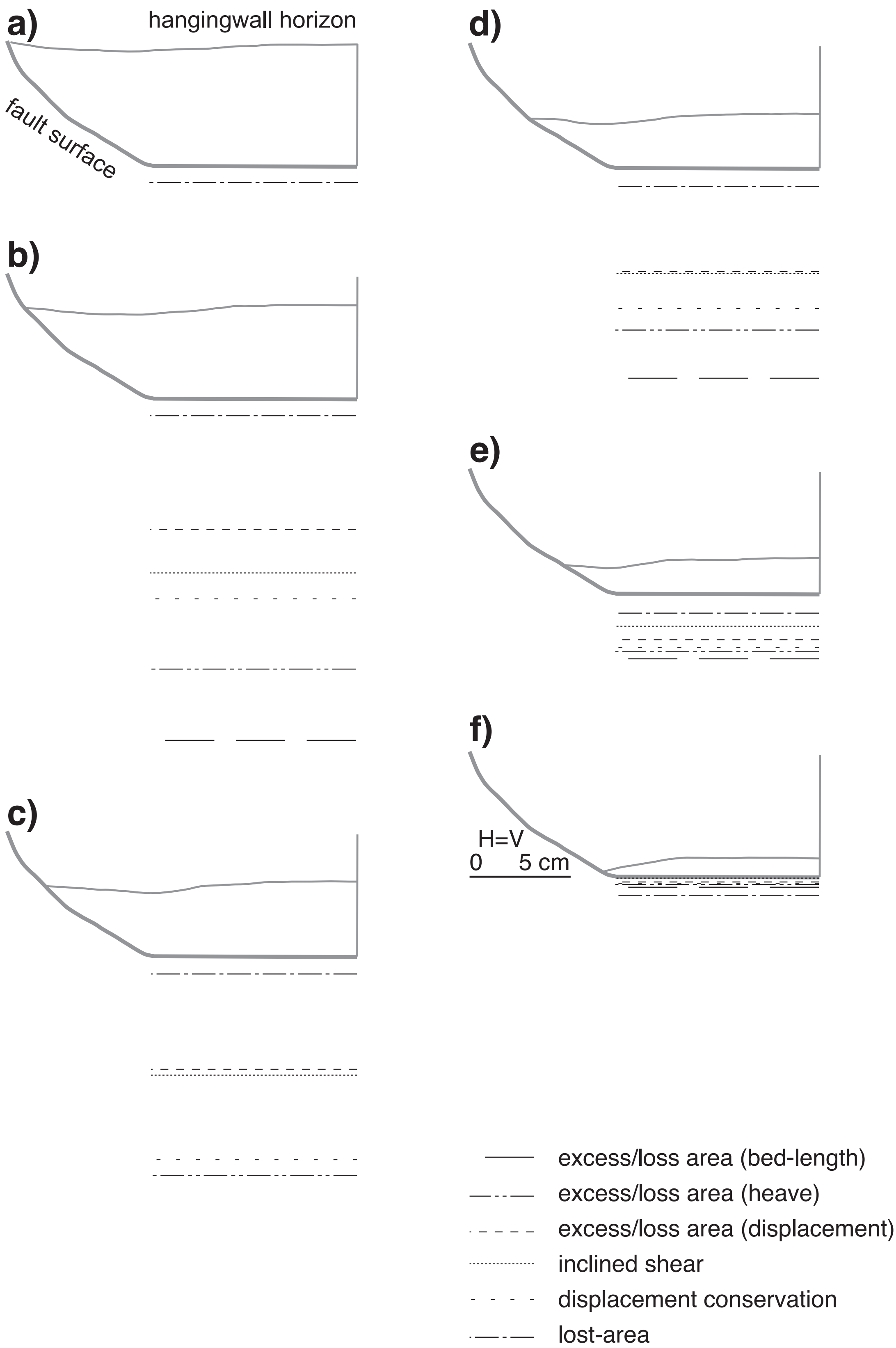


Figure10. Estimations of the detachment depths using various techniques for different beds of the less evolved stage of the Mitra (1993) experiment. The scale is the same for all the line drawings.

