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Tectonic subsidence v. erosional lowering in a controversial intramontane depression: the Jiloca basin (Iberian Chain, Spain)

JOSÉ C. RUBIO & JOSÉ L. SIMÓN*

Departamento de Geología, Univ. Zaragoza, Pedro Cerbuna, 12. 50012 Zaragoza, Spain

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Abstract – The Jiloca basin is a large intramontane, NNW–SSE-trending topographical depression in which the relative role of tectonic subsidence and erosional lowering is currently a matter of discussion. Geometry and facies of the sedimentary infill at its central sector have now been characterized from compiled borehole data, which allows discussions of how the evolutionary model is constrained. The central Jiloca depression contains a Late Pliocene to Pleistocene sedimentary sequence made up of alluvial fan, pediment mantle and episodic palustrine deposits, overlying a carbonate unit that could represent an early lacustrine stage of Late Miocene–Early Pliocene age. The geometry of these units is partially controlled by NW–SE-striking normal faults. Both the morphological depression and the sedimentary basin truncate previous folds, whose traces beneath the Neogene–Quaternary infill have been interpreted from the geology of the basin margins, borehole data and hydrogeological criteria. The northern and southern sectors of the Jiloca depression are bounded by faults showing measurable hectometric-scale throws (Calamocha and Concud faults). Moreover, in the central sector, the ~ 350–400 m tectonic uplift of Sierra Palomera has been interpreted from a morphostructural reconstruction of the tilted block which separates the Teruel and Jiloca graben, being similar to the height of the Sierra Palomera mountain front. All these features are consistent with a tectonic basin developed within the framework of the Neogene–Quaternary extensional evolution of eastern Spain. In contrast, they are hardly compatible with genetic models based on erosional deepening, either topographic lowering by numerous nested Tertiary erosion pediplains, or sub-alluvial Pliocene–Quaternary karstic corrosion.

Keywords: graben, extensional basin, polje, Pliocene, Iberian Chain.

1. Introduction

The Jiloca depression is one of the large extensional basins developed within the central-eastern Iberian Chain, eastern Spain (Fig. 1), linking the two other large basins of Calatayud and Teruel. The Jiloca depression is the youngest of these basins; its development took place during Late Pliocene time, deforming late Neogene erosion surfaces and their coeval deposits in the Calatayud and Teruel basins (Simón, 1983, 1989; Peña *et al.* 1984; Gracia, Gutiérrez & Leránoz, 1988). It also shows clear evidence of Quaternary tectonic activity, such as faulted and tilted Pleistocene deposits, and linear mountain fronts with triangular and trapezoidal facets at its eastern boundary (Simón, 1983; Simón & Soriano, 1993).

A number of recent papers argue against the significance of tectonic subsidence in the development of the Jiloca depression, pointing to erosional lowering as the main factor responsible for the present-day topography (Cortés & Casas, 2000; Casas & Cortés, 2002; Gracia, Gutiérrez & Gutiérrez, 2003). In these studies, an important argument against tectonic subsidence is the 'insignificant filling' (Cortés & Casas, 2000) or the 'reduced thickness of the basin fill' (Gracia, Gutiérrez & Gutiérrez, 2003). These assessments are made without showing precise data, and they were probably based upon the limited exposures of sedimentary units in the scarce and shallow incised stream channels.

Nevertheless, the infill of the Jiloca basin is thicker than that shown by outcrops. The geomorphological setting of the depression (prevalence of sedimentation, very weak incision of the Quaternary fluvial network), particularly in the central sector, enables observation of only the uppermost metres of the sedimentary series. Further information is available from the subsoil, however, mainly from boreholes drilled for water pumping during the second half of the twentieth century. Most data are included in reports and inventories made for public institutions until 1985. These data have been recently compiled, for the central sector of the Jiloca depression, by Rubio (2004). Although the quality of the available information is uneven, an accurate analysis and filtering of the borehole logs provides a useful database of subsoil geology.

Using this dataset, the first objective of the present work is to characterize the geometry of the sedimentary fill of the central sector of the Jiloca basin and to discuss how it constrains the evolutionary model. Our second objective is to discuss the conclusions of the controversial papers mentioned above (Cortés & Casas, 2000; Casas & Cortés, 2002; Gracia, Gutiérrez &

*Author for correspondence: jsimon@unizar.es

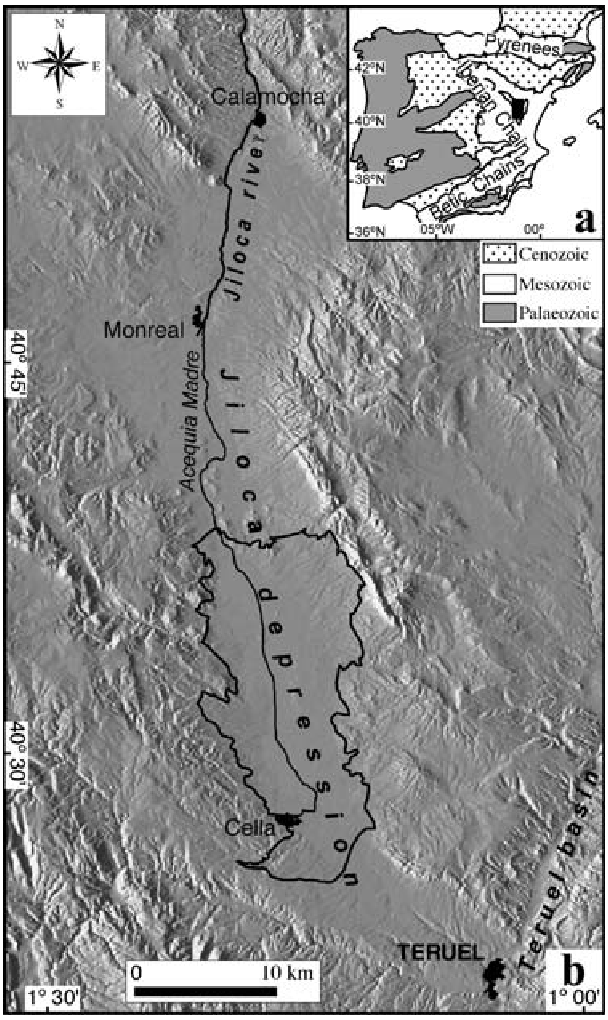

Figure 1. (a) Location of the study area within the Iberian Peninsula. (b) Digital elevation model of the Jiloca depression and surrounding area, obtained from the Carta Digital de España, Servicio Geográfico del Ejército, Spain. The area mapped in Figures 6 and 7 is outlined in black.

