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ORIGINAL ARTICLE

Natural and human-induced dissolution and subsidence processes in the salt outcrop of the Cardona Diapir (NE Spain)

P. Lucha · F. Cardona · F. Gutiérrez ·
J. Guerrero

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Abstract The Cardona Diapir in NE Spain, with a salt outcrop about 0.9 km^2 in area, has a well-developed endokarstic system that used to discharge into the Cardener River. Underground mining for potassium salt carried out from 1930 to 1990 caused significant changes in the topography and hydrology of the diapir. The accumulation of two halite slag heaps, totalling around 10 million tons, locally dammed the surface drainage, creating closed depressions and preferential zones of water recharge. The waters that infiltrated in one of these depressions, largely derived from uncontrolled sewage disposal, led to the generation of a 335-m-long human-induced cave excavated in one of the slag heaps. Moreover, the inflow of freshwater from the surrounding sandstone aquifer, caused by the excavation of a ventilation gallery, resulted in the generation of a 280-m-long cave. In March 1998, the interception of a phreatic conduit by a halite mine gallery 50 m deep caused dramatic changes in the hydrology and geomorphology of the diapir, including: (a) a sudden decline in the piezometric level of the karstic aquifer; (b) the inflow of freshwater and debris from the Cardener River into the endokarstic system and the mine galleries. A tunnel had to be constructed to divert the river flow from the salt outcrop; (c) massive dissolution of salt, creating new cavities and enlarging the pre-existing ones, including both mine galleries or cave passages. The 4,300-m-long Salt Meanders Cave was largely generated by the inrush of water from the Cardener River into the mine galleries; and (d) the generation of a large number of sinkholes in the vicinity of the Cardener River. An inventory of 178 sinkholes has allowed us to estimate minimum probability values of 4.7 and 8 sinkholes/km^2·year for time intervals previous and subsequent to the 1998 mine flood event, respectively.

Keywords Cardona Diapir · Salt karst · Sinkhole hazard · Human-induced subsidence

Introduction

The presence of salt formations at the ground surface or at depth may cause numerous environmental problems, including rapid erosion, regional uplift and subsidence, slope movements, sinkhole activity, and changes in the surface and underground hydrology. These potential threats are largely related to the peculiar characteristics of these rocks: low specific weight, plastic rheology and extreme solubility. The low-density salt bodies, when subjected to differential loading or affected by deviatoric tectonic stresses, may migrate laterally and upwards, causing deformation of the overlying strata and ground surface. The areas that feed the active salt structures may be affected by subsidence, whereas the zones of salt accumulation may undergo a progressive relative uplift (Trusheim 1960). On the other hand, the plastic rheology and high solubility of the salt favour the development of gravitational movements in slopes. A striking example corresponds to the ''salt glaciers'' (namakiers) formed in some salt diapirs in the Zagros Mountains of Iran (Talbot and Rogers 1980; Talbot and Jarvis 1984). The salt, when overlain by a thick overburden in a

P. Lucha (✉) · F. Gutiérrez · J. Guerrero
Edificio Geologícas, C/. Pedro Cerbuna 12,
50009 Zaragoza, Spain
e-mail: plucha@unizar.es

F. Gutiérrez
e-mail: fgutier@unizar.es

F. Cardona
C/. America 29 bis, 08041 Barcelona, Spain
e-mail: fcardonao@gencat.net

sloping terrain, may tend to flow towards the slope, causing deep-seated gravitational slope movements. The Grabens of Canyonlands (Utah), regarded as the largest subaerial mass movement in North America (~60 km^3), are the geomorphic expression of a lateral spreading phenomena caused by the flow of salt formations, overlain by brittle strata, towards the deeply entrenched Cataract Canyon of the Colorado River (McGill and Stromquist 1979; Huntoon 1982).

Surface lowering rates in salt outcrops are commonly on the order of several centimetres per year, and may reach more than 10 cm/year (Mottershead et al. 2006; Bruthans et al. 2006). Although the salt formations are frequently considered as impervious, they may host extensive endokarstic systems (Frumkin 1995, 1998, 2000; Bruthans et al. 2000; Bosák et al. 1999), which constitute pathways for the rapid transport of pollutants. The dissolution of salt ultimately leads to the degradation of the surface waters. The karstification of salt by underground flows may cause a wide variety of subsidence phenomena. Large-scale karstification processes acting over long time periods may generate sedimentary basins (Johnson 1993; Hill 1996), synclinal troughs controlled by a major drainage (Gustavson 1986) and morphostructural depressions, both in the sea floor (Belderson et al. 1978; Jenyon 1986) or on land (Christiansen 1971; Anderson and Hinds 1997; Kirkham et al. 2002; Gutiérrez 2004). At a lower scale, the gravitational deformation and/or the internal erosion processes caused by the karstification of salt by groundwater may result in the generation of a wide spectrum of sinkhole types. The sinkhole hazard may increase dramatically when human activities propitiate the circulation of freshwater through salt formations. This sort of hydrological change may be related to: (a) the decline of the water table, favouring the access of freshwater to salt deposits, as in the Dead Sea coasts of Jordan and Israel (Arkin and Gilat 2000; Frumkin and Raz 2001); (b) the interception of a karstic conduit connected to a freshwater body or aquifer by mining operations, as in Cardona Diapir; (c) the connection of the salt body with a freshwater aquifer developed in adjacent formations; and (d) the influx of freshwater from an overlying aquifer or water body caused by mining, the collapse of mine galleries (Kappel et al. 1999; Andrejchuk 2002), or improperly sealed boreholes (Johnson 1989; Martinez et al. 1998). This paper describes the main natural karstic features of the exceptional Cardona salt outcrop in NE Spain and documents the dramatic effects caused by mining activities on the dynamics of the karst system.

Geological setting

The Cardona salt diapir is located in the eastern sector of the Ebro Tertiary Basin, in the southern foreland basin of the Pyrenees (Fig. 1). The sediments that crop out in the study area correspond to the marine Cardona Saline Formation, Upper Eocene in age and a series of Upper Eocene–Lower Oligocene detrital continental formations deposited after the Priabonian regression (Sáez and Riba 1986). These formations are affected by fold structures with prevailing NE-SW and NW-SE trends (Fig. 1). The tectonic style shows the typical characteristics of folded strata overlying evaporites, with wide and flat-bottomed synclines and narrow anticlines related to the migration of salt from the adjacent synclines and controlled by thrust structures (Sans and Verges 1995; Sans et al. 1996).

According to Pueyo (1975), the Cardona Saline Formation, which constitutes the Cardona salt diapir, from the bottom to the top is made up of: 5 m of anhydrite at the base, 200 m of massive halite (Lower Salt Member) and 50 m of halite and interbedded potassium chlorides (Upper Evaporitic Member). The tightly folded sediments exposed in the Cardona salt outcrop correspond to the Upper Evaporitic Member, composed of three units: A lower unit bearing sylvite (KCl), whose top is at a depth of 600 m in the Cardona Diapir, an intermediate unit bearing carnalite ($KCl \cdot MgCl_2 \cdot 6H_2O$) and an upper halite unit known as the ‘‘top salt’’. The halite of the Upper Evaporitic Member forms layers with microcrystalline texture several centimetres thick separated by clay partings less than 1 cm thick. The sylvite, with micro-mesocrystalline texture, occurs in 10–30-cm-thick beds showing a red to brown colour due to hematite inclusions. The carnalite shows a macrocrystalline texture with euhedral crystals (Esborrany 1997). Seismic data indicate that the planar base of the Cardona Saline Formation dips gently to the north and lies at a depth of 1,500 m (1,000 m below sea level) under the Cardona Diapir (Riba et al. 1975; Esborrany 1997).