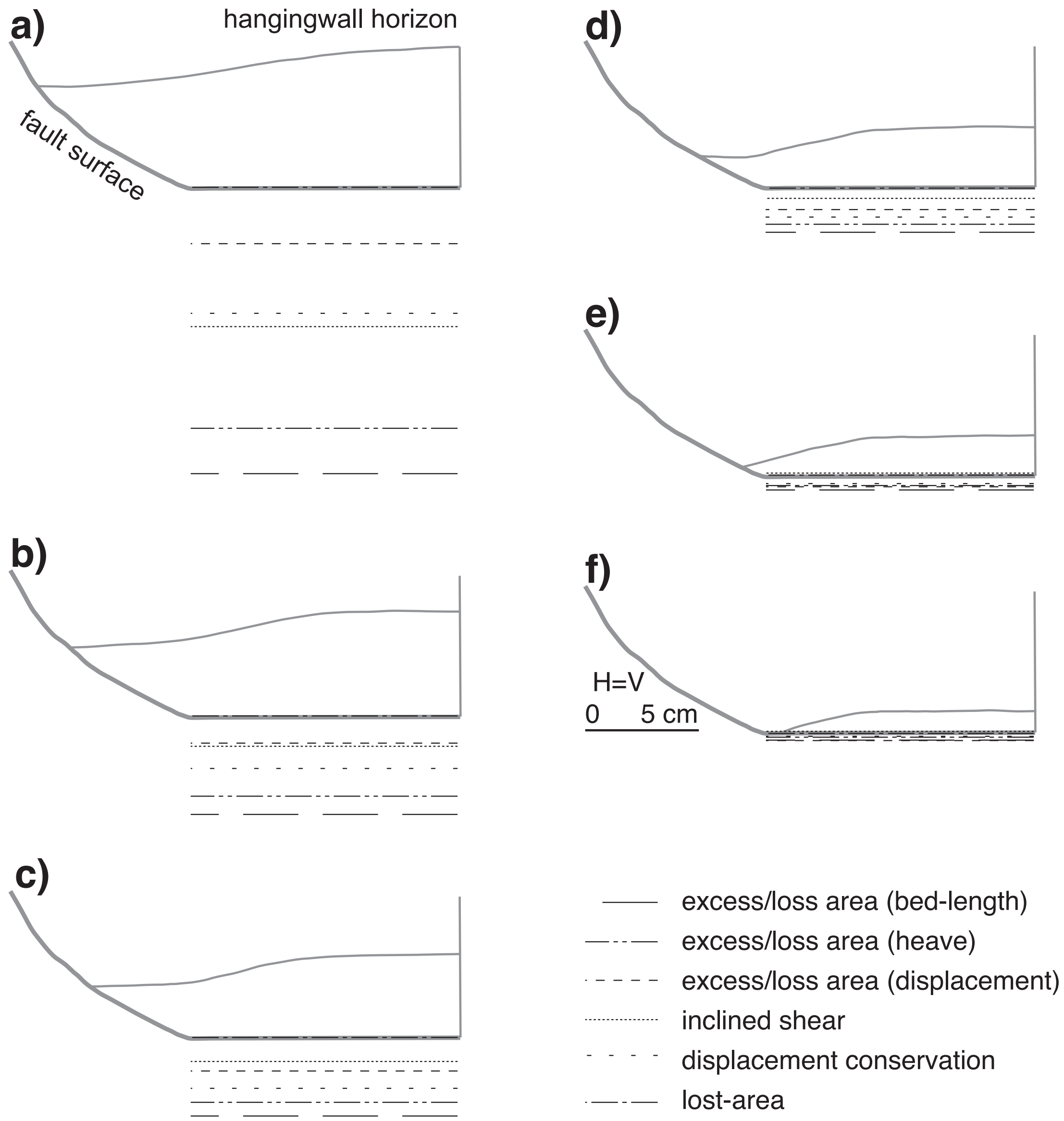


Figure 11. Estimations of the detachment depths using various techniques for different beds of the most evolved stage of the Mitra (1993) experiment. The scale is the same for all the line drawings.

estimations using methods that involve several horizons are not as much deviated from the true detachment depths as the ones carried out with shallow horizons, but they are not as good as those performed using deep horizons. As in the case of the amount of extension estimations, the results obtained using different methods depend on the mechanical properties of the materials employed in the experiments.

The best method to estimate the detachment depth differs depending on the natural example selected; the excess/lost area method (Chamberlin, 1910) using the displacement produces the best agreement between the estimated and the true detachment depths in one of the examples, and the bed-length and displacement conservation method (Williams and Vann, 1987) is the best method for the other. The inclined shear method (White, 1987) is the second best method for both natural examples.

