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Aspects and origins of fractured dip-domain boundaries in folded carbonate rocks

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ABSTRACT

We present comparative field studies in folded areas (Southern France, Moroccan Western Atlas and Abruzzo, Italy) giving new insights into fracture distribution within folded rocks of the shallow brittle crust. We show that the curvature in folds formed in brittle mechanical units is usually accommodated by multiple “dip-domain boundaries” (appearing as curvature discontinuities at fold scale) corresponding to relatively narrow and dense fracture zones, striking parallel or slightly oblique to the fold axis. They separate “dip-domains” where curvature is absent or moderate. It is shown that the dip-domain boundaries (which are obvious in the case of kink folds or box-fold anticlines) are currently present as multiple subtle hinges even when the curvature appears continuous at first sight. The nature of dip-domain boundaries is studied: they often cut through the whole thickness of the mechanical units. Their internal structure varies, and a non-exhaustive typology is proposed. For each type, an interpretative kinematic scenario shows how the dip-domain boundaries could initiate and develop. We suggest two kinds of origins: (1) they could correspond to the reactivation of inherited, along-strike fracture zones (opening-mode fracture concentrations such as big joints, fracture corridors, inherited faults, etc.); (2) they could be created as mechanical instabilities during the fold formation (syn-folding origin), in particular through small reverse faults. In both cases, early zones of weakness localize the dip-domain boundaries, and control the increase in curvature in association with increasing fracture density within the boundary. Because they represent well-defined vertically and axially persistent sub-seismic fracture zones generally limited to the thickness of the folded unit, dip-domain boundaries could enhance the axial permeability of folded and fractured reservoirs.

1. Introduction

Folds, which are very common expressions of rock deformation in the Earth’s crust, have been extensively studied both as geometrical objects (Ramsay, 1967; Suppe, 1985) and as elements of the mechanical and structural evolution of orogens (Price and Cosgrove, 1990). In folds developed in competent lithologies in the upper part of the Earth’s crust, some of the folding strain is often accommodated by fractures. The timing and distribution of these fractures can have a significant influence on the final fold geometry, in particular, whether the fold develops a continuous or discontinuous curvature. In tri-axial buckling experiments with multi-layered paraffin, Bazalgette (2004) and Bazalgette and Petit (2007) produced folds with discontinuous curvature. During these experiments, the spontaneous formation of localized fracture zones caused the folds to divide into a series of planar dip-domains (Suppe, 1983), each separated by a series of “articulations” (Bazalgette, 2004) or “dip-domain boundaries” (Bazalgette and Petit, 2007). The dip-domain boundaries were essentially composed of opening mode fractures, the formation of which ultimately controlled the evolution of the fold geometry and led to the discontinuous fold curvature. Interlayer friction, layer thickness and confining pressure were shown to have a strong influence on the geometry of the experimental folds, and although a wide range of structural geometries was created, all of the folds exhibited discontinuous curvature.

If natural folds develop in a manner similar to the experiments above, then there are significant implications for hydrocarbon exploration and production in folded and fractured reservoirs. Assuming that dip-domain boundaries are zones of intense fracturing and potential high fracture connectivity, they could behave as high permeability drains in folded and fractured reservoirs. Therefore, dip-domain boundaries would need to be explicitly included in fractured reservoir models (e.g., Rawnsley and Wei,

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2001; Rawnsley et al., 2004; De Keijzer et al., 2007) because their presence might significantly impact well performance or the potential for early water breakthroughs. However, and before this can be done, we need a clear understanding of the distribution and internal organization of fractures, and in particular, fractured dip-domain boundaries in folded structures.

A variety of conceptual models for fold-related fracture distributions have been published since the late 1960s, most based largely on the mechanical interpretation of folded and fractured outcrops (Price, 1966; Stearns, 1964; Stearns and Friedman, 1972; Price and Cosgrove, 1990). These works primarily focused on the geometry of fold-related fracture networks. More recent work has emphasized the importance of reactivated and inherited fractures (Guiton et al., 2003; Bergbauer and Pollard, 2004; Bellahsen et al., 2006), as well as the progressively evolving geometry of folds (e.g., Fischer and Wilkerson, 2000). Fold-related fracture prediction has been further enhanced by kinematic and mechanical restorations (e.g., Salvini and Storti, 2001; Maerten and Maerten, 2006), as well as curvature analysis (e.g., Lisle, 1994; Fischer and Wilkerson, 2000; Bergbauer, 2007). Despite these improvements in understanding and predicting fractures in folds, the prediction at the scale of the folded mechanical unit is still complicated by the fact that deformation processes are also strongly linked to the mechanical organization of the folded series. Attempts at correlating fracture distributions with the layer thickness in mono- and multilayered models have been proposed since the 1980s (Ladeira and Price, 1981; Bai and Pollard, 2000), but they are limited to tabular conditions. More complex approaches involving the lithological properties within folded multilayers have been also described, based on natural examples (Hanks et al., 1997; Fischer and Jackson, 1999; Hayes and Hanks, 2008). These studies have pointed out some of the influences of the multi-layering parameters on the folding style, the associated stress and strain distributions, and their impact on the development of fracture patterns.

This paper describes the structure of natural dip-domainal folds in selected outcrops in folded carbonate formations and at different scales. In particular, we aim to describe the detailed internal structure of dip-domain boundaries, and to give insight into the way these boundaries accommodate and result in a discontinuous fold curvature during their development. We propose a simple and non-exhaustive classification of the variety of observed dip-domain

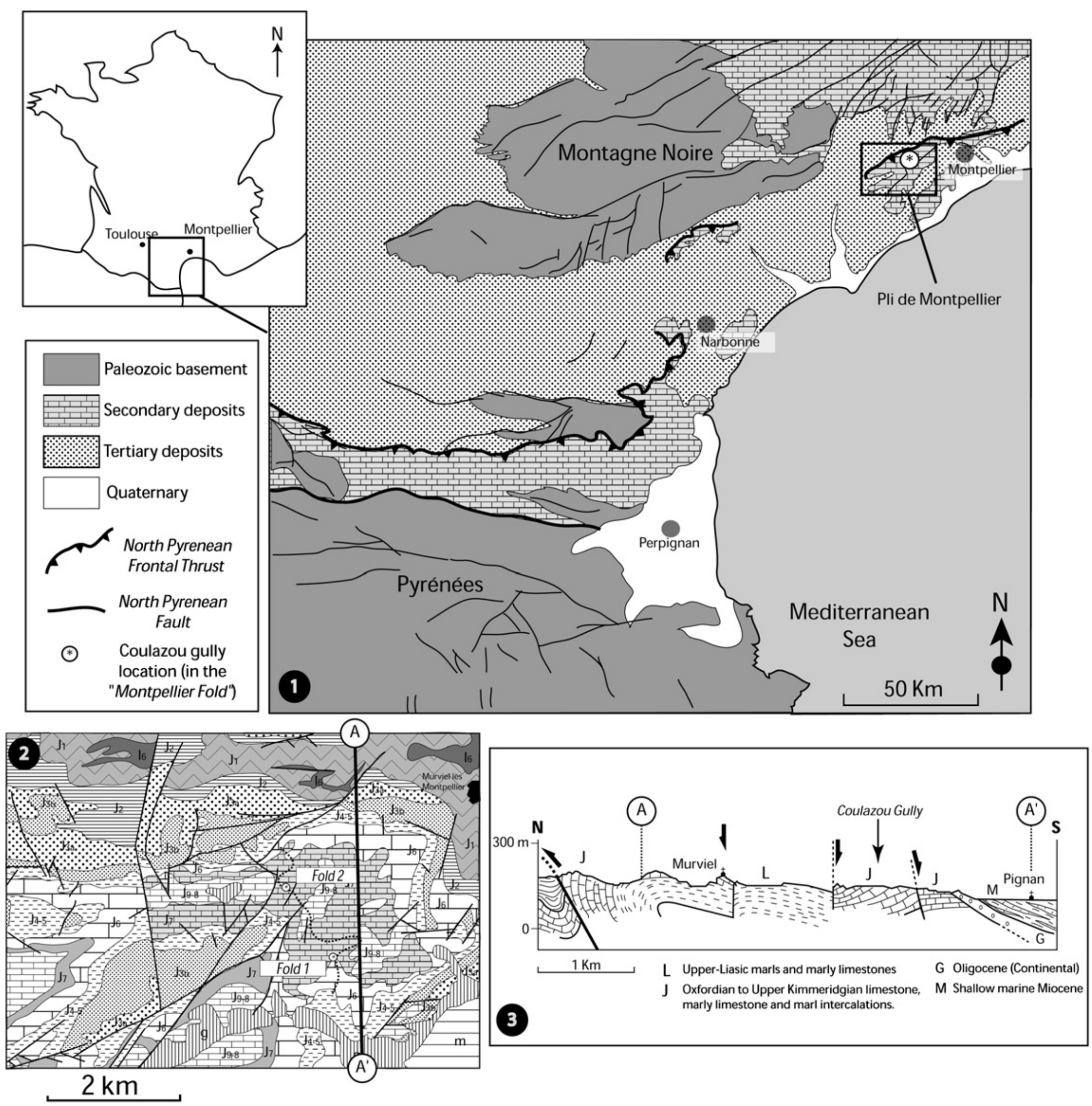

Fig. 1. Geological setting of the Coulazou gully outcrops: (1) Structural sketch showing the location of the Coulazou gully folded outcrops. These outcrops are situated in the "Montpellier Fold", which is interpreted as the northernmost termination of the North-Pyrenean zone (Mattauer, 1971). (2) Structural sketch of the Coulazou gully folded and faulted area. (3) Simplified section of the Montpellier Fold area (modified from Gèze, 1979).

