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Geomorphology 52 (2003) 215–231
GEOMORPHOLOGY
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The Jiloca karst polje-tectonic graben (Iberian Range, NE Spain)

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Received 4 January 2002; received in revised form 2 August 2002; accepted 15 August 2002

Abstract

The Jiloca depression, one of the largest morpho-structural units of the Iberian Range and traditionally considered as a neotectonic graben, is interpreted as a karst polje developed within an active halfgraben. This polje, 705 km^2 in area, constitutes one of the largest documented poljes. Several evidences—(1) a sequence of eight-stepped levels of corrosion surfaces, (2) the reduced thickness of the basin fill, (3) fault-controlled mountain fronts with topographic scarps much higher than the structural throws—demonstrate that great part of the topographic relief of the depression has been generated by corrosional lowering rather than by tectonic subsidence. The height difference between the highest corrosion surface and the polje bottom indicate that the depression has been deepened around 300 m by corrosion processes. The initiation of the karst polje was determined by the creation of the Jiloca halfgraben by normal faults, which deformed a Pliocene regional erosion surface. The development of the polje has been controlled largely by the asymmetric structure and the slight neotectonic activity of the graben. Changes in the position of the polje bottom inferred from the slopes of the different corrosion surfaces (polje paleotopography) may have been controlled by neotectonic movements.

Keywords: Polje; Neotectonics; Corrosion surface; Iberian Range, Spain

1. Introduction

The word polje in Slavic languages means a flat and alluviated field (Sweeting, 1972). The geomorphological term refers to large closed depressions with conspicuously flat bottoms developed on karst rocks. Gams (1978) proposed that the flat floors should be at least 400 m wide and Cvijic (1893) took 1 km as a lower limit. These depressions are generally elongated and oriented parallel to the direction of the structural grain. The sides of the poljes are usually formed by relatively steep limestone slopes. The bottoms of these karstic depressions may be also framed by a stepped sequence of corrosion surfaces, which constitute testimonial remains of previous polje bottoms and record alternating deepening and planation periods. The hydrology of the poljes is characterised by underground drainage through swallow holes (ponors). The bottoms may be flooded when the inflow exceeds the capacity of the ponors and outlet structures or when a rising water table (*vorfluter*) intersects the land surface. Additionally, karstic depressions generated as poljes may have been captured by the fluvial network acquir-

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doi:10.1016/S0169-555X(02)00257-X

ing an open hydrological character (Sweeting, 1972; Roglic, 1974; Ristic, 1976; Jennings, 1985; Bonacci, 1987; Ford and Williams, 1989). In some tectonically active areas like the Dinarics and the Betics (south of Spain) poljes are very frequent large-scale landforms. According to Gams (1978), in the Dinaric karst, the bottom of more than six poljes exceeds 100 km^2 and two of them cover about 400 km^2.

Poljes are considered the most controversial karst landforms of temperate regions (Büdel, 1977). The processes and factors which determine their origin and the development of stepped corrosion surfaces are two of the most debated aspects in this field (Gospodaric and Habic, 1979). Generally, the limestone bedrock of the polje bottom is mantled by a thin veneer of alluvium with an extremely flat topography. The genesis of these depressions is related to the corrosional lowering of the land surface (differential erosion). The flat topography results from corrosion processes acting beneath the alluvial cover (corrosion planation) and controlled by the position of the water table (Ford and Williams, 1989). Numerous authors have suggested that the neotectonic activity may have played a significant role in the genesis of poljes (Cvijic, 1893; Birot, 1949; Lehmann, 1959; Nicod, 1972; Dufaure, 1977; Gams, 1978; Julian and Nicod, 1989). Hydrogeological investigations performed in the Dinaric area demonstrated that the poljes situated at high altitudes are fault-bounded depressions with a thick Neogene sedimentary fill lying on an irregular limestone base. These continental deposits, including a large proportion of lacustrine facies, reach 2500 and 2300 m in thickness in Duvanjsko and Livanjsko poljes, respectively (Milanovic, 1981; Mijatovic, 1984). These features reveal that some depressions in karst areas constitute poljes and tectonic grabens at the same time. The topographic depression and the flat bottoms of these polje-grabens are due mainly to tectonic subsidence and aggradation rather than corrosional lowering and corrosion planation. Recently, it has been suggested that some poljes in the Dinaric karst may be pull-apart neotectonic depressions (Vrabec, 1994).

During the last two decades, a large number of poljes have been recognised in the central-eastern sector of the Iberian Range. These poljes, reviewed by Gracia et al. (1999), have been formed on Jurassic and Cretaceous folded carbonate sediments generally bevelled by extensive erosion surfaces. These "Iberian poljes" are characterised by terraced levels of corrosion surfaces with a concentric distribution. Some of these depressions are strongly controlled by the structure whereas some others do not show any clear tectonic influence. This work reinterprets the Jiloca neotectonic graben as a polje developed within an active half-graben. The geomorphological analysis of this depression, with a mixed karstic and tectonic origin, allows us to evaluate the role played by corrosional deepening (differential erosion) and neotectonic subsidence in the origin and development of the topographic basin. This case study suggests that the genesis of the structurally controlled depressions found in some karst areas may have been misinterpreted.

2. Geological and geomorphological setting

The Jiloca morpho-structural depression is located in the central sector of the Iberian Range (NE of Spain) (Fig. 1). The Iberian Range constitutes an intraplate alpine orogene generated by the tectonic inversion of Mesozoic sedimentary basins from the upper Cretaceous to the middle Miocene. The compressional structures formed throughout this orogenic stage have a dominant NW–SE trend. During the middle Miocene, the gradual change from a compressional to an extensional tectonic regime gave way to the post-orogenic stage of the Iberian Range evolution. Two main episodes of extensional activity have given place to tectonic grabens superimposed on the compressional structures. The first episode in the middle Miocene generated the Calatayud and Teruel grabens. The second episode in the upper Pliocene reactivated the previous tectonic basins and initiated the generation of several halfgrabens like the Jiloca depression (Moissenet, 1980; Simón, 1983, 1989; Hernández and Anadón, 1985; Gabaldón et al., 1991).

