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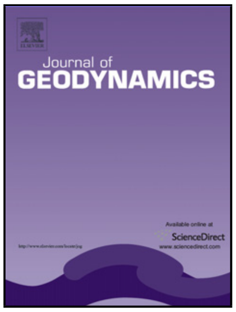

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Geodynamics of oroclinal bending: insights from the Mediterranean

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Abstract

The Alpine Orogen in the Mediterranean region exhibits a series of orogenic curvatures (oroclines). The evolution of these oroclines is relatively well constrained by a plethora of geophysical and geological data, and therefore, their origin can inform us on the fundamental processes controlling oroclinal bending. Here I present a synthesis of the geometry of Mediterranean oroclines, followed by a discussion on their geodynamic origin. The geometrical synthesis is based on a new classification of Mediterranean oroclines, which defines a first-order orocline (Adriatic Orocline) by the general northward-convex shape of the Alpine Orogen from Cyprus to Gibraltar. Superimposed on the limbs of this orocline, are second-, third- and fourth-order oroclines. The major process that led to the formation of the Adriatic Orocline is the indentation of Adria into Europe, whereas second-and third-order oroclines (e.g., Western Mediterranean and Gibraltar oroclines, respectively) were primarily controlled by a combination of trench retreat and slab tearing. It appears, therefore, that the geodynamics of Mediterranean oroclines has been entirely dependent on plate boundary migration and segmentation, as expressed in the interlinked processes of indentation, trench retreat and slab tearing. The relative contribution of specific geodynamic processes, and their maturity, could be inferred from geometrical characteristics, such as the amplitude-to-width ratio, the orientation of the curvature (convex or concave) relative to the convergence vector, and their geometrical relationship with backarc extensional basins (e.g., in the concave side of the orocline). Based on the information from the Mediterranean oroclines, I conclude that oroclinal bending commonly involves lithospheric-scale processes, and is not restricted to thin-skinned deformation. However, contrary to previous suggestions that assume that the whole lithosphere can buckle, there is no clear evidence that such processes occur in modern tectonic environments.

Keywords

Mediterranean, orocline, Alpine Orogen, trench retreat, indentation, slab tear.

1. Introduction

The geometry of the Alpine belt in the Mediterranean region is characterised by a series of tight bends commonly refer to as oroclines (Figure **1**) (Carey, 1955; Lonergan and White, 1997; Rosenbaum and Lister, 2004a; Johnston and Mazzoli, 2009). The term was coined by Carey (1955), who defined an orocline as an orogenic belt that was subjected to bending. In his pioneering work, Carey (1955) included an innovative restoration of the Mediterranean oroclines, illustrating the possibility that different segments of the Alpine-Mediterranean Orogen had once formed a continuous near-linear belt. The implication of this reconstruction - that orogenic belts could undergo continental-scale rotations and translations - is now a widely accepted notion in tectonics. However, at the time of publication, Carey's ideas were difficult to comprehend, because the mechanisms that could possibly control oroclinal bending were unknown.

A few years after the publication of Carey's paper on the orocline concept, the theory of plate tectonics emerged. The recognition of fundamental geodynamic processes, such as seafloor spreading (Dietz, 1961), transform boundaries (Wilson, 1965) and subduction zones (Morgan, 1968), provided compelling evidence for the mobility of continents, and set the ground for understanding how and why oroclines form. Subsequent studies have demonstrated that relatively small continental blocks can travel large distances and then accrete onto the continental margins in convergent plate boundaries (Nur and Ben-Avraham, 1982). Furthermore, plate boundaries themselves, such as subduction zones, were found to be mobile tectonic elements (Elsasser, 1971; Garfunkel et al., 1986) that can retreat or advance independently of the motion of the converging plates (Dewey, 1980; Jarrard, 1986). The recognition of these processes added another level of complexity to the understanding of orogenic processes, and led to the development of geodynamic models that were capable of explaining the origin of curved plate boundaries and associated oroclines (e.g., Schellart and Lister, 2004; Morra et al., 2006; Schellart et al., 2007; Capitanio et al., 2011). Nevertheless, the origin of oroclines has remained a contentious topic in tectonic studies (e.g., Johnston et al., 2013), and there is still much debate on the mechanisms leading to orocline formation.

Proposed processes for orocline formation predominantly belong to one of the following three categories: (1) processes associated with deformation in thin-skinned fold-thrust belts (Marshak, 1988, 2004); (2) lithospheric buckling (Gutiérrez-Alonso et al., 2012; Johnston et al., 2013; Weil et al., 2013); and (3) along-strike variations in the rates of the plate boundary migration (Rosenbaum and Lister, 2004a; Schellart and Lister, 2004). Unfortunately, based on geological case studies, it is commonly difficult to assess the applicability of these processes, particularly because most recent research on oroclines has been focused on Palaeozoic examples for which the geodynamic setting is relatively poorly constrained. A large volume of research has recently been conducted on three Palaeozoic oroclines found in Variscan Europe (Weil et al., 2001; Gutiérrez-Alonso et al., 2012; Weil et al., 2013), Central Asian Orogenic Belt (Levashova et al., 2003; Abrajevitch et al., 2007; Xiao et al., 2010) and Australian Tasmanides (Cawood et al., 2011; Glen and Roberts, 2012; Rosenbaum, 2012; Rosenbaum et al., 2012). All three oroclines demonstrate tight orogenic-scale curvatures and vertical-axis block rotations, but their deep (lithospheric-scale) structure is poorly constrained, and the exact plate tectonic setting during their formation remains speculative. The Palaeozoic examples, therefore, can only provide limited information on the geodynamics of oroclines. In contrast, robust geological and geophysical constraints are available from the Mediterranean oroclines, and these data can be utilised to unravel the fundamental mechanisms controlling oroclinal bending.

The aim of this paper is to analyse the geometry of Mediterranean oroclines and to discuss processes that controlled their formation. Unlike the Palaeozoic examples, oroclinal bending in the Mediterranean region has occurred relatively recently (in the last 30 Ma), and their tectonic evolution is rigorously constrained by a plethora of geological and geophysical data. I argue that the most crucial processes leading to orocline formation in the Mediterranean region were associated with along-strike variations in the rates of plate boundary migration, involving indentation, trench retreat and subduction segmentation. To demonstrate this, I will first present an analysis of the geometry of Mediterranean oroclines irrespective of their paragenesis. This will be followed by a discussion on the major geodynamic processes that led to oroclinal bending in the Mediterranean. The paper will be concluded with a discussion on the role of buckling during oroclinal bending and implications to the reconstruction of ancient oroclines.

2. Geometry of Mediterranean oroclines

Previous work on Mediterranean oroclines have mainly focused on individual curved segments of the Alpine-Mediterranean belt (Figure **1**), such as the Gibraltar Orocline (Lonergan and White, 1997; Platt et al., 2003; Platt et al., 2013), Calabrian Orocline (Van Dijk and Scheepers, 1995; Cifelli et al., 2007; Cifelli et al., 2008), Umbria-Marche Orocline (Speranza et al., 1997), Western Alps (Laubscher, 1991), Carpathian Orocline (Burchfiel, 1980) and Aegean Orocline (Kissel and Laj, 1988). The approach used here is somewhat different, and involves a new classification of Mediterranean oroclines, whereby lower-order oroclines are defined if they are superimposed on the limbs of larger oroclines. The resulting hierarchy of oroclines and a synthesis of their geometrical characteristics are presented in Figure **2** and Figure **3**, respectively.

