Geomorphology 132 (2011) 111–122

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Distribution and causes of landslides in the eastern Peloritani of NE Sicily and western Aspromonte of SW Calabria, Italy

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ARTICLE INFO

Article history:
Received 2 December 2010
Received in revised form 29 March 2011
Accepted 30 April 2011
Available online 5 May 2011

Keywords:
Landslide spatial distribution
Landslide magnitude–area analysis
Fault activity
Rainfall
2009 flood event of Messina

ABSTRACT

The Peloritani and Aspromonte areas are tectonically active mountainous regions of NE Sicily and SW Calabria, respectively, where landslides are the most common hillslope mass-wasting process. This study aims to elucidate the primary controls on the distribution and size of landslides in these two different landscapes. These regions, either side of the Messina Strait, have similar lithologies, but show different morphological characteristics in response to varied neo-tectonic activity and climate. Landslides were identified utilising aerial photographs and Landsat images. Frequency–area statistics were calculated to determine the length-scale of the most frequent interpretable landslides and compare our results with previous studies. The frequency–area power-law exponents (1.99 in Peloritani and 1.94 in Aspromonte) fall within the range of values that have been observed (2.0 ± 0.5) in similar landscapes.

The Peloritani Ridge, Sicily, has range-parallel normal fault segments with the majority of landslides occurring in their footwalls. There seems to be a strong coupling between tectonic activity and landslides, where slope instability is exacerbated by faulting, fracturing or jointing in otherwise low-permeability gneiss and granite bedrock. Conversely, in Aspromonte, Calabria, landslides are restricted to steep valley walls, and are absent from interfluves. This is because landslides are controlled by fluvial incision processes. These observations confirm a relationship between the spatial distribution of landslides and the processes controlling slope failures.

1. Introduction

The behaviour of hillslopes remains a key, but still imperfectly understood, aspect of landscape response to spatial variations in tectonics and climate. Korup et al. (2010) reviewed the role of landslides in mountain range evolution and identified questions for future research. These included whether the locations of clusters of landslides in a landscape could indicate their triggering mechanism. Densmore and Hovius (2000) showed that landslides triggered by earthquakes have a more spatially uniform distribution than those triggered by storms, which tend to be localised along hillslope toes.

The mountain ranges surrounding the Strait of Messina, Italy (Fig. 1), represent part of the Calabrian Arc that was highly deformed by the Neogene–Quaternary Africa–Europe collision (Ghisetti and Vezzani, 1982; Dewey et al., 1989). These ranges are undergoing active extension with the development of normal faults on both sides of the Strait. These faults are responsible for a high level of seismicity. Since the Early–Middle Pleistocene, destructive earthquakes have occurred on both sides of the strait (Baratta, 1910; Schick, 1977; Postpischl, 1985; Boschi et al., 1995; Monaco and Tortorici, 2000; Jacques et al., 2001; Galli and Bosi, 2002). Also illustrating the geomorphic activity of the region, major rainfall-induced landslides occurred in Briga on 1–2 October, 2009 (10 km from the city of Messina), within the area of the present study (Foti et al., 2010). A sudden downpour (22.9 cm in 3 h) initiated devastating mudslides.

Since landslides are often the main contributor to the overall sediment budget coming out of mountainous systems (Hovius et al., 1997; Oguchi et al., 2001; Korup et al., 2010), it is important to understand their distribution and what controls them. The present tectonically active area seems to be clearly also affected by storm-triggered landslides. Therefore, we determined the spatial distribution of the landslides to test Densmore and Hovius's (2000) hypothesis of whether tectonics or rainfall has a stronger control. The well-established relation between the frequency and size of landslides (Guzzetti et al., 2001; Stark and Hovius, 2001; Malamud et al., 2004) is used to compare our results with previous studies, and serves as a general check on the quality of our landslide inventories.

2. Study area

The study area embraces the eastern part of the Peloritani Range, Sicily and the western part of Aspromonte, Calabria (Fig. 1). Although the main lithologies on both sides of the Ionian Sea are granitic and high-grade metamorphic rocks (Lentini et al., 1995), the

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doi:10.1016/j.geomorph.2011.04.036

