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Influence of slip-surface geometry on earth-flow deformation, Montaguto earth flow, southern Italy

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ABSTRACT

We investigated relations between slip-surface geometry and deformational structures and hydrologic features at the Montaguto earth flow in southern Italy between 1954 and 2010. We used 25 boreholes, 15 static cone-penetration tests, and 22 shallow-seismic profiles to define the geometry of basal- and lateral-slip surfaces; and 9 multitemporal maps to quantify the spatial and temporal distribution of normal faults, thrust faults, back-tilted surfaces, strike-slip faults, flank ridges, folds, ponds, and springs. We infer that the slip surface is a repeating series of steeply sloping surfaces (risers) and gently sloping surfaces (treads). Stretching of earth-flow material created normal faults at risers, and shortening of earth-flow material created thrust faults, back-tilted surfaces, and ponds at treads. Individual pairs of risers and treads formed quasi-discrete kinematic zones within the earth flow that operated in unison to transmit pulses of sediment along the length of the flow. The locations of strike-slip faults, flank ridges, and folds were not controlled by basal-slip surface topography but were instead dependent on earth-flow volume and lateral changes in the direction of the earth-flow travel path. The earth-flow travel path was strongly influenced by inactive earth-flow deposits and pre-earth-flow drainages whose positions were determined by tectonic structures. The implications of our results that may be applicable to other earth flows are that structures with strikes normal to the direction of earth-flow motion (e.g., normal faults and thrust faults) can be used as a guide to the geometry of basal-slip surfaces, but that depths to the slip surface (i.e., the thickness of an earth flow) will vary as sediment pulses are transmitted through a flow.

1. Introduction

Early in 2006, a large, thick earth flow (Fig. 1) remobilized on the south side of La Montagna Mountain, near the town of Montaguto in the Campania region in southern Italy (Fig. 2). On April 26, 2006, the toe of the earth flow (referred to as the Montaguto earth flow) covered the east–west-trending Italian national road (SS90), which connects the provinces of Foggia and Avellino. In addition to covering the road, the earth flow damaged buildings and stopped about 30 m from the Benevento–Foggia national railway. The Montaguto earth flow has a long history of periodic activity (Guerriero et al., 2013a; Table 1), but the 2006 mobilization was the largest documented in the previous 70 years (historical records extend back to about 1935), with a total flow volume of 4–6 million m^3 (Giordan et al., 2013; Guerriero et al., 2013a; Lollino et al., 2014). Additionally, the 2006 mobilization was the largest activation of an earth flow in southern Italy since 1996 when the Covatta landslide occurred in the Biferno Valley (Corbi et al., 1999). In 2014, the Montaguto earth flow continues to be an ongoing threat to the road and railway.

Throughout this paper, we use the term earth flow to describe the Montaguto slope failure because it is composed of predominantly fine-grained material and has a flow-like surface morphology (Varnes, 1978; Keefer and Johnson, 1983; Cruden and Varnes, 1996; Hungr et al., 2001). However, most movement of Montaguto earth flow takes place by sliding along discrete shear surfaces (Guerriero et al., 2013a). At Montaguto, as at most slope failures, sliding movement is usually concentrated along basal- and lateral-slip surfaces (Hutchinson, 1970; Prior and Stephens, 1972; Keefer and Johnson, 1983; Baum and Johnson, 1993). The geometry of these slip surfaces can alter slope-stability calculations and mitigation designs (Stout, 1971); design of sampling, instrumentation, and mitigation schemes (Hutchinson, 1983); and pore-water pressures and movement dynamics (see, e.g., Iverson, 1986; Zhang et al., 1991; Baum and Johnson, 1993; Baum et al., 1998; van Asch et al., 2006, 2007). The implications of these observed and modeled effects are that basal- and lateral-slip surfaces should also control the positions and geometries of surface features such as faults, tilted surfaces, streams, springs, and sinks. Coe et al.

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Fig. 1. The Montaguto earth flow on 27 April 2006. Photo taken from a helicopter looking south toward the earth-flow toe.

(2009) inferred that the long-term positions of ponds on the continuously moving Slumgullion earth flow in Colorado were controlled by depressions of the basal-slip surface and suggested that basal control of other surface features could be verified (or denied) through detailed, long-term, multitemporal mapping of surface structures and hydrology. Our working hypothesis in this paper is that a linkage exists between the geometry of basal-slip surfaces and features on the surface of earth flows.

At the Montaguto earth flow, previous work by other researchers has documented the evolution of surface topography (Ventura et al., 2011; Giordan et al., 2013), but the influence of basal- and lateral-slip surfaces on long-term earth-flow evolution has yet to be explored. As a first step toward gaining a better understanding of possible basal- and lateral-slip surface controls of landslide surface features and kinematics at the Montaguto earth flow, Guerriero et al. (2013a) mapped earth-flow structures and hydrologic features (i.e., creeks, springs, and ponds) at nine different dates from 1954 to 2010 (see 1:6000-scale maps in Guerriero et al., 2013a). Herein, we use the multitemporal maps of Guerriero et al. (2013a), combined with recently available shallow-seismic data and digital elevation models (DEMs), to evaluate the relation between slip-surface geometry and surface structures, hydrology, and major kinematic zones (i.e., distinct earth-flow movement zones defined by surface structures). We use DEM differencing (e.g., James et al., 2012) to track sediment pulses and to discuss volumetric variation and the travel time of pulses in the earth-flow source area.

