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The dip of the foreland monocline in the Alps and Apennines

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Abstract

The foreland monocline dips underneath thrust belts and accretionary wedges, both in oceanic and continental subduction zones. We present new data on the dip of the monocline in the frontal part of two orogens, the Alps and the Apennines. There is an overall difference between the dip of the relative monoclines, and there is also a strong lateral variation along both arcs. In the Alps, the regional dip varies between 0° in the remote foreland, to an average of 2–3° at the front of the thrust belt below the foredeep, to about 5° beneath the external thrust-sheets within 40 km from the leading edge of the accretionary wedge. The regional dip of the monocline in the Apennines has an average of 4–5° at the front of the thrust belt below the foredeep, to about 10° beneath the external thrust-sheets within 40 km from the leading edge of the accretionary wedge. There are areas where the dip exceeds 20°. The Apennines though topographically lower than the Alps present higher monocline dips and a deeper foredeep. Moreover, there are variations in the dip of the monocline moving along the strike of the two belts: the low values coincide with Permian–Mesozoic inherited horsts, whereas the steeper values correspond to basinal areas, and they usually match the salients of the thrust belt front. Within the salients the distance between thrust ramps increases. Therefore, there are two orders of mean values of the dip of the foreland monocline, the first at the orogen scale (more than 1000 km wavelength), the second at the regional scale (100–200 km wavelength) within the single orogen. Lateral variations in the lithospheric buoyancy due to the inherited Mesozoic stretching may explain the second order variations in foreland dip, but not the first order mean values which seem to be more sensitive to the geographic polarity of the subduction rather than to the lithospheric composition which is rather similar in the Alpine and in the central-northern Apennines slabs.

Keywords: forelands; monoclines; Alps; Apennines; fore-arc basins

1. Introduction

The foreland monocline (Fig. 1) is a common feature for all thrust belts and accretionary wedges [1,2]. The foreland geology is often understated in regional studies of orogens, in spite of its crucial role in controlling the thrust belts evolution. The foreland monocline tends to increase its dip toward the interior of the belts, both in oceanic and continental subduction zones [3,4] or associated back-thrust belts, and its subsidence rate controls the development of the trench or the foreland basin [5–8]. The basement top in foreland basins is usually convex upward [2]. Usually

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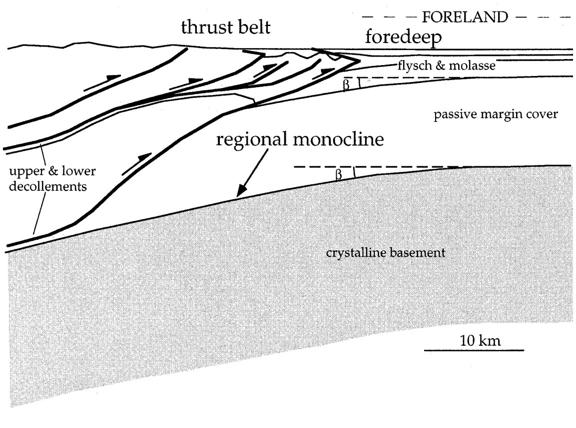

Fig. 1. Idealised front of a thrust belt and the associated regional monocline. The dip β generally increases from the foreland to underneath the thrust belt.

the steeper foreland monoclines are the areas of faster subsidence, whatever their origin.

The dip of the monocline around the orogens of the world can be measured at the base of the foredeep and beneath the front of the thrust belt (Fig. 1). The dip usually ranges between low values of 1–5° to high values of 10–20°. Higher values are quite typical for west-directed subduction zones. Doglioni [7,9] has proposed an eastward mantle flow, causing subduction to be steep if west-directed, in order to explain this observation. Along the strike of any subduction zone, or retrobelt, variation in the monocline dip should have more local causes. Such causes will be explored for the Alps and Apennines accretionary wedges.