The Jiloca depression, at about 1000 m in altitude, is one of the largest intramontane structural basins in the NE of the Iberian Peninsula. This topographic basin is about 70 km in length and its width ranges from 6 to 10 km. The tectonic subsidence in this N–S trending halfgraben is controlled primarily by three NW–SE faults (Calamocha, Palomera and Concud-Caudé) located on the eastern margin with an en-echelon arrangement (Fig. 1). The NW–SE Sierra

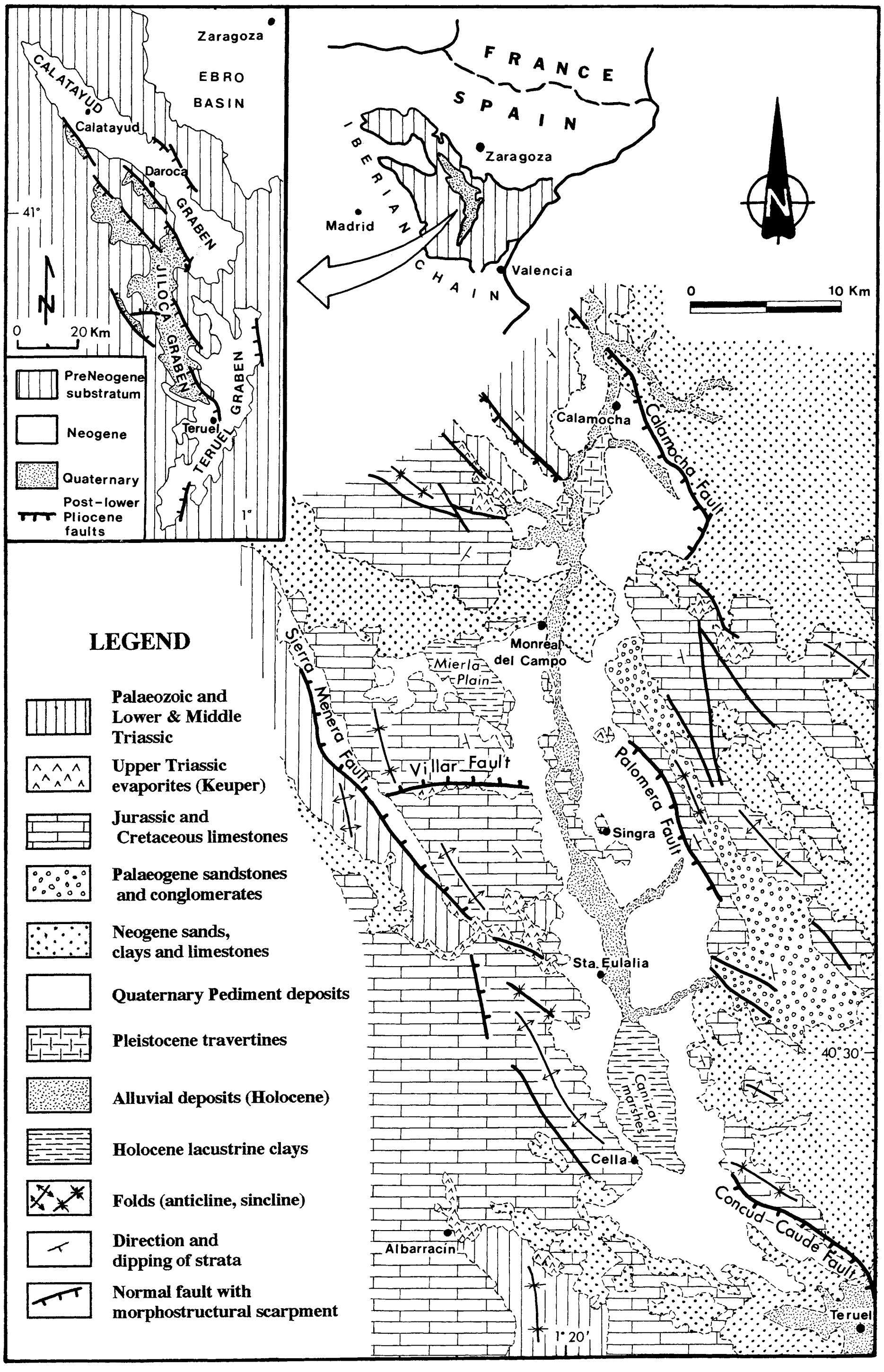


Fig. 1. Location and geological map of the Jiloca depression.

Menera Fault and the E–W Villar Fault on the poorly defined western margin may have also played a significant role in the development of the depression. The Jiloca depression, flanked by mountain fronts up to 400 m high in the eastern margin (Fig. 2), has been traditionally considered as a Plio–Quaternary half-graben. Recently, some geologists have indicated that the generation of this structural depression cannot be explained solely by tectonic subsidence and requires a satisfactory morphogenetic explanation (Cortés and Casas, 2000). These authors indicate that the structural throws of the faults in the eastern margin are much smaller than the associated topographic scarps (mountain fronts). They also point out the reduced thickness of the sedimentary fill and suggest that differential erosion processes may have contributed to the generation of the topographic depression.

The bedrock geology of a great part of the depression is formed by marine Jurassic carbonate formations more than 800 m thick (Fig. 1). These soluble sediments are underlain by an impervious Triassic formation (*Keuper*) made up of marls and clays with evaporites, which constitute the base level of the karst system. In the northern and southern borders of the depression, there are large outcrops of Neogene detrital sediments filling small basins linked to the Calatayud and Teruel post-orogenic grabens (Gabaldón et al., 1991) (Fig. 1). Additionally, to the East of Monreal del Campo, there is a sequence of folded Oligocene conglomeratic sediments. These outcrops of nonsoluble terrigenous sediments restrict the corrosion processes and the extent of the polje. A significant part of the sediments eroded from these detrital units have accumulated in the bottom of the Jiloca depression.

The geomorphology of the region is characterised by extensive high altitude plains (Gracia, 1990; Gracia et al., 1988; Gutiérrez and Gracia, 1997). These plains may correspond to structural platforms and mesas formed by subhorizontal Neogene limestones or to erosion surfaces which truncate the folded Mesozoic sediments. The karstic corrosion processes have played a crucial role in the generation of these planation surfaces (Gutiérrez and Gracia, 1997). The final development of the most extensive erosion surface, the so-called Main Erosion Surface of the Iberian Range (Peña et al., 1984), occurred during the Pliocene (Gutiérrez et al., 1996). This surface has been deformed by extensional tectonics forming a topography controlled largely by faulted and tilted blocks

Fig. 2. View of the Jiloca depression from the top of Palomera mountain front.

(Gutiérrez and Gracia, 1997). Remains of the Main Erosion Surface constitute the hydrographic divide between the Jiloca depression and some adjacent depressions. The study area has a semiarid climate with a strong seasonal contrast in temperature (Ascaso and Cuadrat, 1981). In the bottom of the depression the mean annual temperature and the average precipitation are 10 °C and 400 mm, respectively. In the high margins the mean annual precipitation reaches 700 mm.

3. Results

3.1. General features of the Jiloca Depression

The morphological study of the Jiloca Depression is based essentially on a geomorphological map, at a scale of approximately 1:30,000 and produced by means of aerial photograph interpretation and field survey. This map allows us to analyse the spatial and altitudinal distribution of the corrosion surfaces. Information about tectonic activity (location of earthquake epicentres, recent deformation) and the sedimentary fill (borehole data) of the depression has also been compiled.