In the diapir, the Cardona Saline Formation is overlain by the Suria Sandstone Formation and the Solsona Formation, upper Priabonian-Lower Oligocene and Lower Oligocene in age, respectively (Fig. 2). The Suria Sandstone Formation, around 325 m thick in the Cardona Diapir area, is composed of two members (Saez and Riba 1986; Esborrany 1997): (a) a lower member, 95–110 m thick, made up of alternating grey-bluish tabular sandstone layers and grey-green siltstone layers. The absence of outcrops of this member in the Cardona Diapir is attributed to the diapiric piercing of the Suria Formation by the Cardona Saline Formation (Fig. 2), and (b) the upper member is made up of a 250-m-thick alternation of reddish tabular sandstone layers and siltstone layers. The aquifer, composed by a 30-m-thick sandstone unit at the base of this member, has locally caused water seepages in the Cardona salt mine. The relatively lesser thickness of the Suria Sandstone Formation in the limbs of the Cardona Diapir seems to record the early development of a salt swell

Fig. 1 Geological setting of the Cardona salt diapir in the eastern sector of the Ebro Tertiary Basin

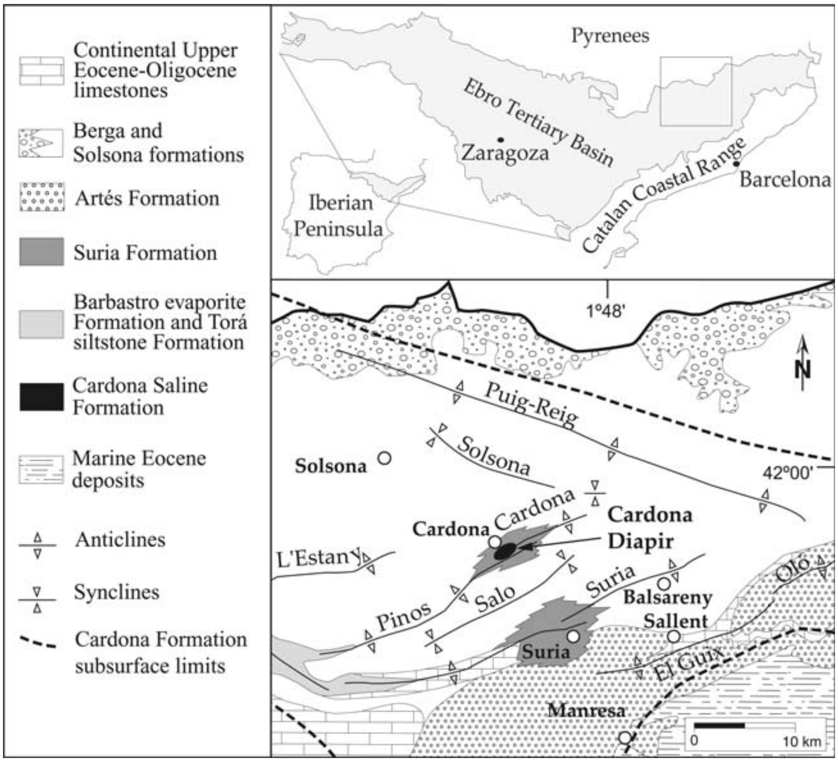
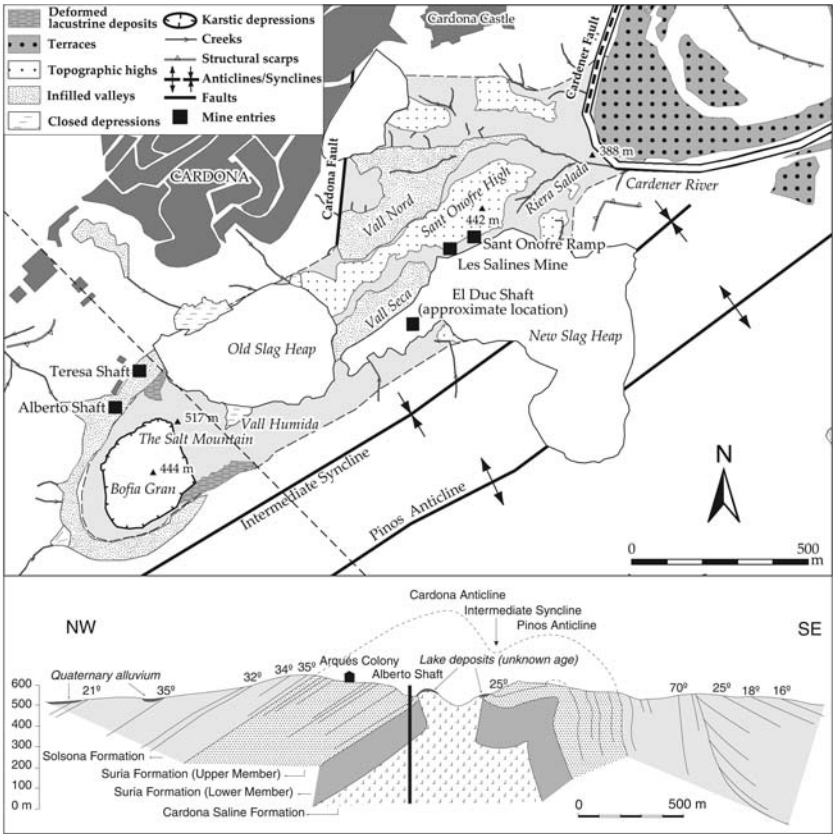


Fig. 2 Sketch showing the main morphostructural and topographic features of the Cardona diapir and geological cross section of the salt structure (modified from Riba et al. 1975). The trace of the cross section is indicated with a dashed line in the lower left corner of the map



coeval to the deposition of this formation. The Solsona Formation, locally more than 1,000 m thick, is formed by an alternation of arkosic sandstones and yellow-reddish shales.

The Cardona salt diapir is located next to Cardona village in the hinge zone of a composite NE-SW trending detachment antiform formed by the Cardona and Pinos anticlines and the Intermediate Syncline (Figs. 1, 2). The Cardona Anticline has its south-western termination around the Bofia Gran (Big Sinkhole) in the Cardona Diapir, and the Pinos Anticline has its northern termination to the east of the Cardona Diapir (Fig. 1). This asymmetric and south verging anticlinal structure has a gentle northern limb, a steep southern forelimb, and a maximum amplitude of 1 km (Sans and Koyi 2001; Sans 2003; Fig. 2). According to Sans (2003), the Cardona–Pinos Anticline developed where the Cardona Saline Formation reaches its greatest thickness and its basal slope is nearly horizontal. The syncline located between the Cardona–Pinos Anticline and the L'Estany Anticline to the north is welded with the subsalt strata, leaving each anticline as a closed salt system (Sans 2003; Fig. 1).

The strongly folded exposed salt body in Cardona can be described as a diapir (O'Brien 1968; Jackson and Talbot 1986) as it has pierced more than 300 m of overburden, showing a 2-6-m-thick melange of country rock and sheared salt at the contact with the sedimentary cover. According to Jackson and Talbot's (1986) classification, the Cardona diapiric structure can be classified as a salt stock (salt plug, salzstöcke, noyau de sel). It has a 250–500-m-wide and 250-m-high stem, and a 60–80-m-high and 400–700-m-wide bulb (Sans 2003; Fig. 2). The overburden in the crest of the Cardona–Pinos Anticline is about 400 m thick, whereas in the adjacent Solsona and Salo synclines it reaches 2,000 and 1,200 m in thickness, respectively (Sans and Koyi 2001; Sans 2003; Fig. 1).

Folding during the Lower Oligocene caused the Cardona salt to flow and accumulate in the Cardona–Pinos Anticline core from the adjacent synclines. Erosion in the crest of the growing anticline thinned the overburden above the salt, increasing the differential loading between the anticline and the synclines and aiding the salt to flow towards the Cardona–Pinos Anticline (Sans and Koyi 2001). In a subsequent stage, evaporites of the salt anticline started to pierce the overburden in the Cardona area. Physical analog models indicate that piercement of the Cardona Diapir occurred after 2.2 km of overburden was eroded from the crest of the Cardona–Pinos Anticline (Sans and Koyi 2001).

