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Orogen-parallel variation in exhumation and its influence on critical taper evolution: The case of the Emilia-Romagna Apennine (Italy)

Marco Bonini

Consiglio Nazionale delle Ricerche (CNR), Istituto di Geoscienze e Georisorse, Via G. La Pira 4, I-50121 Firenze, Italy

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ABSTRACT

The Northern Apennine prowedge exposes two adjacent sectors showing a marked along-strike change in erosion intensity, namely the Emilia Apennine to the northwest and the Romagna Apennine to the southeast. This setting has resulted from Pliocene erosion (≤ 5 Ma) and exhumation, which have affected the whole Romagna sector and mostly the watershed ridge in Emilia. Such an evolution has conceivably influenced the equilibrium of this fold-and-thrust belt, which can be evaluated in terms of critical Coulomb wedge theory. The present state of the thrust wedge has been assessed by crosschecking wedge tapers measured along transverse profiles with fluid pressure values inferred from deep wellbores. The interpretation of available data suggests that both Emilia and Romagna are currently overcritical. This condition is compatible with the presence in both sectors of active NE-dipping normal faults, which would work to decrease the surface slope of the orogenic wedge. However, the presence of Late Miocene-Pliocene passive-roof and out-of-sequence thrusts in Romagna may reveal a past undercritical wedge state ensuing during the regional erosion phase, thereby implying that the current overcritical condition would be a recent feature. The setting of the Emilia Apennine (i.e., strong axial exhumation and limited erosion of the prowedge) suggests instead a long lasting overcritical wedge, which was probably contemporaneous with the Pliocene undercritical wedge in Romagna. The reasons for this evolution are still unclear, although they may be linked to lithosphere-scale processes that have promoted the uplift of Romagna relative to Emilia. The lessons from the Northern Apennine thus suggest that erosion and exhumation have the ability to produce marked along-strike changes in the equilibrium of a fold-and-thrust belt.

1. Introduction and aims of the study

The observation that cross-sectional profiles of fold-and-thrust belts and accretionary prisms are characterized by a wedge-shaped deformed region has led to the formulation of the classical ‘critical Coulomb taper model’ (Davis et al., 1983; Dahlen et al., 1984). This mechanical theory expects that fold-and-thrust belts and accretionary prisms will tend to achieve, through thrust imbrication and accretion, an equilibrium state that is represented by the acute angle at the toe of the wedge (i.e., the critical taper). Such a critical angle is delimited by a basal thrust décollement dipping toward the interior of the chain (angle β), and by the topography sloping toward the deformation front (angle α). More specifically, this model assumes that the geometry of an orogenic wedge is controlled by the relative magnitudes of the frictional strength along the basal thrust décollement and the strength of the overlying wedge (Dahlen, 1990). Since its initial formulation, the theory of critically tapered Coulomb wedges has been extensively applied to several fold-and-thrust belts and accretionary prisms worldwide. Further refinements have demonstrated that taper measurements (α, β) can give an estimate of the strength of both the wedge and basal detachment (Suppe, 2007). An increase in the strength of the basal detachment increases the critical taper, whereas a decrease of detachment strength, or an increase in the wedge strength, decreases the critical taper. Accordingly, variations in wedge geometry have been used to infer across-strike and along-strike changes in the strength of the basal detachment, which may be due to subducting seamounts, localized sedimentation, or caused by a change in décollement lithology or depth (e.g., Lallemand and Le Pichon, 1987; Fagereng, 2011; Ruh et al., 2013; von Hagke et al., 2014).

External and internal factors producing a change in boundary conditions can destabilize a thrust wedge. Typical external factors are erosion of the upper surface and sedimentation at the wedge front, while internal forcing is represented by faulting and isostatic responses. Whereas syntectonic sedimentation is a primary control on the evolution of the foreland region of fold-and-thrust belts (e.g., Mugnier et al., 1997; Fillon et al., 2013), erosion may strongly impact on the development of the hinterland sector of orogens (e.g., Willett, 1999). An unstable wedge in overcritical (or ‘supercritical’) state may evolve

E-mail addresses: marco.bonini@igg.cnr.it, marco.bonini27@gmail.com.