2. Geologic, hydrologic, and climatic settings of the Montaguto earth flow

The Montaguto earth flow is located on the south-facing slope of La Montagna Mountain in the Daunia Mountains (southern Apennines). The geology of Daunia Mountains (Pescatore et al., 1996) is tectonically and stratigraphically complex, with a network of faults and folds affecting sedimentary units. On the south-facing slope of La Montagna Mountain, there are outcrops of the Miocene pelagic deposits of the Daunia unit and of the late-Messinian to early-Pliocene Villamaina Formation (Fig. 3). The Daunia unit (Santo and Senatore, 1988) is composed (from bottom to top) of three formations: (i) the Monte Sidone Formation (about 500 m thick and about 20 Ma) is characterized by a rhythmic, mainly turbidite succession of calcareous sandstone, marl, and clay beds; (ii) the Flysh of Faeto Formation (*Faeto Formation* shown in Fig. 3, 650 m thick and about 11 Ma) is a multilayered formation that is represented by a calcareous-clastic succession characterized by chaotic levels (slumps) and calcareous breccia beds with interbedded calcarenites, marls, and rare clay beds; and (iii) the Toppo Capuana Formation, in stratigraphic continuity, consists of gray clay and gray-clayey marls with few calcareous-clastic, marly, and clayey turbidites and interbedded-sandstone beds. The Villamaina Formation comprises (from top to bottom) brownish-gray sandy and silty-clay beds, conglomerates and sandstones with a few clay beds. In the earth-flow area, the Faeto Formation crops out on the upper part of the slope from an elevation of 650 m above sea level (asl) to the top of the La Montagna Mountain. In the middle and lower parts of the slope, the Villamaina Formation crops out. An unconformity separates the Villamaina and Faeto Formations.

Structural deformation in the earth-flow area resulted from Miocene and Pliocene compressive tectonism (Pescatore, 1978; Patacca and Scandone, 1989) followed by Quaternary tensile stress. Fold axes and faults have two predominant directions, northwest-trending and northeast-trending (Fig. 3; Pinto, 1993). At a regional scale, the earth-flow source area is located within a large overturned fold (about 3 km long in the east–west direction). At a local scale, the source area is within a northeast-trending synclinal fold structure (about 0.6 km long). The strike of the Faeto Formation in this area is about N 40° E and is oriented in the same direction as the hillslope. The western part of the earth flow in the source area failed along steeply (~50°) dipping beds in the Faeto Formation. In the eastern part of the source area, Flysch of Faeto Formation beds dip about ~20° to the southeast, and the formation is very fractured. Farther downslope, the narrowest part of the earth flow (the earth-flow neck) is located in a structural depression created by the intersection of the syncline fold axis with northwest-trending normal faults (Fig. 3). In this area, the earth flow is located east of the fold axis and moves along a bedrock surface roughly parallel to the axis of the syncline. This axial surface is inclined about 10° to the southwest. Downslope from the neck, the earth flow lies between a northwest-trending syncline axis and a parallel-trending normal fault. From an elevation of 500 masl to the base of the mountain, the earth flow occupies a V-shaped valley, but only the upper flanks of the valley are recognizable.

The geological complexity of the area controls groundwater flow and spring positions. Many springs are present in, and adjacent to, the earth flow from about 600 to 850 masl. In the source area, the cumulative flow of water from all the springs in May 2010 (as measured with a bucket and stop watch) was about 2.0 l/s. Farther downslope along the eastern flank of the earth flow, the flow of water from a group of springs that feed a large lake (Rane Lake, described in the Results section) was also about 2.0 l/s in May 2010. The distribution of springs, the variable permeability of outcropping rocks, and the structural setting indicate that the hydrologic system on the south-facing slope of La Montagna Mountain consists of multiple aquifers (Diodato et al., 2014).

Precipitation in the area can be characterized using data from the Orsara di Puglia, Monteleone di Puglia, Savignano Irpino, Faeto, and Bovino meteorological stations (Fig. 2), all located less than about 10 km from the earth flow. The elevations of the meteorological stations range from 650 masl at the Orsara di Puglia and Bovino stations to 900 masl at the Faeto station. Annual precipitation data between 1921 and 2009 indicate that average annual precipitation in the area is about 800 mm, with a range in annual values between 200 and 1400 mm/y. Data regarding the state of precipitation (snow or rain) were not available from the meteorological stations, but in this part of the Apennine chain more than 90% of precipitation is rainfall (Diodato, 1997; Revellino et al., 2013).

3. Materials and methods

3.1. Multi-temporal mapping and analysis

We mapped earth-flow structures and hydrologic features (springs, creeks, and ponds) nine times (i.e., time slices) between 1954 and 2010