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Journal of Structural Geology 28 (2006) 2038–2048

JOURNAL OF STRUCTURAL GEOLOGY

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Transpressional inversion in an extensional transfer zone (the Saltacaballos fault, northern Spain)

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Received 21 June 2006; accepted 23 June 2006
Available online 22 September 2006

Abstract

This paper deals with an extensional transfer zone and its main structure, the Saltacaballos fault, developed during Early Cretaceous times, and obliquely inverted during the Alpine shortening.

Geological mapping and structural analysis were carried out to determine the kinematic history of the deformation. The Saltacaballos ridge is the relay zone between two major and conjugate normal fault systems: the Bilbao and the La Granja-Samano fault systems. Three distinct phases in the structural evolution of this transfer zone can be identified. (1) During the initial stages of extensional deformation, shallow-water marine limestones were deposited on the relay ridge and deep-water marls on the flanking depocenters. At the same time, submarine landslides developed on paleoslope generated either by normal drag or by a fault-propagation fold related to the Saltacaballos normal fault. (2) With increasing displacement, normal faults antithetic to the Saltacaballos fault were developed probably in response to the collapse of its hanging-wall. (3) During the subsequent Alpine compressional stage, these normal faults were reactivated as dextral strike-slip faults as a result of transpressional inversion, whereas previous extensional fault-related folds were tightened. At the same time, some normal faults were overturned as a consequence of passive rotation in fold limbs.

Keywords: Extensional transfer zone; Extensional fault-propagation fold; Slumping; Transpressional inversion tectonics; Fault reactivation; Basque-Cantabrian basin

1. Introduction

Most research on inversion tectonics focuses on cases in which extension and compression directions are similar and oriented perpendicular to the extensional fault trends. This is the case for many conceptual and geometrical models (Bally, 1984; Williams et al., 1989), natural examples (Gillcrist et al., 1987; Butler, 1989; Cartwright, 1989; Bishop and Buchanan, 1995; Dart et al., 1995; Kelly et al., 1999), and analogical models (McClay, 1989; Buchanan and McClay, 1991; McClay and Buchanan, 1992; Eisenstadt and Withjack, 1995; Keller and McClay, 1995). Most studies on inversion tectonics where compression direction is oblique to the extensional fault trends present analogical models (Brun and Nalpas, 1996; Yamada and McClay, 2004; Panien et al., 2005) but there are relatively few field-based studies about the inversion of oblique structures (e.g. Casas-Sainz, 1993; Sinclair, 1995; Thomas and Coward, 1995). In this paper we will use the term transpressional inversion for this process.

In the present study we examine fault inversion structures located in the Basque-Cantabrian region of northern Spain (Fig. 1a). The main extensional fault studied here has a trend oblique to the compression direction. This structure, named the

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0191-8141/$ - see front matter © 2006 Published by Elsevier Ltd.
doi:10.1016/j.jsg.2006.06.013

Saltacaballos fault, is located in Spain's northern coast and can be considered as a transfer-type fault displaying a N-S trend, oblique to the main faults of the area, the Bilbao fault and the La Granja-Samano fault system (Figs. 1b and 2). The latest faults display a NW-SE trend, perpendicular to the main SW-NE extensional direction in the region (Cámara, 1997; García-Mondéjar et al., 2004; Pujalte et al., 2004) (Fig. 2a). The shortening direction that reactivated the Saltacaballos fault and the other faults of the area also had SW-NE orientation (Gómez et al., 2002) (Fig. 2b). These extension and shortening directions have been estimated at neighbour zones to the study area by fault population analysis (Lepvrier and Martínez-García, 1990; Cuevas et al., 1998, 1999; De Vicente et al., 2004).

The studied structures are especially well exposed in the cliffs of the coast. A continuous 2-km-long cross-section of the hanging-wall and foot-wall blocks of the Saltacaballos fault is preserved here, whose structural description and kinematic character are presented in this paper. The field structural data will serve as basis for the proposed model of extension and transpressional inversion, which will be compared with other natural examples.

2. Geological setting

The study area lies on the NE limb of the Bilbao anticline, which is a major structure in the Basque-Cantabrian region. The main sedimentary sequence was deposited in a rift-basin during the Late Jurassic-Early Cretaceous extensional phase, related to the opening of the Bay of Biscay-North Atlantic ocean (Le Pichon et al., 1971; Malod and Mauffret, 1990; Roests and Srivastava, 1991). In this extensional phase of basin development, a succession up to 8000 m thick was deposited in response to crustal stretching. During Late Cretaceous-Cenozoic times, the tectonic regime changed to a compressional one. This change was due to the African plate drifting northwards causing the Iberian microplate to collide against Europe, generating the Cantabrian-Pyrenean orogenic belt in northern Spain (Williams and Fischer, 1984; Muñoz, 1992; Pedreira et al., 2003). During this collision event, the Basque-Cantabrian extensional basin was inverted and many of the original normal faults were reactivated. At the same time, NW-SE trending thrusts and folds, including the Bilbao anticline, were developed.

The rocks outcropping in the study area are Early Cretaceous in age and belong to the Urgonian Complex (Rat, 1959; García-Mondéjar, 1990; Rosales, 1995) (Fig. 1b). This complex is made up of marine sediments and displays important facies and thickness changes within its different units, related to faulting and basin architecture. In the coastal section studied, there are two types of rocks: shallow water massive/tabular platform limestones and deeper water marls and marly-limestones with interbedded slump deposits (Fig. 3) (Rosales, 1999).

