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Late Miocene shortening of the Northern Apennines back-arc

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ABSTRACT

The inner Northern Apennines (western Tuscany and Tyrrhenian basin) is characterized by a relatively thin continental crust (∼20–25 km), high heat flow (>100 mW m^{-2}), and the presence of relevant tectonic elision of stratigraphic sequences, a setting known as *Serie Ridotta*. These features are normally ascribed to an extensional deformation that affected the back-arc area above the subducting Adria plate since the Early-Middle Miocene (∼16 Ma). However, various geophysical studies image the continental crust to be currently affected by W-dipping thrust faults (and associated basement uplifts) that have not been obliterated by this claimed long-lasting extensional process. These observations raise the question whether the thrusts are older or younger than the continental extension. To address this question we have reprocessed and interpreted the deep seismic reflection profile CROP03/c that crosses the onshore hinterland sector, and investigated the structural setting of some of the Late Miocene-Pliocene hinterland basins (Cinigiano-Baccinello, Siena-Radicofani, Tafone, Albegna and Radicondoli basins) that are situated at the front or in-between the basement uplifts. The analysis of field structures and commercial seismic profiles has allowed the recognition that both substratum and basins' infill have been intensely shortened. These findings and the architecture of the basins suggest that the latter developed under a contractional regime, which would have started around 8.5 Ma with the onset of the continental sedimentation. This compressive stress state followed an earlier phase of continental extension that presumably started at ∼16 Ma (with the blocking of the Corsica-Sardinia rotation), and thinned both the continental crust and sedimentary cover producing most of the *Serie Ridotta*. The main phases of basin shortening are bracketed between 7.5 and 3.5 Ma, and thus overlap with the increase in the exhumation rate of the metamorphic cores at ∼6–4 Ma determined through thermochronological data. We therefore propose a correlation between the basin deformation and the activity of the nearby basement thrusts, which would have thus shortened a previously thinned continental crust. This chronology of deformation may suggest a geodynamic model in which the back-arc and hinterland sector of the Northern Apennines was recompressed during Late Miocene-Early Pliocene times. This evolution may be explained through different speculative scenarios involving a blockage of the subduction process, which may vary between end members of complete slab detachment and stalled subduction.

1. Introduction, and aims of the work

Hinterland sectors of fold-and-thrust belts sometime correspond to back-arc extensional areas, which may experience very complex structural evolutions. Back-arc extension is hypothesized to form essentially as a result of the subduction hinge rollback driven by the negative buoyancy of the subducting slab, which in turn depends on the age of the downgoing lithosphere (Molnar and Atwater, 1978; Dewey, 1980; Doglioni, 1991; Faccenna et al., 2001; Hall et al., 2003). Generally, analog and numerical models predict that extension of the overriding plate, resulting from lateral hinge-retreat, is strongly influenced by the velocity of the subducting plate (Faccenna et al., 2001; Hall et al., 2003; Schellart, 2005). Steepening of the subduction slab and development of upwelling system in the upper plate mantle wedge are expected to favor back-arc extension by decreasing the convergent rates and generating horizontal tensional forces in the back-arc side (Uyeda and McCabe, 1983; Tamaki and Honza, 1991; Honza and Fujioka, 2004). Back-arc extensional basins can potentially evolve even up to the opening of narrow oceanic basins (e.g. Sea of Japan, Lau Basin, North Fiji Basin, and Scotia Sea), but, as convergence rates of colliding plates may vary largely in time, these basins are generally ephemeral (Ziegler and

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Cloetingh, 2004). As a result, former extensional back-arc basins have been destroyed by compressional stresses arising from an increase in convergence rates, such as the Sunda Arc and East China rift systems, Black Sea domain (Ziegler and Cloetingh, 2004), Central Andes (Schmitz, 1994), and Japan (Sato et al., 2004; Okada and Ikeda, 2012).

Here we focus on the hinterland sector of the NNW-striking Northern Apennines fold-and-thrust belt, which developed in the Eurasia-Africa collision zone as a result of the Oligocene-Miocene convergence between the Adriatic Plate and the Sardinia-Corsica block (e.g., Boccaletti et al., 1971). The Northern Apennines hinterland is normally referred to as a back-arc area comprising the Tyrrhenian Basin and the numerous marine and continental basins that developed in this region (mostly western Tuscany) since the Middle-Late Miocene (e.g., Boccaletti and Guazzone, 1972; Malinverno and Ryan, 1986; Doglioni, 1991; Faccenna et al., 2001; Carminati and Doglioni, 2012; Fig. 1a). The hinterland experienced a complex structural evolution that is manifested by the scientific debate and the different evolutionary models proposed for this region. In particular, the structural context in which the basins developed is referred to two contrasting settings, (1) a classical extensional model, in which the basins are interpreted as grabens or half-grabens (Trevisan, 1952; Martini and Sagri, 1993), and (2) a model in which the basins developed mainly under compressive conditions (Boccaletti et al., 1999; Bonini and Sani, 2002).