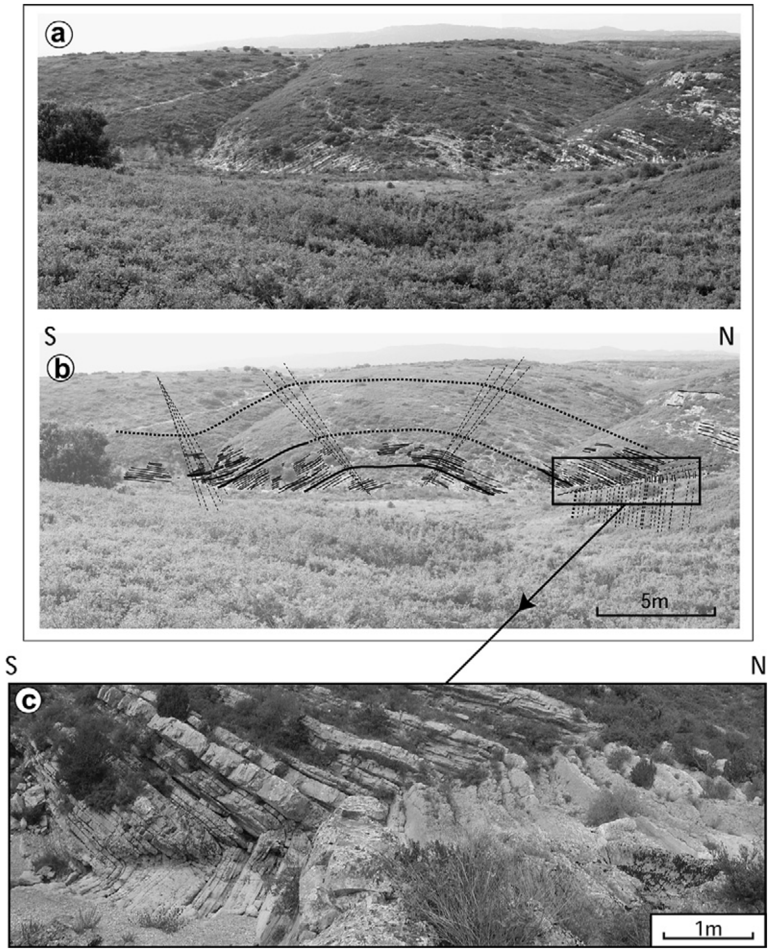

Fig. 2. Example of dip-domainal fold with box-fold like geometry: (a) general view of the outcrop, (b) semi-interpretative sketch, (c) detail of the well-exposed northernmost dip-domain boundary.

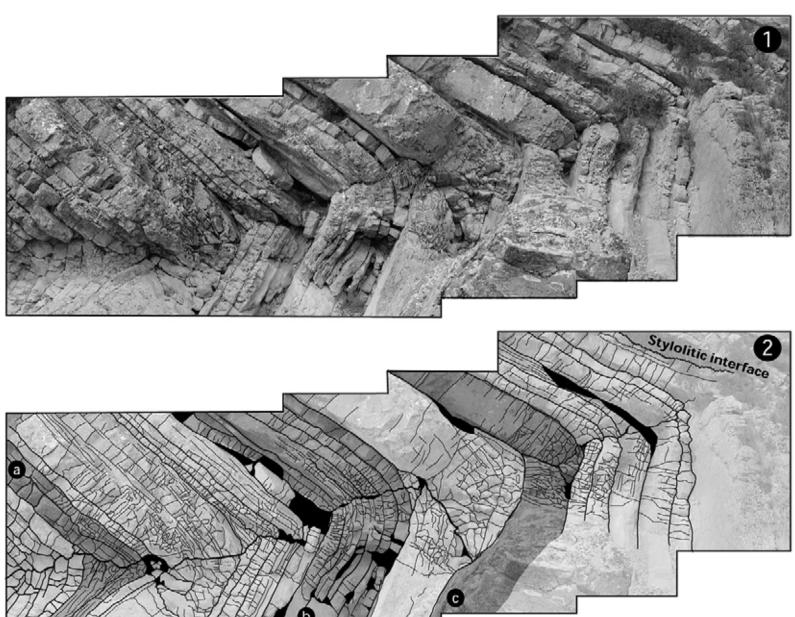

Fig. 3. Detailed view of the well-exposed northernmost hinge of the fold described on Fig. 5: (1) outcrop photograph, (2) semi-interpretative sketch. Zones (a), (b) and (c) are interpreted in Fig. 7.

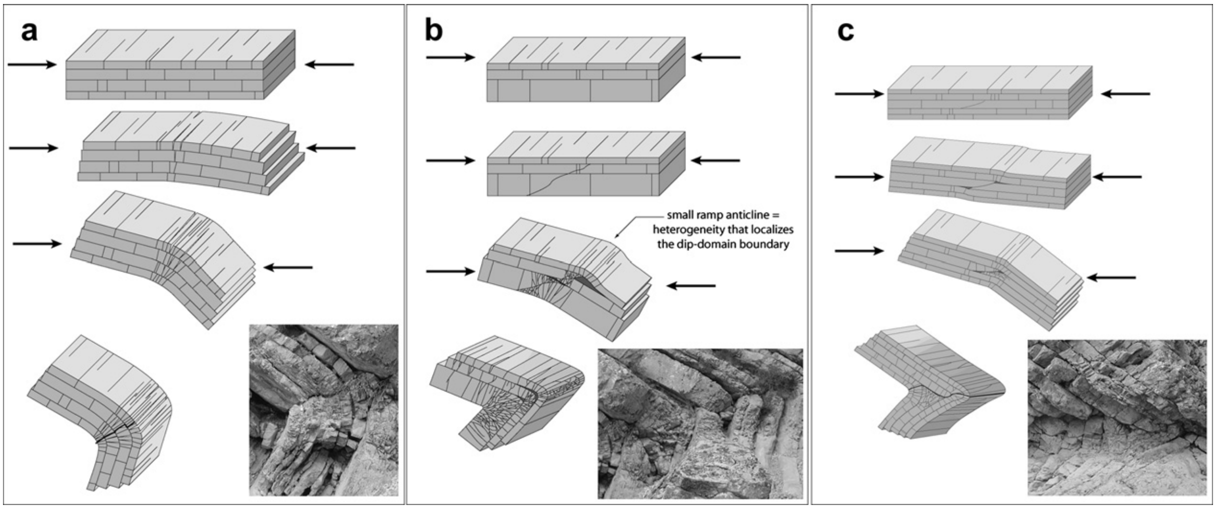

Fig. 4. Mechanical scenarios aiming to explain the dip-domain boundary mechanism of the fold described in Figs. 5 and 6. In zone (a), Curvature is only accommodated by mode I fracture concentration and coalescence. In zones (b) and (c), curvature is initiated in beds affected by early bed-scale reverse faults. Increasing curvature is accommodated by offset on these faults and by the formation of mode I fractures in the zones of stress/strain concentration.

boundaries, and present some ideas on the parameters that most strongly influence dip-domain boundary localization.

2. Methodology

Since one aim of this paper is to demonstrate the validity and the generality of the dip-domain boundary model, we analyzed a wide variety of folded structures at various scales, and in various rock types and structural contexts. The outcrops are located in Southern France (Coulazou gully, Languedoc), in Morocco (Tamzergoute valley, Eastern High Atlas) and in Italy (Montagna della Majella, Northern Apennines). Fold wavelengths vary from several meters (Coulazou gully) or several tens of meters (Tamzergoute area) to tens of kilometres (Montagna della Majella). Regardless of their scale, all of the structures are detachment folds that formed by shortening above weak detachment layers (e.g., Poblet and Mc Clay, 1996). Because the internal properties of mechanical units comprising the folds were expected to exert an important control on the characteristics of dip-domain boundaries, we took care in the field to document properties such as the type and organization of sedimentary facies, and the apparent mechanical coupling between beds.

The carbonate lithologies contained within the competent, folded mechanical unit range from sub-lithographic mudstone (Coulazou gully, Majella Mountain) to bioclastic packstone and grainstone (Majella anticline, Tamzergoute area). Although industrial collaboration constraints dictated that all of our examples involve stiff carbonate mechanical units, we believe similar structures may also be found in tight clastic mechanical units.