3. Transfer structure: the Saltacaballos fault

The Saltacaballos fault can be considered as a transfer structure that accommodates the strain between the two main fault systems of the zone: the Bilbao fault and the La Granja-Samano system (Fig. 2a). Thus, both the Saltacaballos fault and its related structures were developed in an overlapping convergent conjugate transfer zone as defined by Morley et al. (1990). The difference in trend between the Saltacaballos fault and the other regional structures has been recognized in previous studies (Rat, 1959; Foyo Marcos, 1978; Quintana, 1998; Rosales, 1999), which attribute an important paleogeographic and structural role to this fault.

The structure of the Saltacaballos transfer zone is shown in the current section (Fig. 1c) and in a restoration previous to the Alpine shortening (Fig. 1d). During the Early Cretaceous, the Saltacaballos fault was a steep dip-slip normal fault, dipping to the E. In this extensional stage, a ridge developed in the overlapping convergent conjugate transfer zone and controlled the sediment deposition. Platform limestones were deposited on the ridge, located at the foot-wall block of the Saltacaballos fault, whereas deeper water basinal marls and marly-limestones were accumulated on the adjacent depocenters (Fig. 1d). During the Alpine inversion, the Saltacaballos fault exerted a strong control on the deformation process. Its steep dip possibly prevented its reactivation as a reverse fault in its upper part. The shortening was thus accommodated by folds of slight W vergence. The axes of these folds plunge between 10° and 35° N-NW (Fig. 1b). Other structures that accounted for part of the shortening are cleavage, mainly developed in the folds hinge zones and short-cuts structures (Fig. 1c) (Quintana, 1998).

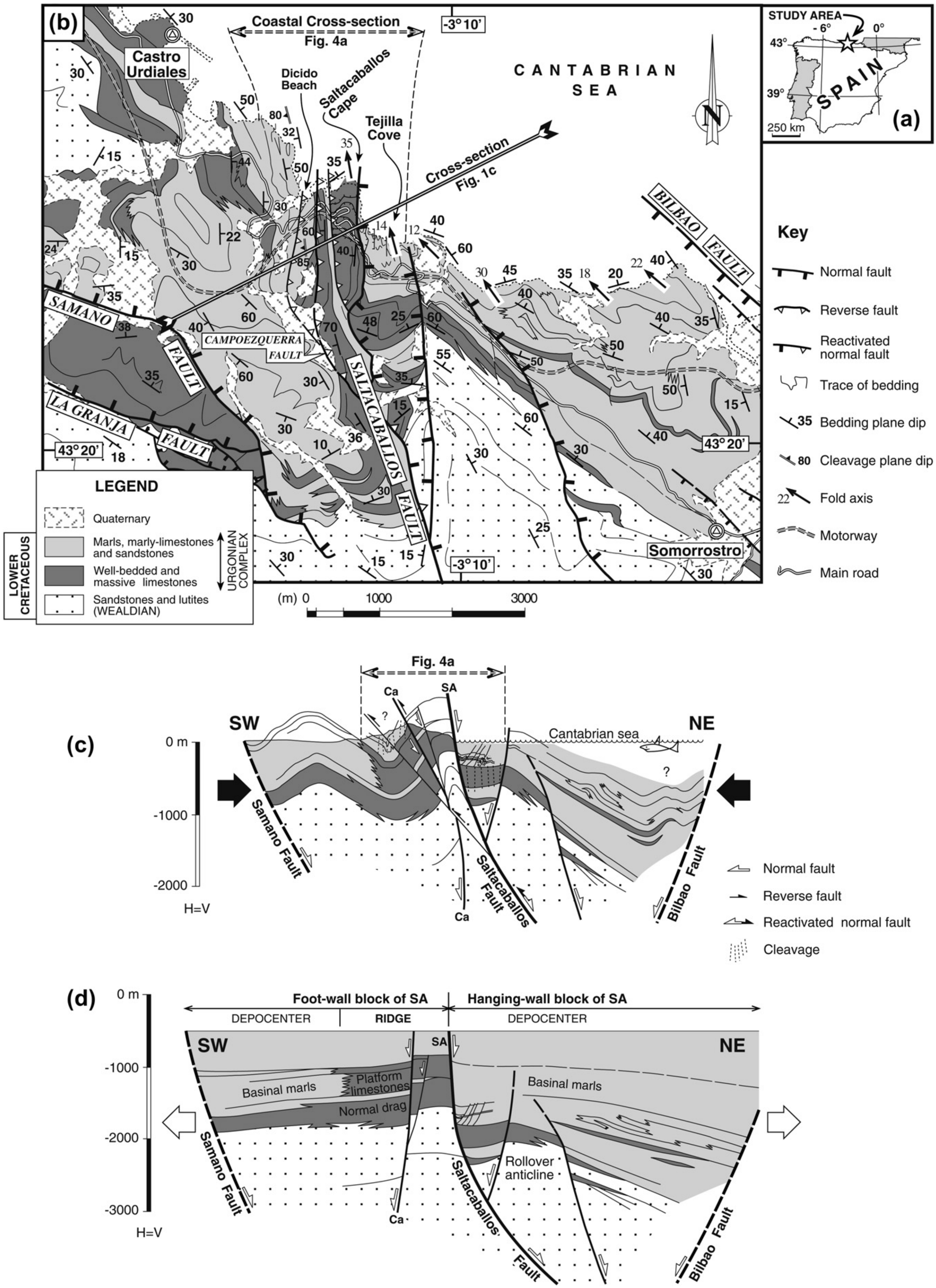
3.1. Hanging-wall structure: Tejilla Cove

The hanging-wall block structure of the Saltacaballos fault has been studied in the cliffs of the Tejilla Cove where a homogeneous sequence of marls and marly-limestone with slumps outcrops (Fig. 3). The development of folds and many faults on this block records higher deformation than in the rest of the section (Fig. 4a). Thus, to better understand these structures, we have made a more detailed section of the coastal cliffs in the immediate hanging-wall of the Saltacaballos fault (Fig. 4c). In this section four main faults, antithetic with the Saltacaballos fault can be observed. These faults display apparent normal-type displacements, e.g. West Wall, East Wall and Abrigo faults, and apparent reverse-type displacements: Corredor fault (Quintana, 2002). Apart from these four major faults and related minor faults, there are another minor faults, in the western most area, which are related to slump development (Figs. 3, 4c and 5).