In this paper we present a new data set on the dip (β) of the foreland regional monocline of the frontal parts of the Alps and the Apennines accretionary wedges (Fig. 2). We used the water divide as a reference with respect to the thrust belt front; it is an arbitrary but useful reference line since it allows for a normalised visualisation of undulations of the orogenic front and the relative foreland monocline (Figs. 3 and 4). In the Apennines, the main outcropping belt is in an extensional tectonic regime. However, extension and compression at the front of the belt are co-genetic since they moved 'eastward' together through time, indicating that they are intimately linked. Therefore the water divide, even if located in the extensional part of the belt should be a useful reference line for the thrust belt analysis.

Our data compilation documents significant differences in the mean dip of the foreland monocline between the Alps and the Apennines, as well as variations along a given belt. We will discuss how these changes in dip along the single orogens are likely to be associated with lateral variations of the inherited crustal and lithospheric thicknesses and compositions. These variations also appear to control 'foreland' seismicity, changes in subsidence rates and propagation of the frontal decollement. It will also be discussed how the distance between thrust ramps is sensitive to the dip of the regional monocline, generating along strike transfer zones and undulations in the thrust belt coincident with variations of the foreland dip.

We measured the present dip of the regional monocline around the foreland–foredeep of the Alps and Apennines (Fig. 2), using seismic reflection profiles available in the literature, some unpublished industrial data and regional geologic balanced cross-sections. Where possible, we used the top of the crystalline basement as key bed of reference, or the top of the undeformed Mesozoic, or other layers that could be assumed to parallel the dip of the foreland monocline. The dip of the monocline in seismic lines not converted to depth was computed assuming standard velocities (e.g. [10] for the Apennines sequences). Where possible, the dip was computed both in foreland areas and below the frontal thrusts. There are more data available for the Apennines due to extensive oil exploration.

2. The dip of the foreland monocline

2.1. Alps foreland monocline

The Alps are a double verging orogen formed since Cretaceous times from the subduction of the Tethys ocean and of the European continental margin beneath the Adriatic plate [11,12]. The Permian–Mesozoic sedimentary cover of the present foreland areas lies on a Variscan basement. The double vergence of the orogen implies the presence of two forelands and two regional

Fig. 2. Dip values of the regional monocline around the Alps and the Apennines. References in the text.

monoclines, one at the front of the western and northern Alps, and the second at the front of the southern Alps. The western and northern Alps are the frontal thrust belt with respect to the subduction zone, whereas the southern Alps are the conjugate retro-belt with respect to the subduction zone. The dip values of the regional monocline in the northern and western foreland of the frontal Alps are relatively low, between 2° and 6° (Fig. 3). Considering the Jura as the real front of the Alps, no significant foredeep occurs in the foreland, and the regional monocline is close to 1°. The main sections where we measured the dip to the north and northeast of the Alps come from the seismic sections by [13–17]; whereas the sections from the northwestern and western front of the Alps come from [11,12,18–20]. The sections from the southern Alps are mainly from [21–25]. Here also the values are relatively low (2–3°). In the western southern Alps, the regional monocline may be either horizontal or even dipping toward the foreland to the south, due to the later oppo-

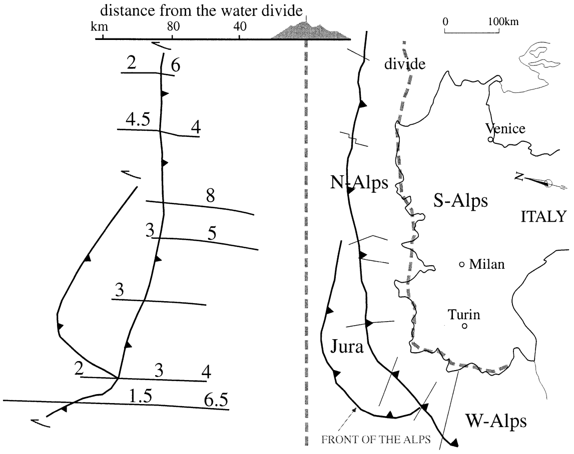

Fig. 3. Profiles of the foreland monocline around the Western and Northern Alps. The profiles are normalised to the top of the basement and the water divide in the belt.

site tilting generated by the Apennines subduction and related foredeep on the pre-existing Alps [26].

