Geoheritage (2023) 15:110
https://doi.org/10.1007/s12371-023-00878-x

ORIGINAL ARTICLE

Ebro Valley Gypsum Escarpment Near Zaragoza (NE Spain)—Combination of Highly Valuable Rock Record, Dynamic Geomorphosites and Associated Cultural Heritage

Piotr Migoń[1] · **Francisco Gutiérrez**[2] · **Carlotta Parenti**[3] · **Jorge Sevil**[2]

Received: 19 January 2023 / Accepted: 7 September 2023

Abstract
The 40-km-long escarpment of the Ebro River valley to the north-west of Zaragoza (NE Spain) is a remarkable geomorphological feature and an important geoheritage locality. Being 30 to 150 m high, the escarpment exposes a complex evaporate-clastic succession of Early to Middle Miocene age, with alternating gypsum and mudstone/marl units, as well as halite beds at depth. The escarpment is a highly dynamic feature, extensively shaped by mass movements of different types, especially in sections where it is directly undercut by the Ebro River. It also hosts abundant evidence of salt and gypsum dissolution, contributing to ongoing instability. Diverse cultural heritage is associated with the escarpment, including an ancient Celtiberian settlement, medieval castles, abandoned villages, rock-cut churches and dwellings and ancient salt mines. Twenty-six possible geosites are identified, with six considered as most representative described in detail. Opportunities to develop the area for geotourism are presented, but these will be associated with challenges of properly managing steep, dynamic and fragile terrain.

Keywords Gypsum · Landslides · Salt dissolution · Scarp retreat · Geotourism · Ebro Basin

Introduction

Geoheritage tends to be associated with the legacy of the past and certain particular values of the geological record, which are considered worth conservation (Brockx and Semeniuk 2007; Reynard and Brilha 2018). Hence, various efforts and projects are aimed at minimising the human impact at geoheritage sites, including their permanent closure to the general public. However, ongoing geodynamic processes may also affect the integrity of geoheritage sites, especially in unstable geomorphic settings such as high-mountain slopes or coastal cliffs (Smith 2005; Smith et al. 2011; García-Ortiz et al. 2014; Pelfini and Bollati 2014). In recent decades, several iconic landforms have been lost due to natural erosional processes, to name the Azure Window in the Gozo Island, Malta (Satariano and Gauci 2019) or the sandstone pinnacle of Mukurob in Nambia (Goudie and Viles 2015), whereas other localities are subject to rapid transformation, evidently accelerated by global climatic changes that cause glacier melting, permafrost decay, enhanced coastal retreat, and consequently, obliteration of old landforms and creation of new ones (Prosser et al. 2010; Gordon et al. 2022; Selmi et al. 2022). Although the loss of specific outcrops and landforms may be regrettable, these ongoing processes are increasingly perceived as an opportunity to learn about the dynamics of the Earth, to better inform environmental management practices, and to convey this knowledge to the general public (Hooke 1994; Reynard 2009; Pelfini and Bollati 2014; Migoń et al. 2019). Among such dynamic sites, those associated with landslides are of particular interest, since they show clearly the sheer magnitude of landscape change and are very relevant for the society (Selmi et al. 2019; Forno et al. 2022; Morino et al. 2022). These erosional processes may contribute to the persistence (or renewal) of sites of geological interest,

---

✉ Piotr Migoń
piotr.migon@uwr.edu.pl

[1] Institute of Geography and Regional Development, University of Wrocław, pl. Uniwersytecki 1, 50-137 Wrocław, Poland

[2] Department of Earth Sciences, Univeristy of Zaragoza, Pedro Cerbuna 12, 50009 Zaragoza, Spain

[3] Department of Chemistry and Earth Sciences, Università degli Studi di Modena e Reggio Emilia, Via Campi 103, 41125 Modena, Italy

sustaining exposure of rock outcrops which would be otherwise very difficult to maintain. In addition, these dynamics may have clear implications for the biotic world and bear on the preservation of cultural heritage, thus helping the holistic understanding of the environment according to the ABC (abiotic-biotic-cultural) concept (Coratza et al. 2016; Gordon 2018; Reynard and Giusti 2018; Pasková et al. 2021; Pijet-Migoń and Migoń 2022). Thus, a combination of "static" and "dynamic" geoheritage enhances the value of a locality and makes it a suitable place to develop various geo-education and geotourism activities.

In this paper, we intend to show how these various aspects of geoheritage combine and what opportunities for geo-education they offer along a nearly 40-km-long gypsum escarpment near the city of Zaragoza in north-eastern Spain. Gypsum rocks of Miocene age are widely exposed in the Ebro Basin, supporting tablelands and dissected uplands further and being concealed under alluvial deposits along the main river valleys (Gutiérrez-Elorza and Gutiérrez-Santolalla 1998) (Fig. 1). They are in fact a part of a more complex sedimentary succession, which also includes clastic and carbonate deposits, as well as other evaporites, including salt, halite and glauberite (Salvany et al. 2007). Some of the best exposures of this continental Miocene succession occur along the north-eastern margin of the Ebro valley close to Zaragoza. This area also hosts spectacular evidence of diverse hazardous geomorphological processes, both gradual and catastrophic (subsidence, mass movements, fluvial erosion), and various examples of utilization of natural resources by humans (defensive structures of various ages, salt mining, recreation). Although geology of the gypsiferous formations, associated landforms and engineering geology problems related to gypsum and salt dissolution have been long in research focus (e.g., Gutiérrez et al. 2015; Sevil et al. 2020), to our knowledge, the geoheritage and geotourism values of the area have not yet been explored and the geo-educational potential remains untapped. The intention here is to fill the gap and the structure of the paper will consequently include the following: (a) an overview of the geological record and geomorphological processes of the study area; (b) a qualitative assessment of geoheritage values; (c) presentation of added cultural values; and (d) exploration of geotourism and geo-educational opportunities, including presentation of geosites of various kinds along with different site-specific challenges.

The list (inventory) and characteristics of geosites emerged from extensive field work, which involved landform mapping and identification of geological units exposed across the study area, aided by interpretation of maps and digital terrain models. The recognition of potential geosites followed an expert evaluation of attributes of specific localities against a broader context of regional geoheritage and geodiversity, coupled with on-site assessment of accessibility and safety conditions. We deliberately avoided a semi-quantitative evaluation, despite its popularity in the literature, considering the following: (a) the existence of various assessment methods, with none being demonstrably better than others (Štrba et al. 2015; Mucivuna et al. 2019; Santos et al. 2019); (b) subjectivity evident in the selection of indicators, selection of criteria for individual indicators and weighting of each component of an assessment within each method; and (c) sufficient experience and knowledge of local conditions by the authors to indicate key localities which collectively would show the diversity of forms and processes in the best and accessible way. For the purpose of this paper, the escarpment is understood as a zone 2–3 km wide, which allows us to include several sites located above the escarpment rim, as well as observation points in the floodplain that offer panoramic views of the escarpment.

Study Area

The study area is located in north-eastern Spain, within the Ebro Cenozoic Basin, to the north-west from the city of Zaragoza (Fig. 1). The Ebro River flows in south-easterly direction, within a ca. 10-km-wide valley floor. However, the river itself is shifted towards the north-east, close to the escarpment that separates the valley floor from the adjacent upland of the Montes de Castejón. The escarpment—the main object of interest in this paper—can be traced as a distinctive geomorphological feature for nearly 40 km, between the northern tributary valleys of the Arba River (Tauste town) and the Gállego River (Juslibol suburb of Zaragoza city). It can be further subdivided into two sections. The north-western one, from Tauste to Castillo de Pola, is nowhere in direct contact with the river channel and the intervening floodplain is used for agricultural activities. The small town of Remolinos is located at the base of the escarpment. Further to the south-east, the river is in direct contact with the escarpment in several places, undercutting its basal part. The height of the escarpment varies from less than 30 m to more than 150 m.

Specific sites of geoheritage interest are scattered all along the length of the escarpment, although they tend to cluster in the north-western and south-eastern section, with only a few in the central sector (Fig. 1). This reflects access limitations. Off-limits military ground occurs immediately above the crest of the escarpment along most of its south-eastern section, whereas the base of the escarpment is either in direct contact with the river and hardly accessible or is located within private properties. However, the general architecture of the escarpment and its geology can be easily seen from the opposite river bank and a few viewpoint geosites (sensu Migoń and Pijet-Migoń (2017)) might be designated there.

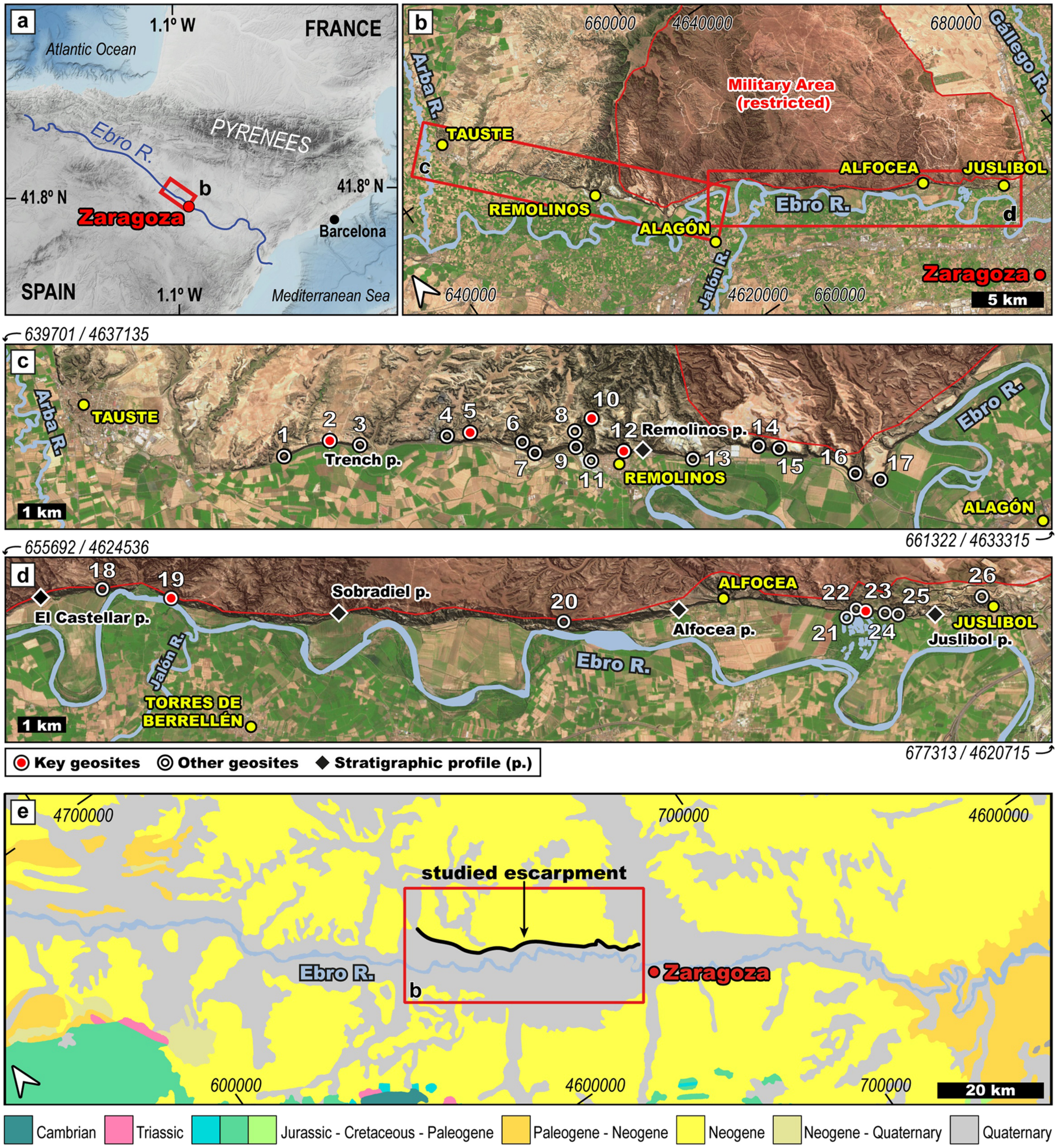

Fig. 1 Location map of the study area. **a** Setting of Zaragoza city within the Ebro Cenozoic Basin, south of the Pyrenees. **b** Satellite image (Sentinel-2, 2022) of the study area showing the Ebro River and its tributaries, the location of Zaragoza and the main towns and suburbs near the escarpment, and the extent of the restricted military area. The escarpment runs between Tauste and Juslibol, separating outcrops of Cenozoic sedimentary rocks in the north-east from the Quaternary alluvium in the Ebro River valley in the south-west. **c**–**d** Details of the, respectively, north-western and south-eastern halves of the gypsum escarpment between the Arba River (Tauste town) and the Gállego River (Juslibol suburb of Zaragoza city). They display the location of the sites of geoheritage interest (i.e., geosites) and of the base of the stratigraphic profiles gathered to construct the lithostratigraphic panel of Fig. 2. Coordinate system: ETRS89 zone 30 N. **e** Chronostratigraphic map to show geological context of the study area in the central sector of the Ebro Cenozoic Basin (source: Mapa de Edades Geológicas de la Península Ibérica, Baleares y Canarias a escala 1:1.000.000, IGME (1995))

Geological and Palaeoenvironmental Context and Background

The investigated area is located in the central sector of the Ebro Cenozoic Basin, which is the southern foreland basin of the Pyrenees. The Cenozoic sedimentary fill of the basin records an overall regressive succession, with an initial marine-sedimentation phase followed by continental sedimentation after the late Eocene (Priabonian) regression. During the late Oligocene and Miocene, the main depocentral area of this endorheic basin was located in the Zaragoza area, where extensive lakes with evaporite and carbonate sedimentation developed (Riba et al. 1983). In the late Miocene, the Ebro Basin was captured by a primitive Ebro River, initiating a headward-propagating change from endorheic to exorheic conditions, leading to the incision of the new drainage network into the sedimentary fill of the basin (Soria-Jaúregui et al. 2018; Benito-Calvo et al. 2022).