In the section we can also see an important shortening near the Abrigo fault, deduced from the folds with interlimb angles close to 90°, and cleavage developed in the hinge zones. The folds of the Tejilla Cove display trends and axial plunges similar to those of the Abrigo anticline (Fig. 4d), east-verging and with their axes plunging 15° to the N.

3.2. Foot-wall structure: Campoezquerra faults and Dicido Beach

The foot-wall block of the Saltacaballos fault is folded by the Dicido syncline and by the La Ponderosa anticline. The


(b)
Coastal Cross-section
Fig. 4a
-3° 10'
Castro Urdiales
Dicido Beach
Saltacaballos Cape
Tejilla Cove
CANTABRIAN SEA
Cross-section Fig. 1c
BILBAO FAULT
SAMANO FAULT
CAMPOEZQUERRA FAULT
SALTACABALLOS FAULT
LA GRANJA FAULT
43° 20'
Somorrostro
STUDY AREA
- 6°
0°
43°
39°
SPAIN
250 km
(a)
Key
Normal fault
Reverse fault
Reactivated normal fault
Trace of bedding
35 Bedding plane dip
80 Cleavage plane dip
22 Fold axis
Motorway
Main road
LEGEND
Quaternary
Marls, marly-limestones and sandstones
Well-bedded and massive limestones
Sandstones and lutites (WEALDIAN)
LOWER CRETACEOUS
URGONIAN COMPLEX
(m) 0 1000 3000
(c)
Fig. 4a
SW
NE
Ca
SA
Cantabrian sea
0 m
-1000
-2000
H=V
Samano Fault
Saltacaballos Fault
Bilbao Fault
Normal fault
Reverse fault
Reactivated normal fault
Cleavage
(d)
Foot-wall block of SA
Hanging-wall block of SA
DEPOCENTER
RIDGE
DEPOCENTER
SW
NE
SA
Basinal marls
Platform limestones
Normal drag
Basinal marls
Rollover anticline
0 m
-1000
-2000
-3000
H=V
Samano Fault
Ca
Saltacaballos Fault
Bilbao Fault

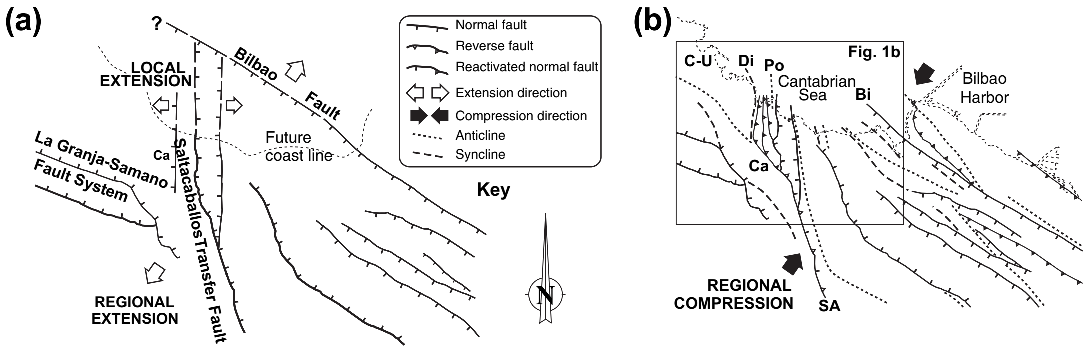


Fig. 2. (a) Plan view reconstruction of the main normal faults of the area during the extensional stage in Early Cretaceous times. Notice the regional SW-NE extension direction orthogonal to the main faults: Bilbao and La Granja-Samano, and the local W-E extension in the Saltacaballos transfer zone. Ca: Campoezquerra fault. (b) Structural map of the Saltacaballos area and surroundings. Di: Dicido syncline; Po: La Ponderosa anticline; SA: Saltacaballos fault; Bi: Bilbao fault; C-U: Castro Urdiales Village. Notice the regional SW-NE compression direction. Location of the Fig. 1b is indicated.

most outstanding structures in this area are faults developed in the common limb of this fold pair (Fig. 4a). These are high angle reverse faults, dipping to the E that we have called Campoezquerra fault system. In this area fold axes plunge 35° to the N (Fig. 1b). To the W there are minor folds in the core of the Dicido syncline, developed in marly-limestones, with interlimb angles close to 90° and axial-planar cleavage (Fig. 4a). The axes and intersection lineations between bedding and cleavage of these folds plunge from 5° to 40° to the NNW (Fig. 4b).

4. Kinematic analysis

In the Tejilla Cove section (Fig. 4c) and in the general coastal section (Fig. 4a), the faults display both normal and reverse apparent displacements. In order to understand the kinematics of these faults we have studied the fault plane fibres and striations (Fig. 4b,d). The sense of movement has been estimated from en-échelon shear veins, releasing steps with fibrous calcite in fault planes, and from asymmetric structures in shear zones (Fig. 6).

4.1. Faults in the hanging-wall block of the Saltacaballos fault: Tejilla Cove

The major faults of the Tejilla Cove, with NNE trend, present two orthogonal fibre systems with E-W and N-S orientation. The fibres record, first, a normal dip-slip movement, with a slight sinistral component. Subsequently, a dextral strike-slip movement with a minor normal or reverse component occurred (Figs. 4d and 6a,b). The timing relationship between normal and strike-slip movements has been stated from the fact that strike-slip striations locally overprint dip-slip fibres.

