Investigating gravitational grabens related to lateral spreading and evaporite dissolution subsidence by means of detailed mapping, trenching, and electrical resistivity tomography (Spanish Pyrenees)

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ABSTRACT

The active lateral spread of the Peracalç Range (Spanish Pyrenees) has developed on a Cretaceous limestone sequence around 250 m thick, underlain by tectonically thickened (~2.5 km) Triassic halite-bearing evaporites and clays. Outward expansion of the Triassic sequence by ductile deformation and probably halokinesis toward the debuttressed and unloaded front of the range has been accommodated in the overlying cap rock through the development of a striking horst and graben morphostructure. Fault scarps show anomalously high height to length ratios (aspect ratio; \( H_{\text{max}}/L \)) compared to the values reported for tectonic faults. This retrogressive gravitational deformation has absorbed a paleodrainage, expressed as wind gaps, hanging valleys, and defeated streams. The significant vertical displacement component in this rock spread is attributed to subsidence caused by interstratal evaporite dissolution, as supported by the dissolution-induced collapse and graben structures mapped at the foot of the range. To our knowledge, the rock spread of Peracalç, covering around 4.5 km² and with a minimum volume of 0.9 km³, is the largest documented landslide of the Pyrenees. The excavation of trenches and the acquisition of electrical resistivity tomography profiles provided information on the thickness and subsurface structure of the graben fills, the age of the lateral spread (older than 45 ka), an unexpected episodic kinematic behavior of the gravitational faults, and the timing of deformation events, including slumping of lake deposits.

INTRODUCTION

Rock spreads (Varnes, 1978; Pasuto and Soldati, 1996) or block spreads (Cruden and Varnes, 1996) typically develop on slopes consisting of brittle rocks underlain by soft formations (Fig. 1). The laterally unconfined soft rock, under the load of the overlying rigid slab, may expand outward, eventually producing a bulge. This extension is accommodated in the overlying cap rock through the retrogressive development of tensile fractures subperpendicular to the displacement direction and the dragging apart of the intervening blocks. The separation of the rigid slab into blocks may occur through preexisting tectonic fractures or newly formed gravitational joints (e.g., Conti and Tosatti, 1996). As spreading progresses, a horst and graben morphostructure controlled by synthetic and antithetic gravitational faults may develop (McGill and Stromquist, 1979; Moore and Schultz, 1999; Micallef et al., 2007). The lateral extension of the soft rock unit is accompanied by vertical contraction, leading to subsidence of the overlying rigid rocks (Schultz-Ela, 2001). Frequently, expansion and vertical flattening attenuate away from the free face, and consequently subsidence increases toward the free face of the slope, leading to downward flexure of the rock slab and/or outward toppling of the decomposed blocks (Fig. 1). The cracks between the blocks may be filled by soft material squeezed up from below or detritus falling from above. Lateral spreads are clearly complex landslides, since they are affected by different types of displacement (translation, subsidence, and rotation), and frequently evolve into other movement types (i.e., topples, rock falls, rotational slides, and earth flows; Rohn et al., 2004). However, they are sufficiently distinctive and endemic to certain geological situations to be considered as a separate landslide typology (Varnes, 1978; Cruden and Varnes, 1996).

Extension of the plastic unit may be related to continuous visco-plastic deformation of argillaceous sediments (Radbruch-Hall, 1978; Varnes, 1978; Záruba and Mencel, 1982), deformation across multiple discontinuity planes and shear zones (Alves and Lourenço, 2010), and the development of closely spaced dilation joints (Mège et al., 2011). More diverse deformation mechanisms may be involved when the brittle cap rock is underlain by soluble evaporitic formations. In these contexts, low-yield-strength salt-bearing evaporites may flow due to differential loading (Harrison, 1927; Huntoon, 1982; Hudec and Jackson, 2007). Moreover, the rigid blocks may undergo substantial subsidence due to interstratal evaporite dissolution favored by enhanced water percolation in the fissured and faulted slope affected by lateral spreading (Fig. 1).

In this paper, we analyze for the first time the Peracalç Range lateral spread, which is to our knowledge the largest slope movement in the Spanish Pyrenees. The Peracalç landslide is a peculiar gravitational slope deformation with excellent examples of gravitational grabens related to both lateral spreading and...
subidence due to interstratal dissolution of halite-bearing evaporites. The paper also documents grabens and collapse structures at the foot of the range related to interstratal evaporite dissolution. These gravitational structures, despite their extent (>5 km²) and geological significance, have been overlooked in previous geological maps and studies. According to our literature review, this is the first rock spread investigated by means of trenching and electrical resistivity tomography (ERT). The main objectives of the work include: (1) characterizing the grabens developed in the lateral spread of Peracalç Range and the evaporite dissolution collapse structures formed at the foot of the range; (2) analyzing the processes and factors involved in the gravitational deformation phenomena, as well as their impact on drainage network development; (3) obtaining information on graben-fill thickness, deformation style, kinematic behavior (progressive versus episodic), and timing of deformation by means of trenching and ERT; and (4) exploring criteria that might be useful to differentiate between gravitational (nonseismogenic) and tectonic (seismogenic) faults. This work illustrates that rock spreads underlain by evaporites may generate significant normal faults with episodic displacement showing structural and geomorphological characteristics similar to those of tectonic origin. However, a good understanding of the geological context and some anomalously high parameters (e.g., height/length ratio of fault scarps, horizontal separation, long-term horizontal and vertical displacement rates) may help to diagnose their gravitational origin, ruling out the seismogenic potential.

**REVIEW ON ROCK SPREADS**

Rock spreads generally develop on stratigraphic sequences that have a nearly horizontal structure or a slight downslope dip. Mauduit et al. (1997), analyzing a large submarine lateral spread in the Gulf of Guinea and based on analogue physical models, concluded that the basal slope angle (i.e., dip of the base of the salt unit) controls both the width of the area affected by lateral spreading and the faulting pattern (“raft tectonics”). For slope angles above a threshold value, wide lateral spreads with three distinctive domains develop—an upslope graben system with synthetic and antithetic listric normal faults, a central raft, and a downslope sequence of half grabens controlled by synthetic listric faults.

Several case studies reveal that large rock spreads may form in low-gradient slopes (Canziani and Pellegrini, 1987). For instance, Pánek et al. (2008) reported on a lateral rock spread with an estimated volume of 400 × 10⁶ m³ in the Crimean Mountains, Ukraine, in a slope with an average gradient of 6° including the headscarp. The development of rock spreads may be favored by a number of factors, such as: (1) lateral unconfinement or debuttressing of the soft rock unit due to erosion or uplift by active faulting (Delgado et al., 2011; Carobene and Cevasco, 2011); (2) increased precipitation and water percolation through fissures, with the consequent softening of the argillaceous rocks (Pasuto and Soldati, 1996) (a similar effect is expected with the presence of evaporites, which may also dissolve, reducing the mechanical strength [Tran et al., 2011] and causing subidence of the overlying rocks); (3) weakening of argillaceous rocks due to expansion and contraction of smectite clay minerals (Pánek et al., 2008); (4) fluvial incision, resulting in a lowering of the water table in evaporitic formations and an increase in the hydraulic gradient, inducing higher groundwater flow rates and favoring karstification (Gutiérrez et al., 2012); and (5) seismic shaking (Micallef et al., 2007; Cauchon-Voyer et al., 2011).

