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Benefits and limitations of different 2D algorithms used in cross-section restoration of inverted extensional faults: application to physical experiments

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Abstract

In recent years, 2D restoration techniques have been systematically used to restore cross-sections through inverted basins. The accuracy of these techniques, and in particular which method better restores the inverted extensional faults to previous stages, is uncertain and difficult to assess in natural examples. To address this drawback, the applicability of flexural slip and vertical/oblique slip restoration techniques, executed with section restoration software, is tested through restoration of physical experiments of inverted extensional faults to their pre-inversion stage. The experiments chosen consist of simple listric and planar faults in which: (1) the original state and the kinematic path followed by the rocks to reach the final state is known, (2) the boundary conditions are known, (3) erosion is absent, and (4) the orientation of extension and compression vectors is equal. Comparing the restored sections with their corresponding actual pre-inversion stage reveals that flexural slip is the best restoration method, whereas the combination of different slip angles method gives the worst results. The accuracy of these techniques depends, to a great extent, on the master fault geometry, the coefficient of friction along it and the amount of inversion. The best results are obtained for a physical model that consists of a listric fault with 60º dip at the top of the rigid footwall, a shallow detachment, low coefficient of friction along the fault and mild amount of inversion. Since the deformation mechanisms and the geometry of the inverted structures are non-identical in physical experiments and in natural examples, the results obtained in our study should be cautiously applied to cross-sections across natural inverted basins.

Keywords: restoration; inversion tectonics; analogue modelling

1. Introduction

It is widely agreed that cross-section restoration is a powerful method of structural analysis. In academia structural geologists use this technique to validate the cross-sections (particularly the sub-surface geometry of the structures) and to determine the original position and dip of the structures, the amount and rates of deformation, the timing of basin formation and evolution, and the kinematic evolution of deformed sedimentary basins. Occasionally this technique is also an aid in determining original spatial relationships between sedimentary facies and gives insight into

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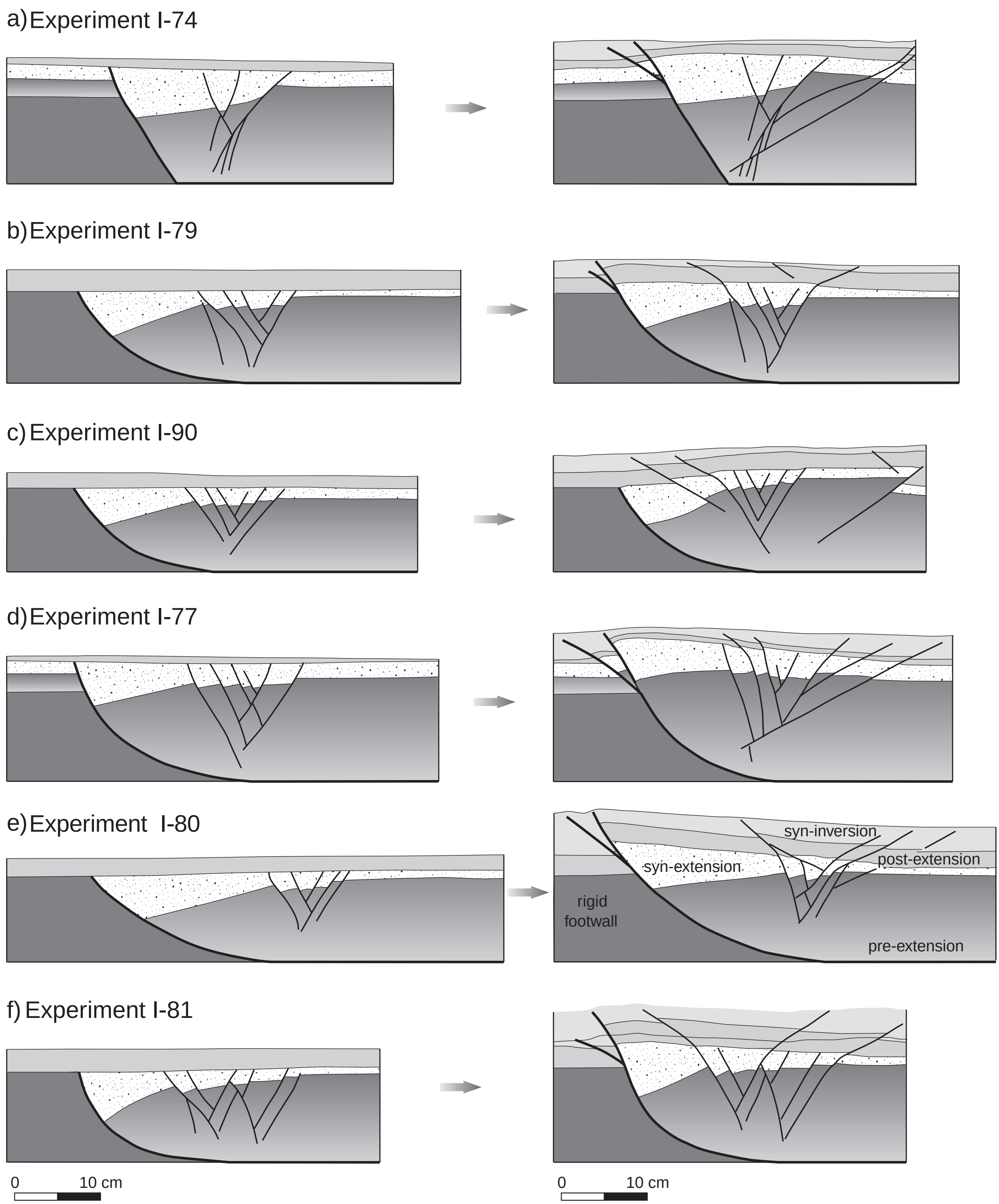

a) Experiment I-74
b) Experiment I-79
c) Experiment I-90
d) Experiment I-77
e) Experiment I-80
syn-inversion
post-extension
syn-extension
rigid
footwall
pre-extension
f) Experiment I-81
0
10 cm
0
10 cm

