THE STRATIGRAPHICAL RECORD AND ACTIVITY OF EVAPORITE DISSOLUTION SUBSIDENCE IN SPAIN

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ABSTRACT: The evaporite formations (in outcrop and at shallow depth) cover an extensive area of the Spanish territory. These soluble sediments are found in diverse geological domains and record a wide time span from the Triassic up to the present day. Broadly, the Mesozoic and Paleogene formations (Alpine cycle) are affected by compressional structures, whereas the Neogene (post-orogenic) sediments remain undeformed.

The subsidence caused by subsurface dissolution of the evaporites (subjacent karst) takes place in three main types of stratigraphical settings: a) Subsidence affecting evaporite-bearing Mesozoic and Tertiary successions (interstratal karst); b) Subsidence in Quaternary alluvial deposits related to the exorheic evolution of the present-day fluvial systems (alluvial or mantled karst); c) Subsidence in exposed evaporites (uncovered karst). These types may be represented by paleosubsidence phenomena (synsedimentary and/or postsedimentary) recognizable in the stratigraphical record, or by equivalent currently active or modern examples with surface expression.

The interstratal karstification of the Mesozoic marine evaporites and the consequent subsidence of the topstrata is revealed by stratiform collapse breccias and wedge-outs in the evaporites grading into unsoluble residues.

In several Tertiary basins, the sediments overlying evaporites locally show synsedimentary and/or postsedimentary subsidence structures. The dissolution-induced subsidence coeval to sedimentation gives place to local thickenings in basin-like structures with convergent dips and cumulative wedge out systems. This sinking process controls the generation of depositional environments and lithofacies distribution. The postsedimentary subsidence produces a great variety of gravitational deformations in the Tertiary supra-evaporitic units including both ductile and brittle structures (flexures, synforms, fractures, collapse and brecciation).

The Quaternary fluvial terrace deposits on evaporite sediments show anomalous thickenings (>150 m) caused by a dissolution-induced subsidence process in the alluvial plain which is balanced by alluvial aggradation. The complex space and time evolution pattern of the paleosubsidence gives place to intricate and anarchical structures in the alluvium which may be erroneously interpreted as pure tectonic deformations. The current subsidence and generation of sinkholes due to suballuvial karstification constitutes a geohazard which affects to large densely populated areas endangering human safety and posing limitations to the development. An outstanding example corresponds to Calatayud historical city, where subsidence severely damages highly valuable monuments. The subsidence resulting from the underground karstification of evaporites has determined or influenced the generation of some important modern lacustrine basins like Gallocanta, Fuente de Piedra and Banyoles lakes. The sudden formation of sinkholes due to the collapse of cave roofs is relatively frequent in some evaporite outcrops. Very harmful and spectacular subsidence activity is currently occurring in the Cardona salt diapir where subsidence has been dramatically exacerbated by mining practices.

1. THE EVAPORITE FORMATIONS IN SPAIN. INTRODUCTION

The Iberian Peninsula constitutes a microplate located in a relatively complex geotectonic setting between the convergent European and African plates. Broadly, the geology of this microplate is formed by pre-Mesozoic metamorfic and igneous rocks in the Hercynian Massif, and mainly Paleozoic to Cenozoic sedimentary rocks in several Alpine orogens and Tertiary basins (Fig. 1). Numerous evaporite formations were accumulated in these orogens and basins. Many of them being exposed at the surface or placed at shallow depths cover an extensive portion of the Spanish territory. Only the evaporite outcrops exceed over 35,000 km^2 in area (Macau and Riba 1962; Ríos 1963; Durán and Val 1984a), i.e., 7 % of the total country (504,750km^2) (Fig. 1).

A great part of the evaporite formations in Spain are characterized by a relatively simple and homogeneous mineral paragenesis, primarily made up of gypsum (usually anhydrite at depth) and halite (salt). Most of the outcropping gypsum correspond to secondary gypsum varieties coming from the

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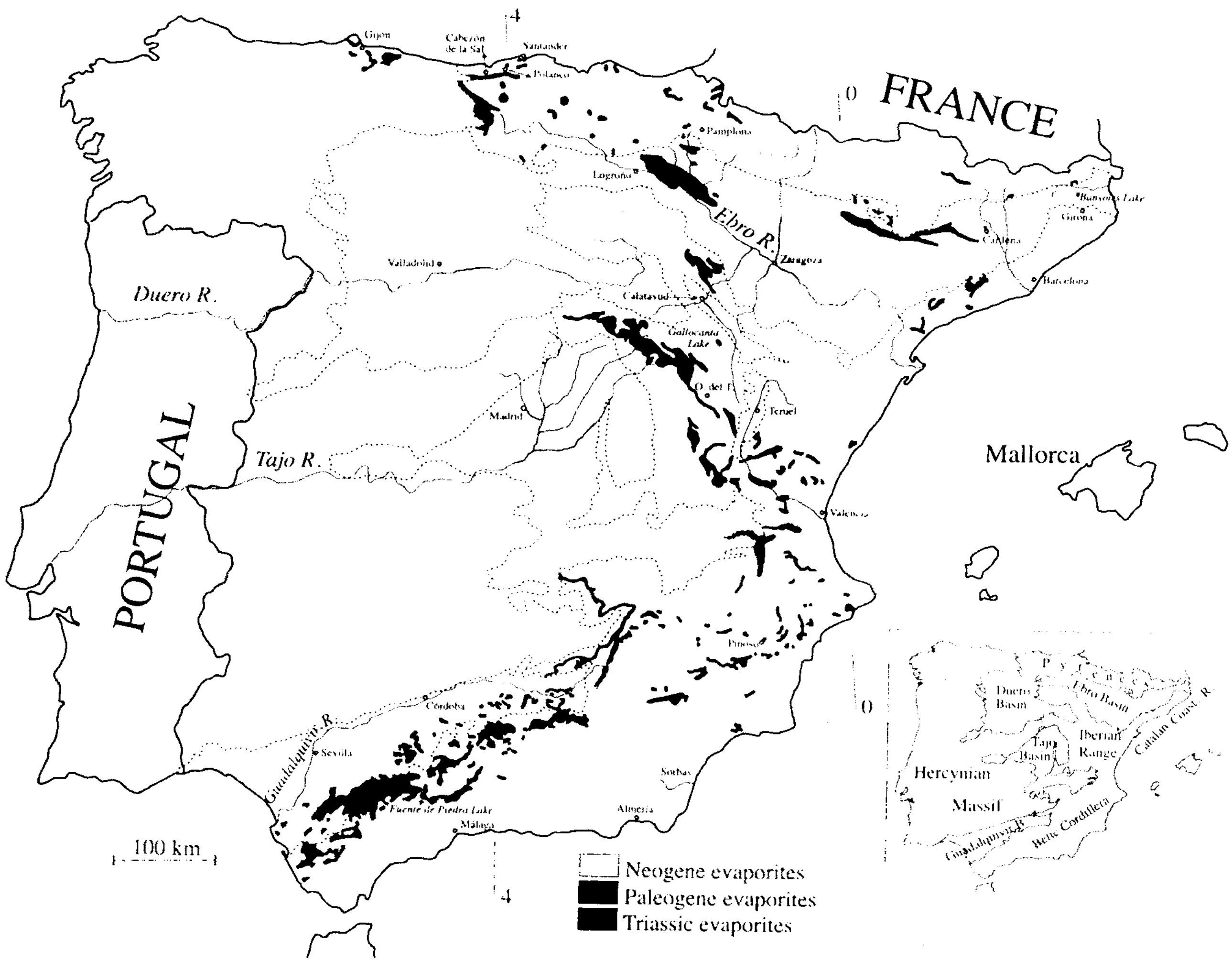

Figure 1. Main evaporite outcrops in Spain and principal fluvial systems crossing evaporite areas. The small sketch indicates the most important geological domains in the Iberian Peninsula.

hydration of anhydrite (precursor), whereas primary gypsum has been preserved only in some Neogene formations and small Quaternary playas. In some cases, the evaporite sequences also contain K-Mg-chlorides and Na-sulfates (Ortí 1989, 2000). Commonly, these highly soluble minerals, particularly halite and some Na-sulfates, are found in boreholes, since they have been dissolved close to the ground causing the wedging out of these formations near the surface. Despite the relatively simple mineralogy, all these evaporite formations usually show great diversity in primary and diagenetic textures and associated lithologies, which can influence the subsurface dissolution processes. However, the mineral paragenesis and the presence of high solubility (of the order of hundreds of gr/l) evaporite minerals is generally one of the main intrinsic factors controlling the development of past and present dissolution-induced subsidence phenomena.

Chronostratigraphically, the evaporite formations record a wide time span from the Triassic up to the present day. Roughly, the evaporite deposition has occurred during the sedimentary and orogenic stages of the Alpine Cycle (Mesozoic and Paleogene time) and also throughout the post-orogenic stage.

Marine Evaporites

The most widespread episodes of evaporitic sedimentation took place in extensive shallow marine platforms during the Triassic. These evaporitic sequences are primarily made up of Ca-sulfates (gypsum/anhydrite) and halite embedded in variegated marls and clays (Ortí 1974, 1987). Borehole data show that salt can reach up to 150m in thickness in a single unit (Castillo 1974; Jurado 1990). The Triassic evaporites crop out in dispersed zones of the Alpine orogens (External Zone of the Betic Cordillera, Iberian Range, Pyrenees, Cantabrian Cordillera and Catalan Coastal Range), locally as diapirs, covering an area over 4,500km^2 (Macau and Riba 1962) (Fig. 1). Although very limited in exposure, sequences of nodular anhydrite up to several hundred metres thick are known from boreholes in the "lowermost Lias" (throughout the Alpine sedimentation realm) and upper Cretaceous deposits (mainly in the Iberian Range). These sulfates, locally bearing some halite, formed in highly subsiding supratidal environments and shallow lagoons, and they reach up to 700m in the "lowermost Lias", and up to 300m in the upper Cretaceous (Castillo 1974; Orti 1987, 1989; Salvany 1990). Close to the ground surface, these units are commonly represented by collapse-breccias of dolomitic composition (the so-called "Carniolas") resulting from evaporite dissolution and collapse/brecciation processes affecting the overlying carbonates.

Most of the exposed evaporite formations were deposited in Tertiary basins of variable tectonic origin (Anadón and Roca 1996; Sanz de Galdeano 1996). Broadly, the Paleogene synorogenic evaporites of the South Pyrenean domain (14,500km^2 in outcrop) are affected by compressional structures (folding and faulting), whereas the Neogene extensional evaporites (16,000km^2 of exposure) show a subhorizontal structure that is only disturbed by gentle tilting and vertical fractures (Fig. 1). Some of these basins underwent a progressive transition from open marine conditions to a continental endorheic regime with both surficial and underground water supplies.

During the Paleogene, the evaporitic sedimentation of marine origin was restricted to the southern foredeeps of the Pyrenees, where evaporite deposition took place during two major phases, the middle Eocene (lower Lutetian) phase and the late Eocene (Priabonian) phase (Orti 1997). The first phase is represented by the Beuda Gypsum in the southeastern sector of the Pyrenees. This formation, which has been tectonically incorporated into the Pyrenean orogenic (allochthonous) belt, is composed of up to 100m of anhydrite/gypsum and minor salt deposits (Orti and Rosell 1997). The second marine phase developed during the Priabonian regression in two subbasins: the Catalonian subbasin to the East, and the Navarrese subbasin to the West. Probably, the two basins were originally linked forming a single sedimentary through 300 km in length (the South-Pyrenean Potash Basin; Riba et al. 1983). These marine evaporites record a considerable accumulation of potassic minerals, including sylvite (KCl) and carnallite ($KMgCl_3 . 6H_2O$), together with halite and anhydrite/gypsum. In the Catalonian subbasin, these sediments -the Cardona Saline Formation, up to 300m thick- are located in the autochthonous zone, while in the Navarra subbasin, the potash sediments -the Guendulain Formation, of up to 100m in thickness- are incorparated into the allochthonous structural units of the Pyrenees (Rosell and Pueyo 1997).