Gutiérrez, 2003), in order to determine which elements of the regional stratigraphic, structural, geomorphological and hydrogeological framework are compatible with the new proposed models and which are better explained by the classic ones. This will obviously require further consideration of geological aspects beyond the results of our study on the sedimentary infilling of the depression.

2. Geological and geomorphological setting

The eastern sector of the Iberian Chain shows a large network of Neogene–Quaternary continental basins which post-date the compressive structures, usually interpreted as extensional graben genetically related to rifting of the Valencia Trough (Vegas, Fontboté & Banda, 1979; Álvaro, Capote & Vegas, 1979; Simón, 1983, 1984). They follow two main trends (Fig. 1b): NNE–SSW (Teruel and Maestrazgo graben, parallel to the Valencia Trough) and NNW–SSE (Jiloca graben).

The whole graben system developed through two main extensional episodes. The first (Miocene) produced the main NNE–SSW-trending graben under well-defined WNW–ESE tension trajectories (Simón, 1984, 1986). During the second episode (Late Pliocene–Quaternary), under a near-multidirectional extension regime, the Teruel and Maestrazgo graben underwent reactivation and the Jiloca graben was newly created. The NNW–SSE trend of the latter was probably controlled by the maximum horizontal stress (S_{Hmax}) trajectories related to recent intraplate compression (Simón, 1989). Evidence of activity during Quaternary times includes decametric-scale offsets on NNE–SSW-striking faults at the boundaries of the Teruel graben (Moissenet, 1985; Simón, 1983) and, probably, hectometric-scale ones in the eastern Maestrazgo graben (Simón, 1984). Decametric-scale offsets in Middle to Upper Pleistocene deposits have also been found at some NW–SE-striking faults at the eastern limit of the Jiloca graben (Capote *et al.* 1981; Simón & Soriano, 1993).

The overall NNW–SSE trend of the Jiloca graben results from an en-échelon, right-releasing arrangement of NW–SE-striking normal faults, the largest ones being located at the eastern boundary: the Calamocha, Sierra Palomera and Concud faults (Fig. 2). The Calamocha and Concud faults cross-cut the Miocene–Lower Pliocene lacustrine deposits of the Calatayud and Teruel basins, respectively (Figs 2, 3), well dated using mammal faunas (Alcalá *et al.* 2000). This allows us to calculate the offsets and constrains the timing of movement on both faults, as will be discussed later. Unfortunately, precise knowledge of the displacement on the Sierra Palomera normal fault is not possible, as no Neogene or Quaternary stratigraphic marker can be recognized in both walls.

The Jiloca basin comprises a large intramontane topographical depression with a smooth bottom at about 1000 m asl (metres above sea level) bounded by ranges and plateaus at 1200 to 1500 m asl (Fig. 1b). The most conspicuous mountain front (some 18 km in length, up to 450 m in height) is that of Sierra Palomera. The basin margins show extensive erosion surfaces (with controversial origin and age, as mentioned in Section 1) which truncate Mesozoic and Palaeogene rocks, whereas the floor is mainly composed of pediment surfaces with associated alluvial deposits coming from both the eastern and western margins. The Holocene and present-day geomorphic processes in the depression show two points of contrast with the surrounding regions: (a) prevalence of sedimentation over fluvial incision (no fluvial terrace has been described in the Jiloca valley south of Calamocha) and (b) internal drainage, with development of palustrine areas (ancient Cañizar lake) that were progressively connected to the Jiloca river by artificial channels between the Roman epoch and the 18th century (Rubio, 2004). Between the localities of Cella and Monreal del Campo (see Figs 1b, 2), the so-called (on maps) 'Jiloca