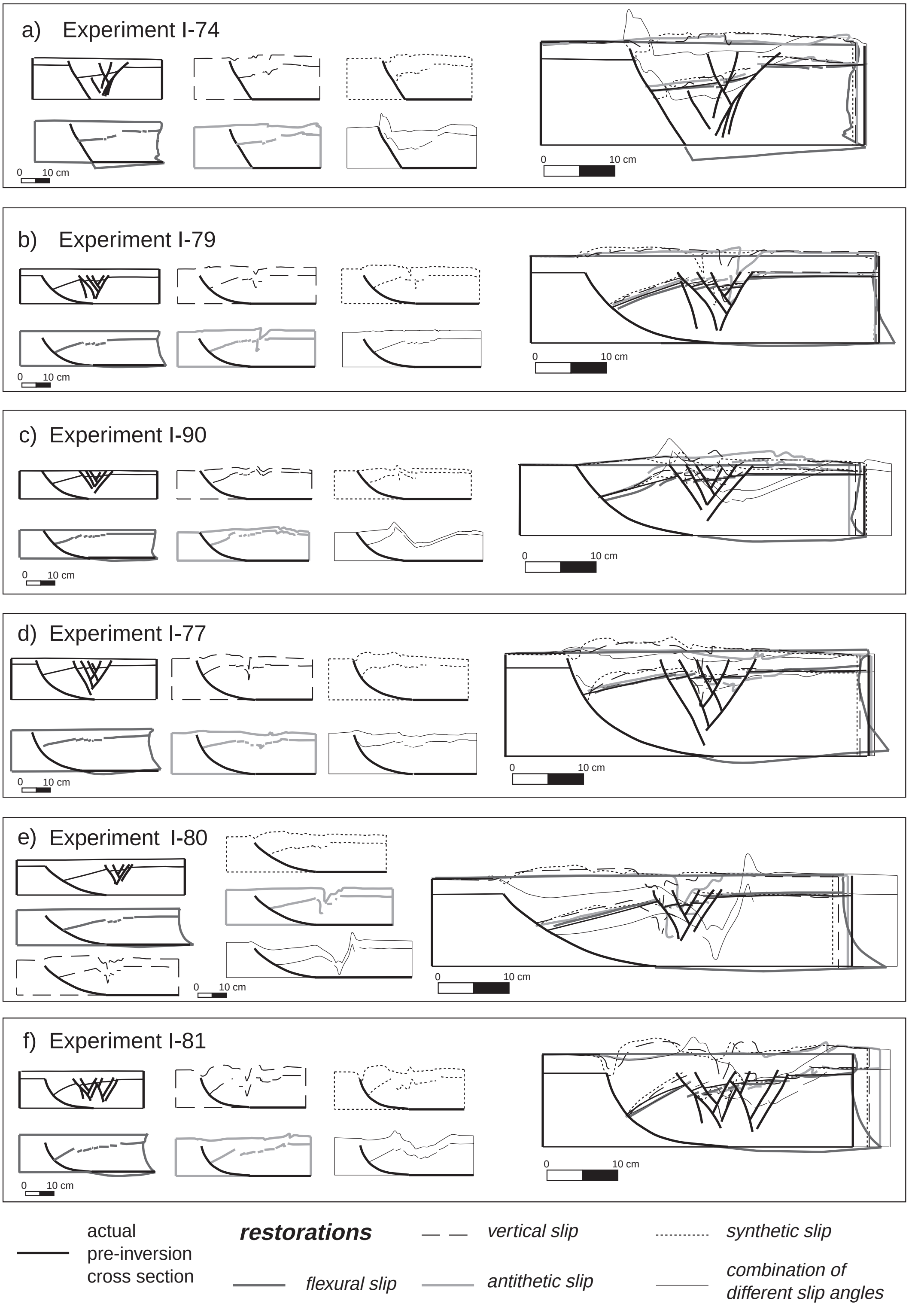
the syn-tectonic sediment patterns. In industry explorationists also use this technique to investigate the hydrocarbon and mineral prospectivity of deformed sedimentary basins. In particular, they use this technique to test the position of source rocks, the validity of migration routes, and the timing of generation, expulsion and migration of hydrocarbons; to analyse the geometry and formation of structural traps; and to determine the timing of trap formation/destruction (Buchanan, 1996).

