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Gravity collapse structures in the Central Precordillera fold-and-thrust belt, Argentina

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Abstract

Several landforms found in the fold-and-thrust belt area of the Andean Central Precordillera of Argentina, which were often associated with tectonic shortening, are in fact related to superficial gravity tectonic structures. These gravitational collapse structures have developed in the western flank of sierras de La Dehesa and Talacasto. These include rock-slides, rock falls, wrinkle folds, slip sheets and flaps, among others; which together constitute a monoclinal fold dipping between 30º and 60º to the west. Gravity collapse structures are parallel to the regional strike of the sierras de la Dehesa and Talacasto are placed in Ordovician limestones and dolomites. Their sloping towards the west, the presence of bed planes, fractures and joints; and the lithology (limestone interbedded with incompetent argillaceous layers) would have favored their occurrence. Detachment and initial transport of gravity collapse structures and rockslides in the western flank of the Sierra de la Dehesa were tightly controlled by three structural elements: 1) the bedding, when It is dipping >30° in the slope direction; 2) joint sets that constitute lateral and transverse traction cracks which release extensional stresses; and 3) discontinuities fragmenting sliding surfaces. Some other factors that could be characterized as local (lithology, structure and topography) and as regional (high seismic activity and possibly wetter conditions during the postglacial period) were determinant in favoring the steady loss of the western mountain side in the easternmost foothills of the Central Precordillera.

Keywords: collapse structures, gravity tectonics, fold-and-thrust belt, Andean Precordillera

Resumen

Numerosas formas de relieve ubicadas en el área de la faja plegada y corrida de la Precordillera Central de Argentina, que a menudo se asocian con una tectónica compresiva, están de hecho relacionadas con procesos gravitacionales superficiales. Estas estructuras de colapso gravitacional se han desarrollado en el flanco occidental de las sierras de La Dehesa y Talacasto, éstas incluyen deslizamientos, caídas de rocas, pliegues en rodilla, deslizamientos planares y flaps, entre otros; que en conjunto constituyen un pliegue monoclinal que inclina entre 30º y 60º hacia el oeste. Las estructuras de colapso por gravedad son paralelas al rumbo regional de la Sierra de la Dehesa y se originan en calizas y dolomías del Ordovícico. Su pendiente hacia el oeste, la presencia de planos de estratificación, las fracturas y diaclasas; y la litología (intercalaciones de calizas con bancos incompetentes arcillosos) habrían favorecido su ocurrencia. El despegue y transporte inicial de las estructuras gravitacionales y deslizamientos de rocas en el flanco occidental de la Sierra de la Dehesa estuvieron estrechamente controlados por tres elementos estructurales: 1) la estratificación cuando inclina >30° en la dirección de la pendiente; 2) los juegos de diaclasas que constituyen grietas de tracción lateral y transversal que liberan tensiones por tracción; y 3) las discontinuidades que fragmentan superficies deslizantes. Algunos otros factores que podrían caracterizarse como locales (litología, estructura y topografía) y regionales (elevada actividad sísmica y posiblemente condiciones más húmedas durante el período post-glacial) fueron determinantes para favorecer la pérdida de equilibrio de la ladera occidental en las estribaciones orientales de la Precordillera Central.

Palabras clave: estructuras de colapso, tectónica gravitacional, faja plegada y corrida, Precordillera

1. Introduction

Several landforms found in the area of the fold-and-thrust belt of Precordillera, which appear to be associated to tectonic shortening, are in fact related to gravity tectonic processes (Twidale, 1971, 1976). Harrison and Falcon (1934, 1936) have identified for the first time these types of structures as collapse structures. Hills (1963), Gutiérrez Peña (1979) and Ollier (1981) have considered these landforms as pseudo-structural modeling, being scarcely discussed in the literature. On the other hand, Budding (1963) introduced the term surficial structures or *décollement*, over collapse structures and pointed out that these structures were of a secondary origin and when not properly recognized, could lead to erroneous structural interpretations. Moussa (1968) described several gravitational gliding-like wrinkle folds and slip-sheets in Utah, USA. Similar collapse structures were described in Argentina, north of the studied area in La Rioja Province by González y Fauqué (1996, 2007) and by Fauqué and Tchilinguirian (2002) in northwestern Argentina.

Narimani *et al.* (2012) identified structures in the Zagros fold-thrust belt (Iran) as thrust related collapse structures. The authors proposed that thrust faults as well as gravity were the main forces controlling the development of these types of collapse structures.

The sierras de La Dehesa and Talacasto are part of the Central Precordillera, located in central-west Argentina, 60 km to the northwest of San Juan City, between 31°S latitude and 68°47'W longitude (Fig. 1a). The regional landscape is mountainous, with narrow valleys and intra-mountain basins trending N-S, and elevations ranging from 800 to 4,000 m asl (Fig. 1a, b).

Gravity collapse structures found in the Central Precordillera fold-and-thrust belt either occur as big rockslides, such as the Talacasto Norte and Talacasto Sur rockslides of the western flank of the Sierra de Talacasto-La Dehesa anticlinal (Esper-Angillieri *et al.,* 2014), or as collapse folds, flaps, slip sheets and rock falls similar to those described by Harrison and Falcon (1934, 1936) (Fig. 1c). In most cases they take place in the limestones of the San Juan Formation (Ordovician age). One of these rockslides megabreccias has been described by Esper-Angillieri *et al.* (2014), but other spectacular gravity-driven blocks found in the western flank of Central Precordillera have received no previous detailed attention.

