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Decoding the role of tectonics, incision and lithology on drainage divide migration in the Mt. Alpi region, southern Apennines, Italy

J.T. Buscher [a,b,*], A. Ascione [c], E. Valente [d]

[a] Andean Geothermal Center of Excellence (CEGA), Universidad de Chile, Plaza Ercilla 803, Santiago, Chile
[b] Department of Geology, Facultad de Ciencias Físicas y Matemáticas, Universidad de Chile, Plaza Ercilla 803, Santiago, Chile
[c] Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse, University of Naples Federico II, Largo San Marcellino 10, 80138 Naples, Italy
[d] Dipartimento di Scienze Umanistiche, Sociali e della Formazione, Università del Molise, Campobasso, Italy

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ABSTRACT

The proclivity of river networks to progressively carve mountain surfaces and preserve markers of landscape adjustments has made analyses of fluvial systems fundamental for understanding the topographic development of orogens. However, the transient nature of uplift and erosion has posed a challenge for inferring the roles that tectonics and/or climate have played on generating topographic relief. The Mt. Alpi region in the southern Apennines has a heterogeneous distribution of elevated topography, erosionally-resistant lithology and uplift, making the area optimal for conducting topographic and river analyses to better understand the landscape development of a transient orogen. Stream length-gradient, normalized channel steepness, stream convexity and first-order channel gradient indices from 10 m digital elevation data from the region exhibit stream profile inconsistencies along the current drainage divide and a dominance of high values subparallel but inboard of the primary chain axis irrespective of known transient landscape factors, suggesting that the current river network may be in a state of transition. The location of these stream profile anomalies both near the modern drainage divide and subparallel to an isolated swath of high topography away from catchment boundaries is thought to be the topographic expression of an imminent drainage divide migration driven primarily by the ~northeast-vergent extension of the western chain axis.

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1. Introduction

Tectonic and climatic processes are generally accepted as the primary drivers for building mountainous landscapes (e.g., Molnar and England, 1990), but isolating the role of individual processes responsible for creating orogens that operate at varying spatial and temporal scales has proven to be challenging. The ability of river networks to preserve distinct topographic features created in response to local short-lived surface changes and/or regional long-term external processes has helped in identifying factors that modulate mountainous topography (Whipple and Tucker, 1999; Snyder et al., 2000; Whipple, 2004; Wobus et al., 2006; Whittaker et al., 2008; Di Biase and Whipple, 2011; Whittaker, 2012). River network development primarily depends on how much sediment discharge (climate), large-scale vertical motion (tectonics), and river substrate strength (lithology) affect the river system (Whipple and Tucker, 1999; Snyder et al., 2000; Whipple, 2001; Whipple, 2004; Wobus et al., 2006; Whittaker et al., 2008; Di Biase and Whipple, 2011; Whittaker, 2012), which ultimately characterizes a river as being detachment-limited (i.e. more prone to incision due to minimal sediment coverage), transport-limited (i.e. less prone to incision due to maximal sediment coverage) or a mixture of these two end-members (e.g., Howard, 1994; Willgoose, 1994; Tucker and Slingerland, 1996; Tucker and Whipple, 2002; Whipple and Tucker, 2002; Attal et al., 2011). Profiles of individual rivers provide a first-order snap-shot of the entire river path from headwater to outlet, with deviations from a steady-state graded profile (i.e. concave-up; Flint, 1974) signifying that river incision has not kept pace with external forces such as tectonics and/or climate (e.g., Whipple et al., 1999; Kirby and Whipple, 2001; Lavé and Avouac, 2001; Whipple and Tucker, 2002; Kirby et al., 2003; Duvall et al., 2004; Zaprowski et al., 2005; Wobus et al., 2006).

The transmission of surface perturbations along bedrock rivers due to local or external forcing can collectively alter drainage networks at the catchment scale, ultimately affecting the stability of drainage divides as demonstrated by modelling studies (e.g., Willett et al., 2001, 2014; Pelletier, 2004; Bonnet, 2009; Perron et al., 2012). Drainage divides may experience short-term horizontal mobility in response to changes in base-level (e.g., Prince et al., 2011) or climatic forcing (e.g., Stark, 2010), as well as long-term migration due to normal faulting propagation at rift margins (e.g., Summerfield, 1991; Gilchrist et al., 1994; Tucker and Slingerland, 1994), topographic advection (e.g., Willett et al., 2001; Willett and Brandon, 2002; Miller and Slingerland, 2006; Ramsey et al., 2007) and/or orographic precipitation (e.g.,

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* Corresponding author.
E-mail address: jbuscher@ing.uchile.cl (J.T. Buscher).