Although cross-section restoration was first presented in oil industry studies in compressional terranes (e.g., Bally et al., 1966; Dahlstrom, 1969, 1970; Royse et al., 1975; Mitra and Namson, 1989), it was soon used in extensional areas (e.g., Gibbs, 1983; Davison, 1986; White et al., 1986; Groshong, 1989; Rowan and Kligfield, 1989; Dula, 1991; Nunns, 1991; White and Yielding, 1991; Arthur, 1993), and also in inverted terranes (e.g., Butler, 1989; Chapman, 1989; Hayward and Graham, 1989; Bishop and Buchanan, 1995; Wang et al., 1995; Hill and Cooper, 1996; Beauchamp et al., 1997; Flöttmann and James, 1997; Bulnes and McClay, 1998) and salt areas (e.g., Worral and Snelson, 1989; Rowan, 1993, 1995, 1996; Hossack, 1994, 1995; Diegel et al., 1995; Hooper et al., 1995; Peel et al., 1995; Schuster, 1995). The first 2D restorations were carried out by hand using the equal area method (Chamberlin, 1910, 1919), the line-length method (Dahlstrom, 1969), or a combination of both (Mitra and Namson, 1989). Later on, to model the actual rock deformation, other 2D cross-section restoration methods such as flexural slip and vertical/oblique slip techniques, were developed mainly taking into account the structural features of each tectonic regime. These restoration techniques were implemented in computer programs that allowed fast and accurate cross-section restoration (e.g., Jones, 1984; Kligfield et al., 1986; Geiser et al., 1988; De Paor and Bradley, 1988). Although natural deformation is considerably more complex than the restoration algorithms, all these algorithms are routinely employed to restore cross-sections because they are relatively easy to implement and conserve the cross-sectional area in the restored state. The choice of the algorithm is important because different algorithms often produce markedly different restored geometries. Since in many natural examples the precise initial disposition of the rocks before deformation is unknown, it is uncertain which restoration algorithm most accurately reproduces the rock deformation and reconstructs the non-deformed state. This is one of the reasons why the choice of the best restoration technique is still under discussion (see Hauge and Gray, 1996, for a summary).

Identification and characterization of inverted extensional faults are common exploration targets in inverted basins. Consequently, there has been considerable interest in applying section restoration techniques in these areas over recent years (see references above). Although many of the algorithms created during the eighties were mainly used to restore extensional faults, they were also used to restore cross-sections involving inverted faults. Thus, sections across inverted terranes have been restored by line-length or a combination of line-length and equal-area restorations (e.g., Butler, 1989; Chapman, 1989; Hayward and Graham, 1989; Guimerà et al., 1995), flexural slip combined with vertical/oblique slip methods (e.g., Bishop and Buchanan, 1995; Bulnes and McClay, 1998), vertical shear restoration (e.g., Wang et al., 1995), oblique shear restoration (e.g., Hill and Cooper, 1996), a combination of bed-length, rigid-body rotation and area balancing methods (Linares, 1996), and line-length restoration modified according to strain measurements (e.g., Flöttmann and James, 1997).

This paper addresses the problem of which is the most reasonable 2D algorithm to restore the reversal movement along inverted extensional faults. Such a reconstruction is a partial restoration of these structures. A test of the methods used to restore the extensional movement along a fault, which is the next step

Fig. 1. Geological interpretation of the pre-inversion stage and an inverted stage of six physical experiments of inverted extensional faults run by Buchanan (1991): (a) 60º planar fault (I-74), (b) 60º listric fault (I-79), (c) 60º listric fault with a high coefficient of friction along the fault (I-90), (d) 60º listric fault with a deeper detachment than the experiment in (b) (I-77), (e) 45º listric fault (I-80), and (f) 80º listric fault (I-81). In the case of the listric faults, the dip has been measured at the top of the rigid footwall. Stratigraphic patterns explained in (e).


a) Experiment I-74
0
10 cm
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b) Experiment I-79
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d) Experiment I-77
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e) Experiment I-80
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10 cm
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10 cm
f) Experiment I-81
0
10 cm
0
10 cm
actual
pre-inversion
cross section
restorations
vertical slip
synthetic slip
flexural slip
antithetic slip
combination of
different slip angles

to obtain a complete restoration of inverted structures, has been extensively investigated during the last decade (e.g., Verral, 1981; Gibbs, 1983; Davison, 1986; White et al., 1986; Williams and Vann, 1987; Rowan and Kligfield, 1989; Groshong, 1989, 1990; Dula, 1991; Nunns, 1991; White and Yielding, 1991; Schultz-Ela, 1992; Xiao and Suppe, 1992). To accomplish our goal we use sections across physical experiments of inverted extensional faults (Fig. 1). The physical experiments chosen have four main advantages with respect to natural examples: (1) the original disposition and the kinematic path followed by the rocks to reach the final state are known; (2) the boundary conditions are known; (3) no erosion occurs; and (4) the cross-section contains the extension and compression vectors, and the structures are perpendicular or sub-perpendicular to the cross-section plane. All the experiments analysed consist of simple listric and planar faults with rigid footwalls and therefore only the hangingwall undergoes deformation. These experimental models are restored in this paper with the aid of the structural modelling software Geosec 2D (Kligfield et al., 1986; Geiser et al., 1988, 1991) using the following algorithms: flexural slip, vertical slip deformation, synthetic oblique slip deformation, antithetic oblique slip deformation, and a combination of synthetic (when restoring the displacement along the synthetic faults within the hangingwall) and antithetic slip deformation (when restoring the displacement along the antithetic faults within the hangingwall) (Figs. 2 and 3). The restored cross-sections are analysed in detail and compared with their corresponding actual geometry before inversion. The accuracy of each algorithm is assessed in relation to the following parameters: master fault shape, master fault dip, detachment depth, amount of friction along the fault and amount of inversion.

This work attempts to help to restore sections across inverted structures to their pre-inversion stage by providing information on: (1) the most satisfactory restoration technique for each inverted structure, (2) the reliability of different restoration methods and the magnitude of error in the restored sections, and (3) the effect of the parameters listed above on the geometry of the restored section. The results obtained here from the analysis of physical experiments have important implications for fault reconstruction and restoration of natural inverted structures as they show conspicuous geometric similarities to the inverted physical models (McClay, 1995). However, caution is recommended when applying the conclusions achieved in this study to natural examples because the materials used in the physical experiments do not necessarily behave as natural rocks.