3. Case studies

3.1. The Coulazou gully, Languedoc, Southern France

The Coulazou gully outcrops are located in the Montpellier Fold region (Fig. 1), which constitutes the northernmost termination of the Northern Pyrenean Front (Mattauer, 1971). The folded lithologies are composed of tight mudstone to wackestone carbonates at the top of the pile (in Rauracian to Tithonian formations) to marly limestones with marl intercalations (in Bajocian–Bathonian to Oxfordian formations). The whole pile is detached upon a Triassic clayey and evaporitic decollement level. The structural style of the Coulazou area is characterized by a succession of east-west trending, 10–50 m wavelength folds that affect meter to decametre-thick mechanical units detached over more marly horizons. Folds in the region exhibit steeply dipping and sometimes overturned limbs (Figs. 2–5). The folds are most often separated by sub-tabular zones that are frequently crosscut by normal faults with directions

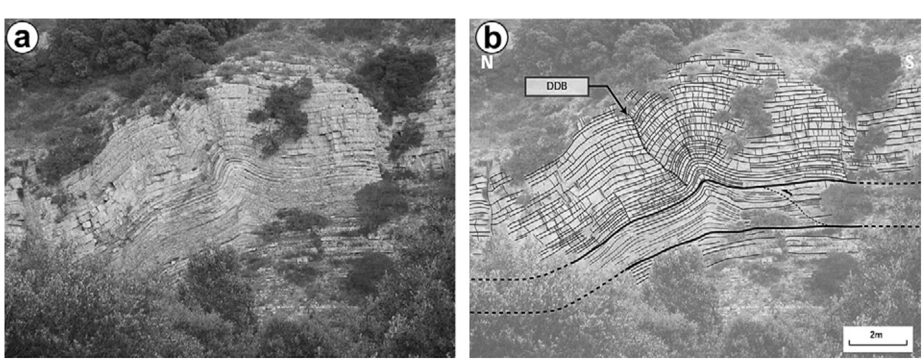

Fig. 5. Example of cusp dip-domain boundary separating two-folds with the same downward concavity. (a) Outcrop photograph; (b) Semi-interpretative sketch. Note that the two-folds separated by the dip-domain boundary (DDB) are themselves non dip-domainal. Their curvature is only accommodated by evenly distributed background (bed-limited) fractures.

compatible with later Oligocene regional EW extension (Arthaud and Laurent, 1995). The folds are mainly box-fold anticlines with a clear dip-domainal geometry.

A general view of our first example (fold 1 on Fig. 1) was taken in the southernmost part of the gully (Fig. 2). It shows a box-fold with a well-exposed dip-domain boundary located in its northern part. The box-fold geometry of this anticline is due to the irregular distribution and the wide spacing of the dip-domain boundaries. In this example, dip-domain boundaries show a spacing of about 10 m. Detailed descriptions of the northernmost one are given on Fig. 3. Mechanical scenarios for the formation of zones (a), (b) and (c) are given on Fig. 4. Scenarios outlined in Fig. 4b and c point out the role of early small reverse faults in the location and evolution of initial flexure in the deformed beds, while continuous surrounding beds can accommodate curvature by way of the formation of multiple mode I fractures (Fig. 4a). Comparable chevron folds associated with small-scale reverse faults are classically described in sandstone formations in Great Britain. (Ramsay, 1974 and Price and Cosgrove, 1990).

The second example (fold 2 on Fig. 1) shows a decametre-scale fold (Fig. 5), which affects a mechanical unit several meters thick. It demonstrates a particular type of dip-domainal fold where a dip-domain boundary separates two folded compartments with the same downward concave shape. This dip-domain boundary appears as a plane linking aligned cusp points (traces) of the successive layers. At some distance, it appears as quite a simple fracture that may have resulted from the coalescence of pre-existing background fractures (i.e., most often opening mode fractures, essentially joints, limited to one single bed). At some distance from this dip-domain boundary, fold curvature is quite regular and does not correspond to the typical dip-domainal geometry. It seems to be accommodated only by pervasive background fractures and by bed-limited, re-opened stylolites. A similar situation can be expected with an upward concave shape. This geometry is drastically different from the usual folds found in the Coulazou gully formed in less tightly coupled layers. The folded layers, here, are affected by very dense and well distributed bed-perpendicular background fractures, in lithologies similar to those of other folds.

3.2. Tamzergoute valley, western high Atlas, Morocco

The Tamzergoute valley (Fig. 6) is located in the westernmost part of the Moroccan High Atlas (region of Imouzer des Ida ou Tanane). In this region, the almost complete Mesozoic sedimentary series deposited from the Triassic rifting stage to the Coniacian tectonic inversion are exceptionally well exposed. The observed outcrops are located respectively in the Aptian (dip-domain boundary A1) and Valanginian formations (dip-domain boundary A2). The sedimentary units were folded and detached upon the Triassic evaporitic level during the Atlasic (Alpine) orogenesis (Amrhar, 1995; Zuhlke et al., 2004). The folded series is characterized by intercalations of thick, soft, marly units and stiff (usually thinner) mechanical units of tight, grainy carbonate facies (packstone to coarse grainstone). The main folds are EW trending. Secondary kinks and small-scale folds with meter to decametre wavelengths are numerous all over the area and generally affect only a single, stiff mechanical unit in a disharmonic style. Outcrops observed in the Tamzergoute valley area typically show dip-domainal folds at very different scales. The two selected examples illustrate two contrasting types of dip-domain boundaries.

Fig. 7 illustrates dip-domain boundary A1 located in a grainy carbonate, stiff, meter thick mechanical unit surrounded by soft, decametre-thick, marl layers. In this dip-domain boundary, most of the curvature is caused by two close small normal faults with their fractured damage zone (i.e., fractures formed in the vicinity of faults and related to stress concentration). The fractures observed within this zone and in the neighbourhood show higher intensities and a limited, yet clear difference of orientation compared to the

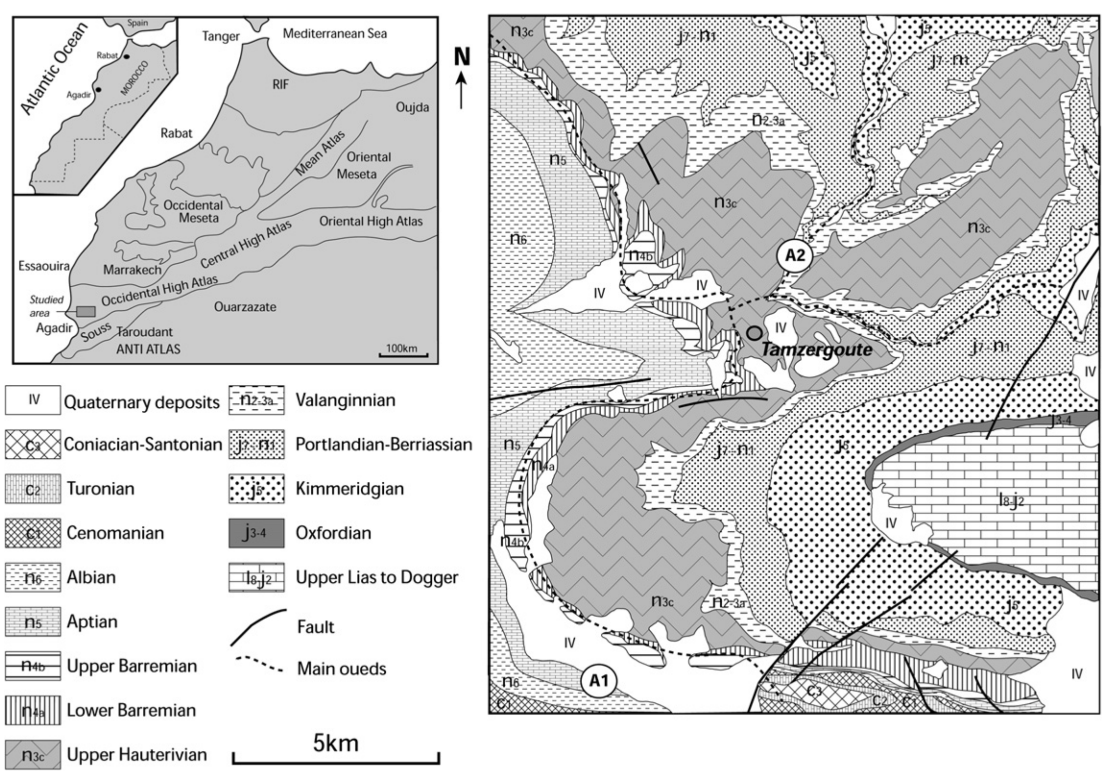

Fig. 6. Structural sketch showing the location of the Tamzergoute valley and of the two examples of dip-domain boundary (A1 and A2) described on Figs. 7 and 8.

background fractures (Fig. 7c). It may be assumed that these two faults were inherited from an early extensional stage because their orientation is compatible with a late Aptian extensional stage (Amrhar, 1995; Zuhlke et al., 2004). Such faults may have acted as potential weakness zones in the stiff mechanical unit, which may have localized the initiation of the dip-domain boundary.