A first-order oroclinal structure is recognised at the scale of the whole Mediterranean, and is termed here the Adriatic Orocline (Figure **2**a). The curved structure wraps the eastern, northern and western margins of the Adriatic Sea, changing the latitude of the Alpine-Mediterranean Orogen from 35-37°N in the western and eastern Mediterranean to 45-49°N in the Alps-Carpathian region. The Adriatic Orocline is characterised by a strongly irregular mushroom-shaped geometry. Its curvature is convex northward, with maximum width and amplitude of ~3800 km and 1740 km, respectively (Table 1 and Figure **3**a).

Superimposed on the Adriatic Orocline, three second-order oroclines can be defined. The characteristic scale of these oroclines is ~2000 km width and 500-1000 km amplitude (Table 1 and Figure **3**f,g). The Western Mediterranean Orocline is characterised by an asymmetric SSE-convex structure, stretching from the Apennines to North Africa and Gibraltar (Figure **2**b). Its amplitude to width ratio (0.55) is considerably higher in comparison to the other two second-order oroclines (0.26 and 0.27, respectively) (Figure **3**h). Farther north, another second-order, northward-convex curvature can be defined (Figure **2**c), stretching from the Ligurian Alps to the southern Carpathians. Finally, the Eastern

Mediterranean Orocline defines a SSW-convex curved segment, stretching from the Dinarides to the Hellenides and Cyprus (Figure **2**d).

Third-order oroclines are typically 350-800 km wide and 100-500 km in amplitude (Table 1). The Gibraltar Orocline (Figure **2**e), which is defined by the continuation of the Betic and Rif chains in southern Spain and northern Morocco, respectively, has a tight westward-convex horseshoe shape (Figure **2**). Its amplitude to width ratio (1.57) is anomalously high (Figure **3**e). The opposite sense, eastward-convex Calabrian Orocline (Figure **2**g), links the ~E-W oriented Sicilian Maghrebides with the NW-SE orientation of the Apennines. A much gentler curvature in the northern Apennines defines the Umbria-Marche Orocline (Figure **2**f). Farther north, the link between the Alps and Apennines in Liguria (the "Ligurian knot", Laubscher et al., 1992) marks an abrupt change in the orientation of the orogenic belt and is the southeastern edge of the westward-convex curvature of the Western Alps (Figure **2**j). The orogenic belt then continues eastwards in a general E-W structural grain, before curving around the Pannonian Basin, forming the relatively large third-order Carpathian Orocline (Figure **2**h). In the eastern Mediterranean, two third-order oroclines can be recognised: the Aegean Orocline and Cyprus Orocline (Figure **2**i,k). Both oroclines have a southward-convex geometry (Figure **3**e) with a relatively low amplitude-to-width ratio (0.25 and 0.29, Figure **3**h).

Three fourth-order oroclines (Hyblean, Jura and Eratosthenes) are superimposed on the larger curvatures (Figure **2**l-n). Their characteristic width is 100-300 km, and their amplitude of 20-70 km is substantially smaller than higher-order oroclines (Figure **3**f-h). All three oroclines have a northward-convex shape (Figure **3**e).

3. Indentation

The indentation of Adria into Europe was responsible for the development of the first-order Adriatic Orocline. Although other mechanisms, such as trench retreat, have substantially modified the oroclinal structure, the general northward-convex shape of the Adriatic Orocline reflects the shape of the Adriatic indenter (Figure **4**a), which was attached to the African plate while moving northward relative to Europe (Channell et al., 1979; Rosenbaum et al., 2004). Indentation commenced in the Eocene (~45 Ma) and resulted in collisional orogenesis in the Alps (Stampfli et al., 1998; Rosenbaum and Lister, 2005; Beltrando et al., 2010). A number of studies have demonstrated that the style of deformation is generally in agreement with the expected strain associated with an indentation mode (Ratschbacher et al., 1991; Regenauer-Lieb, 1996; Regenauer-Lieb and Petit, 1997) (Figure **4**b,c), although the exact geometry and velocity vectors of the indenter are still a matter of debate (Platt et al., 1989; Regenauer-Lieb, 1996; Lickorish et al., 2002; Rosenberg et al., 2004; Rosenberg et al., 2007).

Strain resulting from indentation involves strike-slip faults that accommodate a tectonic escape towards the free boundaries and opposite-sense rotations around vertical axes (Figure **4**c), thus forming an oroclinal structure. Ultimately, the geometry and scale of the orocline is a function of the indenter width, amount of indentation, convergence velocity, the rheological contrast between the two plates, and the exact geometry of the contacts.

While the process of indentation is here attributed to the formation of the first-order oroclinal structure, it can also occur at any other scale. In the Mediterranean, there are at least two examples of fourth-order oroclines that formed by indentation. The Eratosthenes Seamount is a submerged continental fragment belonging to the African plate (Robertson, 1998), which collided with Cyprus and led to a local deflection of the Africa-Europe plate boundary. A second example is the collision of the Hyblean-Malta Plateau, which similarly to the Eratosthenes Seamount, represents a local collision of an African continental fragment along the Africa-Europe plate boundary (Ben-Avraham and Grasso, 1990). Numerical modelling of this collision by Ben Avraham et al., (1995) demonstrated that the formation of the cuspate oroclinal structure can be attributed to the impingement of a relatively buoyant continental fragment (Hyblean-Malta Plateau) into the subduction zone. The buoyant material resists subduction and can thus be responsible for locally pinning the otherwise migrating plate boundary zone.

In summary, formation of oroclines by indentation can operate at all scales, depending on the size of the indenter. The diagnostic features of indentation-related oroclines are: (1) a curved convex geometry towards the direction of indentation; (2) pronounced contractional deformation in the collisional zone; and (3) escape-tectonic structures that move material sideways towards the free boundaries.

4. Trench retreat

Trench retreat has been arguably the most important mechanism that controlled oroclinal bending in the Mediterranean region (Royden, 1993; Faccenna et al., 2004; Rosenbaum and Lister, 2004a). Its driving force is the negative buoyancy of subducting slabs, which can pull the slab in the opposite direction of subduction and can further drive rollback-induced mantle flow (Garfunkel et al., 1986; Schellart, 2004). This positive feedback mechanism, unless stalled by the arrival of buoyant material at the subduction zone (Rosenbaum and Mo, 2011) or compensated by faster convergence (Schellart, 2008), can lead to rapid changes in the geometry of the plate boundary. The overriding plate deformation in response to trench retreat is associated with widespread backarc extension (Jarrard, 1986; Heuret et al., 2007; Schellart and Moresi, 2013).

In the Mediterranean region, the contribution of trench retreat is evident in the formation of second- and third-order oroclines. All three second-order oroclines (Figure **2**), and most evidently the Western Mediterranean Orocline, are characterised by large areas affected by extensional deformation in the concave side of the oroclines (Figure **4**a). These regions, which are occupied by thinned continental lithosphere or new oceanic lithosphere, have been positioned at the overriding plate relative to the retreating subduction zones (Royden, 1993; Wortel and Spakman, 2000; Rosenbaum et al., 2002a; Royden and Papanikolaou, 2011; Carminati et al., 2012). The fact that the areas subjected to backarc extension are geometrically related to the shape of the second-order oroclines (Figure **4**a) indicates that the mechanism of oroclinal bending was directly linked to trench retreat and backarc extension. This concept was adopted in kinematic reconstructions of the western Mediterranean, which demonstrated how the independent (and palaeomagnetically constrained) movement of continental fragments (e.g., Corsica-Sardinia, Kabylies, Balearic Islands and Betic-Rif; Figure **4**a) was made possible by the combination of trench retreat and overriding plate extension (Rosenbaum et al., 2002a; Rosenbaum and Lister, 2004a). These overriding-plate block rotations, which predominantly took place in the extending backarc regions, have resulted in the rearrangement of orogenic segments in a curved manner, thus forming the Western Mediterranean Orocline.