Throughout the entire western flank of the sierras de Talacasto and La Dehesa, secondary structures were interpreted in this paper as gravitational gliding. These include rockslides, rock falls, knee-shape structures, roof and wall structures, slip sheets and flaps, and constitute a monoclinal structure

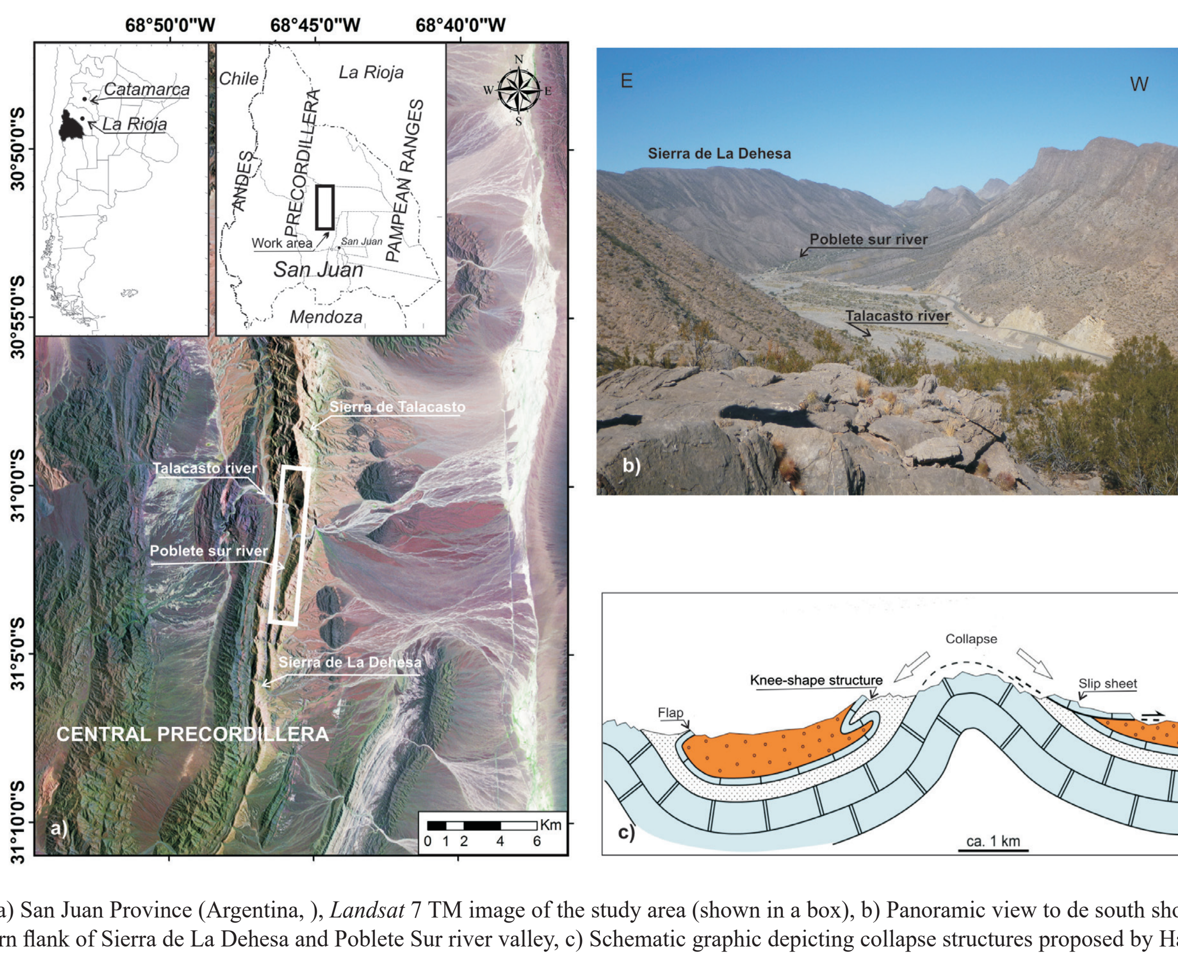

Fig. 1.- a) San Juan Province (Argentina,), *Landsat* 7 TM image of the study area (shown in a box), b) Panoramic view to de south showing the western flank of Sierra de La Dehesa and Poblete Sur river valley, c) Schematic graphic depicting collapse structures proposed by Harrison & Falcon (1934, 1936) for the Zagros fold and thrust belt.