2. Restoration algorithms applied

The physical models presented in this paper have been restored with the aid of computer software. The methods used to restore the reversal movement along previous extensional faults are the flexural slip and various vertical/oblique slip algorithms. These methods assume plane strain and conserve cross-sectional area.

2.1. Flexural slip technique

For constant-thickness strata, the flexural slip method assumes that hangingwall deformation occurs by slip along bedding planes. In the physical models investigated, the footwall is rigid and has retained its initial geometry through the deformation process (Fig. 1). This is why in our restorations the inclined portion of the master fault is considered as a fixed surface against which the internal geometry of the hangingwall is truncated. In addition, we must also assume that there is a stratigraphic horizon at the top of the restored section from which the hangingwall geometry will be generated. In our models, we have chosen the top (or the base) of the post-extension sequence. This stratigraphic horizon has been considered to lie horizontal in the restored sections because it is horizontal in the pre-inversion stage of the physical experiments. Only beds parallel to this horizon maintain their length constant.

Fig. 2. Cross-sections of the physical models illustrated in Fig. 1 restored to their pre-inversion stage using different restoration methods. The flat horizon at the top of the actual pre-inversion cross-section has been omitted for clarity in the right side diagrams.

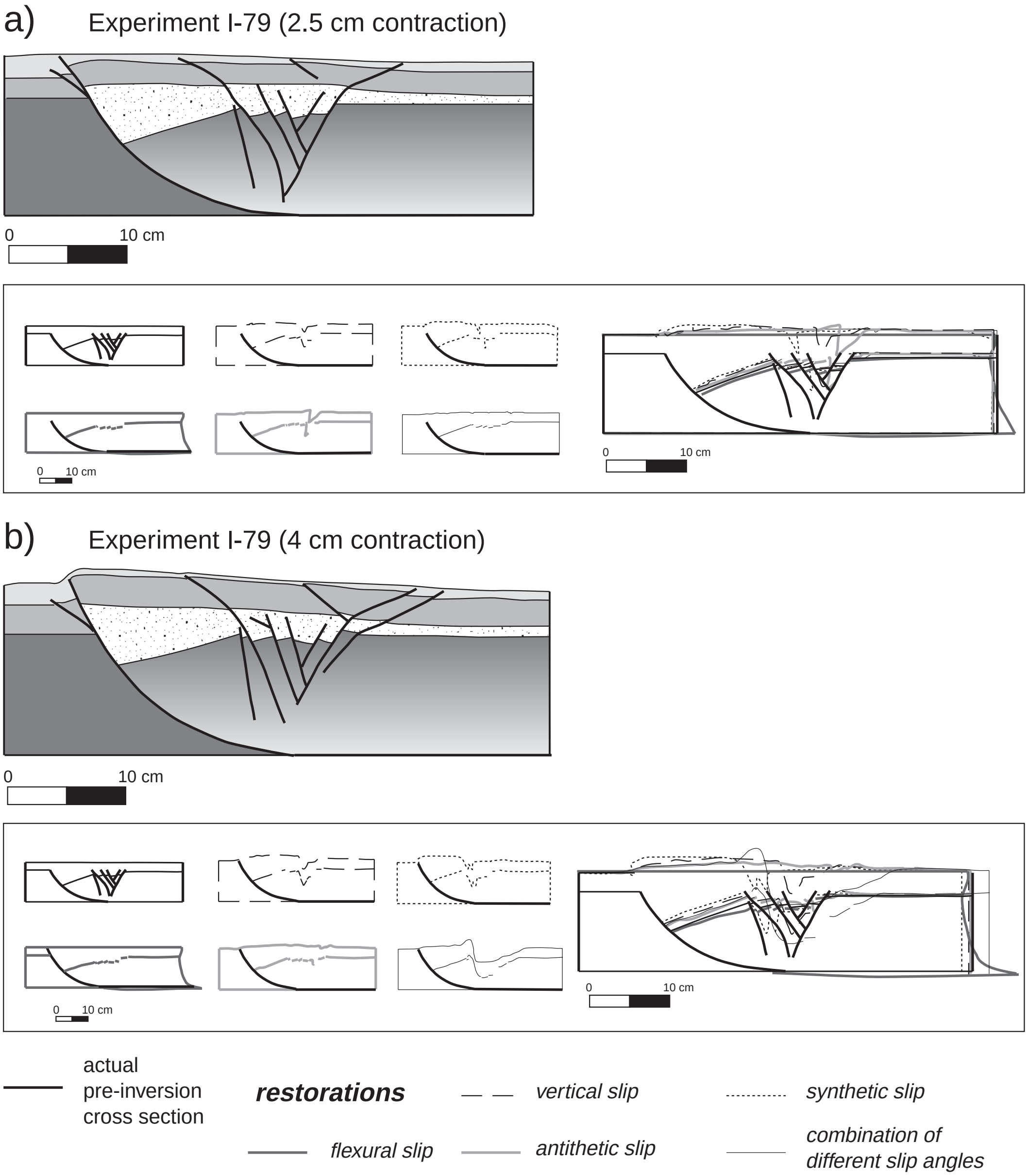

Fig. 3. (a) Inversion of experiment I-79 after 2.5 cm contraction and its restorations using different methods. (b) Inversion of experiment I-79 after 4 cm contraction and its restorations using different methods. The flat horizon at the top of the actual pre-inversion cross-section has been omitted for clarity in the right side diagrams.