On and around the outcropping salts there is a 20–25-m-thick deformed, unconsolidated deposit made up of marls, sands and gravels that contain plant remnants, charophytes, gastropods and ostracods (Figs. 2, 3). A poorly constrained Pliocene-Pleistocene age has been ascribed to these lacustrine sediments by Wagner et al. (1971). They show conspicuous drag folds with subvertical limbs at the diapir rim created by upward movement of the salt. The recent and present-day upward movement of the salt is evidenced by the existence of the salt outcrop (Riba et al. 1975) and geodetic measurements carried out between 1979 and 1986 that indicate an average rate of uplift of 1 mm/year (Cardona Internal Report in Sans 2003). Uplift rates of several millimetres per year have been estimated in the Mount Sedom salt diapir (Israel) (Frumkin 1998). The Roman writer Aulo Gelio reported in the second century about the Cardona Diapir: *Quantum demas tantum acresc*, which means, ‘‘the more it (salt) is mined the more it rises’’ (Cardona and Viver 2002). The observation is probably the first written account of an active diapiric deformation ever reported.

Other structures associated with the diapir are the Cardona and the Cardener faults (Fig. 2). The N-S trending Cardona Fault could be interpreted as a down-to-the-east normal fault and as a fault with left-lateral strike-slip movement (Riba et al. 1975; Esborrany 1997). The inferred NNE-SSW Cardener Fault controls the trajectory of the Cardener River upstream of the Cardona Diapir (Esborrany 1997). The Cardona Fault seems to separate two sectors where the salt has behaved in different ways. To the west of the Cardona Fault, the salt structure has pierced the overburden. Between the Cardona and the Cardener faults, where the contact between the salt and the country rock is more irregular, the piercement of the overburden by the salt is not so obvious (Esborrany 1997).

Main natural geomorphic features of the salt outcrop

Berger and Aghassy (1982) propose three phases of diapir geomorphic development: (a) a positive-relief stage when

Fig. 3 Tightly folded salt in the Salt Mountain capped by deformed lacustrine deposits of probable Plio-pleistocene age

the salt structure forms a domal high with dominant radial drainage; (b) a breached stage when the differential erosion of the dome results in the development of a depression with centripetal drainage surrounded by inward-facing slopes; and (c) an obliterative stage when most of the topographic expression of the diapir is obliterated by erosion, and a floodplain and marsh form in its core. The NE-SW trending salt outcrop of the Cardona Diapir, covering approximately 0.87 km^2, shows different stages of geomorphic development (Fig. 2). The south-western end of the salt outcrop forms a mound of salt about 70 m high, protected by a deformed lacustrine detrital cover (The Salt Mountain; Figs. 2, 3). This positive relief is interrupted by a large polygenetic karstic depression 300 m long and 220 m wide called the Bofia Gran (the Big Sinkhole), which contains bedrock-collapse sinkholes, swallow holes, and spectacular karren fields (Fig. 4). To the northeast of the Salt Mountain the salt outcrop forms an elongated depression with two main flat-bottomed valleys, the Vall Nord and the Vall Seca-Riera Salada, that drain the topographic depression towards the Cardener River (Fig. 2). These two axial valleys are separated by the Sant Onofre topographic high, made up of halite bedrock covered by colluvium and alluvium. The Vall Nord and the Vall Seca-Riera Salada valleys could coincide approximately with the stripes where the carnalite layers intersect the topographic surface. The Riera Salada is narrower and is located closer to the diapir boundary than the Vall Nord because of the south vergence of the salt structure. The salt layers lie almost vertical in the south-eastern limb and dip between 65° and 75° in the north-western limb. The north-eastern margin of the salt outcrop is crossed by a tight meander of the Cardener River (Fig. 2). Boreholes and electrical logs on the south-western bank of the Cardener River indicate that the Cardener alluvium locally reaches more than 25 m thick (Esborrany 1997), recording synsedimentary subsidence phenomena caused by karstification of the bedrock.

Fig. 4 View of the Bofia Gran closed depression showing solution flutes and a sinking stream in a swallow hole

Landscape changes related to salt mining

The extraction of salt in the Cardona Diapir from Neolithic times (López de Azcona 1933; Marin 1926; Riba et al. 1975), and especially potassium-salt mining carried out from the 1930s, have caused a significant transformation of the original topography. There are references to salt mining in Cardona from Roman, Muslim and Visigothic times (Riba et al. 1975). In 1903, the first underground salt mine, known as the El Duc Shaft, was opened in Cardona (Fig. 2). The galleries, excavated by the room-and-pillar method 25 m beneath the ground surface, had a total height of 25 m (Esborrany 1997). In 1930, 4 years before its closure, 150,000 tons of salt had been extracted from this mine (Cardona and Viver 2002). Potassium-salt mining began in Cardona in 1931 (Riba et al. 1975). The Cardona potassium-salt mine consisted of two shafts located to the north of the Salt Mountain, the Alberto and the Teresa shafts, 1,020 and 720 m deep, respectively, and several galleries located mostly to the NW of the salt outcrop (Cardona and Viver 2002; Fig. 2). In 1972, a mining ramp was dug in the Sant Onofre High giving access to a steep, 1,340-m-deep gallery with a ''zigzag'' pattern (Fig. 2). In 1990, when the potassium-salt mines were closed in Cardona, the mining operations had extracted around 38 million tons of minerals, generating a total void volume of approximately 13 hm^3 from the excavation of some 210 km of galleries. The main impact on the landscape caused by the potassium-salt mining was the accumulation of two large slag heaps largely composed of halite (Fig. 2). The older one (Old Slag Heap), with 3 million tons, 90 m high and covering an area of 12.6 ha, was formed between 1925 and 1972 (Fig. 5). This slag heap dammed the drainage to the northeast of Salt Mountain, generating a closed depression known as the Vall Humida (Fig. 2). Georadar investigations indicate that the salt rock head is overlain by 1–6 m of clay-rich deposits in this enclosed depression (Canas et al. 1996). The ''New Slag Heap'', located on the south-eastern flank of the diapir, was created from 1972 to 1990. It contains about 7 million tons of salt, is 150 m high and covers an area of 25.7 ha (Cardona and Viver 2002). This accumulation blocked the Riera Salada valley, creating a closed depression known as the Vall Seca (Fig. 2). The extraction of halite from the New Slag Heap started in 1990 (Esborrany 1997). Later, in 1993, underground halite mining began with the excavation of Les Salines Mine in the Sant Onofre High, with two galleries located 50 and 85 m below the ground surface (Fig. 2). The voids excavated by the halite mining were conceived to store dangerous industrial wastes. In March 1998, the 50-m-deep gallery of Les Salines Mine intercepted a phreatic conduit, leading to a water eruption in the mine and a dramatic decline in the water table. Freshwater of the

Fig. 5 The Old Slag Heap with the Sumider Gran, a collapse sinkhole 50 m across, generated in 1986. The origin of this doline is related to the upward sloping of the roof of a cave developed in the slag heap. The cave was largely excavated by sewage waters

Cardener River, the former base level of the karst aquifer, started to flow into the Les Salines Mine leading to the development of new caves and the formation of a large number of sinkholes (Gutiérrez et al. 2001; Cardona and Viver 2002).