The low-angle slump-related faults of the Tejilla Cove display more diverse attitudes than those of the major faults, with trends ranging from NNE to ENE and dipping towards the NW. These faults present a fibre system with W-E orientation and oblique reverse movement (Figs. 4d and 5).

4.2. Faults in the foot-wall block of the Saltacaballos fault: Campoezquerra faults

The Campoezquerra faults system presents a NNW trend and most of the faults only display fibres with W-E orientation, except for the main fault that we will named Campoezquerra fault. This main fault has a second system of N-S oriented fibres (Fig. 4b). The orientation of these two systems is similar to that of the Tejilla Cove, although in the Campoezquerra fault both senses of movement are oblique reverse: the W-E fibres record sinistral movement, while the N-S fibre system indicates dextral movement. The timing relationship between the two fibre systems could not be stated, although by comparison with the Tejilla Cove, the W-E system is though to have played before the N-S system.

5. Alpine retrodeformation

Fig. 7a presents a 2½ D model and Fig. 7b shows a plan view of the current attitudes of the structures and their kinematic elements. The plunging to the N displayed by the fold axes is highly systematic throughout the area and can be interpreted as a late attitude resulting from tilting of the northern limb of the major Bilbao anticline. This tilting has to be removed in order to restore the extensional and early compressional stages. Accordingly, retrodeformation using the N-120°-E rotation axis of the Bilbao anticline was carried out. After rotation, the trend of the Tejilla major faults gets closer to the N, whereas the slight

Fig. 1. (a) Location of the study area in northern Spain. (b) Geological map of the Saltacaballos area. Notice the N-S trending of the Saltacaballos fault and related structures, located between the NW-SE trending Bilbao fault and La Granja-Samano faults. Location of the Figs. 1c and 4a is indicated. (c) Geological cross-section of the Saltacaballos transfer structure. Ca: Campoezquerra fault; SA: Saltacaballos fault. (d) Restoration of the section 1c in Late Albian times (Early Cretaceous). Notice the facies distribution controlled by the ridge located in the central part of the transfer zone: platform limestones developed on the ridge and basinal marls on the flanking depocenters. Note also the folds developed during the extensional stage: rollover anticline in the hanging-wall of the Saltacaballos fault, and the normal drag syncline in the hanging-wall of the Campoezquerra fault.

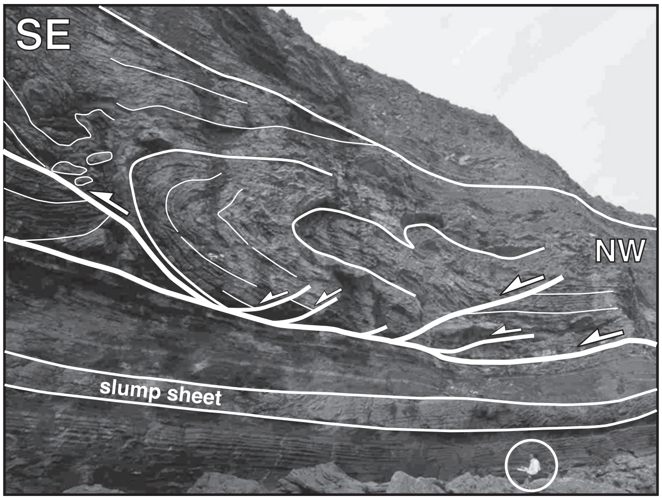


Fig. 3. Major slump developed in marly-limestones in the western cliffs of the Tejilla Cove. Notice the reverse fault developed in the foremost part of the slumped fold and the normal faults developed in its rear part respectively (for location, see Fig. 4c).

normal component of the N-S fibres either disappears or become reverse and the minor oblique sinistral component of the west-plunging fibres also disappears (Fig. 7c,d). Furthermore, the SW-NE trend of the low-angle slump-related faults changes into N-S and their oblique reverse movement becomes a dip-slip movement (Fig. 7e).

The Campoezquerra fault represents a more complex case of restoration because, apart from being affected by late tilting of fold axes, Alpine folding overturned this structure. This fault is now reverse and dips to the E (Figs. 4a and 7a), but becomes a west-dipping normal fault when the common limb of the La Ponderosa and Dicido folds (Fig. 7a) is restored to a subhorizontal attitude (Fig. 7f). The restoration is consistent with the facies distribution controlled by the ridge of the transfer zone during the extensional stage, when a local depocenter was developed on the west side of the ridge (Quintana, 1998) (Fig. 1d). Fig. 7c shows a plan view in which the late Alpine structures have been retrodeformed.

6. Structural evolution model of the Saltacaballos transfer zone: discussion

The proposed structural evolution of the Saltacaballos transfer zone is displayed in the sequential diagram of Fig. 8. The first two stages (Fig. 8a,b) show the development of the Early Cretaceous extensional structures, while the third presents the results of the Alpine compressional stage (Fig. 8c).

We propose normal drag or a monocline fault-propagation fold related to the Saltacaballos fault at the beginning of the extensional stage, giving rise to a paleoslope dipping in the same sense as the Saltacaballos fault (Fig. 8a), consistent with the transport sense of the slump masses (Figs. 3 and 5).