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Willett, 1999; Roe et al., 2003; Anders et al., 2008). The differential influence of tectonic and erosional processes may lead to a drainage divide migration that is out-of-phase with the main topographic crest of a mountain belt, leading to a physical separation of the two at the orogen scale. The movement of the drainage divide away from the crest of maximum peak elevations, where the primary orogen drainage divide is expected, has been shown to be induced by the propagation of deformation within extensional settings and fold and thrust belts (e.g., D'Agostino et al., 2001; Forte et al., 2015).

The decoupling of topographic and drainage network development has also been observed in the southern Apennines of Italy (Amato et al., 1995; Salustri Galli et al., 2002), which has been subject to both NE-verging orogenic transport and extensional faulting. The goal of this study is to help understand the progressive development of the drainage divide in the Mt. Alpi area of the southern Apennines through the interpretation of gross topographic and stream profile features together with analyses of stream profile gradient, steepness and convexity.

2. Tectonic background

The southern Apennines in the Mt. Alpi region are a northeast driven fold-and-thrust belt created by the subduction of the Adria Plate beneath Eurasia (Malinverno and Ryan, 1986) that represent the sum of compressional and extensional tectonics controlled by both thin- and thick-skinned deformation (e.g., Patacca et al., 1990; Cello and Mazzoli, 1998; Patacca and Scandone, 2001; Butler et al., 2004; Shiner et al., 2004; Scrocca et al., 2005; Schiattarella et al., 2006; Mazzoli et al., 2008, 2014). In the late Miocene, back-arc extension of the Tyrrhenian Sea (e.g., Kastens et al., 1988; Faccenna et al., 1996, 1997) occurred concurrently with thin-skinned thrust faulting of the Lagonegro, Apennine Platform and Ligurian Units currently exposed in the Mt. Alpi area, which generated a tectonic wedge (e.g. Sgrosso, 1988; Cello and Mazzoli, 1998; Mazzoli et al., 2014). Back-arc extension trending ~eastward caused down-faulting of blocks, leading to the formation of large coastal grabens that punctuated the southwestern margin of the southern Apennines in the Early Pleistocene (e.g., Sartori, 1990; Savelli and Schreider, 1991).

Starting in the Messinian, the formerly submerged wedge was thrust onto the Apulian Platform (e.g., Butler et al., 2004), above sea level (Ascione and Cinque, 1999), followed by the formation of shallow-water to continental wedge-top basins on top of the Apennine allochthonous units starting in the late part of the Early Pliocene (Mazzoli et al., 2012). Basin subsidence due to slab tear within the down-going Apulian lithosphere followed a progressive southeastward path from c. 4 to c. 2.8 Ma, when the youngest basin (Sant'Arcangelo basin) was formed (Ascione et al., 2012). Uplift of the Nocara anticlinal ridge from the contraction of the structurally lower Apulian Platform (Zuppetta et al., 2004; Capalbo et al., 2010; Mazzoli et al., 2012; Ascione et al., 2012; Giano and Giannandrea, 2014) ultimately separated the Sant'Arcangelo wedge-top basin from the Bradanic foredeep, leading to a change from marine to lacustrine deposition in the basin from 1.0–0.7 Ma (Zavala, 2000; Mattei et al., 2004; Sabato et al., 2005; Capalbo et al., 2010). Subsequently, the Pliocene to Pleistocene Sant'Arcangelo wedge-top basin units were uplifted along with the Nocara ridge in response to progressive post-orogenic (<0.7 Ma) southern Apennines uplift to the southeast (e.g., Cinque et al., 1993; Amato and Cinque, 1999; Ascione et al., 2012). Thin-skinned denudation (Schiattarella et al., 2006; Mazzoli et al., 2008) was generated in response to upper crustal collapse and is believed to have occurred contemporaneously with the compressional deformation of the Apulian Platform carbonates at depth (e.g., Cello and Mazzoli, 1998; Shiner et al., 2004; Mazzoli et al., 2014). At around 0.7 Ma (e.g. Patacca and Scandone, 2001), the southern Apennines were dominated by extension along high-angle normal faults (e.g., Cello et al., 1982; Cinque et al., 1993; Hippolyte et al., 1994; Ascione and Cinque, 1999) that is believed to have overprinted the entire tectonic sequence at depth as well as in the near surface, cutting across the low-angle extensional faults in the upper crust (Mazzoli et al., 2014). Coeval with the onset of extensional deformation, the northeastern side of the southern Apennines experienced uplift starting in the Middle Pleistocene, which is believed to be due to the slab detachment and rebound of the Apulia lithosphere (e.g., Cinque et al., 1993; Ascione et al., 2012, and references therein). Middle to late Pleistocene marine terraces from the Ionian coastal belt point to post-orogenic uplift increasing from NE to SW (e.g., Bordoni and Valensise, 1999; Amato, 2000).