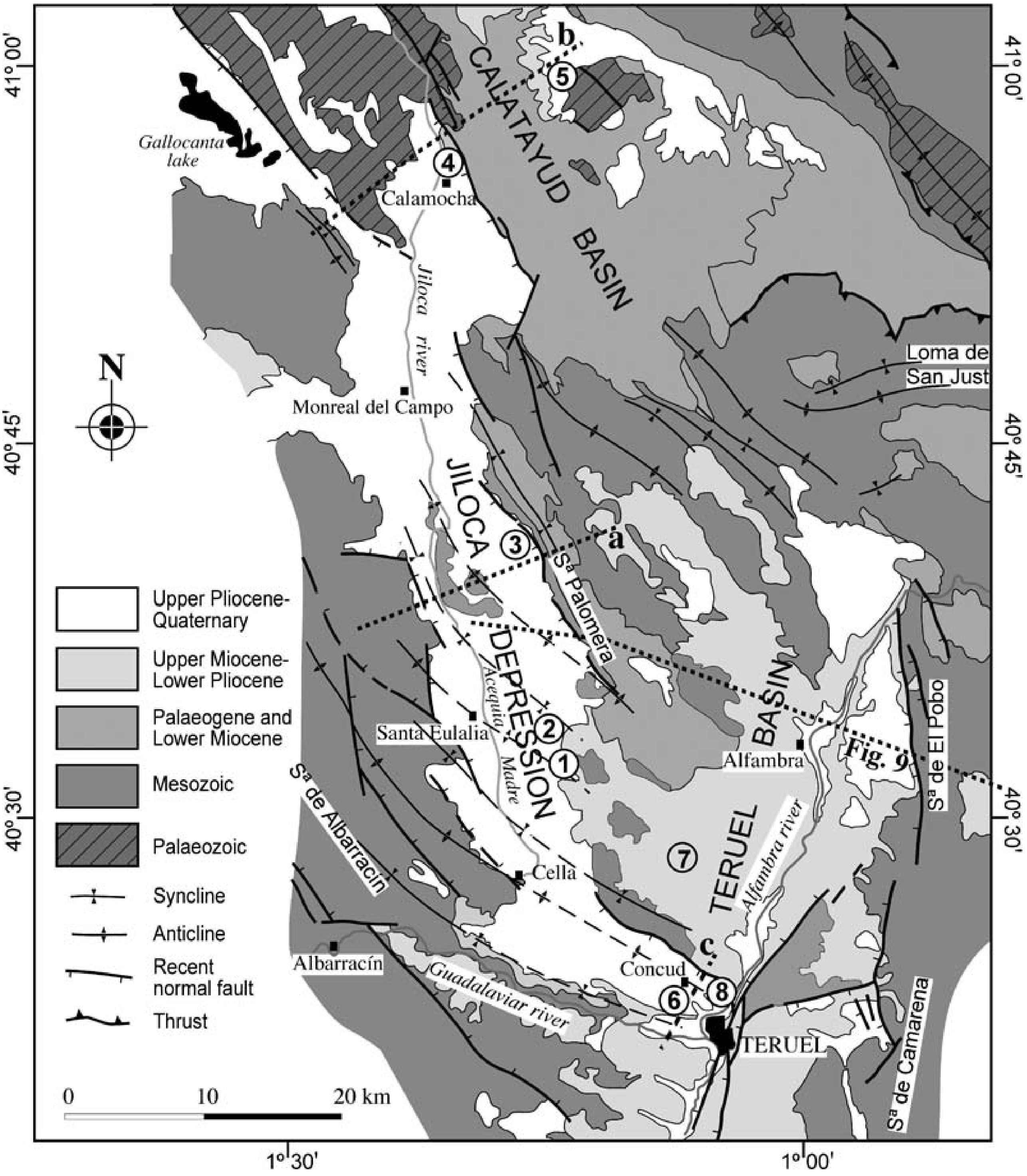

Figure 2. Geological map of the Jiloca depression. Locations of cross-sections of Figure 3 (a, b, c) and Figure 9, as well as sites mentioned in the text (numbers 1 to 8) are shown.

river' is in reality the largest of those artificial channels ('Acequia Madre', according to local toponymy).

3. Results of borehole analysis: lithology of Neogene–Quaternary infilling in the central sector of the Jiloca basin

In a first approach we considered 123 borehole logs included in two inventories (IGME, unpub. report, 1985; EPTISA, unpub. report, 1992). Nevertheless, descriptions of lithological sequences logged in those boreholes (almost all them drilled without core recovery) are not of consistent quality. There are sets of boreholes logged by geologists or competent technicians which provide satisfactory information, together with others containing very poor or ambiguous data. Only those which are detailed and reliable enough have been taken into account in our work, whereas some others have been discarded as unreliable due to the number of

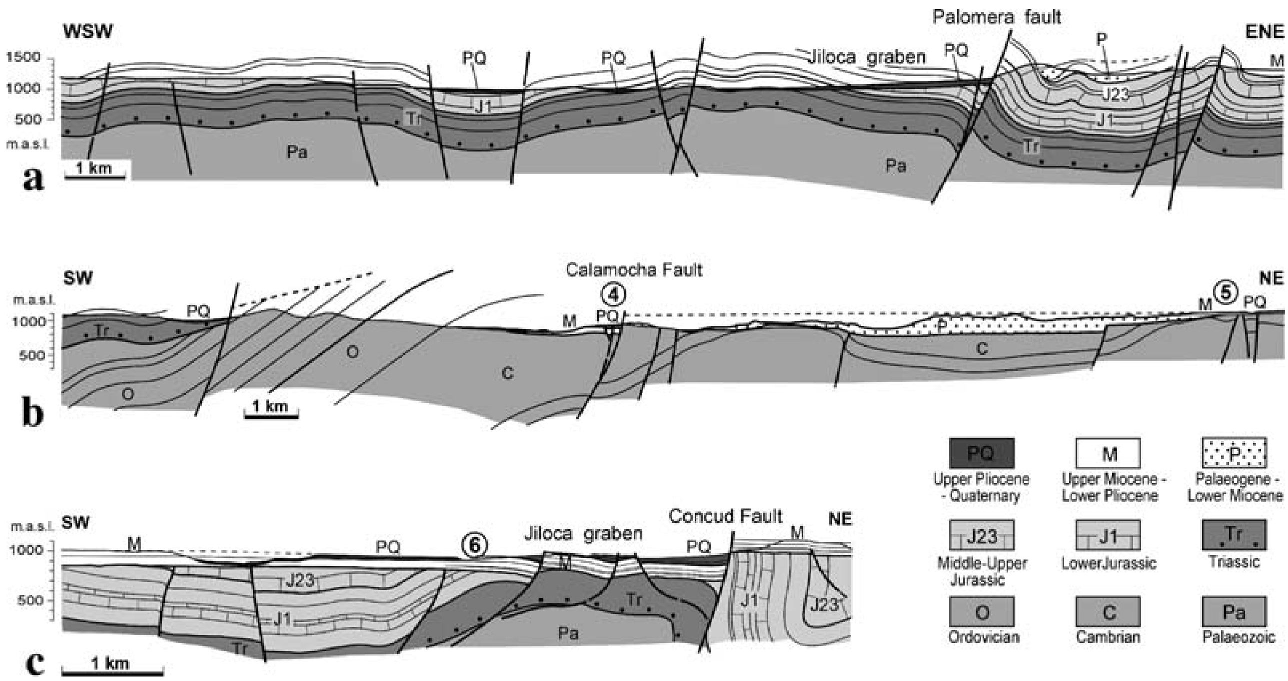

Figure 3. Cross-sections showing the structural throws at the main recent faults in the region. (a) Central sector, Sierra Palomera fault. (b) Northern sector, Calamocha fault. (c) Southern sector, Concud fault. See Figure 2 for locations.

contradictions in rock identification. Some initially ambiguous logs have been interpreted and finally considered in the light of those of neighbouring boreholes. Finally, 48 borehole logs distributed all over the studied area were selected, although only 16 of them (usually located near the graben boundaries) cross the entire Neogene–Quaternary infill (see Table 1). Most of these boreholes were drilled in the 1970s and 1980s for water pumping and are out of use at present. Complementary data were obtained from geotechnical boreholes for the Teruel–Zaragoza motorway and high-speed railway (GPO, unpub. reports, 2000, 2002). However, these did not add substantial information for reconstructing the infill geometry, since unfortunately they only contain information for depths up to 35–40 m and do not cross the entire Neogene–Quaternary sequence.