2.2. Vertical/oblique slip techniques

These methods assume that the hangingwall deformation can be approximated by a horizontal displacement (heave) combined with a displacement parallel to a slip vector (vertical or oblique) which should replicate the internal deformation mechanisms undergone by the rocks (sand in our examples). These techniques were first used in extensional terranes by Verral (1981) and Gibbs (1983) who assumed that the hangingwall moves laterally by a constant amount and slides vertically (vertical simple shear). White et al. (1986) followed the same procedure but they considered an oblique slide angle (inclined simple shear). In our restorations the entire master fault is considered as a fixed surface against which the internal geometry of the hangingwall is truncated. In addition, an imaginary surface parallel to a chosen slip direction through the cut-off point between the top (or base) of the post-extension sequence and the master fault is required to generate the hangingwall geometry. These techniques introduce variations in bed length and thickness that mainly depend on the inclination of the slip vector chosen. To carry out our restorations four slip vectors have been chosen: (1) vertical slip, (2) synthetic slip (the slip vector is parallel to the master fault dip — dip measured at the top of the rigid footwall for listric faults), (3) antithetic slip (the slip vector coincides with the most common dip of the antithetic faults, developed within the hangingwall), and (4) combination of synthetic and antithetic slip (the slip vector chosen to restore the displacement along each fault is parallel to the fault dip) (Figs. 2 and 3).

3. Experimental models

In nature we can only observe the final deformed state. However, this final deformed state can be reached through infinite kinematic paths. The main advantage derived from the restoration of experimental models is that we know the original state (Fig. 1) and the path followed by the rocks to reach the final state. This allows comparison of the geometry obtained in the reconstructions with the actual original geometry and discussion of the accuracy of each restoration algorithm used. Different restoration techniques have been applied to experimental models formed under extensional regimes (e.g., Groshong, 1989; Dula, 1991; White and Yielding, 1991) and under contractional regimes (e.g., Verschuren et al., 1996). Nevertheless, to date, no restorations of physical models of inverted extensional faults have been published except for the Eisenstadt and Withjack (1995) study, in which errors in the estimation of the inversion magnitude are assessed.

Although a large number of experimental models of inverted extensional faults have been performed (e.g., Koopman et al., 1987; McClay, 1989; Buchanan, 1991; Simmons, 1991; Eisenstadt and Withjack, 1995), the scaled 2D sandbox models carried out by Buchanan (1991) are used here. The main reason is that a whole set of experiments using different fault geometries were carried out by this author. The material properties and experimental procedure followed to produce the models were described in detail in Buchanan (1991), Buchanan and McClay (1991, 1992) and McClay (1995). The geological interpretation of these models was carried out by Buchanan (1991). Six experiments of simple listric and planar faults have been chosen: (1) experiment I-74 (60º planar fault), (2) experiment I-79 (listric fault with 60º dip at the top of the rigid footwall), (3) experiment I-90 (listric fault with 60º dip at the top of the rigid footwall — the conditions of this experiment are the same as those in experiment I-79, but in this case there is a high coefficient of friction along the fault), (4) experiment I-77 (listric fault with 60º dip at the top of the rigid footwall — the depth to detachment measured from the top of the post-extension sequence is greater than in experiment I-79), (5) experiment I-80 (listric fault with 45º dip at the top of the rigid footwall), and (6) experiment I-81 (listric fault with 80º dip at the top of the rigid footwall).

Natural inverted areas are usually characterized by oblique orientations of the extension and compression vectors (e.g., Coward et al., 1989; Braathern and Bergh, 1995; Lowell, 1995; Nemcock et al., 1995; Flöttmann and James, 1997). Such situations lead to strike-slip displacements during inversion and involve movement of material in/out of the plane of the section. This violates one of the basic principles of the 2D cross-section restoration methods, and, therefore, these areas cannot be restored with confidence (see Coward, 1996; Hill and Cooper, 1996, for more details). Furthermore, inversion is often accompanied by denudation. Determining the timing and amount of erosion is crucial when restoring cross-sections across inverted areas (Hill and Cooper, 1996).

The six physical models of inverted extensional faults used in this paper (Fig. 1) have been carefully selected to gain insight into the influence of some parameters on the geometry of the reconstructions. To do that: (1) we assess the accuracy of the restorations using different algorithms by comparing the restored cross-sections with the actual pre-inversion cross-sections (Figs. 2 and 3); and (2) we compare the restorations, constructed using a specific method, of different experiments. The influence of the following parameters is checked: (1) master fault shape (experiments I-74 and I-79), (2) master fault dip measured at the top of the rigid footwall (experiments I-79, I-80 and I-81), (3) detachment depth (experiments I-77 and I-79), (4) amount of friction along the master fault (experiments I-79 and I-90), and (5) amount of inversion (experiment I-79 restored to different inversion stages). The geometrical parameters used to assess the accuracy of the restored cross-sections are: the overall shape of the hangingwall; the deviation in detachment depth, cross-section length and beds' elevation; the amount of shortening measured using the top of the post-extension sequence (the base of this sequence in experiment I-90); and the displacement along the master fault undergone by the base of the syn-extension sequence. The last two parameters have been measured and the results are illustrated in Figs. 4 and 5.

4. Results

In the next sections the influence of different parameters on the accuracy of the restorations is described by comparing the restorations of experiment I-79 with the restorations of one or two of the rest of the experiments and with the actual pre-inversion stage. As experiment I-79 is used to check all the parameters, a description of the restorations of this experiment is made in the first section.

4.1. Restorations of experiment I-79

The flexural slip restoration to its pre-inversion stage gives fairly accurate results, with reasonable hangingwall geometry and detachment depth, and relatively minor hangingwall shear (Fig. 2b). The vertical/oblique slip methods produce broadly similar and acceptable results, with accurate cross-section lengths that are slightly under-estimated and hangingwall geometries that are slightly elevated and contain local perturbations, mainly located over the faults, due to complex hangingwall deformation.