Neogene marine evaporites occur very locally in the Penedés Basin (in the Catalan Coastal Range) as lower-middle Miocene Ca-sulfates, and largely in several intramontane basins of the Betic Cordillera. Some of these Betic basins host late Tortonian to early Messinian evaporites -mainly Ca-sulfates and salt-, as in the Fortuna, Lorca, and Granada basins (Dabrio et al. 1982; Playá et al. 2000), whereas the evaporitic sedimentation in the Sorbas, Nijar, San Miguel de Salinas, and Palma de Mallorca basins is mainly represented by primary gypsum Messinian in age (Rosell et al. 1998). For instance, the Messinian sulfates of the Sorbas Basin (up to 130m thick) are made up of 13-14 layers, with individual thickness between <1m and 25m, made up of large selenite crystals (Dronkert 1976, 1985).

Non-Marine Evaporites

The continental sedimentary infill of most of the large Tertiary basins in Spain contain extensive, thick evaporite formations of Paleogene and Neogene ages. These evaporite sediments developed in two main types of depositional settings: a) saline lakes of low ionic concentration, dominated by gypsum precipitation; and b) saline lakes of high salinity, precipitating Na-chloride (halite) and Na-sulfates (glauberite and thenardite) in association with Ca-sulfates (Ortí 1988, 1997). The main Tertiary basins hosting non-marine evaporites include the Ebro Basin (southern foreland basin of the Pyrenees), the Duero and Tajo basins (intraplate basins), the Calatayud and Teruel grabens (Iberian Range), and some intramontane basins in the Betic Cordillera, such as the Baza and the Granada basins.

Later to the accumulation of marine evaporites during the Priabonian regression in the South Pyrenean Potash Basin, the Foreland Ebro Basin became an endorheic basin which experienced extensive evaporite deposition. During the tectono-sedimentary evolution of this basin, the location of the main evaporite formations was controlled by the shifting of the depocenters, which showed an overall north to south migration (Ortí 1997). Immediately after the potash sedimentation in the two aforementioned basins, a broad non-marine evaporitc unit developed from Catalonia to Navarra during the late Eocene - earliest Oligocene, which is represented by the Barbastro Gypsum (up to 300m thick Ca-sulfates bearing halite) in the central and eastern sectors of the basin, and the Puente La Reina Gypsum (300-400m thick, mainly Ca-sulfates) in the western sector (Sáez and Salvany 1990). These formations crop out close to the Pyrenean margin along several diapiric anticline cores. From the middle Oligocene to the lower Miocene, thick evaporitic sequences were deposited in the western depocenter of the Ebro Basin (the Navarra and La Rioja regions). These sequences include the folded unit known as the Falces Gypsum. This unit, up to 1000m thick, crops out in the cores of diapiric anticlines and contains layers of anhydrite, glauberite and halite in the subsurface. The Lerín Gypsum, up to several hundred metres thick, is exposed in the limbs of long folds; borehole data indicate a complex mineral paragenesis which is made up of gypsum/anhydrite, glauberite, polyhalite and magnesite (Salvany 1997; Salvany and Ortí 1997). At the beginning of the Miocene, the basin depocenter shifted to the central sector of the Ebro Basin, where the Zaragoza Gypsum (upper Oligocene?-lower Miocene) was deposited (Quirantes 1978; Riba et al. 1983). This unit, over 150m thick in exposure, crops out as secondary gypsum in a wide area around Zaragoza city (Fig. 1). As revealed by borehole data, this formation contains in the subsurface a significant amount of Na-sulfates (glauberite and subordinated thenardite) and several halite units over 100m thick each one (Torrescusa and Klimowitz 1990; García-Veigas et al. 1994; Ortí and Salvany 1997). The youngest evaporitic sedimentation recorded in the Ebro Basin corresponds to the Cerezo Gypsum (upper Miocene), which is located in the Bureba corridor linking the Ebro and Duero basins. This unit reaches up to 200m in thickness, and is composed of gypsum and anhydrite with intercalated siliciclastic, carbonate, glauberitic and gypsiferous beds (Anadón 1990).

The evaporites in the Tertiary Duero Basin, aged middle-upper Miocene, form restrictred gypsum units (<100m thick) with significant proportion of unsoluble sediments (Ortí 1988; Mediavilla et al. 1996). The Tertiary Tajo Basin is segmented in two basins: the western sector or the Madrid Basin, and the eastern sector or the Loranca Basin. During the Paleogene, the evaporite deposition was restricted to the Madrid Basin, whereas lower-middle Miocene Ca-sulfates occur in the two sectors. The Madrid Basin contains thick Neogene Ca-sulphate sequences which crop out to the southwest of the city of Madrid (Fig. 1). These sequences bear substantial amounts of halite and glauberite in the subsurface (García del Cura et al. 1979; Ortí et al. 1979). The Miocene evaporitic sediments in the Calatayud Graben are made up of Ca-sulfates (over 200m thick) composed of secondary gypsum in outcrop, with considerable amounts of halite and Na-sulfates (glauberite and some thenardite layers) in the subsurface (Marín 1932; Ortí and Rosell 2000). The Teruel Graben hosts several Miocene to Pliocene evaporite units, above 150m in thickness locally (Tortajada Gypsum, Libros-Cascante Gypsum, Aljezares Gypsum and Orrios Gypsum), which are formed mainly by primary gypsum (Ortí 1991). Gypsum units (<100m thick) are known in the Neogene infill of the Granada and Baza basins in the Betic Cordillera. Finally, Quaternary evaporite deposition takes place or has recently occurred in some evaporative playas (De la Peña and Marfil 1986; Pueyo 1991; Pueyo and De la Peña 1991), in an estimated area of 500km^2 (Macau and Riba 1962).

On the basis of geochemical and isotopic studies, the genesis of the Tertiary non-marine evaporites in Spain has been interpreted as the result of recycling processes of Mesozoic (mainly Triassic, lowermost Liassic and upper Cretaceous) evaporites (Birnbaum and Coleman 1979; Utrilla et al. 1992). These recycling processes involve the dissolution and reprecipitation of large volumes of Mesozoic evaporitic sediments during the Tertiary. A large proportion of these solutes was supplied by means of underground water flows (Sánchez et al. 1999) which leached substantial volumes of Mesozoic evaporites via subsurface dissolution processes. In the present day stratigraphical record, such dissolution is reflected by the presence of collapse-breccias ("Carniolas") and "condensed sequences" which pass into the equivalent Mesozoic evaporitic sediments at depth. The underground outflow of solutes could have produced gravitational deformations (subsidence) in the overlying sediments owing to a progressive loss of basal support.

A large variety of subsidence phenomena caused by the subjacent dissolution of evaporites have been recognized in Spain. In some cases, they correspond to active processes which may have counterparts in the paleosubsidence structures recorded in the sediments overlying evaporites. Underground dissolution of the evaporites and the consequent subsidence of the sedimentary cover may take place under different hydrogeological conditions and in several stratigraphical contexts. In this paper, three main types of karst settings are differentiated for the subsidence caused by the subjacent dissolution of the evaporites: a) Uncovered karst where the evaporite formations are exposed to the surface; b) Interstratal karst when the evaporites are overlain by a sequence of lithified sediments (Jennings 1985; Quinlan et al. 1986; Ford and Williams 1989; Bosák et al. 1989; Klimchouk 1996) and c) Alluvial karst (or mantled karst) when the evaporite bedrock is covered by poorly consolidated alluvial deposits (Sweeting 1972; Jennings 1985; Quinlan et al. 1986).

2. DISSOLUTION-INDUCED SUBSIDENCE RECORDED IN MESOZOIC SEDIMENTS (INTERSTRATAL KARST)

In many areas borehole data demonstrates that the Mesozoic evaporite formations (Triassic, "Lower Liassic" and Upper Cretaceous) thin towards the ground surface or pass into a condensed sequence of collapse breccias ("Carniolas") formed by the dissolution of the previously existing evaporites and the brittle disruption of the associated carbonate sediments (Morillo-Velarde and Meléndez 1979; Ortí 1989; San Román and Aurell 1992; Gómez and Goy 1998; Bordonaba et al. 1999). Both the wedging out of the evaporite sequences and the collapse breccias reveal that large volumes of evaporites have been dissolved through underground flows causing the subsidence of the overlying sediments. These groundwater flows were one of the sources for the brines in the lacustrine systems where the Tertiary continental evaporites were formed (Sánchez et al.1990, 1999; Coloma et al. 1997). Although not studied specifically up to date in Spain, these dissolution and subsidence phenomena may have relevant geological implications as it has been demonstrated in other countries (Gustavson 1986; Johnson 1997; Ford 1997; Friedman 1997). It could determine thickness variations in supra-evaporitic units deposited synchronically with the removal of the soluble sediments (synsedimentary subsidence in solution-induced basins) or it could cause gravitational deformations in sedimentary units previous to the dissolution-induced subsidence (postsedimentary subsidence). On the other hand, the unknown presence of evaporite units or their original thickness may make lithostratigraphic and paleogeographic interpretations difficult. Besides, certain Mesozoic evaporite formations (primarily Triassic) constitute the detachment level of thrust belts which have been active during the Tertiary recycling process. It would be interesting to investigate about the role that the subjacent dissolution of evaporites have played in the kinematics of thrust systems (probably supplying evaporites in solution) and in the generation of deformational structures.

3. DISSOLUTION SUBSIDENCE IN TERTITARY SEDIMENTS (INTERSTRATAL KARST)

In several continental Tertiary basins, sediments of the endorheic basin fill overlying evaporitic formations are affected by synsedimentary and/or postsedimentary subsidence produced by the interstratal karstification of the evaporites. The synsedimentary subsidence gives place to local and anomalous thickenings in the sedimentary units coeval to the subsidence. These sediments fill basin-like structures with thickening of the strata towards the core of the structure, convergent dips and cumulative wedge-out systems at the margins (dissolution-induced depositional basins) (Gutiérrez 1998a). This type of subsidence synchronous with deposition has been recognized in Calatayud and Teruel grabens (Iberian Range). This is the case of the carbonate and detrital sequence overlying the Calatayud Gypsum in Calatayud Graben. One particular carbonate unit here ranges from 20 to 110m thick and shows cumulative wedge-out systems. The abrupt thickness changes have been related to the development of dissolution-induced basins during the deposition of the carbonate sediments (Sanz-Rubio et al. 1995, 1996, 1997). In Teruel Graben, the Neogene sediments are locally affected by synsedimentary subsidence resulting from the subjacent dissolution of the Triassic soluble bedrock. The sedimentological analysis of these sediments allows to infer how the synsedimentary subsidence has generated palustrine areas in closed depressions developed in alluvial fan systems. The dissolution subsidence in this palustrine areas was continuously counterbalanced with carbonate and tufa deposition. In places, the complex framework of onlapped dissolution-induced basins shows the anarchic space and time evolution pattern of the karstic subsidence (Gutiérrez 1998a). Karstic subsidence coeval to deposition has also been observed in Miocene sediments surrounding diapiric structures of Triassic evaporites in the Betics. This subsidence has been related to syndiapiric interstratal dissolution of evaporites at the rims of the halokinetic structures (Rodríguez-Estrella 1985).

