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Deep-seated gravitational slope deformations in western Sicily: Controlling factors, triggering mechanisms, and morphoevolutionary models

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ABSTRACT

A study of deep-seated gravitational slope deformation (DSGSD) phenomena affecting areas of various geological and geomorphological settings in western Sicily is described. Western Sicily is underlain by a thin-skinned imbricate wedge of Meso–Cenozoic carbonate and siliciclastic rocks that formed by the stacking of several thrust nappes over the Iblean foreland. Locally, the original thrust sheets are folded and cut by high-angle faults. Large areas of western Sicily now display high relief energy due to Plio-Pleistocene block-faulting and uplifting, and the Quaternary morphogenetic phases are characterised by incision, thereby triggering widespread DSGSDs. To identify controlling factors and triggering causes and to develop reliable morphoevolutionary models for the DSGSDs of western Sicily, a geomorphological study based on field surveys and aerial-photography interpretations was performed. Previous geomorphological data relating to well-known examples of DSGSDs were reconsidered, leading to remarkable revisions of the interpretative models in certain cases. New data were subsequently collected, enabling recognition of additional DSGSD phenomena. The whole body of data involves a total of 27 DSGSDs affecting areas in two specific geological settings: (1) areas with flat thrust surfaces, where differential settlements, back-tilting, lateral spreads in competent rocks overlying marls and clays, large topples, and/or block-type slope movements may develop; and (2) areas where deep-rooted carbonate units come into lateral contact with clayey–marly units along high-angle faults, where lateral spreads in brittle homogeneous rocks, sinking, and/or rock flows may occur. These DSGSD phenomena are associated with different evolutionary stages, allowing a morphoevolutionary model to be defined for the two geological conditions. For these two different morphoevolutionary models, the following structural features play an important role in the development of DSGSDs: (1) where carbonate bodies overlie clayey–marly rocks, triggering of the DSGSDs traces back to deformation of a ductile substratum that follows the exhumation of the flat thrust planes and the underlying clayey–marly rocks due to block-faulting and/or stream incision; and (2) where homogeneous carbonate rocks hundreds of metres thick crop out, the DSGSDs are triggered by very high relief energy and tensile stress that follow the combined actions of Quaternary block-faulting and stream deepening associated with differential erosion.

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1. Introduction

Deep-seated gravitational slope deformation (DSGSD) phenomena have been defined as slope movements with sizes comparable to that of the whole slope (Goguel, 1978) with extremely slow evolution (Ter-Stepanian, 1977) and where the maximum vertical depth and the depth/length ratio are considerable (Hutchinson, 1995). DSGSDs are also characterised by a rupture surface, or a zone separating the moving mass from the intact rock that is not continuous or detected (Sorriso-Valvo, 1995) and by movement directions that may not be influenced by the slope topography (Rybar, 1971).

In the scientific literature, a wide variety of DSGSD phenomena affecting areas with various geological, structural, geomorphological and topographic settings is known (Zischinsky, 1969; Němčok, 1972; Mahr and Nemcok, 1977; Cavallin et al., 1987; Savage and Varnes, 1987; Crosta, 1996; Agliardi et al., 2001; Di Luzio et al., 2004). Rock spreading (Jahn, 1964; Beck, 1968), sackung (Zischinsky, 1966; Agliardi et al., 2009), sagging (Hutchinson, 1988), rock flow (Varnes, 1978), depth creep (Ter-Stepanian, 1966) and deep-seated distortion of steep-sided ridges (Varnes et al., 1989) were recognised in homogeneous (continuous as well as discontinuous) and brittle (Němčok, 1977; Radbruch-Hall, 1978) or ductile–brittle (Genevois and Tecca, 1984; Prestininzi, 1984) rock masses. In the case of heterogeneous rock masses, where a brittle cover overlies a ductile substratum, slopes may develop rock slides (King, 1953), or block glides (Voight, 1973), large rock slides and avalanches (Goguel, 1978), block-type slope movements (Pasek, 1974), back-tilting (Zaruba and Mencl, 1982), lateral spreading

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(Radbruch Hall et al., 1976; Pasuto and Soldati, 1996; Esposito et al., 2007), gravitational mass rock creep (Chigira, 1992), differential settlements of rock blocks (Lunardi and Fornaro, 1980) and cambering and valley bulging (Varnes, 1978).

Triggering mechanisms of DSGSDs include (a) tensile stress owing to the geometry of the relief (von Engelen, 1963); (b) low dispersion of underground fluid (Habib, 1975); (c) reduction of apparent friction within the rocks (Scheidegger, 1973); (d) alternation of glacial pressure and tensile stress for deglaciation (Ferguson, 1967; Jarman, 2006; Hippolyte et al., 2009; Kellerer-Pirklbauer et al., 2010); and (e) increase in pressure, which may produce partial fusion of crystalline rock (Masch et al., 1981) or dissociation of calcium carbonate (Erismann, 1979). Several authors have also agreed to link the genesis of DSGSDs to increases in relief energy (Bisci et al., 1996 and references therein), presence of structural discontinuities (Bovis, 1982; Ambrosi and Crosta, 2006; Brideau et al., 2009; Imre et al., 2009; Jaboyedoff et al., 2009; Pánek et al., 2011), active tectonics (Carton et al., 1987; Dramis and Sorriso-Valvo, 1994; Dramis and Blumetti, 2005; Gutiérrez-Santolalla et al., 2005; Audemard et al., 2010; Carbonel et al., 2013), long-term exhumation control on topography (Agliardi et al., 2013), topographic relief and slope geometry (Ambrosi and Crosta, 2011), and weather and climate (Ballantyne, 2002; Mantovani et al., 2013; Agliardi et al., 2013).