Miocene rocks exposed in the escarpment and the adjacent upland (Fig. 1e) belong to two main lacustrine formations. These are, from base to top (Quirantes 1978) (Fig. 2): (1) the evaporitic Zaragoza Formation; and (2) the carbonate Alcubierre Formation. The conformable contact between these formations records a relatively rapid change into more humid conditions that resulted in the transformation of a playa lake dominated by evaporitic sedimentation into a carbonate lake with more diluted waters (Arenas 1993). Arenas et al. (2001) ascribed the exposed evaporites of the Zaragoza Formation to the tectosedimentary unit UTS T5 (early Miocene), and the

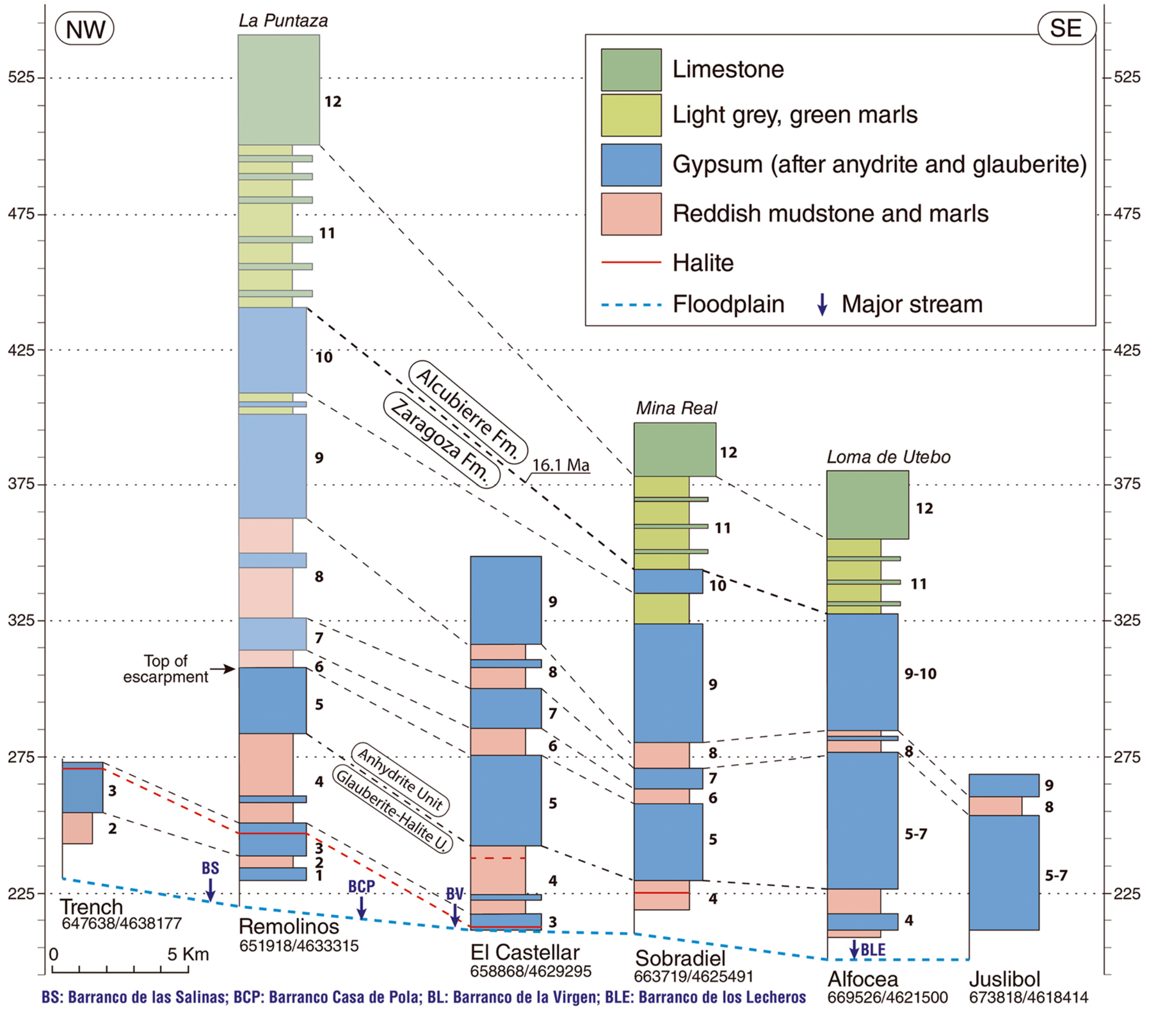

Fig. 2 Lithostratigraphic panel produced with six stratigraphic profiles measured with a DGPS at different sections of the Remolinos escarpment. The stratigraphic columns have been tied to the altitudinal scale considering the elevation at the base of the log. The position of the halite seams is based on the exploration of abandoned mines and the recognition of pointers of dissolution in the trench profile (dissolution residue, dissolution-collapse breccia). The formations and units differentiated by Quirantes (1978) and Salvany et al. (2007) are indicated, as well as the age of the boundary between the evaporitic and carbonate successions determined by magnetostratigraphic studies (Pérez-Rivarés et al. 2004, 2018)

overlying limestones and marls of the Alcubierre Formation to the lower part of unit UTS T6 (Middle Miocene). According to deep borehole data, the evaporitic Zaragoza Formation has a total thickness of around 600 m, and only the upper part of the succession is exposed at the surface (Torrescusa and Klimowitz 1990). The formation, in unweathered zones beneath the surface, consists of anhydrite, halite and glauberite with intercalations of mudstone and marl units. However, in outcrops, it displays secondary gypsum with intercalations of mudstones and marls. In these weathered zones that may reach as much as 100 m deep, halite beds have been dissolved and the anhydrite and glauberite have been transformed into gypsum (gypsification) by hydration and incongruent dissolution, respectively (Salvany 2009). Four lithostratigraphic units are distinguished in the Zaragoza Formation, from base to top: (1) basal marl and anhydrite unit; (2) halite unit, with halite-dominated successions us much as 75 m thick; (3) glauberite-halite unit; and (4) anhydrite unit (Salvany et al. 2007). Only the two upper units are crop out in the escarpment.

The rocks exposed in the north-western part of the escarpment mostly correspond to the glauberite-halite unit (units 1 to 4 in Fig. 2) and include economically valuable packages of halite (NaCl) and glauberite ($Na_2Ca\ (SO4)_2$). Boreholes carried for sodium sulphate exploration south of Zaragoza city revealed a glauberite-rich succession 100 m thick (i.e., glauberite-halite unit) with glauberite packages in the subsurface as much as 30 m in thickness, which is considered to be one of the most important documented glauberite deposits worldwide (Salvany 2009). Halite beds have been exploited by underground mines in the Remolinos area for over more than one millennium (Fig. 3). According to borehole data (Mina Real borehole; Ibérica de Sales pers. comm.), the halite package is 8.7 m thick and is underlain by a section 17 m thick dominated by macrocrystalline glauberite with halite cement (García-Veigas et al. 1994). This glauberite succession grades into secondary gypsum towards the surface, which locally displays pseudomorphic gypsum after glauberite, showing the typical monoclinic prisms of the latter mineral.

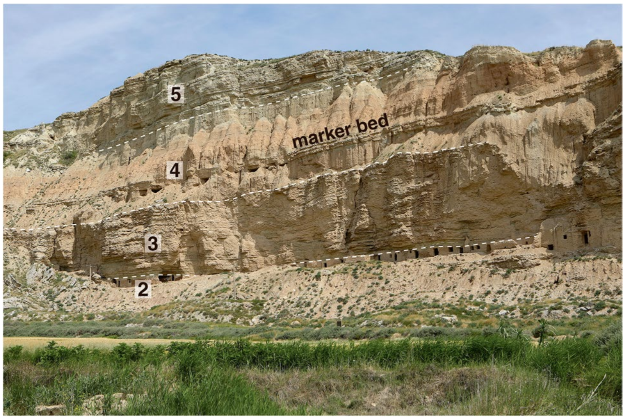

Fig. 3 Section of the escarpment known as “the balcony”, south-east of the village of Remolinos. The unexposed mined halite package is situated within the upper part of unit 3, below 4 m of secondary gypsum. Note marker gypsum bed intercalated in unit 4. Mine entrances were excavated at the base of this accessible and resistant gypsum package. Abandoned dwellings of miners excavated in mudstones of unit 2

Further to the south-east (from El Castellar to Juslibol), most of the escarpment is built of rocks belonging to the anhydrite unit (units 5 to 9 in Fig. 2), with the glauberite-halite unit exposed in the basal part. Hence, thick packages of secondary gypsum are exposed within scarp, whereas the underlying mudstones and marls are largely concealed under extensive talus and landslide deposits. The escarpment area also includes outcrops of paleosinkholes most probably formed by localized interstratal dissolution of salt and filled by collapsed and/or sagged Miocene sediments. These features, also known from elsewhere in the Zaragoza region (Guerrero et al. 2013), typically reach tens of metres across. In the south-eastern sector, in Juslibol area, the gypsum bedrock is covered by deposits of a terrace at the confluence of the Ebro and Gállego rivers, situated around 105 m above the valley floor (Fig. 1). This terrace deposit with growth stratal geometries reaches more than 60 m thick and fills a synsedimentary evaporite dissolution-induced basin ascribed to the early Pleistocene (Benito et al. 1998, 2010).

Geomorphology and Geomorphological Evolution of the Escarpment

The Ebro River escarpment in the study area is remarkably straight, without embayments penetrating into the upland and with only a few tributary valleys graded to the floodplain level of the Ebro. The height of the escarpment varies from less than 30 m at the north-western extremity through ca. 100 m above the village of Remolinos, more than 150 m between El Castellar and Alfocea, and 50–100 m around Juslibol. The altitude of the valley floor descends from 230 to 190 m asl, whereas the highest spot above the escarpment reaches ca. 375 m asl. The topography of the escarpment itself is complex, although rock cliffs in gypsum strata are a unifying theme all along the strike (Fig. 4a, b). Thus, in a few sections, especially at undercut meander bends, a precipitous slope connects the escarpment base with the upland surface (Fig. 4c). More common, however, are segmented slopes consisting of colluvial deposits in the lower part and one or more levels of gypsum and/or limestone cliffs above, separated by less inclined, but still fairly steep (> 30°) segments on soft units. The contact with the upland surface may be sharp or gradual, within a broad slope convexity. The topography above the escarpment rim varies too, but in general, the upland surface tends to be undulating, with broad

Fig. 4 Geomorphic diversity of the gypsum escarpment along the Ebro River to the north-west of Zaragoza. **a** Simple low scarp, with one gypsum unit (top) overlying marls and clays (NW end of the escarpment). **b** Composite section of the escarpment near Remolinos, with three separate gypsum units (indicated by arrows). **c** Direct undercutting of the escarpment by the Ebro River, with evidence of mass movements (head scarps, slid blocks, talus)—near the abandoned village of El Castellar. **d** Stratigraphically controlled stepped topography of the upland above the escarpment near Remolinos, steep slopes occur on gypsum units. **e** Deeply entrenched valley in the gypsum upland next to the escarpment, near El Castellar

flat-floored and trough valleys and repetitive, stratigraphy-controlled topographic steps (Fig. 4d). In a few areas close to the escarpment, the upland is deeply dissected by minor tributaries of the Ebro, forming an intricate pattern of canyons and slots (Fig. 4e). Some of these fluvial incisions are graded to the floodplain level, but others are not and appear as hanging valleys in the middle or top parts of the escarpment (Fig. 5). As a rule, valleys with large catchment areas tend to be graded.

In numerous places, mass movements modified the structure-controlled escarpment relief and they account for more complex hillslope topography (Fig. 6). Geomorphic mapping revealed considerable diversity of slope movements, reflecting primarily specific local geological controls (Gutiérrez et al. 2023). They include rotational slides along curved failure planes with backtilting of the displaced mass and short-runout rock-slope collapses, both involving more than one lithostratigraphic unit, as well as minor rockfalls, backward and forward topples. Fresh open cracks and scarps along the escarpment rim indicate ongoing instability (Fig. 6a). Rotational slides occur wherever mechanically weak mudstone and marl units underlie thick gypsum packages. The largest are around 500 m wide and consist of vertical head scarps, some many tens of metres high and one or more back-tilted slid blocks. Because the mechanical strength of the gypsum packages is rather low, the internal structure of the displaced blocks is characterised by mega-breccias, with angular gypsum blocks of different size embedded within mudstone/marl matrix. Rock-slope collapses also result in the origin of vertical head scarps, but their depositional parts are steep cones of poorly sorted debris (Fig. 6b). Minor rockfalls typically affect gypsum overhangs above slope recesses due to more efficient weathering and seepage along the contact between gypsum packages above and mudstones and marls below, resulting in chaotic boulder piles and small boulder trains (Fig. 6c).