The dissolution-induced postsedimentary subsidence (ductile or brittle) produces the sinking or gravitational deformation of the supra-evaporitic units later to their deposition. This type of subsidence may generate stratiform or local breccias and complex and anarchical deformational structures including flexures, synforms, antiforms (ductile rheology), large collapses, masses of brecciated sediments, fractures (brittle rheology). In two extensive areas of the Calatayud Graben, covering 8 and 14 km^2 in area, the Neogene sediments stratigraphically above the Calatayud Gypsum (including salt and Na-sulfates) have undergone postsedimentary karstic subsidence with a vertical displacement in excess of 200m (Gutiérrez 1995, 1996) (Fig. 2). In Teruel Graben, a synform 1.5km long and 150m in amplitude with a sharp pericline affects Mio-Pliocene sediments. One of the limbs of the structure shows recently active antithetic faults with fresh up-slope facing scarps. These gravitational structures have been attributed to a postsedimentary subsidence phenomena caused by the pervasive dissolution of the underlying Triassic evaporites (Gutiérrez 1998a) (Fig. 3). An additional interest is

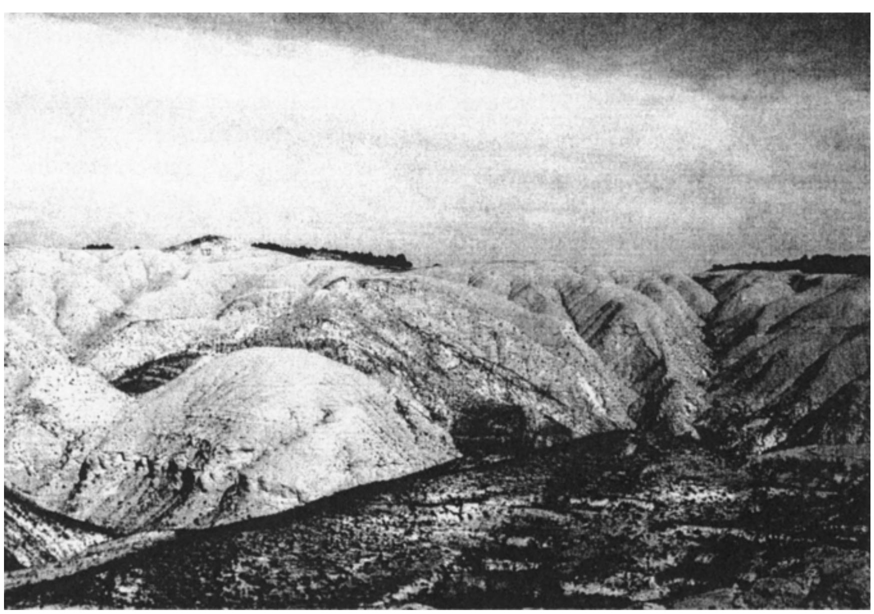

Figure 2. Collapsed and chaotically deformed detrital and carbonate Neogene sediments hosted within the horizontal (stratigraphically lower) Calatayud Gypsum. The undisturbed Miocene gypsum corresponds to the bare land. The sunk clastics and carbonates are partially covered by shrub vegetation. Note the sharp boundary between the supra-evaporitic units and the gypsum (Calatayud Graben, Iberian Range).

Figure 3. Limb of a synform in Mio-Pliocene sediments generated by passive bending due to the interstratal karstification of the underlying evaporite Triassic bedrock. These deformed and fossiliferous sediments affected by non tectonic gravitational deformations are located in the area selected for the definition of the Turolian stage (Teruel Graben, Iberian Range).

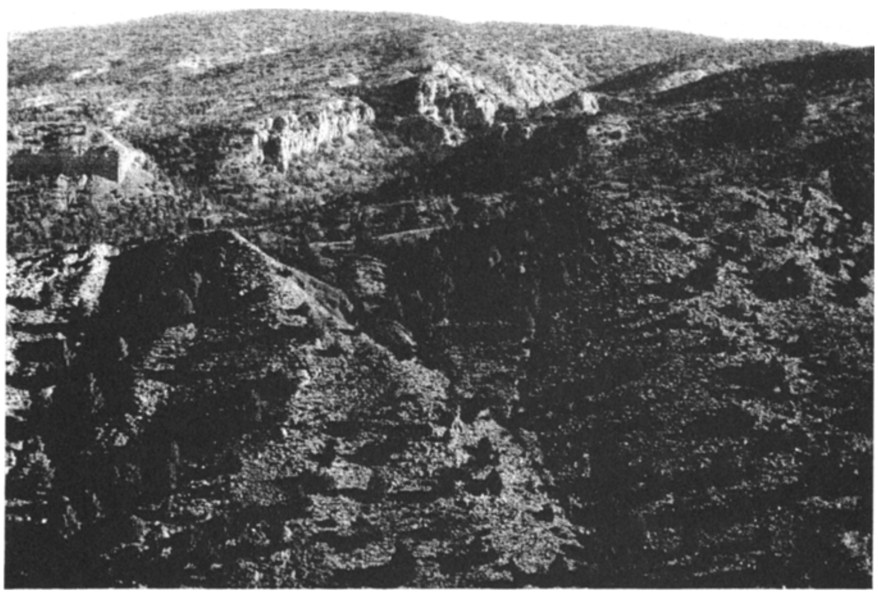

Figure 4. Dissolutional funnel (30m in diameter) developed in Miocene gypsiferous sediments filled with stratigraphically higher Neogene clays (Teruel Graben, Iberian Range). At the background, Jurassic carbonates in the fault-bounded margin if the graben.

that these deformations affect the Miocene sediments selected for the formal definition of the Turolian stage (Calvo et al. 1999). In this Tertiary basin, the interstratal karstification of Triassic and Neogene evaporites has also produced sediment brecciation, flexures (Adrover et al. 1978) and large funnels (30m in diameter) in the Miocene gypsum filled with Tertiary clays (Gutiérrez 1998a) (Fig. 4). Gentle folds and warped structures in Miocene limestone formations resulting from the dissolution of underlying Neogene evaporites have also been reported in the Tajo Basin (Martín-Escorza 1976). Conspicuous examples of gravitational flexures are found in the salt and gypsum bearing sequences of Remolinos salt mine area in the Ebro Basin (Mandado et al. 1984). In this area, the differential dissolution of the salt and gypsum beds gives place to disharmonic flexures and anarchic dips which tend to be directed towards the valleys (Fig. 5).

In the Banyoles-Besalú lacustrine basin, located in the western extreme of the Empordá postorogenic basin (Eastern Pyrenees) (Fig. 1), Plio-Pleistocene lacustrine sediments (including tufa deposits) show abundant ductile and brittle deformations produced by the karstification of the underlying

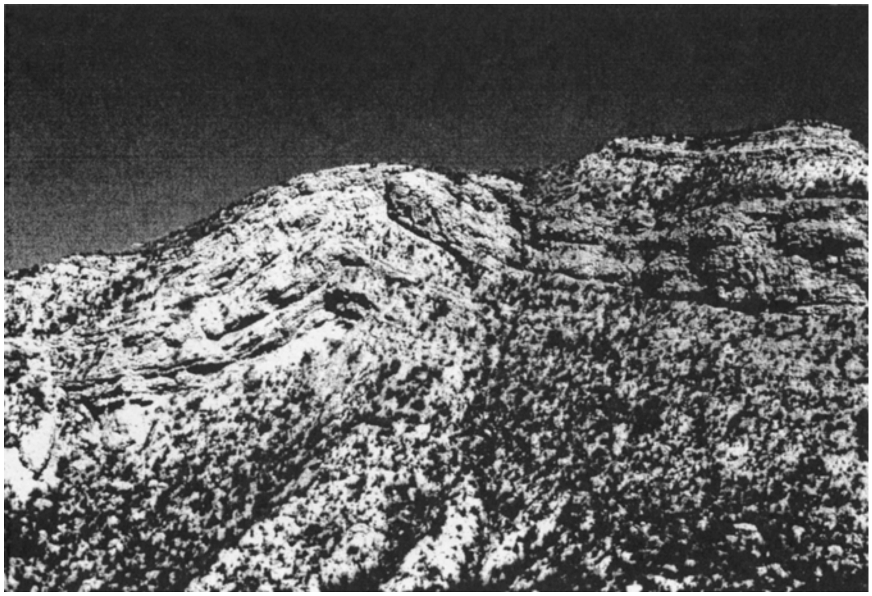

Figure 5. Gravitational flexure in Miocene gypsum and clay sediments resulting from the subjacent differential dissolution of salt layers (Zaragoza Gypsum in Remolinos area, Ebro Basin).

Beuda Gypsum (Solà et al. 1996; Fleta et al. 1996). These calcareous formations display funnel-shaped and cylindrical paleosinkholes up to 30m in diameter (Ros et al. 1996) filled with marls and clays which locally contain abundant Lower Pleistocene fossil vertebrates (Juliá and Villalta 1984). These paleodolines are equivalent to the present collapse-hosted ponds ("stanyols") that frequently form in the vicinity of Banyoles Lake. According to Juliá (1996) the paleosinkhole fills show a marked diachrony in the sedimentary record indicating the random space and time distribution of the subsidence process.

Other types of subsidence features have been recognized in the stratigraphical record of the Tertiary basins, both marine and continental. Van de Poel (1984) reported a 40m thick calcareous collapse breccia in the Sorbas-Nijar Basin related to the dissolution of the underlying Messinian evaporites. Collapse structures up to 2m wide and 2.5m deep filled with carbonate breccias and resulting from the solution of Miocene gypsum have been studied in Madrid Basin (Rodríguez-Aranda et al. 1996; Rodríguez-Aranda and Calvo 1997). In the Duero Basin, dissolutional pipes and troughs up to 5m wide occur in Middle Miocene gypsum sediments (Armenteros and Blanco 1995).

4. PALEOSUBSIDENCE RECORDED IN QUATERNARY ALLUVIAL DEPOSITS (ALLUVIAL KARST)

The most outstanding type of evaporite dissolution-induced paleosubsidence studied in Spain corresponds to the synsedimentary subsidence recorded in Quaternary fluvial terrace sequences overlying evaporite formations of some Tertiary basins (Gutiérrez 1996, 1998a; Gutiérrez and Gutiérrez 1998; Benito et al. 1998, 2000). These stepped terrace sequences inset in the sedimentary fill of the Tertiary continental basins are related to the progressive downcutting of the fluvial systems developed later to the capture and change from endorheic to exorheic conditions of these basins. This change in the morpho-hydrological regime of the Tertiary basins, from "endorheic-aggradational" to "exorheic-incissional", plays a decisive role in the development of the dissolution and subsidence processes, since large volumes of evaporites can be evacuated in solution by the exorheic drainage network. The subsidence in the alluvial plains is produced by the karstification of the evaporites underlying the alluvial deposits (alluvial karst). The soluble bedrock is dissolved by the water flowing through the alluvial aquifer and by rising groundwater flows since the fluvial valleys constitute the base level and discharge areas for regional underground flows. The main fluvial response is aggradation in the accommodation space created by subsidence in order to restore the equilibrium profile of the system. These subsidence phenomena may operate at different scales affecting to large stretches of a valley (kilometric-scale) or to localized areas (metric to hectometric-scale) producing depressions of variable size and geometry. The location of the subsidence may also have a complex space and time evolution pattern. The subsidence-induced deposition gives place to anomalous local thickenings of the alluvial deposits corresponding to certain terrace levels. The subsidence may also control aggradation and degradation processes in correlative marginal sedimentary environments like pediments and alluvial fans. In some cases, it has been observed how the deposits of a single terrace change in a short distance from less than 5m to more than 100m in thickness (Fig. 6). As consequence of the thickening, the sedimentary units corresponding to different terrace levels may be locally superimposed by angular