2.2. *Apennines foreland monocline*

The Apennines are an arc about 1500 km long throughout the Italian peninsula down to Sicily. They mainly formed during the last 30 Ma. They developed on top of a west-directed subduction zone, retreating approximately to the east, and forming an irregular arc from Piemonte-Monferrato in northern Italy, down to north Africa, passing through the Italian peninsula [27–31]. The Apennines foredeep migrated eastward (and northeast or southeast) along the arc as indicated by the depocentre migration both in the central-northern and southern parts of the belt [32–34]. The foredeep propagation occurred on top of the approximately eastward migrating foreland monocline which retreated with the slab. The dip of the foreland monocline in the Apennines is controlled by the hinge of the subduction zone which retreated 'eastward' during the Neogene and Quaternary [27,29,30,51,52].

The values of the Apennines monocline dip have a wide range of angles (Fig. 4). We measured the dip on published sections [21,35–37] for the Po Basin. The sections from the central-northern Apennines are from [10,33,38–41]. The sections used for measuring the dip of the southern Apennines, Ionian sea and Sicily are from [38,42–50]. Some unpublished industrial seismic lines were also used. The lowest dips are in the Mortara area (western Po Basin), Adventure bank (western Sicily), Hyblean Plateau (eastern Sicily) and northern Bradano (Figs. 2 and 4). The steepest values are below the Bologna-Ferrara zone (eastern Po Basin), Pescara offshore (western central Adriatic sea), south Calabria offshore (northwestern Ionian sea) and the Caltanissetta basin (southern Sicily) (Fig. 4). The steepest parts occur along the accretionary wedge salients (see Fig. 4). The steepest parts of the regional monocline are also associated with the lowest values of gravimetric anomalies and heat flow. A clear example is in central Sicily, where a low gravity corresponds to the area of largest dips of the foredeep monocline. The negative gravimetric values are likely related to the lighter foredeep sediments and to the mass deficit due to the subduction. Therefore, the steep monocline would indicate that the shallow part of the slab is steeper.

The average dip of the entire arc is around 6–10° within about 40 km inward from the front of the accretionary wedge. The steepest values correspond to the Mesozoic basins in the foreland.

Significant variations in the dip of the monocline occur along the strike. Moreover, referring to the water divide, the monocline is relatively either more or less advanced. The more distant monoclines (more advanced toward the foreland with respect to the water divide) correspond to areas of salients of the accretionary wedge. In general, but not always, the salients are zones characterised by a steep foreland monocline. The largest salient of the Apennines is in the Ionian sea where the front of the accretionary wedge is at the furthest location from the water divide in Calabria; this salient is located where the longest subduction has occurred and the decollement is more advanced in the basinal sediments and in the Messinian evaporites. Other significant salients are the Gela nappe in Sicily and the three arcs of the northern Apennines buried in the Po Basin which match a steep foreland monocline (Fig. 4).

The dip in the Apennines is controlled by the hinge of the subduction zone which retreated eastward during the Neogene and Quaternary [27,29,30,51,52].

3. Foreland dip versus Mesozoic rift-related paleo-structures

The Apennines main arc exhibits second order arcs of 100–200 km. These salients drape the pre-Neogene lateral variations in thickness, composition and rheology of the passive continental margins (western Adriatic plate, northern Africa) and oceanic embayment (Ionian sea) occurring in the foreland (Fig. 4). For the Mesozoic structural grain of the Alps and Apennines see [53] for the entire Alps, [54,55] for the southern Alps, [56] for the central-northern Apennines, [57] for the southern Apennines, [58] for the Malta escarpment and [59] for Sicily. Horsts and grabens are roughly N–S trending in present coordinates. The Ionian oceanic basin is mainly NW–SE oriented. The salients frequently correspond to zones where the prism interfered with Mesozoic basins, richer in shales and facilitating longer decollement planes.