Geomorphological mapping reveals the presence of eight-stepped corrosion surfaces, asymmetric on both flanks of the depression (Fig. 3). These planated surfaces reflect the asymmetry of the morpho-structural depression. Most of them are located in the western margin where the carbonate outcrops cover a greater extent (Figs. 3 and 4). All of these corrosion surfaces are inset in relation to the remains of the Pliocene Main Erosion Surface of the Iberian Range situated at both margins of the depression. The height difference between the Pliocene erosion surface and the oldest (highest) corrosion surface is generally less than 20 m.

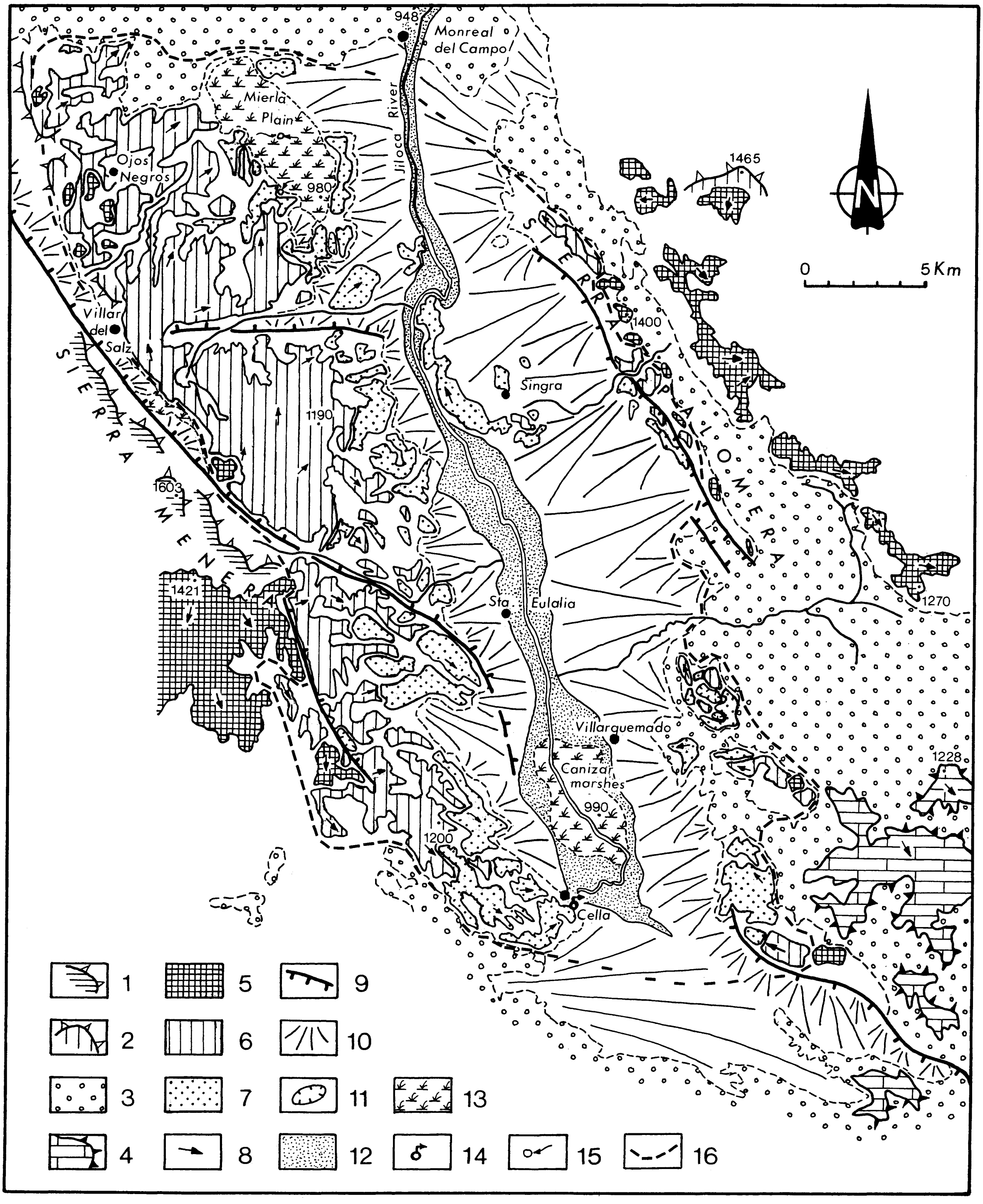
The morphosequence of hanging corrosion levels represents remnants of previous bottoms of the depression. In the bottom of the depression the carbonate bedrock is mantled by a relatively thin cover of alluvium and decalcification clays (*terra rossa*) derived partly form stripping of the higher corrosion plains. Borehole data obtained for hydrogeological exploration (García and Cruz, 1985) indicate that the sedimentary fill in the centre of the basin, far from the active faults, does not exceed 20 m in thickness. Furthermore, the karstified Mesozoic bedrock crops out in some central sectors like Singra and Monreal del Campo (Figs. 1 and 4). The shallow water table in two sectors has given rise to two large swampy areas, Mierla Plain to the NW and Cañizar marshes to the south (Fig. 5). Both palustrine areas have undergone agricultural drainage.

These features reveal that the Jiloca depression corresponds to a structurally controlled karst polje. It has similar morphological characteristics to some nearby smaller poljes like Ródenas, Orihuela del Tremedal (J.L. Peña, personal communication) or Gallocanta (Gracia et al., 1999). However, in the Jiloca karst polje-tectonic graben, several lines of evidence indicate that neotectonic subsidence controlled the initiation and location of the polje. Block tectonics have contributed, together with differential erosion by corrosional lowering, to the generation of the topographic depression, with a mixed karstic and tectonic origin. The relationship between both processes, tectonic subsidence and polje deepening by corrosion, may be analysed from the study of several characteristics of the corrosion surfaces, the geometry of the alluvial fans developed at both margins of the depression and the neotectonic landforms linked to the active faults.

3.2. Characteristics of the corrosion surfaces

The development of the corrosion surfaces is clearly controlled by the distribution of the carbonate outcrops, mainly Jurassic limestone. This lithology covers a great part of the western sector of the Jiloca Depression (Fig. 1) where the corrosion plains reach their largest extent (Fig. 6). On the eastern border, the reduced carbonate outcrops and the tectonic activity of the Palomera mountain front have restricted the development of corrosion surfaces. Only a few isolated benches have been mapped in this flank, which cannot be correlated with the stepped sequence of the opposite margin.