In comparison to the western Mediterranean, the role that trench retreat played in controlling oroclinal bending in the eastern Mediterranean was somewhat smaller, as expressed in the lower value of amplitude-to-width ratio of the Eastern Mediterranean Orocline (Figure **3**b,h). This difference reflects different stages in the history of trench retreat, with the western Mediterranean being a mature system that has essentially consumed all available oceanic lithosphere by subduction. Accordingly, the western Mediterranean was able to develop mature backarc extensional basins that have locally led to continental breakup (Nicolosi et al., 2006; Schettino and Turco, 2006). In the eastern Mediterranean, in contrast, trench retreat has been slower (Royden and Papanikolaou, 2011), and the subducting oceanic lithosphere (Ionian Sea, Herodotus Basin and Levant Basin) has not been entirely consumed (Garfunkel, 1998; Ben-Avraham et al., 2002; Speranza et al., 2012). The overriding plate in the eastern Mediterranean has been stretched substantially (Jolivet and Brun, 2010), but has not reached breakup. The Eastern Mediterranean Orocline, therefore, is potentially still evolving, although its growth is restricted by the confined space of the remaining oceanic lithosphere and its thick sedimentary cover that impedes rollback.

In summary, trench retreat is an efficient mechanism for oroclinal formation, and multiple lines of evidence support its contribution to the development of Mediterranean oroclines. Its major diagnostic features include: (1) evidence for widespread backarc extension in the concave side of the orocline; and (2) evidence for temporal changes in the position of the supra-subduction system (forearc, arc and backarc), following the trajectories of the plate boundary migration.

5. Slab tearing

Propagation of vertical tears in subducting slabs is responsible for subduction segmentation and is intimately linked to the process of trench retreat. Slab tearing is expected to occur at the edges of retreating subduction zones and/or in cases when the rates of trench retreat change along strike (Govers and Wortel, 2005; Rosenbaum et al., 2008; Hale et al., 2010). There are a number of different ways in which slab tearing promotes oroclinal bending. Similarly to the processes discussed in the previous section, tearing is kinematically controlled by trench retreat and backarc extension, which enable oroclinal bending by overriding-plate blocks rotations. This process is further amplified by slab tearing, which would act to create narrower slab segments that are likely to be subjected to accelerated rates of trench retreat (Dvorkin et al., 1993). As a result, lower-order oroclines are likely to be developed, characterised by a higher amplitude-to-width ratio. Another positive feedback mechanism promoting oroclinal bending is the torodial mantle flow, which is applied at the slab edges and allows opposite-sense rotations (Figure **5**) (Schellart et al., 2007). Slab tearing will facilitate this process by enhancing pathways for mantle flow and creating smaller-scale convection cells (Faccenna and Becker, 2010).

The third-order Gibraltar Orocline is an example for oroclinal bending assisted by slab tearing (Figure **5**). In this area, westward trench retreat since the Miocene has been accompanied by vertical slab tearing, leading to the development of the Alboran Sea as a backarc extensional basin (Lonergan and White, 1997). Slab tearing is observed in seismic tomography (Spakman and Wortel, 2004; Garcia-Castellanos and Villaseñor, 2011; Palomeras et al., 2014), and is consistent with the pattern of intermediate-depth seismicity (Meighan et al., 2013, and references therein). Furthermore, mantle anisotropy derived from SKS splitting shows a radial pattern of fast polarization directions around the slab edges (Diaz et al., 2010), supporting the suggestion that slab tearing and rollback have been accompanied by a torodial mantle flow (Figure **5**). Along the tear fault and associated strike-slip faults, “tear-related” magmatism has occurred, driven by the heat supplied from the uprising asthenosphere (Maury et al., 2000; Pérez-Valera et al., 2013). These processes were accompanied by rotations of crustal blocks around vertical axes, involving counterclockwise rotations in the Betics and clockwise rotations in the Rif (Lonergan and White, 1997; Platt et al., 2003). The collective evidence, therefore, clearly demonstrates that the formation of the tight horseshoe oroclinal structure has been controlled by the combination of trench retreat and slab tearing.

A similar mechanism, involving slab tearing and trench retreat, has been responsible for the formation of the Calabrian Orocline (Faccenna et al., 2004; Govers and Wortel, 2005; Cifelli et al., 2008; Rosenbaum et al., 2008; Argnani, 2009). In this region, a series of tear faults have been developed to accommodate along-strike variations in the rates of trench retreat, with many of the tear faults providing pathways for “tear-related” magmatism (Gvirtzman and Nur, 1999; Rosenbaum et al., 2008; Gasparon et al., 2009). Similarly to the situation in the Gibraltar Arc, evidence from SKS splitting is indicative for asthenospheric torodial flow around the edges of the Calabrian slab (Civello and Margheriti, 2004; Lucente et al., 2006). At the overriding plate, the along-strike variations in the rates of trench retreat gave rise to the opening of the asymmetric, wedge-shaped, Tyrrhenian Sea as a backarc extensional basin (Malinverno and Ryan, 1986; Faccenna et al., 1996; Rosenbaum and Lister, 2004b). This process was accompanied by opposite-sense block rotations of crustal blocks (Channell et al., 1980; Scheepers et al., 1993; Scheepers et al., 1994; Speranza et al., 1999; Gattacceca and Speranza, 2002; Speranza et al., 2003; Mattei et al., 2004; Cifelli et al., 2007). The magnitude and timing of block rotations, as inferred from palaeomagnetic data, is indicative of progressive oroclinal bending, combined with the presence of lateral heterogeneities within the subducting lithosphere (Cifelli et al., 2008).

In summary, feedback effects between trench retreat and slab tearing act to accelerate the process of oroclinal bending and can lead to the development of mature third-order oroclines. Oroclines formed by these processes are typically characterised by the following diagnostic features: (1) a tight curvature with a high amplitude-to-width ratio; (2) occurrence of tear-related magmatism along the limb(s) of the orocline(s); and (3) syn-oroclinal strike-slip faulting.

6. Discussion

6.1. Formation of Mediterranean oroclines

The examples from the Mediterranean region provide compelling evidence for the role of plate boundary migration during oroclinal bending. The formation of the Mediterranean oroclines, in the last ~30 Ma, has involved extreme changes in the Africa-Europe plate boundary, associated with trench retreat, subduction segmentation and local collisions. During this period, the convergence of Africa with respect to Europe has been characterised by a consistent and slow northward trajectory (Rosenbaum et al., 2002b). It seems, therefore, that plate convergence has played a relatively minor role in controlling changes in the actual configuration of the plate boundary. This is not surprising, because enhanced rates of plate convergence would reduce the effect of trench retreat (Schellart, 2005), meaning that the slow movement of Africa with respect to Europe since the Oligocene has provided ideal kinematic boundary conditions for triggering rapid rates of trench retreat and backarc extension (Jolivet and Faccenna, 2000).

In the absence of a significant plate convergence component, the primary control on the rate and orientation of trench retreat is the availability of subductable oceanic lithosphere. Areas occupied by oceanic lithosphere are likely to be consumed by subduction and subjected to trench retreat, whereas the arrival of continental lithosphere or bathymetric highs at the subduction zone resists subduction and impedes slab rollback (Rosenbaum and Mo, 2011; Moresi et al., 2014). Therefore, any heterogeneity in the subducting lithosphere is likely to result in along-strike variations in the rates of trench retreat and the formation of oroclines. Commonly, this is accompanied by slab tearing and subduction segmentation. Accordingly, the geometry of oroclines, such as Gibraltar and Calabrian oroclines, may reflect the shape of pre-existing oceans and the structure of lithospheric heterogeneities within the downgoing plate. The same concept has also been demonstrated in other tightly curved plate boundaries, such as the ones surrounding the Caribbean Sea (Pindell et al., 1988), Scotia Sea (Barker, 2001) and Banda Sea (Hall, 2012).