Pasuto and Soldati (1996), in their review on rock spreads, indicated that displacement rates for these types of slope movements are typically between 0.1 mm/yr and 10 cm/yr. According to Cruden and Varnes (1996), block spreads are characterized by extremely low displacement rates (<16 mm/yr). In the rock spread of the grabens of Canyonslands, Utah, Marsic et al. (2003), combining global positioning system (GPS) and differential interferometric synthetic aperture radar (DInSAR), measured a maximum horizontal deformation rate of 6 mm/yr and a relative regional subsidence of up to 3 mm/yr, in agreement with the data presented by Furu et al. (2007). Rohn et al. (2004), for a lateral spread developed on calcareous rocks underlain by marls and halite-bearing clays (northern Calcareous Alps, Austria), recorded mean horizontal displacement rates of 11.4 mm/yr using GPS. Delgado et al. (2011), applying DInSAR, measured average displacement rates between 0 and 2 mm/yr in a lateral spread in southern Spain, and recognized a slight acceleration after a rainfall episode equivalent to the average annual precipitation. Viero et al. (2010) indicated that the displacement rate in the active Cinque Torri lateral spread, Italian Dolomites, is too slow to be measured by means of GPS over a monitoring period of 3 yr. Vlcko (2004), in...
the lateral spread that constitutes the foundation of the United Nations Educational, Scientific, and Cultural Organization (UNESCO) site Spis Castle, Slovakia, reported average dilation rates from 0.27 to 3.25 mm/yr for specific fissures using crack gauges. Petro et al. (2004) recorded mean horizontal separation rates of 0.19 mm/yr in fissures equipped with crack gauges for a lateral spread developed in the Strechovy volcano, Slovakia. Displacement in lateral spreads is partitioned in multiple fissures, and consequently measurements from cracks constitute partial and minimum values of the overall gravitational deformation. In spite of the low velocity, continuous displacement on spreading slopes may constitute a threat to any engineering structure, including dams, tunnels, pipelines, or transportation infrastructure. The zones of maximum differential displacement can be preliminarily recognized with a reasonable level of confidence by means of detailed geomorphological mapping. Lateral spreads can also have significant hydrological implications, since they may disrupt surface drainage, create internally drained depressions, and enhance focused water infiltration along extensional fractures.

To our knowledge, the largest documented subaerial rock spread is the grabens of Can-
Figure 2. Geological setting of the study area. (A) Geological sketch of the Pyrenees showing the main structural units (after Rosell and Linares, 2001). The most extensive outcrops of Permian–Triassic evaporites, and the general location of the study area (bold rectangle), which is traversed by the Étude Continentale et Océanique par Réflexion et Réfraction (ECORS) seismic profile, are indicated. (B) N-S geological cross section synthesizing the ECORS profile (after Berástegui et al., 1993). (C) Simplified geological map of the Les Nogueres structural unit showing the location of our study area (bold rectangle) (after Rosell, 1963, 1970, 1994; García-Senz, 2002). (D) Schematic geological cross section of the study area (after Rosell, 1994).
dissolution, and probably also halokinesis of this formation have played an instrumental role in the development of the investigated gravitational deformations. In outcrop, the Keuper facies displays reddish and multicolored clays with secondary gypsum. Klimowitz and Torrescusa (1990), based on borehole data from the South Pyrenean unit, differentiated a lower evaporitic unit with a high proportion of halite and an upper clay unit with anhydrite. The highly variable thickness of the lower evaporitic unit recorded from boreholes seems to be related to local tectonic thickening and probably halokinesis: 465 m in Surpirenaica-1 borehole, 30 km west of the study area, and 1240 m in Isona-1 borehole, 25 km to the south. The upper clay unit reaches 130 and 200 m in these boreholes, respectively. Although there are no borehole data from the study area, the presence of halite at depth is proven by the saline springs of Morreres and Gerri de la Sal, in the Noguera Pallaresa valley (Fig. 3). The latter is used for the production of salt. Most likely, the exposed sediments of the Keuper facies correspond to a condensed residual sequence resulting from the vanishing of the most soluble evaporites by dissolution, as is commonly the case in many salt-bearing evaporitic formations (Warren, 2006; Gutiérrez and Cooper, 2012).

Other lithological units exposed in the footwall of the Morreres back thrust include (5) relatively small bodies of dolerites (ophites) intruded within the Keuper facies and mostly attributed to sills injected in Triassic times (Hartevelt, 1970) and (6) the Paleozoic and Mesozoic formations on both sides of the Morreres back thrust, which are unconformably overlain by Oligocene conglomerates deposited in alluvial-fan environments, i.e., the Pyrenean Molasse (Rosell and Riba, 1966; Saura and Teixell, 2000). These detrital sediments once covered most of the Paleozoic and Mesozoic rocks in the study area, before the excavation of the Senterada–Gerri de la Sal depression. The conglomerates situated north of Montcortés village correspond to the d’Envall Conglomerates, which are Oligocene in age (Rosell, 1963, 1970; Saura and Teixell, 2000; Saura, 2004; Beamud et al., 2011). This folded detrital formation, 250–550 m thick, truncates the underlying thrust faults of the Les Nogueres structural unit (Fig. 2D). It consists of scarcely cemented, massive and poorly sorted gravel with chaotic fabrics, including meter-sized boulders mostly derived from the Lower Triassic Buntsandstein facies.

The following formations have been mapped in the hanging wall of the Morreres back thrust (South Pyrenean unit) (Fig. 4A): (1) The exposed Jurassic rocks are restricted to small outcrops...
of Middle Jurassic (Dogger) black dolomites associated with the Morreres back thrust. The Erinya-1 oil exploration borehole (Lanaja et al., 1987), located just next to the southwestern edge of the study area (Fig. 2C), penetrated a Jurassic sequence, 1600 m thick, with an upper anhydrite unit 700 m in thickness. This evaporitic unit might be present at depth beneath the Peracalç Range (hanging wall of the Morreres back thrust) and could have played a role in the development of the analyzed deep-seated slope movements. (2) The Early Cretaceous carbonate succession (Aptian-Albian), with a stratigraphic thickness of around 1000 m, constitutes most of the outcropping rocks in the Peracalç Range. Detailed mapping of these units and gravitational fault scars has been instrumental for the identification and characterization of the deep-seated slope movements affecting the brittle carbonate sequence underlain by the ductile and soluble Keuper facies. The differentiation of lithostratigraphic units is based, with some simplifications, on the stratigraphic framework established in previous works (Rosell, 1963, 1970, 1994; Mey et al., 1968; Garrido and Ríos, 1972; Peybernés, 1976; Martínez, 1982; Rosell and Llompart, 1982; Bernaus et al., 2000; García-Senz, 2002). (2a) The early Aptian Prada and Cabó Formations, around 500 m thick, consist of gray and blackish micritic limestone with marls. This stratigraphic unit associated with the Morreres back thrust frequently exhibits a thick, massive, and chaotic breccia composed of large blocks embedded in red clays. Locally, blocks of Jurassic units are recognized within these breccias. Several nonexclusive interpretations can be proposed for this unit: a tectonic breccia related to shearing caused by the underlying back thrust; a dissolution and collapse breccia generated by the karstification of the underlying Triassic evaporites; or a rauhwacke resulting from the dissolution of the evaporitic components once incorporated in a tectonic breccia associated with a thrust controlled by a lubricating evaporite formation (Warren, 2006). Similar