Natural and human-induced caves

Up to six caves had been documented in the Cardona salt outcrop previous to flooding of the Les Salines Mine in 1998:

(a) The 640-m-long Forat Mico Cave has it access point in a bedrock-collapse sinkhole located in the Bofia Gran (Fig. 6). This NE-SW trending cave has an altitude difference of 25 m and is composed of two levels gently inclined to the northeast with a tortuous meandering pattern (Cardona 1994). The development of this multi-level cave may have been controlled by both the entrenchment of the base level and the diapiric rise of the salt body. The larger section of the upper level suggests that it remained active for a longer time span (Palmer 2000). According to Frumkin's (2000) terminology, the lower level, 320 m long and with a height difference of 10 m, corresponds to an integrated cave system with a distinct open outlet. It displays a rudimentary branchwork pattern favoured by point recharge from a small catchment area (Palmer 2000). The meandering pattern of the lower passage seems to be related to its low gradient, which allows alluvium to settle down and shield the channel bottom, favouring lateral dissolution (Frumkin 1998; Cardona 2004). Most of the sections are tall and narrow, and some of them display flat roofs, suggesting a paragenetic origin modified by later incision under vadose conditions. Thus, it corresponds to a drawdown vadose cave in the sense of Ford (2000). The Forat Mico Cave was explored for the first time in 1967, the longest known salt cave in the world for 15 years.

(b) The 280-m-long Del Riu Cave is located right beneath the La Minilla gallery, following the same trajectory with a marked right angle (Fig. 6). La Minilla is a nearly horizontal ventilation gallery excavated in 1930 to connect the Teresa Shaft, at 82 m below the ground surface, with the outdoors at the foot of Salt Mountain. The Del Riu Cave was primarily generated by freshwaters coming from a sandstone aquifer of the upper unit of the Suria Formation intersected by the La Minilla gallery close to the Teresa Shaft. The existence of this human-induced cave was initially detected in 1966 by speleologists (Moreno and Victoria 1969). It has a rectangular section around 30 m wide and 10 m high, and its flat ceiling displays a meandering channel. The flat ceiling may be indicative of temporary phreatic conditions. The lateral expansion of this cave has been favoured by the sealing effect of clay deposits accumulated in the floor. A similar situation has been described in the salt caves of Mount Sedom by Frumkin (1998). The walls show well-defined dissolution notches that record stages of water-level stabilization. In its eastern end there is a small lake that was totally drained in 1998 when the Les Salines Mine intersected a phreatic conduit, indicating that the Del Riu Cave is hydraulically connected with the north-eastern sector of the diapir and the Cardener River (Cardona and Viver 2002).

(c) The 335-m-long Riera Salada Cave, also known as the Dels Derrubis Cave and the Rierol Salat Cave, is a branchwork cave carved in the halite debris accumulated in the Old Slag Heap (Cardona 1990). Consequently, its formation is younger than 1925. One of its entrances is the Sumider Gran, a subcircular collapse sinkhole 50 m across, formed in 1986 on the slag heap (Figs. 5, 6). The water flow in this cave, largely coming from the disposal of sewage in the closed depression located to the NW of the Old Slag Heap, used to emerge at the foot of the slag heap and infiltrate in the Vall Seca. From 1990 the cave water drains into a collapse sinkhole developed on the halite bedrock exposed in the floor of the passage (Cardona and Viver 2002).

(d) The Pinsota Cave, discovered in the 1980s, is a small chamber inlet cave located in a salt outcrop to the south of the Cardona Castle (Figs. 2, 6).

(e) The Sant Onofre Cave, about 100 m long, is located in the north-eastern sector of the Sant Onofre High at 5–15 m above the Cardener River channel. The outlet of this cave is the Sant Onofre Spring (Fig. 6). The speleologists who explored the cave in 1967 described it as 1.5 m wide and 0.5 m high with stinking waters revealing the hydraulic connection between sewage-disposal sites of Cardona village with the karstic aquifer during that time (Cardona and Viver 2002).

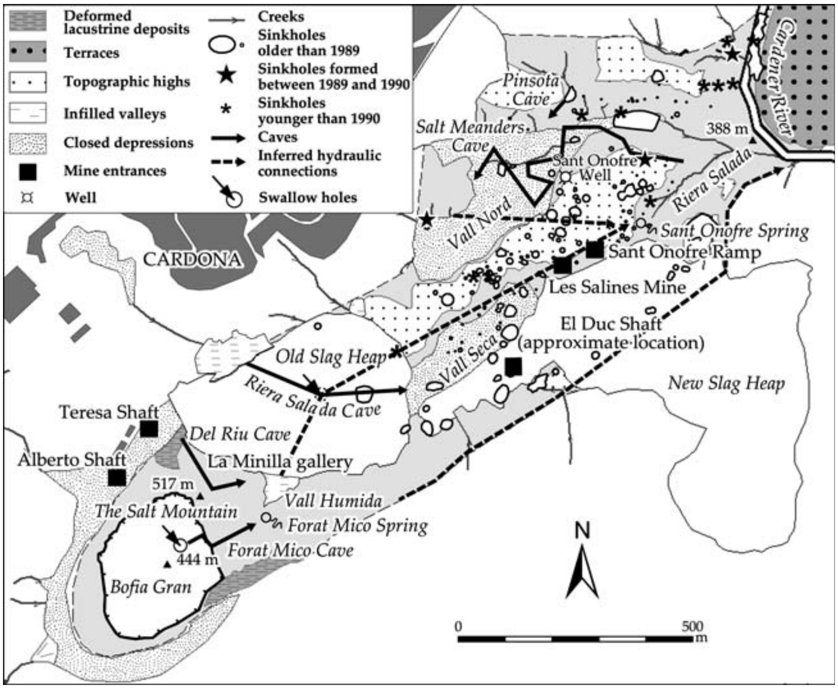


Fig. 6 Sketch showing the main geomorphic features of the Cardona Diapir. The *dashed black lines* represent underground hydraulic connections demonstrated by tracing tests, speleological explorations and inflows of water into mines

The inflow of water from the Cardener River into the mine galleries, caused by the connection of a phreatic conduit with the Les Salines Mine in March 1998, resulted in the generation of a cave system linked to the intercepted natural passage (Fig. 7). This cave system, known as the Salt Meanders Cave, with a total length of 4,300 m, can be considered the third longest salt cave in the world after the 5,685-m-long Malham Cave of Mount Sedom in Israel (Frumkin 2000) and the 5,010-m-long cave of Tři Naháč (Three Naked Men Cave) in Iran (Bruthans et al. 2000; Figs. 6, 7). The Salt Meanders Cave is composed of four main connected passages. The Upper Passage, 200 m in length, displays a slightly inclined profile, a relatively straight trajectory and a T-shaped cross section. The wide uppermost portion of the cross section has an arched roof, where preserved, and a flat base. The flat base is explained by the shield effect caused by the alluvium deposited in the channel bottom, which inhibited dissolution (Cardona 2004). As it is beneath the Cardener River level, it has been interpreted as a paragenetic phreatic passage through which brines from the karst system used to discharge into the Cardener River by upward flows. Very few phreatic salt passages have been described in the literature (Frumkin 2000). Its interception by the Les Salines Mine caused a dramatic drop in the base level of the karstic aquifer involving a reversal in the flow direction (Fig. 8). Subsequently, the Cardener River water started to flow into the mining galleries through this passage. The lower section of this passage records the incision developed under vadose conditions later than its interception by the mining operations. The eastern end of this passage, at about 70 m from the Cardener River and 12–24 m below the ground surface, contains a breakdown pile with abundant gravel derived from the Cardener River channel (Cardona and Viver 2002; Barrera 2000). A belt of sinkholes that coincides with the location of the Upper Passage has been identified on the surface (Barrera 2000). The rest of the passages of the Salt Meander Cave system—Fritz Künzel, Felix and Les Cascades, approximately 600, 800 and 1,500 m long, respectively—correspond to the meandering canyons carved in the floor of the mine galleries and ramps by the freshwater flow derived from the Cardener River. All of them display tall and narrow sections and were developed between March 1998 and June 2000. These passages show numerous terraces and hanging cutoff meander loops covered by gravels coming from the Cardener River (Fig. 9). The Fritz Künzel and the Felix passages are two slightly inclined, superposed passages that were generated during Cardener River floods that occurred in 1999 and 2000, respectively. The eastern termination of the Felix passage shows breakdown piles largely composed of the material used to fill the sinkholes triggered by the flooding of the mine at the confluence between the Riera Salada and the Cardener River (Cardona and Viver 2002). The Les Cascades meandering canyon, excavated in the steep Sant Onofre Ramp, is up to 40 m deep and has an elevation difference of 187 m. An entrenchment of 40 m in 2.25 years provides an incision rate of 17.7 m/year, significantly higher than the 8.8 mm/year rate measured in the Mount Sedom natural passages (Frumkin 1995).