It appears, therefore, that the geometry of oroclines can provide a clue on the geodynamic processes that controlled their formation. The amplitude-to-width ratio in second-order Mediterranean oroclines informs us on the role of trench retreat, with higher values predicting a major contribution by this process and a mature backarc extension. In the third-order oroclines, higher values of amplitude-to-width ratio correspond to oroclinal bending assisted by slab tearing. Furthermore, the relative orientation of curvature is also process-dependent and can thus help unravelling the geodynamics of oroclines (Figure **6**). With Africa moving generally northward towards Europe (Rosenbaum et al., 2002b), it is expected that crustal blocks belonging to the African plate will result in northward convex structures if subjected to indentation (Figure **6**b). Indeed, Figure **3**e shows that northward convex curvatures (Adriatic, Hyblean and Eratosthenes oroclines) are the ones associated with indentation. In contrast, southward convex curvatures are the ones formed by trench retreat parallel to plate convergence (Figure **6**c). This pattern is recognised in the second-order Western Mediterranean and Eastern Mediterranean oroclines and in the third-order Aegean and Cyprus oroclines. The formation of these oroclines is attributed to the overall northward subduction of the African plate, and the slow plate convergence that has failed to compete with the faster rates of southward trench retreat. This is the reason why the most extreme expressions of trench retreat, accompanied by slab tearing, occur in west- and east-facing curvatures (Gibraltar and Calabrian oroclines; Figure **6**d). In these cases, the orientation of trench retreat was perpendicular to plate convergence, thus allowing a rapid ~E-W migration of the plate boundary.

6.2. Roles of thin-skinned deformation and buckling

In earlier work on oroclines, much emphasis was given to the role of thin-skinned deformation during oroclinal bending (Marshak, 1988; Macedo and Marshak, 1999; Marshak, 2004). These studies have demonstrated (e.g., in sandbox experiments) that orogenic curvatures can develop in response to interactions between foreland obstacles and the fold-thrust wedge, or due to other heterogeneities in the architecture of the fold-and-thrust belt, such as lateral variations in the thickness of a pre-deformational basin fill or the strength of the detachment surface (Marshak, 1988; Macedo and Marshak, 1999). These mechanisms provide a reasonable explanation for the origin of relatively gentle orogenic curvatures in thin-skinned fold-thrust belts, such as the Appalachians' salients and recesses. Nevertheless, such processes have not likely played a primary role in the development of the much deeper Mediterranean oroclines (e.g., Figure **5**). The geodynamics of oroclinal bending, as inferred from the Mediterranean examples, has involved bending and tearing of the plate boundary in response to indentation and trench retreat. The upper crustal expression of these processes may involve block rotations within the fold-thrust belt, but the fundamental control on oroclinal bending is dictated by the whole lithosphere. For example, based on seismic tomography, it has been shown that even the gentle curvature of the Umbria-Marche Orocline (Figure **2**f) is rooted in the lithosphere, as indicated by a similar curvature of the lithospheric slab at 35-100 km depth (Lucente and Speranza, 2001). Out of all the oroclines discussed in this paper, the only one that does not seem to be related to lithospheric-scale deformation is the fourth-order Jura Orocline (Figure **2**m), which developed farther from the plate boundary on top of a Triassic décollement (Laubscher, 1972).

With thin-skinned deformation playing a relatively minor role in the development of oroclines, one must consider the geodynamics of lithospheric deformation in order to unravel the origin of oroclines. The mechanisms discussed in this paper - indentation, trench retreat and slab tearing - have being studied extensively, and their applicability to geodynamics is supported by observations and modelling (e.g., Schellart et al., 2007; Billen, 2008; Thatcher, 2009; Stadler et al., 2010, and numerous other references). Nevertheless, in a large number of recent publications, it has been assumed that the process of oroclinal bending involved buckling of the whole lithosphere (Gutiérrez-Alonso et al., 2012; Pastor-Galán et al., 2012; Johnston et al., 2013; Weil et al., 2013). In comparison to the geodynamic processes discussed in this paper, buckling is a fundamentally different mechanism, because it considers that the tectonic forces that allow oroclinal bending were applied parallel to the orientation of the pre-existing near-linear belt (e.g., see figure 3b in Gutiérrez-Alonso et al., 2012). Evidence supporting buckling, for example in the late Palaeozoic Iberian-Armorican Orocline, includes palaeomagnetic data that suggest vertical-axis block rotations, and structural data from joints and faults (Gutiérrez-Alonso et al., 2012, and references therein). In addition, the occurrence of post-orogenic magmatic rocks in the core of the orocline has been interpreted to represent post-thickening delamination due to buckling (Gutiérrez-Alonso et al., 2011). Regardless of the large volume of palaeomagnetic, structural and geochemical data from the Iberian-Armorican Orocline, the suggestion that oroclinal bending must have formed by lithospheric-scale buckling remains tenuous, because the observations are not unique and can be explained by a range of other mechanisms. For example, oroclines formed by a combination of trench retreat and slab tearing (e.g., Calabrian Orocline) can also possess similar structural characteristics, including opposite-sense block rotations and limb-parallel strike-slip faults. More diagnostic for buckling is the evidence for outer-arc extension and inner-arc shortening (Weil et al., 2013), but it is also possible that such structures represent alternating episodes of contraction and extension in the forearc region (e.g., Van Dijk and Scheepers, 1995). Finally, the occurrence of mantle-derived magmatism during oroclinal bending (Gutiérrez-Alonso et al., 2011) could also be explained in the context of slab tearing (Gvirtzman and Nur, 1999; Maury et al., 2000; Rosenbaum et al., 2008; Gasparon et al., 2009).

Based on the above arguments, I argue that the idea that lithospheric-scale buckling has controlled oroclinal bending is supported by inconclusive evidence. Johnston and Mazzoli (2009) have suggested a buckling model for the Calabrian Orocline, driven by the convergence of Africa and Europe. However, contrary to the expectation from the buckling model, the role of plate convergence in Mediterranean tectonics has actually been reduced during oroclinal bending (Jolivet and Faccenna, 2000). With the absence of unambiguous examples for buckled oroclines in modern orogenic belts, and the lack of support from geodynamic modelling, one must conclude that buckling is not a primary mechanism in the geodynamics of oroclinal bending.

6.3. Implications for reconstructions of ancient oroclines

The reconstruction of ancient oroclines remains a problematic issue. If ancient oroclines formed in a similar way to modern analogues, then it is likely that the geodynamic processes associated with their formation occurred at scales and durations that are too difficult to detect by the resolution of available geological data. The Calabrian Orocline, for example, developed during a period of less than 10 Myr and involved geodynamic interactions (trench retreat and slab tearing) that were ostensibly unrelated to the larger-scale plate kinematics of Africa-Europe convergence. Tracing evidence for such processes in the Precambrian or Palaeozoic geological record is a challenging task.

Regardless of the difficulty in reconstructing ancient oroclines, the existence of diagnostic features outlined in this paper, may provide some clues on the major geodynamic processes associated with their formation. For example, the occurrence of syn-oroclinal extensional sedimentary basins in the concave side of the orocline is a diagnostic feature for trench retreat. The value of the amplitude-to-width ratio could inform us on the maturity of the system, and the occurrence of asthenospheric-derived magmatism could account for slab tearing. Such interpretations, however, should be treated with caution, because with the absence of direct constraints on the geodynamic processes (e.g., seismic tomography, geodetic measurements), there are normally multiple ways that can explain the same geological observations.