The slopes between different stepped corrosion surfaces show convex–concave longitudinal profiles. Those linking young surfaces are always steeper than the slopes linking high-old surfaces, which show more gentle profiles. All the hanging planation surfaces generated by corrosion lack any cover of surficial


948
Monreal
del Campo
Mierla
Plain
Jiloca River
Ojos
Negros
980
1465
0
5 Km
Villar
del
Salz
1400
Singra
SIERRA PALOMERA
1190
SIERRA MENERA
1603
1421
Sta. Eulalia
1270
Villarquemado
Canizar
marshes
990
1228
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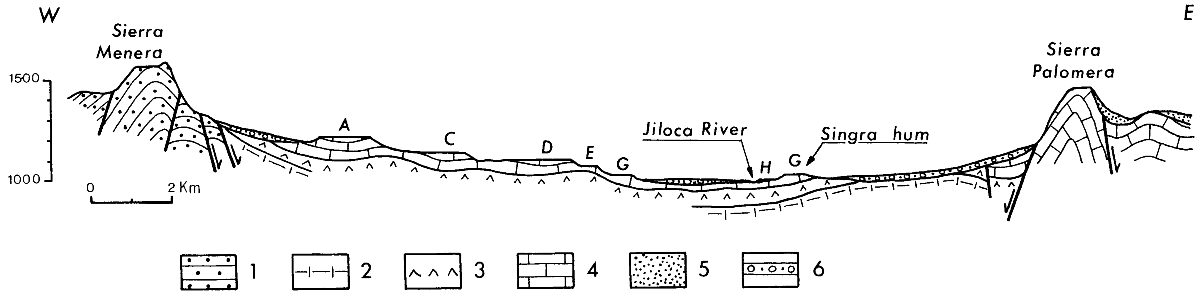


Fig. 4. Cross-section in the central sector of the Jiloca Polje. (1) Paleozoic quartzites, (2) Lower and middle Triassic conglomerates and carbonates, (3) Upper Triassic clays and evaporites, (4) Jurassic limestone, (5) Paleogene detrital sediments, (6) Quaternary alluvial fans. Letters refer to corrosion surface levels.

deposits and display a considerable degree of karstification with pan-shaped solution dolines and extensive karren development. Some of the karren types, such as *hohlkarren* (undercut solution runnels) have been formed beneath a soil cover. The covered karst features are superimposed by bare karst morphologies, such as *rillenkarren* (solution flutes), indicating that these surfaces were previously veneered by drift material.

In order to simplify the geomorphological map presented in this work, the eight levels of hanging corrosion surfaces have been lumped in two groups: high surfaces (A, B, C and D) and low surfaces (E, F, G and H) (Table 1). The high surfaces are well preserved and locally cover as much as 8 km^2. In contrast, the remains of the low surfaces are always smaller than 1 km^2 in area (Fig. 3). The corrosion levels show a general slope (0.2%) towards the north. In addition to this general trend, the local incline of the corrosion surfaces reaches up to 5%. The slope of the corrosion surfaces of each level allow us to reconstruct the paleotopography of the polje bottom during the different morphogenetic stages of the evolution of the karstic depression. These slopes indicate the position of the local topographic base levels (deeper areas). Locally, some surfaces are surrounded by remains of older surfaces framing nested polje bottoms, nowadays hanging and captured by the drainage network. This is the case of the Almohaja polje in the western margin of the Jiloca Depression (Fig. 7).

In the central sector, the high surfaces show a clear slope towards the North (Mierla Plain), whereas the low surfaces have a dominant slope to the East (Palomera Fault) (Fig. 3). This change in the topographic gradient between the northern high and low surfaces suggests a shift in the location of the lowest part of the polje throughout its episodic deepening. In contrast, the youngest surfaces show slopes controlled by local depressions and the current polje bottom.

3.3. The alluvial fans and the polje bottom

The alluvial fans developed in the polje bottom are inset in relation to the low corrosion surfaces. The eastern fans are much larger than the western ones and in both margins three fan generations (morpho-sedimentary units) have been differentiated. These fans show a progressive shift of alluvial accumulation towards distal areas. On the western flank the oldest fan generation has a reduced extent, restricted to the foot of the E–W trending Villar Fault, with slopes higher than 4%. The deposits are more than 8 m thick and are caped by petrocalcic horizon (Gracia et al., 1987). This sedimentary unit shows evidence of neo-

Fig. 3. Geomorphological map of the Jiloca Polje. (1) Morpho-structural scarps on Paleozoic quartzites, (2) Morpho-structural scarps on Mesozoic limestones, (3) Outcrops of Tertiary detrital sediments, (4) Structural platforms and mesas on Neogene limestones, (5) Main Erosion Surface of the Iberian Range, (6) High corrosion surfaces, (7) Low corrosion surfaces, (8) Topographic gradient, (9) Normal fault escarpment, (10) Quaternary alluvial fans, (11) Closed depression, doline, (12) Polje bottom and alluvial plain, (13) Palustrine depressions, (14) Springs, (15) Ponor, (16) Polje limit.

Fig. 5. Aerial view of the Cañizar swampy area in the southern sector of the Jiloca Polje.

tectonic deformation including normal faults with metre-scale throws, extensional gashes and anomalous dips in the proximity of the fault scarp. The intermediate fan generation has lower gradients (1–1.3%) and a thin unit of undeformed deposits. This is the fan with greatest morphologic expression. The youngest fan unit corresponds to telescopic debris cones located at the edge of the flat bottom of the polje.

The east margin fans have larger areas and steeper gradients. The deposits of the oldest sedimentary unit

Fig. 6. Stepped corrosion surfaces in the western margin of the Jiloca Polje, Santa Eulalia area.

Table 1
Average heights (m) of the karstic corrosion surfaces of the Jiloca polje

Surfaces	Northern sector	Central sector	Southern sector
Higher			
A	1240	1280	1320
B	1130	1260	1280
C	1070	1190	1220
D	1040	1150	1180
Lower			
E	1025	1120	1130
F	1010	1060	1100
G	1000	1020	1080
H	980	1000	1040
Bottom			
	950	970	1000

crops out at the foot of Palomera Fault dipping up to 30° towards the depression axis, although locally the strata dip towards the fault. This sedimentary unit is formed by a thick sequence of angular gravels with a large proportion of reddish and cemented sand and silt beds. At the foot of the mountain front, the sediments of this old and deformed unit are truncated by an erosional surface, which distally gives way to the aggradation surface of the intermediate fan unit. The deposits of this intermediate unit unconformably overlie the sediments of the old unit with an offlap disposition. They are formed by orange gravels less than 2 m thick. The youngest unit constitutes telescopic fans with gradients around 2%, and comprises thin sand and silt-rich deposit.

A morphometric analysis of the alluvial fans and their drainage basins has been performed, solely taking into account the youngest fans of the central sector (Singra–Santa Eulalia, see Fig. 3). The relationships between the fan areas (Fa), fan gradients (Fg) and drainage basin areas (Da) have been plotted in Fig. 8 and equations of the form $\mathrm{Fa}=p\mathrm{Da}^q$ and $\mathrm{Fg}=a\mathrm{Da}^b$ have been obtained. Despite the similar relief, lithology, climate and vegetation cover, quite different trends have been obtained for the fans of both basin margins.