Since the end of the 1970s, many geomorphological studies in western Sicily (Agnesi et al., 1978, 2000a and references therein; Monteleone et al., 2010) have described a number of DSGSDs and defined their distribution and types. Because the geological models of the 1970s and 1980s favoured a belt formed by thick Mesozoic carbonate units overthrusting clayey or clayey–marly masses over subhorizontal Upper Oligocene–Miocene surfaces (Catalano and D'Argenio, 1982), the researchers at the time traced the triggering cause of the deep-seated movements in brittle rock bodies back to the deformation of the supposedly ductile substratum. Recent geological data collected from high resolution seismic profiles and detailed field surveys (Catalano et al., 1996, 2000; Avellone et al., 2010) have suggested the presence of Plio-Quaternary high-angle faults that cut across the older thrusts and juxtapose carbonate units against clayey or clayey–marly units. These new geological views provided the opportunity to develop a geomorphological study focussed on re-examining the triggering mechanisms of DSGSD phenomena in western Sicily, to identify additional DSGSDs and to propose appropriate morphoevolutionary models. The results of the study are described in this paper.

2. Geological setting

Sicily is commonly considered to be part of the SE-verging Alpine orogenic belt in the central Mediterranean region. The western Sicily fold-and-thrust belt (Fig. 1) connected eastern Sicily to the Late Cenozoic Maghrebian chain submerged between Sardinia and Sicily (e.g., Catalano et al., 1989). Several imbricate units, emplaced essentially during the Miocene, form the belt. Three tectonic units have been

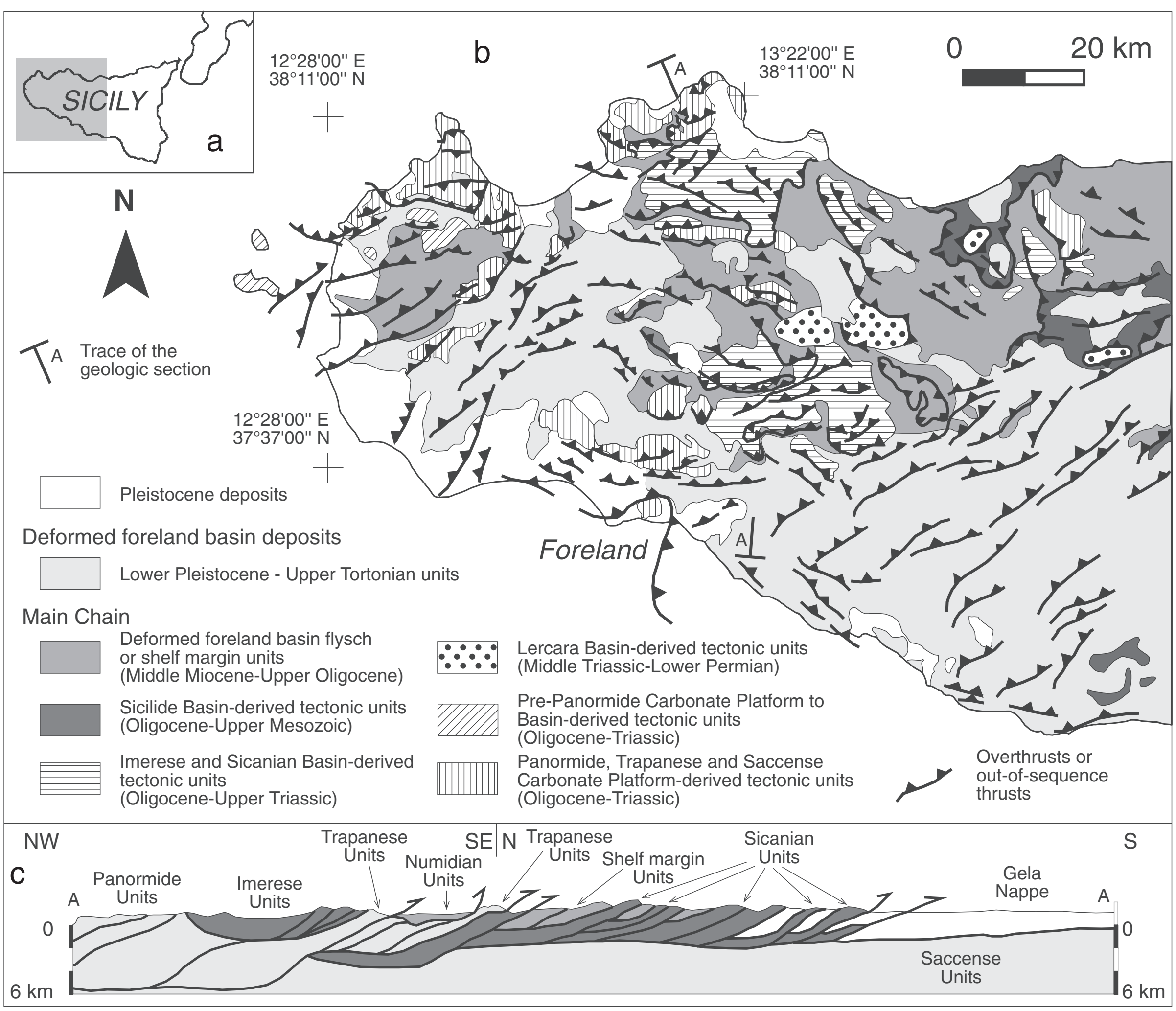

Fig. 1. The study area. (a) Location of the investigation area. (b) Generalised geological map of western Sicily. (c) Geological cross section through the mountain chain and the foredeep region (simplified from Catalano et al., 1996).

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