Fig. 7 Map of the Salt Meanders Cave (modified from Cardona and Viver 2002)

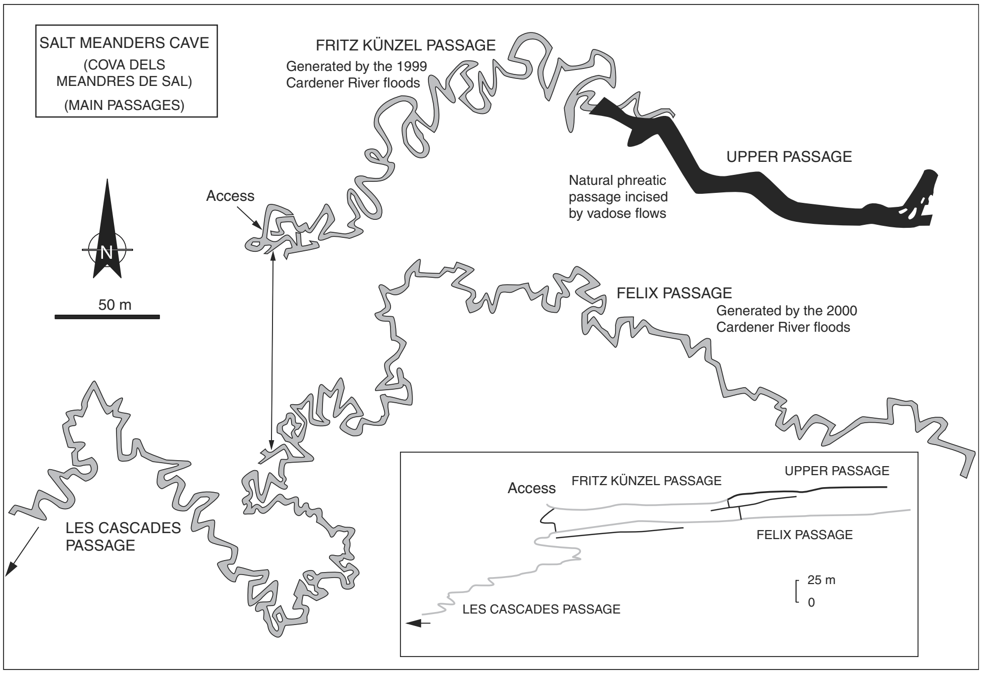
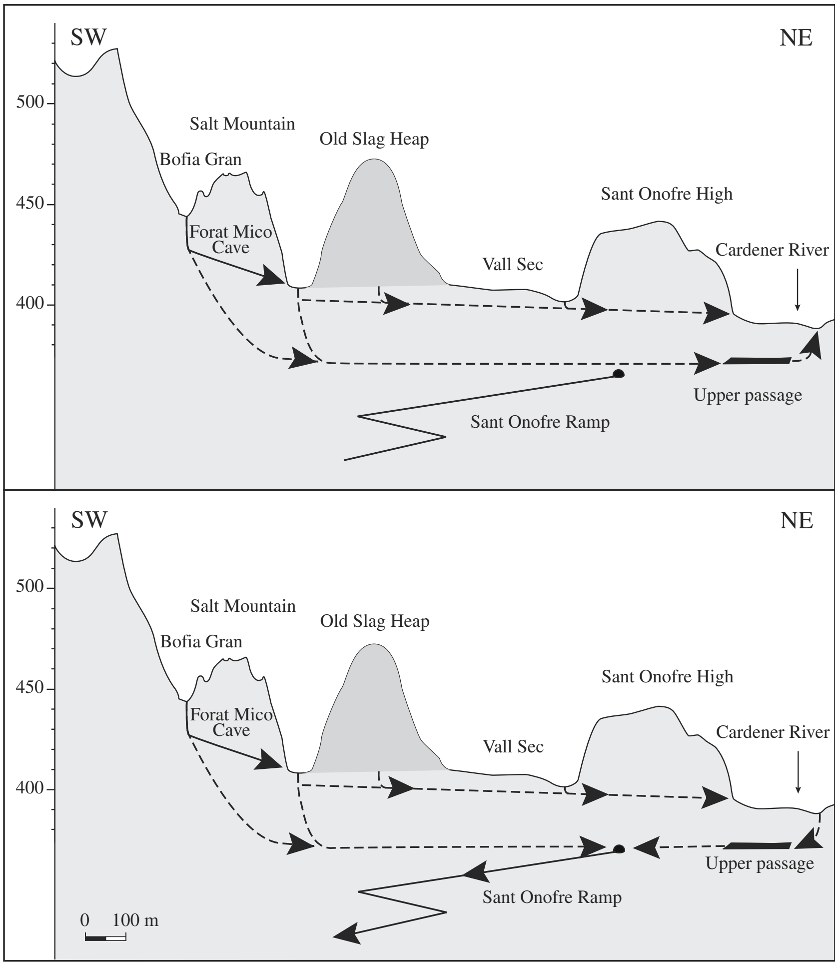


Fig. 8 Diagram illustrating the main effects in the underground hydrology caused by the interception of a phreatic karst conduit connected to the Cardener River by the Les Salines Mine in March 1998. *Dashed lines* indicate possible flow lines



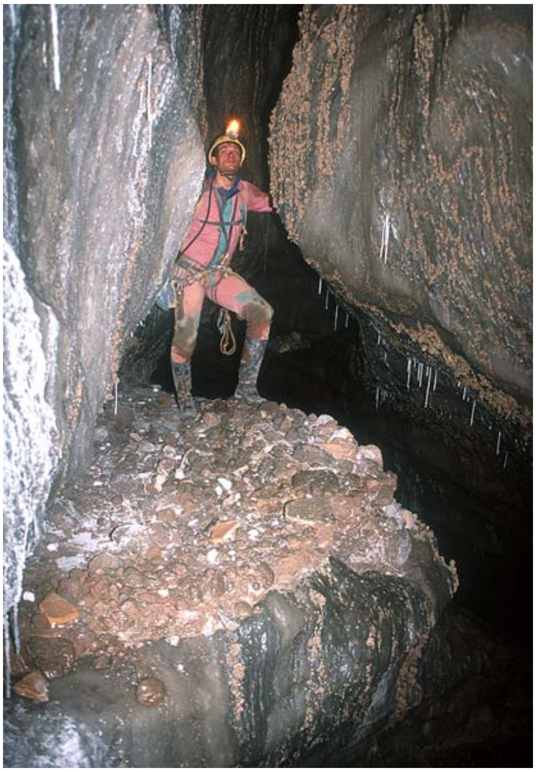


Fig. 9 Gravel derived from the Cardener River covering a terrace developed in the Salt Meanders cave