As Fig. 8A shows, the fans of both margins are clearly discriminated. The East margin fans are comparatively larger than the West margin fans. In this sense, strong differences in the p values were interpreted by Rockwell et al. (1985) as an indication of tectonic uplift and Hooke (1972) pointed out that tectonics and uplift rate may cause oversized fans.

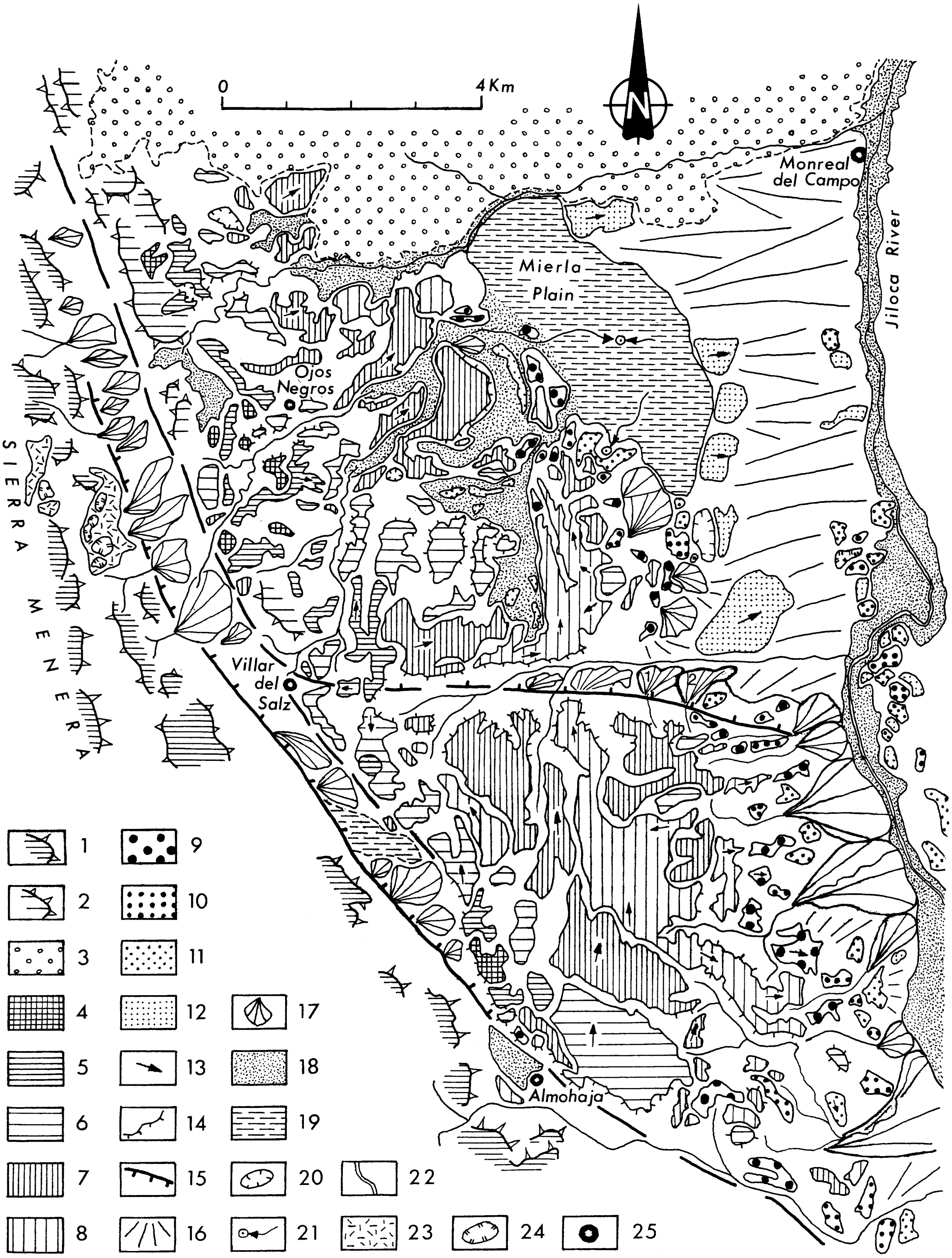
Both margins are also discriminated when fan gradient is plotted versus the drainage basin area (Fig. 8B). Following similar observations made by Silva et al. (1992) and Harvey (1997) in fans of the western USA and SE Spain, this relationship suggests that in the East margin fans debris flow processes are more important than that in the West margin, where fluvial processes (sheet floods) seems to predominate.

Only two fans of the West margin (numbers 1 and 2, Fig. 8) show very similar trends to the East margin fans. As can be observed in Fig. 7, these two fans are located at the foot of the Villar Fault and they show anomalous linear escarpments parallel to the fault, indicating a recent tectonic deformation. If fans 1 and 2 were removed from the West margin population, both populations would be more clearly differentiated in the plots and slopes of the fitted lines in both graphics would be more similar.

A thin veneer of clay deposits with a subhorizontal topography covers the lowest sectors of the depression bottom. In Singra area, the drift cover is interrupted by several residual hills of Jurassic limestone and Triassic evaporitic shales (*hums*). Some outcrops of impervious Triassic sediments occur in the surroundings of these inliers (Fig. 4). The limestone hills have been locally planated displaying some low corrosion surfaces.

During the late stages of the polje evolution, the bottom of the karstic depression has undergone a compartmentalisation, splitting into two sectors (Mierla and Cañizar bottoms) divided by the Singra *hums*. The bottom of Mierla and Cañizar, 18 and 7 km^2 in area, respectively, constitute swampy areas largely transformed for agricultural use (Fig. 3). Several swallow holes or ponors have been recognised in the Mierla Plain (Fig. 7). One of them, located in the SW of the depression, occurs at the foot of a scarped amphitheatre forming a blind valley. The Cañizar marsh, in the southern sector of the polje, is frequently inundated during rainy periods (Fig. 5).

The polje bottom has numerous karst springs commonly located at the foot of the limestone marginal slopes. In the Cañizar marsh numerous springs were active during historic times. At present, the water table has been lowered due to water withdrawal for irrigation. The most important spring is situated in the southern sector of the polje, in Cella village, which


0
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N
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Jiloca River
Mierla Plain
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Villar del Salz
Almohaja
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yields 2000 l/s during high discharge. This spring water flows along an artificial channel built in the 18th century (Deler, 1995) which drains the depression axis to the north and connects with some other springs in Monreal del Campo village.

The polje has been captured by headwards erosion of the Jiloca River, transforming the closed polje into an open polje (externally drained) (Cvijic, 1893). The lack of fluvial terraces and the reduced incision in the Jiloca River valley downstream of the capture area suggests that the capture took place in relatively recent times (Gracia, 1990; Gutiérrez et al., 1996). It seems that the capture of the polje has been produced by simple headward erosion in the Jiloca valley without the interplay of neotectonic activity.