Our analysis suggests that the results of some of the methods used to estimate the extension in upper structural levels should be taken with caution because the amounts obtained may differ substantially from the true values. This may be one of the reasons why estimates of the amount of stretching obtained from measurements of crustal thickness and subsidence

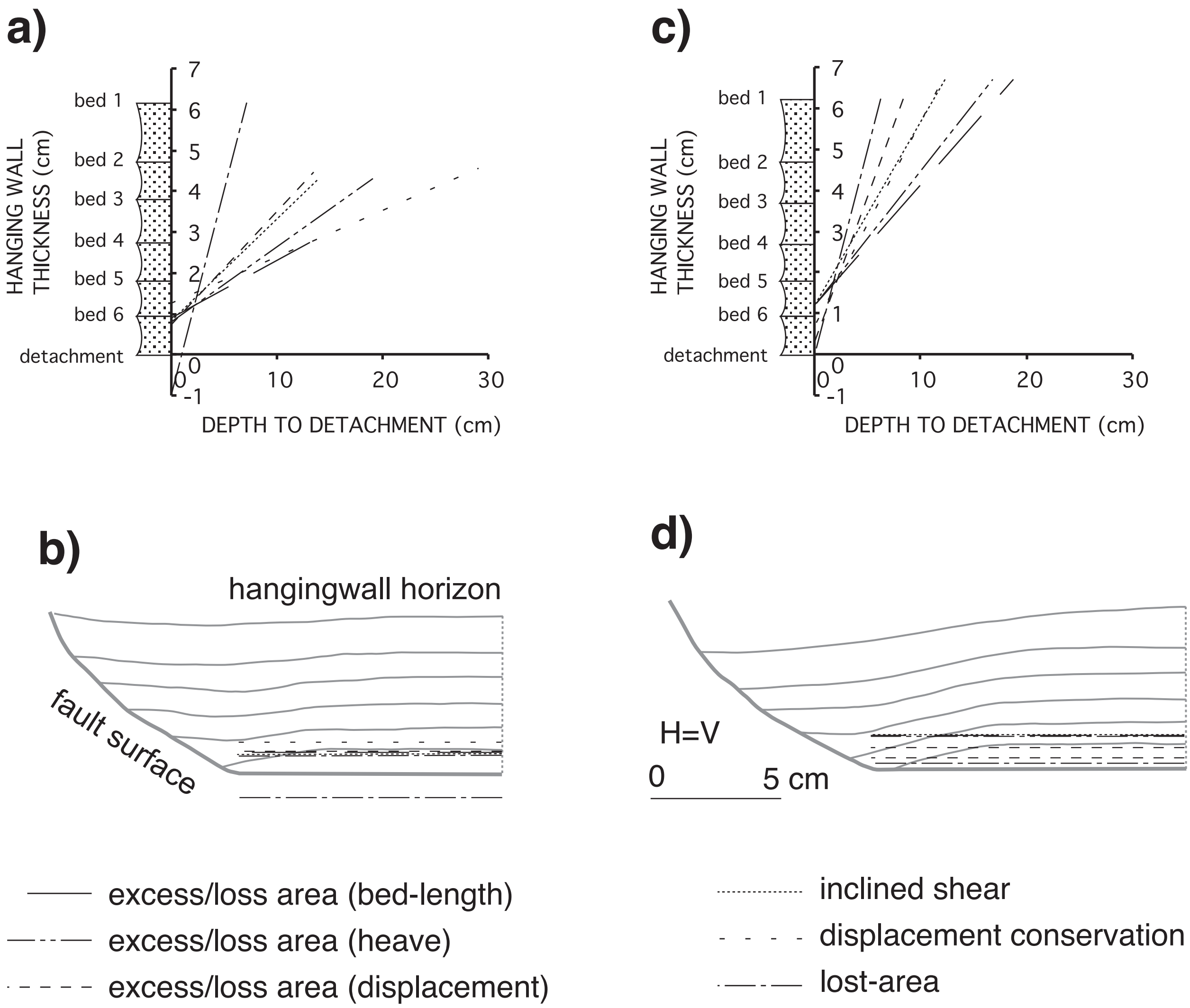


Figure 12. Graphs to estimate the depth to detachment according to the technique by Bulnes and Poblet (1999) using data from all the other methods for both the less evolved (a and b) and the most evolved (c and d) stages of the Mitra (1993) experiment. The scale is the same for all the line drawings.

using deep reflexion or refraction profiles are in some cases difficult to reconcile with those obtained from observed normal faults in the brittle upper crust (e.g. De Charpal et al., 1978; Le Pichon and Sibuet, 1981; Chenet et al., 1982; Wood and Barton, 1983; Ziegler, 1983, 1992; Steckler, 1985; Barbier et al., 1986; Artyushkov, 1987; Pinet et al., 1987; Faure and Chermette, 1989; Bois, 1993).