Apart from geological control, the importance of fluvial undercutting in promoting large-scale slope instability is evident (Fig. 6b). Nearly half of the length of the escarpment between Castillo de Pola and Juslibol, where the river directly interacts with the escarpment, is affected by landslides (Gutiérrez et al. 2023), whereas rockfalls and small collapses dominate the north-western section, towards Remolinos and Tauste. Numerous abandoned meander loops and oxbow lakes within the Ebro floodplain indicate long history of channel migration, cut-offs and avulsions, and hence interactions with the escarpment in different places at variable times (Peña-Monné et al. 2021).

Although apparently not dominant, karstic processes facilitated by the presence of halite, glauberite and gypsum in the bedrock have also played some role in the geomorphic evolution of the escarpment. Near-surface interstratal salt dissolution results in the subsidence of the overlying strata, condensing the stratigraphic succession and reducing its mechanical strength, which in turns favours slope instability processes. Collapse sinkholes occur associated with gypsum outcrops, although it is not always clear whether they originated through roof collapses in natural cavities or abandoned salt mines. The retreating escarpment face has also exposed cross-sections of paleosinkholes in gypsum, filled with foundered bedrock (i.e., breccia pipes, sagged beds) and dissolution residues.

Geoheritage Qualitative Assessment

Rock Record

The key geoheritage value of the Tauste—Juslibol escarpment in terms of rock record lies in an excellent, almost uninterrupted, continuous exposure of the Miocene continental sedimentary fill of the Ebro Cenozoic Basin, spanning ca. 4 million years (Pérez-Rivarés et al. 2004, 2018) and revealing more than 200 m of the total thickness of the succession. The outcrops are dominated by alternating gypsum and mudstone/marl packages of variable thickness, recording multiple expansion-contraction and progradation-retrogradation cycles in the laterally connected playa and distal alluvial fan depositional environments. However, the exposed gypsum is a secondary deposit, whereas the unweathered

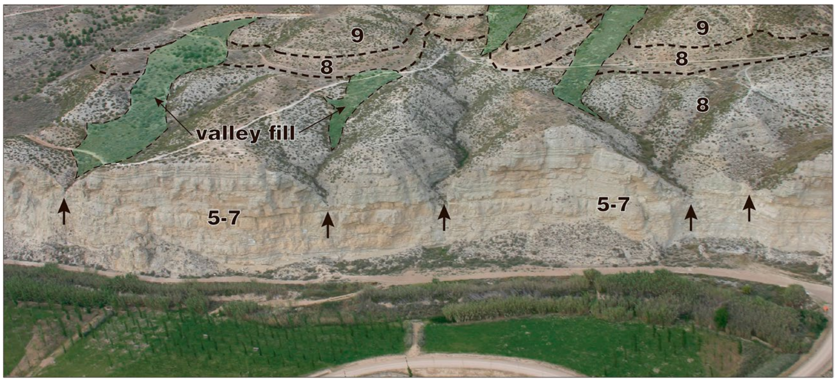

Fig. 5 Section of the gypsum escarpment east of the Juslibol oxbow lake with low-order hanging valleys (arrowed) carved in a thick gypsum package (unit 5–7). Valley fills marked with green polygons

Fig. 6 Diversity of mass movements along the Ebro valley escarpment. **a** Upper part of a large rotational slide, with a slid block partitioned by deep trenches. **b** Site of a large rock-slope collapse triggered by direct fluvial undercutting, with depositional cone below vertical head scar (El Castellar locality). **c** Minor rockfall from a gypsum bed (indicated by broken lines), resulting in irregular pile of large boulders (yellow dotted line). **d** Cliffs in slightly cemented Quaternary alluvial fan gravels, with a back-toppled rock tower in the centre (perched alluvial fan of the Barranco de Pola)

evaporites consist of anhydrite, halite and glauberite. Hydration of anhydrite and incongruent dissolution of glauberite led to the origin of gypsum. Details of geological history of the Miocene succession exposed along the escarpment are provided in numerous publications (e.g., Arenas et al. 2001; Salvany et al. 2007; Pérez-Rivarés et al. 2018).

Exposures of halite and glauberite are extremely rare in nature due to their high solubility, with equilibrium solubilities in pure water and normal conditions of 356 gr/L and 118 gr/L, respectively, in contrast with the solubility of gypsum of 2.6 gr/L (De Waele and Gutiérrez 2022). However, within the Ebro valley escarpment around Remolinos, there occur numerous abandoned mines that provide access to halite beds in subsurface conditions. It can be observed that halite packages rapidly pinch out towards the surface, grading into a dissolution residue overlain by deformed supra-salt strata (Fig. 6a). This residue, locally as much as 8 m thick, typically consists of massive dark brown clay with calcium sulphate nodules, representing the less soluble components of the salt deposit, dark grey clay partings and anhydrite nodules embedded in the salt. Saline efflorescences provide evidence of current salt dissolution within the rock massif, seepage of the resulting brines towards the surface and evaporative precipitation. Despite the rapidity of salt dissolution, an exceptional exposure of a halite bed can be observed at a location where the foot of the escarpment has been rapidly undermined by erosion (30T 661777/4626794) (Fig. 6b). Evidence of halite deposition in the Miocene is also observed in the clay unit 2 in the form of decimetre-scale cubic hopper crystals of pseudomorphic gypsum after halite, embedded into red mudstone.

Landforms and Landform Patterns

Considerable geoheritage values of the Ebro River escarpment near Zaragoza arise from the combination of several factors:

properties of the landforms themselves and their associations (intrinsic values), their excellent visibility due to semi-arid climate and scarce vegetation cover and generally good access. Geomorphology of the escarpment is evaluated as outstanding for the following reasons. First, the escarpment itself, almost 40 km long and without any major interruption by large fluvial valleys, marked by nearly continuous vertical cliffs, is a rare geomorphic feature (De Waele and Gutiérrez 2022). Although gypsum uplands are widespread in the central sector of the Ebro Basin, none terminates in an escarpment of comparable length height or sharpness. Second, its value is enhanced by the along-strike diversity of height and slope form, reflecting differences in lithostratigraphy, distance from the river and the geomorphic imprint of mass movements. Thus, the role of various controls on the development of escarpments can be illustrated. Third, the escarpment is a dynamic feature, subject to ongoing retreat due to mass movements and weathering, and segmentation by fluvial dissection, with evidence of all these processes clearly seen. Of particular importance are different patterns of slope evolution in sections experiencing contemporary fluvial undercutting and those disconnected from the river (i.e., variable channel-hillslope coupling). Fourth, vertical cliffs present along most of the escarpment length show various geological features (sedimentary architecture, post-sedimentary deformations, paleokarstic features), allowing one to trace various relationships between geology and landforms.

Extraordinary hillslope morphology of the escarpment is complemented by superlative fluvial geoheritage represented by the adjacent Ebro valley and its tributaries. The meandering Ebro River channel near Zaragoza is known for its numerous shifts across the floodplain, evidenced by multiple generations of abandoned meanders, oxbow lakes, dead arms of the river and gravelly point bars. Reasons for the fluvial dynamics reside in both climate- and discharge-related fluvial events, and probably also channel adjustments to dissolution-induced subsidence in the floodplain (Benito et al. 1998; Guerrero et al. 2013; Peña-Monné et al. 2021). In addition, patterns and timings of late Holocene aggradation and incision have been recognized in a small tributary valley dissecting the gypsum escarpment, Barranco de la Virgen (Constante et al. 2010), helping also to understand socio-economic consequences of fluvial dynamics.

Cultural Heritage

Apart from considerable geodiversity and multiple geoheritage values, rich cultural heritage spanning more than 2000 years is associated with the gypsum escarpment, adding to the value of the area and increasing its attractiveness for geotourism. In fact, most of this cultural heritage is closely linked with geology, landforms and landscape dynamics—an aspect increasingly emphasized nowadays (Del Monte et al. 2013; Coratza et al. 2016; Pasková et al. 2021; Pijet-Migoń and Migoń 2022). Three main interrelated elements are defensive structures of various ages, built on top of the escarpment, settlements (existing and abandoned) with sites of historical interest and various remnants of salt mining and processing. In contrast to the next, down-valley section of the gypsum escarpment to the south-east of Zaragoza, no remnants from the Civil War exist in the study area, as it lacked strategic importance being far from the main communication lines.

Defensive Structures and Settlements

The oldest defensive structure in the study area is Valdetaus—a remnant of a Celtiberian (pre-Roman) settlement at the westernmost part of the escarpment (see Table 1, no. 1 and Supplementary materials). Although the preserved evidence is scarce and limited to rather inconspicuous foundations of a few houses exposed during archaeological excavations, the locality helps to understand the choices made to establish a place of living in the ancient times. Sitting atop of the escarpment, on a spur between the front face and a steep side of a valley draining the hinterland, it allowed the inhabitants to have both easy access to fertile land in the valley floors, mainly the Ebro valley itself, and good vantage point over a large area. The base of the spur was additionally protected by a purposefully dug trench 2–3 m deep, ca. 10 m wide and more than 150 m long.

The strategic significance of the escarpment, towering above the fertile lands in the Ebro valley and overlooking an important communication route from Zaragoza along the river to Navarra, was clearly appreciated during the times of Christian Reconquest of Aragón and after that. Small castles were built on top of the scarp, such as Pola to the east of Remolinos (see Table 1, no. 16 and Supplementary materials), Miranda to the west of Juslibol and one above Juslibol itself. Remnants of watchtowers support walls and underground rooms survived. The castle of Pola overlooked a small settlement, which was abandoned as early as in the seventeenth century. However, among the castles and associated settlements, the most important was El Castellar and its history will be presented in more detail, as it nicely illustrates the underpinning role of geodiversity in the cultural heritage context.

The former village of El Castellar is situated at a strategic location for both defensive and communication purposes, lying at the confluence of the Jalón and Ebro rivers and at the extreme of a major transhumance route that connects the Pyrenees with the Ebro valley, via the Barranco de la Virgen. It has a poorly known history, but it recently awoke interest because it was the birthplace of Juan Pablo Bonet (1573–1607), an internationally recognized pedagogue who wrote the first book on deaf-mute teaching. According to

Table 1 Geosites along the gypsum escarpment. The six key geosites are highlighted in bold. For location, see Fig. 1

No.	Name/description	Principal interest	Secondary interest	Access
1	Valdetaus—Celtiberian settlement	Use of terrain configuration for defensive purposes	Anthropic landforms, minor paleosinkholes	Unrestricted—short walk
2	**Trench**	**Lithology and cross-section of gravitational rock-mass deformation**		**Unrestricted—short walk**
3	Open cracks next to trench	Mass movements—initial phase		Unrestricted —short walk
4	Panoramic view of the upland (NW of Remolinos)	Stratigraphically-controlled landscape		Unrestricted—short walk
5	**Sinkhole field**	**Karst processes**		**Unrestricted—longer walk**
6	Fluvial canyon	Rock-slope failures and sedimentary record of falls into the channel		Unrestricted—short walk
7	Backtilted gypsum tower	Mass movements		Observation from the roadside
8	Viewpoint above Remolinos	Geomorphological Landscape—from floodplain to upland		Unrestricted—longer Walk
9	Ramp road next to Remolinos	Large paleosinkholes		Unrestricted—short walk
10	**Barranco de las Salinas**	**Salt mines**	**Bedrock channels along access path, evaporate sediments**	**Unrestricted—longer walk**
11	Salt pans in Remolinos	Salt processing		Unrestricted—direct access by car
12	**Rock-hewn church in Remolinos and viewing point**	**Geomorphological landscape—from floodplain to upland**	**Cultural heritage (rock church), land use**	**Unrestricted—short walk**
13	Rock fall and road re-alignment at Remolinos	Geomorphological hazards		Unrestricted—direct access by car
14	Outcrop of three gypsum beds	Geology of Miocene succession	Mass movements	Observation from the roadside; optional short walk
15	Undercutting of gypsum beds and minor falls	Rock-controlled mass movements		Observation from the roadside; optional short walk
16	Castillo de Pola—viewing point	Geomorphological landscape—from floodplain to upland	Historical defensive structure	Unrestricted—longer walk
17	Quaternary gravel deposits	Stepped sequence of alluvial fan morpho-sedimentary units	Mass movements	Unrestricted—short walk
18	Santa Inés landslides	Mass movements		Only to see from afar (private property)
19	**El Castellar**	**Mass movements in direct contact with the river**	**Historical defensive structure, abandoned village**	**Viewpoint on the opposite river bank (military training area)**
20	Alfocea landslides	Landslides in direct contact with the river	Fluvial processes in meandering river	Viewpoint on the opposite river bank (military training area)
21	Juslibol oxbow lake	Fluvial geomorphology and channel change	Ecology; former resource exploitation	Unrestricted—longer walk
22	Juslibol—viewing point on top of the escarpment	Geomorphological landscape—from floodplain to upland	Historical defensive structure; land use	Unrestricted—longer walk
23	**Juslibol—paleosinkhole**	**Karst processes**	**Erosion processes**	**Unrestricted—longer walk**
24	Juslibol—rock-slope collapses	Mass movements		Unrestricted—longer walk
25	Juslibol—hanging valleys	Fluvial erosion		Unrestricted—longer walk
26	Juslibol—deformed terrace deposits	Fluvial deposition and effects of ground subsidence		Unrestricted—longer walk

Note: designation of walks as “short” (less than 15 min one way) or “longer” (> 15 min) reflects the distance of a respective geosite from a place, which can be reached by car on an ordinary road

Gascón Ricao (2007), the oldest written reference to El Castellar dates back to 1091. However, the site was likely occupied much earlier, possibly already in pre-Roman times by Celtiberian tribes. Later, El Castellar was probably the site of the Castra Aelia, a settlement mentioned by Tito Livio, where Quinto Sertorio established a camp around 77 BC during the first Civil War of the Roman Republic (Gascón Ricao 2007). Younger remains from the Imperial epoch provide evidence for the presence of a Roman settlement, probably related to the exploitation and trading of salt from the nearby mines. In the Middle Ages, after the Reconquest, El Castellar experienced significant expansion and became a settlement with hundreds of inhabitants and four churches or chapels (Palasí 1988).