The inherited Permian and Mesozoic architecture of horsts and grabens generated lateral var-

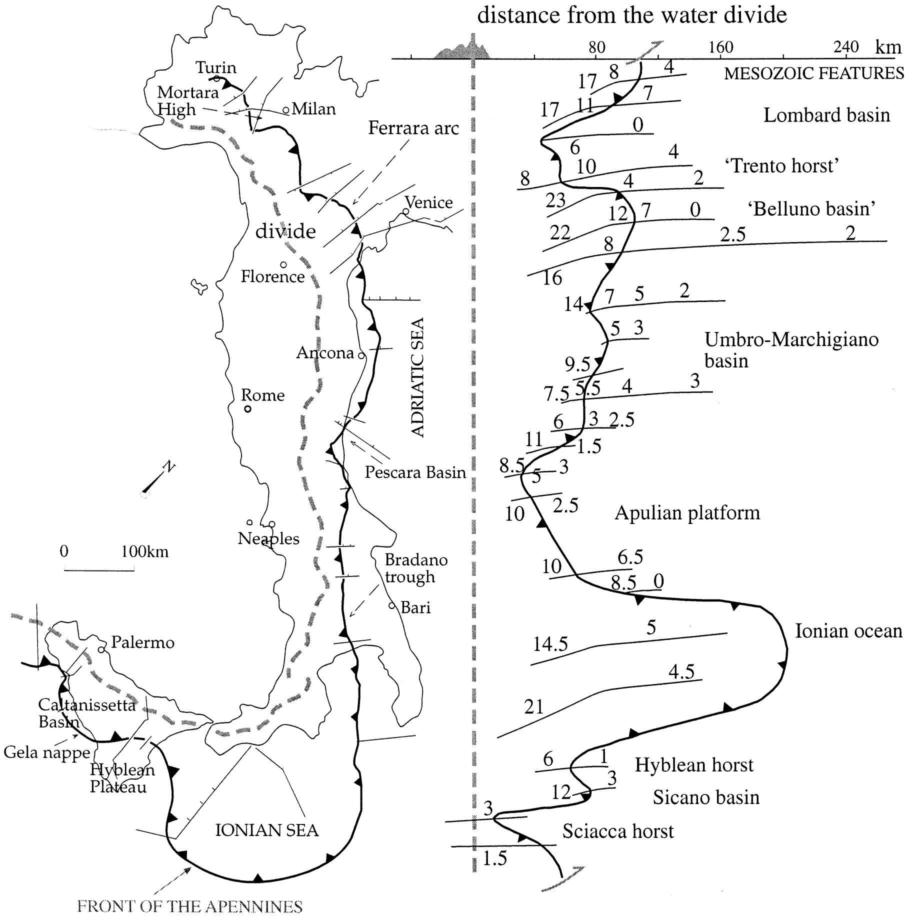

Fig. 4. Profiles of the foreland monocline around the Apennines. The profiles are normalised to the top of the basement and the water divide in the belt. Names to the right are the Mesozoic inherited structures of the foreland. Names to the left are related to the Neogene–Quaternary features.

iations in the mechanical behaviour when involved in the thrust belt. We observe that the steepest dips of the foreland monocline correspond to the Permian and Mesozoic structural basins and transfer zones formed in the overlying accretionary prism along the horst–graben margins. In the Po basin, the most advanced parts of the front of the accretionary prism coincide with low values of the magnetic anomalies which might indicate a deeper basement [60].

Similarly, in the Alps there are significant arcs (or salients) which are associated with lateral changes of foreland dip and inherited Mesozoic structures; the most evident is the Giudicarie belt in the central part of the southern Alps which is a left-lateral transpressive zone formed at the boundary between the Lombard basin to the west and the Trento horst to the east [61]. Thrusts propagated more southward in the basinal sequences of the Lombard basin (salient) with respect to those of the Trento horst (recess). Other salients are associated with the areal distribution of salt sequences (e.g. the Jura mountains, detached in the Triassic salt).