Dip-domain Boundary A2 is observed in a mechanical unit comprising four positive (thickening upwards) stratigraphic sub-sequences (PSS-1 to PSS-4), which together form an entire negative (thinning upwards) stratigraphic sequence (Fig. 8). This larger negative sequence is surrounded by marl-dominated successions, each of which is several hundred meters thick. The dip-domain boundary accommodates a 10°–15° dip variation between the northern and the southern compartment in the sub-tabular, top compartment of a large-scale fold. It is mainly constituted by a decametre-scale normal fault that presents an offset that varies from a few decimetres to several meters (from the top to the base of the outcropping fault). A small amount of curvature is accommodated by a secondary normal fault located in the neighbourhood of the main one. The main normal fault is also associated with a dense damage zone mainly composed of oblique fractures with shear offsets (especially in the hanging wall) vanishing away from the main fault. It accommodates a large part of dip change. The density of these damage zone fractures varies within the different beds forming the sub-sequences. This shows that the organization of the sedimentary sequence controls the details of the mechanisms of dip-domain formation. Fracture densities are generally higher in the upper parts of each positive sub-sequence, i.e., in lithologies that contain the highest carbonate fractions. Note the particular case of PSS-4 which is the lowest and the thickest sub-sequence, where one can observe three main zones of dense fracturing because this sub-sequence can itself be divided into three other positive sub-sequences of lower order. Fracture intensity is higher in the upper part of each of these sub-sequences of lower order, which are also the most carbonate-rich. From a mechanical stratigraphy point of view, there is a good correlation between the carbonate fractions, the stiffness and the fracture density of layers at the whole negative sequence scale. The upper sub-sequences,

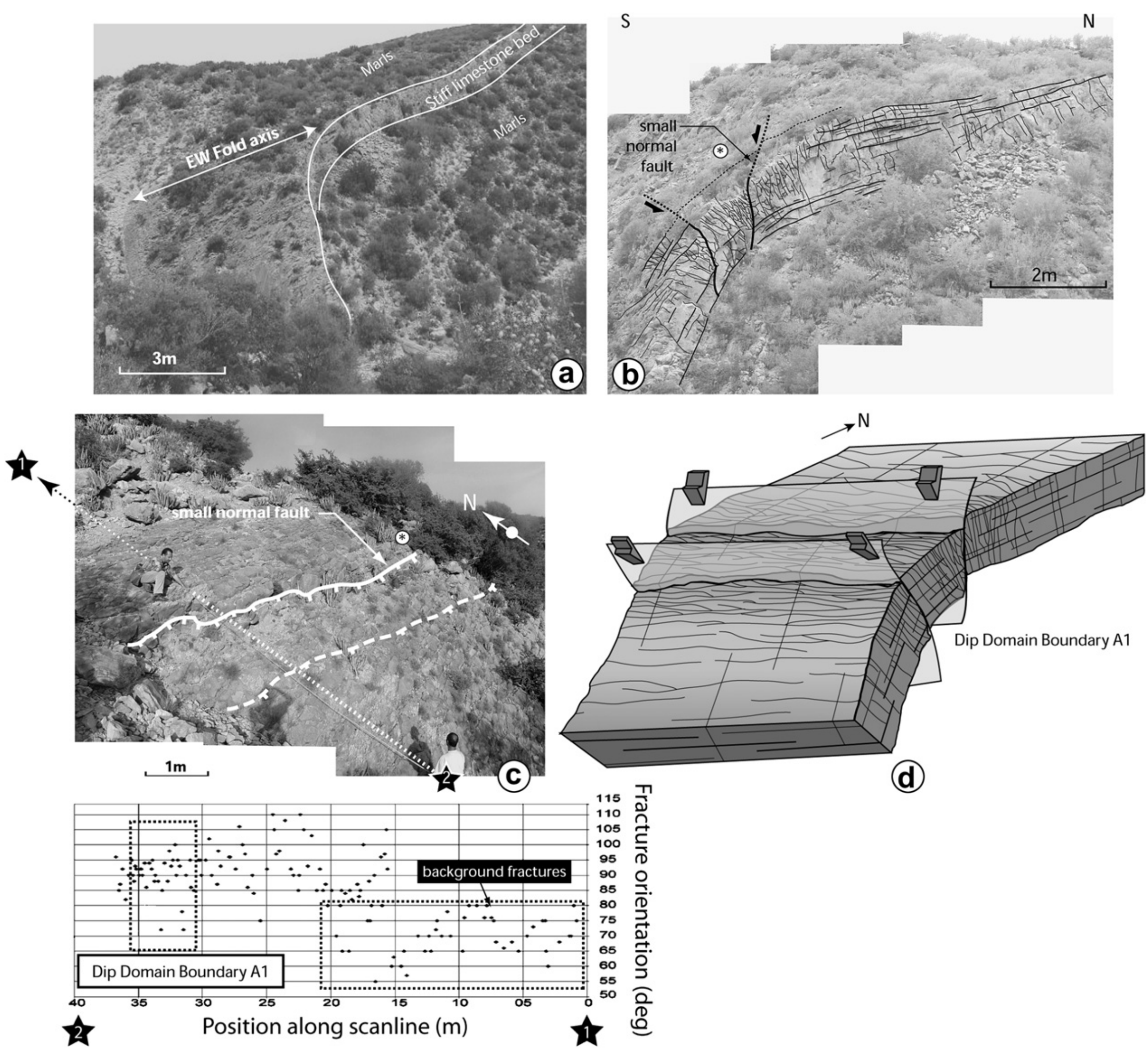

Fig. 7. Fold dip-domain boundary A1 formed by two small-scale normal faults in Aptian formation of the Tamzergoute valley. (a) General outcrop view, (b) semi-interpretative sketch of an NS section, (c) top view of the 2 small faults, the fracture orientations plotted along the (AB) scanline show a slight but clear re-orientation of the fractures in the dip-domain boundary compared to the background fractures. Background fractures may be related to a pre-folding deformation stage. (d) synthetic 3D sketch of the dip-domain boundary.

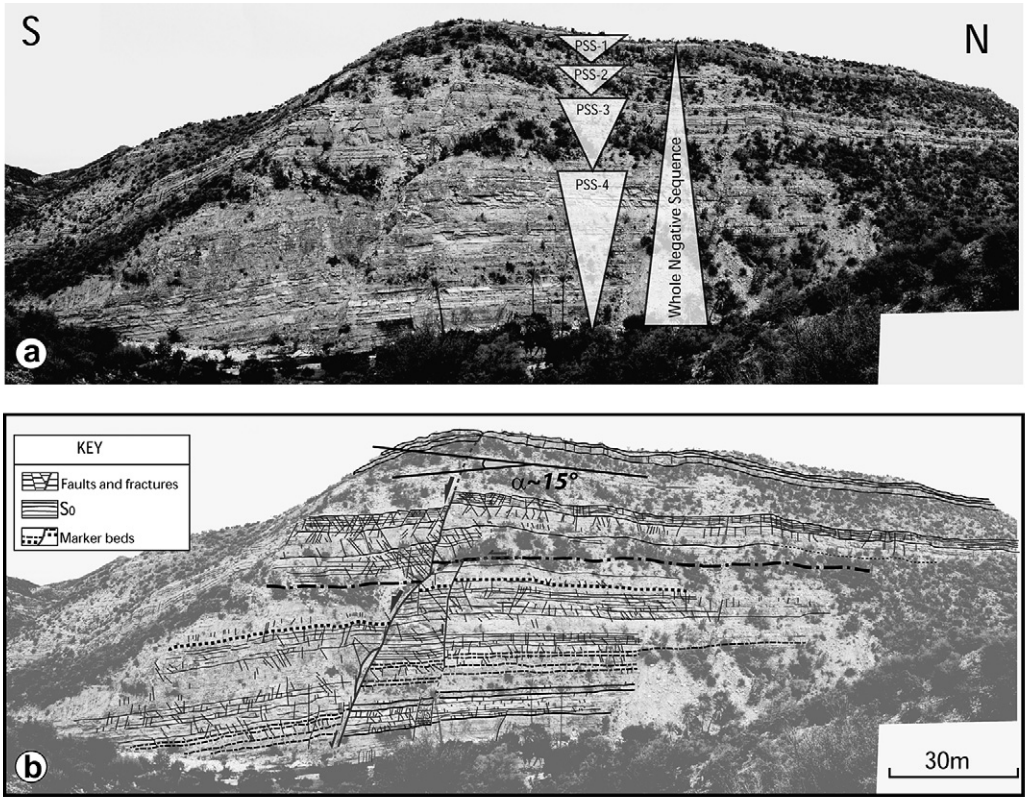

Fig. 8. Fold dip-domain boundary A2 formed by a metric offset normal fault affecting a Valanginian limestone mechanical unit. The pile is composed of 1 complete negative sequence that is formed by 4 positive sub-sequences (PSS-1 to PSS-4). (a) Outcrop photograph, (b) semi-interpretative sketch. Note the influence of the different lithologies forming the sub-sequences on the damage zone fracture density (see text).

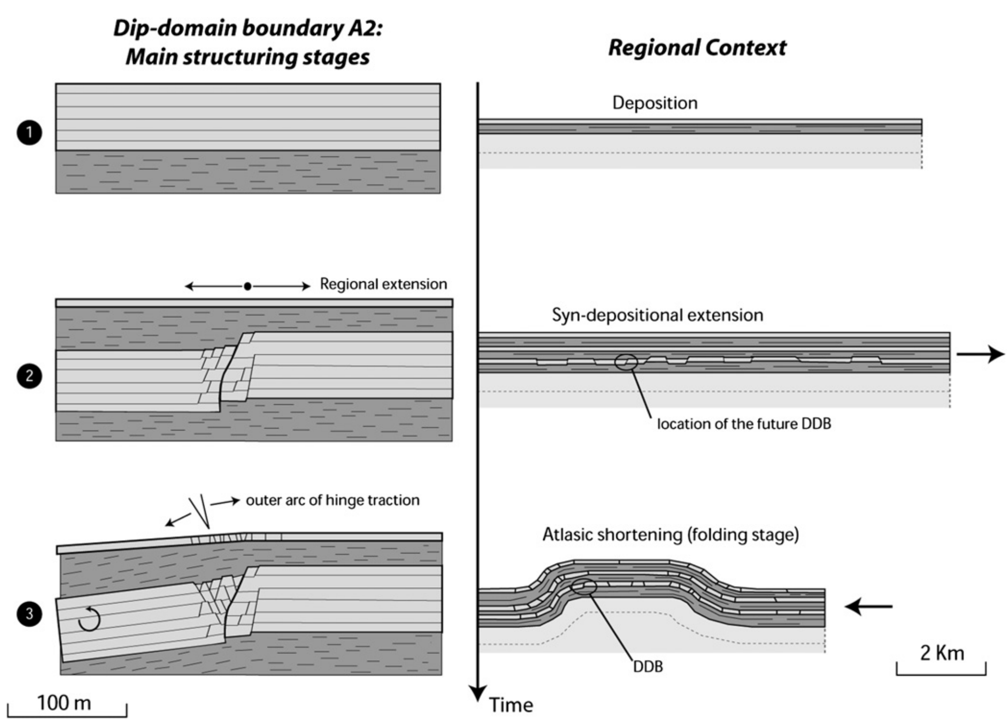

Fig. 9. Structuring scenario showing the main stages of formation of the large-scale dip-domain boundary (DDB) described in Fig. 8. (1) Sediment deposition; (2) Normal faulting and parallel oblique fracturing (primarily formed damage zone) during syn-depositional extensive stage; (3) dip-domain boundary initiation and development on the pre-formed normal fault: the rotation of the left compartment is assisted by normal offset on the conjugated oblique fractures created during this last stage.