Surface and underground hydrology

The study area has a mean annual precipitation of 500 mm. The absence of saline springs in the surroundings of the salt outcrop indicates that there is no significant transference of underground water from the karstic aquifer to the Suria Formation and that the salt body constitutes an isolated aquifer that discharges into the Cardener River. Data from electrical logs and boreholes suggest that the karstification of the salt rarely occurs beyond 50 m below the surface (Esborrany 1997). In 1984, the annual recharge of the salt karstic aquifer was estimated at 290,000 m^3, corresponding to 96,000 m^3 of sewage waters coming from Cardona village (Geoconsulting 1984). Most of the sewage water used to be poured in the closed depression that exists between the Old Slag Heap and the northern flank of the Cardona Diapir, causing the formation of the Riera Salada Cave and ultimately the pollution of the karst system and the Cardener River water (Fig. 2). Some of the underground hydraulic connections inferred from tracing tests, speleological explorations and seepages in mines are depicted in Fig. 6. The Bofia Gran karstic depression and the Forat Mico Spring are connected through the lower level of the Forat Mico Cave. Before 1990, the infiltration waters from the closed depression located in the north-western flank of the Old Slag Heap used to flow through the Riera Salada Cave, appearing in a spring located in the eastern edge of the Old Slag Heap. This flow was intercepted by a sinkhole formed in the floor of the Riera Salada Cave in 1990. The connection between this sinkhole and the Sant Onofre Spring, approximately 1 km to the northeast, was demonstrated by a fluorescein test (Cardona and Viver 2002). Moreover, the water that infiltrates in the Vall Humida also surges in the Sant Onofre Spring. In the Vall Nord area, the brines of the karstic aquifer used to discharge into the Cardener River through the Upper Passage of the Salt Meanders Cave before its intersection by the Les Salines Mine in 1998. The underground flow path depicted along the south-eastern flank of the Cardona Diapir represents the karstic conduits developed at the contact between the salt and the country rock, which caused the flooding of the El Duc Mine in 1934.

It has been estimated that the salt diapir releases around 350,000 m^3 (≈11 l/s) of saline water per year through underground flow (Esborrany 1997). This water used to cause a significant degradation of the Cardener River flow, a tributary of the Llobregat River, which supplies water to Barcelona city. To partially overcome this problem, a pipe about 100 km long was constructed in 1989 to divert the brine to the sea. This pipe collects approximately 50% of the saline water flow of the diapir, including the Sant Onofre Spring (4 l/s), the brine pumped in the Sant Onofre Well (1 l/s), and the flow of the ephemeral Riera Salada Creek (0.1 l/s; Esborrany 1997). The Sant Onofre Well, located in the northern slope of the Sant Onofre High, was dug to pump the water that entered in the Sant Onofre Ramp in 1985. The rest of the surface and underground water that flows through the salt diapir, approximately 180,000 m^3/year, used to discharge into the Cardener River channel alluvium before the 1998 mine flood event. Prior to this flood event, the groundwater and the runoff used to supply between 115,000 and 65,000 tons per year of salt to the Cardener River (Fayas 1972; Geoconsulting 1984). Lowering rates of 2–3 and 5 cm/year have been estimated for the salt outcrop and the Old Slag Heap, respectively, from the growth rate of pedestals (Servicio Geológico de Cataluña 1992). Accurate measurements carried out by means of erosion pins and digital elevation models constructed with a total constructed with a total station yield lowering rates of 11–22 mm per 100 mm of rainfall (Mottershead et al. 2006).

Spatio-temporal distribution of sinkholes

In order to analyse the spatio-temporal distribution of sinkholes and the impact of the March 1998 mine-flooding event on the subsidence activity, an inventory of 178 sinkholes has been elaborated from the following sources of information (Fig. 6): (a) a thematic sinkhole map elaborated in 1967 (SIE-CEA 1967). This map includes the sinkholes developed in the Vall Seca-Riera Salada area before the accumulation of the New Slag Heap; (b) aerial photographs from December 1982, with an approximate scale of 1:13,500; (c) aerial photographs from September 1989 and September 1990, at an approximate scale of 1:5,000; and (d) detailed field surveys conducted in the autumn and the spring of 2004 and 2005, respectively. Although the elaborated database and maps constitute an incomplete sinkhole inventory, largely due to the scale limitations of the aerial photographs and the anthropogenic infill of some depressions, they allow us to obtain minimum estimates of the density and the probability of occurrence of sinkholes. The Old Slag Heap and the three sinkholes identified in this sector have not been included in the analysis so as to reduce the heterogeneity of the study area. The remaining 175 sinkholes, distributed over an area of 0.75 km^2, have a density of 233 sinkholes/km^2 and cover a percentage area of 10.5%.

The majority of the dolines corresponds to subcircular and scarp-edged bedrock collapse sinkholes that may also affect mantling deposits (cover and bedrock collapse sinkholes). The diameter of the dolines ranges between 135 and 1 m. However, most of the dolines are small and have diameters less than 2 m (Fig. 10). A total of 137 sinkholes have been identified in the 1967 map and the 1982, 1989 and 1990 aerial photographs. These sinkholes cover 9.9% of the salt outcrop (0.75 km^2, excluding the Old Slag Heap) and yield a density of 182 sinkholes/km^2. Some practical considerations may be inferred from the spatial distribution of this sinkhole population formed before December 1990 (Fig. 6): (a) The Sant Onofre High and the Vall Seca-Riera Salada areas were the sectors of the salt outcrop more susceptible to sinkhole formation. This spatial-distribution pattern may be partly related to the SE vergence of the salt structure; (b) the sinkholes tend to form clusters and belts with a prevailing NE-SW orientation, revealing the control exerted by structure on the subsurface dissolution processes; and (c) the high proportion of large sinkholes identified in the Vall-Seca-Riera Salada valley could be conditioned by the distribution of carnalite deposits (Floquet 1933). The comparison between the sinkhole maps produced with the September 1989 and the September 1990 aerial photographs, both 1:5,000 in scale, indicates that at least three sinkholes were formed during this time span in the salt outcrop (0.63 km^2, excluding the two slag heaps). These data yield a minimum probability of occurrence of 4.7 sinkholes/km^2 year.

A total of 38 new collapse sinkholes were mapped during the 2004 and 2005 field surveys. Most of these depressions are a few meters across, show fresh scarped edges and are primarily located in the confluence area of the Vall Nord and Riera Salada valleys with the Cardener River (Figs. 6, 11). According to the accounts provided by local speleologists and residents, the majority of these sinkholes occurred catastrophically soon after the mine flood event of March 1998. One of these sinkholes corresponds to an elongated depression about 100 m long developed in the thalweg of the Cardener River, which acted as a major swallow hole. This sinkhole population allows us to estimate a minimum probability of occurrence of 8 sinkholes/km^2 year for the time interval comprised between the 1998 flood event and the last field survey carried out in 2005. This value, obtained with a minimum number of sinkholes and a large time span is about two times higher than the sinkhole frequency estimated from the 1989 and 1990 sinkhole data, reflecting the impact of the mine flood event on the sinkhole activity. Some effects on the processes involved in the generation of sinkholes caused by the interception of a phreatic karstic conduit (Upper Passage of the Salt Meanders Cave) by the Les Salines Mine include: (a) the creation of new cavities and the enlargement of pre-existing ones by the rapid inflow of fresh water from the Cardener River into the endokarstic system and the mine galleries; (b) the reduction or elimination of the buoyant support caused by a sharp decline of the piezometric level; and (c) the replacement of a slow and highly concentrated phreatic flow by a rapid downward flow of freshwater under vadose conditions. This new flow regime favoured the prompt weakening of the salt-cavity roofs by dissolution and the downward migration of detrital deposits through karstic conduits (suffusion).