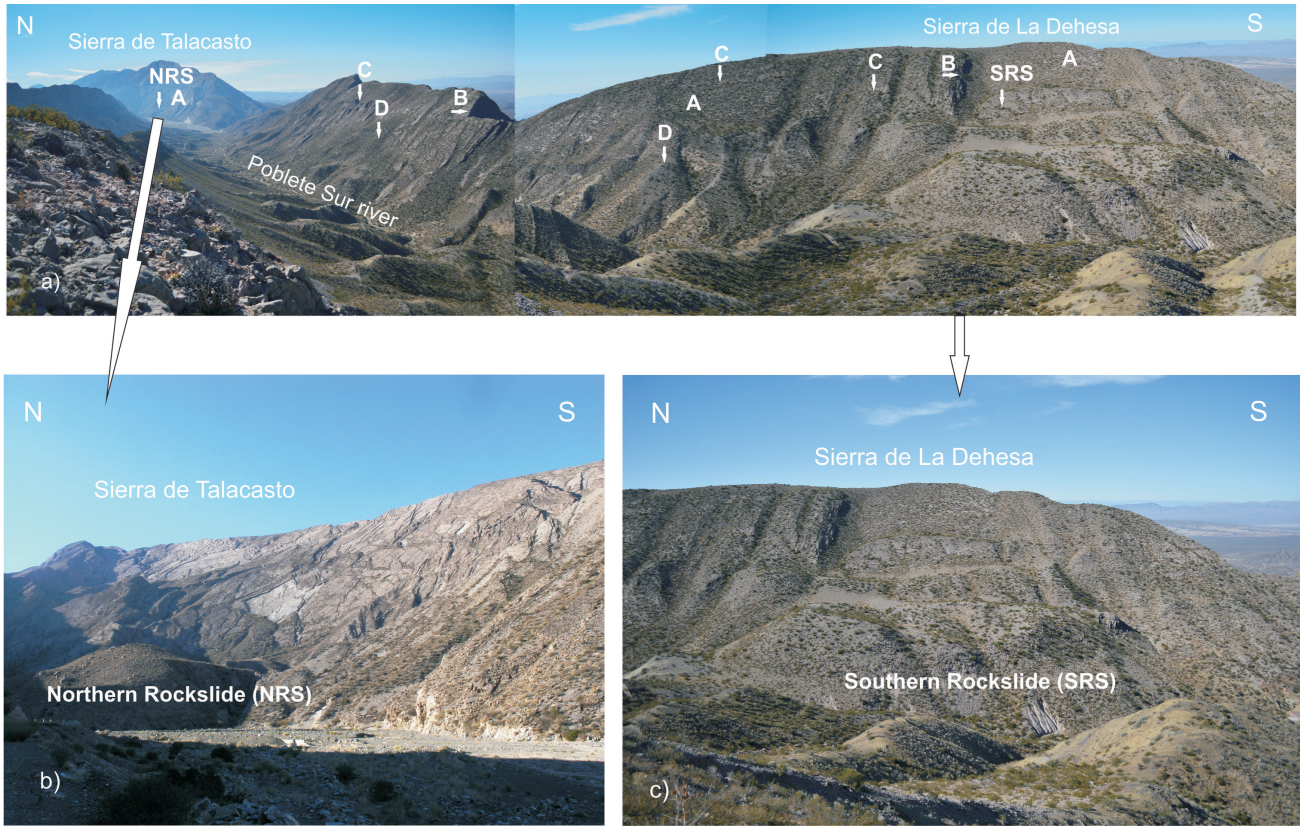

Fig. 2.- a) General view to the northeast of the sliding area with main collapse structures: Talacasto-La Dehesa rockslides, North (NRS) and South (SRS), slip surface (A), lateral breakage wall (B), transtensional fault (C), unstable slab (D). Relief from top of ridge to Poblete Sur river is ~300 m.

dipping between 30º to 60º W. These structures are parallel to the regional trend of the mountain ranges and develop in carbonate rocks of Ordovician age (San Juan Formation). All of these identified collapse structures have their resting locations not far from their zone of origin, and are typical in mountain slopes or rock exposures where the slope angle is close to, or parallel to the strata dip. Their movement is controlled by planar structural discontinuities, such as faults, joints and layers as well as the presence of weaker formations within the rock successions (Fig. 2a,b and c). The area provides an unparalleled opportunity to examine grand-scale examples of well-preserved gravity slide blocks and to learn more about their origin.

The purpose of this paper is to describe and characterize existing collapse structures along the easternmost thin-skinned fold-and-thrust belt of the Central Precordillera, using mainly detailed field work, satellite images and joint analysis, in order to better understand the role of gravity in the genesis of these non-compressional structures.

2. Geological and tectonic setting

Between 28º and 32ºS latitude, an extended zone of crustal seismicity in central-northern Argentina, delineates a flat-slab subduction zone; where the Nazca plate moves subhorizontally for several hundred kilometers, before continuing its descent under the South American Plate (Kendrick *et al.,* 2003). The upper-plate has high levels of seismicity, and it was here where the most destructive earthquakes in the last century in San Juan, Argentina have taken place. These were the earthquakes of 1894 (Ms 7.5), 1944 (Ms 7.0) and 1977 (Ms 7.4) as was pointed out by Perucca *et al.* (2006). In this flat-slab segment, the Argentine Precordillera is a major geologic province in central-western Argentina, approximately 400 km long, in the north-south direction. The Precordillera is located between the High Cordillera of the Andes on the west and Western Pampean Ranges on the east (Fig. 1a). Main Quaternary deformations and seismogenic structures known in Argentina are located along the flat-slab segment, including the Precordillera and the Western Pampean Ranges (27º-33º S latitude), located in the frontal portion of the Andean orogenic belt. These morphostructural units show complex interactions between thin-skinned and thick-skinned structural styles (Costa *et al.,* 2000; Perucca and Vargas, 2014).

The Central Precordillera is formed by mountain ranges running from 29º to 32ºS latitude. It has been described by several authors (Jordan *et al.,* 1983; Allmendinger *et al.,* 1990; von Gosen, 1992; Jordan *et al.,* 1993; Cristallini and Ramos, 2000) as a typical thin-skinned thrust-and-fold belt, mainly developed in Paleozoic times (Alonso *et al*., 2005; Álvarez-Marrón *et al*., 2006) with Neogene reactivations. This belt is formed along west dipping, imbricated structures, rooting down to a 5-6 km deep main décollement (Figure 3a, b).. Besides, the Central Precordillera registered a Paleozoic compressional deformation event that resulted in folding and faulting of early Paleozoic sedimentary strata. They are mainly Siluric and Devonian rocks, which constitute a system of imbricate east-verging thrusts that merge into a detachment near the base of the Ordovician limestones, and include associated fault propagation folds (Von Gosen, 1992). Synorogenic Neogene deposits indicate that major thrusts, with east vergence, moved to the east between ~20 Ma ago and present time (Jordan et al., 1993). These Neogene to Quaternary sediments unconformable onlap onto the Paleozoic rocks and sometimes, reactivation of thrust faults resulted in overthrusting of the younger units. In turn, Cenozoic faults have caused passive block rotations of Paleozoic structures (Álvarez Marrón et al., 2006).

Sierra de La Dehesa constitutes an asymmetrical fold with a steep eastbound slope. The bedding angle (~ 30°W) is the same as the ground surface and can therefore be classified as a cataclinal (Cruden, 2000, 2003). Lithology also favors the presence of these collapse structures, with rock units with a marked competency contrast (limestone interbedded with clayey layers).

The stratigraphic succession exposed in the area is composed by a sequence of Ordovician carbonates covered by clastic sediments of Silurian, Devonian and Neogene ages (Fig. 3a).

The calcareous San Juan Formation (Kobayashi, 1937) is 380 m thick and is formed by well stratified limestones with thin intercalations of shale that contains a shaly limestone member in the basal part.