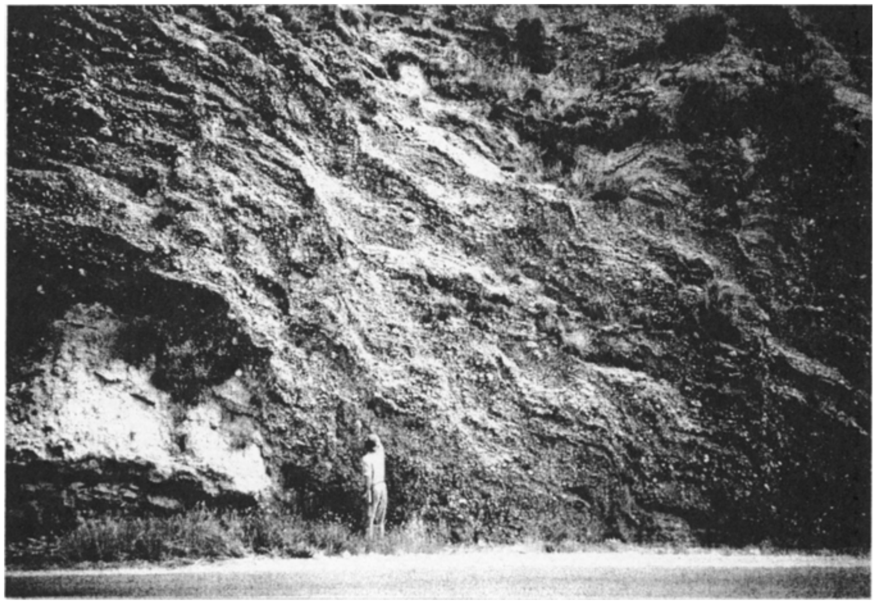

Figure 6. Synsedimentary deformations (flexure and fractures) in thickened Quaternary terrace deposits of the Tajo River overlying horizontal Miocene gypsum sediments (road linking Estremera and Illana villages, Madrid Basin).

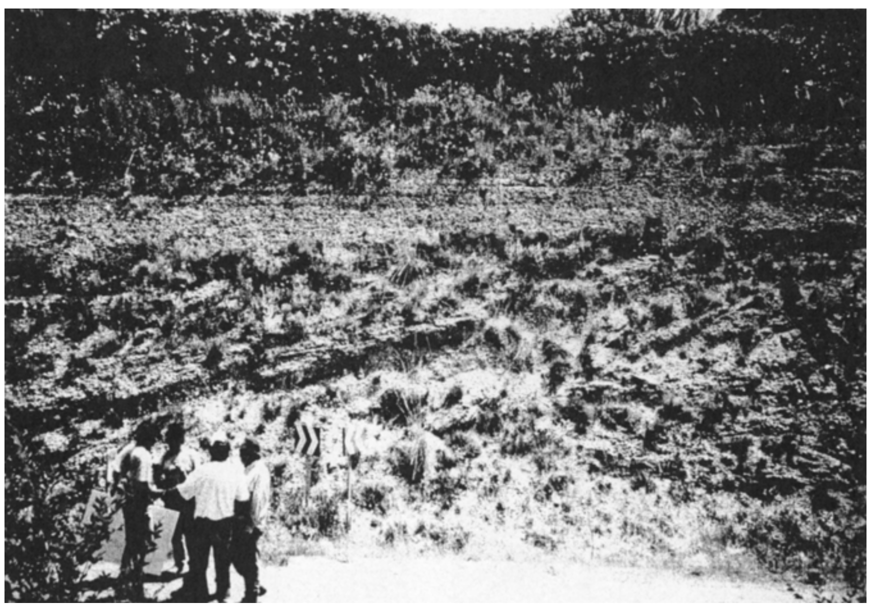

Figure 7. Quaternary deposits of two terrace levels of the Tajo River bounded by angular unconformity. The younger and undeformed terrace overlies a thickened and deformed older terrace deposit. The thickening and deformation of the older terrace results from dissolution-induced subsidence coeval to deposition (Madrid Basin).

unconformity or disconformity (Fig. 7). The variable magnitude of the subsidence (thickening) recorded in the different alluvial levels indicates that both dissolution and subsidence rate may be controlled by several factors: extrinsic factors like climate (paleohydrology) or neotectonics and intrinsic factors such as the lithostratigraphy of the bedrock (solubility).

The alluvium overlying the evaporite sediments, in cases with horizontal structure, is generally affected by numerous synsedimentary and postsedimentary deformational structures, both ductile and brittle. These gravitational structures include: basin structures with centripetal dips and growth strata towards the core (cumulative wedge-out systems) which may host palustrine deposits developed in swampy subsiding depressions, flexures (Fig. 6), paleosinkholes (local bending if ductile rheology or collapse-structures with well-shaped or funnel-shaped failure surfaces if brittle rheology) (Figs. 8, 9 and 10), extensional fissures and vertical collapse chimneys (Fig. 11). Some thickened terraces show intricate structures

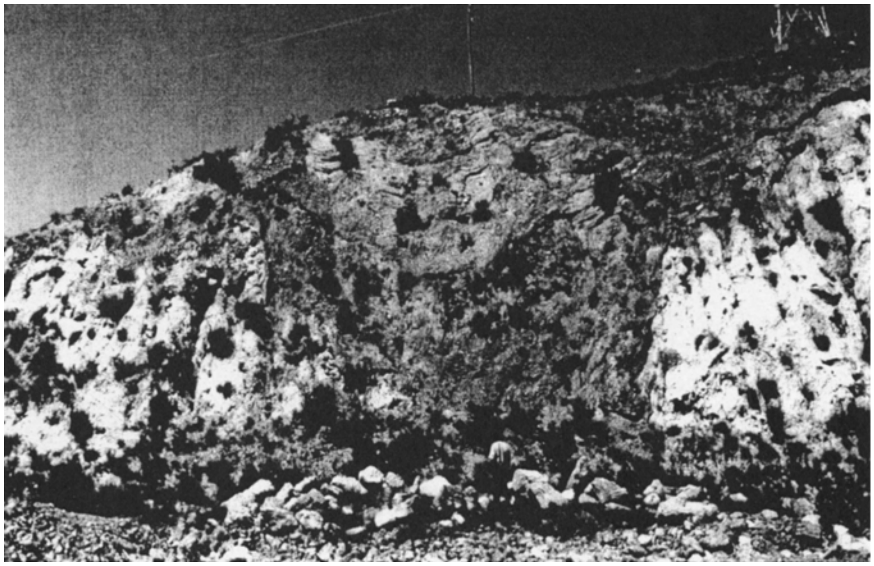

Figure 8. Paleosinkhole in Quaternary terrace deposits of the Alfambra River overlying the Tortajada Gypsum (Teruel Graben, Iberian Range). The flexure and synthetic and antithetic failure planes reveal that both bending and collapse mechanisms operated in the generation of the sinkhole.

Figure 9. Paleocollapse bounded by vertical failure planes in Quaternary terrace deposits of the Alfambra River overlying the Tortajada Gypsum (Teruel Graben, Iberian Range). A recent sinkhole next to the paleocollapse affecting a railway track which never came into operation. Photograph taken in June 1996.

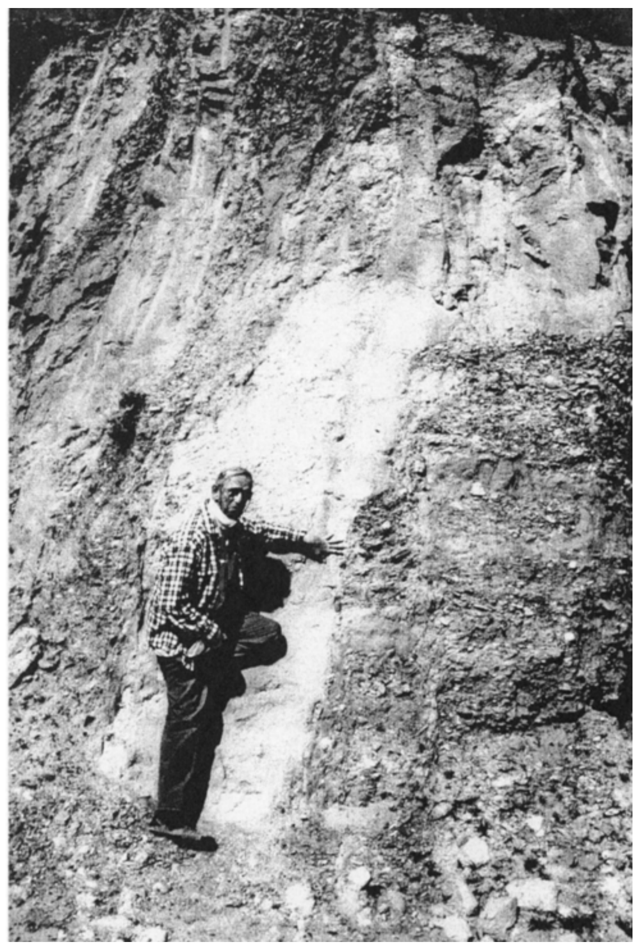

Figure 10. Margin of a paleocollapse with nearly vertical failure planes affecting Quaternary terrace deposits of the Jalón River overlying the Miocene Calatayud Gypsum (Calatayud Graben, Iberian Range). Dr. Kenneth S. Johnson 1.9m high for scale.

Figure 11. Collapse chimney affecting a thickened mantled pediment deposit in the Alfambra River valley (Teruel Graben, Iberian Range).

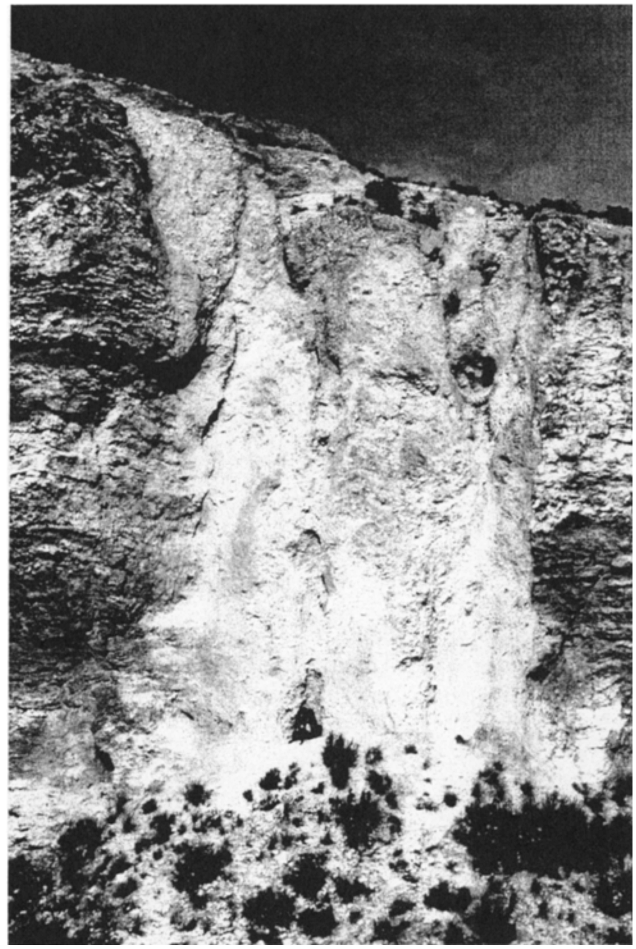

Figure 12. Vertical dissolutional conduit in the horizontal Zaragoza Gypsum filled with detrital deposits coming from the overlying Quaternary mantled pediment (right margin of the Ebro Valley in the outskirts of Zaragoza city). Rucksack 0.5m high for scale.

like large basins or troughs hosting smaller-scale synsedimentary basin structures with variable geometrical relationships or postsedimentary collapse structures affecting synsedimentary ductile deformations. This complexity reflects the apparently anarchic evolution pattern of the karstic subsidence.