The village was probably largely destroyed in 1466 in a struggle between feudal warlords (Asso 1798). A census from 1543 indicated 17 occupied homes in El Castellar and according to parochial documents, the last inhabitants moved down peacefully to Torres de Berrellén village in 1574. In 1585, the village was reported as already in ruins and its churches were soon after closed to worship because of their ruinous state. The reasons of gradual abandonment are however not entirely clear. Although historians emphasize social and economic factors (Gascón Ricao 2007), the environmental ones could have been as much important. These would include the following: (1) lack of drinkable water; (2) destruction of human structures by landsliding; and (3) potential lateral shifts in the Ebro River path, with the latter two spatially and temporarily associated. It seems reasonable to assume that at the start of the Christian settlement in the twelfth century, the channel of the Ebro River was located further to the south, and the inhabitants of El Castellar had direct access to fertile land along the northern bank of the river. Assuming the present-day configuration of geomorphology, with the village site directly overlooking the river and steep, infertile gypsum upland above, there would be no arable area to sustain the local population. At some stage, the highly unstable river channel shifted to the foot of the escarpment, blocking direct access to crop fields in the floodplain and triggering escarpment collapses by fluvial undercutting. Dating of aggradation and incision phases in the tributary drainage, within which the village of El Castellar was located (Constante et al. 2010), suggests that the shift of the Ebro channel towards the escarpment occurred at around 1500 AD. After the shift of the Ebro River channel to the north bank, landslides have likely become much more frequent due to escarpment undercutting. Much of the castle of El Castellar was destroyed in successive landslides, so the only disconnected remnants now exist at the very edge of the escarpment.

Nowadays, only three settlements exist at the foot of the escarpment, Remolinos in the north-west, Alfocea and Juslibol in the south-east, the latter being a part of the city of Zaragoza. This paucity of settlements is partly related to the proximity of the Ebro River to the escarpment in the southern part of the area, restricting the areas considered safe in terms of flood hazards, leaving little space for the development of cultivated lands and hampering along-river communication, and partly to the presence of a large military training area of San Gregorio, which includes all the grounds above it, from Juslibol to the Casa de Pola Barranco (Fig. 1). The village of Remolinos existed as early as in the twelfth century and its economy was based on salt mining and farming the fertile floodplain of the Ebro River. It has several objects of historical interest, such as the late eighteenth century main village church with paintings by Francisco de Goya, the rock-hewn chapel of Santo Cristo de la Cueva dated to the fourteenth century (see Table 1, no. 12), remains of rock-cut dwellings within the gypsum cliffs (Fig. 3), salt evaporation ponds and numerous entrances to old salt mines, some partially or completely collapsed.

Salt Mining

Salt was probably mined in the vicinity of Remolinos already in the Roman times, but the oldest account was given in the tenth century by the Persian writer Al-Razi (Calvo 2001). Later in the Middle Ages, the mines around Remolinos started to be named regularly in the legal documentation of the Crown of Aragón. Between the fourteenth and sixteenth centuries, the Crown's monopoly over the process of salt extraction and processing increased, albeit by means of leases. The salt mines were not regulated by mining laws until 1849, so before that, there was no obligation for the mines to be managed by a mining engineer, which meant that, as can be seen today, the workings and accesses lacked any order. In 1869, salt extraction, processing and distribution were liberalised and in 1888, in addition to the two main state-owned mines namely "La Real" and "Torres de Berrellén", there were already more than a hundred private mining concessions in the area. In the 1920s, the level of corporate concentration and salt production increased despite only eight mines being active (i.e., "El Ángel", "El Balcón", "La Real", "La Veneciana", "Tomasa", "El Gallo", "Juan José" and "Rectificación de la Encarnación"). From that time onwards, all the main mining concessions in the area were controlled by "Ibérica de Sales". In 1989, salt mining in "La Real" ceased and from the 1990s to the present, all the salt extraction has taken place in "María del Carmen" mine. The extraction is conducted by the room-and-pillar method. Then, the mineral is classified according to quality to be used either for road de-icing or production of edible salt by means of the evaporation ponds located between Tauste and Torres de Berrellén (Calvo 2008).

Nowadays, remnants of salt mining are abundant around Remolinos and include abandoned underground mines in numerous canyons, some of which can be accessed, ruins of mine buildings next to entrances to galleries, openings of long collapsed mine adits, trenches and causeways used to transport salt from the mines to processing plants, ruins of processing facilities and storage buildings, rock-cut dwellings of miners' families and evaporation ponds located both on the plateau above the escarpment and at the base of it.

Potential for Geotourism and Geo-Interpretation

Geosites

Geosites identified along the gypsum escarpment vary in terms of content and accessibility. Some are specific localities which are either rock outcrops or medium-size/minor landforms (or both at the same time), available to inspect and examine closely, at a maximum on-site interaction. Others are localities, which for various reasons are difficult to be approached closely, but are sufficiently well exposed to be seen from a relatively close distance. The third group are panoramic viewing points, which allow the visitors to see wider sections of the escarpment and its broader context (viewpoint geosites—Migoń and Pijet-Migoń (2017) or geodiversity sites—Brilha (2018)). Finally, there are longer road/dirt track sections enabling one to follow specific geological and geomorphological features for some distance while moving by car or bike (or less conveniently, on foot). However, in the following text, they are all considered simply as "geosites".

Leaving the last group aside, the inventory includes 26 localities along the escarpment (Fig. 1, Table 1). They comprise six key geosites, identified as such based on expert knowledge of the authors, which together give an overview of the geoheritage of the area without missing any of its key components and 20 sites of secondary (supplementary) interest. The key geosites have the highest scientific value and several of them are associated with significant cultural heritage. From the practical geotourism perspective, they can be visited in 1 day, following a specific itinerary. The other sites may also have considerable geoheritage value, but are less convenient to visit, or they illustrate similar themes as the key geosites, but in a different section of the escarpment. The key geosites will be characterised in more detail below, whereas the remaining ones are only listed in the table, with more information and photographs provided in the supplementary materials (Supplement A).

Here, it might be useful to note that a term "complex geosite" is also present in the literature (e.g., Forno et al. 2022), emerging from "geomorphological landscapes" (Reynard 2005), in which recognition and selection of individual geosites might be difficult. The term is applied to large areas, especially in high mountains, shaped by one overarching geological or geomorphological process such as glacial erosion or deep-seated gravitational slope deformation (DSGSD). Would it be helpful to consider the 40-km-long escarpment in a similar way, as one complex geosite? Whereas it is true that the escarpment shows spatial continuity and its geology and geomorphological evolution will be fully understood if various localities are examined. Individual localities presented here are not functionally connected and understanding of one does not necessarily require consideration of another one (unlike the DSGSD areas). Moreover, the concept of "complex geosite" that covers a few tens of kilometres concept might work well for science-based evaluation, but is less practical from conservation and management point of view, especially if a such "complex geosite" extends over administrative boundaries Fig. 7.

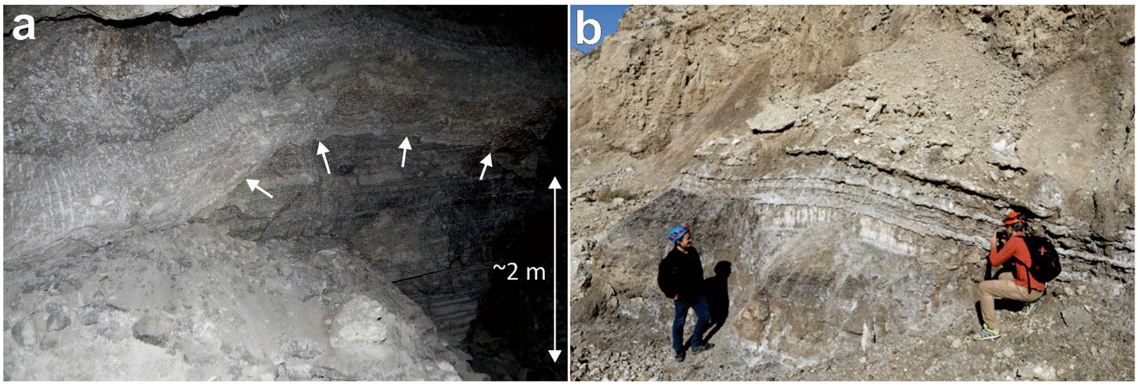

Fig. 7 Subsurface and surface exposures of halite. **a** Sharp lateral and vertical contact (arrows) between the layered halite package in unit 3 and the dissolution residue made up of clay and calcium sulphate nodules. The contact corresponds to the dissolution front that progresses downwards and laterally into the salt body. Note the monoclinal fold in the residue draping the sloping dissolution surface. **b** Exceptional halite exposure within unit 4 in a section of the escarpment affected by rapid retreat

Trench in Gypsum and Glauberite Sediments (Site no. 2)

Although gypsum and clastic sediments are exposed all along the escarpment, the trench located about 6 km to the north-west from Remolinos, next to the road to Tauste and nearly perpendicular to it (Fig. 1). Excavated for the construction of a water pipe, it gives a unique opportunity to complement the usual front view with a transverse view. As such, it shows the deformation style of the sedimentary succession in a cross-section near the face of the escarpment (Figs. 8 and 9). The trench is 130 m long, 55 m wide and up to 40 m deep in total. The trench walls expose two units of the Zaragoza Formation (units 2 and 3). The lower part is made of mudstones, marls and glauberite beds of unit 2 (see Fig. 2), whereas the upper part is made of a thick gypsum package derived from glauberite, testified by abundant pseudomorphic crystals. Decimetre-scale hopper crystals of pseudomorphic gypsum after halite also occur in unit 2, embedded into red mudstone. They can be attributed to precipitation of halite within soft deposits of saline mud flats from interstitial brines affected by evaporative pumping and subsequent diagenetic replacement by gypsum. Na-sulphate efflorescences (mirabilite?) at the base of trench walls indicate ongoing glauberite dissolution and re-precipitation (Fig. 8b, 9). A salt bed used to occur within the gypsum bed, but was completely dissolved, resulting in the brecciation of the topmost part of the gypsum package (unit 3).

From geomorphological perspective, the most interesting part of the trench wall is a ca. 50 m wide zone immediately beyond the escarpment, which records brittle deformation of the sedimentary succession, clearly marked by vertically offset beds (Fig. 8a, 9). It consists of two grabens and an intervening horst, separated by faults and additionally cut by open solutional features. The NE graben shows some backtilting (ca. 5°) and an arcuate cavity related to an internal collapse attributable to subsurface glauberite dissolution. The fissures were subsequently filled by soft gypsiferous silts with angular gypsum clasts. Interestingly, there is no vertical offset across the NE graben and that of the SW graben is very limited, indicating that the deformation is dominated by subsidence rather than outward displacement. These downthrown blocks are expressed in the landscape as narrow rock benches parallel to the escarpment, separated by fault scarps and open cracks (Fig. 8c, d). Thus, the trench shows effects of differential subsidence accommodated by gravitational faulting, primarily induced by interstratal glauberite dissolution and consequent removal of basal support, enhanced by topographic factor (i.e., groundwater discharge, unloading). A short walk along the rim of the escarpment towards south-east would reveal several other downthrown and disintegrated gypsum blocks, with roofed cavities in between, likely also generated by combination of interstratal dissolution and outward mass movement.

Sinkhole Field (Site no. 5)

The sinkhole field is located within the gypsum upland, but close to the rim of the escarpment, 3 km to NNW from Remolinos (Figs. 10 and 11). It occurs in a NNW-directed flat-bottomed valley carved into units 3 and 4 that has been disrupted by sinkholes. A total of eight collapse sinkholes can be clearly observed, with the most impressive one being 60 m long and up to 50 m wide, with the depth of c 15 m. The three bedrock collapse sinkholes located in elevated areas on the north-west margin of the valley puncture unit 4, which is made up of mudstone with a distinctive gypsum intercalation. The NW sinkhole of this group looks fresh, whereas the other two have a degraded appearance. The other five sinkholes are active cover and bedrock collapse sinkholes that affect unit 3 and the overlying alluvium of the valley fill. The two collapse sinkholes situated on the south-west side are nested within a relatively large sagging basin with vaguely defined edges. The three central sinkholes form an alignment attributable to the discontinuous collapse of a NNW-oriented cave passage. These collapses have disrupted an old drainage, partitioning it into an upstream blind valley that flows into sinkholes, acting as ponors (swallow holes) and a downstream beheaded valley. The two southern sinkholes are connected by the remnant of a cave section below a rock bride. On the north-west edge of the central sinkhole, there is a blind passage a few metres long related to the collapse of gypsum in unit 3. The breakdown affects strata situated below the now dissolved halite bed located in the upper part of unit 3. This evidence, together with the position of the sinkhole floors below that of the former halite bed, indicates that the sinkholes cannot be related to either halite dissolution or salt mining. Instead, it is most probably related to gypsum and/or glauberite dissolution focused at the base of unit 3, underlain by the impervious marls and mudstone of unit 2. This interpretation is supported by the fact that the nearby Ojo Salado saline springs, located 350 m to the south-east, emerge at this stratigraphic contact, functioning as an inception horizon. In the central sinkhole of the alignment, there is an exposure several metres thick of an old sinkhole fill, attesting for a complex history of sinkhole filling and reactivation. The cliffed and locally overhanging margin of this depression displays abundant evidence of instability, including unloading cracks and fresh rock falls. This depression also shows a recent nested collapse sinkholes. This geomorphic evidence reveals ongoing expansion and deepening of this active sinkhole, adding to its value as a geosite.