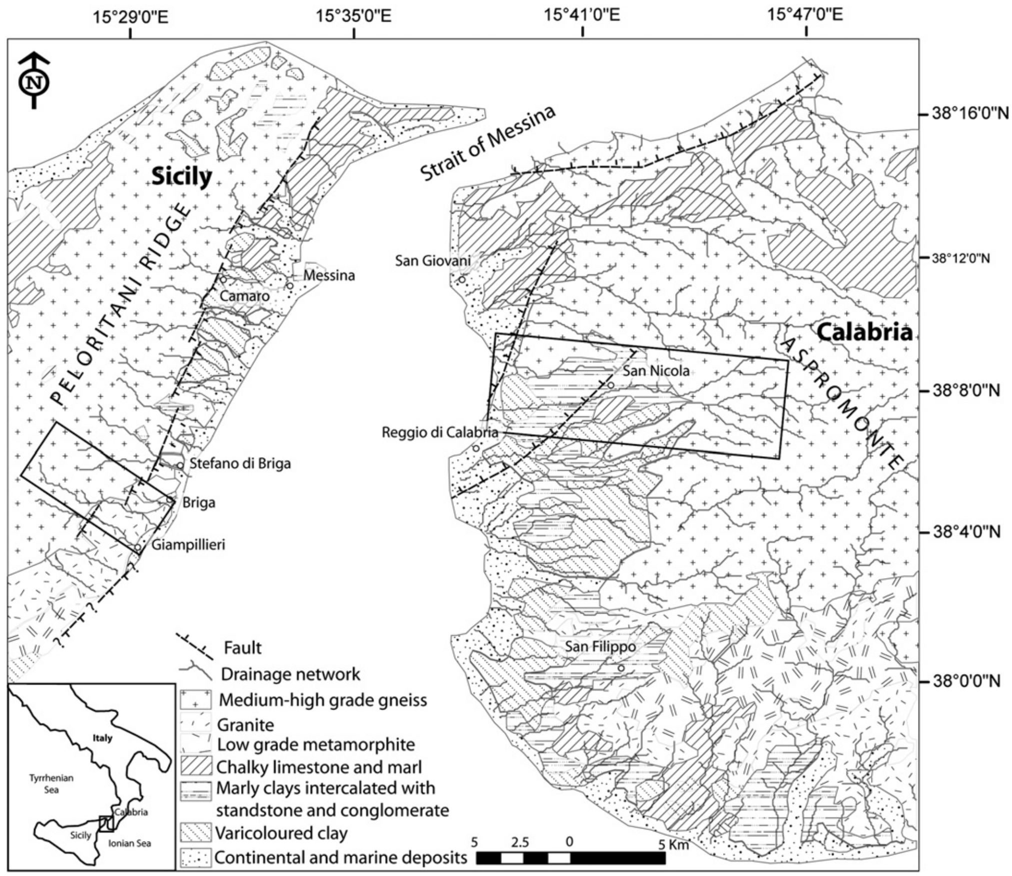

Fig. 1. Location map of the study areas with geologic information and drainage networks. Locations mentioned in the text are shown. After the geological map of Messina Province (Lentini et al., 1995). Rectangles show areas of data collection for analyses illustrated in Figs. 10 and 11.

morphologies of the ranges on either side of the Ionian Sea are different (Fig. 2). The Peloritani Range is rugged and uneven, where crystalline rocks are dissected by narrow valleys with steep hillslopes. In the Aspromonte, the topography has flat interfluves above dissected topography carved into the basement rocks.

Tectonically, the area is part of the Calabria–Peloritani Arc, formed by convergence between the African and European plates during the Tertiary Period. Since the Pliocene, Sicily has been decoupled from the subduction system by a number of extensional faults fragmenting the Hercynian orogens (Ghisetti and Vezzani, 2002; Fiannacca et al., 2008). In the Peloritani, active extension is in the WNW–ESE direction, developing NNE–SSW oriented normal faults. There are a number of normal fault segments parallel to the strike of the coastline of Sicily, causing ductile–brittle deformation in the footwalls of these faults. As a consequence, a shear zone has developed on the eastern flank of the Peloritani Ridge, parallel to the coast (Pezzino et al., 2008). In Aspromonte, NW–SE directed extension has produced fewer NE–SW oriented normal faults that are oblique to the coastline. Flights of marine terraces indicate increasing time-averaged uplift rates, from the Middle–Late Pleistocene, away from the Strait of Messina, associated with increased seismic activity (Catalano and Guidi, 2003; Antonioli et al., 2006). Holocene paleo-shorelines are represented by beach deposits, tidal notches and abrasion platforms (Antonioli et al., 2006).

There are a number of recording rain-gauges in the study area operated by the Italian Hydrographic Service (Fig. 2). As part of the present research (Goswami, 2011), average monthly rainfall data over 70 years (1930–2000) were used to analyse the distribution of rainfall in Peloritani. For Aspromonte, data were used from the rainfall contour maps of 30 years duration from 1978 to 2007 (Federico et al., 2008). The contour maps reveal minimum precipitation on the western side of Calabria associated with orographic shielding of air masses coming from the south-southeast side of the mountains. Furthermore, elevated areas receive higher precipitation in the eastern part of the Peloritani. A general southward increase in rainfall, away from the Strait, is observed in both the Peloritani and Aspromonte. The hydrological system is highly torrential, with no surface water flow during the spring and summer months, but very heavy flow in the autumn and winter. Hence, the mean annual precipitation is low but highly seasonal.

3. Methods

3.1. Landslide mapping

Traditional methods for mapping landslides from aerial photographs were used, such as identifying tonal contrast, size and shape, and position and orientation (for example, elongated downslope). A landslide inventory map was prepared using aerial photographs at 1:10,000 scale, Google Earth™ images and topographic contour maps developed from the ~28 m resolution Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Digital Elevation Models (DEMs) (Hayakawa et al., 2008). For any given area, the mapping reveals the landslides visible at a particular time; the aerial photographs cover 2003 for Peloritani and 2002 for Aspromonte. Shadows in the aerial photographs indicated the positions of valleys and ridges. Care was taken while mapping near densely populated areas. Features that had the possibility of a human origin were excluded. For example, areas near quarries were avoided to exclude slides that might have been caused by extraction of materials. Results were compiled using ArcGIS™.

The landslide boundaries in the aerial photographs were identified based on attributes such as headwall scarps, chutes representing