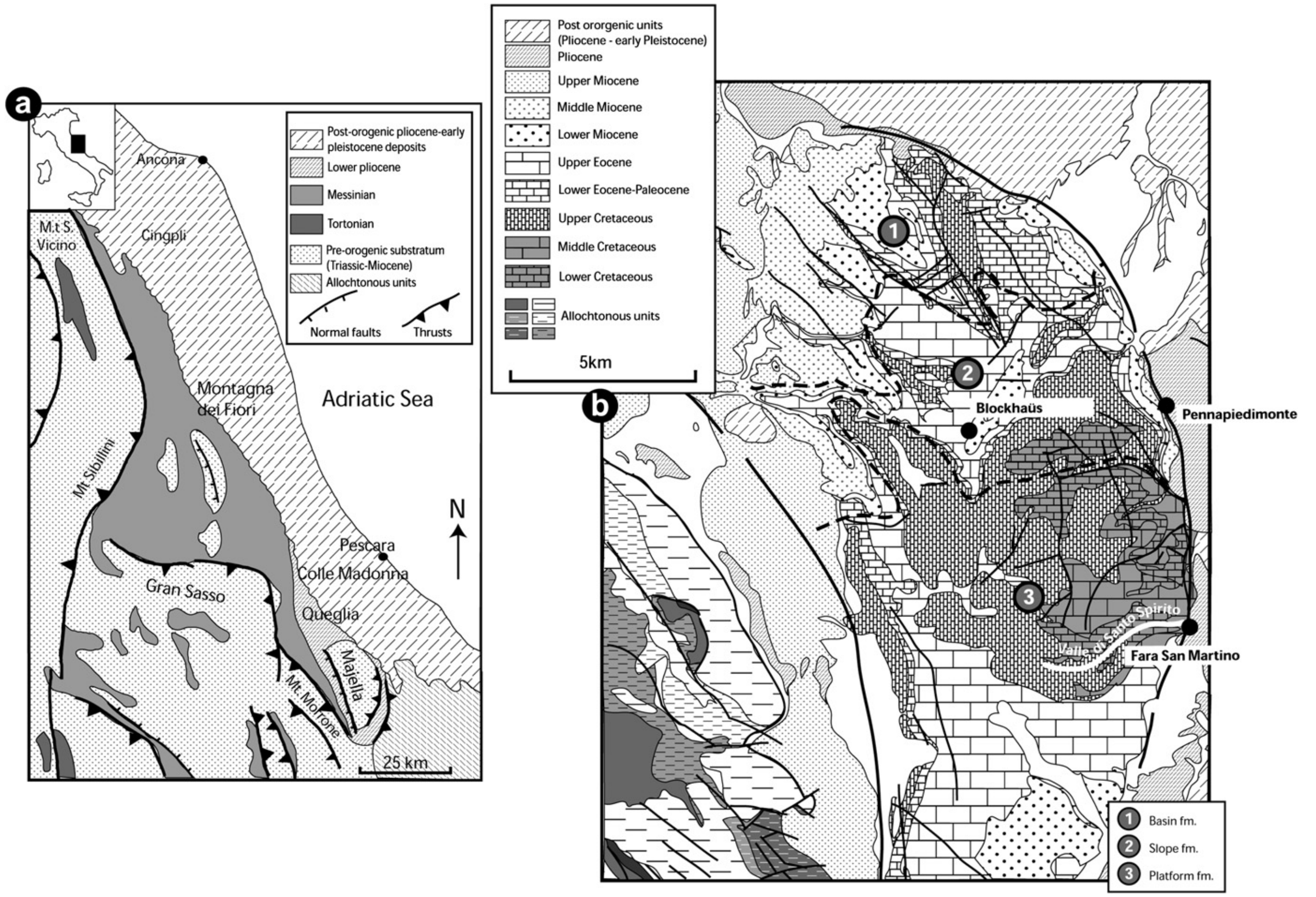

Fig. 10. Geographical location and structure of the Majella Mountain Anticline. (a) Structural sketch of central-northern Apennines (modified from Scisciani et al., 2002). (b) Structural sketch of the Majella anticline.

which are also the more marly ones, are less fractured than the lower ones, which contain higher carbonate proportions.

Fig. 9 presents a simple scenario to describe the main stages of formation of dip-domain boundary A2, taking into account the role of the large-scale normal fault and that of damage zone fractures in curvature accommodation.

3.3. The Montagna della Majella anticline (Abruzzo, Italy)

The Montagna della Majella is an north–south trending, 10–15 km wavelength anticline located in the northern Apennine fold and thrust belt (Fig. 10a). The folded units (Fig. 10b; 1–3) comprise: (1) porous bio-calcarenites (basin formation in the northern part of the anticline); (2) coarse calcarenites, breccia deposits and carbonate turbiditic sequences (in the slope and proximal basin formations of the central part of the anticline), and (3) finely grained limestones (mudstone to fine grainstone sequences) with floatstone lenses in the platform formations in the central–southern part of the anticline (Fig. 10). The structures described here are located in the platform formations of the central–southern fold part. Such observations do not apply to other compartments due to the strong control of lithology on the deformation style. The folded pile was initially deformed during the preliminary extensional stage of Adriatic rifting, which occurred from Tortonian to Messinian (Scisciani et al., 2002). Scisciani et al. assumed that the shortening started during late Messinian, reactivated pre-existing extensional fractures and initiated a large-scale thrust at the front of the future fold. On a cross section (Fig. 11), the anticline appears very asymmetric and shows three distinct structural compartments. (1) The western fold limb is characterized by a slightly west dipping section where curvature observation is difficult due to poor exposure (dense karstified normal fault sets are present). (2) The central fold part (sub-tabular to slightly east dipping) is slightly curved and is well-exposed in the Valle di Santo-Spirito gully near the town of Fara-san-Martino and in the valley south of the Monte-Acquaviva summit. (3) The eastern fold limb is

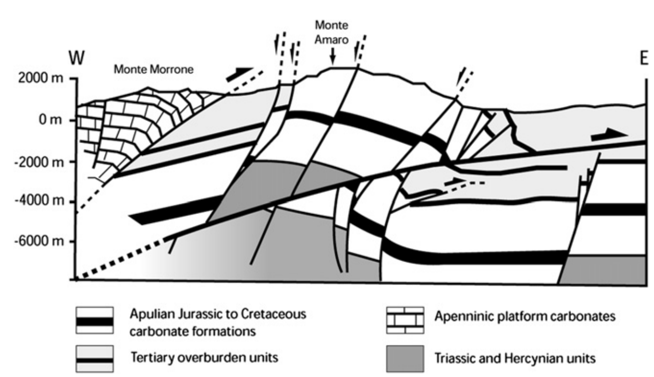

Fig. 11. Schematic E-W cross-section showing the large-scale structure of the Majella anticline (Simplified from Scisciani et al., 2002). (1) Low-dipping western flank, (2) Sub-tabular central fold part, (3) steeply-dipping eastern flank.

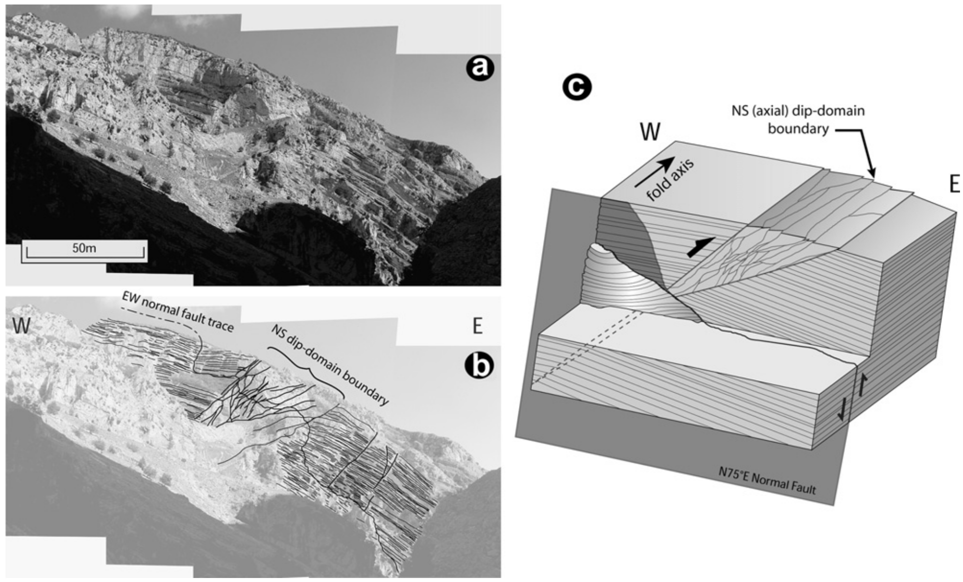

Fig. 12. Description of a dip-domain boundary zone situated in the low dip, slightly curved central fold part. (a) Outcrop photograph, (b) semi-interpretative sketch, (c) schematic 3D block diagram.