Fig. 8 Trench near Remolinos (site no. 2). **a** General view of the near-marginal deformation zone with broken gypsum beds, grabens and dissolution features (note people for scale at the base of the trench wall). **b** Extensive white efflorescences of sodium sulphate (mirabilite?) in the lower part of mudstone/marl unit. **c** Deep open cracks in the vicinity of the trench indicate ongoing instability of the escarpment. **d** Downthrown blocks provide evidence of other collapses induced by lack of vertical and lateral support

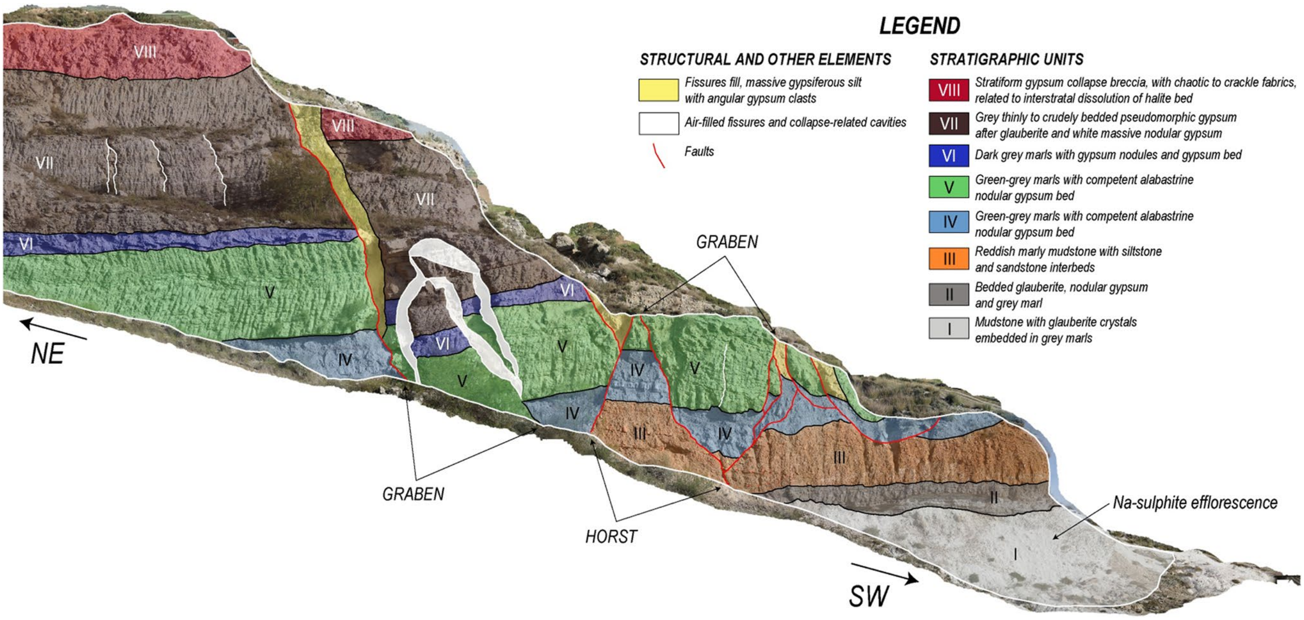

Fig. 9 Stratigraphy and deformation structures exposed in the trench wall (site no. 2). Compare with Fig. 8a

The site can be easily accessed from the exit of the Val de Moñete valley, by either climbing the upland spur above the valley and following a path running more or less parallel to the escarpment rim, or first following the valley floor and then turning onto the plateau. In each case, it is about 15–20 min one way. The selection of the former option allows one to have a panoramic view of the upland surface (site no. 4; view presented in Fig. 4d), with its stepped tableland topography consisting of cliffs and structural benches supported by gypsum beds, separated by slopes of variable inclination cut in marls and clays. These, in turn, are prone to water erosion generated by occasional heavy rains and are locally dissected by a dense network of gullies and ravines.

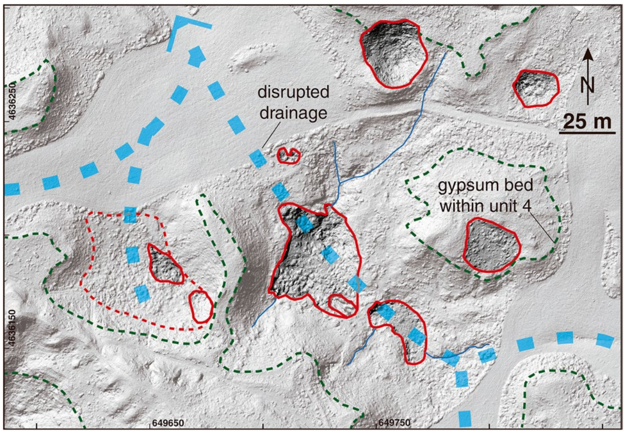

Fig. 10 Sinkhole map on a shaded relief model generated with a high-resolution digital elevation model produced by Structure from Motion Photogrammetry from images captured by a drone. The dashed line indicate the old drainage disrupted by collapse sinkholes

Barranco de las Salinas (Site no. 10)

The ravine of Barranco de las Salinas, with the exit at the outskirts of Remolinos, provides an easy access (ca. 25 min one way) to two abandoned salt mines, Mina del Gallo and Mina Los Papeles. Both allow one to see halite beds in situ, otherwise invisible at the surface, whereas the valley sides in the immediate vicinity show effects of interstratal salt dissolution and subsidence in the overlying gypsum and mudstone/marl beds. Deformation structures are clearly visible above the mine entrances and include local passive-bending folds with metre-scale amplitude and rather random orientations attributable to differential interstratal dissolution and sagging subsidence (Fig. 12).

The mines consist of winding horizontal galleries and larger exploitation chambers, up to 6 m high and partly filled with debris. The halite bed belongs to unit 3 and consists of centimetre- to decimetre-scale, turbid (with fluid inclusions) to transparent, white to dark grey halite beds with micro-nodules and nodules of anhydrite and partings of dark clay (Fig. 13a). The halite package subject to mining, 6 m thick, was differentiated into three sections, comprising the upper (3 m) and lower (2 m) bodies of relatively pure salt, separated by a clay-rich section 1 m thick. The blocks of this impure salt used to be accumulated as stone walls up to 6 m high at the flanks of the mine galleries, providing lateral support to the walls.

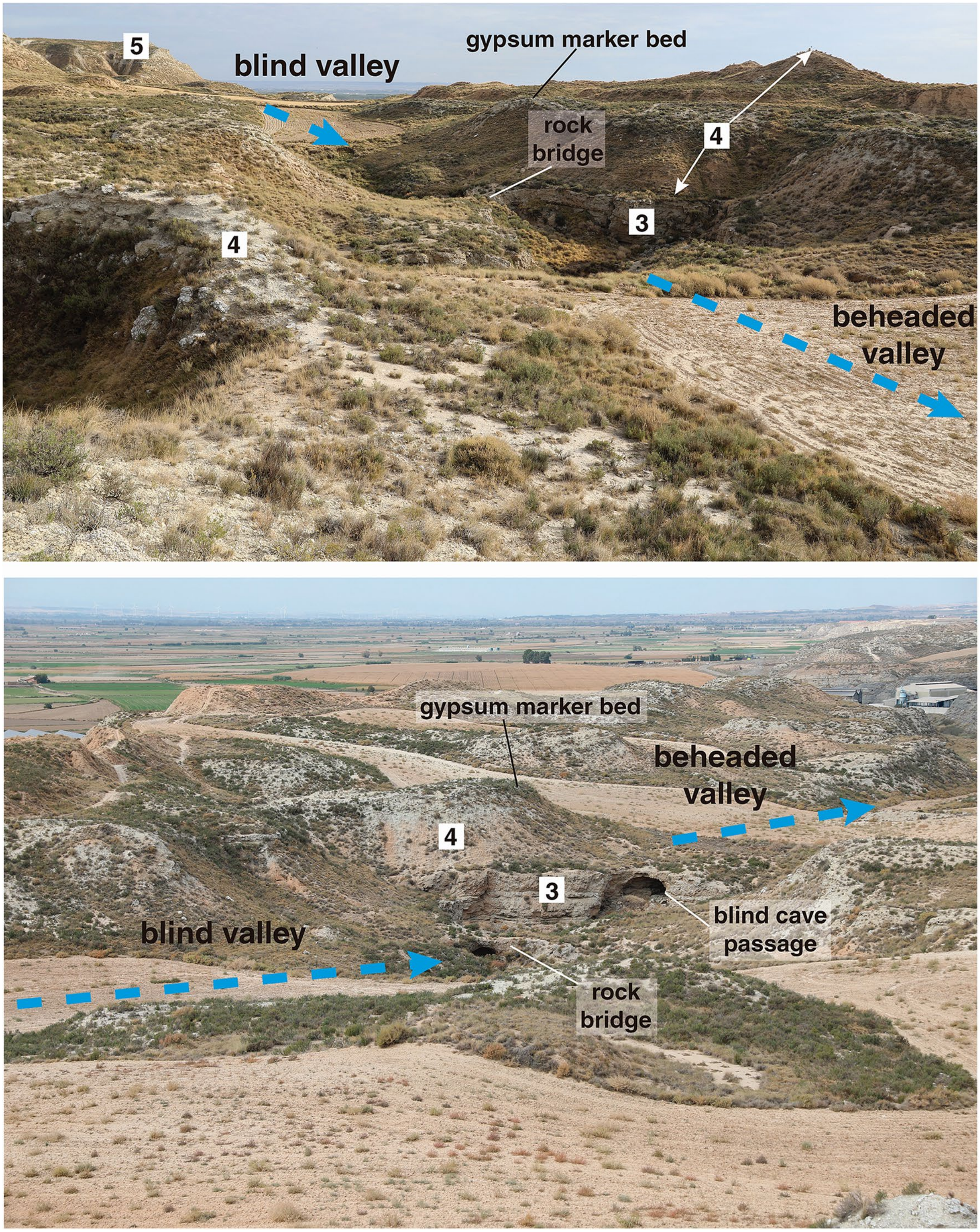

Fig. 11 Sinkholes and related landforms at the site no. 5. The upper panel shows a view upstream, whereas the lower panel shows a downstream view. Numbers 3–5 refer to lithostratigraphic units within the Miocene succession (compare Fig. 2)

The path to the mines passes several places where salt precipitation with popcorn and stalactite morphologies associated with brine seepages can be seen within rock cliffs inside the ravine (Fig. 13b). As an unrelated theme, the path follows the bedrock channel, usually dry, with various minor landforms resulting from bed erosion (potholes, steps, pools) and frequent rockfalls.

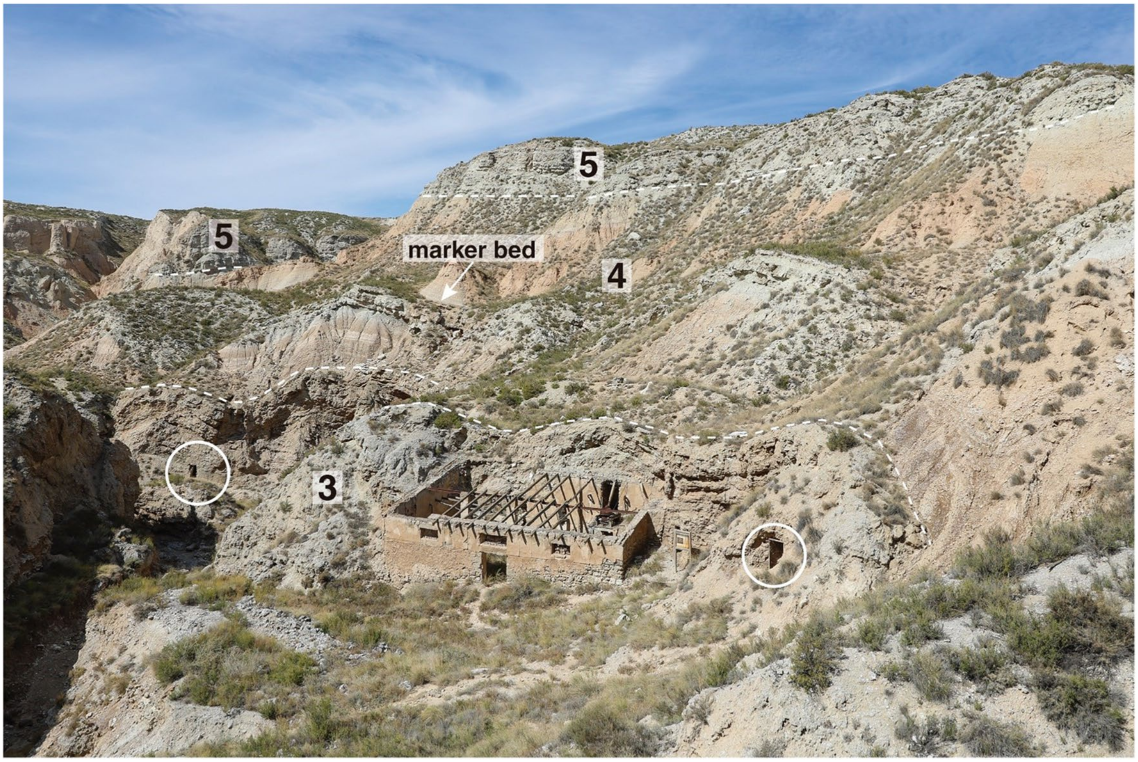

Fig. 12 Abandoned mines in the Barranco de las Salinas. Mine entrances are located in the upper part of unit 3, where the halite seam is located. Circles indicate entrances to the mines. Gentle folding at the top of unit 3 is related to differential interstratal dissolution of salt and sagging of the overlying beds (numbers 3 to 5 refer to the lithostratigraphic log, Fig. 2)