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toward a critical taper through frontal imbrication and/or extension of the wedge to reduce its upper surface angle α (e.g., Platt, 1986). Thrust wedges experiencing important erosion are forced into undercritical (or 'subcritical') conditions, and normally develop internal thickening in an attempt to increase the angle α (e.g., DeCelles and Mitra, 1995). Persistent activity and formation of internal contraction structures can drive significant exhumation of deep units from the wedge interior (e.g., Malavieille, 2010).

The present study focuses on the Northern Apennine orogenic wedge (Italy), the prowedge of which is characterized by a marked along-strike variation in the structural level of exposed rock units. In particular, shallower rock units (oceanic-derived Ligurian Units) are exposed in the northwestern sector (Emilia Apennine), and deeper rocks (i.e., the tectonically underlying Marnoso Arenacea sandstones) occur in the southeastern sector (Romagna Apennine). Apatite fission-track data and vitrinite reflectance analysis have revealed that in the Pliocene (ca. 5 Ma) the Romagna Marnoso Arenacea Formation was buried beneath a thick package of Ligurian Units that later have been nearly completely eroded (Zattin et al., 2002; Cerrina Feroni et al., 2001). The localization of erosion in a specific sector of a fold-and-thrust belt (Romagna) has an obvious impact on the stability and evolution of the critical taper, in that massive erosion is expected to force the wedge into a persistent undercritical state. The Apennine thrust wedge may thus represent an ideal location for analyzing the interplay between erosion and other factors (such as pore fluid pressure and basal friction) controlling wedge dynamics. The presence in the region of numerous deep wells drilled for hydrocarbon exploration provides data that may help to constrain pore fluid pressure, which is a primary parameter controlling the wedge state. This study exemplifies how erosion may alter the equilibrium of a thrust wedge, and control the tectonic style and complex deformation patterns resulting from this destabilization.

2. Regional tectonic setting

The Northern Apennine is an active, northeast-verging fold-and-thrust belt that has been developing since the onset of collision between the Adria microplate and the Corsica-Sardinia block in the Late Eocene (e.g., Molli, 2008, and references therein). The Emilia and Romagna sectors form the exposed contractional pro-side of the Northern Apennine thrust wedge, which continues northeastward and becomes buried beneath the Quaternary sediments of the Po Plain (Fig. 1a, b). This buried fold-and-thrust belt has been identified through commercial seismic profiles that have disclosed the presence of blind southwest-dipping thrusts and associated folds arranged in arcuate trends in map view (Pieri and Groppi, 1981; Barberi and Scandone, 1983) (Fig. 1a, c). The transition between the exposed pro-side wedge and the topographically flat Po Plain is marked by the Pede-Apennine margin, which corresponds to the surface manifestation of a system of SW-dipping thrust faults referred to as Pede-Apennine thrust (e.g., Bonini, 2013, and references therein). In some models, the Pede-Apennine thrust is taking up the horizontal (eastward) push of the mantle and asthenospheric wedge accommodating the partial delamination of the downgoing Adriatic lithosphere (e.g., Doglioni et al., 1994; Ventura et al., 2007; Fig. 1c).

The Jurassic to Eocene Ligurian Units are allochthonous thrust sheets that consist of ophiolites and their oceanic sedimentary cover scraped from the oceanic crust of the western Tethys (Abbate and Sagri, 1970). These units are the highest in the thrust pile and tectonically overlie the Tuscan and Umbria-Marche units originally deposited over the western continental margin of the Adria microplate. The continental sequence basically consists of a basal layer of Triassic anhydrites and dolostones (Burano Fm.), which is followed upsection by a Mesozoic-Paleogene carbonate succession that is in turn overlain by Late Oligocene to Miocene siliciclastic foredeep sequences (Fig. 1c).