An example for a comparison between modern and ancient oroclines is shown in Figure **7**, highlighting the strongly contorted structures that can be developed in forearc regions. The spatial distribution of Devonian-Carboniferous forearc units in the New England Orogen (eastern Australia, Figure **7**a) delineates an ear-shaped structure (Rosenbaum, 2012; Rosenbaum et al., 2012), with the strongest oroclinal-related deformation concentrated in the “core” of the structure (Nambucca Block, Figure **7**a) (Shaanan et al., in review). The origin of this curved structure is enigmatic, particularly because its offshore continuation is entirely unknown. Nevertheless, the comparison of this system with the oroclines in the central Mediterranean (Figure **7**b) is intriguing. Both systems show that the expression of oroclinal bending in the forearc regions could be strongly irregular. Furthermore, observations from the Ionian Sea show that the interactions between two systems undergoing trench retreat in opposite directions (Calabrian and Hellenic trenches) could result in a local collisional zone between the two accretionary complexes (Huguen et al., 2001; Polonia et al., 2011; Gallais et al., 2012). Whether or not this collisional zone is equivalent to the syn-oroclinal deformation in the Nambucca Block is an open question.

Additional observations from the New England Orogen on syn-oroclinal extensional tectonism (Korsch et al., 2009) and tear-related volcanism (Caprarelli and Leitch, 2001; Li et al., 2014) further support a geodynamic origin involving trench retreat and backarc extension.

7. Conclusions

Oroclines in the Mediterranean region occur at multiple scales, with smaller oroclines superimposed on the limbs of larger oroclines. The fundamental processes that controlled their formation were associated with migration and segmentation of the Africa-Europe plate boundary, involving indentation, trench retreat and slab tearing. All these processes involved lithospheric-scale deformation, suggesting that the role of thinned-skinned deformation in triggering oroclinal bending was relatively minor. Using the Mediterranean region as a natural laboratory for the study of oroclines, it is concluded that similar processes may have controlled the formation of other oroclines in modern and ancient tectonic environments. Finally, the lack of conclusive evidence for lithospheric-scale buckling in modern oroclines calls for revisiting the validity of this mechanism, which is commonly applied in reconstructions of ancient oroclines.

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Figure Captions

Figure 1. Relief map of the Mediterranean Sea (from Amante and Eakins, 2009) highlighting the structural grain of Alpine-Mediterranean oroclines.

Figure 2. Classification of Mediterranean oroclines based on a scale-dependent order, whereby smaller oroclines are superimposed on the limbs of larger oroclines.

Figure 3. (a-d) Geometry of Mediterranean oroclines calibrated for a uniform width. In all diagrams, oroclines are rotated in a way that their widths and amplitudes are aligned parallel to the horizontal and vertical axes, respectively. (e) The azimuth orientation of the oroclines relative to a northward convex curvature. (f) Widths of oroclines. (g) Amplitudes of oroclines. (h) Amplitude-to width ratios of oroclines.

Figure 4. (a) Tectonic setting of the Adriatic indenter relative and the geometry of the first-order Adriatic Orocline. Ba, Balearic Islands; Be, Betic; Co, Corsica; Ka, Kabylies; Ri, Rif; Sa, Sardinia. (b) Indentation-related structures in the Alpine collisional zone during Alpine collision (40-35 Ma) (Ratschbacher et al., 1991). GF, Guidicarie Fault; PF, Pustertal Fault; TF, Tonale Fault. (c) Predicted slip lines in response to indentation (Regenauer-Lieb, 1996). Note the similarity between the predicted slip lines and the geometry of the Tonale, Guidicarie and Pustertal faults.

Figure 5. Schematic block diagram illustrating the inferred shape of the slab in Gibraltar and its associated vertical tears (after Palomeras et al., 2014). Blue lines indicate fast polarization directions of SKS splitting measurements (Diaz et al., 2010), which represent fossil mantle anisotropy that is consistent with the expected torodial mantle flow around the slab edges. Curved red arrows represent the sense of block rotations inferred from palaeomagnetic data (Platt et al., 2013, and references therein).

Figure 6. Schematic illustration of possible changes in the geometry of the Africa-Europe plate boundary. V_C = rate of plate convergence; V_R = rate of trench retreat. (a) Fixed plate boundary oriented E-W, with the African plate subducting beneath Europe. (b) Northward convex boundary in response to indentation. (c) Southward convex boundary due to trench retreat ($V_R > V_C$). (d) Eastward and westward convex boundaries due to trench retreat perpendicular to plate convergence assisted by lithospheric-scale tear faulting.

Figure 7. Complex oroclinal structures in ancient and modern forearc regions, shown in a similar scale. (a) The ear-shaped structure of the southern New England Orogen (eastern Australia) is indicated by the rotation of forearc basin blocks (dark grey) and the structural fabrics in the accretionary complex (light grey) (after Li et al., 2012; Li and Rosenbaum, 2014). Stars show locations of syn-oroclinal, and supposedly tear-related, volcanism (Werrie Basalt and Alum Mountain). The thick black line is an inferred curved structural marker (serpentinites) that delineates the shape of the oroclines (Rosenbaum, 2012). NB, Nambucca Block. (b) The central Mediterranean Calabrian and Hellenic forearc regions (grey areas). Note that trench retreat in opposite two directions has resulted in a collisional zone between the Calabrian accretionary wedge (CAW) and the Hellenic accretionary wedge (HAW). Dashed lines indicate the structural grain within the accretionary complexes based on seafloor lineaments, anticlinal folds and reverse faults (Polonia et al., 2011; Gallais et al., 2012; Polonia et al., 2013). Stars show locations of the Mount Etna-Hyblean tear-related volcanism. The thick black delineates the approximate shape of the oroclines.

Table 1. Geometrical aspects of Mediterranean oroclines.

Order	**Name**	**Width (km)**	**Amplitude (km)**	**Amplitude/ Width**	**Orientation relative to northward-convex**
1	Adriatic	3814	1740	0.46	1E
2	Western Mediterranean	2082	1145	0.55	148E
2	Alps-Carpathian	1819	468	0.26	6W
2	Eastern Mediterranean	2309	623	0.27	150W
3	Gibraltar	350	549	1.57	114W
3	Calabrian	361	267	0.74	115E
3	Umbria-Marche	406	66	0.16	37E
3	Carpathian	835	377	0.45	29E
3	Western Alps	388	219	0.56	68W
3	Aegean	765	225	0.29	165W
3	Cyprus	458	113	0.25	178E
4	Hyblean	308	59	0.19	3E
4	Jura	267	68	0.25	36W
4	Eratosthenes	110	19	0.17	0