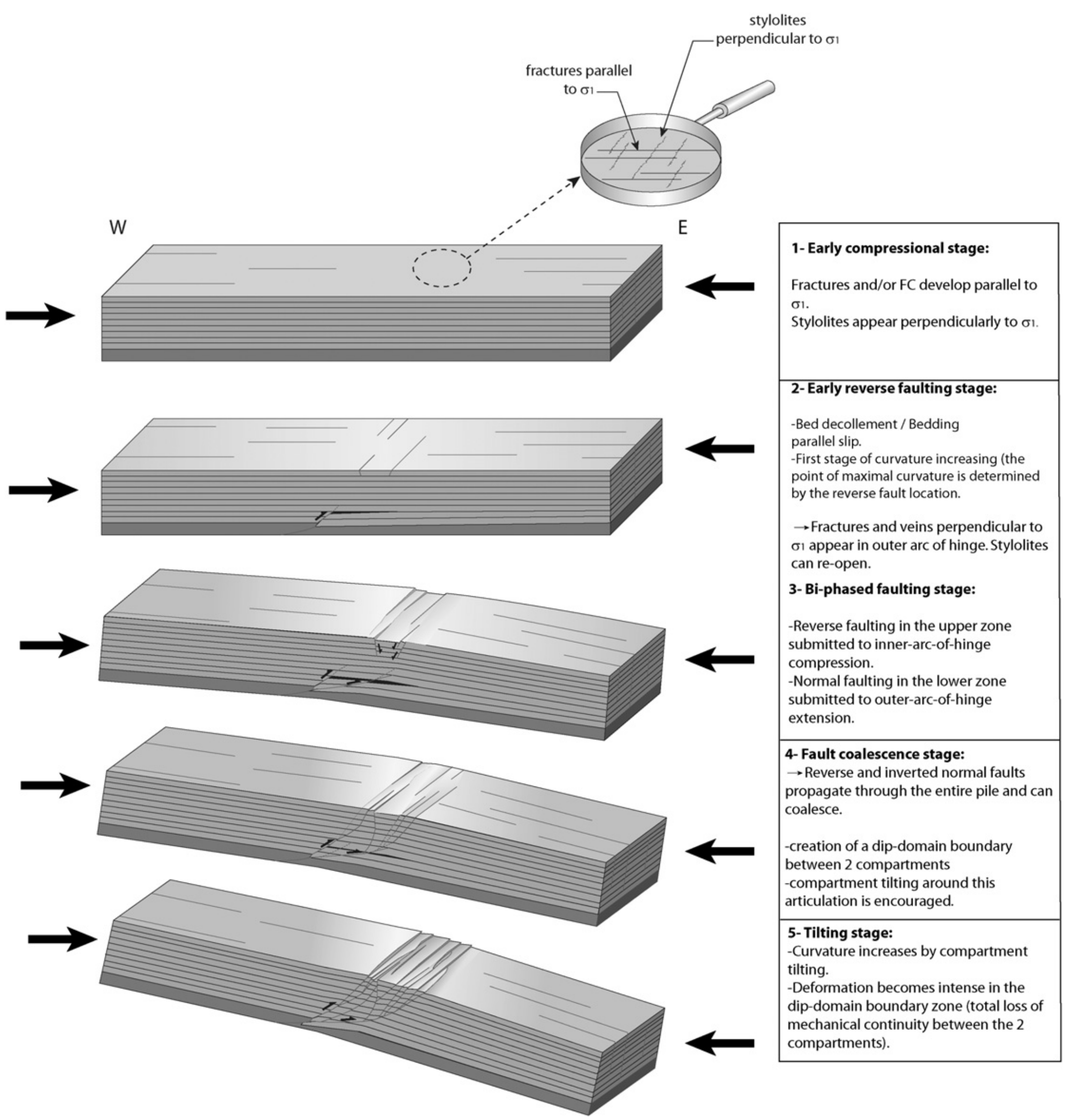

Fig. 13. Scenario presenting the main stages of structuring of the dip-domain boundary described in Fig. 12.

more strongly curved and presents high dips with local overturned zones documented near the town of Palombaro.

Two types of dip-domain boundaries have been documented in the Majella anticline: The most obvious one consists of a complex isolated and inclined V-shape fracture zone several tens of meters wide (Fig. 12). It accommodates a dip variation of 15° and corresponds to the transition between the easternmost part of the central fold compartment, which dips slightly to the east, and the eastern flank. This complex fracture zone can be interpreted as a shortened pre-existing graben. A sequence of events that may have led to development of such a dip-domain boundary is illustrated in Fig. 13. First, the graben is initiated due to a local outer arc of hinge extensional regime in relation to the offset of an underlying reverse fault located on a potential decollement level during the first shortening stages (Fig. 13; 1–3). Secondly, this pre-formed graben is inverted and coalesces with the compressive underlying structure (Fig. 13; 4). Finally, it becomes a weakness zone that localizes the dip-domain boundary during later shortening stages (Fig. 13; 5). Another interpretation could relate that structure to the reactivation of a normal fault zone inherited from a previous extensional deformation documented in the region (Scisciani et al., 2002). The second type of dip-domain boundary is present all over the eastern limb of the fold (Figs. 14 and 15). This limb is characterized by a strong curvature at the regional scale, which appears continuous from a distance. However, closer observations show that curvature is accommodated by relatively tight, small-scale, dip-domain boundaries. They consist of small, tilted normal faults with centimetre to meter offsets. Some of them initiated as individual opening mode joints (developed sub-orthogonal to layering) or as shear mode fractures (with low angle and small offset). They were both able to be reactivated by shear movement during the curvature evolution, whereas others seem to have been initiated as normal faults (Andersonian style, conjugate and tilted faults with well-developed damage zones). These small faults are dip-domain boundaries formed by the axial planes of successive small kinks (limbs forming domains of constant dip), which accommodate the general curvature of the eastern compartment of the anticline. In this case, pre-existing small-scale fractures that formed during extension, as shown in Fig. 11, appear to have determined the location and style of dip-domain boundaries during later contractional folding. In this specific case, pressure-solution processes (highlighted on the field by dense sets of tectonic stylolites) may have played a significant role in the differential deformation affecting the outer and inner hinge of the fold. Fig. 16 takes into account the previously described geometries and synthesizes the geometry of the central-eastern sector of the Majella anticline.

4. Discussion

The first result of the presented studies is that numerous folds exhibit dip-domainal geometries, many more than those currently recognized as box-folds. Indeed, the examples presented show that in numerous folds developed in brittle mechanical units, fractured dip-domain boundaries are responsible for the accommodation of the major part of the curvature, without significant visible contribution of classically described ductile deformation. Although dip-domain boundaries in carbonate rocks may occur in other structures, the internal architecture of those that we have identified can be classified into five main types described in Table 1. Each type corresponds to a specific kinematic scenario.

When comparing these types of dip-domain boundaries, it is interesting to note that examples showing clear compressive features do not dominate, although this might be expected in a compressive context. In carbonates, compression could generate stylolites, but dip-domain boundaries do not generally appear as densely stylolitized zones. In the Majella anticline (Fig. 12c) dip-domain boundaries do appear as shortened complex structures, but these features may represent the reactivation of an early-formed graben related to a deeper thrust (Fig. 13, step2). In our study, the only example where dip-domain boundaries localize on shortening structures may be the Coulazou gully, where the kinematic analysis makes early reverse faults form at the initiation stage. Globally, extensional features (mode I fractures, oblique fractures, normal faults) are dominant initial structures as shown in all the other examples of dip-domainal folds that we examined. When present in the dip-domain boundaries, bedding-perpendicular stylolites are often re-opened and can participate in the general curvature accommodation.