Figure 4. (A) Geological map of the Peracalç-Puigcerver area. See location in Figure 3. (B) Image of the overturned northern limb of the Peracalç syncline showing distribution of the formations Senyús–Font Bordonera (7), Lluçà (6), and Santa Fé (5). Circled person for scale. (C) Geological cross section a-b across the eastern sector of Peracalç Range, covering a broader transect than the map. Cross section based on Rosell (1963), García-Senz (2002), Saura (2004), and our new data.
breccias have been documented by Canérot et al. (2005) in the Lauriolle diapir, French Pyrenees. (2b) The Senyús and Font Bordoner Formations (late Aptian–Albian), 300 m in cumulative thickness, have been grouped as a single cartographic unit. The Senyús Formation (late Aptian) is made up of micritic limestones with a small proportion of intraclasts and bioclasts. In the Flamencell valley, it overlies the Keuper facies (Fig. 4A). The Font Bordoner Formation (late Aptian–Albian) consists of gray limestones and marls with a hardground at the top, which includes a significant accumulation of glauconite. (2c) The Albian Lluçà Formation, 250 m thick, is composed of alternating limestones and calcarenites with some grainstone and marl layers. The top of this unit corresponds to an erosional surface on which Late Cretaceous limestones were deposited disconformably. (2d) The Late Cretaceous sedimentation is recorded by the Senyús Formation (late Cenomanian), ~25 m thick, and the upper Triassic rocks in the footwall of the Morreres back thrust. (2e) The Senyús Formation (late Aptian–Albian), 300 m in cumulative thickness, have been grouped as a single cartographic unit. The Senyús Formation (late Aptian) is made up of micritic limestones with a small proportion of intraclasts and bioclasts. In the Flamencell valley, it overlies the Keuper facies (Fig. 4A). The Font Bordoner Formation (late Aptian–Albian) consists of gray limestones and marls with a hardground at the top, which includes a significant accumulation of glauconite. (3) In the upper and southern sector of the Peracalç Range, the marine Cretaceous succession is unconformably overlain by Upper Cretaceous conglomerates of the Pobla de Segur Formation. This massive, poorly sorted, and polymictic conglomerate unit is composed of alternations of limestones and marls with a hardground at the top, which includes a significant accumulation of glauconite. (4) The Late Cretaceous sedimentation is recorded by the Senyús Formation (late Cenomanian), ~25 m thick, and the upper Triassic rocks in the footwall of the Morreres back thrust. (5) The Late Cretaceous sedimentation is recorded by the Senyús Formation (late Cenomanian), ~25 m thick, and the upper Triassic rocks in the footwall of the Morreres back thrust. (6) The Senyús Formation (late Cenomanian), ~25 m thick, and the upper Triassic rocks in the footwall of the Morreres back thrust.

**METHODOLOGY**

The investigation was carried out in the following phases. Initially, the main landslide complexes and subsidence morphostructures related to interstratal karstification of evaporites were recognized on the basis of previous geological maps (Rosell, 1963, 1994) and the geomorphological interpretation of aerial photographs, 1:33,000 and 1:60,000 in scale, taken in 1956 and 2002, respectively (Fig. 3). The resulting cartographic scheme was used to select the most interesting areas for the production of more detailed maps. This investigation is focused on the graben depressions generated by lateral spreading and dissolution-induced subsidence in the Peracalç Range and those resulting from collapse caused by interstratal karstification of evaporites in the Montcortés Lake area. Subsequently, 1:5000 scale geological maps were produced in these areas including information on the stratigraphy and structure of the bedrock, as well as the distribution of landforms and deposits related to gravitational surface deformation (e.g., fault scarps and graben fills). These

![Figure 5](https://example.com/figure5.png)
maps, covering around 13.5 km², have been elaborated by direct mapping in the field and partially refined using 1:18,000 and 1:22,000 aerial photographs.

In the next step, three backhoe trenches were dug across gravitational fault scarps or traversing their projected trace on recent deposits. The selection of the trench sites, two in the lateral spread of Peracalç Range (trenches 1 and 2; Fig. 6) and one at the edge of an evaporite dissolution-induced graben east of Montcortés Lake (trench 3; Fig. 5), was based on the 1:5000 geological-morphostructural maps. We followed the classical procedure applied for the study of paleoseismological trenches (McCalpin, 2009a). After cleaning the trench walls, a reference grid with horizontal and vertical strings spaced 0.5 or 1 m was placed on the shaded side of the trench, which was logged on graph paper. Material datable by the accelerator mass spectrometry (AMS) radiocarbon method or optically stimulated luminescence (OSL) was collected, preferably from the units bracketing the faulting events. The main purposes of these
GEOLOGICAL AND GEOMORPHOLOGICAL MAPPING OF THE PERACALÇ RANGE AND THE SENTERADA–GERRI DE LA SAL DEPRESSION

Geological and geomorphological mapping of the Peracalç Range and the associated erosional deformation between the Flamicell and Noguera Pallaresa River valleys reveals the presence of three landslide complexes covering a total area of 22 km² (Fig. 3, inset). The development of these anomalously large deep-seated slope movements is favored by thick (~2.5 km) halite-bearing evaporites and argillaceous sediments in the footwall of the Mórreres back thrust and a high local relief generated by fluvial dissection and differential erosion; the area has not been glaciated (Bordonau, 1992; Bru et al., 1994).

The Puigcerver-Senterada landslide, covering 3.1 km², is located on the east margin of the Flamicell valley (Fig. 3, inset, letter c). The displaced mass includes Cretaceous and Triassic rocks of the upper and lower blocks of the Mórreres back thrust, respectively. The headscarp of this landslide is defined by a prominent triangular facet, 175 m high, in the resistant limestone of the Mórreres back thrust hanging wall (Fig. 3). The western margin of the Noguera Pallaresa valley is affected by the Gerri de la Sal–Peracalç Range lateral spread (Fig. 3, inset, letter a), around 6.9 km² in area. This landslide mainly displaces Triassic limestones and detrital rocks, as well as the underlying clays and evaporites of the Keuper facies. The saline springs situated at the foot of the landslide strongly suggest that gravitational deformation caused by subsurface evaporite dissolution plays a significant role in the development of this slope movement.

Both the Puigcerver-Senterada and the Gerri de la Sal–Peracalç Range landslides show large enclosed depressions with perennial lakes (i.e., Pla de Corts west of Peracalç) at the foot of amphitheater-like scarps indicative of back tilting. These geomorphic features suggest that these landslide complexes correspond, at least partly, to rotational slides controlled by deep-seated failure surfaces rooted in the Triassic clays and evaporites. Assuming an ellipsoidal geometry for the sliding planes, we have tentatively estimated volumes of 0.76 km³ and 0.27 km³ for the Gerri de la Sal–Peracalç Range and Puigcerver-Senterada slope movements, respectively. The convex toes of these landslides have deflected the Flamicell and Noguera-Pallaresa Rivers, showing anomalous curved traces. Lacustrine deposits mapped in the bottom of the Flamicell valley (Fig. 3), and dated at 1304–1231 cal. yr B.P. with terrestrial snail shells collected from the top of the sequence (Table 2), provide evidence for a late Holocene landslide-damming episode of the Flamicell River.

