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Topography, exhumation, and drainage network evolution of the Apennines

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The present-day topography of the Italian peninsula results from the interactions between crustal-mantle and surface processes occurring since the Late Miocene. Analysis of exhumation and cooling of crustal rocks, together with Quaternary drainage evolution, helps to unravel the tectonic-morphologic evolution of the Apennines by distinguishing end-member models, and hence describing the orogenic belt evolution. The pattern of regional topography, erosional history and present-day distribution of active deformation suggests that the eastward migrating extensional-compressional paired deformation belts may still control the topography of the northern Apennines, albeit at slower rates than in the past. Conversely, Quaternary drainage evolution in the central and southern Apennines suggests that the topography of these regions underwent a Quaternary regional arching, which is only partly consistent with the persisting migration of the compressional-extensional pair.

Introduction

Structural, sedimentological and volcanological observations show that the Neogene-Quaternary geological history of the Apennines was dominated by the coexistence of paired, eastward-migrating extensional and compressional deformational belts (Elter et al., 1975) driven by the passive sinking rollback of the Adriatic-Ionian lithosphere (Malinverno and Ryan, 1986). It is now widely recognized that interactions between surface and crustal processes is a first-order factor controlling the evolution of orogenic belts (Zeitler et al., 2001). Detailing the changes in the morphology and the associated surface processes acting in these belts throughout their evolution is thus important for understanding the underlying driving mechanisms. Exhumation and rock uplift rates, changes in drainage patterns and depositional environments constrain conceptual geodynamical models and can be used to quantitatively test numerical models.

Two end-member views have been outlined in the literature for the topographic evolution of the Apennines:

i) In the first, the Apennines have existed as a self-similar, eastward-migrating topographic high throughout Neogene-Quaternary times. The present morphology thus represents the present-day expression of a continuous process. This concept implies the view that crustal shortening to the east is still active all along the Apennines and kinematically related to back-arc crustal extension to the west of the drainage divide (Cavinato and DeCelles, 1999). This view has strongly influenced geomorphologic studies and is deeply rooted in the literature (e.g. Mazzanti and Trevisan, 1978; Alvarez, 1999).

ii) An alternative hypothesis views the Apennine topography as decoupled from the tectonic deformation of the Apennine orogenic wedge. This view is supported by various structural, geophysical and morphological lines of evidence, such as the significant enlargement and arching of the Italian peninsula, the free-air gravity anomaly spectral signature and the lack of significant crustal shortening active east of the topographic high, particularly in the central and southern Apennines (Carminati et al., 1999; D'Agostino et al., 2001).

The conceptual models outlined above predict very different patterns of erosion and drainage evolution through time which allows us to focus here on two main topics. The first is the distribution and intensity of erosion rates in the northern Apennines over the Neogene-Quaternary time-scale, as determined by thermochronological data, while the second focuses on the evolution of the Quaternary intramontane basins and their associated drainage network.

Tectonic setting

The Apennines are formed by a Neogene thrust and fold belt system which developed during the eastward retreat of west-dipping subduction of the Adriatic-Ionian lithosphere. Foredeep subsidence and thrust stacking in the eastern external parts coexisted with western back-arc extension and volcanism (Serri et al., 1993; Jolivet et al., 1998). Sedimentary units originally deposited on the Adriatic lithosphere were progressively accreted to the Apennines wedge (Patacca et al., 1992).

The Early-Middle Pleistocene alluvial and transitional deposits filling the Adriatic foredeep have been regionally tilted to the NE (Kruse and Royden, 1994) and incised by a parallel drainage system. The central and southern Apennines (south of 43°N) currently show little evidence of active compression and the tectonic regime is instead dominated by active NE-SW crustal extension. Compressive focal mechanisms and shortening are still active in the external parts of the northern Apennines (Frepoli and Amato, 1997) where intermediate earthquakes, down to depths of 90 km, may suggest a still active subduction (Selvaggi and Amato, 1992). Historical and recent seismicity, active faulting (Valensise et al., this volume), and geodesy (Hunstad et al., 2003) indicate that 3–5 mm/yr of extension may be accommodated across the central-southern Apennines in a 30–50 km wide belt. This belt of active extension closely follows the regional topographic culmination close to the drainage divide. The relative positions of drainage divide, highest elevations and the eastern front of normal faulting vary along the Apennines (Figure 1). In the northern Apennines, the striking correspondence of these three elements may suggest that the topography is controlled by an eastward-migrating wave of normal faulting, lowering the west side of the orogenic belt (Mazzanti and Trevisan, 1978). In the central and southern Apennines, the drainage divide is localized along the crest of the regional topographic culmination, while the highest peaks are probably controlled by selective erosion in the southern (Amato et al., 1995) or advancement of the extensional front in the central Apennines (D'Agostino et al., 2001).