Loose sediment deformations are also common in the thickened alluvium like overpressure-induced mud diapirs and a large variety of fluidization and liquefaction structures produced by high or excess pore fluid pressure. These are favored by the subsidence-induced high sedimentation rate with water-saturated detrital sediments (including low permeability clays and marls) and the sudden sinking processes. Some of these soft sediment deformations are gravel pockets (chaotic and irregular masses of clasts within a fine-grained deposits), dish structures, load casts, flame structures, sand dikes.

In outcrops where the alluvium-bedrock boundary is exposed, the evaporitic strata locally show dissolutional conduits (cylindrical or funnel-shaped) filled with detrital material including large clasts (pebbles and cobbles) coming from the overlying terrace or pediment sediments (Fig. 12). Cavities and collapse structures solely affecting the evaporites or both the bedrock and the alluvial cover have also been observed (Fig. 13). All these features reveal that two interconnected aquifers, both in the alluvium and in the evaporite bedrock may contribute to the subjacent dissolution processes. The paleosubsidence structures found in the stratigraphical record provide a valuable and practical information about the subsurface processes involved in the currently active subsidence which poses undesirable problems to development.

This type of paleosubsidence (alluvial karst setting) has been recognized in some of the most important fluvial systems of Spain, in stretches where they dissect evaporite sediments of several Tertiary basins. In the western sector of the Ebro Basin, dissolution-induced thickenings and deformations affect terrace deposits of the Ebro and Aragón rivers crossing

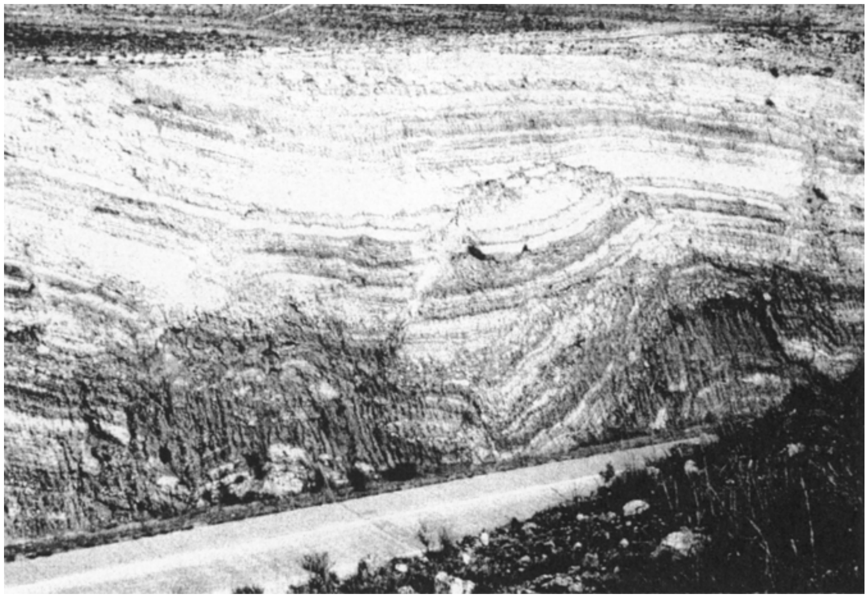

Figure 13. Collapse structure with a semicircular failure surface in the salt and Na-sulfates bearing Calatayud Gypsum. This collapse structure which has not affected the land surface reveals the presence of a deep-seated karst in the Jalón River valley. Trench in the Madrid-Zaragoza motorway (N-II road).

the folded Falces and Lerin Gypsum formations (Leránoz 1992, 1993; Hidalgo and Rosino 1992). In the central sector of the Ebro Basin, the main fluvial systems affected by subsidence caused by the karstification of the horizontally lying Zaragoza Gypsum are the Ebro River and the lower reaches of its tributaries: Gállego, Jalón, Huerva and Ginel rivers (Gutiérrez and Gutiérrez 1998; Benito et al. 2000). In this sector, dissolution-induced synsedimentary subsidence has also been analyzed in sediments filling small tributary valleys which record carbonate and peat deposition in palustrine environments developed in subsidence depressions (Arauzo and Gutiérrez 1994, 1995; Gutiérrez and Arauzo 1997). In the Gállego valley, the thickened terrace deposits fill a trough around 30km long and 8km wide generated by the suballuvial karstification of the halite and Na-sulfate bearing Zaragoza Gypsum. An isopach map of the Quaternary fluvial deposits shows the irregular bedrock-alluvium contact and allows to differentiate several depocenters. The magnetostratigraphic dating of the terrace sediments discriminate two periods of greater subsidence and alluvial thickening. During the first period (Matuyama, pre-0.78ky) the cumulative subsidence affecting to three terrace levels reached 165m. In the second period (Brunhes, post-0.78ky) a single terrace records a synsedimentary subsidence greater than 30m (Benito and Pérez-González 1993, 1994; Benito et al. 1996, 1998). The deposits of certain terrace levels of the Huerva and Jalón rivers also show thickenings of at least 60m (Gutiérrez and Gutiérrez 1998). At the right margin of the Jalón valley, fluvio-lacustrine tufa deposits disconformably overlying the horizontal Tertiary gypsiferous sediments (Zaragoza Gypsum) have been analyzed (Gutiérrez and Sancho 1997; Arenas et al. 1998, 2000). They show a complex framework of basin structures with synsedimentary thickenings (from 20 to 50m) and centripetal dips generated by dissolution-induced subsidence coeval to tufa deposition. Probably, these sediments are linked to the Jalón River Quaternary evolution and were generated in a paleospring area similar to the present ones located in the floodplain.

In the Madrid Tertiary Basin, evaporite dissolution paleosubsidence has been recognized in terrace deposits of the Tajo River and its tributaries Jarama, Tajuña, Manzanares, Henares and Guadarrama rivers. Royo Gómez et al. (1929) observed anomalous thickenings and paleocollapse structures in terrace deposits of the Manzanares, Jarama and Guadarrama fluvial systems. In the Jarama valley, the sedimentary units corresponding to at least two terrace levels are locally superimposed due to synsedimentary karstic subsidence (Pérez-González 1971). Terraces of the Manzanares River record alluvial thickenings in excess of 20m including subsidence-induced lacustrine deposits (Pérez-González 1980, 1994; Arche 1981). In the Tajo valley, between Zorita de los Canes and Villamanrique de Tajo, a sequence of 11 stepped terraces has been studied. One of this levels shows a sharp thickening downstream of Fuentidueña de Tajo, changing from 3m to more than 60m thick. This thickness increase matchs with the lateral change from detrital to evaporitic facies in the Tertiary bedrock (Pinilla et al. 1995). Paleosinkholes have been observed in Quaternary terraces in the Henares, Jarama and Tajuña rivers (López-Vera and Pedraza 1976; Silva et al. 1988a).

In Calatayud Graben (Iberian Range), 10 stepped alluvial levels have been identified for the Jalón-Jiloca fluvial system.

The deposits of some Lower Pleistocene (Matuyama, pre-0.78ky) terrace levels locally reach over 100m in thickness. In places, the Quaternary alluvial sediments overlying the Miocene Calatayud Gypsum are intensely deformed (Fig. 10), whereas the underlying soluble bedrock remains undeformed. The sedimentological analysis of some terrace deposits shows how the synsedimentary subsidence has controlled the fluvial style, the generation of depositional environments, the channel path and the sedimentary processes. The thickness magnitude and location of the different terrace deposits indicates that synsedimentary karstic subsidence has decreased and migrated downstream throughout the evolution of this system (Gutiérrez 1994, 1996, 1998a).

In Teruel Graben (Iberian Range), the terrace deposits of the Alfambra River are affected by subsidence in several sectors owed to the alluvial karstification of different evaporite formations. In the northern sector of the Tertiary graben (Villalba Alta-Escorihuela area), the Alfambra River terraces show local thickenings (>40m), paleosinkholes and basin-like structures hosting palustrine deposits with both synsedimentary and postsedimentary deformations and stacked sedimentary units bounded by angular unconformity. All these anomalous features are related to the suballuvial dissolution of the Orrios Gypsum (Moissenet 1983, 1985, 1989). In a lower reach where the Alfambra River crosses the Tortajada Gypsum (Cuevas Labradas-Tortajada sector), 11 stepped alluvial levels have been recognized. The synsedimentary karstic subsidence affects to several alluvial levels, including both mantled pediment and terrace deposits. The thickened alluvium (>60m) of a single terrace fill a dissolution-induced basin more than 3km long. Some outcrops show magnificent paleosinkholes (Gutiérrez et al. 1985; Moissenet 1989) (Figs. 7 and 8) and uncommon "gravel pockets" interpreted as fluid escape structures (fluidization). The lithostratigraphic composition of the sediments filling the Tertiary graben is considered to be the main factor controlling dissolution and subsidence during the Quaternary evolution of this fluvial system (Gutiérrez 1998a, b). Further downstream, to the south of Concud Fault, the sediments of a particular terrace show anarchic gravitational deformations and a sharp thickness increase reaching more than 55m. These anomalous characteristics have been related to the dissolution of the Triassic evaporite bedrock (Gutiérrez 1998a). The terrace deposits host an important archeological and paleontological site (Cuesta de la Bajada), Lower Pleistocene in age. The preservation and concentration of fossil and archeological remains found in this site have been explained by the high subsidence-induced sedimentation rate in the fluvial system which attenuates the biostratinomic dispersion of the elements (Santonja et al. 1997).

Deformations and anomalous thickenings affecting Quaternary alluvial deposits overlying evaporites have also been reported in geological settings different to the Tertiary continental basins. In the south-eastern sector of the Iberian Range (Gestalgar, Valencia), terrace deposits of the Turia River over Triassic evaporites locally reach more than 40m in thickness (Martinez 1991). The Quaternary alluvial deposits linked to the Fluviá River in Besalú area (Girona) show abundant deformations, paleosinkholes and thickenings (>60m) caused by the alluvial karstification of the Beuda Gypsum (Solà et al. 1996). In the Neogene Sorbas Basin (Betic Cordillera), the sediments of some terrace levels of the Aguas River overlying the Sorbas Gypsum display peculiar features including local thickenings and cumulative wedge-out systems, superimposed units bounded by unconformable contacts, local brittle and ductile deformations, fluidization and liquefaction (dewatering) structures and lacustrine deposits developed in sagging pools (Mather et al. 1991). Although these Quaternary deformations have been interpreted as diapiric (halokinetic), it is likely that dissolution-induced subsidence has contributed to the generation of these structures.

