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Late Pleistocene differential uplift inferred from the analysis of fluvial terraces (southern Apennines, Italy)

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ABSTRACT

The stratigraphic architecture and morphological assemblage of the Pleistocene fluvial terraces contained in two contiguous fluvial valleys are used to understand the spatial distribution and the timing of the differential uplift that affected two different geological and geomorphological settings of an active orogen. The study areas, both placed in the eastern sector of the southern Apennines of Italy, are the Sant'Arcangelo sedimentary basin and the Valsinni Ridge anticline. Pleistocene uplift rate of 0.7–0.9 mm y^{-1} and historical earthquakes affecting those areas suggest active tectonics. Based on the synthem units used to classify the fluvial deposits in the field, several strath, fill, and fill-cut terraces have been mapped in the middle valleys of the Agri and Sinni rivers. Four Middle Pleistocene high terraces (Qes) are found in the Sant'Arcangelo Basin and cut its infill, and three Late Pleistocene low terraces (Qt) are found at both the Agri and Sinni valley flanks. The Agri and Sinni rivers cross-cut the NW–SE-oriented fold-and-thrust belt of the southern Apennines from W to E, producing a transverse drainage. As a result, ten- to hundred-metre deep gorges and wide floodplains were created in the middle reach of the river valleys. Computation of the bedrock incision rates from the Qes_1, Qes_4, and SQt_1 terraces, corresponding to 1.2 ± 0.2 mm y^{-1} at 400–240 ka and 0.8 ± 0.2 mm y^{-1} in the last 240 ka, together with the terrace profile arrangements in the Agri and Sinni valleys, allow for the documentation of i) the differential uplift of the study area and ii) the age of terrace abandonment corresponding to the beginning age of the vertical incision in the valley floor sediments to form the Qt terraces. The differential uplift is subsequently discussed in a space and time–sequence evolution of the Late Pleistocene to assess the complex morphotectonic development that occurred in the eastern threshold of the basin. The differential uplift of both the Sant'Arcangelo Basin and Valsinni Ridge would appear to indicate that buried fold-and-thrust structures that affect the Mesozoic–Cenozoic sedimentary nappes are still active, and they also controlled the slab retreat processes in the Mediterranean region during the Late Pleistocene.

1. Introduction

River terraces are globally distributed landforms that are formed on the flanks of river valleys in a wide range of climatic and tectonic settings when base level lowering results in erosion and river downcutting (Leopold et al., 1964; Bull, 1991; Merritts et al., 1994; Schumm et al., 2000; Pazzaglia and Brandon, 2001; Bridgland et al., 2007; Bridgland and Westaway, 2008a,b; Vandenberghe, 2008; Gibbard and Lewin, 2009; Wegmann and Pazzaglia, 2009; Westaway et al., 2009; Lewin and Gibbard, 2010; Stokes et al., 2012 and references therein). A river terrace is a more or less flat surface that is bounded by sloping surfaces on the upslope and downslope sides, and its formation first requires the aggradation of channel and floodplain sediments, followed by a vertical incision into the valley floor sediments or into the bedrock (Stokes et al., 2012). The interpretation of river terraces in relation to causal mechanisms, such as climate change, sea-level variations, and tectonics is still widely debated in the international literature (*e.g.*, Blum and Törnqvist, 2000; Maddy et al., 2000; Pazzaglia and Brandon, 2001; Hancock and Anderson, 2002; Starkel, 2003; Bridgland et al., 2007; Bridgland and Westaway, 2008a,b; Vandenberghe, 2008; Gibbard and Lewin, 2009; Vandenberghe et al., 2011; Ramos et al., 2012). In long-term river evolution (commonly millions of years), the lowering of regional base level is controlled by the spatial and temporal variability of the tectonic uplift rates that depends on the geodynamic setting, whereas in short-term evolution, climate and sea level changes are responsible for producing fluvial aggradation or incision (Stokes et al., 2012). In the Quaternary, episodes of fluvial aggradation are typically associated with glacial periods during which scarce vegetation cover promoted an intensive slope denudation and an increase of the sediment supply in the valley floor. In contrast, the vertical incision of floodplain sediments formed terraces that are more concentrated during interglacial periods, when an improvement of the vegetation cover reduced the sediment supply in the valley floor, in the initial transition from cold to warm conditions, or during a brief warm interstadial within a cold period (Bridgland, 2000; Maddy et al., 2001; Bridgland and Westaway,