Bordering the Sierra de La Dehesa to the East, there is a steep inclined thrust zone carrying a pile of Ordovician limestones of the San Juan Formation. The Ordovician sequence stands vertical or is overturned in the eastern flank of this sierra while in de Western portion dips to the west with angles varying between 60º to 25º and is overlain by Silurian clastic beds. This gives an asymmetric topographic profile for this mountain range, steep in the east and gently dipping in the west (Fig. 3b).

The Talacasto River flows antecedently to the mountain range and controlled by one of the E-W fractures, but their north and south tributaries are arranged in the direction of stratification and main faulting, which indicates a strong lithological and structural control.

Esper-Angillieri *et al.* (2014) compared rockslides occurrence patterns on the sierras de Talacasto and La Dehesa (western portion of Precordillera Central), to lithology, geo-

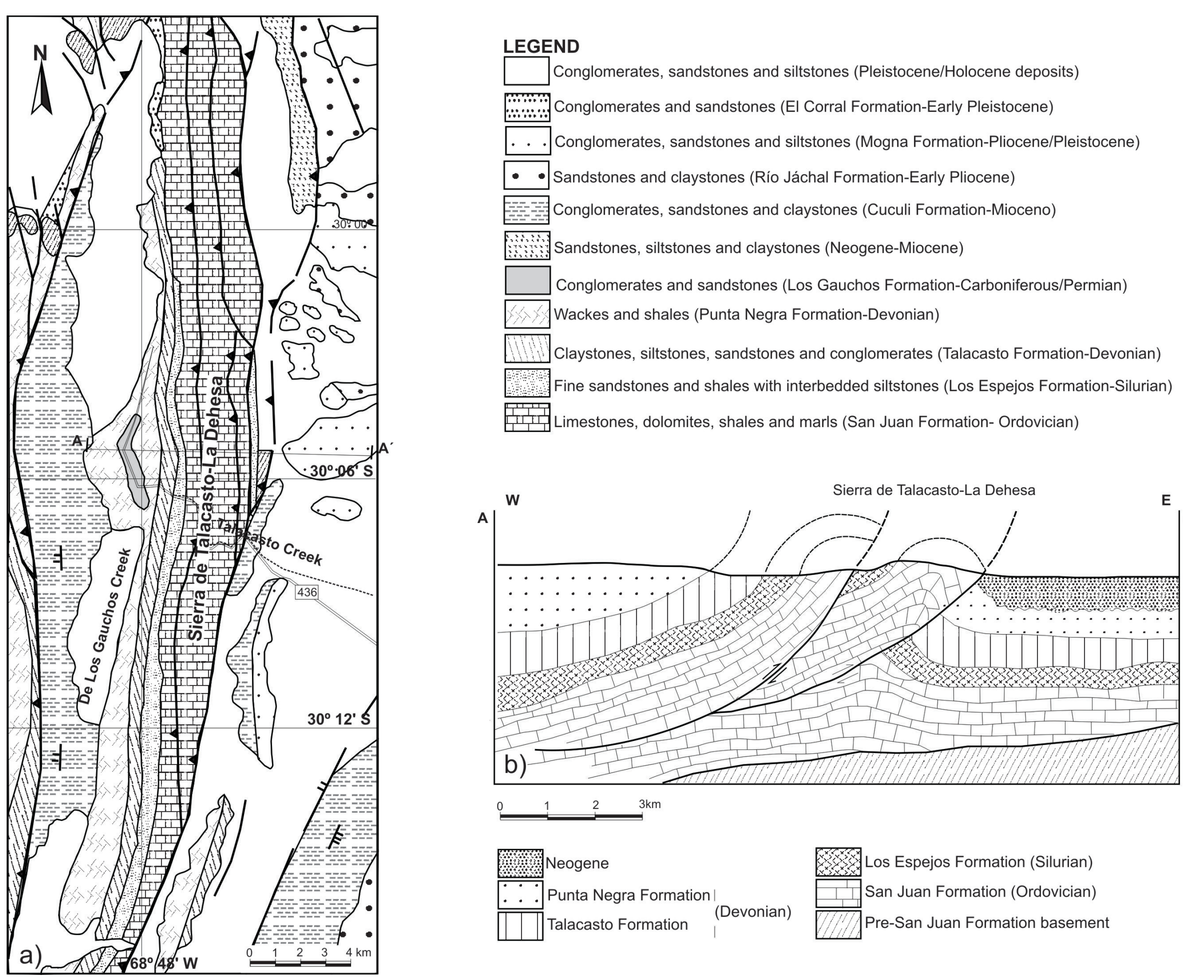

Fig. 3.- a) Geological map of the studied area, modified from Furque et al. (1998) and b) A-A' Schematic structural cross section across the study area, based on Furque et al. (1998).

