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 orocline 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 orocline 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 orocline 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, orocline 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 orocline is recognised at the scale of the whole Mediterranean, and is termed here the Adriatic Orocline (Figure 2a). 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 3a).

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 3f,g). The Western Mediterranean Orocline is characterised by an asymmetric SSE-convex structure, stretching from the Apennines to North Africa and Gibraltar (Figure 2b). 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 3h). Farther north, another second-order, northward-convex curvature can be defined (Figure 2c), 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 2d).

Third-order oroclines are typically 350-800 km wide and 100-500 km in amplitude (Table 1). The Gibraltar Orocline (Figure 2e), 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 3e). The opposite sense, eastward-convex Calabrian Orocline (Figure 2g), 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 2f). 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 2j). 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 2h). In the eastern Mediterranean, two third-order oroclines can be recognised: the Aegean Orocline and Cyprus Orocline (Figure 2i,k). Both oroclines have a southward-convex geometry (Figure 3e) with a relatively low amplitude-to-width ratio (0.25 and 0.29, Figure 3h).

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

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 4a), 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 4b,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 4c), 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 cuspat 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 4a). 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 4a) 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 4a) 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 3b,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 toroidal 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 toroidal 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 toroidal 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 oroinal 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 oroinal bending and can lead to the development of mature third-order oroines. Oroines 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 oroiline(s); and (3) syn-oroclinal strike-slip faulting.
6. Discussion

6.1. Formation of Mediterranean oroelines

The examples from the Mediterranean region provide compelling evidence for the role of plate boundary migration during oroclinal bending. The formation of the Mediterranean oroelines, 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 oroelines. Commonly, this is accompanied by slab tearing and subduction segmentation. Accordingly, the geometry of oroelines, such as Gibraltar and Calabrian oroelines, 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 oroelines 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 orocinal 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 6b). Indeed, Figure 3e 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 6c). 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 6d). 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 orocinal 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 orocline 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 orocline 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 2f) 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 2m), 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 orocline 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 orocline 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 7a) delineates an ear-shaped structure (Rosenbaum, 2012; Rosenbaum et al., 2012), with the strongest orocinal-related deformation concentrated in the “core” of the structure (Nambucca Block, Figure 7a) (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 7b) is intriguing. Both systems show that the expression of orocinal 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-orocinal 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 orocinal 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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References


Ridge and surroundings from combined swath mapping and seismic reflection profiling. Tectonophysics 343, 21-47.


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 toroidal 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-orocinal, 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.

<table>
<thead>
<tr>
<th>Order</th>
<th>Name</th>
<th>Width (km)</th>
<th>Amplitude (km)</th>
<th>Amplitude/Width</th>
<th>Orientation relative to northward-convex</th>
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Figure 5
Click here to download high resolution image
Figure 6
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