Remolinos Viewing Point (Site no. 12)

An excellent viewing point is located immediately above Remolinos, at the edge rim of the escarpment, overlooking the town and the wide floodplain of the meandering Ebro River. A number of large- and medium-scale geomorphological features can be observed, in clear connection to the bedrock geology. Major landforms are the undulating upland surface supported by the thick gypsum package of unit 5, the dissected escarpment, which is here ca. 100 m high, and the flat floor of the Ebro valley. A view towards the tributary valley that dissects the marginal part of the upland and the escarpment shows how the alternation of stronger gypsum units and weaker

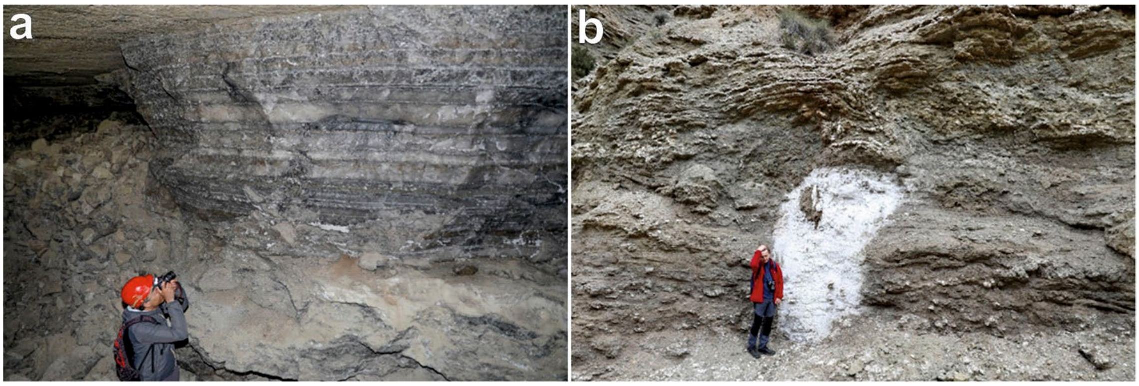

Fig. 13 Halite in the Barranco de las Salinas. **a** Halite package of unit 3 in El Gallo mine, consisting of centimetre- to decimetre-thick beds with white anhydrite micronodules and partings of dark clay. Note the roof corresponding to the planar base of a gypsum bed, and blocks accumulated at the wall of the gallery, derived from an impure clay-rick section. **b** Halite efflorescence associated with a seepage point in an exposure of the halite-bearing unit 3. Note the synsedimentary box synform in the overlying gypsum beds (upper layers are not folded)

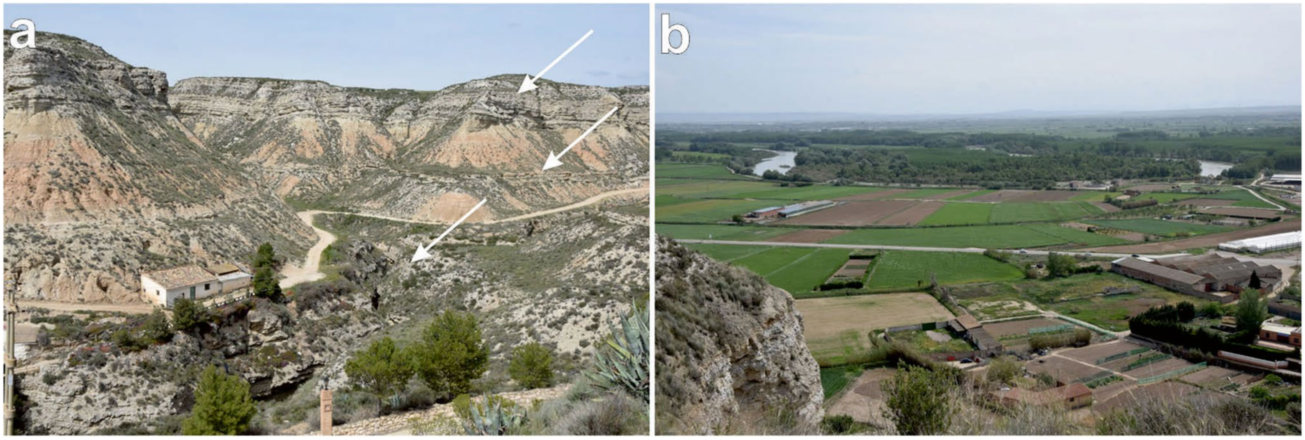

Fig. 14 Panoramic views from the viewing point above Remolinos. **a** Marginal, dissected part of the upland, with three gypsum units (arrowed; units 3, 4 and 5 in Fig. 2) exposed within valleysides. **b** View towards the Ebro River, with extensive floodplain and wide meander from the ground

clayey-marly units controls the step-like morphology of the valleysides, with the former supporting cliff lines and structural benches (Fig. 14a). An ephemeral drainage incises into the lowest gypsum package 3, carving a narrow slot within an older, box-shaped valley. The vicinity of the viewing platform also allows one to see various types of slope movements affecting the gypsum cliffs (detached and tilted rock towers, rockfall deposits at the base), as well as a large meander bend of the Ebro River, highlighted by the belt of riparian forest (Fig. 14b). Salt pans and salt heaps at the outskirts of the village are also easily seen.

The path to the viewing platform starts in the village, at the base of the escarpment, and is 0.5 km long. A short detour (50 m) leads to the site of cultural interest, the chapel of Santo Cristo de la Cueva, which is a fourteenth century construction partly hewn into the rock. The terrace in front of the chapel is also a good observation point, although it is about 15 m below the level of the top platform. Within the interior of the chapel, numerous roof and wall cracks can be seen, being just another line of evidence that the gypsum cliffs are very unstable.

El Castellar Landslide (Site no. 19)

The site of the abandoned village of El Castellar itself is not accessible (military training area), but the opposite bank of the Ebro River is an excellent viewing point towards the landslide that occurred within the escarpment and affected the castle, other landslides, the mouth of the Barranco de la Virgen and some of the ruined buildings of the village. It also allows one to see a considerable part of the stratigraphic succession exposed in the escarpment zone (Fig. 15).

The Ebro valley escarpment at El Castellar, 110 m high, is made of an alternation of gypsum and mudstone packages, including units 3 to 9, with the odd numbers corresponding to the evaporites (see Fig. 2; 15). Unit 3, which includes the ca. 8-m-thick halite bed, is largely concealed by slope deposits, and the 25-m-thick unit 4 is discontinuously exposed along the lower part of the cliff. Gypsum units 5 and 7, along with intervening mudstone units 6 and 8, account for the uneven profile of the slope, with vertical sections developed in gypsum. However, all these units are poorly differentiated in the morphology of the cliff, apparently due to relatively recent massive slope collapse along a dilatation crack system penetrating throughout the succession. Unit 9 is a massive gypsum package that forms the caprock of the escarpment. Lying on weak mudstone package, it is cut by numerous deep cracks subparallel to the cliff face. Their ongoing opening leads to topples and minor collapses, sustaining the cliff form, but also contributing to progressive destruction of the ruins of the castle and associated buildings.

The central section of El Castellar escarpment bears evidence of a relatively recent rock-slope collapse (post-fifteenth century, when the castle was still in use), which affected the entire height of the slope. It includes the fresh vertical scar in the upper part and the massive debris cone below, c 90 m long and 180 m wide, with the apex some 70 m above the river level. Its surface part is armoured by big blocks of gypsum derived from the caprock unit 9. Several secondary scars within the debris cone, and associated colluvial aprons labelled as CP1 (oldest) to CP3 (youngest) (Fig. 15), record the history of subsequent slides within the cone, likely induced by episodic fluvial undercutting during floods.

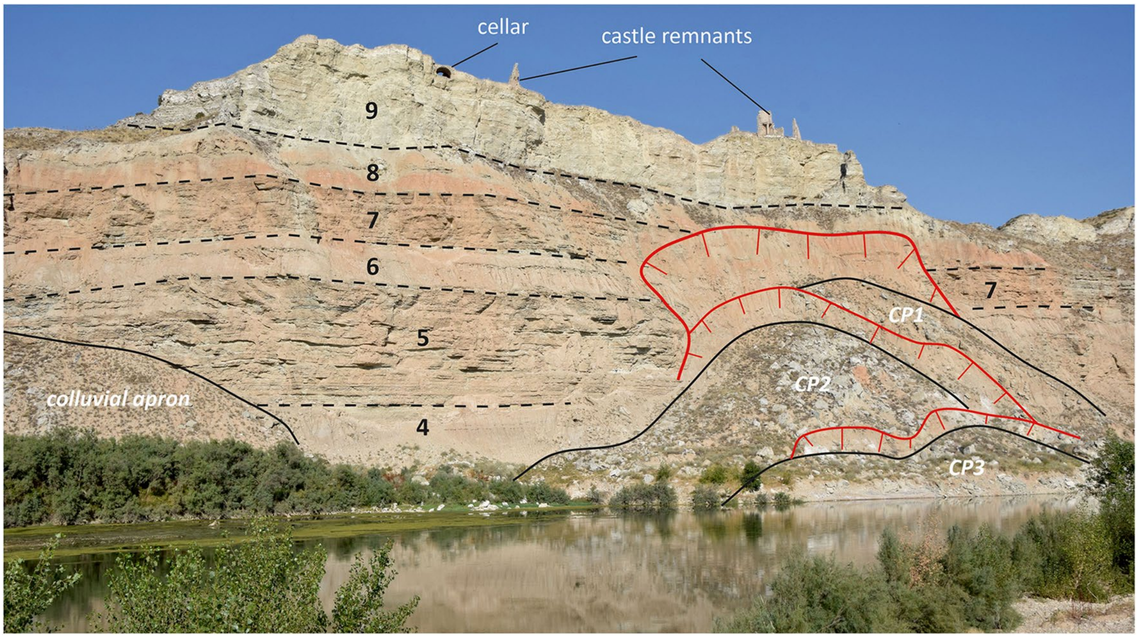

Fig. 15 Escarpment at El Castellar, with a large landslide (crown indicated by red line) that affected the medieval castle (on top of the cliff). Numbers 4 to 9 refer to regional stratigraphy shown in Fig. 2, letter codes CP1 to CP3 indicate consecutive phases of landslide evolution (from oldest to youngest)

From the viewing point, one can also see that the El Castellar landslide was not a unique event in the geomorphological evolution of the escarpment. Evidence of large landslides is ubiquitous around El Castellar, exemplified by several large scars affecting the upper portions of the scarp and huge debris aprons mantled with big blocks of gypsum derived from the cliffs, both during the landslide events and subsequent rock falls. Some of the colluvial bodies are in direct contact with the river, being subject to ongoing undercutting, whereas others are separated from the channel by the floodplain or paleomeanders.

Juslibol Paleosinkhole (Site no. 23)

Gypsum cliffs at Juslibol are up to 60 m high and show a simple, nearly vertical slope profile, reflecting uniform bedrock at this section of the escarpment. They expose the thick, merged gypsum unit 5–7 (Fig. 2), above which lies the thin (less than 10 m) mudstone/marl package of unit 8, whose basal contact corresponds to a wide bench. The top of the escarpment displays a low cliff on gypsum unit 9. Gypsum cliffs are generally continuous, except one place immediately above the visitor centre of Juslibol Nature Reserve. Here, long-term escarpment retreat has cut through a deep paleosinkhole, in which reddish mudstones of unit 8 are foundered into the underlying gypsum (Fig. 16). The subsided material shows an inner synformal structure (basin structure with centripetal dips in 3D) and marginal collapse faults. Subsequent erosion acted mostly along the margins of the sinkhole, incising steep ravines and isolating the central part of the fill as a distinctive protruding cone ca. 15 m high, representing a peculiar case of relief inversion.

Accessibility, Interpretation Provisions and Future Opportunities

Accessibility of the study area for the general public varies. A large part of the upland above the escarpment, from Remolinos to Juslibol, is occupied by the military as a training ground and is technically off-limits. The no-go zone does not include the escarpment face itself, but this is still difficult to visit due to its location on private properties, excessive steepness of the terrain, or both. However, these sections of the escarpment can be easily viewed from the distance, including observation points on the opposite side of the Ebro River. By contrast, the westernmost part has no access constraints and visitors can freely move around the upland. A road connecting the towns of Alagón and Tauste runs along the base of the escarpment and offers good views, as well as access to specific points of interest (our geosites no. 1 to 17). Likewise, the easternmost section at Juslibol is open and partially developed as recreation grounds for the city of Zaragoza, including some educational facilities focused on valley floor ecosystems.