Analysis and correlation of the 48 selected borehole logs allow us to identify a number of different lithological units that make up the infill of the Jiloca basin. At the same time, boreholes crossing through the entire Neogene–Quaternary infill serve to constrain its geometry as well as the overall structure of the Mesozoic substratum (see Section 4). Unfortunately, the reports of boreholes do not refer to the palaeontological content of sediments, nor do they include geophysical logs. Lithology and colour are therefore the only criteria available for correlation. Nonetheless, these usually are conclusive enough for the aim of the present study, as they can be easily compared with equivalent sedimentary units cropping out in the surrounding areas. Three main Neogene–Quaternary units have been distinguished (Fig. 4):

Unit 1. Varied-colour (grey, white or yellow) clay, marl and limestone which constitute the lowermost unit infilling of the Jiloca basin in a part of the study area. This unit attains its maximum recorded thickness at borehole TO-3, where 71 m of grey marls with minor clay intercalations overlie Jurassic limestones. It could correlate with the Upper Miocene–Lower Pliocene lacustrine sediments of the neighbouring Teruel basin (IGME, 1983*b*). This correlation is more reliable in the southern sector, where boreholes VI-2, VI-15 and VI-17 (see Figs 4, 6) cross the entire thickness of the unit (22 to 45 m) and show a sequence of interbedded white limestone and grey marl very similar to the uppermost lacustrine deposits cropping out only 2 km east of site VI-17 (Fig. 5a, b; site 1 in Fig. 2).

Unit 2. Interbedded calcareous conglomerate, sandstone and silt, red to orange in colour, with mean grain size decreasing towards the centre of the basin. Conglomerates show a low to medium degree of cementation. These deposits correspond to alluvial fan and pediment-mantle deposits coming from the bordering mountains, and probably represent most of the Jiloca basin infill. Some borehole logs suggest a gradual sedimentary transition from the underlying Unit 1, as shown also by field sections where the boundary with Lower Pliocene lacustrine carbonates of the Teruel basin is exposed (Fig. 5a). The sequence culminates with a pediment clastic cover, showing in some cases an unconformity at its base (Fig. 5b), which crops out extensively in the central plain. Lithology, colour, cementation and stratigraphic relationships allow attribution of this unit to the Villafranchian (Late Pliocene).

Table 1. Borehole data: location, characteristics and log results

	UTM Coordinates								
Borehole	X	Y	Altitude (m asl)	Depth (m)	Use	Date	Thickness of units 2 + 3 (m)	Thickness of Unit 1 (m)	Substratum
A-1	639733	4501159	984	356	None	1986	20	0	Jurassic
A-2	642353	4495327	981	54	Irrigation	1978	49	> 5	?
A-7	640045	4495660	1005	110	Irrigation	1976	18	0	Muschelkalk
A-20	640163	4499745	977	160	Irrigation	1976	18	0	Jurassic
A-21	639022	4499984	1003	110	Irrigation	1976	18	0	Jurassic
C-9	643688	4486883	997	80	Irrigation	?	54	0	Jurassic
C-19	643408	4484493	1008	46	Irrigation	1975	37	0	Jurassic
C-21	643045	4484510	1020	74	Irrigation	< 1985	50	0	Jurassic
C-22	643051	4484114	1020	70	Irrigation	< 1985	60	0	Jurassic
C-31	644693	4480838	1018	51	Irrigation	1975	> 51	?	?
C-33	644361	4481293	1019	106	Irrigation	1982	55	0	Jurassic
C-45	643726	4483752	1010	55	Irrigation	< 1985	48	0	Jurassic
C-84	648642	4479476	1009	60	Supply	?	> 60	?	?
C-87	648396	4480282	1007	58	Supply	?	> 60	?	?
C-92	648854	4480918	1012	75	Irrigation	?	> 75	?	?
C-101	650095	4478656	1012	64	Irrigation	< 1985	> 64	?	?
C-113	649059	4477966	1016	50	Irrigation	< 1985	> 50	?	?
C-121	648248	4478608	1014	48	Irrigation	< 1985	> 48	?	?
SE-2	647624	4494017	1013	30	None	1984	27	> 3	?
SE-3	642084	4489143	1027	95	None	1975	9	0	Jurassic
SE-20	642910	4491709	990	48	Irrigation	1986	> 48	?	?
SE-23	643314	4490782	995	100	Irrigation	1977	41	44	Keuper
SE-33	643849	4487806	996	27	Irrigation	1950	> 27	?	?
SE-39	643122	4492506	989	44	None	?	42	> 2	?
SE-45	644071	4492387	987	48	None	1985	> 48	?	?
SE-49	644702	4492071	993	52	Irrigation	1957	41	> 11	?
SE-53	645757	4490664	1005	57	Irrigation	1972	51	> 6	?
SE-55	645445	4489814	1001	43	None	?	> 43	?	?
SE-56	645496	4491735	1002	50	None	1984	> 52	?	?
SE-65	645294	4493170	996	51	Irrigation	1984	> 52	?	?
T-8	643763	4494682	978	32	Irrigation	1981	22	> 10	?
T-24	644973	4494245	988	33	None	1978	20	> 13	?
T-28	644349	4495360	981	28	Irrigation	1980	26	> 2	?
T-29	645092	4496072	989	26	Irrigation	1978	16	> 10	?
T-30	645360	4494988	988	20	None	1978	16	> 4	?
T-37	646259	4494618	996	30	None	1978	24	> 6	?
T-55	645674	4493890	995	32	None	1975	30	> 2	?
TO-3	643688	4496442	979	130	None	1965	25	71	Jurassic
VI-2	648704	4485384	1024	234	Supply	1984	35	45	Jurassic
VI-6	648132	4484166	1007	60	Irrigation	1984	45	> 20	?
VI-15	649309	4485286	1035	153	None	1984	10	38	Jurassic
VI-17	647658	4487810	1015	100	None	1976	18	22	Jurassic
VI-21	645759	4489061	1000	70	Irrigation	1999	46	> 4	?
VI-37	647005	4485658	995	52	Irrigation	1986	45	> 7	?
VI-41	647166	4484959	996	60	Irrigation	1976	36	> 24	?
VI-43	647298	4484277	995	50	Irrigation	1980	47	> 3	?
VI-48	647548	4483682	996	60	Irrigation	1980	50	> 10	?
VI-54	646973	4483951	992	40	Irrigation	1977	> 40	?	?