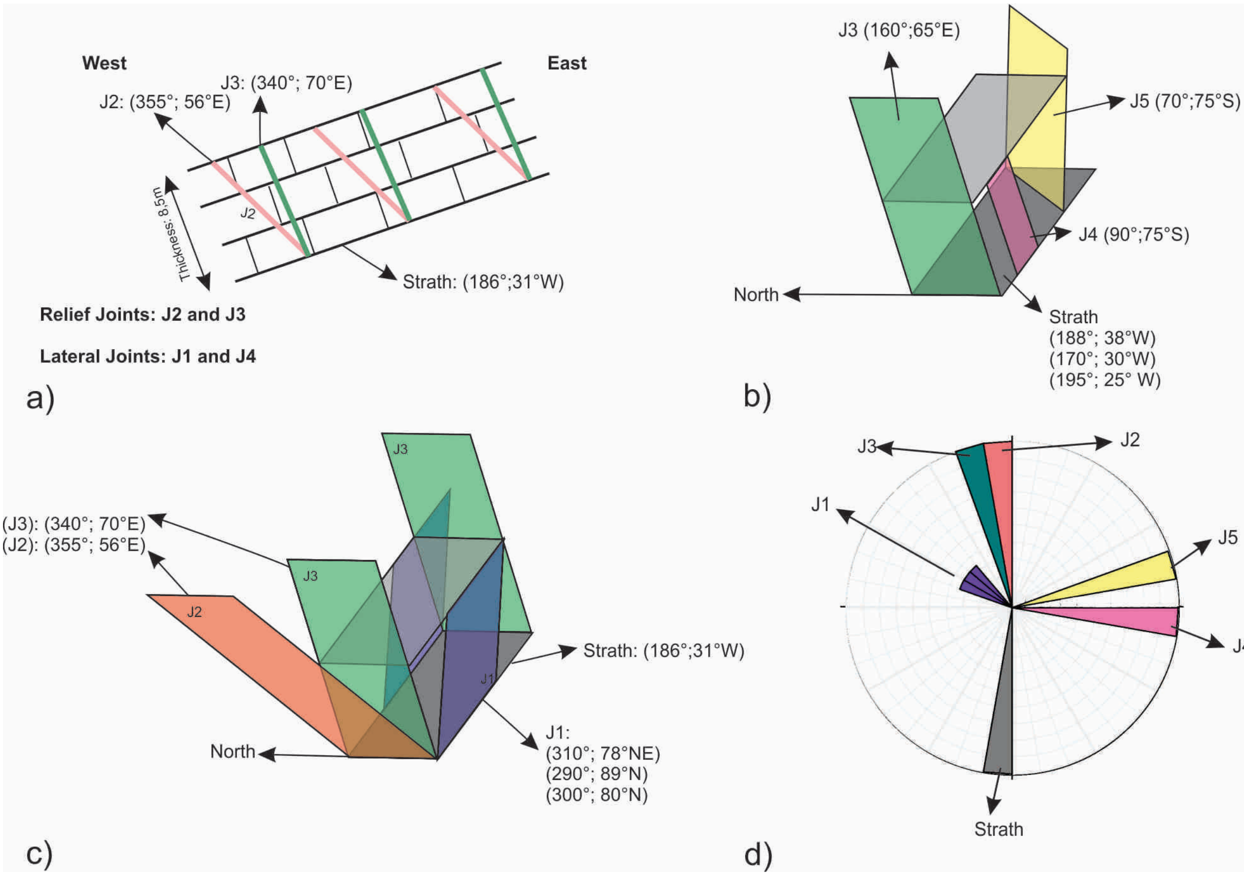

Fig. 4.- Main joint orientations: a), b) and c): N-S (stratification); NW-SE (J1), NNW-SSE (J2, J3 and J5) and W-E (transtensional joints J1 and J4), d) Rose diagram showing main joints sets and bedding planes.

logical structures, and seismicity records. After analysis of the spatial relationships among the western flank slides and the distribution of seismic epicenters, historical earthquakes and neighboring Quaternary faults, they concluded that these Quaternary rockslides were triggered by shallow seismicity associated to active faults.

3. Methodology

Both the structural and geomorphic analysis were made using topographic data, fieldwork and digital satellite imagery (Landsat 7-TM and SPOT 5). We measured the orientation of joints at representative sites across the western flank of Sierra de La Dehesa (Figure 4). Data was plotted and analyzed in stereographic plots using the Stereonet 9 software, developed by R. Allmendinger, Cornell University (http://www.geo.cornell.edu/geology/faculty/RWA/programs/stereonet.html).

High resolution satellite imagery (August 2002 SPOT 5 with a 2.5-m spatial resolution) from Google Earth™ was used and georeferenced to a Geographical coordinate system (WGS84). A digital elevation model (DEM) was constructed using GIS software and information obtained from ASTER GDEM V2 (NASA, 2011). This model was used to prepare a slope map with five categories, each characterized by a different hue color and expressed in degrees. Contour levels, which have elevation values expressed in meters asl (above sea level), were extracted automatically from the DEM with a 20 m equidistance. A digital 3D model of the local topography was generated to allow a better visualizing of the slides. Highest elevations are shown in red, while lowest areas are shown in blue/white.

4. Results

Detachment and initial tectonic transport of rockslides on the western flank of the Sierra de la Dehesa was mainly controlled by four structural elements: 1) parallel bedded strata; 2) lateral joints; 3) interbedding surface ruptures, and 4) layers dipping > 30°, in the same direction of the slope. These four elements are required to make the ruptures kinematically possible.

Parallel layer slip to the west is a common feature within the different strata as revealed by slickensides and striae on bedding planes. In these areas where pure planar slides predominate, calcareous strata from 0.20 to 1.50 m thick moved over pelitic banks forming blocks up to 2 m^3 that accumulated at the slope foot. The size of these blocks is conditioned by different sets of joints.

The sedimentary rocks are strongly fractured by at least five sets of joints, one of which dipping as the slope (striking 170º to 195º,dipping 17°, 25º, 30º, 38º W). The most relevant