Peracalç Range Lateral Spread

In the laterally unconfined northern flank of the Peracalç Range, with a local relief of around 450 m, the carbonate sequence (250 m thick overlying plastic and soluble Triassic clays and evaporites) has spread in a NNE to NE direction toward the Montcortés depression (Fig. 4). Lateral extension has been accommodated in the brittle carbonate slab through the development of a conspicuous horst and graben morphostructure controlled by a swarm of gravitational normal faults with prevailing ENE-WSW and NW-SE trends (Figs. 4, 6, 7, and 8A). Long and fresh open fissures up to several meters wide are also common in both bedrock exposures and in the sediment-filled graben floors (Figs. 6 and 8B). The fault block topography descends in a step-wise manner toward the Montcortés depression; the bottom of the highest and lowest grabens are situated at 1332 and 1110 m above sea level (asl), respectively (Fig. 6C). In plan view, the graben system displays an overall curved arrangement with the convexity pointing downslope, similar to the trace of the Mórreres.

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TABLE 1. SUMMARY OF ELECTRICAL RESISTIVITY TOMOGRAPHY (ERT) FEATURES

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<th>Profile 2a</th>
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<td>2 m (inner reels)</td>
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*The profiles were acquired with a set of four reels: the two inner reels with 20 electrode positions each, and the two outer with 12 positions spaced double than the inner ones.
†RMS—root mean square.
back thrust and the tectonic structures mapped in the hanging wall (Figs. 4 and 6A). The development of this lateral spread, with a significant subsidence component, may be attributed to the following processes: (1) extension of the ductile Triassic sediments toward the laterally debuttressed front of the range, (2) halokinetic flow of the thick halite-bearing Triassic evaporitic sediments toward the unloaded foot of the Peracalç Range, and (3) differential subsidence of the fault blocks in the carbonate sequence due to interstratal karstification of the underlying evaporites. The extension would have been accompanied by vertical contraction and the consequent subsidence of the overlying carbonate sediments. The bulge mapped north of the Peracalç Range reaches 1750 m in length and 400 m in width. The en echelon fault arrays bounding the graben depressions are expressed in the landscape as low-sinuosity fault scarps with very limited dissection (almost no fault facets), locally interrupted by evident relay ramps in the soft-linked stepover zones (Figs. 7D and 8D). The N-dipping synthetic faults generate downslope-facing scarps, whereas antithetic faults produce upslope-facing scarps acting as barriers for the surface runoff and sediment transport. Fault scarps reach 62 m in height (Fig. 7) and 1650 m in length. The number of faults and grabens, as well as the evidence of activity, increases toward the curved central sector of the graben system, where extension is expected to reach the highest magnitude and rate (Fig. 6A). The extensional morphostructures of the Peracalç Range closely resemble the grabens and fissures described in the grabens of Canyonlands, Utah (McGill and Stromquist, 1979; Moore and Schultz, 1999; Baars, 2000). These grabens also show an arcuate arrangement, but with the convexity pointing upslope.

Several geomorphic features indicate that the Peracalç Range used to have a N- to NE-directed drainage that has been largely disrupted by the development of transverse horsts and grabens (Figs. 6A and 6B). Evidence of the deformed and aborted paleodrainage includes: (1) perched abandoned stream courses in horst blocks (wind gaps) (Fig. 8E); (2) conspicuous knick points in drainages at the upstream margin of grabens (hanging valleys) (Fig. 8A); (3) sediment-filled closed depressions upstream of antislip fault scarps, corresponding to defeated streams (Fig. 8B), and beheaded streams recognized downstream of these fault scarps; and (4) topographically lowest areas of internally drained graben floors coinciding with paleodrainage courses, defined by wind gaps in the adjacent horsts (Fig. 6A). At the present time, the area has a very poorly developed drainage network dominated by subsurface water flow, i.e., a very low runoff coefficient. Most of the precipitation infiltrates through fissures and fractures, favoring the karstification and weakening of the underlying evaporites and clays. The course of some new streams follows graben depressions and connects with old northward-directed drainages, forming a peculiar orthogonal or trellis pattern (i.e., graben system III in Fig. 6A). Lateral spreading in the grabens of Canyonlands has caused a similar impact on the drainage network (Trudgill, 2002; Commins et al., 2005).

Using the cross section constructed across the central sector of the lateral spread (Fig. 6C), we roughly calculated the amount of extension achieved in the Peracalç Range by dip-slip displacement on the mapped normal faults. Extension related to horizontal separation on faults and fissures has been obviated due to the short age of data. Horizontal extension (E) produced by each fault on the cross section was estimated considering a wide fault dip angle (β = 60°–80°) and the vertical displacement estimated with the available topographic data (H) and assuming a nearly horizontal topography prior to faulting (E = H/tan β). According to our calculations, the lateral spread has accommodated a cumulative horizontal extension of the order of 42–138 m, representing an increase of 3.42%–12.13% in the original length of the brittle carbonate sequence overlying the Morreres back thrust.

Four graben systems may be differentiated in the Peracalç Range (Fig. 6A). In the upper and western sector, we mapped a complex NNW-ESE–trending graben that is 1625 m long and up to 400 m wide (Figs. 6A and 6B). In total, 17 fault scarps have been mapped, together with a number of open fissures up to 280 m long. The wide open fissures developed in the northern margin of this graben indicate outward toppling of lime stone blocks, with the consequent oversteepening of the slope forming its southern margin (Fig. 8B). The locally dissected scarps associated with the master synthetic fault displays one of the few triangular facets recognized in the area and developed on Oligocene conglomerates. The fault pattern shows a sharp change in the

<table>
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<th>Code and location</th>
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<th>Calibrated age (yr B.P., 2σ)</th>
<th>OSL age (yr B.P., 2σ)</th>
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<td></td>
<td>1958–1952 (0.01)</td>
<td></td>
</tr>
<tr>
<td>MT1-2 trench 1</td>
<td>Poz-22650 AMS</td>
<td>Charcoal</td>
<td>70 ± 30</td>
<td>258–222 (0.25)</td>
<td>139–30 (0.73)</td>
</tr>
<tr>
<td>BV 1 outcrop</td>
<td>Poz-22471 AMS</td>
<td>Land snail shell</td>
<td>1335 ± 30</td>
<td>1304–1231 (0.84)</td>
<td>1208–1181 (0.15)</td>
</tr>
<tr>
<td>MT2-3 trench 2</td>
<td>MAD-5406 OSL</td>
<td>Sands</td>
<td></td>
<td>48,674–42,328</td>
<td></td>
</tr>
<tr>
<td>MT2-4 trench 2</td>
<td>MAD-2707 OSL</td>
<td>Sands</td>
<td></td>
<td>17,692–15,760</td>
<td></td>
</tr>
<tr>
<td>MT2-5 trench 2</td>
<td>MAD-5806 OSL</td>
<td>Sands</td>
<td></td>
<td>45,518–39,376</td>
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</tr>
</tbody>
</table>

Note: Bold type indicates calibrated age ranges with relative area higher than 0.7.

*AMS—accelerator mass spectrometry; OSL—optically stimulated luminescence.