As rifting progresses and fault displacement increases, strata rotate until reaching a dip in opposite sense to the Saltacaballos fault. At the same time antithetic normal faults develop in the hanging-wall block of the Saltacaballos fault and truncate the slump sheet (Figs. 8b and 4c). Similar examples of normal drag or forced folds are common in classical areas of extended terranes as Gulf of Suez (e.g. Patton, 1984; Sharp et al., 2000; Khalil and McClay, 2002) Norwegian margin (e.g. Withjack et al., 1989; Corfield and Sharp, 2000) or Rhine Graben (Laubscher, 1982; Maurin, 1995), and have been modelized in different experiments (Withjack et al., 1990; Withjack and Callaway, 2000; Hardy and McClay, 1999). However there are relatively few studies about extensional fault propagation and synrift sedimentation; Gawthorpe et al. (1997) show the development of two synrift wedges with opposite divergence in a Gulf of Suez example: in the first wedge, strata thin towards the fault zone whereas in the second one, strata thickens into the fault. This case is similar to the synrift sedimentation in the hanging-wall block of the Saltacaballos fault, in which a paleoslope dipping in the same sense as the fault is developed in a first stage (Fig. 8a) whereas in a second stage the strata of the paleoslope rotate and reach a dip in opposite sense to the fault (Fig. 8b). However our interpretation is different than the one of Gawthorpe et al. (1997) because they relate the change of wedge divergence with the surface break by a planar propagating normal fault, whereas we explain the change of dip of the strata and the antithetic normal faults as a consequence of hanging-wall collapse related to the listric geometry of the Saltacaballos fault at depth.

During the subsequent Alpine transpressional stage the normal faults were reactivated as dextral strike-slip faults (Fig. 8c), and the extensional-related previous folds were tightened. Thus the normal drag in the hanging-wall block of the Campoezquerra fault (Fig. 8b) gave rise to the Dicido syncline (Fig. 8c). The tightening of this fold and the La Ponderosa anticline produced a passive overturning of the Campoezquerra fault, which changed from a west-dipping attitude during the extensional stage (Fig. 8b) to an east-dipping attitude after limb rotation (Fig. 8c). As the shortening progressed, short-cuts could have been developed (Fig. 8c). Similar overturned normal faults have been described in other inversion zones such as the Suez Gulf (Knott et al., 1995), or the Rocky Mountains (McClay et al., 1989; McClay and Buchanan, 1992). In this last example, normal fault rotation is caused by a propagating thrust in the foot-wall block, but in the Saltacaballos area, the Campoezquerra overturned normal fault can be explained by the passive rotation of the fault during fold tightening (Quintana et al., 2004).

We propose an orthogonal extension for the Saltacaballos fault and related minor faults, with normal dip-slip movement during the extensional regime (Fig. 8a,b). This implies local W-E extension during the Early Cretaceous in the relay ridge between the La Granja-Samano fault system and the Bilbao fault (Fig. 2a). During the Alpine compression, most of the faults were reactivated as dextral strike-slip faults with a slight reverse component. The N-S trending of these faults and their kinematic vectors might imply that the Alpine compression direction is approximately SW-NE (Fig. 8c), consistent with the regional compression direction (Fig. 2b).