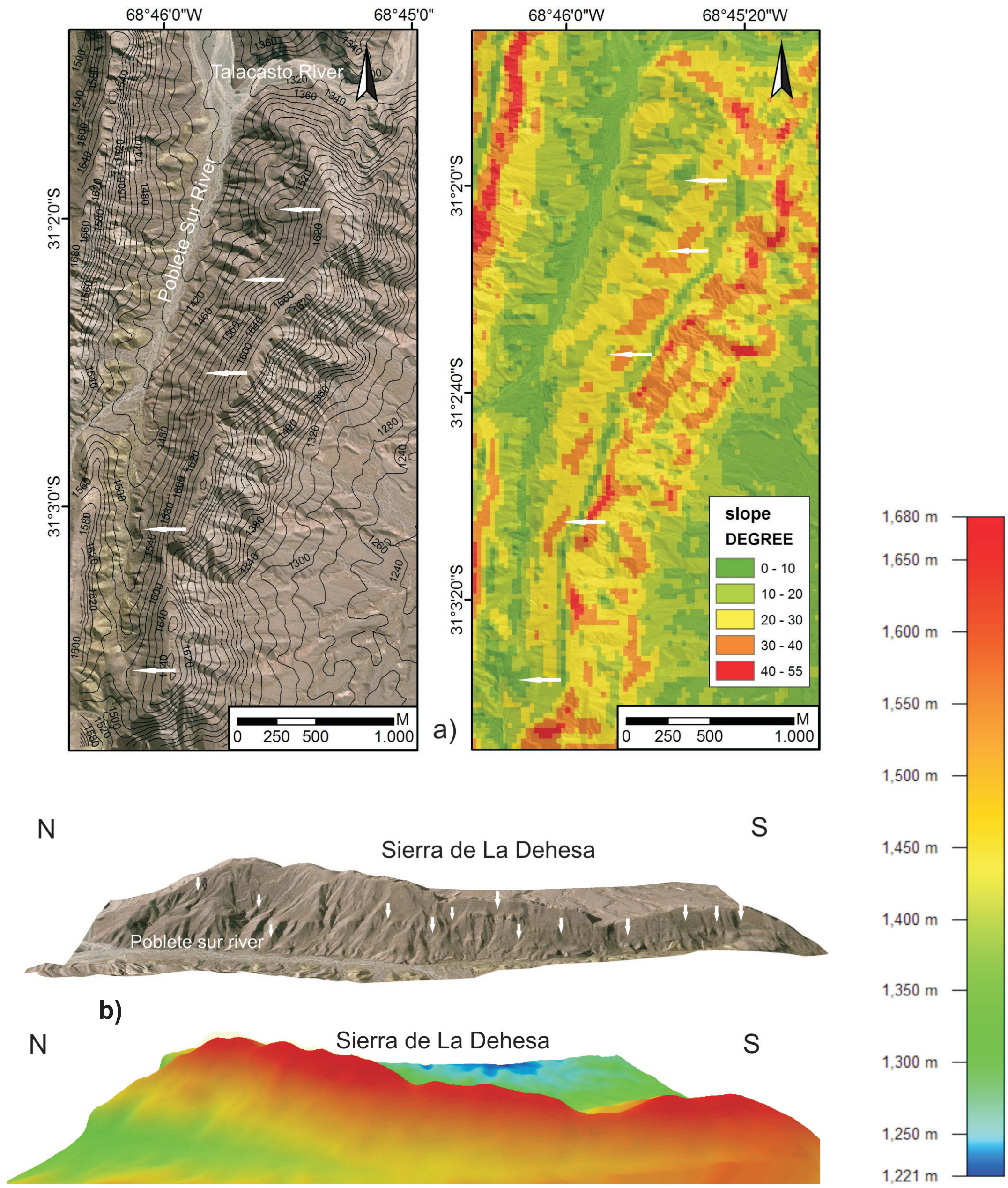

Fig. 5.- a) Maps showing contour lines and inclination of the slopes in Sierra de La Dehesa area, b) 3D View (Google Earth™) and DEM data of western flank of Sierra de La Dehesa topography.

in order to facilitate formation of slides, are the sub-vertical joints (J1), dipping 80º-89º N with an azimuth of 300º - 290º, which occur at regular distances of metric orders. Subordinately, joints J2 (trending 340º and dipping 70º E) and J3 (trending 355º and dipping 56º E) are recognized . These joints, but mainly the subvertical set (J4), trending 90° and dipping 75° S, mark the boundaries of the slipped layers (Figure 4a, b, c and d).

Detachment and initial transport of rockslides were strongly controlled by three structural factors: 1) parallel layers with a dip angle > 30° in the same direction of the slope; 2) lateral stress releasing transversal traction cracks conformed by J1 and J4 joints; 3) ruptures between the sliding surfaces (J2 and J3) associated with longitudinal traction cracks.

Lithological-structural context described in this study have resulted in several large landslides on the western flank of sierras de Talacasto-La Dehesa, where a portion of Ordovician carbonates have slide downhill over Silurian shales in some sectors. These slides are similar in appearance and kinematics to the block-glide landslides of Western USA, described by Braddock (1978) and in northwestern Argentina, described by Fauqué and Tchilinguirian (2002).

Two big rock-slides (named North slide and South slide) were recognized in the area, with the North slide occurring in sierra de Talacasto and the South slide in sierra de La Dehesa (Esper-Angillieri *et al.,* 2014). The proposed model for both slides is a translational or planar slide, which occur along a broadly planar surface accompanied by shear or tensile faults

Fig. 6.- a) Breaking knee-shape structure in Ordovician carbonate rocks, view to the south. Person in lower right corner provide scale, b) view to the north of the folded structure, c) Slide sheet in limestones of San Juan Formation, view to the south and d) view to the north of another slide sheet.

and joints. Throughout the western flank of Sierra de la Dehesa, other gravitational collapse structures, similar to those described by Harrison and Falcon (1934, 1936) have been recognized (Figure 1c).

On the 1:100,000 scale topographic map, the observed slopes obtained in the eastern flank of sierra de La Dehesa range between 20° and 40° although considerably lower slope values, from 0° to 20°, were obtained in its western flank..

The slope map obtained from the topographic sheets simplified the geomorphologic analysis of this study (Figure 5a, b). For instance, gravitational processes predominate with mountain slopes inclinations higher than 20°, whereas fluvial processes are frequent with inclinations lower than 20°. Figure 5b shows using DEM, a N-S western flank shaded rock-slope relief where collapse structures beginning above 1,550 m asl are clearly distinguishable.

All collapse structures present themselves as slides, flaps or wrinkle folds (among others) with vergences according to a higher order fold limb dip direction (to the west). A gravitational collapse during a latest stage of the Andean uplift and folding process could be assumed.

According to Harrison and Falcon (1936) these collapse structures can be classified as: 1) rotational collapse structures (flaps); 2) cascade folds, whose trains are essentially disharmonic folds; (ie. they overlie unfolded units or are affected by other types of folding); and 3) sliding sheets (Figures 6, 7 and 8).