3.4. Structural landforms and neotectonics

The general geometry of the polje and the distribution of the corrosion surfaces are controlled largely by the structure of the Jiloca halfgraben. The eastern edge of the polje coincides with the mountain fronts of the active margin of this neotectonic halfgraben (Palomera and Concud-Caudé) (Fig. 1). In the western margin the distribution of the much larger corrosion surfaces is compartmentalised by the Sierra Menera and Villar faults (Figs. 1 and 2).

In this sector of the Iberian Range, different types of morphological and stratigraphical markers allow us to identify frequent neotectonic deformations (Moissenet, 1980; Simón, 1983, 1989; Gracia, 1990; Gracia and Gutiérrez, 1996; Gutiérrez and Gracia, 1997; Gutiérrez, 1998). Quaternary alluvial fan deposits have been deformed by the Sierra Menera, Villar and Palomera faults. These recent neotectonic deformations are especially intense at the foot of Palomera mountain front, which defines the active margin of the Jiloca halfgraben. The deformation in the piedmont sediments and the geomorphic anomalies of the mountain front (trapezoidal facets and hanging canyons) confirm that neotectonic subsidence has contributed to the generation of the relief in this linear escarpment in addition to the structurally controlled corrosional lowering of the polje bottom. Although it is very difficult to estimate the structural throw of the Palomera Fault due to the folded structure of the Jurassic sediments, it does not exceed some tens of metres and lower than 100 m according to Cortés and Casas (2000). On the other hand, it is also not possible to evaluate which part of the throw has been achieved during the development of the depression (Plio–Quaternary times), since this fault has been active for a long time throughout the geological history of the area. This evidence reveals that a great part of the topographic relief of the mountain front is related to the corrosional lowering of the polje bottom.

Very dramatic examples of Holocene deformation have been identified in the eastern margin of the Jiloca polje-graben. In Aguatón (Sierra Palomera, 7 km to the NE of Singra) (Burillo et al., 1985) and in Rubielos de la Cérida (12 km to the east of Monreal del Campo) (Capote et al., 1981; Gutiérrez et al., 1983), normal faults with metre-scale throws affect slope deposits containing Iron-Age pottery remains.

The Quaternary tectonic movements have controlled the location of the polje bottoms and the topography of the corrosion plains. The Sierra Menera Fault separates two clearly different sectors in the polje (Fig. 3): in the northern sector the corrosion surfaces are inclined to the North (Mierla Plain) and in the southern sector the gradient of the corrosion surfaces is directed towards the Cañizar marshes. It seems that the Sierra Menera fault has controlled the topography of the polje bottom since the early evolutionary stages.

In the northwestern sector of the polje the slope direction of the corrosion surfaces has changed throughout the evolution of the depression. The incline in the high planation surfaces is directed towards Mierla Plain (Fig. 7). In contrast, the low surfaces show predominant slopes towards the current bottom of the polje, drained by the Jiloca River. A similar situation has been mapped to the south of Villar Fault. The corrosion surfaces A, B and C show a northwards inclination; surface D has a double North and East

Fig. 7. Geomorphological map of the northwestern sector of the Jiloca polje. (1) Morpho-structural scarps on Palaeozoic quartzites, (2) Morpho-structural scarps on Mesozoic limestones, (3) Neogene detrital sediments, (4) Main Erosion Surface of the Iberian Range, (5)–(12) Corrosion surfaces A–H, (13) Topographic gradient, (14) Scarped edge of corrosion surface, (15) Normal fault escarpment, (16) Quaternary alluvial fans, (17) Debris cone, (18) Jiloca River floodplain, (19) Swampy depression, (20) Doline, (21) Ponor, (22) Artificial channel, (23) Mine tailing, (24) Mine pit, (25) Village.

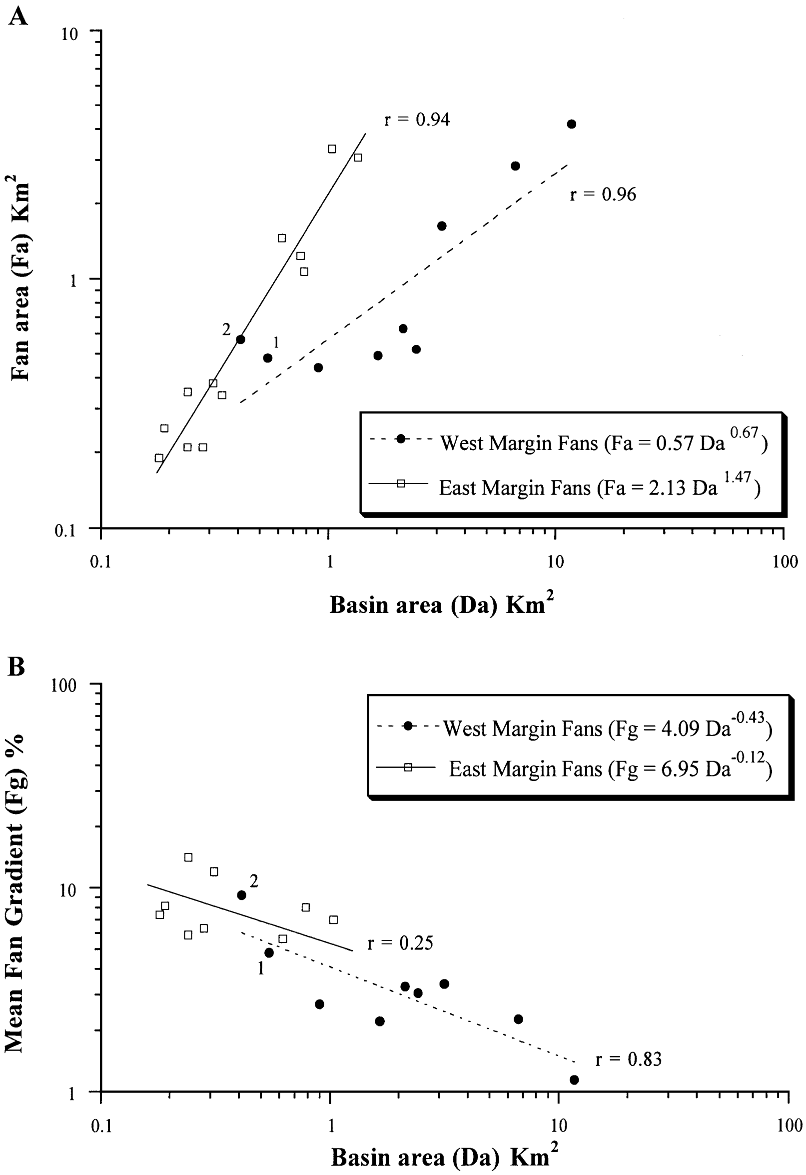

Fig. 8. Relationship between the area of the alluvial fans and their drainage basins in the East and West margin of the central sector of the Jiloca Polje.

inclination (Fig. 3); and surfaces E and the lower ones have eastwards gradients (Fig. 7). The change in the location of the lowest sector of the polje (from the north to the east) recorded in the sequence of corrosion surfaces may have been triggered by the tectonic reactivation of the Jiloca halfgraben during the development of surface D.