The oceanic lithosphere and the thinned continental lithosphere which underwent magmatic underplating are the segments of lithosphere which are commonly observed along subduction zones. The rifting process along passive continental margins generates horsts and grabens that may correspond at depth to areas of, respectively, lower and higher degrees of intrusions of mafic rocks from the mantle. This underplating makes the rifted area heavier and therefore easier to subduct. Therefore, the inherited Permian and Mesozoic rift could have controlled the lateral variations of the regional monocline dip which is a function of the degree of 'subductibility' of the foreland. Conversely, the pattern of the thrust belt front might be a key in predicting the lateral changes of the foreland monocline dip and the lateral changes in crustal history. The relatively steeper monocline is suggested to be an area of easier subduction and corresponds to the zones of higher subsidence rates. Opposite examples are the Hyblean plateau in Sicily (shallow dip, about 3–5°) and the Ferrara arc in the Po basin (high dip, about 20°) which are, respectively, a pre-subduction structural high where the Plio–Pleistocene foredeep subsidence rates have been in the order of 0.1 mm/yr, and a structural low, where the coeval foredeep subsidence rates exceeded 1 mm/yr [7]. Low values of the foreland monocline dip are regularly associated with a more internal front of the accretionary wedge and a shorter distance between thrust ramps, whereas high dip angles show more advanced thrusts into the foreland and wider distances between thrusts ramps (e.g. the Gela Nappe in southern Sicily, Fig. 4).

Therefore, we may argue the following comments: (a) high values for the monocline dip are associated with salients which characterise the Apennines and, to a lesser extent, the Alps; (b) the salients are associated with Mesozoic rift basins, of which the shaly infilling resulted in relatively long decollements when involved in thrusting and, hence, in a relatively advanced position of the orogenic front; (c) the combination of (a) and (b) implies that high values for the monoclinal dip are associated with Mesozoic rift basins; (d) the relation in (c) may be explained by the effect of the Mesozoic rifting on the lithosphere, in terms of subductibility; (e) more specifically, rifting causes density variations: thinning is followed by underplating which eventually results in denser and hence more subductable lithosphere below rifts.

4. Foreland dip versus thrust belt structure, foredeep and seismicity

The more advanced area or salient of the accretionary wedge corresponds to an area where the distance between the thrust ramps is larger and the structural and topographic elevation of the prism is lower. These are in general also the areas where the foreland monocline is steeper [2]. The Apennines foredeep was punctuated by the growth of folds which terminated along transfer zones. Therefore, they formed several irregular basins constrained by this structural framework; this partly explains the several formational names describing the Neogene stratigraphy of the Apennines.

Thrusts frequently merge into common decolle-

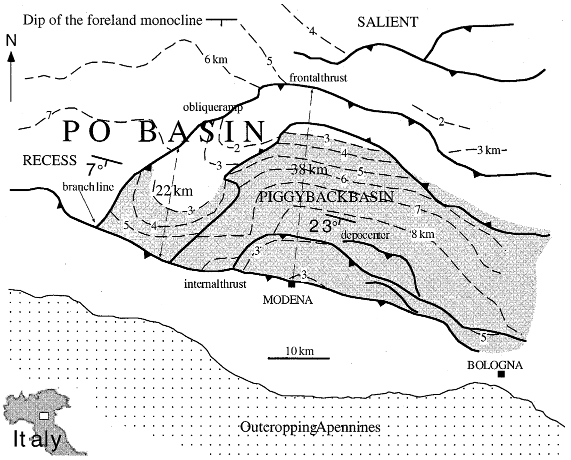

Fig. 5. Piggy-back basin buried in the Po Plain, northern Italy, and representing the northeast front of the Apennines accretionary wedge. The numbers indicate the thickness in kilometres of the Pliocene and Quaternary foredeep sediments filling the piggy-back basin and coeval with the thrust growth. Note the arcuate shape of the main frontal thrust, generating a salient of the accretionary prism which coincides with a Mesozoic basin and high values of the foreland monocline. A lower value of the monocline occurs to the west, in the recess of the thrusts. The thrusts branch to the west and the piggy-back basin narrows along the same direction. The area where the basin is thicker than 3 km is shaded. The main subsurface data are from [35].