A flap is a common type of gravity structures, formed by a partial fold limb inversion, collapsing downhill. The sequence is overturned back without rupturing, while the lower strata remain in their normal position. We here consider, in coincidence with Harrison and Falcon (1934), that several overturned folds observed in the western flank of sierra de La Dehesa are purely gravitational structures type flap, resulting from the collapse of over steepened flanks into fluvial valleys. The characteristics and types of collapse structures differ markedly along the entire flank: in some places, the collapse structures are very incipient or not exist, while in other sectors they are very well developed. Cascade folds and large planar rock slides are found in some sections, separated by W-E fractures. Furthermore, the presence of multiple and persistent sliding surfaces, stacked and parallel to each other, indicates that the initial transport involved complex movements similar to the sliding of a deck of cards, where the speed of the layers increases towards the top due to accumulated displacement. Thus, the upper layers exceed lower strata displacement and travel longer distances.

Other structures are simple folds and knee folds, most of them are present as fractured or as slipped planes. An example of knee fold is shown in Figure 6a,b. On its eastern flank, strata dip 30º to the east and to the west; the layers are convex up (antiform) to almost get vertical to the western flank. Such folds, with predominantly northerly strikes, typically exhibit shallow-dipping bedding; which then steepens

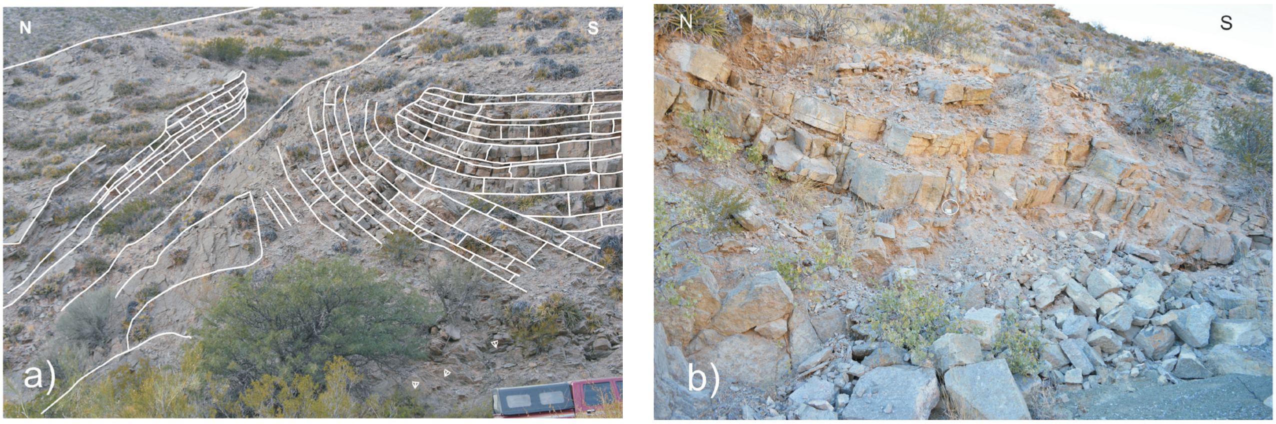

Fig. 7.- a) The change in the attitude of the limestone layers looks similar to Harrison and Falcon's roof and wall collapse structure, white circle shows flap type structure; b) Footwall strata are essentially undeformed. The white circle shows a notebook as scale.

up rapidly westward and downward into steep to overturned slip. These knee folds are mainly observed in the western flank of the Sierra de La Dehesa anticline. This seems an apparent complexity reflected both in the against-the-slope dips and in the high dispersion of the structural data. Furthermore, knee folds exhibited relatively independent vergences relative to those of higher-order structures. These vergences are consistently directed towards structural slopes also indicating an origin caused by gravitational collapse and erosion during the latter stages of Andean uplift and folding.

5. Discussion and conclusions

Gravity collapse structures are produced by purely downslope gravitational movements. Structures of this type were described by Harrison and Falcon (1936, 1934) as cascade