Unit 3. Alluvial deposits, brown to grey in colour, which exhibit a low degree of cementation. Grading from the mountain fronts towards the centre of the depression, they include: (3a) alluvial fan gravels, the most conspicuous ones lying close to Sierra Palomera scarp (Fig. 5c, d); (3b) a relatively thin sequence of brown gravel and sand associated with pediment surfaces in intermediate areas; (3c) grey silt and clay with abundant organic matter, originating in central palustrine areas in periods of internal drainage. By comparison with similar deposits observed in field outcrops, usually separated from the Villafranchian unit by an erosional unconformity, they can be attributed to the Quaternary period. Thin fluvial deposits (gravel, sand and silt) linked to the ‘true’ Jiloca river appear only north of Calamocha (see Fig. 2), out of the study area.

The former units provide a stratigraphic record that can correlate fairly well with the upper part of the sedimentary sequence of the neighbouring Calatayud and Teruel basins. Unit 1 is probably an equivalent of their latest stages of lacustrine sedimentation, ranging from Late Miocene to early Late Pliocene in age. In the case of the Teruel graben, such lacustrine and palustrine deposits include (Weerd, 1976): carbonates of the Alfambra Formation (Upper Vallesian–Turolian), lutite and gypsum of the Tortajada Formation (Upper Turolian), and carbonates of the Escorihuela Formation (Ruscinian). These formations have been precisely dated by means of macro- and micromammal fauna

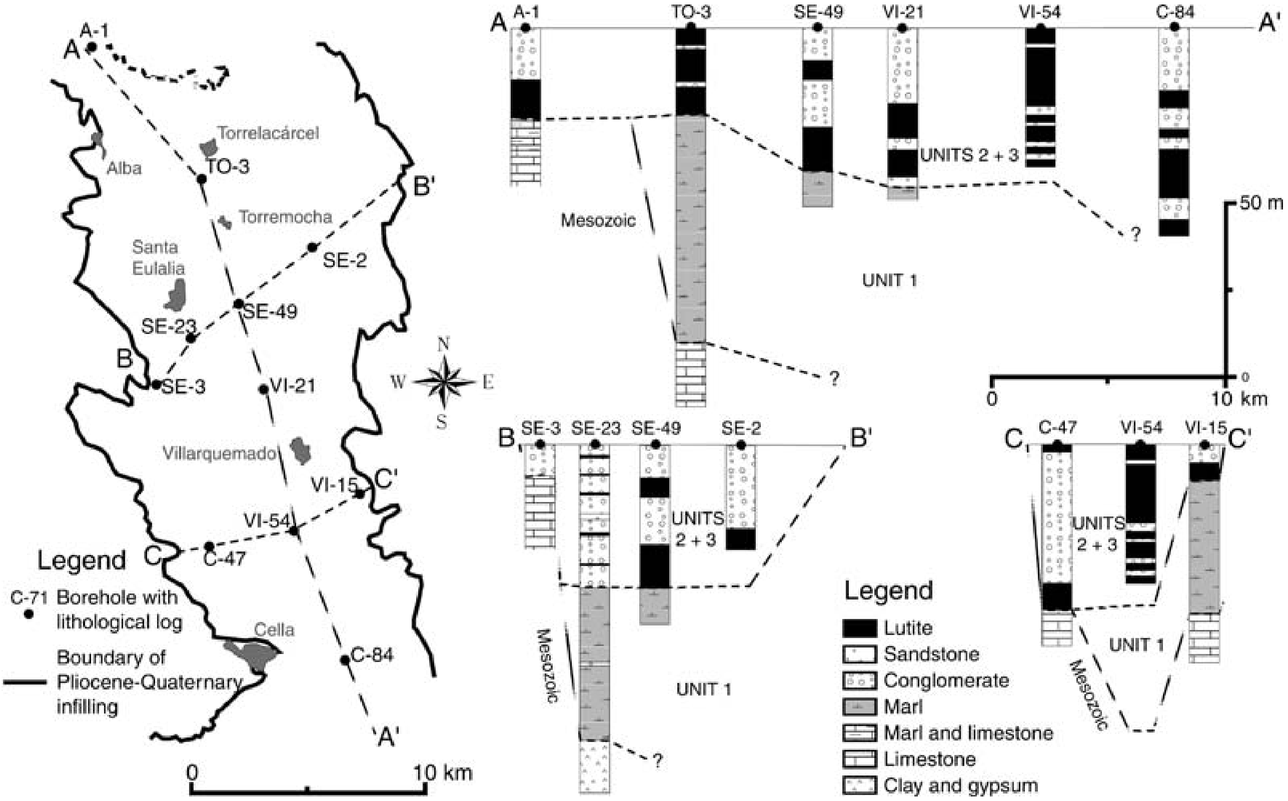

Figure 4. Lithology of sedimentary infill of the Jiloca basin from selected borehole logs. Units 1, 2 and 3 are described in the text.

(Alcalá *et al.* 2000). Unit 2 can be correlated with the alluvial ensemble characterizing the Villafranchian of both neighbouring basins. This is made up of red lutites (Lower Villafranchian) and pediment-mantle gravel and silt (Upper Villafranchian), the latter being associated with a pediment level which covers vast areas of graben bottoms (Peña *et al.* 1984). Unit 3 of the Jiloca depression is an equivalent of the Quaternary pediment and alluvial fan deposits also present, although more reduced, in the Calatayud and Teruel basins. The unusual feature of the Jiloca depression is that most of its bottom has not undergone the Quaternary fluvial incision (it has continued to be internally drained up to historical times), so that the typical sequence of nested fluvial terraces is almost absent.

4. Geometry and interpretation of the sedimentary infill

Geometry of the Neogene–Quaternary infill can be reconstructed from those borehole logs reaching the Mesozoic substratum, although the remainder provide minimum thickness data that help to constrain the model. Such a reconstruction is displayed by the isopach maps of Figures 6 and 7a, corresponding to Unit 1 and Unit 2 + Unit 3, respectively. In Figure 6, those boreholes reaching the Mesozoic substratum (either Triassic or Jurassic in age) have been identified. In both figures, the total thickness of the sedimentary units considered in each case is labelled for those boreholes that reached the base. Data on 'minimum thickness' for the rest of the sites are not labelled (they can be read in Table 1), but they are fully compatible with the drawn isopachs.