ment planes which may have different depths in the upper crust (from a few hundred meters up to several kilometres). The ramp distance is controlled by a number of factors, i.e. depth of the decollement, basal friction in the decollement plane, magnitude and orientation of the stress field, strength of the rocks overlying the decollement, etc. The thrusts undulate along the strike as the former parameters change along the belt. For example, lateral and oblique ramps are particularly evident along facies changes in the sedimentary cover or in the basement. Thrusts may be highly undulated and anastomosed in inhomogeneous settings (Fig. 5). Therefore, the distance between ramps may rapidly vary along the strike through transfer zones. Usually the distance among major ramps in the Apennines is between 5 and 15 km at the front of the accretionary prism. Therefore, the basins forming at the front and on top of the active thrusts and folds have a shape that is determined by the distance between the ramp-related folds, the dip of the foreland monocline and the along-strike variation of the two former values.

Different angles of the regional monocline, combined with the sediment supply in the foredeep, contribute to controlling the mechanics of the fold development: the steeper and the deeper the monocline is, the more the fold can be loaded by sediments, and the higher is the lithostatic load acting on the decollement. Moreover, the variable angle of the regional dip generates variable values of the normal and shear stresses induced by the regional maximum horizontal stress acting on the basal decollement which usually parallels the regional dip.

Usually the frontal basal decollement of thrust belts parallels the dip of the regional monocline, e.g. [62,63]. The critical taper of an accretionary wedge is defined as the shape that is on the verge of failure under horizontal compression [64]. The lower side of this triangle is the basal decollement. The critical taper is strongly dependent on the basal decollement friction: the less friction there is, the smaller the critical taper of the wedge is. Its upper side is, by definition, the averaged wedge topography which may or may not be the same as the fold crest envelope. The angle between the envelope of the fold crest and the basal decollement is usually in the order of 7–8° [65]. Therefore, when the monocline dips toward the interior at angles higher than 8–10°, the envelope of the fold crest may also dip towards the interior of the belt (Fig. 6). The Apennines show different cases where the envelope to the fold crest dips either toward the interior or toward the foreland of the accretionary wedge, and these cases are mainly a function of the dip of the foreland monocline (Fig. 6).

On the other hand, when the foreland monocline and the frontal decollement are less steep (less than 8–10°), there is little accommodation space, the accretionary wedge largely outcrops and it is more deeply eroded, supplying clastic sediments to the foredeep (Fig. 6). Therefore, there might be a fold which, moving along the strike, is lying both on a steep regional monocline and on a shallow counterpart (e.g. in the Po Basin): the result is that the same fold is buried by