Finally, earthquake data from the Jiloca depression and adjacent areas have been compiled for the time span 1760–2000, including historical (1760–1955) and instrumental (1956–2002) records (Mezcua and Martínez-Solares, 1983; IGN, 2002). The epicenters of 11 seismic events are located in the bottom of the polje-graben, or its surroundings (Fig. 9). All of them

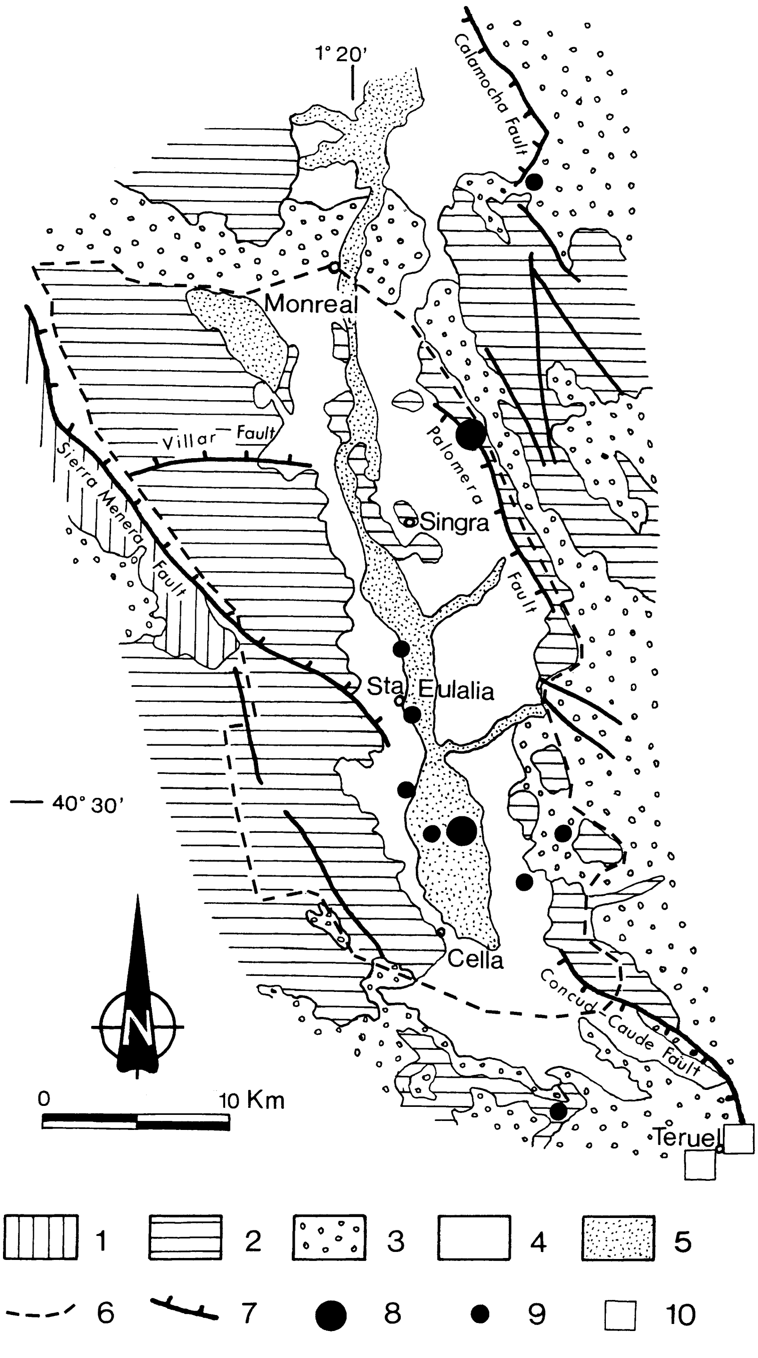

Fig. 9. Location of earthquake epicenters in the Jiloca polje-graben. (1) Paleozoic, (2) Mesozoic, (3) Tertiary, (4) Quaternary pediments and alluvial fans, (5) Polje bottom and alluvial plain, (6) Polje limits, (7) Normal fault. Earthquake epicenters: (8) Magnitude >3.0, (9) Magnitude ≤ 3.0, (10) Preinstrumental earthquakes (only Intensity is available).

Table 2
Main characteristics of earthquakes recorded in the Jiloca polje

Location	Date	Longitude	Latitude	Depth (km)	EH (km)	EZ (km)	Magnitude
Teruel	6 November 1761	1°05′W	40°20′N	–	–	–	–
Teruel	8 December 1955	1°07′W	40°20′N	–	–	–	III[a]
Bueña	14 September 1972	1°16.1′W	40°41.8′N	14	7	13	3.8
Villarquemado	1 January 1986	1°18.7′W	40°31.9′N	5	3	5	3.0
Villarquemado	16 May 1987	1°12.3′W	30°30.9′N	30	–	–	2.8
Teruel	26 April 1988	1°11.7′W	40°21.8′N	5	–	–	3.0
Santa Eulalia	27 June 1989	1°18.5′W	40°33.8′N	5	2	2	2.2
Torremocha	5 July 1989	1°18.8′W	40°35.5′N	10	1	2	2.4
Santa Eulalia	25 January 1999	1°17′W	40°30′N	8.8	2.5	2.3	3.1
Villarquemado	2 January 2000	1°18′W	40°30′N	9.1	5.2	10.6	1.9
Villarquemado	4 March 2000	1°14′W	40°29′N	0.0	5.4	–	1.9

EH: epicenter location horizontal error, EZ: maximum depth error.
[a] Intensity in the Mercalli scale, magnitude not available. Source: Mezcua and Martínez Solares (1983) and Boletín de Sismos Próximos, National Geographical Institute, Madrid (IGN, 2002).

have low magnitudes (lower than 4.0), and may be considered as surface earthquakes (Table 2). Considering that the Epicenter Location Horizontal Errors are lower than 7 km, five earthquakes seem to be related to the Sierra Menera Fault, one with Palomera Fault and five with Concud-Caudé Fault (Fig. 9). These data indicate a slight seismotectonic activity concentrated in the southern sector of the depression, but not in the central and northern areas where the most prominent topographic escarpments occur.

4. Origin and development of the Jiloca polje-graben

4.1. The polje initiation

The origin of poljes in their initial evolutionary stages has been explained by differential erosion due to corrosional lowering (Roglic, 1960; Gams, 1992) or by the generation of topographic depressions resulting from tectonic subsidence (Grund, 1903 in Bögli, 1980; Mijatovic, 1984). The litho-structurally controlled corrosional lowering, which commonly operates on karst rocks in contact with impermeable lithologies, tends to produce elongated poljes parallel to the structural grain. The poljes initiated by fault-controlled tectonic subsidence align their margins with the active faults, whereas poljes initiated by downwarping processes (Gutiérrez and Valverde, 1994) may develop more irregular shapes.