TABLE 2. CODE OF SAMPLE DATED, LOCATION, LABORATORY NUMBER (POZ—POZNAN RADIOCARBON; MAD—LABORATORIO DE DATACIÓN DE LA UNIVERSIDAD AUTÓNOMA DE MADRID), DATING METHOD, MATERIAL, CONVENTIONAL AGES; CALIBRATED RADIOCARBON DATES AT 2σ, AND CALIBRATED AGES AS YR B.P. AT 2σ (USING CALIB 6.0.1 AND THE DATA SET INTCAL 09,14E; REIMER ET AL., 2009).
Figure 7. (A) Photograph of graben I (Fig. 6) at the head of the lateral spread showing the trace of trench 1 and profile ERT-1 (ERT—electric resistivity tomography), sited across the projection of an antithetic fault scarp in a depression related to a paleodrainage. See location in Figure 6. The colluvium at the foot of the scarp on the left (Roca de Perauba), 62 m high, is affected by multiple antislope scarps with open fissures. (B) Sketch showing the morphostructural features of the graben. (C) Open fissures in colluvium at the foot of the master synthetic fault scarp. Circled person for scale. (D) Image of the antithetic faults scarps. The antislope scarp in the central portion of the image shows a compound beveled geometry. The scarp in the foreground shows two en echelon fault segments with a relay ramp in the stepover.
Figure 8. (A) General view of graben II (see Fig. 6A for location of all five parts of Fig. 8). Photograph taken from the upper part of the antithetic fault scarp toward the synthetic fault scarp, showing a faulted paleodrainage (hanging valley). (B) Graben I bounded by synthetic and antithetic faults. The uphill-facing scarp associated with the latter has defeated a stream generating an elongated enclosed depression. Inset shows fissure resulting from outward toppling of the block to the left. (C) Bulge at the foot of the Peracalç Range affecting a recent detrital cover. The slope above has been breached by the lower graben IV. (D) Relay ramp at the transfer zone of two en echelon fault segments (stepover) in the northern margin of graben II. (E) Wind gaps in the horsts flanking graben II.
eastern sector of this graben: (1) There are a higher number of faults, some of which adopt a NW-SE trend. (2) The graben depression is split into two grabens separated by an internal horst controlled by synthetic and antithetic secondary faults (Fig. 6C). (3) There are numerous open fissures in the graben floors. Only the largest ones have been depicted in the map. This change in the fault pattern may be partly related to spatial variations in the amount of extension and the lithology of outcropping rocks, i.e., conglomerates in the western sector and mainly limestones in the eastern zone (Fig. 4). Faulting might be partly accommodated by the development of drape folds in the conglomerates, in which fault and fold scarps degrade at a much higher rate. The eastern portion of this graben, which constitutes the head of the lateral spread, shows the most extensive and conspicuous evidence of recent deformation. The fault scarp at the southern margin of the graben reaches 62 m in height. At the foot of this nearly vertical scarp, there is a dense system of antithetic upslope-facing scarps and open fissures displacing a slightly cemented talus deposit (Fig. 7). These features seem to correspond to a keystone graben related to active vertical and horizontal displacement on the master fault. The antithetic faults in this graben locally display conspicuous beveled compound scarps and accommodation ramps in stepover or transfer zones (Fig. 7). Trench 1 was excavated on a sediment-filled depression across the eastward projection of a beveled antithetic fault scarp (Figs. 6A and 7A). An aborted paleodrainage has been inferred in the western sector of the graben through the SW-NE alignment of the following geomorphic features (Fig. 6A): the lowest point of an internally drained depression in the graben axis, an alluvium-filled enclosed depression in a defeated stream segment (Fig. 8B), and a wind gap corresponding to the beheaded stretch of the stream.

The main structure in the eastern sector corresponds to a NW-SE–trending graben that is 1750 m long and 120–205 m wide (Fig. 6A). The northeastern margin of this graben is controlled by an en echelon fault array with both soft-linked and hard-linked transfer zones. The former are expressed as relay ramps (Fig. 8D) and the latter as sharp bends in the fault scarps resulting from the linkage of fault segments through the breakage of former accommodation ramps. To the NE of this graben, there is a poorly defined horst and graben morphostructure developed on densely forested steep slopes. To the SW of the main graben we mapped a set of closely spaced and low-relief NW-SE fault scarps bounding shallow graben depressions with vague margins. In this sector, we identified a cover of locally derived carbonate detrital breccias embedded in decalcification clays of unknown age. The area deformed by the main graben used to have two SW-NE-oriented drainages, recognized by hanging valleys (Fig. 8A), the lowest points of the internally drained graben floor, and wind gaps in the horst situated to the NE (Figs. 6A and 8E). At the western edge of the graben system II, we identified a major paleodrainage revealed by the SSW-NNE alignment of sediment-filled depressions corresponding to downthrown or fault-blocked stream segments, wind gaps, and beheaded valleys (Fig. 6A).

Graben III, situated at an intermediate topographic level, may correspond to the westward projection of the main graben in sector II (Fig. 6A). This depression, controlled by left-stepping en echelon faults in the southern margin, is 1700 m long, up to 170 m wide, and has an ENE-WSW orientation. The eastern sector of the graben is drained longitudinally by a creek that exits the depression through a water gap and connects with an old S-N-oriented stream, which has been beheaded by gravitational faulting (Fig. 6A). The graben floor in its southeastern sector is overlapped by the toe of a slide. Trench 2 was excavated across the northern fault scarp of this graben.

Graben system IV includes three E-W–trending depressions situated at the lowest elevation (Fig. 6A). In this lower sector, the slopes are extensively covered by unconsolidated gravels with a fine-grained matrix derived from reworked Oligocene conglomerates. The northern margin of the central graben shows a conspicuous beheaded paleodrainage (wind gap). The eastern graben, situated at a lower elevation, has been founded by a collapse structure defined by an arcuate scarp and related to interstratal karstification of the underlying evaporites (Figs. 6A and 6B). This subsided area forms part of the Montcortés Lake collapse area (Fig. 9). North of the western and central grabens, there is an E-W bulge (Figs. 6 and 8C). Detrital cover deposits in this sector show an open antiformal structure concordant with the topography. The occurrence of bulges is a common feature at the toe of lateral spreads (e.g., Pasuto and Soldati, 1996; Pánek et al., 2008). The development of the bulge at the foot of Peracalç Range seems to be related to the outward extrusion of the Keuper facies. This lateral and upward flow may result from both visco-plastic deformation of argillaceous sediments and halokinesis favored by differential loading (Harrison, 1927; Potter and McGill, 1978; Hunt, 1982; Jackson, 1995; Furuya et al., 2007; Hudec and Jackson, 2007; Kirkham et al., 2002; Lucha et al., 2012).

The maximum height and length of nine uphill-facing scarps and two downhill-facing scarps were measured using a laser hypsometer (Nikon Forestry Pro) and our maps, respectively. Scarp length corresponds to the tip-to-tip straight horizontal distance. We selected the main fault scarps bounding the graben depressions and ruled out a number of downhill-facing scarps for which it was not possible to identify the location of the scarp crest due to erosional modification of the slope profile and the presence of dense forest. Aspect ratios ($H_{\text{max}}/L$) were plotted together with the global data set presented by Davis et al. (2005) for tectonic faults with lengths between 100 m and 10 km. The average aspect ratio of the nine uphill-facing scarps is 0.029, ranging from 0.010 to 0.063, and with a standard deviation of 0.015 (Fig. 10). Antislip scarps show a general direct relationship, with higher heights for increasing length, but with significant scattering and low coefficient of determination for a power-law regression ($H_{\text{max}} = 0.0255L^{0.108}, R^2 = 0.47$). Cartwright et al. (1995) also found significant data scattering when analyzing the ratio between maximum vertical displacement and length of normal faults in the grabens of the Canyonlands, Utah. In a later study, Grosfils et al. (2003) indicated that Cartwright et al. (1995) underestimated the displacement to length relationships by assuming a limited thickness for the graben fill. The average aspect ratio derived from the two downhill-facing scarps associated with master faults is 0.05, i.e., almost twice as high as the value calculated for the uphill-facing scarps. Gutiérrez et al. (2012) calculated average aspect ratios of 0.008 and 0.02 for downhill-facing and uphill-facing scarps, respectively, in a graben generated by subsidence due to interstratal dissolution of evaporites (Iberian Range, NE Spain).