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2008b; Vandenberghe, 2008). River terraces, in the lowland reach of fluvial valleys, are also produced by base-level lowering driven by glacioeustatic sea level fluctuations (Maddy et al., 2001; Bridgland and Westaway, 2008b). In such situations, the climate is a dominant factor in controlling the fluvial system evolution, leading to the formation of a single terrace level. Conversely, the production of multiple river terrace levels requires a base-level lowering trend or tectonics (Stokes et al., 2012). In active tectonic settings and upstream of the mouth of rivers, where sea-level oscillations do not influence the fluvial system (*sensu* Blum and Törnqvist, 2000), a marked base-level lowering carves strath terraces in bedrock channels and not particularly pronounced base-level lowering produces fill terraces in valley floors (Leopold et al., 1964; Bull, 1991; Merritts et al., 1994; Pazzaglia and Brandon, 2001; Gibbard and Lewin, 2009). Specifically, fluvial terraces can be produced in a single catchment by different tectonic actions, such as block faulting, anticline fold growth, and regional rock uplift, associated with distinct stress fields (*e.g.*, Rockwell et al., 1988; Molnar et al., 1994; D'Agostino et al., 2001; Lavé and Avouac, 2001; Vannoli et al., 2004; Scharer et al., 2006; Wilson et al., 2009). The terrace arrangement occurs because of non-uniform block faulting, folding, or isostatic uplift (Schumm et al., 2000; Burbank and Anderson, 2001; Westaway, 2012), which can provide a large amount of information on the differential rock uplift of a segment of a fluvial valley. As an example, a differential uplift using the arrangement of fluvial terraces as morphotectonic markers has been recognised within a catchment of a tributary of the Yellow River (Vandenberghe et al., 2011). A kinematic model of a detachment fold and a differential uplift in the Kashi–Atushi fold system of Tibet has been explained by the tilting affecting the fluvial terraces during the growth of a fold (Scharer et al., 2006). In addition, the fluvial terraces of the Italian Apennines have been used to constrain the Pleistocene kinematics of buried fault-propagation folds (Wilson et al., 2009). In the northern and central Apennines, the response of fluvial terraces to a Quaternary uplift of approximately 0.3–1.0 mm y^{-1} has been addressed over several decades with different approaches and tools (Vannoli et al., 2004; Cyr and Granger, 2008; Wegmann and Pazzaglia, 2009; Wilson et al., 2009; Troiani and Della Seta, 2011 and references therein). In the northern and central Apennines, the primary mode of relief generation in the last 900 ka was tectonic uplift, but climate variations also trigger headward erosion, stream piracy, and river terrace formation (D'Agostino et al., 2001; Nesci et al., 2010) that contributed to relief production. The rivers recording an unsteady and non-uniform incision controlled by a differential tectonic uplift suggest a near-attainment of dynamic equilibrium between the tectonic uplift rates and the erosional processes (Simoni et al., 2003; Cyr and Granger, 2008). In the southern Apennines, a mean uplift rate of 0.5–0.6 mm y^{-1} in the last 700 ka has been computed (Amato, 2000; Schiattarella et al., 2003, 2006; Westaway and Bridgland, 2007), and it is quite similar to the uplift affecting the northern and central Apennines. The amount of the uplift has been defined using the tectonic displacement age of several land surfaces and marine terraces (Amato, 2000; Schiattarella et al., 2003, 2013). This situation has also been investigated *via* numerical modelling and using large fluvial and marine staircase terraces to conclude that both the southern Apennines and Calabria regions do not exhibit a steady-state condition (Westaway and Bridgland, 2007). In addition, the Late Quaternary fault activity has been demonstrated by using fluvial and marine terrace analysis and numerical modelling (Caputo et al., 2008). It follows that increases in the uplift rates are characteristic of the early Middle Pleistocene in this active tectonic setting. The south of Italy lies within a plate boundary zone along which the African plate is subducting and within which the continental crust is extending. Thus, it is important to know the response of surface landforms to the Middle and Late Pleistocene vertical crustal motions (Westaway and Bridgland, 2007). In the axial zone of the southern Apennines, remnants of erosion surfaces suspended at different elevations above the sea level (Schiattarella et al., 2013), and distributed fluvial terraces are the main landforms that suggest a large-scale Quaternary uplift. Both landforms furnished information on the rate of uplift and its driving mechanism in a single catchment basin (Boenzi et al., 2004; Caputo et al., 2008) or in the whole chain (Schiattarella et al., 2006; Westaway and Bridgland, 2007). They are also suitable geomorphological markers for distinguishing the uniformly distributed rock uplift in a catchment that produces similar altitude in the up-thrown block, and the non-uniformly distributed rock uplift that generates an uneven altitude in the up-thrown block and thus a differential uplift.