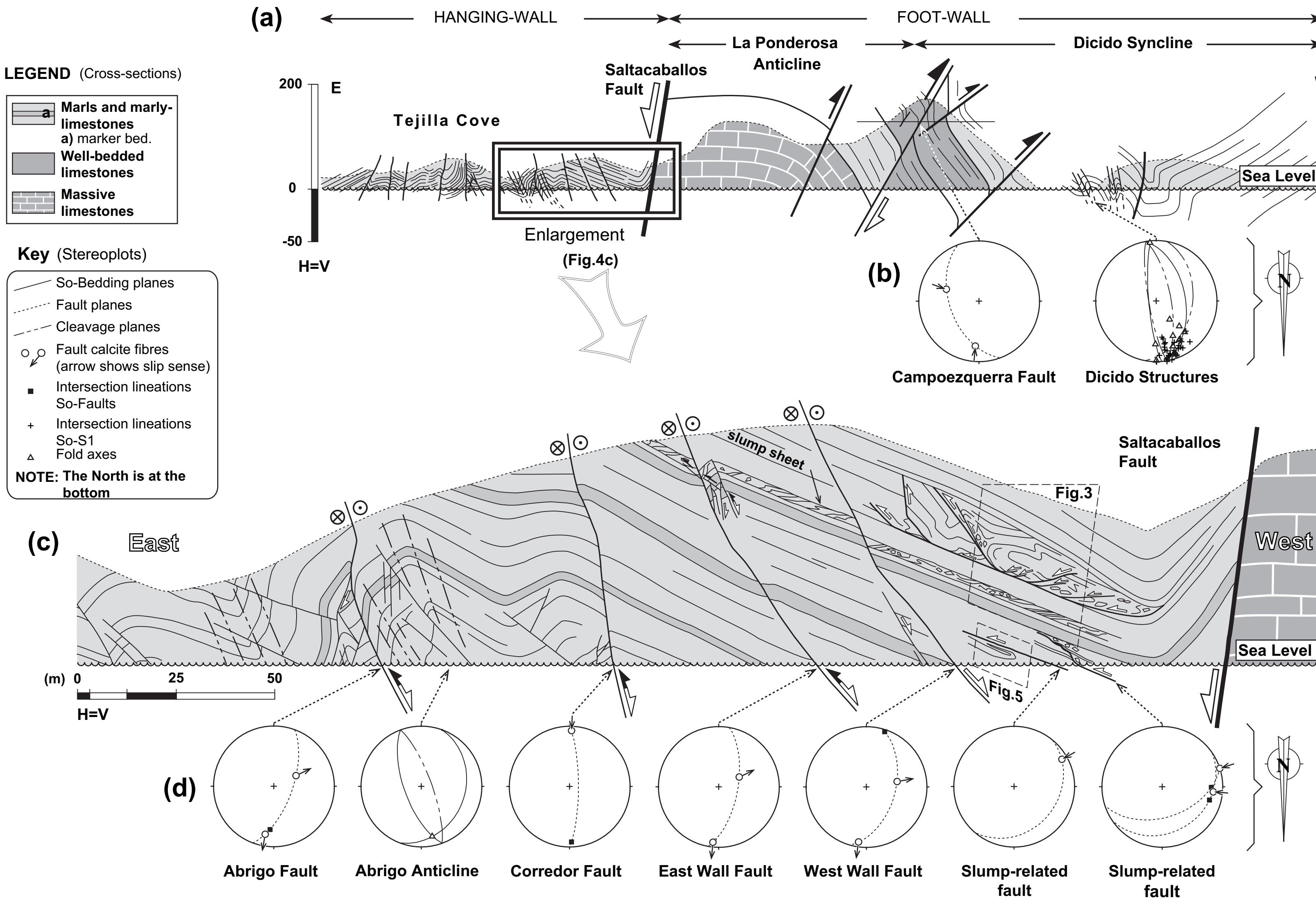


Fig. 4. (a) Coastal cross-section of the hanging-wall and foot-wall blocks of the Saltacaballos fault (for location, see Fig. 1b,c). The movement sense of the faults is apparent. Rectangle indicates location of Fig. 4c. (b) Equal area stereoplots showing different structural elements of the Campoezquerra fault and the Dicido syncline. (c) Detailed structural section of the western Tejilla Cove cliffs. The main Tejilla faults display apparent normal or reverse movements and dips in a sense opposite to the Saltacaballos fault. In the western part of the section there are slump structures with related faults. Notice the slump sheet truncated by the West and East Wall faults. Location of the Figs. 3 and 5 are indicated. (d) Equal area stereoplots showing kinematic indicators of the Tejilla faults and other structural elements. The main faults record two subsequent movements: normal and dextral strike-slip.

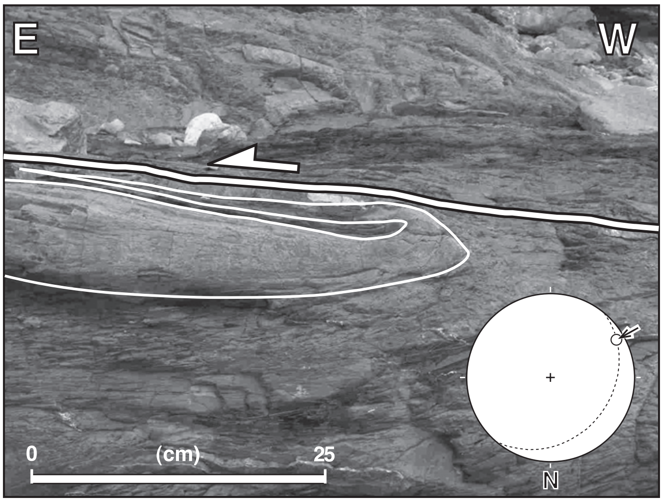


Fig. 5. Low-angle reverse fault and related slump syncline (for location, see Fig. 4c). The equal area stereoplot show the fault kinematics. The N is at the bottom in the stereoplot.

7. Conclusions

During the Early Cretaceous extensional phase, the Saltacaballos area was a transfer zone between two major and conjugate normal fault systems: the Bilbao and the La Granja-Samano fault system. In this stage shallow-water marine limestones were deposited on the interbasinal relay ridge and deep-water marls on the flanking depocenters. The Saltacaballos fault was the main fault in the transfer zone and its hanging-wall block was the most subsident depocenter of the area. During the subsequent Alpine shortening, the Saltacaballos transfer zone underwent oblique inversion.

On the basis of geometric superposition of different structures and of the kinematic analysis of the faults, we have established the following events for the evolution of the Saltacaballos transfer zone.

(1) The first event was the development of submarine slumps, and related reverse faults, in the hanging-wall block of the Saltacaballos synsedimentary normal fault. This is consistent with a slope dipping in the same sense as the fault produced either by normal drag or by a fault-propagation fold related to the buried extensional Saltacaballos fault.

(2) As fault displacement increases, antithetic normal faults were developed in the hanging-wall block of the Saltacaballos fault possibly as a consequence of hanging-wall collapse related to the listric geometry of the Saltacaballos fault at depth. These normal faults display dip-slip striations recording a local W-E extension direction in the transfer zone, orthogonal to the Saltacaballos fault. This direction contrasts with the regional SW-NE extension direction in the Basque-Cantabrian basin during Early Cretaceous times.

(3) The third event was a transpressional inversion during the Alpine shortening. In this stage, the previous normal faults were reactivated as dextral strike-slip faults, sometimes with a slight reverse component. This implies a SW-NE compression direction, similar to the regional compression direction. In this compressional stage, previous extensional folds were tightened and some normal faults were overturned as a consequence of passive rotation in the fold limbs.

Acknowledgements

This work is part of Luís Quintana's Ph.D. Thesis Project (funded by the Instituto Geológico y Minero de España) and based on the poster presented at the Inversion Tectonics Symposium of the 32nd International Geological Congress, Florence 2004. R.E. Holdsworth and Josep Anton Muñoz are thanked for their very helpful reviews that led to a significant improvement of the manuscript. We gratefully acknowledge the careful work on the figures of Inmaculada Carmena and the field assistance of Álvaro Cuesta. Drs. Luís González Menéndez, Ana Ojanguren and Jorge Gallastegui are thanked for reviewing the English version of the manuscript.