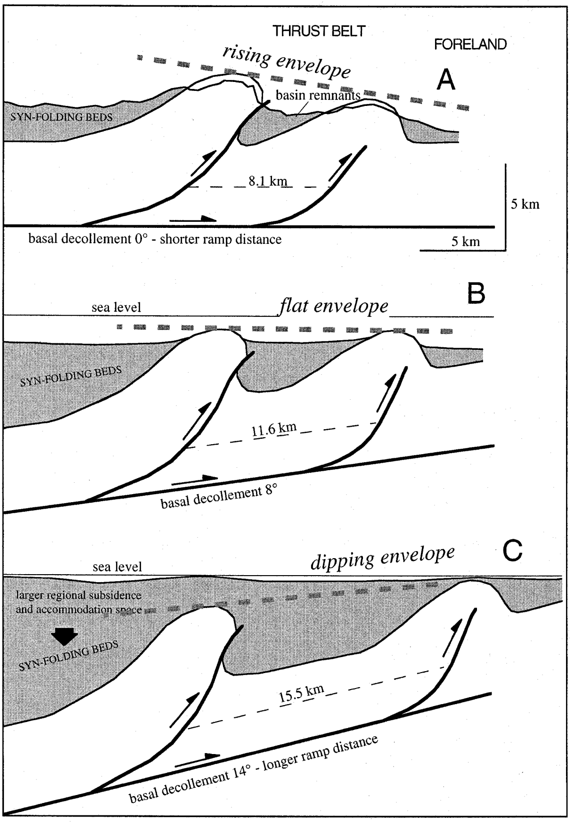

Fig. 6. The frontal thrusts and associated folds of an accretionary wedge may have an envelope to the fold crest rising (A), flat (B) or dipping (C) toward the hinterland. These variations are primarily controlled by the dip of the foreland monocline which usually parallels the basal decollement. This should control different accommodation space for the syntectonic sedimentation which is obviously larger where there are high rates of subsidence of the foreland basement monocline (C). Distance between thrust ramps increases with the dip of the basal decollement, and thrust-top basins widen increasing ramp distance. This is a common case at the front of the buried Apennines wedge, where Mesozoic structural basins and thin continental or oceanic crust occur in the foreland.

growth sedimentation in the steep part, where the onlaps of the growth strata migrated toward the hinge zone of the fold, simulating a 'transgression' due to the high subsidence; on the shallow monocline, the same fold is rather eroded and the onlaps of the growth strata migrated away from the hinge zone, simulating a 'regressive' trend at the same time.

The accommodation space associated with high dips of the foreland monocline is an area that may be filled by different amounts of thrust-sheets; the remaining free area may be entirely or partially filled by sediments. The different propagation of thrust-sheets is a function of the basal friction acting on the decollement plane which is controlled by lithology, pore-fluid pressure, depth of the decollement, temperature, etc.; low strength lithology as salt at a shallow depth provides an excellent decollement layer which may lead to a larger thrust-sheet propagation than in adjacent sectors of a thrust belt, even where there are no significant variations in the dip of the foreland monocline, e.g. the salient of the Jura mountains [66,19]. Two main cases can be distinguished, i.e. where the basal decollement is controlled mainly either by friction or by viscous behaviour; the viscous behaviour has a larger distance between thrust ramps [67]. Based on physical models, thrust spacing increases with basal friction and with decollement depth [68,69].

There are 'foreland' earthquakes around the Apennines located along the Tremiti fault system [70], which have been interpreted as the right-lateral transfer zone between the larger slab retreat of the central-northern Adriatic lithosphere and the Puglia area [71]. This differential retreat was interpreted to be caused by the lower rate of penetration into the mantle of the Mesozoic rift-related thicker and lighter Puglia lithosphere during the Pleistocene compared to the northern counterpart. There are also earthquakes in the Po Basin, e.g. the Reggio Emilia (October, 1996) which developed well below (16 km) the basal decollement of the accretionary wedge (4–10 km). This earthquake had a strike-slip focal mechanism and is located at a change in dip of the foreland monocline (7–9° to the west and 15–20° to the east). We speculate that the differential subsidence rates at both sides of the monocline require a transfer zone which should be active during the general rollback of the subduction zone. A similar case appears to be the Malta escarpment, which is an inherited Mesozoic margin between the continental crust in eastern Sicily and the oceanic Ionian basin. The two lithospheric slabs west and east of the escarpment clearly rollback at different rates, due to the higher density of the oceanic Ionian lithosphere. The larger retreat of the subduction hinge in the Ionian sea and consequently of the foreland monocline implies that the Mesozoic Malta escarpment has been reactivated as a right-lateral transfer zone for this differential motion of the foreland. This could kinematically explain the eastern Sicily foreland seismicity. In summary, the lateral variations in dip of the foreland monocline controlled by the pre-existing Mesozoic rift-related lateral changes in lithospheric composition and thickness could explain the enigmatic seismic provinces in the foreland or below the foredeep, which do not always follow the outcropping thrust-belt features.