The aims of this work were to investigate the effects produced by the spatial and temporal variability of the tectonic uplift on two different geological settings, a sedimentary basin and a mountain ridge, using fluvial terraces as passive markers of deformation and to investigate how this uplift is uniformly or non-uniformly distributed in the two areas. We have attempted to address the problem in the Sant'Arcangelo Basin and in the Valsinni Ridge located on the eastern side of the southern Apennines chain of Italy by means of the analysis of Late Pleistocene fluvial terraces localised in the middle reach of both the Agri and Sinni river valleys (Fig. 1). These valleys, cross-cutting both the Sant'Arcangelo sedimentary basin and the Valsinni Ridge anticline, are meaningful areas for the study of tectonic behaviour of two different landscapes in a still active orogeny. The Agri and Sinni rivers flowing from west to east to the Ionian Sea are good examples of transverse drainages that affect both the NW–SE-trending fold-and-thrust belts of the southern Apennines and the Bradano Foredeep. They carve into several hundred metres of the Mesozoic to Quaternary deposits of the chain-producing narrow to wide fluvial valleys, providing excellent exposure to several orders of Pleistocene fluvial terraces. The geological and morphological analysis of the fluvial terraces in the middle reach of the Agri and Sinni rivers, the computation of the bedrock incision rate and the abandonment age of the Late Pleistocene fluvial terraces, in the sense of the first vertical incision in the valley floor sediments that formed the terraces, allowed us to estimate the space–time variability and time–sequence morphotectonic evolution of the Late Pleistocene differential uplift that affected two different geological settings of a tectonically active chain.

2. Geological and geomorphological settings

The southern Apennines chain (Fig. 1a), a Miocene to Pleistocene fold-and-thrust belt, is composed of east-verging tectonic units (Pescatore et al., 1999 and references therein) overlapping on the Apulian Platform and is characterised by large duplex geometries (Patacca and Scandone, 2007 and references therein). The most recent shortening occurred on the front range of the chain, deforming the Pleistocene sediments and volcanics (Pieri et al., 1997). Moreover, extensional tectonics has displaced the orogeny and is still active along the axis of the Apennines chain (*e.g.*, Cinque et al., 1993; Amato and Montone, 1997; Schiattarella, 1998; Giano et al., 2000; Schiattarella et al., 2006; Barchi et al., 2007; Patacca and Scandone, 2007, among others). The average direction of the chain axis is approximately N150°, which corresponds to the strike of both the main thrusts and the coaxial normal faults. Such a complex structural setting produced a mountain chain over 2000 m high and a watershed oriented NW–SE that separates the drainage network towards the Tyrrhenian Sea (south-west), Adriatic Sea (north-east), and the Ionian Sea (east). From a geological and geomorphological point of view, the fold-and-thrust belt of the southern Apennine chain can be roughly divided into three zones (inner, axial, and outer belts) parallel to its NW–SE-elongation axis. The inner belt corresponds to the Tyrrhenian side of the Apennines and is composed of Cretaceous to Oligocene deep-sea pelagic successions (Ligurian and Sicilian units; Ogniben, 1969) overthrusted on Mesozoic shallow-water carbonate units that form the Cilento Promontory with a maximum elevation at Cervati Mt. (1900 m a.s.l.). The axial belt is formed by the sedimentary fold-and-thrust sequences of the southern Apennines, mainly composed of Mesozoic to Cenozoic shallow-water