**Collapse Structures and Grabens Related to Interstratal Dissolution of Evaporites in the Montcortés Lake Area**

The structure of the Montcortés Lake area corresponds to an E-W–trending antiformal syncline with evaporitic Triassic sediments in the core, overlain by limestones of the older Muschelkalk facies (Fig. 3). The Triassic formations in the northern limb of the antiformal unconformably overlie by gently folded Paleogene conglomerates. Geological and geomorphological mapping reveals an ellipsoidal evaporite collapse area, 1.6 km in length, affecting the lower part of the Peracalç Range and Montcortés Lake area (Figs. 3 and 5). The boundary of this internally drained area of subsidence, including Montcortés Lake, is defined by arcuate scarps (Fig. 9A). In the northern sector of the collapse area, there is an ENE-WSW–trending graben that is 1450 m long and up to 630 m wide.
Secondary graben depressions with conspicuous geomorphic expression occur on both sides of this structure. The fault scarp at the southern margin of the graben displays conspicuous facets on ophites 25–30 m high. The bottom of the northern secondary grabens is affected by scarp-edged and subcircular collapse sinkholes.

Trench 3 was excavated across the southern fault scarp of the northeastern secondary graben (Fig. 9A). The mapped graben structure is related to the collapse of the crest of an antiform due to interstratal karstification of the evaporites forming its core. Similar graben structures, although tens of kilometers long, have been developed in the salt anticlines of the Paradox Basin, Utah and Colorado, in which cores consist of salt walls up to 4 km high (Cater, 1970; Doelling, 2000; Gutiérrez, 2004). In northern Michigan, Black (1997) reported graben valleys around 0.5 km wide generated by interstratal dissolution of gypsum controlled by preexisting tectonic fault and joints. Similar features (Heuschkel Park sag, Spring Valley structure) have been also identified in the Carbondale collapse center, Rocky Mountains, Colorado (Kirkham et al., 2002). Gutiérrez et al. (2012) investigated a 1.7-km-long graben in the Iberian Range, NE Spain, formed in the crest of a monocline generated by sagging due to karstification of subjacent Triassic evaporites.

Bathymetric surveys (Corella et al., 2011) reveal that Montcortés Lake, 525 m long and 30 m deep, corresponds to a karstic depression resulting from the coalescence of several collapse sinkholes. The arcuate scarps situated NE of the lake and crosscutting the secondary graben indicate that Montcortés Lake is the bottom of a larger collapse structure controlled by complex ring faulting, and that it is younger than the graben on which it is superimposed. Corella et al. (2011), in cores retrieved from the meromictic Montcortés Lake, inferred three major phases of landsliding that occurred around 1010, 1600, and 6000 cal. yr B.P. These subaqueous landslides were probably induced by undermining and loss of basal support related to dissolution-induced collapse events. The graben system has distorted a preexisting N-S drainage. The north-eastern secondary graben east of Montcortés Lake has downfaulted sections of a S-directed paleostream, leaving a perched paleovalley in between (Fig. 9B). The coincidence of a collapse sinkhole in the NE graben floor with the trace of this paleodrainage may be related to more karstification below a former local base level and higher infiltration in the lowest point of an internally drained area. The graben and the large collapse structure have also disrupted the N-S drainage that used to flow along the Montcortés Lake area. Moreover, the north-western secondary graben also has faulted a S-heading stream. In the bottom of this graben, there is also a collapse sinkhole.

**TRENCHING AND ERT**

**Selection of Trench Sites**

The locations of the three trenches excavated across gravitational faults, which subsequently determined the distribution of the three ERT profiles, were based on the following criteria: (1) accessibility, i.e., some favorable sites were discarded because they were not accessible even...
Grabens related to rock spreading and evaporite dissolution collapse

Trench Site 1

A 128-m-long ERT profile (ERT 1) was acquired in a nearly flat depression related to a paleodrainage at the eastern sector of graben I (Fig. 6). The geoelectrical profile, with a N010E orientation, was situated across an antithetic fault scarp (N145E) on exposed limestone and traversing the eastward projection of another antislope fault scarp (Fig. 7A). The trace of the ERT 1 profile overlaps the location of trench 1, excavated across the projected trace of the southern N105N-striking fault. Highly resistive limestone bedrock of the Senyús Formation (ρ >350 Ωm) and low-resistivity Quaternary detrital cover (ρ <350 Ωm) may be differentiated in the ERT 1 profile (Fig. 11A). The spatial relationships between the two resistivity units allow us to infer a concealed graben, ~50 m wide, in which the cover deposits may reach 5–10 m in thickness. This interpretation is in agreement with the morphostructural map, showing a graben structure to the west of the profile. The S-dipping fault controlling this graben was exposed in trench 1. At the site of the northern fault scarp, the ERT profile reveals Quaternary deposits juxtaposed against bedrock.

Trench 1, around 21 m long and 2.3 m deep, exposed the concealed S-dipping fault interpreted in the ERT 1 profile (Fig. 11B). The limestone bedrock of the Senyús Formation displayed a very irregular pinnacled rockhead locally coated with cohesive red clay corresponding to a karstic residue. Two sedimentary packages can be differentiated in the cover deposits. The older units (2 and 3) are offset by the normal fault and restricted to the downthrown block. The undeformed younger units (4 and 5) extend across the whole trench and truncate the normal fault. Unit 2 consists of massive reddish-brown silty clay with matrix-supported subangular pebble- and granule-gravel with chaotic fabrics. This clastic unit is interpreted as a debris-flow facies. Unit 3 is brown massive sandy clay with scattered granule- and pebble-sized clasts and small gravel channels. This unit records low-energy water flows. Charcoal collected 110–120 cm above the base of the unit has yielded an age of 2140–1987 cal. yr B.P. at 2σ (Table 2). Unit 4 is made up of stratified subrounded and well-sorted loose granule- and pebble-gravel. The channeled base of this unit truncates the normal fault (event horizon) and units 3 and 2 in the downthrown block. The southern channel seems to be related to a longitudinal drainage developed along the axis of the graben situated to the west (Figs. 6 and 7), and its location is probably controlled by the concealed graben inferred from the ERT 1 profile. A 139–30 cal. yr B.P. age was obtained from a charcoal sample collected 10 cm above the base of this unit. Unit 5 consists of massive brown silty sand with subangular pebble-gravel. The upper 30-cm-thick part of this unit is highly disturbed by ploughing and shows a darker color. The fault exposed in the northern sector of the trench, with a 57°S dip, juxtaposes the massive units 2 and 3 against highly brecciated bedrock with shear fabrics. The lower part of unit 2 seems to fill a 50-cm-wide fissure associated with the fault. This fissure together with the low dip of the fault suggest a significant horizontal displacement component, with resulting heave and dilation. In the east side of the trench, unit 3 next to the fault shows clasts with reoriented fabrics subparallel to the failure plane.