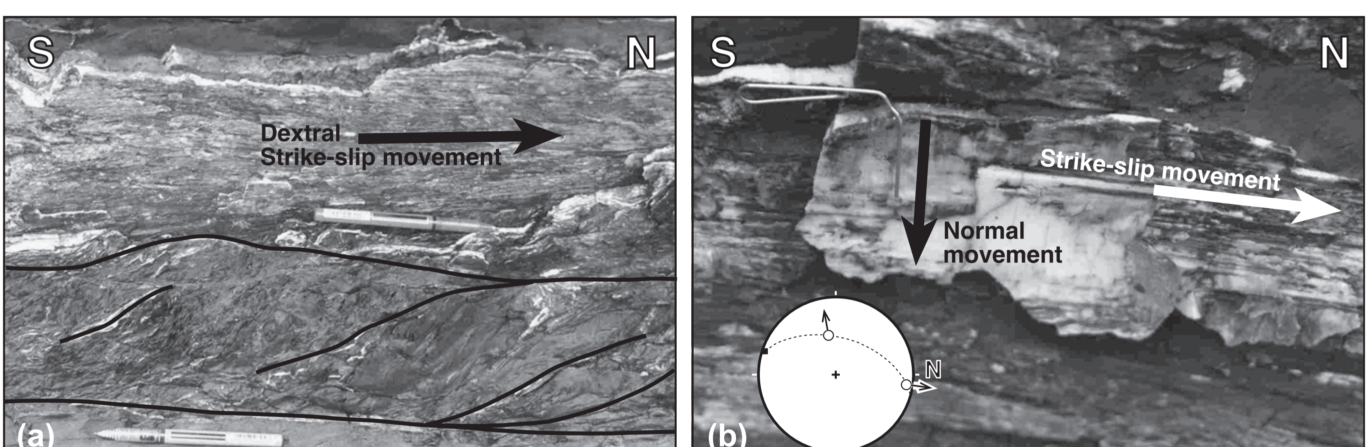


Fig. 6. Kinematic indicators in the West Wall fault. (a) Subhorizontal fibrous calcite on early normal fault plane reactivated as strike-slip fault (upper part of the photo). The movement sense has been estimated from the asymmetric structures in the lower part of the photo. (b) Two orthogonal calcite fibre systems indicating normal and strike-slip movement in the same fault plane. The equal area stereoplot shows the orientation of the fault plane and the sense of movement of the two calcite fibre systems. The N is to the right in the stereoplot.