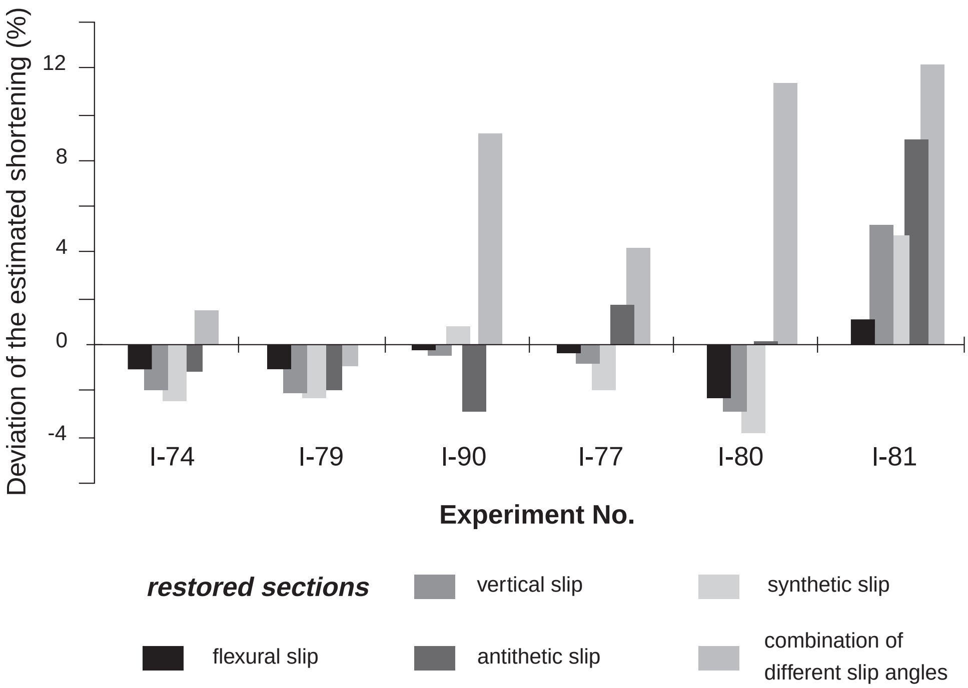

Fig. 4. Graph showing the deviation (%) of the shortening measured on the restored cross-sections illustrated in Fig. 2 with respect to the shortening measured on the actual physical models illustrated in Fig. 1.

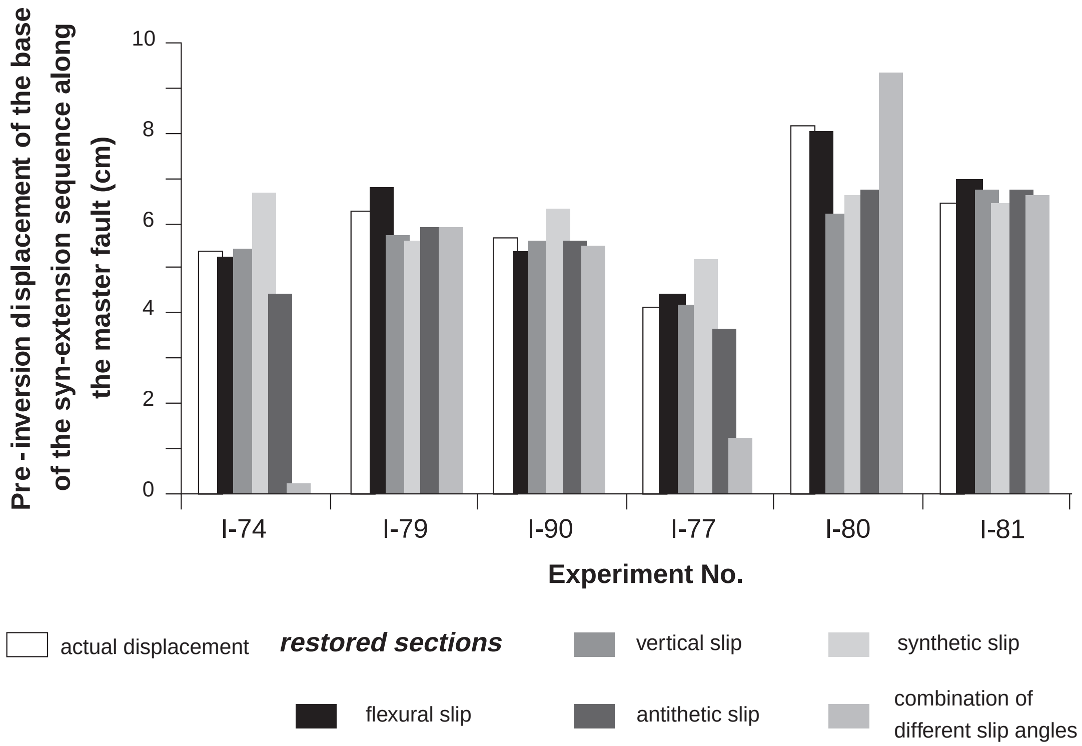

Fig. 5. Graph showing the pre-inversion displacement of the base of the syn-extension sequence along the master fault measured on the six physical models illustrated in Fig. 1 and on their restorations using different algorithms illustrated in Fig. 2.

Of these methods, the combined slip angle method gives the best results and the synthetic case shows the greatest departure from the actual geometry.