The stratigraphic and structural relationships observed in the trench record a minimum of one displacement event on the exposed fault, which occurred between deposition of units 3 and 4 (Fig. 11C). The available numerical ages provide a poorly constrained age of 2.0–0.1 ka for this faulting event. The stick-slip displacement style inferred for this gravitational fault is coherent with the compound scarp associated with this structure to the west, showing an upper beveled and degraded segment and a steep and fresh-looking younger segment. These features are characteristic of fault scarps that undergo episodic rejuvenation (e.g., McCalpin, 2009b). Assuming that unit 3 was deposited on both sides of the fault, as suggested by its sedimentological characteristics, its thickness between stations 16 and 17 provides a minimum estimate for the vertical offset of 100 cm. Unit 2 is not taken into account because it is discontinuous (locally interrupted by bedrock). Considering a maximum age of...
2.0 ka for the faulting event and a minimum vertical separation of 100 cm, we can calculate a minimum apparent vertical slip rate of 0.5 mm/yr. Following McCalpin (2009c), we use the term apparent because the slip rate has not been estimated for closed slip cycles (McCalpin, 2009c). The actual value may be significantly higher because we use a maximum age and a minimum displacement. Moreover, this apparent slip rate is obtained close to the tip of the fault. Much higher rates can be expected at the central sector of the structure, where the displacement-per-event values are generally higher.

**Trench Site 2**

This site is located in the western sector of the intermediate graben III. Trench 2 was excavated across the northern antithetic fault scarp (Fig. 6). The ERT 2b profile, 400 m long, was acquired along the graben axis and centered at the intersection with profile ERT 2b and trench 2. The contrast between the high-resistivity calcareous bedrock of the Senyús Formation and the more conductive graben fill in profile ERT 2a allows us to estimate an approximate thickness of 40 m for the latter (Fig. 12A). The high-resistivity upper unit of the western sector of the profile corresponds to a mapped landslide deposit, made up of brecciated limestone superimposed on the finer-grained graben fill (Fig. 6). The ERT 2a profile, 150 m long, was obtained perpendicular to the trenched fault scarp and next to the site of trench 2. It clearly captures the S-dipping fault that juxtaposes the high-resistivity \( \rho > 350 \text{ \Omega} \text{m} \) limestone bedrock underlying the upper part of the scarp against the more conductive Quaternary graben fill (Fig. 12B). Unfortunately, this fault was not exposed in trench 2 because it was beyond the maximum range of the backhoe.

The 18-m-long and 2.1-m-deep trench 2 was excavated across the 8-m-high antithetic...
Grabens related to rock spreading and evaporite dissolution collapse

Figure 12. Electrical resistivity tomography (ERT) profiles (A) ERT 2a (longitudinal) and (B) ERT 2b (transverse) acquired in trench site 2. (C) Log of trench 2 and topographic profile of the scarp. (D) Photograph of trench 2. OSL—optically stimulated luminescence.
Trench Site 3

Trench 3 was excavated across the N-facing scarp defining the S margin of the northeastern secondary graben in Moncértés Lake area. Here, Oligocene conglomerates unconformably overlie the northern limb of the evaporite-cored Bellera antiform. The trench, 10 m long and 1.9 m deep, was excavated in a crop field near the eastern tip of a 110-m-long fault scarp, around 2 m high at the trench site and clearly degraded by agricultural activity.

Two main units made up of stratified gravels were exposed in the trench on both sides of the N-dipping normal fault F1, which is considered to be the master fault (Fig. 13). Unit 1, in the footwall of fault F1, is brown stratified, sub-rounded, polymeric, and cemented Oligocene pebble-cobble-gravel. Unit 2, in the hanging wall of fault F1, is made up of loose, stratified, rounded, and polymeric gravel and abundant secondary carbonate. Unit 2 has a finer texture and a lighter-brown color than unit 1. Fault F1 was exposed in a 25-cm-wide shear zone consisting of gravels with reoriented fabrics. Fault F2 is associated with a 28-cm-wide fissure filled with reddish-brown clay and scattered rounded gravels. The gravels in the wedge-shaped body between the fault and the fissure show obvious shear fabrics. Fault F3 is defined by an 80-cm-wide zone of dilated and sheared gravels with reoriented
fractures filled with downward percolated red-brown matrix. Moreover, the presence of fissures and dilated gravels indicates evaporite dissolution at depth. The trench was limited by permit constraints. However, the length of the trench was limited by permit constraints.

DISCUSSION AND CONCLUSIONS

In the laterally unconfined Peracalç Range, with a local relief of around 450 m, the thick (~2.5 km) halite-bearing argillaceous Triassic sediments, overlain by a carbonate and conglomerate sequence 250 m thick, have expanded outward, generating a bulge at the foot of the range. Lateral extension has been accommodated in the overlying brittle sequence through the development of a prominent horst and graben morphostructure covering around 4.5 km². Two main mechanisms may have been involved in the lateral migration of the Triassic clays and evaporites favored by differential loading: (1) ductile deformation of argillaceous sediments toward the laterally debuttressed front of the range, and (2) halokinetic flow of the halite-bearing evaporites toward the unloaded foot of the range (i.e., Huntoon, 1982; Simpson, 2004; Lucha et al., 2012). The horst and graben structure also shows a significant vertical displacement attributable to subsidence caused by interstratal karstification of evaporites. This interpretation is supported by the presence of grabens and collapse structures caused by evaporite dissolution in the erosional depression situated at the foot of the range, together with major saline springs in the adjacent Noguera-Pallaresa River valley. The lack of deep subsurface data precludes testing the hypotheses proposed about the mechanisms involved in the gravitational slope deformation. Deep boreholes equipped with inclinometers would allow us to obtain quantitative information on the contribution of the different deformation components to the overall displacement, their distribution at depth, and their short-term temporal variability.

A minimum volume of 0.9 km³ has been estimated for this active lateral spread, excluding the unknown thickness of Triassic clays and evaporites involved in the gravitational deformation. This is our knowledge the largest landside documented in the Pyrenees. The graben depressions, up to 1.7 km long and 400 m wide, are bounded by low-sinuosity downhill- and uphill-facing scarps controlled by synthetic and antithetic faults with en echelon arrangement. These normal faults, with prevalent ENE-WSW to NW-SE strikes, seem to have been guided by the preexisting tectonic structure, largely related to the underlying Morrerès back thrust. Obvious accommodation ramps can be observed in the stepovers associated with overlapping fault segments. The development of horsts and grabens has deformed and aborted a former N- to NE-directed paleodrainage, recognizable as wind gaps in the upper part of the horsts, hanging...
valleys in downhll-facing scarps, and closed depressions associated with streams defeated by antitse scars.

The following factors have favored the development of the Peracalç Range lateral spread: (1) Thick soluble and ductile halite-bearing Triassic sediments are overlain by a brittle carbonate sequence affected by tectonic faults subparallel to the range front. The Triassic sediments are susceptible to ductile deformation, halokinosis, and rapid dissolution. (2) Lateral debudding and unloading of the Mesozoic sediments formed the Peracalç Range, once covered by a thick Oligocene sequence of conglomerates. Considering an overburden thickness of 450 m and a minimum density of 2 g/cm³, we can estimate a stress release due to differential erosion at the foot of Peracalç Range of ~9 MPa. (3) Massive amounts of water infiltrated through tensile fissures in the lateral spread, dominated by internal drainage. The incorporation of water contributes to reduce the mechanical strength of the Triassic formation by increasing the water content in the clayey sediments and rapidly dissolving the evaporites (Tran et al., 2011; Gutiérrez and Cooper, 2012). (4) There is evidence of loss of basal support and subsidence due to dissolution of evaporites within the Peracalç Range and at its foot.