The Ligurian Units progressively overrode the foredeep basins that developed ahead of the migrating thrust wedge. Nowadays, the Ligurian Units constitute an extensive 4–5 km-thick stack of thrust sheets in the Emilia Apennine, where the basal tectonic contact and the underlying Late Oligocene-Miocene foredeep deposits are exposed along the (axial) watershed ridge as well as in a few tectonic windows (Bobbio, Mount Zuccone and Salsomaggiore; Fig. 1a). In contrast, the Romagna Apennine to the southeast is characterized by the dominant outcropping of the Miocene Marnoso Arenacea foredeep deposits, with patches of Ligurian Units outcropping as klippen in restricted areas (Val Marecchia and San Piero in Bagno syncline; Fig. 1a). The geometrical relationships between these units are illustrated in a longitudinal geological section crossing the Emilia and Romagna Apennine (Fig. 1d). Emilia and Romagna also show different physiographic features, particularly the main watershed of the Emilia Apennine exhibits a higher elevation (with peaks often exceeding 2000 m) with respect to that of the Romagna Apennine, where the Mount Falco is the highest peak (1658 m; Fig. 1d).

Apatite fission-track data from the Romagna Marnoso Arenacea record burial depths tapering from 5 km to 2.5 km toward the foreland, a setting compatible with the existence of a now-eroded wedge of Ligurian Units above the Marnoso Arenacea (Zattin et al., 2000, 2002). The erosion of the Ligurian Units in the Romagna Apennine started at 4–5 Ma, and occurred at rates up to 1.2 mm/yr (Zattin et al., 2002). Cerrina Feroni et al. (2001) obtained similar results on the basis of vitrinite reflectance and sedimentological analysis of the terraced deposits of the Pede-Apennine margin, and also argued that the main erosion episode occurred in Middle Pleistocene. The occurrence of a widespread wedge of Ligurian Units in Romagna is also supported by the presence of material eroded from these units in the large slump bodies emplaced within the Marnoso Arenacea (Lucente and Pini, 2003; Bonini, 2006).

More recent thermochronologic (apatite (U-Th)/He and fission track) data record erosion rates of the Romagna Apennine of ~1 mm/yr over a period of ~3–5 Ma (Thomson et al., 2010; Fig. 2). In the Emilia Apennine, exhumation has been restricted to the watershed ridge since ~8 Ma at rates of ~0.4 mm/yr, which increased to ~1 mm/yr in the Pliocene (ca. 3 Ma) (Thomson et al., 2010). In contrast, less than ~2 km of erosion have affected the Emilia Apennine over the same time period, which led to the preservation of the thick layer of Ligurian Units. Thomson et al. (2010) attribute such a dissimilar behaviour to dominant vertical material motion in Romagna and dominant horizontal motion in Emilia. The Northern Apennine is thus composed of two main sectors that experienced markedly different rates of erosion, which are likely to have profoundly influenced the Pliocene-Quaternary evolution of this orogenic wedge.

3. The critical taper model

The critical taper model is based on the analogy between thrust belts and unconsolidated material (e.g., soil or snow) pushed in front of a bulldozer. A critically tapered wedge advances steadily along its base, accretes material at its front, and maintains a stable taper angle. Deviations from this state will lead the thrust wedge to deform internally, in order to decrease or increase its topographic slope depending on whether the wedge is overcritical or undercritical, respectively. Therefore, every orogenic wedge tends to develop its own 'critical taper', which depends on the properties of the material composing the wedge and the strength of the basal thrust fault (Davis et al., 1983; Dahlen, 1990). In the special case of a mechanically homogeneous wedge (i.e., all the properties are constant within the thrust wedge), the critical taper equation of Dahlen (1990, Eq. (99)) is:

$$(\alpha + \beta) \approx \frac{(1 - \rho_f/\rho_w)\beta + \mu_b(1 - \lambda_b) + S_b/\rho g H}{(1 - \rho_f/\rho_w) + 2(1 - \lambda_w)\left(\frac{\sin\phi_w}{1 - \sin\phi_w}\right) + C/\rho g H}, \quad (1)$$

where ρ_f is the density of the fluid (seawater or air) above the wedge, ρ_w is the average wedge rock density, λ_b and λ_w are the pore-fluid factors