A frequent characteristic of the fluvial valleys developed in the Tertiary evaporitic terrains is their assymmetrical configuration, flanked by a sequence of stepped terraces (recording synsedimentary karstic subsidence) at one margin and a prominent linear gypsum scarp at the opposite margin (Fig. 14). This type of geomorphological arrangement is found in numerous valleys in the Ebro Tertiary Basin including the Ebro, Gállego, Jalón, Huerva, Ega, Aragón and Arga rivers; in the Tajo Tertiary Basin like the Tajo, Tajuña, Jarama, Manzanares and Henares rivers; the Jalón, Jiloca and Perejiles rivers in Calatayud Neogene Graben and the Alfambra river in Teruel Neogene Graben. These linear escarpments with vertical cliffs, commonly in excess of 100m high, locally show geomorphic anomalies such as hanging tributary creeks and triangular facet-like morphologies (Fig. 14). Several authors have attributed some of these valley margins to active normal faults (Ibáñez and Mensua 1976; Silva et al. 1988a, b). Other studies relate the genesis of some of these scarps to the overall downcutting and persistent lateral migration of the fluvial systems throughout their evolution (Gutiérrez et al. 1993, 1994; Gutiérrez 1998a). Subsidence, especially active at the foot of the scarps where the soluble bedrock is mantled by a thin alluvial cover, tends to confine the channel at the scarped side of the valley. The rapid retreat rate of these gypsum scarps, causative of the hanging valleys, is favoured by river undercutting and the generation of numerous joint-controlled slope movements which are readily removed by fluvial erosion (both chemical and mechanical) (Navas 1988). A meaningful fact is that gypsum clasts are almost absent in the gravel channels of these rivers. The rectilinear pattern of the scarps results from the joint-controlled evolution of the cliffs.

These escarpments generally show numerous ancient and currently active slope movements, chiefly rock-falls, topples and rotational slides (Fig. 15). Commonly, the gypsum cliffs develop large joint-controlled stress release cracks which act as preferential water inflow paths. The percolating water widens these discontinuities at the top of the cliffs generating pipes, sinkholes and elongated closed depressions which may

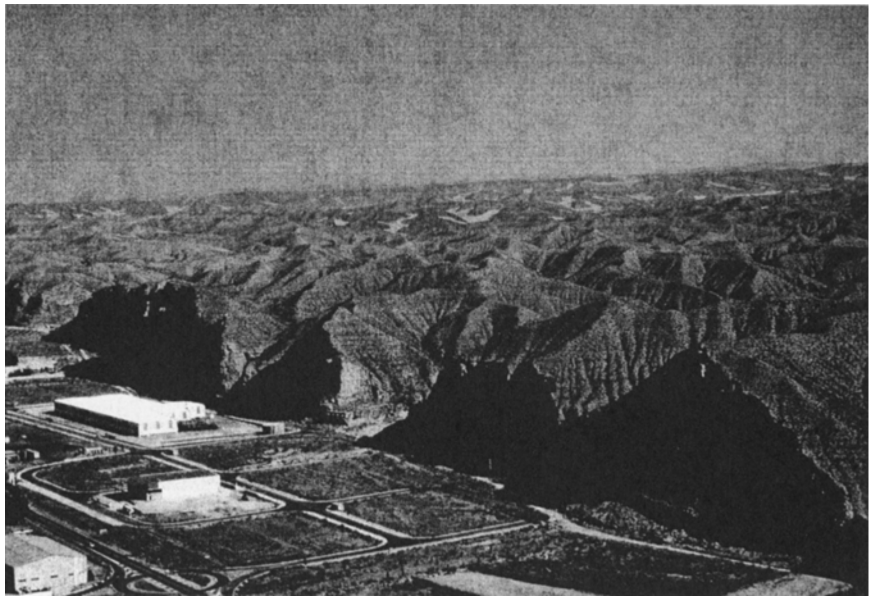

Figure 14. Joint-controlled rectilinear escarpment excavated at the left margin of the Ebro Valley in the Zaragoza Gypsum Miocene sediments (Alfajarín escarpment, Ebro Basin). Note the 100m high triangular facet-like morphologies and the hanging valleys draining small watershed in the gypsum outcrop.

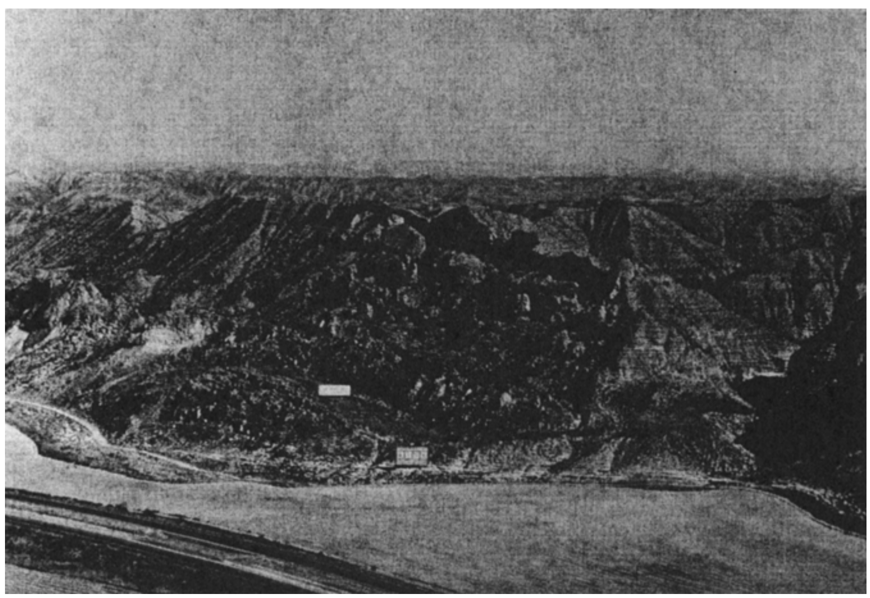

Figure 15. Multiple rotational gypsum slide in the Alfajarín scarp (left margin of the Ebro Valley). The stepped blocks with fresh scarped scars show a significant vertical displacement caused by the subjacent dissolution of the Zaragoza Gypsum. This active landslide has a large (>100m) corridor at the head produced by stress-release, joint-controlled dissolution and lateral spreading of the slided blocks.

reach more than 100m in length (Gutiérrez et al. 1993, 1994) (Fig. 15). The subsurface dissolution processes reduce the overall mechanical strength of the rock massif and high water pressure reduces the effective normal stresses and shear strength for a potential failure surface. In some landslides, the slided mass show significant vertical displacement (subsidence) with graben-like structures produced by subsurface evaporite dissolution and loss of basal support (Fig. 15).

Some gypsum slope movements have caused catastrophic effects involving casualties and significant financial loss. In Azagra, built at the foot of a gypsum scarp (Ega River, Navarra), rock-fall events occurred in 1856, 1874, 1903 and 1946 killed a total of 106 people (11, 91, 2 and 2 respectively) (Faci et al. 1988a; ITGE 1988; Diaz de Terán et al. 1997). Damage to property has also been reported in the village of Falces (Ega River, Navarra) (Faci et al. 1988b; ITGE 1988). In Calatayud city, at the foot of a vertical gypsum cliff flanking the Jalón valley (Calatayud Graben), a rock-fall killed one person in 1988. In June 1997 a gypsum-fall buried a recently built house (Gutiérrez 1998a). In some places, like Carcar (Ega River) and Cuevas Labradas (Alfambra River), slope movements have dammed the rivers and caused flooding of the alluvial plains (Ayala et al. 1988; ITGE 1988; Leránoz 1993; Gutiérrez 1998a). Presently, this hazard threatens to some reaches of several fluvial systems, like some sectors of the Ebro River in the Remolinos-Juslibol scarp (Gutiérrez and Gutiérrez 1998). The significance of subsurface dissolution and subsidence in the instability of slopes with evaporites was clearly demonstrated by the Santa Cruz de Moya landslide (Cuenca), occurred in April 1984 and affecting to Triassic clays and evaporites in the Iberian Range. The generation of this 100,000Tm slide was favoured by the subsurface dissolution of 40,000Tm of evaporitic sediments and the development of a sinkhole-saline spring at the foot of the slope (Durán and Val 1984b).

Very frequently, the anomalous features found in the Quaternary terrace deposits overlying an evaporitic bedrock (thickenings, superimposed units, deformations, fluidization and liquefaction structures) have been interpreted without considering the soluble nature of the substratum. In the central sector of the Ebro Basin, the local subsidence structures and dissolutional conduits filled with detrital sediments in the Ebro River terraces were erroneously related to old periglacial processes (Johnson 1960; Brosche 1971, 1972, 1978; Bomer 1978). In many cases, the deformations affecting the alluvial cover have been attributed to neotectonic activity, like in the Alfambra valley (Peña et al. 1981; Simón 1983, 1984) and in several fluvial systems in the Tajo Basin (Silva et al. 1988a, b; Giner and De Vicente 1995). In the Tajo Basin, the brittle deformational structures have even been applied to determine recent and present-day stress tensors (Giner and De Vicente 1995; De Vicente et al. 1996). The fluidization and liquefaction structures observed in these sediments are commonly considered to be the product of paleoseismicity (Giner and De Vicente 1995) without bearing in mind any other triggering mechanism in this peculiar karst setting (sediment loading, collapse-induced shaking). On the other hand, the superposition of the stratigraphical units corresponding to different terrace levels has lead to chronological mistakes. The interpretation of these controversial structures should consider all the possible genetic causes (including dissolution-induced subsidence) and argue criteria which could help to elucidate their origin.

5. ACTIVE SUBSIDENCE IN THE ALLUVIAL KARST SETTING

The currently active subsidence caused by the suballuvial dissolution of an evaporitic bedrock generates closed depressions (alluvial dolines or sinkholes) with a wide variation in size and morphology. Depending on whether dissolution acts at the alluvium-bedrock boundary or within the evaporite sediments, subsidence solely affects the alluvial cover or both the alluvium and the evaporitic bedrock. Two extreme subsidence mechanisms may operate depending on the mechanical behavior of the sediments: bending (ductile rheology) and collapse (brittle behavior) generating diffuse-edged shallow dolines and scarp-edged sinkholes respectively (Figs. 16 and 17). The collapse sinkholes are specially dangerous since they commonly occur in a sudden and catastrophic way. The study of both, the modern sinkholes and the paleosinkholes recorded in old alluvial sediments reveals that both mechanisms may take part in the subsidence doline genesis (Fig. 8). In addition to the sinking process, subsurface

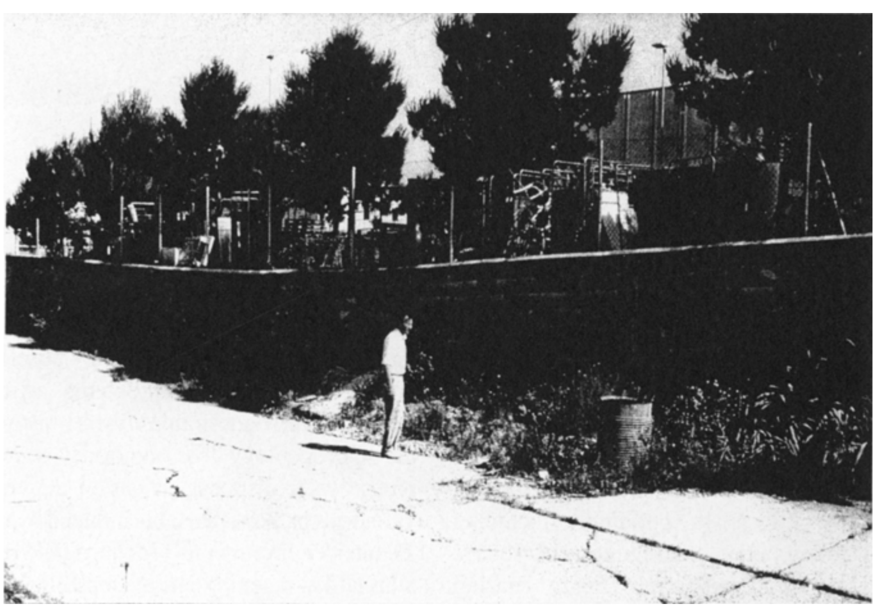

Figure 16. Diffuse-edged subsidence doline in the Portazgo industrial state built on a terrace of the Ebro River overlying the Zaragoza Gypsum (outskirts of Zaragoza city, Ebro basin).