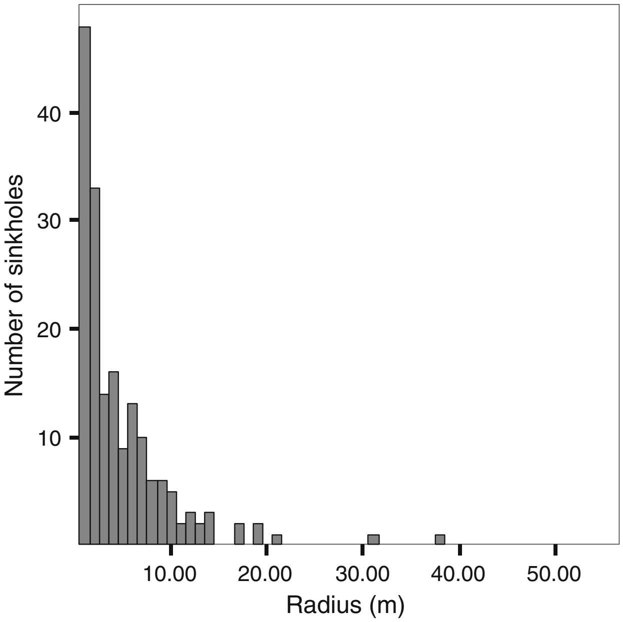


Fig. 10 Histogram relating the number of sinkholes and their radius

Mine-flooding events and detrimental effects

In addition to the March 1998 flood event, the Cardona salt mines have suffered from other major water entries coming either from intercepted karst conduits, the sandstone rocks that surround the salt diapir or from disrupted surface pipes (Esborrany 1997). In 1934 the El Duc potassium-salt mine was flooded by freshwater when one of the galleries breached the diapir walls. The water surged from the strongly karstified contact between the salt body and the sandstone aquifer units of the Suria Formation. In May 1985 water entered the Sant Onofre Ramp. The smell of the water allowed the mining engineers to infer a hydraulic connection in the karst system between this artificial cavity and the closed depression located to the NW of the Old Slag Heap, which was used for the disposal of sewage water. The Sant Onofre Well was dug to pump water from this ramp. In 1995, several seepages in the Les Salines Mine were attributed to the infiltration of water caused by the failure of a sewage-water pipe in the Vall Nord. The collapse of the pipe was due to the catastrophic formation of a sinkhole induced by leakages in the sewage pipe. In March 1998, the interception of a phreatic passage (Upper Passage of the Salt Meanders Cave) had dramatic consequences on the hydrology and geomorphology of the salt diapir, including: (a) a sharp decline in the piezometric surface of the karst aquifer changing numerous karstic conduits from phreatic to vadose conditions; (b) the artificial creation of a new base level causing the underground discharge of both the Cardener River fresh water and the karst aquifer brines into the Les Salines and Sant Onofre mines; (c) massive dissolution of salt involving the creation of new subsurface voids and the enlargement of preexisting ones. The flood event resulted in the generation of the 4,300-m-long Salt Meanders Cave, primarily composed of a karstic passage connected to three main meandering canyons carved in the floor of mine galleries which can be correlated with flood events of the Cardener River; and (d) the occurrence of a large number of sinkholes. Fortunately, the flood event took place after the project on using the mine galleries for the disposal of industrial wastes (mainly heavy metals) had been rejected in November 1997. Some of the main detrimental effects caused by this flood event on the mining industry and the infrastructures include: (a) the economic losses related to the temporary interruption of mine production; (b) damage caused by the sinkhole activity on the mine infrastructure; (c) the excavation of a tunnel in the neck of the Cardener River meander, with a total cost of 6.6 million euros, to divert its flow from the salt outcrop; (d) the construction of a new stretch of the C1410a road to bypass the salt outcrop affected by catastrophic subsidence (Fig. 11c); and (e) the continuous infill of sinkholes.

Fig. 11 Sinkholes induced by the March 1998 mine flood event in the vicinity of the Cardener River. **a** A composite collapse sinkhole generated in the Cardener River bed through which water sank into the mine galleries. **b** Collapse sinkhole affecting the brine collector at the confluence between the Riera Salada and the Cardener River. **c** Sinkhole affecting the old C1410a Road

Conclusions

Rock salt is frequently considered an impervious material and an appropriate lithology for the storage of waste material. However, in the Cardona Diapir there was strong geomorphic and hydrochemical evidence for the existence of a network of karstic conduits that discharged into the Cardener River: (a) large bedrock collapse sinkholes; (b) areas with internal drainage; (c) caves explored by speleologists, like the 640-m-long Forat Mico Cave; and (d) an increase in the salinity of the Cardener River flow, which could not be solely explained from the input of solutes by surface runoff and the discharge of groundwater through cover deposits. About 210 km of galleries were excavated from 1931 to 1990 by potassium-salt mining, creating a total volume of 13 hm^3. This mining led to the accumulation of two large slag heaps made up of halite with a total volume of 10 million tons and covering an area of 38.4 ha (28 % of the salt outcrop area). In addition to the impact caused on the aesthetics of this outstanding geological site, the slag heaps disturbed the local drainage, generating closed depressions acting as preferential infiltration zones of freshwater. The infiltration of water in an enclosed depression used for the disposal of sewage water resulted in the development of the 335-m-long Riera Salada Cave, excavated in the halite debris of the Old Slag Heap. The sewage water also contributed to the pollution of the endokarstic system and the Cardener River waters. On the other hand, the influx of freshwater from the sandstone aquifer units that surround the salt body propitiated by the excavation of mine galleries resulted in the generation of the 280-m-long Del Riu Cave, whose trajectory is controlled by an overlying mining gallery. In March 1998, a 50-m-deep gallery of the Les Salines halite mine, initially conceived to store industrial wastes, intercepted a phreatic karstic conduit, causing the irruption of fresh water from the Cardener River into the mine galleries.

Some lessons that can be learnt from the Cardona Diapir experience include:

- Salt formations may have a well-developed endokarstic system that may make difficult the mining operations and threaten the safety of underground disposal sites. These karstic conduits may undergo dramatic changes in short periods of time.
- The changes in the local drainage may cause variations in the infiltration pattern, leading to the development of new underground karstic passages and sinkholes.
- The influx of freshwater in salt mines and caves from adjacent or overlying aquifers and water bodies may cause massive salt dissolution and catastrophic subsidence.
- The inflow of freshwater in salt mine galleries may be caused by stoping processes, the excavation of an adjacent or overlying aquifer, improperly sealed boreholes and the interception of a karstic conduit, as the case of the 1998 flood event in Cardona salt mine.

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References

Andrejchuk V (2002) Collapse above the world's largest potash mine (Ural, Russia). Int J Speleol 31(1/4):137–158

Anderson NL, Hinds RC (1997) Glacial loading and unloading: a possible cause of rock salt dissolution in the Western Canada Basin. Carbonate Evaporites 12(1):43–52

Arkin Y, Gilat A (2000) Dead Sea sinkholes- an ever-developing hazard. Environ Geol 39(7):711–721

Belderson RH, Kenyon NH, Stride AH (1978) Local submarine salt karst formation on the Hellenic Outer Ridge, Eastern Mediterranean. Geology 6:716–720

Berger Z, Aghassy J (1982) Geomorphic manifestations of salt dome stability. In: Craig RG, Craft JL (eds) Applied geomorphology, Allen and Unwin, London, pp 72–84

Bosák P, Bruthans J, Filippi M, Svoboda T, Smíd J (1999) Karst and caves in salt diapirs, SE Zagros Mts. (Iran). Acta Carsol 28(2):42–74

Bruthans J, Filippi M, Palatinus L (2000) New findings about salt karst in Zagros Mountains, Iran. Paper presented at the fourth European Caving Expedition Symposium, pp 42–46

Bruthans J, Asadi N, Filippi M, Vilhelm Z (2006) Environ Geol (this issue)

Barrera EL (2000) Huecos en el valle salado de Cardona. Previsiones y posibles efectos 65

Canas JA, García F, Clapés J, Osorio R, Pérez V, Pujades LG, Caselles O (1996) Estudio mediante técnicas de Geo-radar del subsuelo y galerías de la mina de sal abandonada de Cardona para su habilitación como itinerario cultural. Geogaceta 20(4):966–969

Cardona F (1990) El carst salino de Cardona. Paper presented at the 5° Congreso Español de Espeleología, Santander, pp 401–408