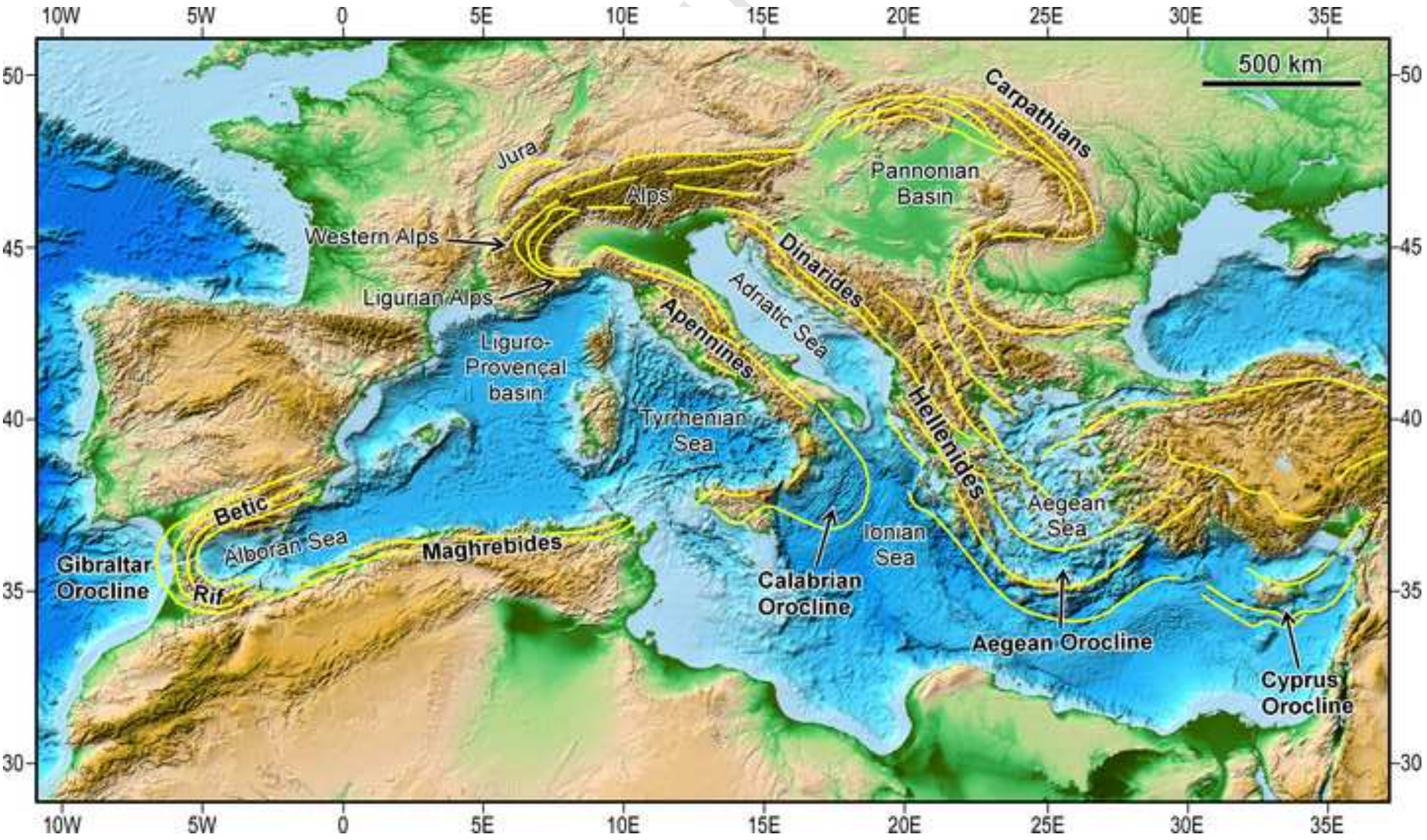
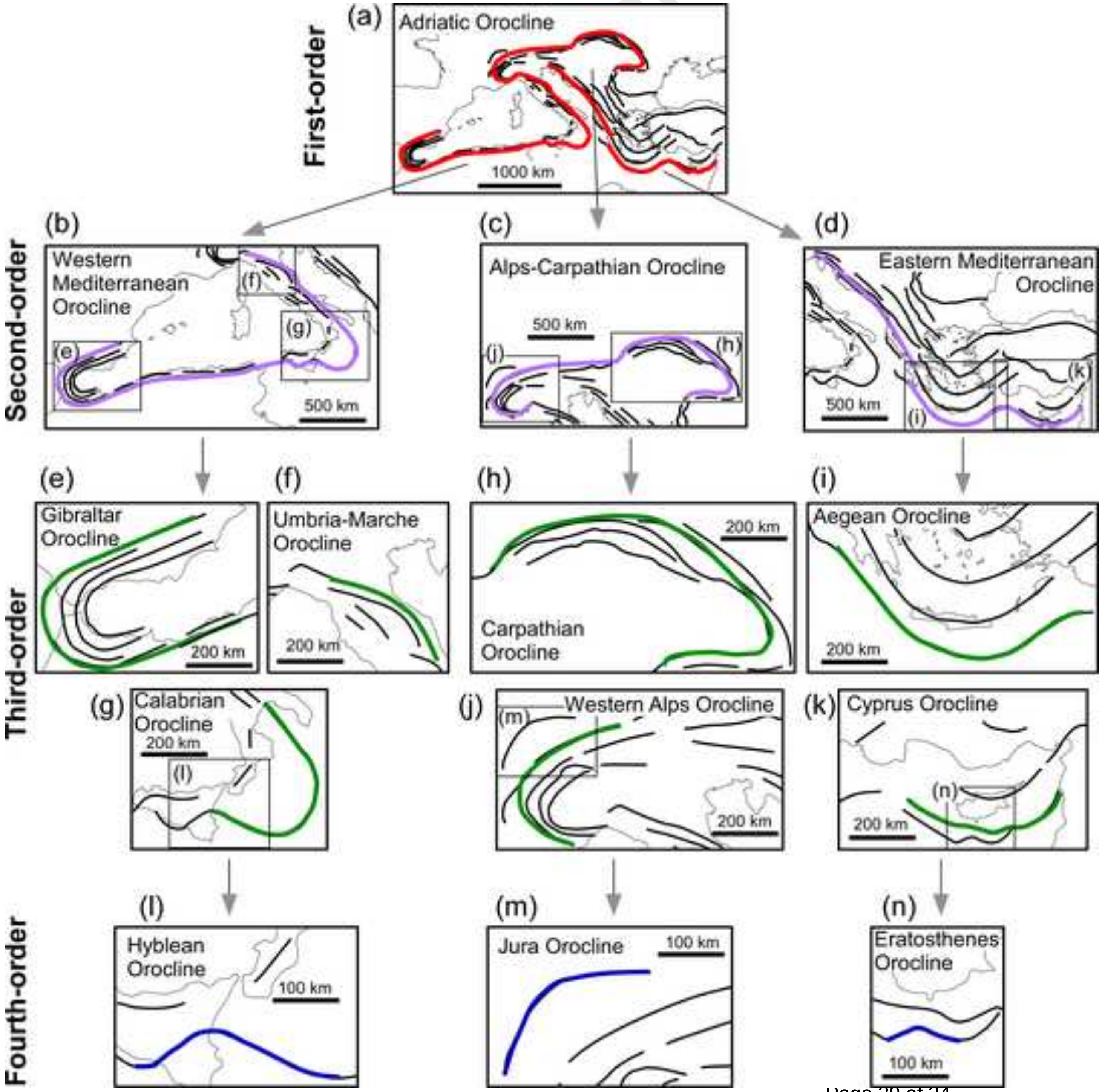

10W
5W
0
5E
10E
15E
20E
25E
30E
35E
50
45
40
35
30
500 km
Carpathians
Jura
Alps
Pannonian Basin
Western Alps
Dinarides
Ligurian Alps
Adriatic Sea
Apennines
Liguro-Provençal basin
Hellenides
Tyrrhenian Sea
Aegean Sea
Betic
Alboran Sea
Maghrebides
Ionian Sea
Gibraltar Orocline
Rif
Calabrian Orocline
Aegean Orocline
Cyprus Orocline