Figure 1 Shaded topography of the Italian peninsula (Oblique Mercator Projection) with swath profiles across northern, central and southern Apennines. Upper, median, and lower lines in the profiles correspond to maximum, average, and minimum elevation perpendicular to a 40-km swath.

Legend: AL, Apuane Alps; AB, Arno basin; MF, Monte Falterona; CB, Colfiorito basin; FB, Fucino basin; BB, Boiano basin; VA, Val D'Agri basin; VD, Vallo di Diano; TAW, Tyrrhenian-Adriatic watershed.

Thermochronological data and exhumation history

Low temperature thermochronology is ideally suited for reconstructing the thermal history of rocks in the uppermost part of the crust because it records time and rates of cooling related to rock exhumation. Measurements are mostly carried out on apatite fission-tracks (AFT), since they yield times and rates at which rocks cooled below approximately the 110°C isotherm. Since the geothermal gradient is usually poorly constrained, exhumation rates are commonly affected by significant errors. Whenever the elevation-dependence method can be adopted, whereby several samples from different elevations along a transect are analysed, the geothermal gradient has not to be introduced in order to obtain the exhumation rate. The (U-Th)/He analyses on apatite, being based on a closure temperature of ca. 70°C, allow a closer view of the latest stages of exhumation. Unlike the geological evolution of the Apennines, which is fairly well known, its geomorphic history has only recently aroused widespread scientific interest, also because of the availability of thermochronological data. A preliminary study on exhumation rates in the northern Apennines, based on apatite fission tracks, was published by Boettcher and McBride (1993). Since then, the regional knowledge of exhumation rates over different time spans has been increasing at a fast pace (Abbate et al., 1994; Balestrieri et al., 1996, 2003; Ventura et al., 2001; Zattin et al., 2002).

On a regional scale, AFT data indicate that higher exhumation rates are at present occurring at Mt. Falterona, over the drainage divide of the northern Apennines, consisting of Miocene foredeep deposits (Marnoso Arenacea Fm.). According to Zattin et al. (2002), the pre-exhumation configuration features a 4- to 5-km-thick cover (depending whether a geothermal gradient of 20°C/km or 25°C/km is assumed) of overlying Ligurian Units and Epiligurian Units, which was completely eroded in the last 5 Ma at a mean rate, then, of 0.8 to 1 mm/yr. A thickness of 3.8 km was calculated by Reutter et al. (1983) in the same Formation approximately at the same site and for the same chronological interval, by working out vitrinite reflectance data. A residual veneer of Ligurids, presently buried under the fluvial

deposits both in Mugello and in the nearby Casentino basin indicates that the 5-km-thick Ligurids cover had not been completely unroofed when the basin became the site of flood plain sedimentation, that is around 2.0 Ma (Benvenuti, 1997).

AFT analyses, carried out west of the drainage divide, gave Pliocene-Quaternary mean exhumation rates ranging from 0.5 to 1.7 mm/yr across the Apuane Alps (Abbate et al., 1994) and Late Miocene-Quaternary mean denudation rates of 0.3–0.4 mm/yr in the Ligurian Apennines (Balestrieri et al., 1996). It should be pointed out that higher rates in both areas derive from cooling rates assuming a geothermal gradient of 30°C/km. Lower rates (0.5 mm/yr and a minimum of 0.2 mm/yr, respectively) derive directly from the slope of the age-elevation profiles. A mean exhumation rate of 0.2–0.3 mm/yr in the Ligurian Apennines since Late Miocene and of 0.5 mm/a in the Apuane Alps since Early Pliocene can be held as reference values. Further recent investigations in the Apuane Alps area (Balestrieri et al., 2003) allow a more detailed time span of exhumation rates to be worked out. Between ca. 11 Ma and ca. 6 Ma, the cooling rate was between 10 and 16°C/Ma which corresponds, assuming a geothermal gradient of 25°C/km (Pasquale et al., 1997), to exhumation rates of 0.4–0.6 mm/yr. Between 6 Ma and 4 Ma, cooling rates increased to between 38 and 55°C/Ma. equivalent to an exhumation rate of 1.3–1.8 mm/yr, assuming a geothermal gradient of 30°C/km. The last part of the thermal path (4 Ma to present) is not well constrained due to lack of AHe data, but the average exhumation rate is between 0.6 and 0.9 mm/yr (assuming a geothermal gradient of 30°C/km). The slowing down of the exhumation rate since Middle Pliocene is certainly related to the surface exposure of the highly resistant rocks belonging to the Tuscan Metamorphic Unit and Paleozoic Basement which began to occur at that time, as proven by the lithologic composition of the continental basin fed to the east by the Apuane Alps erosion (Calistri, 1974). Despite the lower exhumation rates, the present average altitude of the Apuane peaks (1500 to 1900 m) is very close to that of the Apennine divide. The local relief of the Apuane Alps reflects the greater resistance of the underlying rock types which contrast so strongly in form with the adjacent Apennine range that the Apuane Alps have been considered a separate range of a possibly different origin (Wezel, 1985).