The results for Unit 1 and Unit 2 + Unit 3 have been presented and discussed separately owing to differences both in degree of knowledge and geological meaning. As explained above, Unit 1 shows well-characterized lithology but controversial age. Palaeontological data which could enable a reliable identification are absent in the studied logs. Unfortunately, no sample could be obtained from the boreholes in order to carry out a specific study. We have considered the possibility of an Early Jurassic (Pliensbachian–Toarcian) age for this unit, since the corresponding formations in the regional stratigraphic record (Cerro del Pez, Barahona and Turmiel formations) show a marl sequence of comparable thickness. Nevertheless, Unit 1 should then be concordant within the Jurassic series, which is not the case; on the contrary, it seems to cover different Lower Jurassic units, and it directly overlies Upper Triassic clay and gypsum at borehole SE-23 (Fig. 6). If the correlation with Upper Miocene–Lower Pliocene lacustrine carbonates of the Teruel basin is correct, as discussed in Section 3, Unit 1 could represent an early stage of basin development in the central Jiloca depression, prior to the main overall subsidence period in Late Pliocene times. However, from the available data, this should be considered only as a hypothesis.

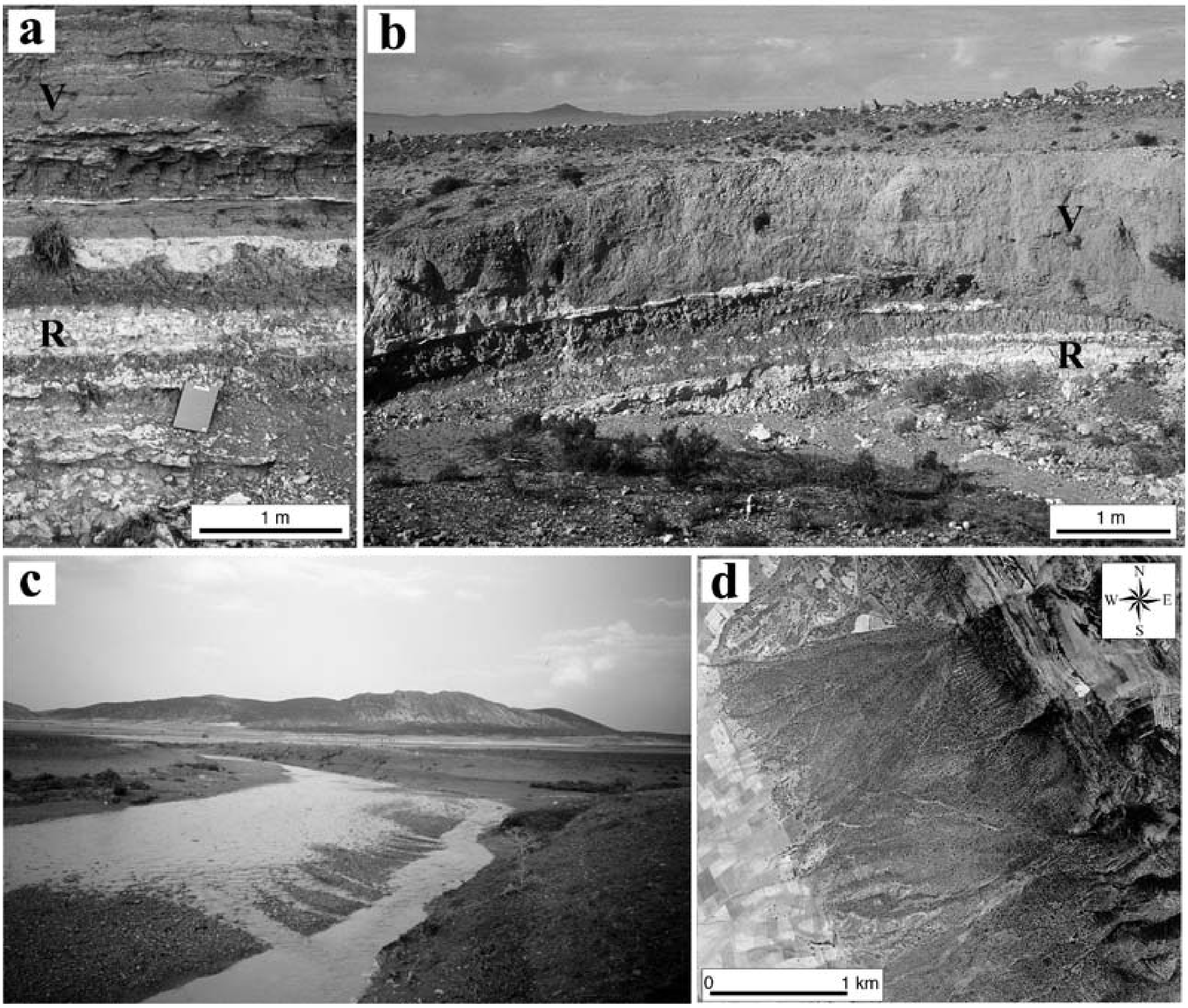

Figure 5. (a) Sedimentary sequence showing a gradual transition between Ruscinian lacustrine carbonates (Lower Pliocene, labelled as R) and Villafranchian lutites (Upper Pliocene, V) at Rambla de Villarrosano (site 1 in Fig. 2). (b) Unconformity between Ruscinian carbonates and Villafranchian pediment mantle at Barranco Ramón (site 2 in Fig. 2). (c) Sierra Palomera mountain front as seen from the centre of the Jiloca basin. (d) Aerial view of a Quaternary (active at present) alluvial fan close to Sierra Palomera scarp (site 3 in Fig. 2).

The geometry of such a hypothetical initial basin is represented by the isopach map of Figure 6. A tenuous control by NW–SE-striking faults can be seen, with the main sedimentary space being located at the central Jiloca basin (Sierra Palomera sector) and a possible depocentre east of Santa Eulalia. Unfortunately, the isopachs are not constrained close to Sierra Palomera, due to the lack of subsoil information from that sector. On the other hand, the absence of Unit 1 in a number of boreholes north of Cella allows a reliable trace of isopach 0 in the southwest. Finally, isopachs seem not to close towards the southeast, so that a connection to the uppermost, Lower Pliocene lacustrine deposits of the Teruel basin is quite probable.