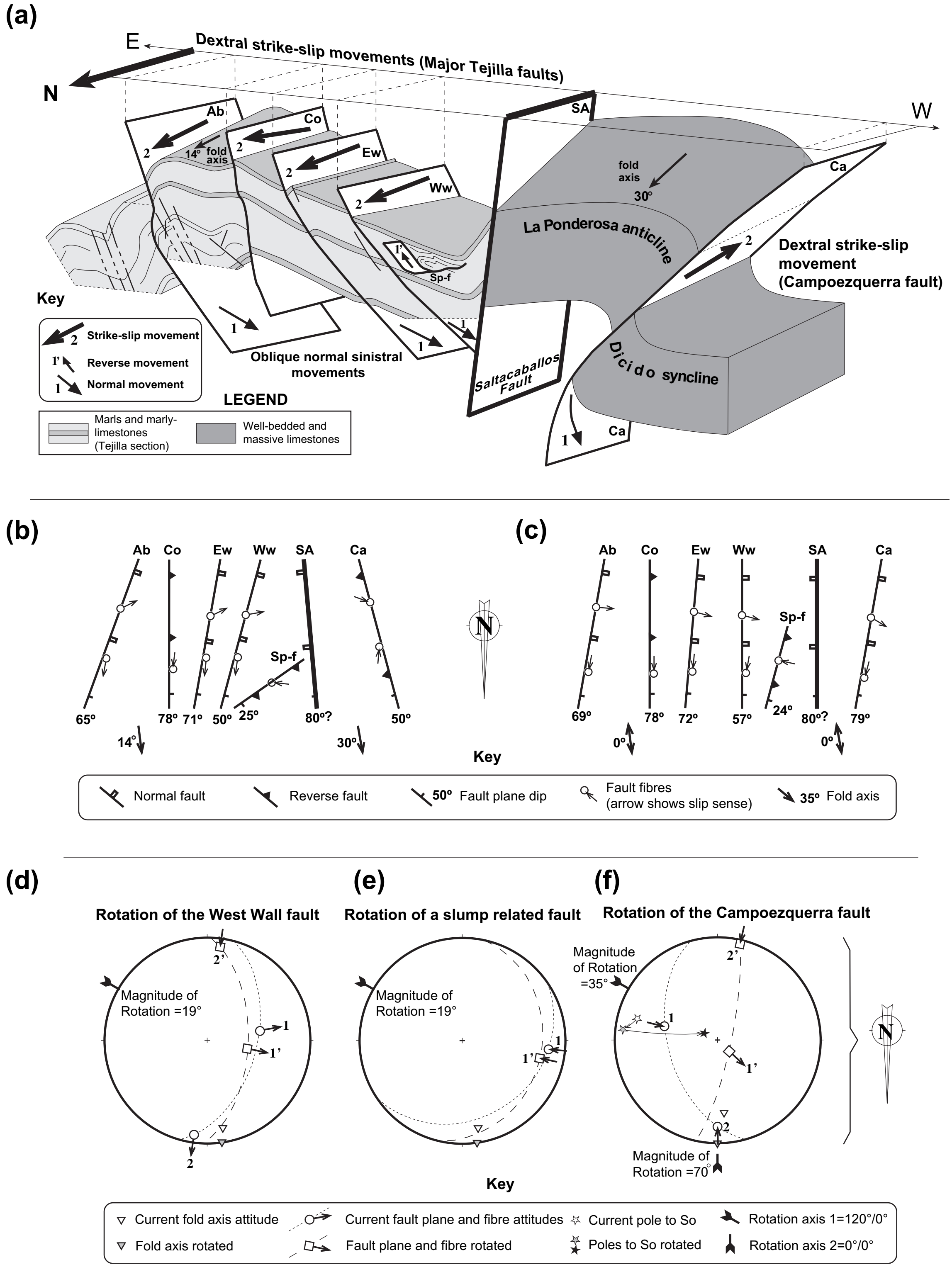


Fig. 7. 2½ D model (a); and plan view (b) of the hanging-wall and foot-wall blocks of the Saltacaballos fault. The major Tejilla faults display oblique normal sinistral movements and dextral strike-slip movements (normal and reverse). Notice the fold axes plunging to the N. Ca: Campoezquerra fault; SA: Saltacaballos fault; Sp-f: Low-angle slump-related fault; Ww: West Wall fault; Ew: East Wall fault; Co: Corredor fault; Ab: Abrigo fault. (c) Plan view of the main faults in the study area with the partial Alpine (SA, Sp-f, Ww, Ew, Co and Ab) and complete Alpine (Ca) deformation removed. The N is downwards in the plan views. 2½ D model and plan views not to scale. (d, e, f) Equal area stereoplots showing the retrodeformation of the Alpine deformation: (d, e) retrodeformation of the fold axes plunge in a major Tejilla fault, and in a slump-related fault: (f) Alpine retrodeformation of the Campoezquerra fault. Notice that in the extensional stage this fault could have been a normal fault dipping to the W.

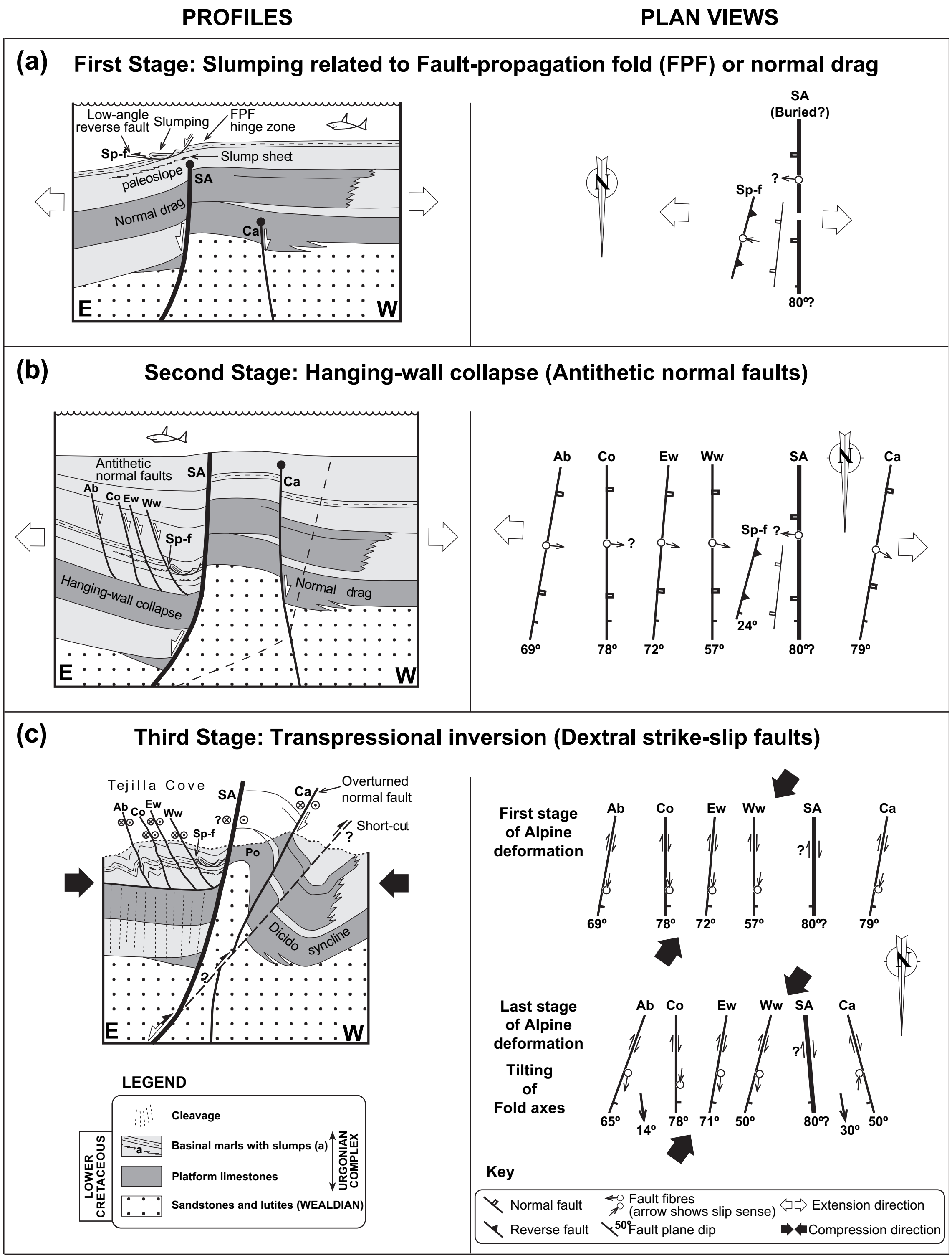


Fig. 8. Proposed evolution of the Saltacaballos transfer structure shown in profile (left) and in map view (right). Not to scale. (a) First stage: slumping related to normal drag or a fault-propagation fold above the Saltacaballos normal fault. (b) Second stage: antithetic dip-slip normal faults related to collapse of the hanging-wall block of the Saltacaballos fault. Notice the local W-E extension direction (c) Third stage: reactivation of the normal faults as dextral strike-slip faults, tightening of previous extensional fault-related folds and overturning of the Campoezquerra fault. The reverse movements in profile are apparent. Notice the regional SW-NE compression direction. Ca: Campoezquerra fault; SA: Saltacaballos fault; Sp-f: Low-angle slump related fault; Ww: West Wall fault; Ew: East Wall fault; Co: Corredor fault; Ab: Abrigo fault; Po: La Ponderosa anticline.

Stereographic projections have been made with the 6.3.0X version of Stereonet program by Richard Allmendinger. Also supported by the Consolider–Ingenio 2010 Programme, under project CSD2006–0041, TopoIberia.

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