Figure 2


First-order
(a) Adriatic Orocline
1000 km
Second-order
(b) Western Mediterranean Orocline
(e)
(f)
(g)
500 km
(c) Alps-Carpathian Orocline
500 km
(j)
(h)
(d) Eastern Mediterranean Orocline
500 km
(i)
(k)
Third-order
(e) Gibraltar Orocline
200 km
(f) Umbria-Marche Orocline
200 km
(h) Carpathian Orocline
200 km
(i) Aegean Orocline
200 km
(g) Calabrian Orocline
200 km
(l)
(j) Western Alps Orocline
(m)
200 km
(k) Cyprus Orocline
(n)
200 km
Fourth-order
(l) Hyblean Orocline
100 km
(m) Jura Orocline
100 km
(n) Eratosthenes Orocline
100 km

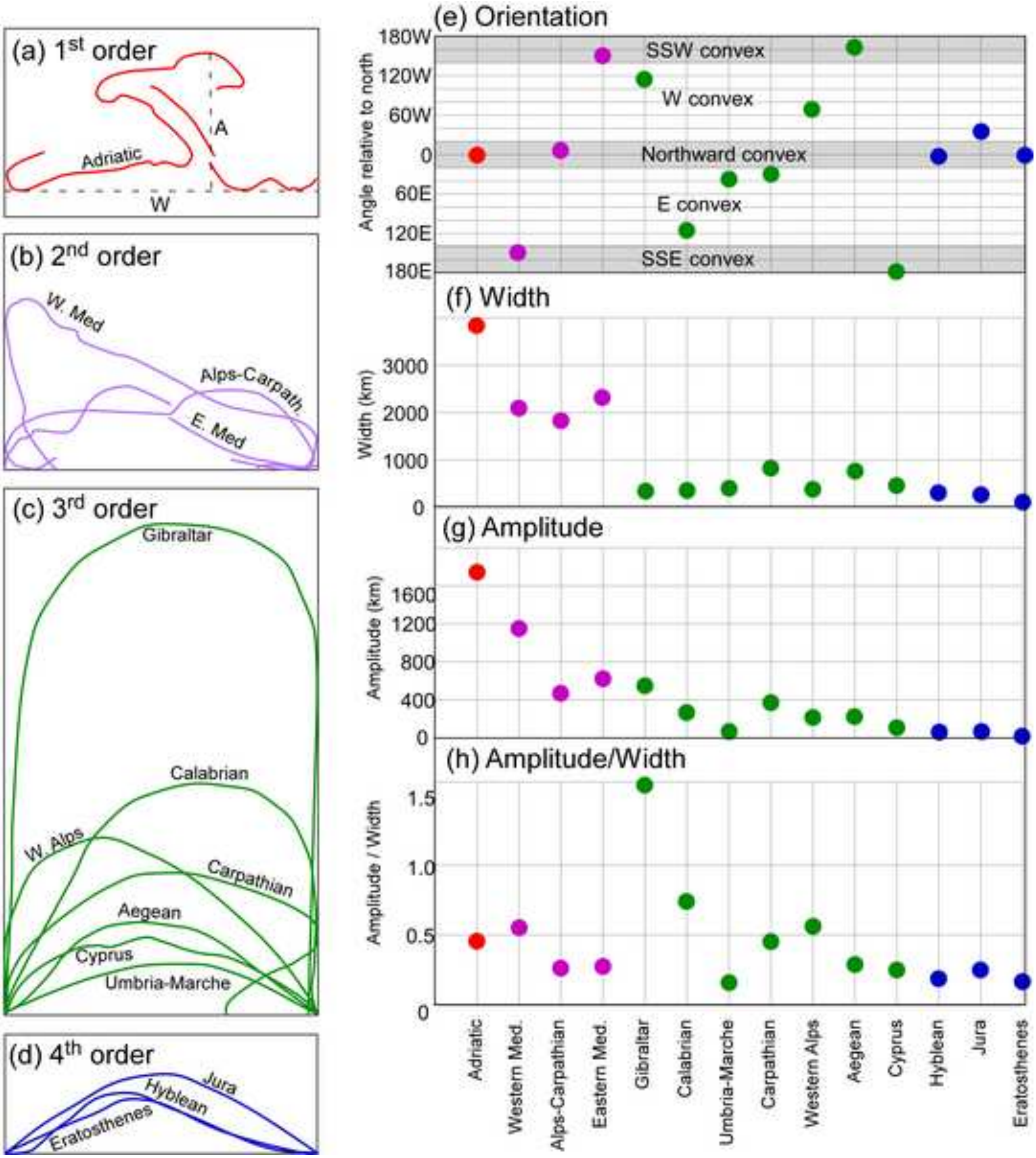

(a) 1st order
Adriatic
A
W
(b) 2nd order
W. Med
Alps-Carpath
E. Med
(c) 3rd order
Gibraltar
Calabrian
W. Alps
Carpathian
Aegean
Cyprus
Umbria-Marche
(d) 4th order
Jura
Hyblean
Eratosthenes
(e) Orientation
Angle relative to north
180W
120W
60W
0
60E
120E
180E
SSW convex
W convex
Northward convex
E convex
SSE convex
(f) Width
Width (km)
3000
2000
1000
0
(g) Amplitude
Amplitude (km)
1600
1200
800
400
0
(h) Amplitude/Width
Amplitude / Width
1.5
1.0
0.5
0
Adriatic
Western Med.
Alps-Carpathian
Eastern Med.
Gibraltar
Calabrian
Umbria-Marche
Carpathian
Western Alps
Aegean
Cyprus
Hyblean
Jura
Eratosthenes