The widespread red clastic deposits that fill most of Jiloca basin (Unit 2 + Unit 3), although not precisely dated, can be attributed to Late Pliocene and Quaternary times based on uncontroversial geological and geomorphological correlation in the framework of the Neogene basins of the central-eastern Iberian Chain (IGME, 1983*b*). Units 2 and 3 have been grouped since they cannot be distinguished from one another in every borehole. They define an asymmetric basin, with thickness broadly increasing towards the west and attaining 60 m at borehole C-22 (Fig. 7a). Coeval displacement on two NNW–SSE-striking faults (Santa Eulalia and Cella faults) can be invoked to explain variations in thickness at the western edge. Activity on the Sierra Palomera fault cannot be assessed in the same way, due to the lack of available subsoil data from this area. Nevertheless, morphometric analysis of the alluvial fans and geomorphic features at the mountain front suggest that Quaternary activity was especially intense at this fault (Gracia, Gutiérrez & Gutiérrez, 2003). The

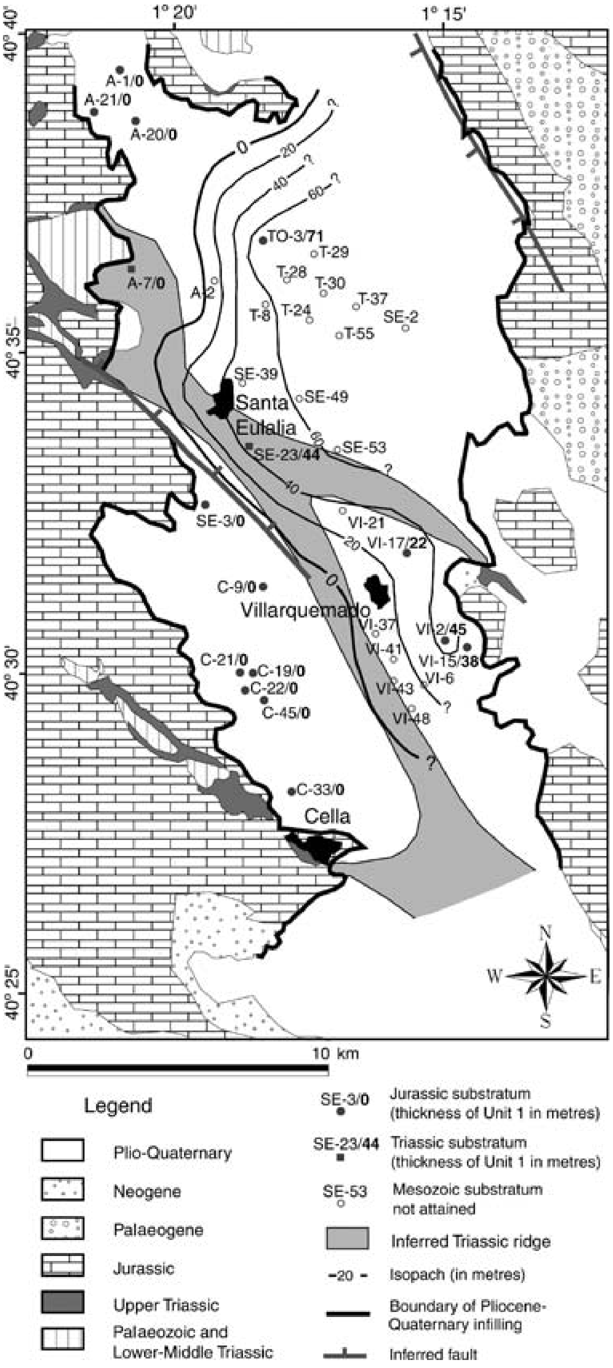

Figure 6. Isopach map of sedimentary Unit 1 (Upper Miocene–Lower Pliocene?) from borehole logs. The nature of the Mesozoic substratum is approached from borehole data and the geology of the basin margins. Isopachs in metres.

southernmost sector of the studied area also shows high-thickness Plio-Quaternary infill, although not clearly related to active faults in this case; joint thickness of Units 2 + 3 exceeds 75 m at borehole C-92 (the borehole did not reach the substratum). The facies distribution, as expressed by the percentage of coarse clastic components within the total sequence (Fig. 7b), suggests a concentric sedimentary pattern, with active source areas all around the depression and two distinct depocentres located close to the basin axis (northeast of Santa Eulalia and south of Villarquemado, respectively).

Another point of interest for interpreting the Jiloca basin is the overall structure of the Mesozoic substratum. Boreholes which cross through the entire infill provide additional information that, together with geology of the basin margins, help to constrain this structure. The latter is characterized by a set of NW–SE-trending folds, roughly parallel to the normal faults but oblique to the overall graben trend, so that some of them go across the basin. The main anticline cores can be reconstructed from both direct and indirect evidence:

(a) Triassic units crop out in anticline structures at the basin boundaries. In some cases, they can be fairly well correlated from one side of the Jiloca depression to the other (Santa Eulalia–Villarquemado and Cella–Caudé anticlines; see Fig. 6).

(b) Unlike most areas, where Lower Jurassic limestones make up the basin substratum, Triassic clay, gypsum and dolostone have been found directly below Plio-Quaternary deposits at sites SE-23 and A-7. Their locations are compatible with the trace of the above mentioned Santa Eulalia–Villarquemado anticline (Fig. 6).

(c) A conspicuous hydrogeological boundary has been detected within the Jurassic aquifer along the Santa Eulalia–Villarquemado line. Northeast of this discontinuity, piezometric levels range between 945 and 950 m asl (e.g. 946 m at well TO-3), constituting a recharge zone of the Jurassic aquifer. In contrast, southwest of it, piezometric levels range between 980 and 995 m asl (e.g. 984 m at well C-9); here we find a discharge area of the Jurassic aquifer (up to 25–27 hm^3/year) which gave rise to the ancient Cañizar lake (11 km^2 in surface in historic times). This hydrogeological setting could easily be explained by considering the presence of an impervious Upper Triassic clay and gypsum ridge separating the two areas of the Jurassic limestone aquifer.

