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Geomorphology and geochronology of sackung features (uphill-facing scarps) in the Central Spanish Pyrenees

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Abstract

The paper analyses uphill-facing scarps and associated troughs developed in the oversteepened slopes of two neighbouring glacial valleys in the central Spanish Pyrenees. Previous studies of sackung landforms in the Pyrenees have argued for deglacial unloading as the genetic mechanism, but this causal and temporal relationship has not been proved due to the lack of chronological data. The antislope scarps in the two studied locations, Vallibierna and Estós, are developed in Palaeozoic metasedimentary rocks (parallel to the contour lines and the structural grain), occur in the intermediate sector of the hillslope, and are up to 0.5 km long and several meters high. A trench was excavated in a sackung trough fill in each of the valleys in order to gain information about their chronology and genesis. Charcoal from the lowermost unit in Vallibierna provided an age of 5.9 cal. ka for the sackung and extrapolation of the three dates obtained in Estós indicates that the trough formed ca. 7.6–7.8 cal. ka. Deglaciation of the studied sectors of the valleys occurred between 16 and 13 ka. The time lag of >5 ka suggests that glacial erosion and the subsequent debutressing of the oversteepened valley walls created slopes predisposed to sackung development, but did not initiate the movement. Seismic shaking is proposed as a probable triggering factor. This hypothesis, although supported by the sudden deformation event recorded by a failure plane exposed in Vallibierna trench, and by the seismic and neotectonic activity of the area, cannot be proved due to the lack of chronological information about paleoearthquakes.

Keywords: Sackung; Uphill-facing scarps; Gravitational spreading; Trenching; Seismic activity; Pyrenees

1. Introduction

The term sackung, German word for sagging, was first introduced by Zischinsky (1966, 1969) to designate the surface manifestations of deep-seated rock creep in slopes on foliated bedrock. In the

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subsequent literature, sackung (plural sackungen) generically refers to linear geomorphic features produced by gravitational spreading in slopes (Varnes et al., 1989; Crosta, 1996; Ward, 2003). The most characteristic sackung-type landforms are uphill-facing scarps (also called antislope scarps, counter scarps, or antithetic scarps) associated with linear depressions lying at the upslope side of the scarps (Radbruch-Hall, 1978; Varnes et al., 1989). These peculiar landforms commonly form complexes parallel to the contours and ridge tops in the upper sector of steep slopes. The uphill-facing scarps that split the ridge tops into two crests give place to double or twin ridges (*dopplegrate*) and ridge-top depressions. These depressions show a graben-like appearance when scarps with opposite orientations affect the ridge crests. Some authors note arched uphill-facing scarps with a downslope convexity (Jahn, 1964; Beck, 1968; Varnes et al., 1989). The asymmetric troughs associated with these scarps frequently host closed depressions with ephemeral ponds where deposition of fine-grained material takes place. The presence of small shallow sinkholes has also been reported along these depressions despite the absence of soluble rocks (Bovis, 1982; McCalpin and Irvine, 1995). McCalpin and Irvine (1995), from a compilation of published sackung scarp dimensions carried out by McCleary et al. (1978), give 15–300 m and 1–9 m as typical ranges of scarp length and height, respectively. Other frequent geomorphic features found in slopes affected by sackungen are downhill-facing scarps with accompanying linear depressions and a bulge at the toe of the slope (*talzuschub*) (Nemcok, 1972; Mahr, 1977; Radbruch-Hall, 1978; Varnes et al., 1989). In some cases, the upper sector of the slopes shows a curved downhill-facing scarp resembling the head scar of a landslide (Soeters and Rengers, 1983; Bordonau and Vilaplana, 1986; McCalpin and Irvine, 1995; Agliardi et al., 2001). Some authors also mention saddles in secondary ridges (McCalpin and Irvine, 1995) or different types of mass movements in the lower parts of the slope (Radbruch-Hall, 1978; Crosta, 1996; Agliardi et al., 2001).

Examples of sackung-type landforms have been documented from most of the important mountain belts (Radbruch-Hall, 1978; Crosta, 1996). They are particularly frequent in steep-sided ridges flanked by deep glacial valleys. The sackungen inventory elaborated by McCleary et al. (1978) yields 400–1200 m and 25–50° as typical ranges of slope height and gradient. According to Varnes et al. (1989), massive ridges with rounded crests are more favourable for sackungen development than narrow ridges. Sackung scarps have been observed in a wide variety of lithologies including metamorphic, sedimentary, volcanic, and plutonic rocks (Radbruch-Hall, 1978; McCalpin and Irvine, 1995). The persistent orientation of the sackung features parallel to the contour lines indicates that topography is the main factor that controls their trend. In numerous cases, a clear parallelism has been found between the direction of the sackungen and the strike of any set of discontinuity planes (bedding, jointing, cleavage, and foliation) (Jahn, 1964; Tabor, 1971; Bovis, 1982; Soeters and Rengers, 1983; Varnes et al., 1989; Corominas, 1990; McCalpin and Irvine, 1995; Kellogg, 2001; Agliardi et al., 2001; Di Luzio et al., 2004).

Several mechanisms have been proposed to explain the origin of the uphill-facing scarps. The earliest researchers (e.g., Paschinger, 1928) and some other authors quoted by Tabor (1971) ascribed the sackung scarps to structurally controlled differential erosion, primarily due to frost action, nivation processes, and aeolian deflation. Subsequent theories attribute sackung features to deformational processes that involve different modes of lateral spreading in rock masses (Fig. 1). Jahn (1964), for example, suggested that the uphill-facing scarps result from the combination of gravity-induced spreading of fractured ridges and erosion in the uphill sides of the resulting tension cracks (Fig. 1A). That author stresses the downward removal of particles through the cracks (ravelling) in the development of the trenches. Other authors suggest that the uphill-facing scarps and troughs are produced by the differential downslope bend of rocks affected by steeply dipping discontinuity planes (Ter-Stepanian, 1966; Zischinsky, 1966, 1969; Tabor, 1971) (Fig. 1B). In this model, the troughs correspond to linear depressions developed between the rocks rotated valleyward and the undisturbed rocks. Tabor (1971) believes that the zone of creep may extend as much as 200 m below the surface. Bovis (1982) proposes that the sackung features are produced by a combination of flexural slip toppling of block slabs defined by joints steeply dipping into the slope and erosion of the upslope side of the resulting linear