Figure 4

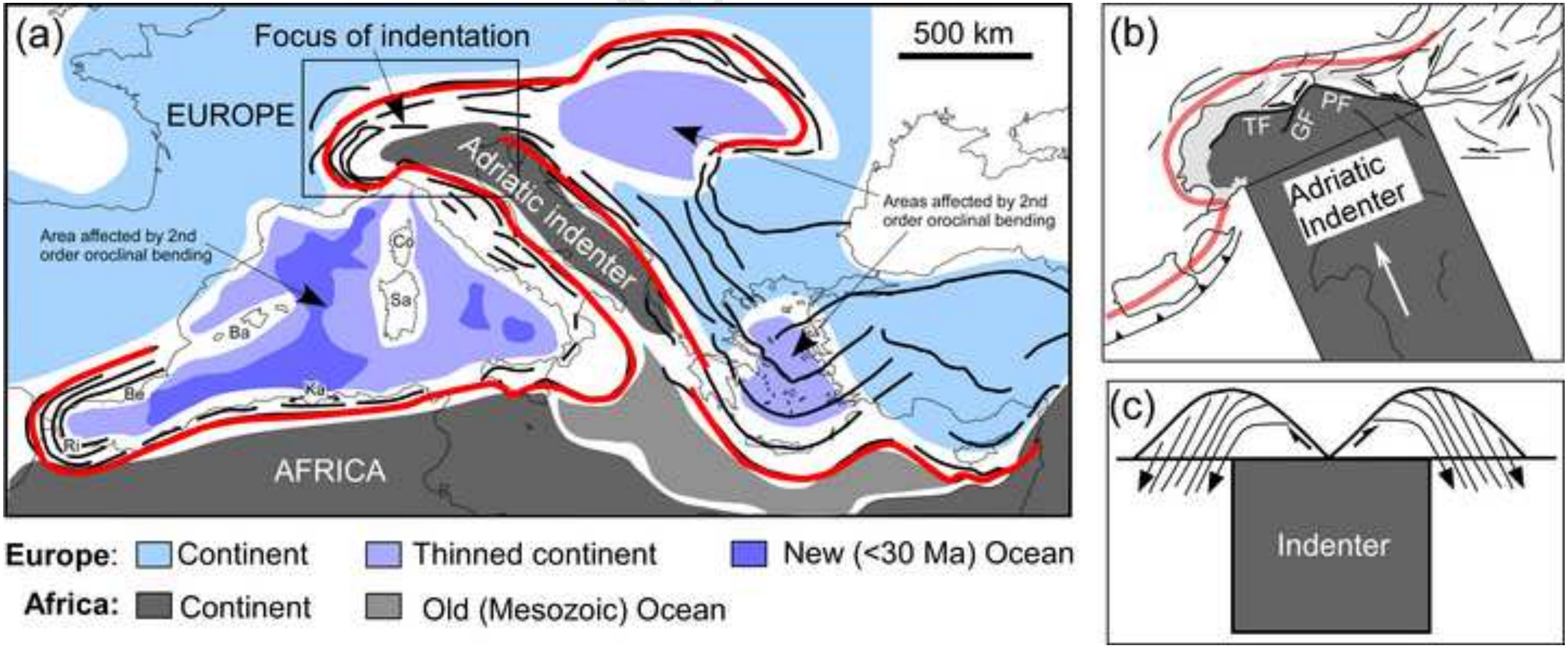

(a)
Focus of indentation
500 km
EUROPE
Adriatic indenter
Areas affected by 2nd order oroclinal bending
Area affected by 2nd order oroclinal bending
Co
Sa
Ba
Be
Ka
Ri
AFRICA
(b)
TF
GF
PF
Adriatic Indenter
(c)
Indenter
Europe: Continent
Thinned continent
New (<30 Ma) Ocean
Africa: Continent
Old (Mesozoic) Ocean

Figure 5

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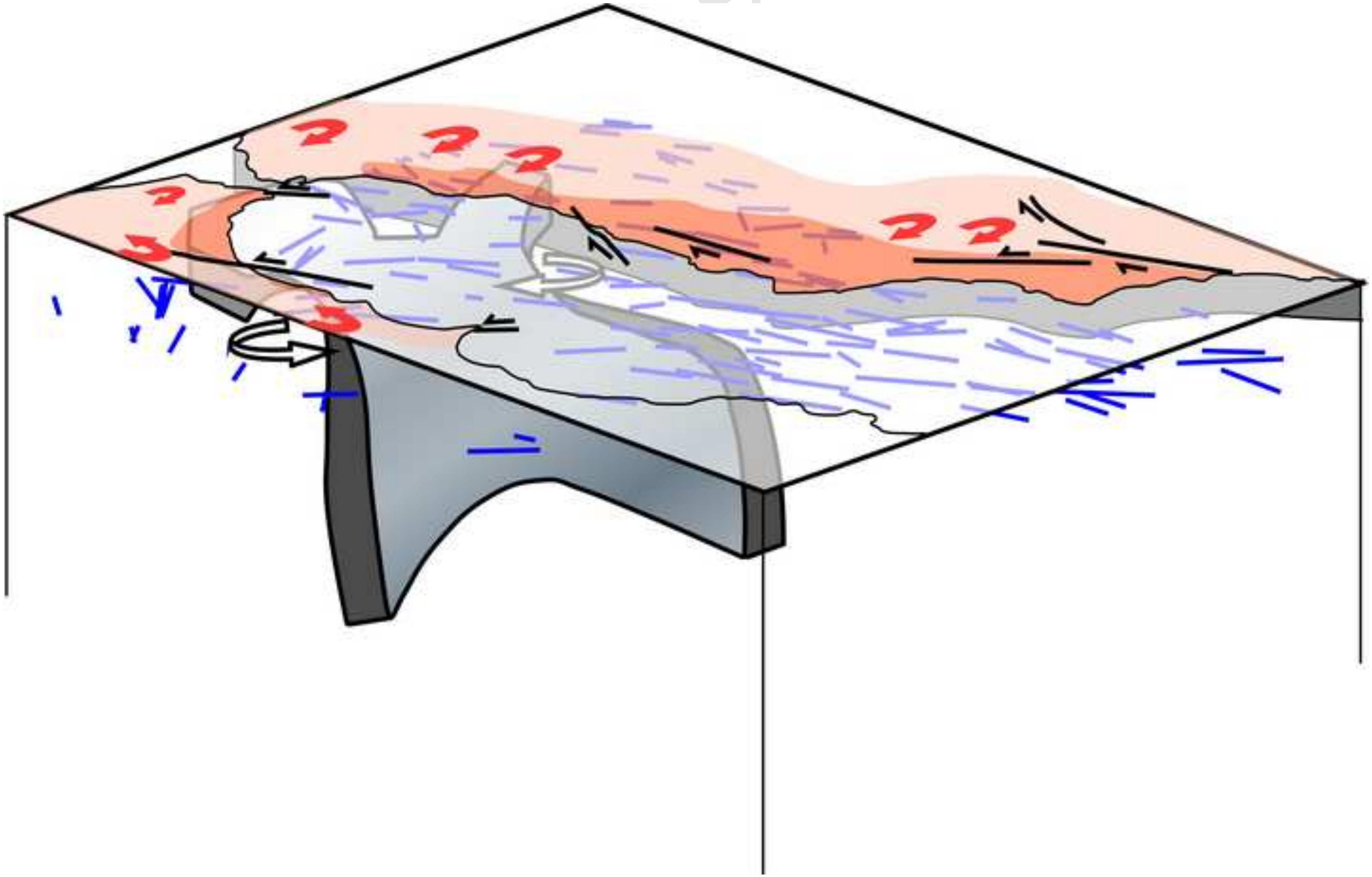

Figure 6

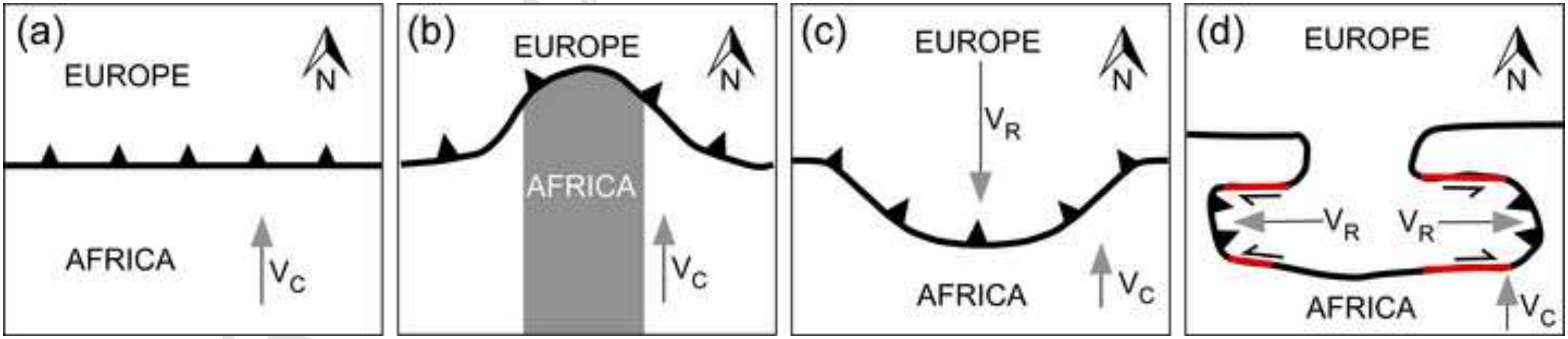
(a)
EUROPE
N
AFRICA
V_C
(b)
EUROPE
N
AFRICA
V_C
(c)
EUROPE
N
V_R
AFRICA
V_C
(d)
EUROPE
N
V_R
V_R
AFRICA
V_C

Figure 7