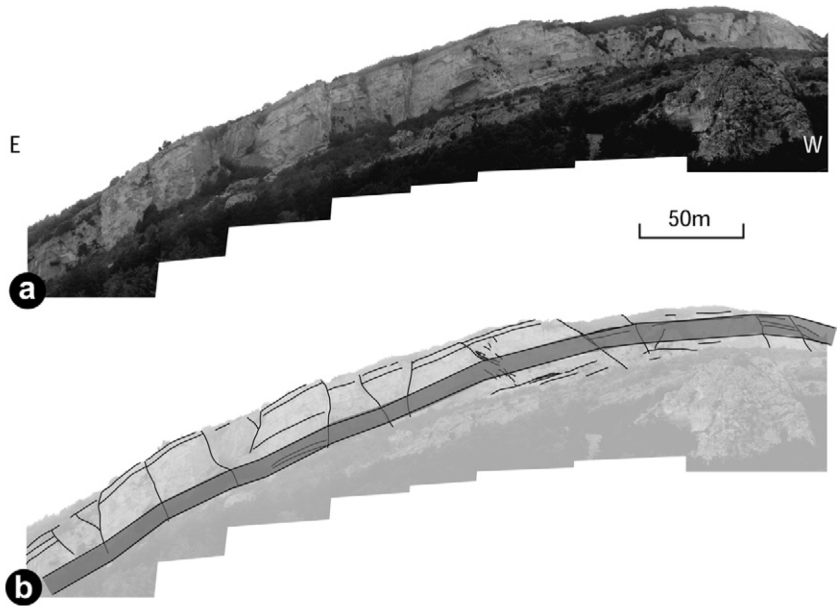

Fig. 14. View of the eastern limb of the Majella anticline showing a curvature accommodated by multiple dip-domain boundaries. Dip-domain boundaries are normal faults localizing slight kinks. (a) Outcrop photograph. (b) Semi-interpretative sketch presenting dip changes around each dip-domain boundary.

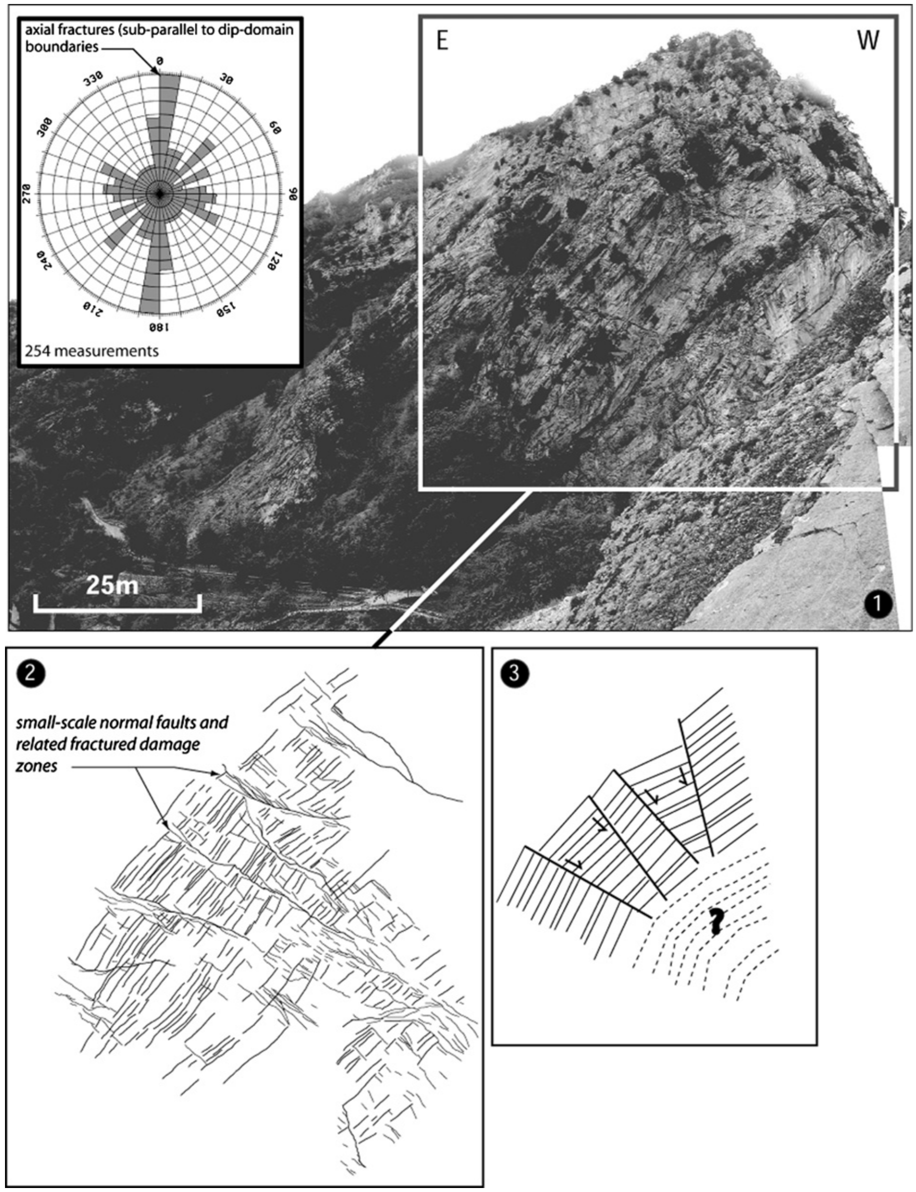

Fig. 15. Dip-domainal eastern fold limb. In this strongly east dipping limb, curvature is accommodated by the succession of small-scale kinks localized by early small normal faults and vertically persistent mode I fractures. (1) Outcrop-view and rose-diagram based on the interpretation of a (1/30000) aerial image centered on the southeastern limb of the anticline, (2) semi-interpretative sketch, (3) interpretative sketch illustrating this mode of curvature accommodation.

5. Mechanical scenarios for the localization and development of dip-domain boundaries

On the basis of field observations, we propose five major types of dip-domain boundaries in folded carbonate rocks (Fig. 17), which may not be exhaustive.

(1) Chevron hinge type, initiated by internal thrusting as shown in the first example studied in the Coulazou gully.
(2) Cusp type, shown in the second example studied in the Coulazou gully.
-(3) Multiple kink type, shown in the Majella anticline eastern limb.
(4) Normal fault type, shown in the Tamzergoute examples.
(5) Inverted graben/normal fault type, shown in the Majella anticline central low dipping compartment.

Structures comprising dip-domain boundaries appear to have one of two origins:

(1) A pre-folding origin, where fractures localizing the dip-domain boundaries are created before the fold-related compression during earlier deformation processes (type 3 and 4)
(2) A syn-folding origin (type 1, 2 and possibly 5), where fractures are initiated as mechanical instabilities during the first stages of curvature. However, in both cases, during the global curvature increase, fracture density tends to increase in dip-domain boundary zones with the rotation (increasing dip difference) of isolated domains (with constant dip or not) in which deformation (background fracturing) is not expected to evolve.

The dip-domain boundary concept has important implications for the mechanisms of fold development and amplification. It is not compatible with the active-hinge folding mechanism (developed since Suppe, 1983 and modelled by Salvini and Storti, 2001), which involves the development of a trail of damage (fracturing) within mechanical units left by the passage of a migrating axial surface (i.e., dip-domain boundary).

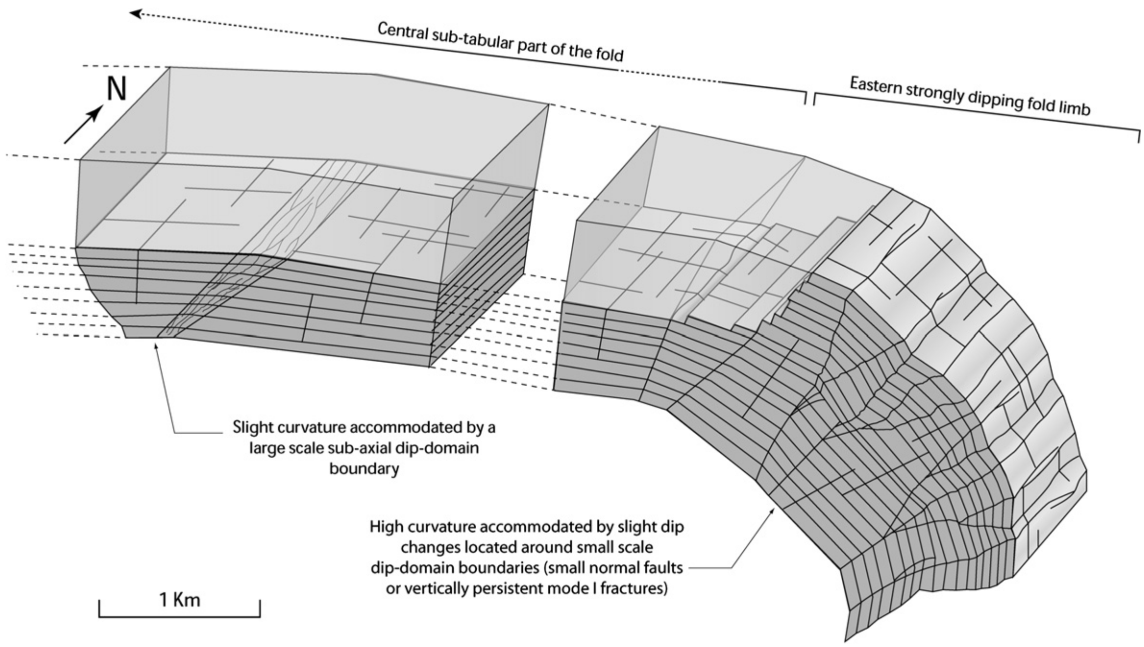

Fig. 16. 3D diagram showing a reconstitution of the central-eastern Majella anticline compartments. The low dip central part is slightly curved and presents a large-scale dip-domain boundary that could be inherited from a pre-existing graben. The strongly dipping eastern limb presents a well expressed curvature accommodated by multiple kinks localized by small scale normal faults and vertically persistent mode I fractures.