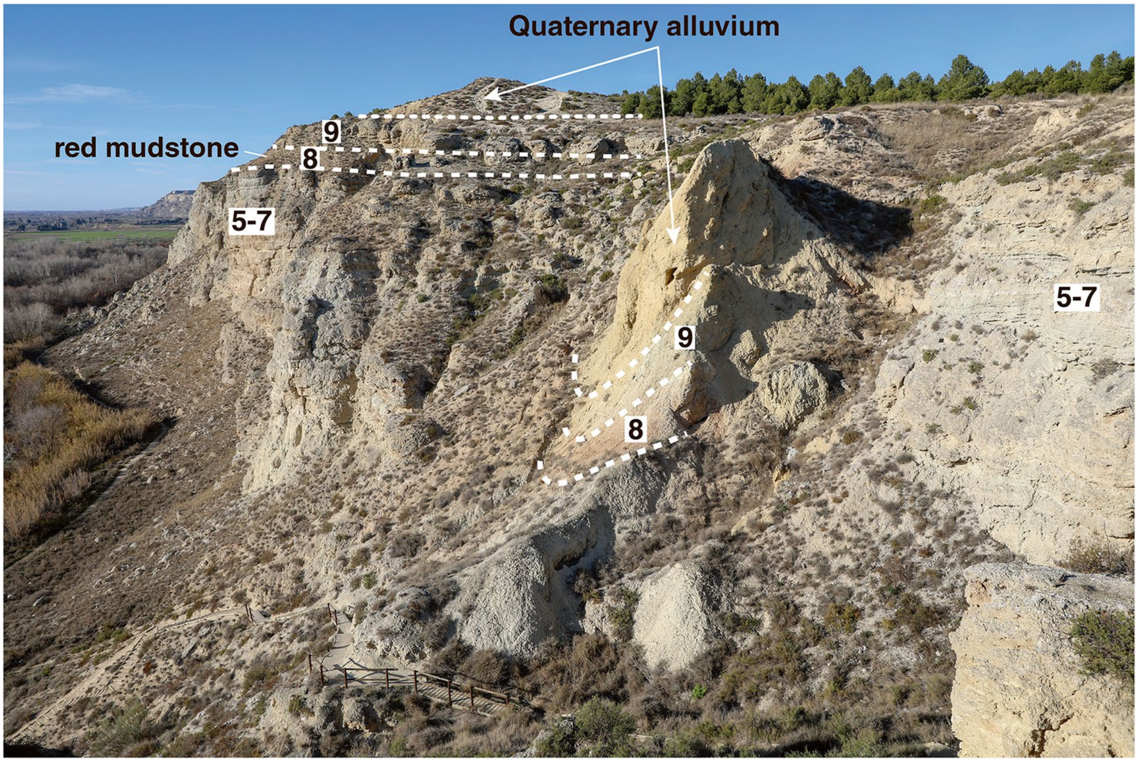

Fig. 16 Fill of a paleosinkhole (yellow colour, right part of the image) exposed within the escarpment above the oxbow lakes at Juslibol. Gypsum cliffs and the floodplain of the Ebro valley in the background (left). Numbers 5–9 refer to lithostratigraphic units within the Miocene succession (compare Fig. 2)

Despite the proximity to a large city of Zaragoza and convenient access to at least some sites of geoscientific value presented above, geoheritage aspects of the gypsum tablelands, including the Ebro valley escarpment, seem to be rather overlooked and existing interpretation provisions are remarkably few. The only sector of the escarpment that has been developed is that next to Juslibol, where a visitor centre was built above an oxbow lake, resulting from a meander cut-off during the great 1961 Ebro River flood. The focus of educational activities is on ecology and biodiversity rather than on geology and landforms, although the origin of the oxbow lake and the biological significance of the boundary between gypsiferous steppes and riparian environments are explained. Interpretative facilities include thematic paths in the nature reserve, interpretation boards, guided tours and programmes for schools. The centre can be accessed by a 10–15-min walk from a parking area, and during weekends and holidays there is a touristic train service. Paradoxically, this educational infrastructure focused on the understanding of fluvial dynamics gets inundated quite often during ordinary floods.

Nevertheless, a waymarked path from the visitor centre ascends to the escarpment top and several interpretation panels in the vicinity address issues of contemporary landform dynamics, such as rock-slope failures and channel path change (Fig. 17). The panel by the road from Juslibol explaining cliff instability is, however, not erected in the optimal place, since the explanation focuses on the role of fluvial undercutting but the location is not anywhere near the river (Fig. 17a, b). Moreover, the best viewing spot on top of the escarpment lacks interpretation provisions.

The other easily accessible sector of the escarpment, around Remolinos, is poorly developed for geotourism, although history-focused information boards in the centre of the village do emphasize salt mining and salt processing. The path to salt mines is signposted, but the panels at the mines themselves are very worn down and would require renewal. None of the viewing points on the escarpment has interpretation facilities and sites of historical interest (Valdetaus, Castillo de Pola) are not explained either. Although there is a fairly dense network of footpaths in the marginal parts of the plateau, none is a properly waymarked hiking trail.

Therefore, diverse geoheritage aspects of the escarpment can be considered as an untapped resource, which can however be rather easily developed to serve geotourism and geoeducation purposes. Recommended actions include the following: (a) signposting and waymarking access routes to the best vantage points above the escarpment (geosites no.

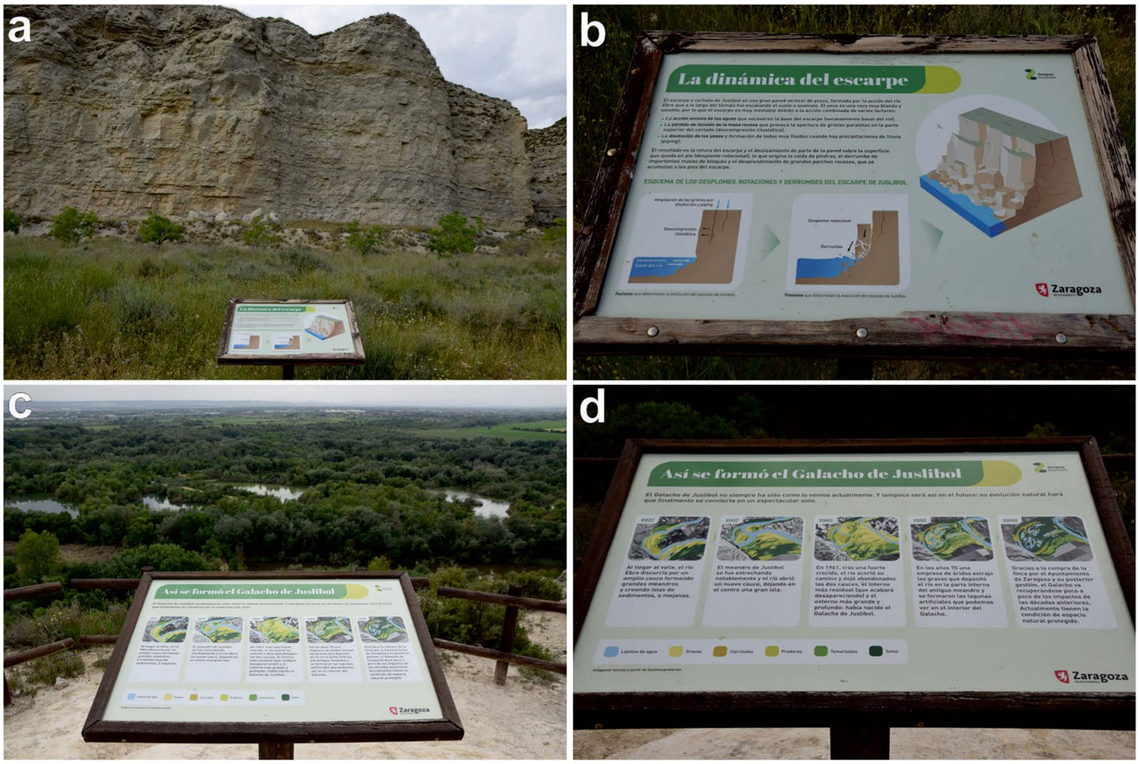

Fig. 17 Interpretation facilities at Juslibol. **a**, **b** Explanation of rock cliff failures (context and close-up)—notice that even though the panel highlights the role of fluvial undercutting, no direct contact with the river occurs near the place of its erection. **c**, **d** Explanation of channel pattern change at the viewing point above the escarpment (context and close-up)

8, 12 and 16), as well as to observation points on the floodplain, on the opposite bank of the Ebro River (geosites no. 19 and 20); (b) erection of interpretation panels at key sites, which depending on the locality would either explain rocks and landforms at the site itself or rock—landforms relationships and longer-term landform evolution patterns that can be recognized from the viewpoint geosites; (c) adding information about geoheritage to information panels located in the villages along the escarpment, which currently focus only on history and historical monuments; and (d) developing web-based resources, with the use of opportunities provided by modern technologies (aerial imagery from drones, digital elevation models). These can be particularly useful to offset access limitations along a substantial part of the escarpment.

Challenges—Managing Landform Instability

The cliffed gypsum escarpment represents a very dynamic setting from geomorphological perspective. This is due to combination of internal and external factors, resulting in considerable instability and high frequency of mass movements, as evident from the visible landform record and clearly indicated by historical sources. Internal factors include alternating occurrence of competent gypsum beds separated by mechanically weak mudstones and clays, high degree of fracturing of gypsum and their overall low rock-mass strength, and the presence of highly soluble halite and glauberite layers at depth. These lithological and structural properties favour landslides, rock falls and whole rock-slope collapses along the escarpment face, as well as ground subsidence and the evolution of sinkholes both within the upland and in the valley floor. A significant part of subsidence is likely induced by roof collapses over abandoned salt mines, propagating to the surface and causing the development of sinkholes. It is estimated that more than 40% of the length of the escarpment between Tauste and Juslibol bears evidence of large mass movements of different types, excluding the ubiquitous small-size rockfalls and topples. The most important external factor is fluvial undercutting by the Ebro River, whose channel is now in direct contact with the escarpment base along 5.5 km of its course. However, given frequent shifts of the channel in the past, the total length of the escarpment remodelled by fluvially induced landslides is expectedly much bigger. Rapid solutional and mechanical erosion of both bedrock and landslide deposits results in the fast long-term retreat of the escarpment, producing striking hanging valleys and intervening triangular facets. Bank undercutting and slope collapses also occur within deeply incised tributary valleys and ravines, and although the slope sections affected are not as large and long as those along the Ebro, they can be nevertheless impressive (e.g., geosite no. 6). The close proximity of the river is, however, not a prerequisite to develop mass movements. The entire section of the escarpment between Tauste and Castillo Pola is far from the active channel belt, and yet the evidence of landslides, rockfalls and topples is ubiquitous. In addition, in several sections, one can see shallow trenches and open cracks parallel to the escarpment rim, indicating ongoing instability. The geosite no. 2 provides an insight how the movement of gypsum blocks is accomplished.

This dynamics has evidently been a problem since ancient times and may have been instrumental in depopulating and eventually abandoning El Castellar village, subsequently leading to partial destruction of the remains of the castle. Likewise, abandoned cave dwellings and collapsed salt mine entrances around Remolinos point to persistent problems with slope and mine instability. Nowadays, rock-slope failures threat the roads (geosites no. 13, 20) and cultural relicts such as El Castellar castle (geosite no. 19). They are also an important factor to consider while developing the escarpment for tourism, recreation and education. For example, some cliff sections in Juslibol show deep cracks intersecting the entire height of the cliff, dense networks of minor cracks, and large overhangs, making the cliffs very prone to failures (Fig. 18a, b). Similar deep cracks and overhangs occur in the canyons dissecting the escarpment, such as that leading to the abandoned salt mines at the geosite no. 10. Even the lowest section of the escarpment near its northwesternmost

Fig. 18 Examples of geomorphic instability affecting possible developments for geotourism and geo-education. **a** Strongly disintegrated gypsum cliff at Juslibol, with multiple open cracks. **b** Close-up of a densely cracked section of a cliff. **c** Unstable roof and rock debris on the floor of a cavern inside the collapse sinkhole (site no. 5). **d** Evidence of considerable water erosion within mudstones. **e** Accelerated erosion occurs along paths running up straight upslope (arrows)

extremity shows open cracks (geosite no. 3). At the sinkhole site (geosite no. 5), the roofs of the natural tunnel between two dolines and of the cave penetrating into the rock are very unstable, rendering the places very unsafe (Fig. 18c). Altogether, these instabilities provide significant constraints to develop a trail network, the use of which would not compromise the safety of visitors.

Another problem is erodibility of the substrate, especially mudstones. Although they hardly form cliffs, they nevertheless support fairly steep slopes (up to 30° or so), both within the front of the escarpment and along the canyons. Evidence of water erosion triggered by infrequent, but heavy rainfall occurs widely in the form of gullies and minor ravines, as well as rills on unvegetated surfaces (Fig. 18d). The issue is exacerbated by human activities, especially off-road driving, which produces rills more than 0.5 m deep, which act as unnatural pathways for runoff that can quickly reach the streambeds (Fig. 18e). If an organized trail network is to be developed in the future, these steep sections of existing paths should be avoided.

Conclusions

The prominent escarpment of the Ebro River valley that occurs to the north-west of Zaragoza represents an important and highly diverse geoheritage, yet its value seems to have been largely overlooked. It is neither protected in recognition of its geoscientific qualities, nor is developed for tourism, despite the proximity of a large city and learning centre. The only exception is the Juslibol suburb of Zaragoza, where part of the floodplain and now flooded former gravel pits have been converted into recreational grounds and the place of ecological education, but the geoscience component is almost neglected. Off-limit status of most of the upland surface above the escarpment due to military presence and ongoing salt and gypsum mining and processing near Remolinos contribute to limited appreciation of geoheritage value of the area.