3. Study area

3.1. High topography architecture and development

The topographic framework of the western part of the Mt. Alpi region is defined by high isolated carbonate peaks and ridges (elevations >1600 m) bound by well-developed semi-elongate to elongate intermontane basins (Fig. 1a). The high topography along the western chain axis primarily consists of Apennine Platform carbonates (e.g. Mts. Raparo, La Spina and Pollino), while Mts. Alpi and Sirino are made up of Apulian Platform and Lagonegro carbonates, respectively, that are typically found structurally lower in other locations of the southern Apennines (Fig. 2) (Mazzoli et al., 2001; Aldega et al., 2003; Corrado et al., 2005). The morphology of these high peaks is typically defined by steep peaks >30° and distinct high-angle normal faults (Mazzoli et al., 2014), reflective of the most recent thick-skinned extension. This is especially evident at Mt. Alpi, where a steep (~50°) high-angle fault scarp controls the morphology of the western flank of the mountain (Fig. 3a) (Mazzoli et al., 2014). Three of these high peaks (Mts. Sirino, La Spina and Pollino) extend along the southern Apennines drainage divide trending ~NW-SE with the chain axis, while two isolated peaks (Mts. Alpi and Raparo) located east of the drainage divide follow a ~N-S trend and stand above the surrounding topography despite being located away from the drainage divide and line of maximum elevation (Fig. 1a). Topographic profiles both along and across the chain axis reveal a locus of high topography between Mts. Sirino, Alpi, La Spina and Raparo peaks, with elevation decreasing progressively to the east and west but dropping more sharply north of Mt. Raparo, south of Mt. Alpi and west and south of Mt. Sirino (Fig. 1b). The Cogliandrino River valley extending ~N-S between Mts. Sirino and Alpi also stands notably higher than surrounding basins as part of the local topographic high.

Complementing the topographic evidence for surface uplift, low-temperature thermochronometry data from bedrock samples show that the pattern of recent exhumation also coincides with the local topographic high. Young apatite (U–Th)/He (AHe) and fission track (AFT) cooling ages (ranging from 1.6 to 1.9 Ma and 1.5 to 3.2 Ma, respectively) from Mt. Alpi and Mt. Sirino (Corrado et al., 2005; Mazzoli et al., 2006, 2008, 2014; Iannace et al., 2007; Invernizzi et al., 2008), located in the footwall of the ~ESE-vergent Cogliandrino low-angle detachment fault, reflect rapid exhumation (~1 mm/yr) of these units, with rates decreasing to <0.6 mm/yr starti'ng at ~1.5 Ma (Fig. 1) (Mazzoli et al., 2014). Bedrock cooling ages north and south of the Mt. Alpi area are notably older than those from Mts. Alpi and Sirino (AHe = 3.4 to 5.9 Ma and AFT = 3.8 to 9.2 Ma), with exhumation rates inferred to be <0.6 mm/yr from at least 4 Ma to the Present (Mazzoli et al., 2014). Despite the close proximity of Mt. Raparo to Mts. Alpi and Sirino, this peak is believed to have experienced a different exhumation history because it is located in the hanging wall of the Cogliandrino detachment fault (Mazzoli et al., 2014).

3.2. Intermontane basins

The intermontane basins interspersed between the high carbonate peaks collectively formed in response to ~NE-SW Quaternary extension

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