The oldest numerical age obtained from the trenched graben deposits provides a minimum age of 45 ka for the lateral spread of Peracalç Range. Several lines of evidence indicate that this landslide has evolved retrogressively and that the highest rate of differential deformation is currently occurring in the head sector: (1) The upper graben system shows the largest and more fresh-looking open fissures, as well as the scarps with the lowest degree of degradation. (2) The infill of graben III, situated in an intermediate position, may reach 40 m, whereas the upper graben is largely devoid of sedimentary fill. (3) Fault segments show a higher degree of hard-linkage, suggesting an older age. (4) The drainage network in the upper part of the lateral spread is completely disrupted, whereas in the lower graben, there has been some adjustment between the new streams governed by the grabens and the preexisting transverse drainages.

According to our calculations, the horizontal separation (heave) related to dip-slip displacement on normal faults in the lateral spread of Peracalç has accumulated a cumulative extension of around 42–138 m. Considering this deformation range, which excludes the dilatation component on faults and fissures, and the minimum age of the slope movement (45 ka), we can tentatively estimate an average long-term horizontal displacement rate of 0.94–3.06 mm/yr. The active slope movement of Peracalç, with extensive bedrock exposure, offers excellent opportunities to investigate the kinematics of a large rock spread involving evaporite dissolution, using geodetic techniques such as GPS and DInSAR. The latter technique may provide average displacement rates and deformation time series with a high spatial resolution and accuracy, allowing the analysis of the spatial and temporal variability of the ground deformation (i.e., Furuya et al., 2007).

Average maximum height to length ratios \( H_{\text{max}}/L \) of 0.05 and 0.029 have been calculated for a limited number of downhll-facing and uphill-facing scarps in the lateral spread of Peracalç Range, respectively. The higher aspect ratios obtained for the downhill-facing scarps are most likely related to the larger throw on the master fault, which accommodate most of the vertical displacement. Grosfils and the preexisting transverse drainages. (2003) calculated a maximum displacement to fault length ratios \( D_{\text{max}}/L \) ratio of 0.045 for the master fault of Devils Lane graben (graben of Canyonsland, Utah), the only structure of this large-scale lateral spread for which information on the graben-fill thickness was available. Dawers et al. (1993), using data from Quaternary normal fault scarps in the Volcanic Tableland, California, and including faults for which lengths spanned three orders of magnitude, estimated maximum \( D_{\text{max}}/L \) of the order of 0.01. A similar \( D_{\text{max}}/L \) relationship is found for short faults (10–1000 m) combining several data sets (Cowie and Scholz, 1992; Schlische et al., 1996; Davis et al., 2005). The \( H_{\text{max}}/L \) ratios obtained for the scarps of the Peracalç lateral spread, which are a minimum estimate for the \( D_{\text{max}}/L \) ratio (aggradation and erosion in the footwall and hanging wall, respectively), suggest that gravitational fault scarps in lateral spreads tend to have higher aspect ratios than tectonic faults. For instance, fault scarp number 5 has a maximum height of 42 m. However, the maximum displacement on this fault is greater than 80 m, considering that the graben fill reaches at least 40 m, as indicated by the ERT profiles; i.e., \( D_{\text{max}}/L \) is twice as high as the \( H_{\text{max}}/L \) ratio. A similar finding was presented by Gutiérrez et al. (2012) analyzing fault scarps associated with a graben generated by interstratal dissolution of evaporites in the Iberian Range, Spain. The high aspect ratios of the investigated fault scarps may be related to two circumstances: (1) Vertical displacement on these faults is significantly higher than on tectonic faults of comparable length due to subsidence caused by interstratal karstification of the evaporites underlying the brittle plate. (2) These faults are gravitational structures merely a few hundred meters deep, whereas tectonic faults may go through the whole seismogenic crust. Several studies report on the higher aspect ratios of gravitational fault scarps compared to those of tectonic origin including sackung (McCalpin, 1999), landslides (Cotton, 1999), and faults scarps generated by evaporite dissolution collapse (Gutiérrez et al., 2012). On the other hand, the apparent vertical slip inferred from trench 1 (>0.5 mm/yr) suggests that gravitational faults may reach significantly higher displacement rates than tectonic faults in the investigated geotectonic setting (i.e., Ortuño et al., 2008). These criteria may be useful to elucidate whether active fault scarps correspond to tectonic structures (seismogenic) or to gravitational failures (nonseismogenic). Hell Creek fault, British Columbia, Canada, illustrates the relevance of this dilemma. This fault with prominent geomorphic expression is considered by the provincial utility (BC Hydro) to be the main seismogenic fault that could impact the Terzaghi Dam (McCleary et al., 1978; Ertsec, 1981), whereas the Geological Survey of Canada attributes this controversial structure to nonseismic gravity failure (Clague and Evans, 1994).

Lateral spreads are generally assumed to be extremely slow slope movements characterized by progressive displacement. However, the geometric relationships observed in trenches 1 and 2 provide evidence for episodic displacement. In trench 2, we have inferred a minimum of three to four faulting events, one of them recorded by the development of subaqueous slumps in lake deposits at around 45–42 ka. A recent faulting event has been identified in trench 1, the poorly constrained age (2.0–0.1 ka) of which overlaps the timing of the two most recent landsliding phases identified in Montcortés Lake deposits (Corella et al., 2011). The unexpected stick-slip kinematic behavior of this deep-seated slope movement may be related to subsidence caused by interstratal dissolution of the underlying halite-bearing evaporites. Although dissolution by groundwater flow operates in a continuous fashion, subsidence through brittle collapse may be a stepwise process occurring when the lack of basal support generated by karstification reaches a stability threshold. Dissolution processes may be enhanced by higher groundwater recharge due to higher precipitation and/or higher infiltration induced by surface faulting and fissuring. It may also increase due to erosional base-level lowering, involving an increase in the hydraulic gradient and favoring the deepening of groundwater flows. On the other hand, gravitational faulting events may be also triggered by seismic shaking. The Pyrenees is one of the most seismically active areas in Western Europe (Nicolas et al., 1990) and has been the site of destructive earthquakes in the past (e.g., Susagna et al., 1994; Olivera et al., 2006; Dubos- Sallée et al., 2007), some of them with \( M_w > 6 \). However, the
poorly constrained chronology of the inferred displacement events and the lack of numerically dated paleoseismic records in the area preclude exploration of this hypothesis.

An ellipsoidal evaporite collapse area, 1.6 km long, has been identified at the foot of Peraçà Range, affecting one of the lowest grabens of the lateral spread. Moreover, a complex 1.4-km-long graben with conspicuous fault scarps has been mapped in the Montcortès Lake area. This graben resulted from the collapse of the crest of the Bellera antiform, as a result of interstratal karstification of the halite-bearing evaporites of its core. Similar structures, but with a much larger scale, have been documented in the salt anticlines of Caneiros and Utah and Colorado (Cater, 1970; Doelling, 2000; Gutiérrez, 2004). These graben depressions with nested collapse sinkholes have deformed and aborted a paleo-drainage, expressed as wind gaps. The evaporite dissolution-collapse structures mapped at the foot of Peraçà Range support the idea that sub-surface due to interstratal evaporite karstification plays a significant role in the development of the Peraçà lateral spread.

The study area, situated astride two major structural units of the Pyrenees bounded by the Morreos back thrust, has received disparate structural units of the Pyrenees bounded by the Montcortès lateral spread. Moreover, a complex 1.4-km-long graben, affecting one of the lowest grabens of the Montcortès lateral spread. This case study suggests that, as a result of interstratal karstification, the Bellera antiform, as a result of interstratal karstification plays a significant role in the development of the Peraçà lateral spread.

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