The hypothesized compressional basin origin has been usually discarded mostly on the basis of indirect evidence. Specifically, the presence of (1) a thinned continental crust (~20–25 km in the hinterland vs. 35–45 km toward the foreland; Cassinis et al., 2005), (2) the occurrence of magmatism (Serri et al., 1993), (3) high heat flow (>100 mW m^{-2}, which in geothermal areas may exceed 250 mW m^{-2}; Mongelli et al., 1998; Della Vedova et al., 2001), positive Bouguer gravity anomaly (Marson et al., 1998), and (4) extensional seismicity (mostly in the axial zone; Pondrelli et al., 2006) have been used as evidence for long lasting (post Early Miocene) extension in the Northern Apennine hinterland (e.g., Mongelli et al., 1998; Liotta and Ranalli, 1999; Pauselli et al., 2006; Brogi et al., 2005a; Fig. 2a). In addition, high-pressure and low-temperature mineral phases in the metamorphic rocks exposed in the hinterland (Alpi Apuane, Mid-Tuscany Metamorphic Ridge, Argentario Promontory) suggest peaks in baric conditions varying between 0.8 and 1.2 GPa corresponding to original crustal depths in the range of 30–45 km (Jolivet et al., 1998; Molli et al., 2002; Rossetti et al., 2002). The current crustal thickness in the hinterland is ~20–25 km (Fig. 2a), and this suggests post Early Miocene thinning of the continental crust, which is attributed to either synorogenic (Storti, 1995; Jolivet et al., 1998; Rossetti et al., 2002; Molli, 2008) or post-orogenic extension (Carmignani and Kligfield, 1990; Carmignani et al., 1994).

On the other hand, the results of various geophysical approaches image the hinterland continental crust considerably shortened by thrust faults (Arisi Rota and Fichera, 1985; Bally et al., 1986; Ponziani et al., 1995; Cassano et al., 1998; Scarascia et al., 1998; Finetti et al., 2001; Fig. 2b). The occurrence of a shortened but still thinned continental crust in the Northern Apennines hinterland may thus represent an apparent contradiction, although the thrust faults could have represented fossil structures at the time the basins developed. Another apparent paradox is the occurrence of important elision of the sedimentary cover, a phenomenon known since long time as *Serie Ridotta* (Signorini, 1949) and more recently attributed to low-angle extensional faulting (Lavecchia et al., 1984; Bertini et al., 1991; Brogi et al., 2005a), which would spatially coexist with the shortened crust. These observations raise some questions, one of which is whether the thrust faults are older or younger than the *Serie Ridotta*. The definition of the structural setting of the hinterland basins and of their relationships with structures in the substratum is thus crucial for deciphering this complex tectonic setting.

We approached this problem by integrating different datasets, specifically commercial and deep seismic lines, new field structural data and detailed mapping of selected key areas in the Northern Apennines hinterland. We first present the reprocessing and seismic interpretation of the hinterland segment of deep profile CROP03/c. We continue with the analysis of surface structures near the Neogene hinterland basins, and discuss the link with the deeper structures imaged in commercial seismic profiles. We then propose a geodynamic model that may reconcile the above ostensible discrepancies into a unique scenario by discussing the effects of possible breaks in the subduction of the Adriatic slab, as proposed previously in the form of stalled (e.g., Fellin et al., 2005) or detached subducting slab (Wortel and Spakman, 2000).

2. Geologic setting of the Northern Apennines hinterland

2.1. Stratigraphic and tectonic setting

The hinterland basins developed over a substratum mostly composed of Jurassic to Eocene Ligurian Units, which represent the remnants of the sedimentary cover scraped-off from the oceanic crust of western Tethys (Abbate and Sagri, 1970). These units are the uppermost ones in the Apennine thrust pile and overlie the Tuscan Units originally deposited over the western margin of the Adria Plate. The late Cretaceous to Oligocene Sub-Ligurian Units belong to a paleogeographic domain transitional between the Ligurian and Tuscan units, and for this reason they are sandwiched in-between the latter units. The Tuscan Units are composed of Late Triassic-Cretaceous carbonates resting above a thick layer of Triassic evaporites (Burano Fm.; Bortolotti et al., 1970). The Oligocene-Early Miocene Macigno sandstones overlie the carbonate rocks in the hinterland; the sandstones manifest the deposition that took place in the foredeep basins developed ahead of the migrating chain front as shortening involved the continental margin of Adria (Bortolotti et al., 1970; Ricci Lucchi, 1986). The Triassic-Oligocene Tuscan metamorphic units and the underlying Paleozoic crystalline basement represent the exhumed part of the Adria continental crust; these rocks are exposed only at the Mid-Tuscany Metamorphic Ridge and other metamorphic cores, which define a roughly NNW-trending regional topographic ridge acting as the backbone of the Northern Apennines hinterland (Fig. 1a).

The Northern Apennines can be broadly referred to as a general duplex geometry in which the Ligurian Units represent the roof thrust sheet overlying the foreland Tuscan Units affected by link thrusts splaying from the basal Burano Fm. décollement. This geometry has been well documented for the axial part of the chain (e.g., Cerrina Feroni et al., 2001). The same relationships can be also identified in the hinterland, though this area is characterized by the frequent lamination and elision of the tectonic *nappe* pile leading often to the direct superposition of the Ligurian Units over the Late Triassic evaporites (Burano Fm.). This setting is regionally known as *Serie Ridotta* (Signorini, 1949), and has been mostly attributed to low-angle normal faulting (Lavecchia et al., 1984). In this model, the Ligurian Units tectonically overlie the evaporite Burano Fm. along low-angle normal faults and the overlying carbonate rocks along high-angle ramps, producing a pinch-and-swell geometry (e.g., Bertini et al., 1991). The *Serie Ridotta* would have affected the most internal parts of the orogen since the Early to Middle Miocene in the frame of late orogenic gravity collapse (Carmignani et al., 1994; Keller et al., 1994; Jolivet et al., 1998). This extensional process is believed to have led to the exhumation of the Mid-Tuscany Metamorphic Ridge-Alpi Apuane metamorphic alignment, and to have produced the tectonic elision of stratigraphic sequences, which is