In summary, thermochronological data show that the long-term exhumation of the northern Apennines has occurred at an average rate of 0.7 mm/yr since 11 Ma. This value is remarkably close to the average erosion rate evaluated from the sediment volume deposited in the Adriatic foredeep (Bartolini et al., 1996). Local accelerations of exhumation rates coincide with the onset of normal faulting and intramontane basin deposition through the creation of local relief and accommodation space for sediments (Balestrieri et al., 2003). Acceleration of exhumation rates in the Mt Falterona area took place about 3 Ma later than the onset of similar exhumation in the Apuane Alps. This acceleration and migration of the locus of highest erosion rate is consistent with an eastward migrating pulse of normal faulting and enhanced local relief creation.

Evolution of the drainage network and the “watershed” basins

The present-day shape of the Italian peninsula is closely linked with the recent formation of a long-wavelength topography responsible for raised Pleistocene marine sediments and terraces on both flanks of the range (Bordoni and Valensise, 1998; D’Agostino et al., 2001). This morphological evolution is associated with a major change of the depositional environments in the intramontane basins: Upper Pliocene to Middle Pleistocene fluvial-lacustrine environments changed to Middle to Upper Pleistocene fluvial-alluvial sequences in a regionally correlated phase of basin fill incision and drainage integration (Bartolini and Pranzini, 1981; D’Agostino et al., 2001). The Early Pleistocene is characterized by lacustrine environments in most of the intramontane depressions, recorded by widespread lake beds that are revealed within the incised basin fills (Bosi and Messina, 1991; Bartolini, 2003). The Early-Middle Pleistocene lacustrine deposits are generally overlain by units that are transitional from lacustrine and low-gradient fluvial environments to coarser deposits representative of alluvial fans (Miccadei et al., 1998). This transition is frequently marked by erosion and incision of the lake beds so that the Middle Pleistocene deposits are often entrenched and unconformably overlie the fluvial-lacustrine units. After the Middle Pleistocene, deposition of lacustrine sediments in the intramontane basins was drastically reduced and continued only in basins that maintained internal drainage. Over the Quaternary as a whole, but with slightly different timing, this evolution is typical of the intramontane basins of the northern (Argnani et al., 1997) and southern Apennines (Capaldi et al., 1988). The only surviving closed (Fucino and Colfiorito) and semi-closed (Boiano, Vallo di Diano, Val d’Agri basins) basins are those on the Apennine watershed, most distant from the marine base level, where continued normal faulting is still able to provide local subsidence that defeats their capture by the regional drainage network. These basins generally contain aggradational sequences up to 1000 m thick, made up of poorly exposed fluvial and lacustrine Pleistocene sediments drilled by boreholes or imaged by seismic reflection lines (Cavinato et al., 2002). These basins are bounded by normal fault systems, displaying evidence of Late Quaternary-Holocene faulting events, and their historical seismicity includes $M > 6$ seismic events along basin-bounding faults (Valensise et al., this volume). In contrast to the fluvially-dissected landscapes and incised continental Pleistocene sequences that are common farther from the drainage divide, these “watershed” basins are characterized by flat and weakly incised lacustrine depositional surfaces, alluvial plain and fan surfaces that suggest an incomplete integration with the regional drainage network. Historical drainage operations, aimed at increasing agricultural land, artificially lowered basin outlets or excavated artificial galleries, causing the disappearance of seasonal or perennial lakes such as the shallow but large Fucino lake, finally drained in 1875 AD.