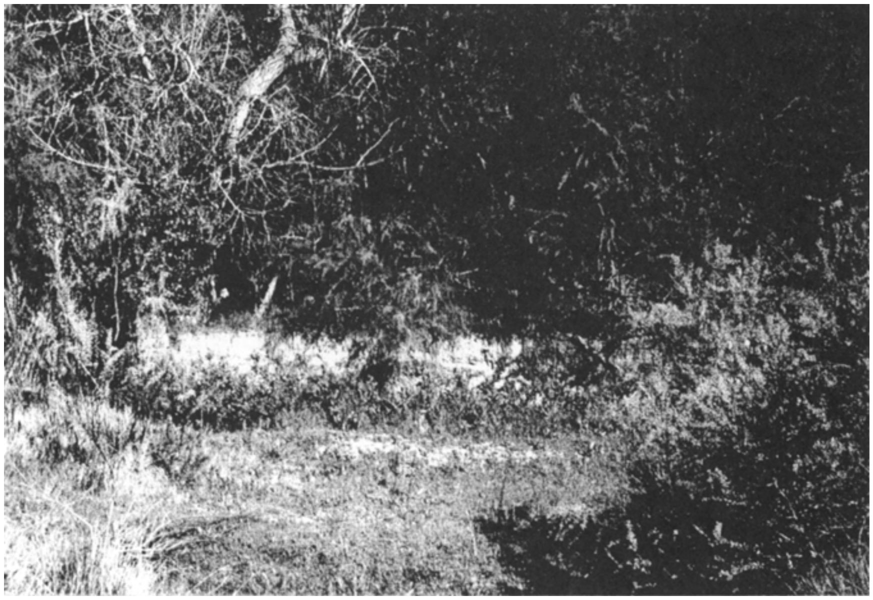

Figure 17. Scarp- edged collapse sinkhole in the Ebro River floodplain (La Alfranca Nature Reserve).

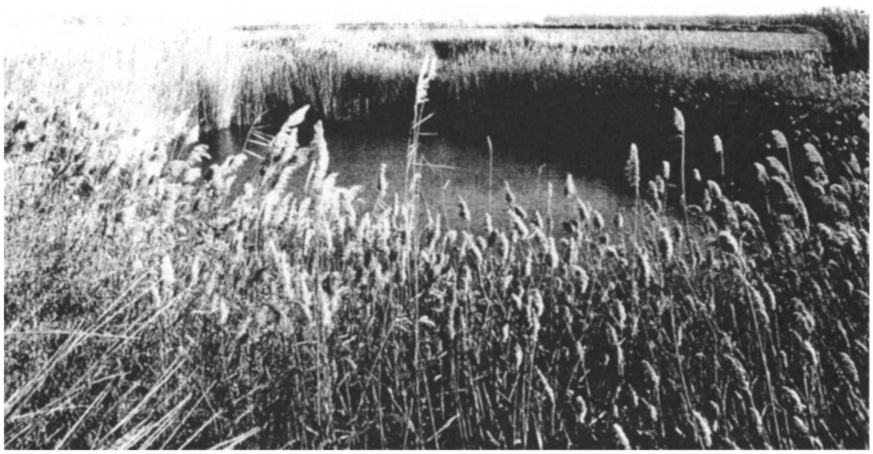

Figure 18. Pool with palustrine vegetation within a subsidence depression in the Ebro River floodplain. This wetland (Ojos de Matamala) in an alluvial sinkhole with high ecological value constitutes a legally protected area.

mechanical erosion (piping) and downward migration of detrital sediments through dissolutional voids may be involved in the subsidence phenomena (Gutiérrez and Gutiérrez 1998).

In some densely populated areas, the active subsidence constitutes a geohazard with great social and economic impact (Fig. 16). Subsidence affects to buildings, including invaluable historical monuments, communication routes, pipework, irrigation network and crop fields causing significant direct and indirect financial losses and a large number of inconveniences. Paradoxically, human activities enhance the threat accelerating or triggering the processes that lead to the ground subsidence. Frequently, when human-induced sinkholes cause high economic losses, legal actions and financial liability problems arise. These anthropic activities with undesirable effects mostly involve alterations in the hydrogeology like additional water input from broken pipes, water disposal, irrigation network and practices and variations in the water-table induced by water pumping. Other frequent environmental problems linked to the sinkholes in the alluvial karst setting are related to the use of the subsidence dolines to dump uncontrolled industrial and domestic waste. On the other hand, these closed depressions may intersect the water-table hosting wetlands (ponds and swamps) which locally constitute riparian environments of great ecological and aesthetic value, like some examples in the Ebro and Jalón valleys (Fig. 18).

Some of the most hazardous zones in Spain correspond to fluvial valleys developed in evaporitic sediments of Tertiary basins, like the Ebro Basin, Calatayud and Teruel grabens and Madrid Basin. In these areas most of the sinkholes occur in the lower alluvial levels and in zones where the evaporite bedrock is mantled by a relatively thin alluvial cover (unaffected by synsedimentary karstic subsidence). The hazard is locally very harmful since most of the human activity and development (vulnerable elements) is concentrated in the valley bottoms and on Quaternary alluvial deposits. In the Ebro Basin, the worst subsidence damage affect to the outskirts of Zaragoza city (Soriano and Simón 1995; Benito et al. 1995; Gutiérrez and Gutiérrez 1998) (Figs. 16 and 17). Documents reporting about the problems caused by sinkholes to the construction of an irrigation channel (Canal Imperial) date back to the end of the 18th century (Sástago 1796). In the surroundings of Zaragoza subsidence has been responsible for the abandonment of a recently built village, pulling down of factories, disruption of communication routes and water supply, a gas explosion, etc. A broad review of the geological hazards related to evaporite dissolution in the Ebro Basin is given by Gutiérrez and Gutiérrez (1998). In the historical city of Calatayud (Calatayud Graben), built on an alluvial fan at one margin of the Jalón valley, most of the old buildings are severely damaged by subsidence. These include historical monuments of great architectural and artistic worth dating back from the 12th century (Gutiérrez 1998a; Gutiérrez et al. 2000). In the Alfambra valley (Teruel Graben) sinkhole activity affects to an old railway route which never came into operation (Gutiérrez 1998a) (Fig. 9). In both the Alfambra and Jalón floodplains, subsidence gives place to large closed depressions (over 1km in axial length) which control the river channel path and its sinuosity (Gutiérrez 1996, 1998a).

In Madrid Basin, the rapid growth of Madrid metropolitan area towards the evaporite domain (SE) has propitiated the generation of numerous geotechnical problems in buildings (Mercamadrid and urban areas close to Rivas-Vaciamadrid) and infrastructures, specially the subway (Durán et al. 1989). A large number of actively subsiding closed depressions have been observed in the lower reaches of the Tajuña valley (Silva et al. 1988a) and in the Tajo valley (Pinilla et al. 1995). The subsidence hazard caused by the karstification of the Beuda Gypsum affects to alluvial levels genetically linked to the Fluviá River (Eastern Pyrenees, Girona). Collapse activity frequently damages buildings in Besalù village (Solà et al. 1996) and crop fields in La Plana de Tortellá where large endokarstic systems have been explored (Miret et al. 1999).

Although in an interstratal karst setting, a striking example of subsidence damage in buildings corresponds to the village of Orihuela del Tremedal (Teruel), in the Iberian Range. In this small village, the recent subsidence damage caused by the dissolution of Triassic evaporites overlaid by carbonate sediments has lead to the pulling down of more than 20 buildings. In Teruel city, a construction built on an old gypsum quarry filled with rubble and waste material has been distorted due to both dissolution and compaction (Gutiérrez 1998a).

6. EVAPORITE DISSOLUTION AND SUBSIDENCE IN LACUSTRINE BASINS

Subsidence caused by subsurface dissolution of evaporites may result or take part in the generation of lacustrine basins. Lake systems in depressions generated by dissolution-induced subsidence are relatively frequent in the Triassic evaporite outcrops of some Alpine Ranges. The so-called "Betic endorheism" corresponds to a large number of ephemeral lakes of great environmental interest developed in the extensive Antequera Triassic outcrops in Cádiz, Sevilla, Córdoba, and Málaga provinces (Durán 1984; Durán and Molino 1986; Durán et al. 1999). The Fuente de Piedra Lake (Málaga) together with Gallocanta Lake, is the largest lacustrine system in Spain ($13km^2$). Its genesis is related to large scale subsidence caused by the removal of evaporites by means of underground rising flows (Linares and Rendón 1999) (Fig. 1). The Medina Lake (Cádiz) results from the subsidence caused by dissolution of Triassic evaporites subsequent to its diapiric rising which affected to a terrace of the Guadalete River dated with archeological remains as Middle Pleistocene (Rodríguez-Vidal et al. 1993a, b). In the Iberian Range there is a large number of subsidence-generated lakes and paleolakes in the Triassic outcrops, like in Guadalajara Province or the Tortajada Lake in Teruel. The Gallocanta lacustrine system, in the central sector of the Iberian Range (Teruel and Zaragoza), is located at the bottom of a karst polje whose deepening by corrosion processes acting in the carbonate sediments ceased when the underlying impervious Triassic shales and evaporites where reached, favoring the development of the lakes. The recent morpho-sedimentary evolution of the lake system, which show conspicuous circular geometries, is partially controlled by karstic subsidence (Gracia 1992, Gracia et al. 1999). Some lakes in Triassic evaporites are also found in the Pyrenees, like the Estaña Lake in the Eastern Pyrenees (Lleida).

The most remarkable lacustrine basin generated by collapse activity due to evaporite dissolution corresponds to the Banyoles Lake in the Eastern Pyrenees (Girona). This lake $1.2km^2$ in area is formed by several coalescent collapse structures resulting from the interstratal karstification of the Eocene Beuda Gypsum. The gypsiferous sediments are removed by artesian underground flows coming from the nearby Garrotxa calcareous range. This artesian groundwater flow arise at the lake bottoms with high hydraulic head. According to Bischoff et al. (1994), gypsum dissolution in the karstic aquifer is enhanced by dedolomitization reactions. High resolution seismic reflection surveys reveals the presence of collapse structures (funnel and bowl-shaped) in the lake bottom (Canals et al. 1990). Historic collapses in the lake bottom have been documented and sudden water level fluctuations have been related to the sinking processes (Brusí et al. 1987, 1992). Nowadays, the formation of collapse sinkholes commonly hosting ponds (estanyols) in the vicinity of the lake is relatively frequent. These sudden collapses preferably occur during periods of low hydraulic head of the upwelling groundwater discharge (García-Gil et al. 1985; Brunet et al. 1985; Brusí et al. 1987, 1992). These sinkholes have locally damage crop fields and roads.

7. SINKHOLES IN EXPOSED EVAPORITE OUTCROPS (UNCOVERED KARST)

Dissolution subsidence also affects to the evaporitic sediments exposed to the surface without any kind of insoluble cover. In this karst context, the most common perceptible subsidence type is the sudden and localized generation of collapse sinkholes. These sinkholes generally show scarped edges and may reach several tens of meters in diameter and depth. The downward movement of the karst bedrock is due to the infall of the roof of an underground void. This void may be a dissolutional conduit or a cavity produced by the progressive fall of the ceiling of a deeper cavity which advances towards the ground surface by a stoping process. In some cases the sinkholes form dense doline fields and constitute the surface evidence and access point of cave systems. Spain has a considerable number of large cave systems developed in evaporite rocks, chiefly gypsum (Durán and Val 1984a; Ayala et al. 1986; Calaforra and Pulido-Bosch 1989, 1996). These caves, up to 4km long, are generally located at a low depth and constitute extensive underground dissolutional voids, frequently several thousands of cubic meters in volume (Durán and Val 1984a). The Cueva del Agua System (Sorbas, Almeria), 1350m long, is the longest gypsum cave in Spain, while Túnel del Sumidors (Vallada, Valencia), 210m deep, the deepest one.