4.2. Master fault shape (listric/planar)

The experiments used to check the influence of the master fault shape in the different restorations are: I-74 (planar) and I-79 (listric) (Fig. 1a and b). Flexural slip restoration of the planar fault is less accurate than for the listric case because the detachment depth is clearly over-estimated (Fig. 2a and b). Vertical/oblique slip methods are also generally worse for planar faults, especially the combined method, which produces hangingwall geometries that are unacceptable. In most restorations of the planar fault experiment, beds' elevation and the length of the restored sections are more deviated from their actual disposition than in the listric fault restorations.

4.3. Master fault dip at the top of the rigid footwall (listric faults)

The experiments used to check this parameter are: I-79 (60º), I-80 (45º) and I-81 (80º) (Fig. 1b, e and f). Flexural slip restorations of experiments I-80 and I-81 are less accurate than for experiment I-79 because the detachment depths are more deviated (specially in experiment I-81) and hangingwall shear is more significant (specially in experiment I-81) (Fig. 2b, e and f). Vertical/oblique slip techniques give also the best results for experiment I-79 because the restorations of experiments I-80 and I-81 contain bed perturbations more significant than for experiment I-79. Of these techniques, the antithetic slip method is the best one for experiments I-80 and I-81, whereas the combined slip technique produces unacceptable geometries for the same experiments. It appears that increments in the master fault dip lead to increments in the restored section length. Thus, restored sections of experiment I-80 are clearly shorter (except for the restoration using the combined slip method) than the actual cross-section, restorations of experiment I-79 are slightly shorter, and restorations of experiment I-81 are substantially longer.

4.4. Detachment depth

The experiments used to check this parameter are: I-79 (shallow) and I-77 (deep) (Fig. 1b and d). Flexural slip restoration of the deep detachment model produces accurate results with reasonable hangingwall geometry, but the detachment depth is more deviated and hangingwall shear more significant than for the shallow detachment experiment (Fig. 2b and d). Vertical/oblique slip methods give worse results for the deep detachment experiment, mainly due to local anomalies close to the master fault tip, but they are also acceptable. Unlike the shallow depth experiment, the antithetic slip method gives the best restoration of the deep detachment experiment, and both the antithetic slip and the combined slip angle methods produce restored sections longer than the actual cross-section.

4.5. Coefficient of friction along the fault

The experiments used to check this parameter are: I-79 (low friction) and I-90 (high friction) (Fig. 1b and c). Flexural slip restoration of the high friction experiment is slightly less accurate than for the low friction experiment because the detachment depth is more deviated (Fig. 2b and c). Vertical/oblique slip methods are also worse for the high friction experiment. The combined slip technique gives unacceptable results for this experiment. The rest of these methods produce admissible results but the length of the restored sections, beds' elevation and geometry are more deviated from their actual disposition than in the low friction experiment.

4.6. Amount of inversion

To check this parameter two different inversion stages of experiment I-79 have been analysed: after 2.5 cm contraction, and after 4 cm contraction (Fig. 3). The flexural slip method gives excellent results in both cases, but hangingwall shear is greater and the detachment depth more deviated in the 4 cm contraction stage. Vertical/oblique slip restorations of this experiment are acceptable except for the combined slip case. However, they are worse than for the 2.5 cm contraction stage because both the length of the restored sections and beds' elevation are more deviated from their actual disposition. Deviation in beds' elevation is particularly notorious near the master fault tip.

4.7. Quantitative analysis

Measurement of the restored lengths of the top (or base) of the post-extension sequence shows that most results range between 12 and -4% of the actual lengths (Fig. 4). In general, the best algorithm is the flexural slip method, whereas the worst one is the combined slip method, which, except for experiment I-79, always over-estimates (sometimes significantly) the lengths. Of the different models, the listric fault with 80° dip at the top of the rigid footwall (experiment I-81) produces the worst results for all algorithms except for the flexural slip method.

Flexural slip method gives the most regular results in measurement of the displacement of the base of the syn-extension sequence along the master fault, always with small deviations from the actual displacement (Fig. 5). On the contrary, the combined slip method sometimes gives accurate results (experiments I-79, I-90 and I-81) and sometimes the more deviated ones (experiments I-74 and I-77).

4.8. General comments

Due to the assumptions and templates used in the restorations carried out by flexural slip (see Section 2.1), both the elevation and the horizontal disposition of the top (or the base in experiment I-90) of the post-extension sequence match with its actual elevation and disposition (Figs. 2 and 3).

In general, the flexural slip method appears to give the best results. In all the sections restored by flexural slip, the geometry of the rollover obtained corresponds quite well with its actual geometry (Figs. 2 and 3). Nevertheless, this method slightly over-estimates the detachment depth, and the vertical loose line located opposite the rigid footwall in the pre-inversion stage becomes a curved line after restoration. Although most of the contraction during inversion is accommodated by reverse faulting and folding, a certain amount may be accommodated by tectonic compaction of the sand. Thus, McClay (1995) documented that volume contraction occurs during early inversion stages. The curvature of the loose line opposite the rigid footwall in the restored cross-sections may be caused by heterogeneous tectonic compaction of the sand and also because small-scale contractional structures may have not been taken into account in the restorations. This suggests that the flexural slip method may accumulate errors when restoring sections involving series of faults. Tectonic compaction and no restoration of small-scale contractional structures may also explain the under-estimation of the cross-section length and shortening obtained in many sections restored by flexural slip (Figs. 2–4). Shortening under-estimations obtained in restorations of physical experiments of inverted extensional faults using the line-length method were previously documented by Eisenstadt and Withjack (1995).

The assumptions and templates used in the vertical/oblique slip restorations (see Section 2.2) cause both the depth and the flat-lying disposition of the detachment to coincide with its actual depth and disposition (Figs. 2 and 3).