The initiation of the Jiloca polje was determined by the tectonic subsidence caused by the activity of the normal faults located on the eastern margin of the depression. This tectonic deformation tilted the Pliocene Main Erosion Surface of the Iberian Range generating an asymmetric neotectonic basin (Jiloca halfgraben) which controlled the early configuration of the polje. Tectonic subsidence would have concentrated the runoff towards the bottom of the depression, which attained a position closer to the water table. The new hydrological conditions favoured corrosion planation processes and the development of the polje within a neotectonic graben. From the structural viewpoint, the Jiloca polje can be considered as a tectonic graben polje (Cvijic, 1918), tectonic polje (Julian and Nicod, 1989) or a structural polje (Ford and Williams, 1989).

4.2. The deepening of the polje and the development of stepped corrosion surfaces

Since the early stages, the Jiloca depression, with a mixed tectonic and karstic origin, acted as a collector of detrital material. The carbonate bedrock was veneered by alluvial deposits coming from the erosion of the margins of the depression. The deepening of the polje bottom took place by the corrosional lowering of the rockhead by dissolution processes acting beneath the alluvial cover. The suballuvial solution of the carbonate rocks has been called cryptokarstic corrosion (Nicod, 1976; Fabre and Nicod, 1982) and is controlled largely by the position of the water table (Birot, 1949; Pfeffer, 1973; White, 1988; Ford and Williams, 1989). The bottom of the polje can be also lowered by erosion and evacuation through ponors of the clastic sediments covering the karst bedrock. The deepening of the weathering front and the fluvial erosion of the topographic surface are similar to the generation of etched surfaces in crystalline rocks (*Doppelten Einebnugsflächen*) (Büdel, 1957). Thus, some authors consider that this theory could be applied to the development of poljes (Büdel, 1977; Thomas, 1989a,b).

The deepening of the polje bottom progresses until the topography reaches the level of frequent inundation (epiphreatic zone). Once this situation is reached, the corrosion processes tend to expand the polje bottom by retreat of the marginal slopes and by elimination of residual hills (*hums*). In this sense, the resulting corrosion plains produced by the progressive retreat of the karst uplands have a similar morphologic evolution to pediplains (Ford and Williams, 1989). The corrosion processes producing the widening of these plains are known as rim corrosion (Roglic, 1940) or perimetric corrosion (Milanovic, 1981).

The sequence of eight-stepped levels of corrosion surfaces records alternating periods dominated by deepening or by planation and expansion of the polje bottom. The deepening by downward dissolution and the development of corrosion surfaces by corrosion planation would be controlled by the position of the water table (base level for corrosion plain development) (Ford and Williams, 1989). A relative lowering of the water table increases the hydraulic gradient inducing the deepening of the polje bottom by vertical dissolution. When the polje reaches the water table, free vertical drainage is no longer possible and horizontal dissolution produces the planation and expansion of the polje bottom.

The variations in the relative position of the polje bottom and the water table may be due to neotectonic activity and climatic changes. The neotectonic subsidence in the Jiloca halfgraben would cause a relative rise of the phreatic zone. Climatic changes towards more humid (biostasy) or arid (rhesistasy) conditions (Erhart, 1955) would lead to a rise or drop in the water table, respectively. Probably, the position of the water table in the area has also been affected by the rapid entrenchment undergone by the drainage network during the Quaternary in this sector of the Iberian Range. This lowering of the regional base levels is related largely to the capture of internally drained Neogene basins like the Calatayud and Teruel grabens. In the case of the Jiloca polje-graben, the available data do not allow the factors which controlled the generation of the mapped morphogenetic surface to be inferred. Genetic interpretation is limited to a great extent by the lack of absolute chronological data about the corrosion surfaces.

Five stepped levels of corrosion surfaces have been recognised in all of the studied karst poljes in nearby areas of the Iberian Range: seven poljes in Sierra de Albarracín (Peña et al., 1989), Layna Polje (Gracia et al., 1996) and Gallocanta Polje (Gracia et al., 1999, 2002). The larger amount of morphogenetic episodes recorded by the eight levels of corrosion surfaces in the Jiloca polje may be related to its peculiar tectonic setting. The neotectonic subsidence affecting the Jiloca polje-graben may have favoured the generation of a larger number of deepening and planation cycles.

The height difference between the highest corrosion surface (A) and the polje bottom provides an estimate of the deepening of the depression produced by corrosional lowering. The altitude difference in the northern, central and southern sectors is 290, 310 and 320 m, respectively (Table 1). These figures reveal that the generation of the Jiloca topographic depression is primarily due to differential erosion by corrosional lowering rather than to neotectonic subsidence as has been traditionally assumed.

The deepening of a polje may cease when the bottom reaches an impervious and insoluble formation. This situation leads to the abortion (Gutiérrez and Valverde, 1994; Gracia et al., 1996) or sterilisation (Nicod, 1979) of the karstic depression. Currently, the corrosional lowering in some sectors of the Jiloca polje has stopped where the impervious Triassic units underlying the Jurassic carbonates have been intersected (Fig. 4).

5. Conclusions

The Jiloca depression, one of the largest morphostructures of the Iberian Range and traditionally considered as a neotectonic graben, has a mixed karstic and tectonic origin. This depression has been reinterpreted as a karst polje developed within an active halfgraben.

The Jiloca polje, 705 km^2 in area, constitutes one of the largest karst polje that have been described, since the biggest poljes in the Dinaric karst, Lika Polje and Livanjsko Polje reach 700 and 405–433 km^2, respectively (Gams, 1978; Bögli, 1980; Mijatovic, 1984). Several features like the stepped sequence of eight levels of corrosion surfaces and the reduced thickness of the alluvial infill indicate that most of the relief in the topographic depression has been generated by corrosional lowering rather than by tectonic subsidence. The height difference between the highest corrosion surface and the polje bottom yields a topographic deepening by corrosion processes of 300 m. The initiation and location of the polje was determined by neotectonic movements which started the generation of the Jiloca halfgraben deforming an extensive Pliocene erosion surface (Main Erosion Surface of the Iberian Range). The asymmetric configuration and development of the polje have been controlled largely by the structure and neotectonic activity of the graben. This tectonic activity is recorded in deformed Quaternary alluvial fan deposits and can be inferred from changes in the location of the polje bottom inferred from the slope of the corrosion surfaces.

This work demonstrates how large morpho-structural depressions developed in karst rocks, considered as tectonic in origin, may have been generated largely by corrosional lowering rather than by tectonic subsidence. The morphological analysis of this depression may provide an estimate of the deepening produced by corrosion processes. Similarly, the study of the neotectonic features found in a karst polje gives information about the role played by active tectonics in the origin and development of these karstic depressions.

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