Nevertheless, the nearly 40-km-long escarpment zone abounds in localities, which can be considered as geosites, allowing the visitors to learn about different aspects of geological history of the Ebro Basin since the Miocene to the Quaternary and its geomorphological evolution. Collectively, they address a wide range of themes, from depositional patterns in semi-arid playas through post-depositional changes affecting evaporitic deposits, solutional (karstic) processes and their impact, fluvial erosion and channel path changes, mass movements, to mining history, mineral processing and geomorphological underpinning of human occupation of the land. The latter are important as they provide linkage to human history, land use and cultural heritage, putting geoheritage in wider perspective. Another significant observation is that the Ebro valley escarpment is a highly dynamic feature, affected by ongoing slope instability, especially in sections where the river is in direct contact with the escarpment. The area abounds in landslides and rock-slope collapses, being also affected by karst dissolution, episodic runoff erosion and mining-related ground subsidence. This hazardous surface dynamics is both an opportunity, allowing to learn about processes shaping the Earth's surface more effectively than elsewhere, and a challenge for any future attempts to develop the escarpment for geotourism.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12371-023-00878-x.

Acknowledgements Research stay of PM in Spain was financially supported by the Bekker Fellowship awarded by the Polish National Agency for Academic Exchange (contract no. PPN/BEK/2020/1/00047/U/DRAFT/00001). JS has a predoctoral contract (PRE2018-084240) cofinanced by the Spanish Government and the European Social Fund (ESF). We thank an anynomous reviewer for comments and suggestions for improvement and the editor, Kevin Page, for very helpful guidance at the revision stage.

Author Contributions All authors have contributed to this study (PM—field survey, landform mapping, geosite selection; FG—field survey, geological and landform mapping, UAV survey and data processing; CP—field survey and landform mapping; JS—field survey, geological mapping). The first draft of the manuscript was mostly written by PM and supplemented by the remaining authors. All authors commented on previous versions of the manuscript and approved its final content.

Funding This work was supported by projects (CGL2017-85045-P, PID2021-123189NB-I00) of the Spanish Government (Ministerio de Ciencia e Innovación).

Declarations

Conflict of Interest The authors declare no competing interests.

References

Arenas C (1993) Sedimentología y paleogeografía del Terciario del margen pirenaico y sector central de la cuenca del Ebro (Zona aragonesa occidental). University of Zaragoza PhD Thesis. Available at: http://zaguan.unizar.es

Arenas C, Millán H, Pardo G, Pocoví A (2001) Ebro Basin continental sedimentation associated with late compressional Pyrenean tectonics (north-eastern Iberia): controls on basin margin fans and fluvial systems. Basin Res 13:65–89

Asso I (1798) Historia de la economía política de Aragón. Francisco Magallón, Zaragoza

Benito G, Pérez-González A, Gutiérrez F, Machado MJ (1998) River response to Quaternary subsidence due to evaporite solution (Gállego River, Ebro Basin, Spain). Geomorphology 22:243–263

Benito G, Sancho C, Peña JL, Machado MJ, Rhodes EJ (2010) Large-scale karst subsidence and accelerated fluvial aggradation during MIS6 in NE Spain: climatic and paleohydrological implications. Quat Sci Rev 29:2694–2704

Benito-Calvo A, Moreno D, Fujioka T, López GI, Martín-González F, Martínez-Fernández A, Hernando-Alonso I, Karampaglidis T, Bermúdez de Castro JM, Gutiérrez F (2022) Towards the steady state? A long-term river incision deceleration pattern during Pleistocene entrenchment (Upper Ebro River, Northern Spain). Global Planet Change 213:103813

Brilha J (2018) Geoheritage: inventories and evaluation. In: Reynard E, Brilha J (eds) (2018) Geoheritage. Assessment, Protection, and Management. Elsevier, Amsterdam, pp 69–85

Brockx M, Semeniuk V (2007) Geoheritage and geoconservation – history, definition, scope and scale. J Royal Soc West Aust 90:53–87

Calvo M (2001) Las minas de sal de Remolinos. Rev Minerales 2:3–22

Calvo M (2008) Minerales de Aragón. PRAMES, Zaragoza

Constante A, Peña-Monné JL, Muñoz A (2010) Alluvial geoarcheology of an ephemeral stream: implications for Holocene landscape change in the central part of the Ebro Depression, Northeast Spain. Geoarchaeology 25:475–496

Coratza P, Gauci R, Schembri J, Soldati M, Tonelli C (2016) Bridging natural and cultural values of sites with outstanding scenery: evidence from Gozo, Maltese Islands. Geoheritage 8:91–103

De Waele J, Gutierréz F (2022) Karst hydrogeology, geomorphology and caves. Wiley-Blackwell, Chichester

Del Monte M, Fredi P, Pica A, Vergari F (2013) Geosites within Rome City center (Italy): a mixture of cultural and geomorphological heritage. Geogr Fis Dinam Quat 36:241–257

Forno MG, Gianotti F, Gattiglio M, Pelfini M, Sartori G, Bollati IM (2022) How can a complex geosite be enhanced? A landscape-scale approach to the deep-seated gravitational slope deformation of Pointe Leysser (Aosta Valley, NW Italy). Geoheritage 14:100

García-Ortiz E, Fuertes-Gutiérrez I, Fernández-Martínez E (2014) Concepts and terminology for the risk of degradation of geological heritage sites: fragility and natural vulnerability, a case study. Proc Geol Assoc 125:463–479

García-Veigas J, Ortí F, Fernández-Nieto C (1994) Modelo hidroquímico de sedimentación de glauberita-halita: sondeo PURASAL, Formación Yesos de Zaragoza (Mioceno inferior, Cuenca del Ebro). Geogaceta 16:136–139

Gascón Ricao A (2007) El hechizo de El Castellar. Cuadernos de Aragón 35, Zaragoza

Gordon JE (2018) Geoheritage, geotourism and the cultural landscape: enhancing the visitor experience and promoting geoconservation. Geosciences 8:136

Gordon JE, Tormey D, Wignall R, Brazier V, Crofts R (2022) Climate change will challenge the management of geoheritage in protected and conserved areas. Parks Stewardship Forum 38(1):56–63

Goudie A, Viles H (2015) Landscapes and landforms of Namibia. Springer, Dordrecht

Guerrero J, Gutiérrez F, Galve JP (2013) Large depressions, thickened terraces and gravitational deformation in the Ebro River valley (Zaragoza area, NE Spain). Evidence of glauberite and halite interstratal karstification. Geomorphology 196:162–176

Gutiérrez F, Mozafari M, Carbonel D, Gómez R, Raeisi E (2015) Leakage problems in dams built on evaporites. The case of La Loteta Dam (NE Spain), a reservoir in a large karstic depression generated by interstratal salt dissolution. Eng Geol 185:139–154

Gutiérrez-Elorza M, Gutiérrez-Santolalla F (1998) Geomorphology of the Tertiary gypsum formations in the Ebro Depression (Spain). Geoderma 87:1–29

Gutiérrez F, Sevil J, Migoń P (2023) Landslides in the Remolinos gypsum escarpment (NE Spain). Controls imposed by stratigraphy, fluvial erosion and interstratal salt dissolution. Landslides 20:2075–2093. https://doi.org/10.1007/s10346-023-02090-y

Hooke JM (1994) Strategies for conserving and sustaining dynamic geomorphological sites. In: O'Halloran D, Green C, Harley M, Knill J (eds) Geological and landscape conservation. The Geological Society, London, pp 191–195

Mapa de Edades Geológicas de la Península Ibérica, Baleares y Canarias a escala 1:1.000.000 (1995) IGME, Madrid

Migoń P, Pijet-Migoń E (2017) Viewpoint geosites – values, conservation and management issues. Proc Geol Assoc 128:511–522

Migoń P, Kasprzak M, Woo K-S (2019) Granite landform diversity and dynamics underpin geoheritage values of Seoraksan Mountains, Republic of Korea. Geoheritage 11:751–764

Morino C, Coratza P, Soldati M (2022) Landslides, a key landform in the global geological heritage. Frontiers Earth Sci 10:864760

Mucivuna VC, Reynard E, Garcia MGM (2019) Geomorphosites assessment methods: comparative analysis and typology. Geoheritage 11:1799–1815

Palasí F (1988) Novena a Nuestra Señora del Castelar. Artes Gráficas El Noticiero, Zaragoza

Pásková M, Zelenka J, Ogasawara T, Zavala B, Astete I (2021) The ABC concept—value added to the Earth heritage interpretation? Geoheritage 13:38

Pelfini M, Bollati I (2014) Landforms and geomorphosites ongoing changes: concepts and implications for geoheritage promotion. Quaest Geogr 33(1):131–143

Peña-Monné JL, Sampietro-Vattuone MM, Longares-Añadrén LA, Sánchez-Fabre M, Constante A (2021) Interactions between fluvial dynamics and scarp retreat in the Central Ebro Basin during MCA and LIA periods: paleogeographical and geoarchaeological reconstruction. Paleogeogr, Paleoclimatol, Paleoecol 567:110301

Pérez-Rivarés FJ, Garcés M, Arenas C, Pardo G (2004) Magnetostratigraphy of the Miocene continental deposits of the Montes de Castejón (central Ebro basin, Spain): geochronological and paleoenvironmental implications. Geol Acta 2:221–234

Pérez-Rivarés FJ, Arenas C, Pardo G, Garcés M (2018) Temporal aspects of genetic stratigraphic units in continental sedimentary basins: examples from the Ebro basin, Spain. Earth Sci Rev 178:136–153

Pijet-Migoń E, Migoń P (2022) Geoheritage and cultural heritage – a review of recurrent and interlinked themes. Geosciences 12:98

Prosser CD, Burek CV, Evans DH, Gordon JE, Kirkbride V, Rennie AF, Walmsley CA (2010) Conserving geodiversity sites in a changing climate: management challenges and responses. Geoheritage 2:123–136

Quirantes J (1978) Estudio sedimentológico y estratigráfico del Terciario contniental de Los Monegros. Institución Fernando El Católico, Diputación Provincial de Zaragoza, Zaragoza

Reynard E (2005) Géomorphosites et paysages. Géomorphol Relief Process Environ 3:181–188

Reynard E (2009) Geomorphosites: definitions and characteristics. In: Reynard E, Coratza P, Regolini-Bissig G (eds) Geomorphosites. Pfeil Verlag, München, pp 9–20

Reynard E, Brilha J (2018) Geoheritage. In: Assessment, Protection, and Management. Elsevier, Amsterdam

Reynard E, Giusti C (2018) The landscape and the cultural value of geoheritage. In: Reynard E, Brilha J (eds) (2018) Geoheritage. Assessment, Protection, and Management. Elsevier, Amsterdam, pp 147–166

Riba O, Reguant S, Villena J (1983) Ensayo de síntesis estratigrafica y evolutiva de la cuenca terciaria del Ebro. Geología de España. Libro Jubilar J.M. Ríos. IGME, 2, 131–159

Salvany JM (2009) Geologia del yacimiento glauberitico de Montes de Torrero. Universidad de Zaragoza, Zaragoza

Salvany JM, Garcia-Veigas J, Ortí F (2007) Glauberite-halite association of the Zaragoza Gypsum Formation (lower Miocene, Ebro Basin, NE Spain). Sedimentology 54:443–467

Santos DS, Reynard E, Mansur KL, Seoane JCS (2019) The specificities of geomorphosites and their influence on assessment procedures: a methodological comparison. Geoheritage 11:2045–2064

Satariano B, Gauci R (2019) Landform loss and its effect on health and wellbeing: the collapse of the Azure Window (Gozo) and the resultant reactions of the media and the Maltese community. In: Gauci R, Schembri JA (eds) Landscapes and landforms of the Maltese Islands. Springer, Cham, Switzerland, pp 289–303

Selmi L, Coratza P, Gauci R, Soldati M (2019) Geoheritage as a tool for environmental management: a case study in northern Malta (Central Mediterranean Sea). Resources 8:168

Selmi L, Canesin TS, Gauci R, Pereira P, Coratza P (2022) Degradation risk assessment: understanding the impacts of climate change on geoheritage. Sustainability 14:4262

Sevil J, Gutiérrez F, Carnicer C, Carbonel D, Desir G, García-Arnay A, Guerrero J (2020) Characterizing and monitoring a high-risk sinkhole in an urban area underlain by salt through non-invasive methods: detailed mapping, high-precision leveling and GPR. Eng Geol 272:105641

Soria-Jáuregui A, Jiménez-Cantizano F, Antón L (2018) Geomorphic and tectonic implications of the endorheic to exorheic transition of the Ebro River system in Northeast Iberia. Quat Res 91:472–492

Smith BJ (2005) Management challenges at a complex geosite: the Giant's Causeway World Heritage Site, Northern Ireland. Géomorphologie: relief, proc, environ 11:219–226

Smith BJ, Pellitero Ondicol R, Alexander G (2011) Mapping slope instability at the Giant's Causeway and Causeway Coast World Heritage Site: implications for site management. Geoheritage 3:253–266

Štrba Ľ, Rybár P, Baláž B, Molokáč M, Hvizdák L, Kršák B, Lukáč M, Muchová L, Tometzová D, Ferenčíková D (2015) Geosite assessments: comparison of methods and results. Current Iss Tour 18:496–510

Torrescusa S, Klimowitz J (1990) Contribución al conocimiento de las evaporitas Miocenas (Fm. Zaragoza) de la Cuenca del Ebro. In: Ortí F, Salvany JM (eds) Formaciones evaporíticas de la Cuenca del Ebro, cadenas periféricas y de la zona de Levante. Enresa, Barcelona, pp 120–123