Irrespective of the drawbacks presented, when used carefully the techniques to estimate the extension and the detachment depth in rollover anticlines over listric normal faults may put additional constraints on the construction of geological sections across these structures because they can be used to extrapolate them beyond the limits of the available data in deep and perhaps hidden, or poorly constrained, parts of the structure. In turn, both types of techniques may assist in validating geological sections in an easy and quick way without restoring them. Although these techniques can be used as partial alternatives to cross-section balancing and restoration methods, it is preferably to use them in conjunction and also use appropriate methodologies to reconstruct the entire geometry of the listric faults at depth.

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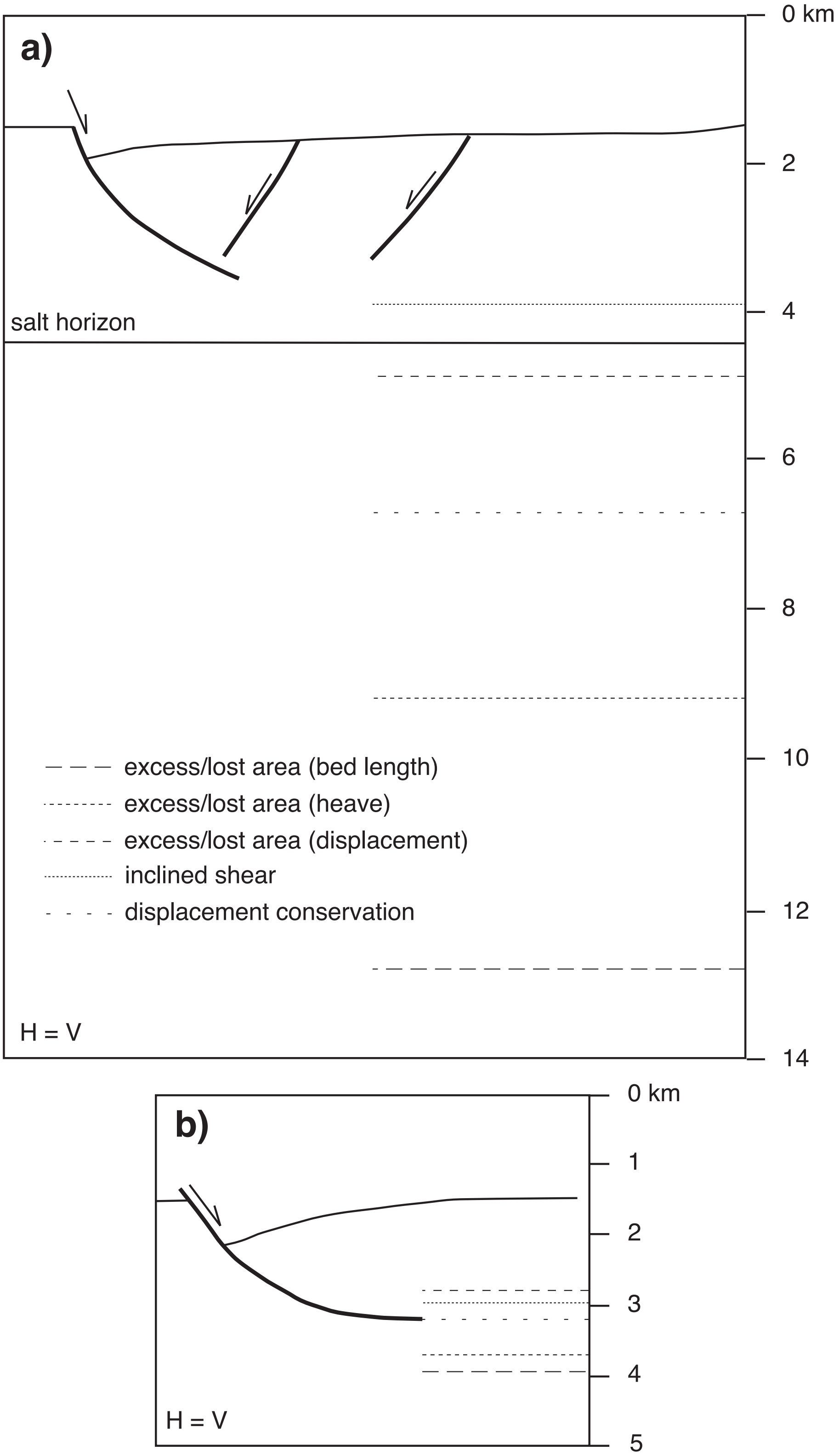

Figure 13. Estimations of the detachment depth using various techniques for the bed displayed in the section across a listric normal fault in the Norwegian continental margin (a) and for the bed displayed in the section across a listric normal fault in the Gulf Coast (b). The cross sections are modified from Dula (1991). The lost-area diagram (Groshong, 1994) has not been applied to the natural examples because it requires several horizons.

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