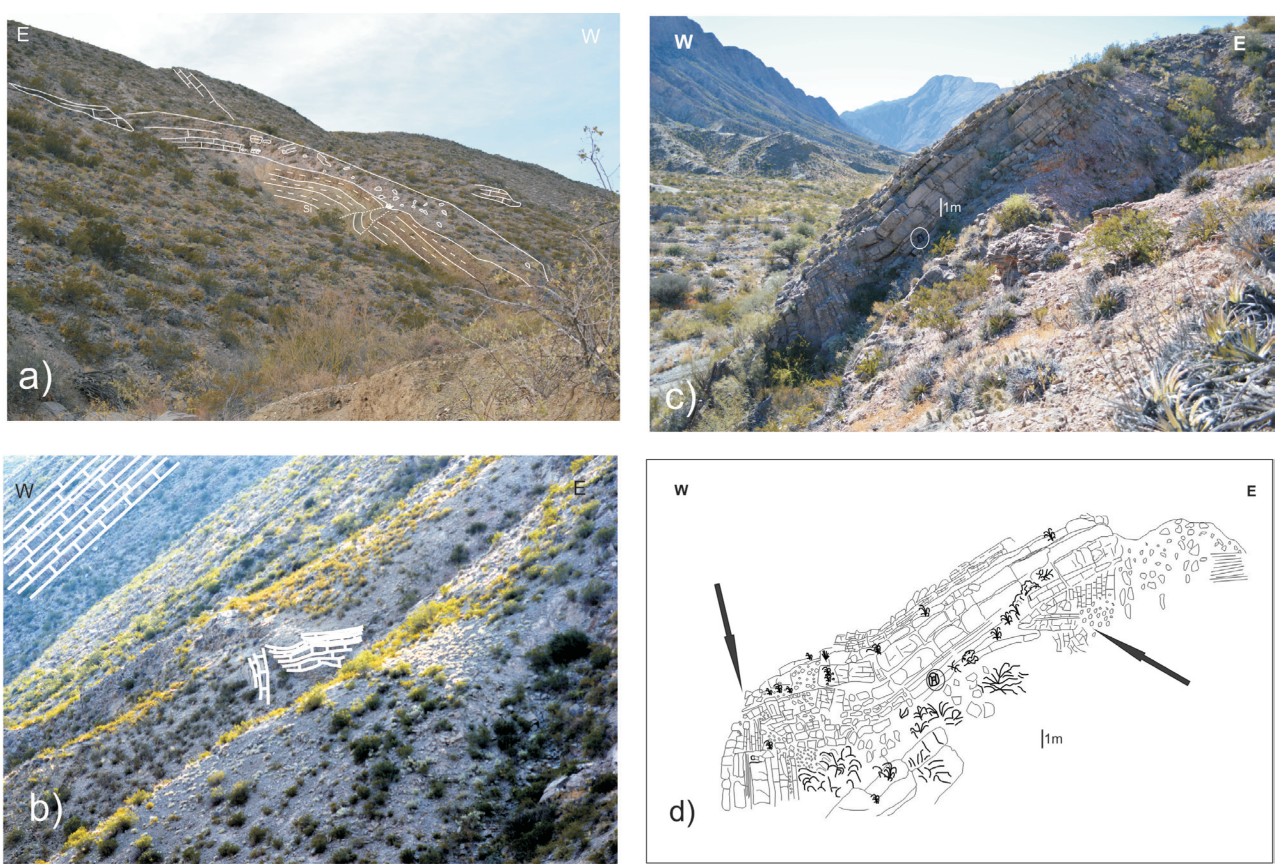

Fig. 8.- a) View to the south of gravity folded and faulted limestones, b) Similarly, to the north there is also a collapse slip-sheet structure, c) The fractured wrinkle fold geometry of the limestone layers, as well as the emplacement of the low dip angle of the limestone rocks over its overturned layers, is similar to Harrison and Falcon's roof and wall structure. These discrete rock blocks then have moved down the fold limb by gravity to form common collapse structure addressed by Harrison and Falcon (1936).

folds; slip sheets and flaps (recumbent folds). They have been attributed to slip or gliding of competent sheets of rock (limestones) over incompetent shales in anticlinal ridges.

Harrison and Falcon (1936) considered these structures could have formed subsequently to fold growth, similarly as classically interpreted collapse development. However, de Sitter (1964) considered that some of these structures (flaps) are doubtless due only to gliding, with the slide of slab of competent sedimentary rock on a gliding surface formed by an exceptionally incompetent layer. De Sitter (1964) suggested the flap structures could have originated early in the folding stage and that they were later accentuated by gravitational collapse of the orogenic chain. Sherkati *et al*. (2005) re-analyzed the Iranian flap structures previously described by Harrison and Falcon (1936, 1934) and proposed a synchronous evolution associated with progressive migration of the syncline hinge. This kinematic interpretation of flap development is shared by other authors, based on observations of natural examples (Mercier *et al*., 1994, 2007; Saint Bezar *et al*., 1998, 1999). In any case, a flap development requires the disruption of the limestone layers in the structure (Sherkati *et al*., 2005) a disruption that could have been triggered by erosion, suggesting the folding process was active in subaerial conditions. The Neogene thin-skinned fault structure of the sierra de Talacasto-La Dehesa was exhumed and eroded, and then gravity started to work on the suitably oriented slopes. Collapse of the uppermost layers can occur constituting a preferential landslide detachment layer.

Several authors have interpreted these structures as folds caused by compressive shortening.. However, the gravity folds are disharmonic and show opposite vergences to those related to drag folds developed on the flanks of the main anticline, showing also a basal detachment that separate this of an unfolded substrate. Furthermore, as was pointed by Ollier and Pain (2000), these folds and related structures were formed subaerially, after incision of the river valleys. The folded slabs usually give rise to a synform and their location and topographic expression change according to the dip of the beds and the glidding fault. The folded slabs are strongly fractured during the slipping and folding in superficial conditions and the brittle material behavior throughout downslope movement. So, differential displacement occurs on vertical joints in the carbonates rocks, forming centimeter-size blocks.

Applying Harrison and Falcon's (1934, 1936) criteria, two sorts of collapse structures in the form of roof-and-wall structures are found in the western flank of Sierra de La Dehesa. These are like rockslide and collapse structures thought to have been caused mainly by gravity subsequently to fold amplification and uplift related to the Andean orogeny. Thus, these structures are classified as common collapse structures in this paper.

The combination of steep slopes, pre-existing inclined lithological and structural anisotropies, led to the initial detachment and sloping down of the Sierra de la Dehesa western flank.

San Juan Province is characterized by semi-arid to arid conditions with dry climates, high summer temperatures, short lived cold winters (−18°C to 0°C), scarce precipitation (below 100 mm/year) and strong winds. Daylight temperature ranges from as high as 35 °C in summer (with peaks exceeding 40 °C) to lows of 16 °C during the dry winters (peaking at −8 °C). Perrin and Hancox (1992) pointed out that slides formed as a result of intense rainfall are more fluid and tend to spread out more across a depositional area, whereas seismically induced landslides may have a blockier appearance and a more limited depositional extent as it occurs in the studied area. However, even though Esper-Angillieri *et al.* (2014) considered the occurrence of paleoearthquakes as the triggering mechanism for La Dehesa rockslides (North and South), some of these collapse structures on the western limb of sierra de La Dehesa were slowly developed, possibly at millimeters to meters per year rates. This mechanism was previously identified in the Eastern Mojave Desert (USA) by Davis and Friedman (2005) where initial detachments from bedrock sources were facilitated by pre-existing structural and stratigraphic anisotropies.

The existence of these structures located in the western flank of sierra de La Dehesa, all of which seem to have a potential origin as collapse structures, lead us to examine the validity of the theory that some folded structures described in mountainous areas of the fold and thrust belt of Precordillera are only the direct result of lateral compression. We conclude that the combination of steep slopes and pre-existing inclined anisotropies, both stratigraphic and structural, led to the initial detachment and downslope movement of the collapse structures and slide sheets in the Sierra de La Dehesa.

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