Detailed geological and geophysical investigations in the Fucino basin document (Figure 2) the persistent Plio-Quaternary lacustrine environments and the asymmetrical geometry of the basin

Figure 2 Fucino basin schematic map. The color scale corresponds to the vertical coseismic deformation of the 1915 Ms 6.9 earthquake (fault parameters from Ward and Valensise, 1989). Main Quaternary basin-bounding faults are shown as black lines. Thin dashed white lines indicate isochron contours (in ms TWT) of the Plio-Quaternary basin fill (from Cavinato et al., 2002). TAW, Tyrrhenian-Adriatic watershed. Also shown is the schematic cross-section across the basin (redrawn from Cavinato et al., 2002); MC, Meso-Cenozoic rocks; S1, Upper Pliocene-Early Pleistocene; S2, Early Pleistocene-Holocene.

fill thickening toward the master NW trending fault systems that ruptured during the 1915 Ms = 6.9 Fucino earthquake. The geometry of the basin fill shows that the fault segment which ruptured during that earthquake may have accumulated a vertical offset larger than 1000 m by repeated 1915-like seismic events. The remarkable correspondence between the distribution of the 1915 coseismic vertical deformation and the extent of internal drainage provides a striking example of the struggle of intramontane basin faults to preserve internal drainage in the “watershed” basins against integration by regional drainage network by repeated seismic events that “dam” externally flowing rivers or by providing local subsidence not compensated by basin aggradation.

In most places today the effects of downcutting by the regional network dominate over the local subsidence caused by slip on the active faults. For this reason, except in some of the higher and more distant parts of the regional network, the more subtle geomorphological effects of fault activity are usually obscured.

The evolution from an internally-drained system to a through-going river network was ultimately related to the development of a long-wavelength topographic bulge and regional uplift. D’Agostino et al. (2001) used the spectral ratio (admittance) of free-air gravity anomalies to topography to show that long-wavelength topography is supported by mantle dynamics, which is consistent with geological evidence showing the absence of significant Quaternary crustal thickening or underplating. They argued that the Quaternary evolu-

tion of the Italian peninsula has been controlled by the formation of a NW-SE long-wavelength (> 150 km) topographic bulge. In most places today the effects of downcutting by the regional network dominate over the local subsidence caused by slip on the active faults. For this reason, except in some of the higher and more distant parts of the regional network, the more subtle geomorphological effects of fault growth and interaction are usually obscured. The surviving closed or semi-closed basins along the divide allow us to see the interaction between the regional downcutting and normal faulting. The preservation of these basins on the watershed is related to two factors:

- i) They are both far from the base levels of the streams that are trying to capture them. The wave of regressive erosion triggered by the base level fall has effected these internal regions later than those basins closer to the coasts, such as the Tiber, Sulmona, and Campo Imperatore basins. Once captured, the increased discharge through these well-integrated basins makes it likely that fluvial incision rates at their outlets will always dominate over local vertical motions related to faulting.
- ii) Normal faulting is most active along the crest of the topographic bulge. Only in this location can faulting efficiently delay the capture of closed basins by causing subsidence that preserves internal drainage.

The Apennines provide an ideal place for observing this type of interaction because of their short distance from the marine base level, so that effects of base-level variations are rapidly propagated upstream, and because the active faulting is localized on top of the long-wavelength bulge.

Discussion

The consistency between various geological, geomorphologic and geophysical data sets suggests that a still active extensional-compressional migrating belt may control the topography in the northern Apennines. Seismological and geodetic evidence, together with tomographic images of a mantle low-velocity zone (Lucente et al., 1999), suggest that crustal deformation may be driven by the passive sinking of the Adriatic lithosphere. This driving mechanism is evidenced in the geomorphology through the eastward migration of significant exhumation rates and the close correspondence of highest elevations, drainage divide and eastern front of normal faulting.

Geological reconstructions provide rates of eastward Neogene migration of volcanism and crustal deformation of about 1–2 cm/yr (Jolivet et al., 1998). The lack of evidence for such high values of present-day rates of deformation may suggest that the whole geodynamic processes is currently slowing down.

In the central-southern Apennines, the internally-drained Pleistocene drainage system evolves to a through-going river network in association with the whole arching of the Italian peninsula contemporaneously with a significant slowing down of foredeep subsidence and compressional deformation in the Adriatic side. Uplift of marine deposits and incising drainage is symmetrical to both sides of the range. Active extension is now focused along the top of the regional topography and watershed where continuing normal faulting and basin subsidence “shield” intermontane basins form integration in the regional drainage network. This evolutionary pattern seems to be scarcely consistent with the continuing migration of the extensional-compressional belt, and is instead more likely related to a late-stage phase of the Adriatic lithosphere subduction.

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