Restorations carried out by vertical/oblique slip techniques are characterized by the presence of gentle to close folds deforming the hangingwall beds (Figs. 2 and 3). These irregularities are mainly located over the master fault tip and/or over the ramp-flat inflection point. Beds' elevation is over-estimated in all the vertical, antithetic and synthetic slip restorations (the most successful position is given by the antithetic slip restorations), whereas it is under-estimated in the restorations carried out using a combination of different synthetic and antithetic angles. The restored beds' irregularities and the incorrect beds' elevation are responsible for errors in the estimation of bed length and amount of shortening (Fig. 4). Thus, large anticlines coupled with significantly elevated beds produce under-estimations of bed length and shortening. In general, the antithetic slip method provides the best restored cross-sections, whereas the combined slip method produces the worst results (except for the case of experiment I-79) (Figs. 2 and 3).

5. Discussion

The accuracy of the restored cross-sections depends partially on how well the chosen restoration algorithms model the rocks' (in this case the sand) deformation (Rowan and Kligfield, 1989). Inaccuracies may occur because each restored cross-section has been obtained by applying a single restoration method, i.e., a specific deformation mechanism. However, in both physical experiments and in nature more than one deformation mechanism may act during tectonic inversion. Moreover, in restorations here using vertical/oblique slip methods, the slip orientation is constant. However, in both physical experiments and in nature the slip vector may not be uniform all over the section. In addition, there are limitations because of the necessary assumptions upon which the restoration techniques are derived. Thus, the techniques applied in this paper to restore the hangingwalls of 2D sandbox models of inverted extensional faults to their pre-inversion stage are based on geometric rules which do not take into account area variations caused by tectonic and weight compaction of the sand. The simulation of several deformation mechanisms, non-uniform slip vectors, and tectonic and weight compaction of the rocks would require more complex interactive algorithms, which are beyond the scope of this paper. In this sense, the restoration techniques used in this paper are linear transformations, and therefore, they cannot properly approximate to the non-deformed states (see Wickham and Moeckel, 1997).

The preliminary results achieved here should be extended only carefully to natural examples. Although many similarities between the experimental models of inversion used in this paper and some natural examples have been documented (e.g., McClay, 1995; Buchanan and Warburton, 1996), this does not imply that natural examples and experimental models are genetically comparable. For instance, only the behaviour of the hangingwall has been analysed because in the physical models used the footwall remains completely undeformed. However, in nature it may undergo deformation. Moreover, many natural extensional basins undergo transpressional or strike-slip inversion, and erosion and subsequent deposition. Often reconstruction of inverted basins requires additional techniques such as 3D restoration, and vitrinite reflectance and fission track analysis to obtain the amount of denudation and the timing of inversion and erosion (Hill and Cooper, 1996).

Assuming that the results derived from inverted physical models are applicable to natural inverted basins, this study shows that the flexural slip method is appropriate to restore sections across these areas to their pre-inversion stage. Nevertheless, inaccuracies in bed lengths and over-estimations of the detachment depth may occur as a consequence of the restoration methodology. In the case of inverted basins involving series of faults, accumulative errors in the restored bed lengths and fault shapes are expected because of the successive restoration of the movement along each fault. Vertical/oblique slip methods are acceptable only in some particular cases, and therefore, we disapprove the indiscriminate use of these techniques. Some inaccuracies in cross-sections restored by both flexural slip and vertical/oblique slip methods appear to be a function of the actual geometry of the faults, coefficient of friction along the faults and amount of inversion. Therefore, we propose an analysis of these parameters within the inverted basin and comparison to physical experiments to ascertain the magnitude of error. These restoration techniques, if properly used, are valuable tools to validate and/or modify interpretations in areas of inversion tectonics.

6. Conclusions

Several points arise from the restorations of physical experiments of inverted extensional faults to their pre-inversion stage carried out using flexural slip and vertical/oblique slip techniques with the aid of the software Geosec 2D:

(1) The flexural slip technique appears to be the best restoration method in all the experiments. Omissions and/or errors in the restoration of the movement along small-scale faults, coupled with tectonic compaction of the sand, may cause the curved pin lines, and under-estimations of beds length and shortening observed in most restorations. In all cases the detachment depth obtained using this method is slightly deeper than its actual position.

(2) In the restorations carried out using vertical/oblique slip techniques, beds' length and thickness differ more from the actual ones than in the flexural slip restorations. The hangingwall beds restored by vertical/oblique slip techniques exhibit irregularities (gentle to close folds) mainly located over the tip and/or over the ramp-flat inflection of the master fault. In general, the restorations more similar to the actual experiments result from the application of the antithetic slip method, whereas the worst restorations are the ones constructed using a combined slip angle method.

(3) The accuracy of the restoration techniques used in this research, and particularly the accuracy of the vertical/oblique slip methods, depends on the master fault shape (planar or listric), the master fault dip, the detachment depth, the amount of friction along the fault and the amount of inversion. The influence of the parameters related to the fault geometry, i.e., fault shape and dip, is more significant than the influence of the rest of parameters. All the parameters listed affect unequally some geometric elements such as bed length, amount of shortening estimated, detachment position and, in the restorations using vertical/oblique slip methods, bed irregularities and displacement along the master fault.

The main drawback of restoring physical experiments instead of natural examples is to what extent the experiments reflect the nature, so that the results obtained here should be cautiously applied to sections across natural inverted basins. Thus, some phenomena that often occur in natural examples, such as transpressional/strike slip inversion tectonics, erosion and subsequent deposition, footwall deformation, combination of different deformation mechanisms, non-uniform slip, and tectonic/weight compaction, have not been considered in these restorations.

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