Cardona F (1994) El Forat Mico y el karst en sal de Cardona. Tecnoambiente 38:73–80

Cardona F (2004) Morfogènesis de les cavitats en sal de Cardona. Paper presented at the 1er Congrés Catalá d'Espeleologia, Esplugues de Llobregat (Barcelona), 30 October–1 November 2004, pp 158–166

Cardona F, Viver J (2002) Sota la sal de Cardona, p 128

Christiansen EA (1971) Geology of the Crater Lake Collapse Structure in the Southeastern Saskatchewan. Can J Earth Sci 8:1505–1513

Esborrany (1997) Estudi de viabilitat d'un dipósit subterrani controlat de residus especials a l'antigua mina de sal de Cardona

Fayas JA (1972) Inyección profunda de residuos industriales. Agua 73:26–41

Floquet M (1933) Estudio de las avenidas de agua en minas de potasa. Caso particular de Cardona, Cardona, p 34

Ford D (2000) Speleogenesis under unconfined settings. In: Klimchouk AB, Ford DC, Palmer AN, Dreybrodt W (eds) Speleogenesis. Evolution of karst aquifers , pp 319–324

Frumkin A (1995) Rapid entrenchment of stream profiles in the salt caves of Mount Sedom, Israel. Earth surf process landf 20:139–152

Frumkin A (1998) Salt cave cross-sections and their paleoenvironmental implications. Geomorphology 23:183–191

Frumkin A (2000) Speleogenesis in salt-The Mount Sedom area, Israel. In: Klimchouk AB, Ford DC, Palmer AN, Dreybrodt W (eds) Speleogenesis. Evolution of karst aquifers, pp 443–451

Frumkin A, Raz E (2001) Collapse and subsidence associated with salt karstification along the Dead Sea. Carbonat Evaporites 16(2):117–130

Geoconsulting-Dirección general de Obras Hidráulicas (1984) Estudio hidrogeológico de las aportaciones subterráneas del arroyo salado al río Cardener, Primera fase

Gustavson TC (1986) Geomorphic development of the Canadian River Valley, Texas Panhandle: an example of regional salt dissolution and subsidence. Geol Soc Am Bull 97:459–472

Gutiérrez F (2004) Origin of the salt valleys in the Canyon Lands section of the Colorado Plateau. Evaporite dissolution collapse versus tectonic subsidence. Geomorphology 57:423–435

Gutiérrez F, Orti F, Gutiérrez M, Pérez-González A, Benito G, Gracia Prieto J, Durán Valsero JJ (2001) The stratigraphical record and activity of evaporite dissolution subsidence in Spain. Carbonate Evaporites 16:46–70

Hill C (1996) Geology of the Delaware Basin, Guadalupe, Apache, and Glass Mountains, New Mexico and West Texas. Permian Basin Section-SEPM, Publication no. 96-39, p 440

Huntoon PW (1982) The Meander anticline, Canyonlands, Utah: An unloading structure resulting from horizontal gliding on salt. Geol Soc Am Bull 93:941–950

Jackson MPA, Talbot CJ (1986) External shapes, strain rates, and dynamics of salt structures. Geol Soc Am Bull 97:305–323

Jenyon MK (1986) Salt tectonics. Elsevier, London

Johnson KS (1989) Development of the Wink sink in West Texas, USA, due to salt dissolution and collapse. Environ Geol Water Sci 14(2):81–92

Johnson KS (1993) Dissolution of Permian Salado Salt during Salado time in the Wink area, Winkler County, Texas. New Mexico Geological Society Guidebook, 44th Field Conference, pp 211–218

Kappel WM, Yager RM, Todd MS (1999) The Retsof Salt Mine Collapse. In: Galloway D, Jones DR, Ingebritsen SE (eds) Land subsidence in the United States. US Geological Survey, Circular 1182, pp 111–120

Kirkham RM, Streufert RK, Kunk MJ, Budhan JR, Hudson MR, Perry WJ (2002) Evaporite tectonism in the Lower Roaring Fork River valley, west-central Colorado. In Kirkham RM, Scott RB, Judkins TW (eds) Late cenozoic evaporite tectonism and volcanism in west-central Colorado, Boulder, Colorado 366, pp 73–99

López de Azcona JM (1933) Industria Neolítica de Cardona. Notas y comunicaciones del Instituto Geológico y Minero de España

Marin A (1926) La Potasa. Boletín del Instituto Geológico y Minero de España 48, p 355

Martinez JD, Johnson KS, Neal JT (1998) Sinkholes in evaporite rocks. Am Sci 86:38–51

McGill GE, Stormquist AW (1979) The Grabens of Canyonlands National Park, Utah: Geometry, Mechanics, and Kinematics. J Geophys Res 84(B9):4547–4563

Moreno MC, Victoria JM (1969) El karts salino de Cardona. EspeleoSie 4:20–26

Mottershead DN, Duane WJ, Inkpen RJ, Wright JS (2006) An investigation of the geometric controls on the morphological evolution of small-scale salt terrains, Cardona, Spain. Environ Geol (this issue)

O'Brien GD (1968) Survey of diapirs and diapirism. In: Braunstein J, O'Brien GD (eds) Diapirsm and diapirs. AAPG, Tulsa, pp 1–9

Palmer AN (2000) Hydrogeologic control of cave patterns. In: Klimchouk AB, Ford DC, Palmer AN, Dreybrodt W (eds) Speleogenesis. Evolution of karst aquifers, pp 77–90

Pueyo JJ (1975) Estudio petrológico y geoquímico de los yacimientos potásicos de Cardona, Suria, Sallent (Barcelona, España), Doctoral thesis, Universitat de Barcelona, p 351

Riba O, Maldonado A, Ramírez J (1975) Mapa Geológico de España, Scale 1:50.000, 2nd series, no. 330, Cardona, Madrid, Instituto Geológico y Minero de España, Servicio de Publicaciones del Ministerio de Industria, p 58

Sáez A, Riba O (1986) Depósitos aluviales y lacustres paleógenos del margen catalán de la Cuenca del Ebro. In: Anadón P, Cabrera L (eds) Guía de las excursiones del XI Congreso Español de Sedimentología, Barcelona, pp 1–29

Sans M (2003) From thrust tectonics to diapirism. The role of evaporites in the kinematic evolution of the eastern South Pyrenean front. Geol Acta 1(3):239–259

Sans M, Koyi HA (2001) Modelling the role of erosion in diapir development in contractional settings. In: Koyi HA, Mancktelow NS (eds) Tectonic modelling: a volume in honour of Hans Ramberg: Boulder, Colorado, Geological Society of America memoir, vol 193, pp 111–122

Sans M, Verges J (1995) Fold development related to contractional salt tectonics: Southeastern Pyrenean Thrust Front, Spain. In: Jackson MPA, Roberts DG, Snelson S (eds) Salt tectonics: a global perspective: AAPG Memoir 65, pp 369–378

Sans M, Muñoz JA, Vergés J (1996) Triangle zone and thrust wedge geometries related to evaporitic horizons (southern Pyrenees). Bull Can Pet Geol 44(2):375–384

Servicio Geológico de Cataluña, Sección de Geotecnia e Hidrología (1992) Recuperación de la Vall Salina de Cardona. Primera Fase (Unpublished)

SIE-CEA (1967) Mapa de dolinas del afloramiento de sal de Cardona (Unpublished)

Talbot CJ, Jarvis RJ (1984) Age, budget and dynamics of an active salt extrusion in Iran. J Struct Geol 6:521–533

Talbot CJ, Rogers EA (1980) Seasonal movements in a salt glacier in Iran. Science 208:395–397

Trusheim F (1960) Mechanism of salt migration in northern Germany. Bull Am Assoc of Pet Geol 44:1519–1540

Wagner G, Mauthe F, Mensik H (1971) Der Salztock von Cardona in Nordostpanien. Geol Rundschau 60:970–996