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Earthflow sediment production and Holocene sediment record in a large Apennine catchment

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ABSTRACT

Landscape evolution in active mountain chains can be dominated by gravitational slope movements. This is observed in a large portion of the Reno river catchment, Apennines, Italy, where weak rocks, such as clayshales, are subject to earthflows that control hillslope morphology and supply sediments to the channel network. In this paper, we evaluate the sediment flux generated by earthflows and compare it with Holocene-averaged deposition rates to assess the contribution of mass movements to landscape evolution. Present-day hillslope sediment flux is estimated by combining measured displacement rates (72 inclinometers) and spatial attributes of earthflows and historical frequency of reactivations. Averaged sediment yield (~1.6×10^3 t/km^2/yr) compares well with similar studies on earthflow-dominated landscapes, despite notable differences in methodology.

In the study area, the connectivity between hillslopes and the stream network is well developed and no significant sediment sinks influence the sediment transport processes. We document best estimates of regional sediment fluxes and related uncertainties, based on available data. Coarse limestone fragments, present in the clayshales, are used as a natural sediment tracer to allow a comparison with sedimentation rates taking place at the mouth of the intramontane catchment. Here, available borehole logs, ^{14}C datings and stratigraphic correlations of the alluvial fan are used to obtain an estimate of the deposition that took place during Holocene times. Taking also into account the role of solute transport, sedimentation rates are compared to earthflow sediment production rates. Results show a good agreement and demonstrate that earthflows are the primary mass wasting process in these weak rock lithologies.

We document best estimates of regional sediment fluxes and related uncertainties. Present earthflow sediment production outpaces Holocene-averaged sedimentation rates by a factor of two. The gap between sediment production and deposition can be partly justified by uncertainties associated with our estimates and by time-scale differences. With this respect, the dynamic equilibrium between erosion and deposition, is likely affected by intra-Holocene oscillations at a short time scale (10 to 1 ky) attributable to climate variability. Terraced deposits documenting sedimentary episodes would also support such interpretation.

1. Introduction

The sediment budget of large mountainous catchments results from the interaction of many different processes acting along the channels and over the hillslopes. The quantification of the contribution of each process to the sediment budget is, indeed, very complicated and involves the measurement or estimate of several variables.

The importance of landsliding as relief-shaping agent has long been recognized (Korup et al., 2010). The total amount of sediment produced by landslides within a given catchment is a function of their magnitude and frequency (Reid and Page, 2002). Inventories of landslides show that the frequency of landslide is a function of landslide magnitude both in space and time (Guzzetti et al., 2002; Brardinoni and Church, 2004). Such properties can be used to extrapolate predictions, though substantial uncertainty is still not resolved for extreme ends. In general, it can be said that the rate of sediment production from landslides varies greatly, depending on the observation period and impact of extreme events (Korup et al., 2010).

Slow-moving landslides like earthflows have been seldom treated as source of sediment to regional sediment budget. In this paper we use the term earthflow to identify landslides that show intermittent flow-like movement of plastic, clayey soil , facilitated by a combination of sliding along single or multiple discrete shear surfaces and internal shear strains (Keefer and Johnson, 1983; Hungr et al., 2012). Other authors used the term mudslide (Hutchinson, 1988; Picarelli et al., 2005), composite or complex earth slide–earth flow (Cruden and Varnes, 1996), debris slide (Schulz et al., 2009). This kind of

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mass movements, in spite of producing flow-like morphology, has velocity profiles that often show the existence of thin shear surfaces where most of the deformation takes place (Hungr et al., 2001).

Earthflows exhibit movements that are persistent through time with rates classified as “very slow” or “extremely slow” (Cruden and Varnes, 1996). Landslide movement is typically controlled by fluctuations in piezometric pressure. Periodic increases of the rate of movement have been documented in relation to specific rainfall episodes (Corominas et al., 2005; Schulz et al., 2009) or to the seasonal pore-water pressure increase (Coe et al., 2003; Macfarlane, 2009; Wienhöfer et al., 2011). Despite the periodic accelerations, movements can proceed for centuries with slow velocities (Schulz et al., 2009; Rutter and Green, 2011). Only during catastrophic generalized failures can velocities increase to “moderate” to “rapid” values in the Cruden and Varnes (1996) velocity scale (Petley et al., 2005; Picarelli et al., 2005).

It is difficult to ascertain whether all earthflows experience periodic catastrophic failures or slow movement can be sustained in the long-term. A recent analysis of instrumental and geomorphological data pertaining to slow moving landslides indicates that in many cases there is no evidence to indicate rapid movement during long-term evolution (Glastonbury and Fell, 2008).

Due to such characteristics, it is difficult to discern the state of activity (Cruden and Varnes, 1996), based on qualitative observation. The discrete boundary between active (or reactivated) and dormant phenomena, in particular, fades whenever displacement rates are in the order of cm/month. Instrumental measurements are then required to get an appropriate description of the velocity and, hence, of the state of activity.

Velocity measurements performed at specific locations, either on the surface or at depth, are usually available for specific phenomena over short time series (months to years) and their interpretation in the context of long-term evolution is problematic.