The collapse sinkholes are relatively frequent in the extensive evaporitic outcrops (35,000 km^2), specially in the Triassic evaporites of the Alpine ranges which locally show evidences of recent or currently active diapiric activity. Sinkholes are relatively abundant in the vast Antequera Triassic outcrop (Durán 1984; Durán and Molino 1986; Calaforra and Pulido-Bosch 1999, Durán and López-Martinez 1999). The genesis of these collapse landforms, up to 50m in diameter, preferentially located in the center of salt-bearing diapiric domes, has been related with the halokinetic rising of the soluble sediments (Durán 1984; Calaforra and Pulido-Bosch 1999). The sudden formation of a large number of sinkholes have also been reported in the Triassic evaporites of the southern sector of the Iberian Range and its transition with the Betics, in Castellón, Valencia and Alicante provinces (Ibáñez 1980, 1983; Garay 1990a, 1991). According to Garay (1991), most of the newly formed collapses are located in areas where the hydrogeological conditions have been altered by human activity. In the western Pyrenees, the Estella Triassic diapir (Pamplona) has a collapse shaft 64m deep resulting from the sinking of a vertical cave (Eraso 1959). Collapse activity has also been studied in Triassic diapirs where large volumes of salt are extracted by solution mining (introducing unsaturated water and recovering a brine) like in Pinoso and Polanco diapirs. In the Pinoso diapir (Alicante, Betics) collapse depressions reach 40m in diameter and 50m in depth (Garay 1990b). Sinkholes in Polanco (Cantabria, Cantabrian Mountains) frequently host ponds (Cendrero and González 1980) suggesting that the underground cavities have been flooded. In this area, mining subsidence has severely affected buildings in Cabezón de la Sal town and has damaged the Santander-Oviedo road. In addition to the Triassic evaporites, sinkholes have also been formed in Upper Cretaceous gypsum outcrops in the Iberian Range, like in an area to the north of Cañamares village (Cuenca).

The endokarst developed in some outcrops of Tertiary evaporites has given place to collapse dolines. The Sorbas Gypsum outcrop, around 12km^2 shows a large number of sinkholes up to 50m in diameter resulting from the collapse of the dense network of caves (Pulido-Bosch 1982, 1986; Calaforra et al. 1991; Pulido-Bosch and Calaforra 1993; Calaforra and Pulido-Bosch 1997) (Fig. 19). The exceptional Estremera or Pedro Fernández cave (Madrid, Madrid Basin) is a joint-controlled maze cave developed in Miocene gypsum which was declared Artistic and Historical Monument in 1972 because of the extraordinary Neolithic and Bronze Age remains found in the cave (Almendros and Antón 1983; Ortiz 1997). This outstanding cave was discovered thanks to a collapse caused by a tractor (Eraso 1995). A peculiar example is the Sima de la Fumarolas in Granada Neogene basin (Montevives, Granada, Betics), a cave and collapse structure 9m deep developed in celestite ($SrSO_4$) mineral deposits (Fernández-Rubio et al. 1975). These deposits were formed by synsedimentary and/or early diagenetic replacement of stromatilitic carbonates interfingering and prograding onto Messinian evaporites (Martín et al. 1984). The walls and fissures of the sinkhole and cave are partially lined by strontianite ($SrCO_3$) and gypsum. The genesis of this joint-controlled small cave with a high ambient temperature has been related to the circulation of artesian thermal waters. Although not very common, collapse sinkholes have been observed in uncovered continental Tertiary evaporites, like in the Barbastro Gypsum, within the Ebro Basin, in the Tortajada Gypsum in Teruel Basin (Sánchez-Fabre 1989; Gutiérrez 1998a) and in Miocene gypsum outcrops in Madrid Basin (Garcia-Abad and Moreno 1994).

8. HUMAN-INDUCED CATASTROPHIC SUBSIDENCE IN THE MINED CARDONA SALT DIAPIR

Some of the most spectacular examples of natural and human-induced catastrophic subsidence are found in the Cardona salt diapir (Cardona 1990a, b), Priabonian marine evaporites deposited in the Catalan subbasin of the South Pyrenean Potash Basin. This ellipsoidal salt outcrop, declared Natural

Figure 19. Collapse sinkholes in the Sorbas Gypsum outcrop linked to the Cueva del Agua Cave System (Sorbas Basin, Betic Cordillera).

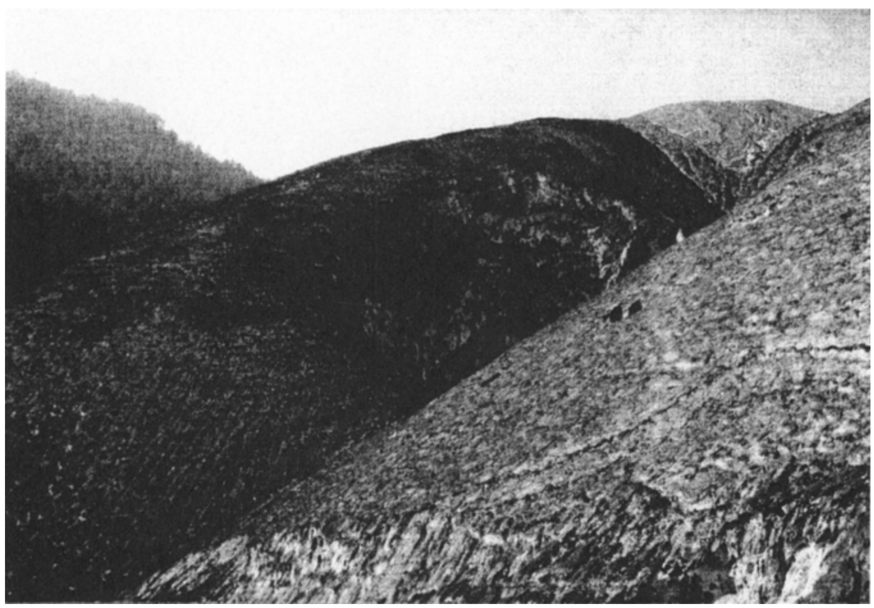

Figure 20. Collapse 50m in diameter formed in 1986 in a salt slag heap abandoned in 1970 (Cardona salt diapir, Ebro Basin).

Treasure by the UNESCO is probably the most extensive in Western Europe (1500 meters by 500). It corresponds to the core of a truncated diapiric dome which forms an elongated topographic depression drained by an ephemeral and intermittent creek (Vall Salina) and a small stretch of the Cardoner River, a tributary of the Llobregat River. The meander that crosses an extreme of the salt outcrop has been cut off by an artificial channel. However, during high stage, when the channelization is insuficient, part of the discharge flows through the natural channel. The highly saline water that flows out at San Onofre spring, which collects the underground water of the Vall Salina, is derived to the Mediterranean Sea through a 100km long pipe built to avoid the salinization of the Llobregat River, which supplies water to Barcelona city. The salt, containing K-Mg-chlorides (sylvite and carnallite), has been mined between 1930 and 1990 by means of underground galleries with a "zigzag" pattern reaching more than 1300 m in depth. The extraction works have produced dramatic changes in the landscape and in this rapidly evolving karstic hydrogeological system. Two slag heaps were formed by the dumping of the waste material from the mines. The "old one", around 3 million tons and 80 m high, was formed from 1930 to 1970. The "new slag heap" (1970-1990), about 7 million tons of salt with a higher purity (92% of salt) is being reworked for salt extraction at the present time.

According to historical documents dating from the beginning of the 19th century (Cardona 1990b), the underground solution of the salt has generated caves and frequent collapses both in the exposed salt and in the alluvial sediments of both the Vall Salina and Cardoner River (Martel 1902). Some of the sinkholes in the intermittent Vall Salina act as swallow holes or karst windows. The Bofia Gran is the largest closed depression (300 by 200 m), called *bofias* by the locals, which is composed by numerous absorption features generated by both collapse and surface solution. This depression hosts the entrance of the Forat Micó Cave, the largest cave system in the salt (640m) with a peculiar meandering pattern and a permanent flow of saline water. The salt caves evolve very rapidly due to the extremely high dissolution rate and their limited stability. During 25 years of speleological explorations, some caves have disappeared and some others have been created (Cardona 1995). Caves and collapse structures younger than 20 years old have been formed in the "old slag heap" (abandoned in 1970). The Riera Salada Cave, formed in this artificial salt mountain reaches 335m in length. In 1986, the collapse of this cavity produced a sinkhole 50m in diameter and 61m deep (Fig. 20). Besides, a large sinkhole formed in this slag heap is used to dump rubbish and pour sewage enhancing the natural dissolution.

Recently, new shallow galleries were excavated to obtain salt and create a store for industrial waste. In March 1998, the collapse of one of these galleries lead to a water irruption in the mine and a dramatic decline of the water-table. Now, the fresh water of the Cardoner River, former influent base level of the system, drains downwards into the gallery producing massive solution of the bedrock and the uncontrollable generation of an enormous number of sinkholes (Fig. 21) damaging roads, buildings and mine machinery. Dye tracing has demonstrated the water inflow from the Cardoner River to the galleries and the "underground capture" of the fluviokarstic system by the artificial cavities. In a large flat bottomed closed depression close to the river, a general subsidence in excess of 3m has been estimated for a time period lower than 1 year. In May 1998, newly formed dissolution passages were detected by drilling.

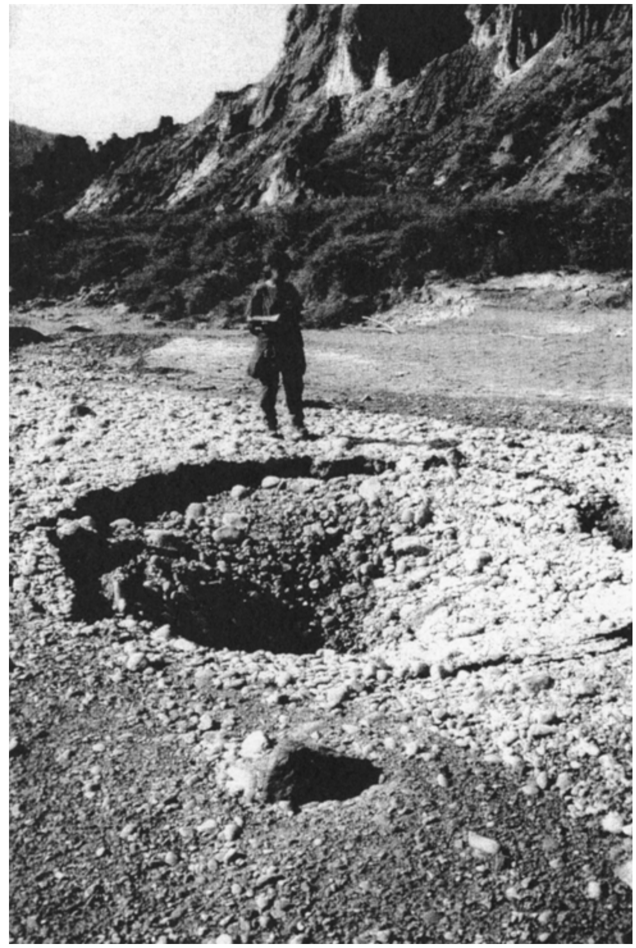

Figure 21. Active human-induced sinkhole (less than 15 days old) in the Cardoner River. Salt outcrop at the background (Cardona salt diapir, Ebro Basin).

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