5. Concluding remarks

The analysis of the dip of the foreland monocline in the Alps and the Apennines shows that there are two orders of dip variations, i.e. (1) among the two belts and (2) at the regional scale within the single orogens.

1. The Alps and the Apennines have, respectively, low (2–4°) and high (5–12°) mean values of the dip of the regional monocline. This observation confirms the profound differences between these two orogens; the Apennines, in spite of their younger, mainly Neogene age, and their lower topography, show the steepest values and the highest subsidence rates in the foredeep. The subsidence in foredeeps has been ascribed to the load of thrust-sheets [5,6,72] or/and to the slab pull [73,74]. However, we note that along the Apennines subduction portions of the Adriatic continental lithosphere some 70–90 km thick [75], subduct underneath the central-northern Apennines with a dip of the regional foreland monocline ranging between 10° and 20°. Similar continental lithospheric thicknesses occur also around the Alpine arc but there the foreland dips are lower (3–5°), indicating that lithospheric composition alone (buoyancy) and rheology are not sufficient to explain the differences in subduction style and the related mean dip values of the foreland monocline. The eastward relative mantle flow that anchors the slab has been interpreted as another complementary mechanism to explain the higher subsidence rates of west-directed subduction zones, such as the Apennines [9,30]. This could explain the paradox that the topographically higher Alps have a lower dip of the regional monocline and shallow foredeep with respect to the Apennines, which have lower elevation, a steeper monocline and a deeper and faster subsiding foredeep [7]. The Alps are, generally speaking, associated to an 'E'-directed subduction (western Alps and their southward prolongation; in this interpretation the E–W trending part of the Alps where subduction dips to the south has been considered as a right-lateral ramp of the European subduction underneath the belt [76], and not as a true S-directed subduction. The differences between the Alps and Apennines both in terms of foredeep and general features of the orogens may also be interpreted in terms of rollback rate with respect to convergence rate. Where the slab-pull seems to dominate [74], the subduction could be considered as a passive feature and the eastward mantle flow is apparently not required; however, the slab-pull is strongly questionable in cases such as the central-northern Apennines where the buoyant continental lithosphere has been subducted down to 2–300 km with a contemporaneous similar amount of eastward retreat of the slab, and the slab-pull alone does not seem to be efficient enough to explain such a rollback.
2. Along the strike, the forelands both in the Alps and the Apennines show lateral dip variations due to inherited passive margin-related structures. The highest dips correspond to pre-existing basinal areas, where usually the thrust belt exhibits a salient and a lower structural elevation. Lower inclinations are frequent where the foreland is composed of inherited Mesozoic horsts or basement highs which correspond to thicker, more buoyant, continental crust, determining a recess in the thrust belt and a relatively more concentrated structural high. The widest salient of the Apennines, which is indicated by the furthest distance of the front of

the accretionary prism from the water divide, is located in the Ionian sea, where oceanic lithosphere subducts (Fig. 4). Therefore, the less dense lithosphere controls the largest amount of rollback and it determines the dip of the foreland lithosphere. At the regional scale, within the single orogen, the lateral variations of the foreland monocline dip appear mainly controlled by lateral changes in lithospheric buoyancy.

We observe a larger distance between the thrust ramps on steeper dips of the foreland monocline. Moving along the strike, the same fold may be either sealed by overlying sedimentation in a faster subsiding foredeep, or subaerially eroded whether it develops, respectively, on a steep or on a shallow foreland monocline.

Piggy-back or thrust-top basins are controlled by the distance between the ramps of the growth folds at the margins of the basin, and therefore they are wider when they develop on top of inherited Mesozoic basins or in areas where the frontal decollement is more advanced due to the presence of low strength layers.

The foreland is often the seat of crustal seismicity, particularly in the Apennines foreland. The differential retreat of the foreland monocline might be responsible for such a seismicity which is usually concentrated along narrow transfer zones, orthogonal to the belt and separating foreland monoclines with different angles such as along the Malta Escarpment east of Sicily.

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