Very recently, Mackey and Roering (2011) made an effort to quantify earthflow movement over significant spatial and temporal scales in northern California . They measured earthflow movements exceeding 5 m over 60 years (>80 mm/yr) by comparing LiDAR (light detection and ranging) and orthorectified historical aerial photographs. Their results demonstrate that earthflows are capable of generating a sediment yield that is more than half the estimated total sediment yield. Comparable results were found by Kelsey (1978) following a similar photogrammetric study of a nearby catchment.

In this work, we analyze earthflow activity over a large portion of the Reno river catchment, Apennine Italy, where clay shales of the Ligurian units outcrop and landsliding is the main relief-shaping agent. We take advantage of the data measured by 72 inclinometers over 23 earthflows to characterize the representative velocities of gravitational slope movements within the study area. The estimate of hillslope sediment delivery rate to the channel network is based on mapped connectivity, earthflow velocities, and geometric similarities describing the depth of sliding. Thanks to peculiar lithological characteristics of the Ligurian units, we are able to isolate the volumetric fraction of the Holocene deposits (fan and terraces) that is derived from the Ligurian units. We then compare present-day landslide-related hillslope sediment flux to Holocene deposits to assess the contribution of earthflow movement to regional erosion rates and their control of landscape evolution.

2. Study area

The Reno river catchment is located in the Northern Apennines of Italy (Fig. 1). Its mountainous portion extends over an area of 668 km^2, rising from an elevation of 56 m to the highest point at 1922 m. A large alluvial fan dominated by gravel deposits is present at the mouth of the intramontane valley.

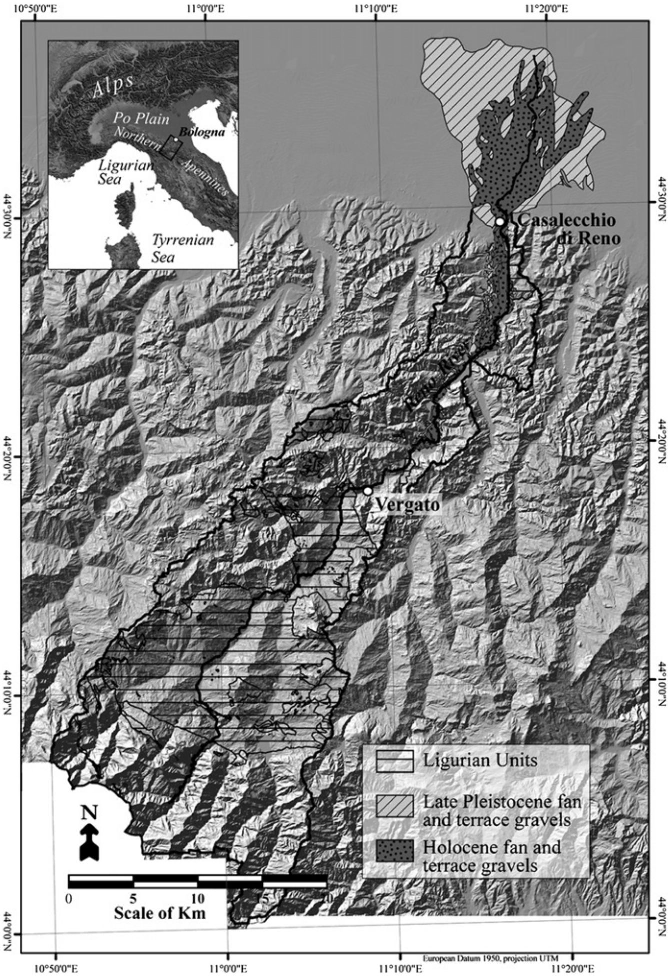

Fig. 1. Sketch map of the Reno river intramontane catchment and alluvial fan.

Rocks pertaining to the Ligurian domain constitute about one third of the catchment bedrock. They consist of chaotic clay shales and include limestone clasts (gravel to boulder size) embedded into the clayey matrix as relics of original calcareous beds (Pini, 1999). The clay-shale bedrock shows a structure of small iso-oriented particle aggregates (scales) with dimensions ranging from millimeters to centimeters. Getting close to the surface, the clayshale is subject to stress relief, swelling and weathering which progressively obliterate the scaly structure and induce a color change from dark gray to brown. In the remaining portion of the Reno catchment, the bedrock mainly consists of stratified sedimentary rocks, dominated by arenaceous flysch.

The style of landsliding, on Ligurian Units, is dominated by complex earth slides/earthflows (Cruden and Varnes, 1996) that we term earthflows, as explained in the introductory section. Earthflows typically have a bowl-shaped source area, an elongate transport zone and a lobate toe that reaches the trunk stream at the bottom of the slope or, alternatively, merges with other earthflows generating coalescent multiple phenomena.

Earthflow bodies slowly move downslope. The movement generally exhibits a seasonal pattern and mostly develops along discrete sliding surfaces with internal deformation of the sliding mass. First-time failures are observed in the source area as localized retrogressive rotational slides whose deposits feed the earthflow body (Berti and Simoni, 2012). Paroxystic reactivations of the whole deposit are much less frequent and can be catastrophic for properties, buildings and roads. They are usually triggered by multiple retrogressive failures of the headscarp and the downslope propagation of the