The fracture concentrations that we observed in dip-domain boundaries, and conversely, the relatively low deformations exhibited by rocks between dip-domain boundaries (i.e., within dip-panels), appear more compatible with the fixed-hinge folding model as defined in De Sitter (1956). An explanation may be that the kinematics of the dip-domainal folds observed in our study are not essentially controlled by the displacement above a thrust-plane or by the bending of the units over its ramp. Instead, they are, at least partially, accommodated by buckling-related amplification, which is in turn accommodated by fracture densification (and to a certain extent increase in the angle) of dip-domain boundaries as described in the experiments of Bazalgette and Petit (2007). In other words, the evolution of fold curvature has its own mechanical history, which is not dependant on the geometry of the underlying detachment, or the migration of fold axial surfaces.

Table 1
Summarized typology of dip-domain boundaries based on the modes of curvature accommodation deduced from outcrop observations.

Dip-domain boundary type:	Mode of curvature accommodation	Field examples
Cusp dip-domain boundary separating non-constant dip-domains	Cusp style: dip change along a highly persistent discontinuity formed by background joints coalescence	Coulazou gully (Languedoc, France)
Chevron hinge	– Opening mode fractures – Re-opened stylolites – Small reverse faults – Brecciated zones	Coulazou gully (Languedoc, France)
Multiple kinks	– Small normal faults – Highly persistent opening mode fractures	Majella anticline (Abruzzo, Italy)
Normal fault	– Normal faults (large scale or small-scale) – Associated damage zone	Tamzergoute valley (Morocco)
Inverted graben/ normal fault	– Inverted graben or normal fault – Associated damage zone.	Majella anticline (Abruzzo, Italy)

When dip-domain boundaries originate from inherited, pre-folding structures (which may be the most common case), not all pre-existing fracture zones can localize dip-domain boundaries. The following conditions are needed to initiate localization:

- Pre-existing fractures must be correctly oriented, i.e., parallel or sub-parallel to the future fold axis, i.e., sub-orthogonal to the general shortening direction.
- Pre-existing fractures, whatever their type, must be sufficiently individualized and must affect at least a large part of the mechanical unit thickness to allow localization of a dip-domain boundary. Although not presented in this study, the axial fracture corridors (Petit et al., 2001) seem particularly prone to initiate dip-domain boundaries. Indeed the association of their constitutive fractures typically crosscut the entire thickness of the formed mechanical unit. Conversely, pervasive (background) fractures, even if they can be involved in the dip-domain boundary, cannot impose their localization. Their role in curvature accommodation appears therefore more diffuse.

When they have a syn-folding origin (implying the absence of large-scale structural heterogeneities), the localization of dip-domain boundaries fractures could form as mechanical instabilities involving some “plastic” yielding (Biot, 1961; Chapple, 1969; Suppe, 1985) after a certain amount of elastic deformation. Plasticity is expressed here by multiple fractures under elastic-brittle conditions. Such approach is classically described as responsible for the failure of layers subjected to buckling. In the field examples presented, as well as in the experiments of Bazalgette and Petit (2007) the yield stress was probably reached simultaneously in multiple locations during increasing strain, leading to the sequential initiation of multiple dip-domain boundaries. At present no physical model for such behaviour exists. Such localized fold-related fracture networks are likely to be approached in the future in relation to the recent development of the theory of constitutive instabilities applied to shear-bands and fracture prediction (Chemenda, 2007).

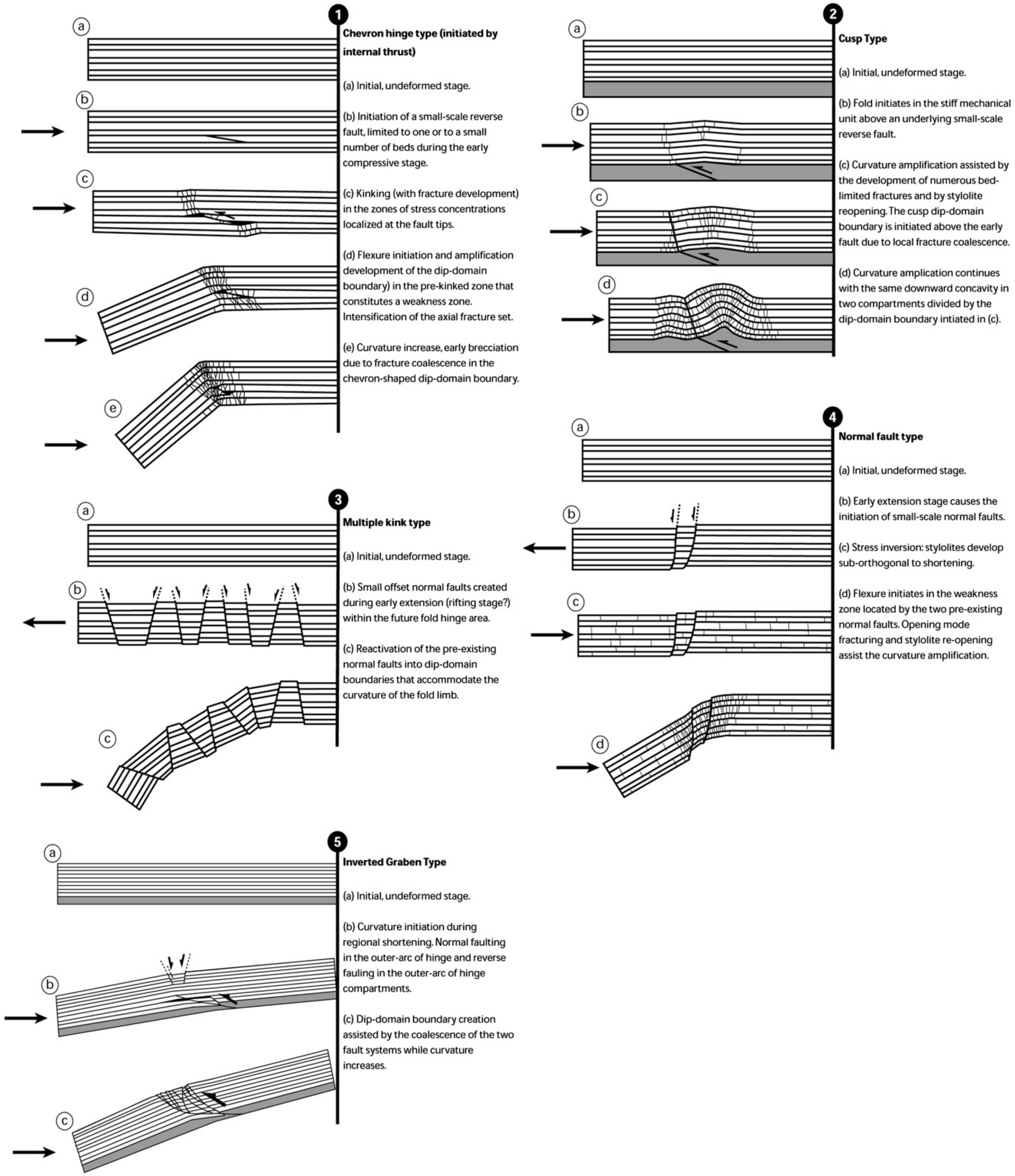

Fig. 17. mechanical scenarios for the five dip-domain boundary types.

6. Conclusion

This study shows that the curvature of natural folds developed in brittle carbonate rocks is often less continuous than commonly assumed. When examined in detail, the curvature of many folds appears to be accommodated along subtle dip-domain boundaries. These boundaries are formed of narrow, discontinuous fracture zones that strike sub-parallel to the fold axis, and that typically cut across entire competent mechanical units. They separate non- or slightly, and continuously, deformed rock compartments where fracturing is typically bed-limited, appearing as dip-domains, or dip-panels. The dip difference accommodated by the individual dip-domain boundary is often small, but the associated damage can be important, especially when the dip-domain boundaries are widely spaced.

Although five different types of dip-domain boundaries were recognized, many others may exist, especially those that may involve the reactivation of fracture corridors. Irrespective of their internal structure, dip-domain boundaries are often inherited from pre-existing well-oriented fracture concentrations whose initial geometry can control to some extent the final fold geometry. They can also initiate as instabilities at the onset of folding in layers, which may be intact (unfractured) or homogeneously pre-fractured. Although our kinematic models for the localization of dip-domain boundaries were derived for carbonate mechanical units, they may also apply to clastic series.

In the framework of this study, it was not possible to clearly identify the physical parameters that control the transition from obviously dip-domainal box or kink folds, to folds with seemingly regular curvature, but in reality which contain subtle dip-domain boundary distributions. Following the work of Bazalgette and Petit (2007) we hypothesize that among influential parameters are the confining load applied to the mechanical units, and the friction at the bedding interfaces that controls the capacity to bed-parallel slip. These parameters identified experimentally are obviously difficult to approach from an outcrop point of view and need specific cases. As a way forward, theoretical and numerical modelling studies could be used to quantify their relative importance.

The densely fractured dip-domain boundaries that we have identified correspond to subtle zones of dip change, striking sub-parallel to the axis of folded horizons. As such, these fracture zones could have a major influence on the large-scale dynamic properties of folded carbonate reservoirs, as they can form important fluid drains. They could be recognized by careful analysis of dip and curvature attributes on 3-D seismic horizons corresponding to the considered mechanical unit. Their association with cross-fold fracture zones (possibly fracture corridors) may constitute a significant part of the potential sub-seismic drain network that needs to be implemented in dynamic reservoir modelling.

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