5. Discussion: topographic depression and sedimentary basin, erosional lowering v. tectonic subsidence

We should now refer to the papers mentioned in Section 1, which state that erosional lowering instead of tectonic subsidence is the main factor responsible for the development of the Jiloca. We will discuss their conclusions in the light of (a) our results about the basin filling, and (b) diverse aspects of the structural and geomorphological regional framework.

Casas & Cortés (2002) propose that the Neogene depressions within the central Iberian Chain are residual basins located in synclinal areas, being prolongations of Palaeogene basins developed within the frame of the Alpine compressive structures. According to the

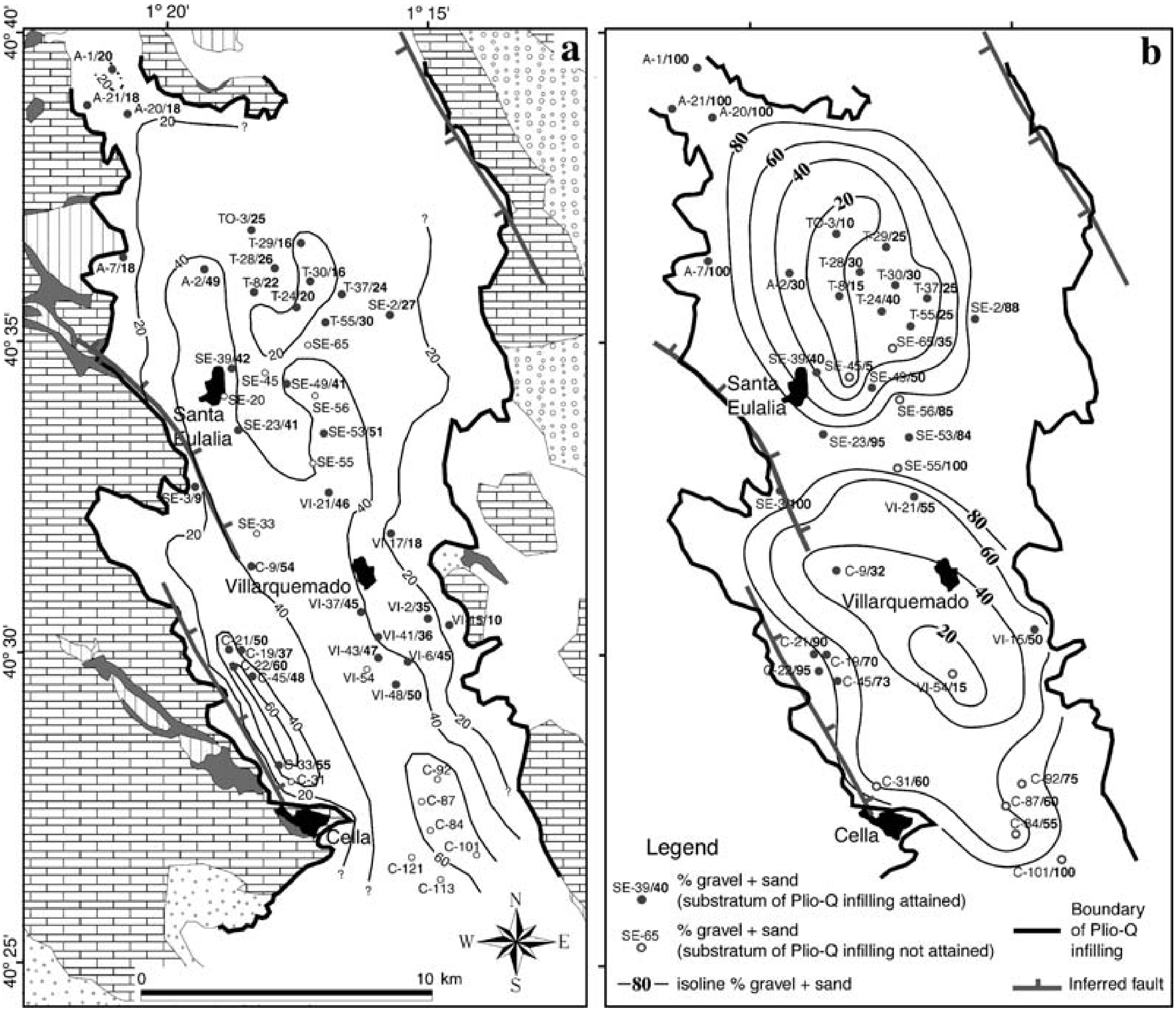

Figure 7. Characteristics of Unit 2 + Unit 3 (Upper Pliocene and Quaternary) from borehole logs. (a) Isopach map; isopachs in metres; legend as in Figure 6. (b) Facies map: percentage of coarse clastic deposits (gravel + sand) in the total sequence.

authors, the present-day landscape does not reflect any significant tectonic subsidence but a progressive lowering during successive erosional events in response to Palaeogene–Early Miocene compressive uplift. The erosion surfaces observed at different heights in the surrounding region would represent up to seven originally stepped, almost non-deformed erosion surfaces, instead of two or three polygenic surfaces displaced and tilted by extensional Neogene faults, as was previously proposed (Riba, 1959; Simón, 1983, 1984; Peña *et al.* 1984; Gracia, Gutiérrez & Leránoz, 1988; Gutiérrez & Gracia, 1997).

Gracia, Gutiérrez & Gutiérrez (2003) re-interpret the Jiloca depression as a karst polje developed during Pliocene–Quaternary times within an active half-graben. Although tectonic subsidence could control the initiation and location of the polje, the topographic depression is considered to have been essentially deepened (some 300 m) by solution processes, giving rise to a sequence of eight stepped levels of karst corrosion surfaces. The prominent topographic scarps at the eastern mountain fronts are disregarded as possible evidence of large fault displacements; they are considered to be a result of differential erosion, and therefore much higher than the structural throws. On the other hand, as the bottom of the depression was covered from the time of the earliest stages by clastic deposits coming from the margins, the proposed model needs to invoke kryptokarstic corrosion acting beneath the alluvial cover as the main deepening mechanism.

Both articles point to erosional lowering as the main factor responsible for the present-day topographic depression, as opposed to tectonic subsidence. Nevertheless, the conclusions of the first paper about the mechanisms and ages of such erosion processes do not agree with those of the second paper. For example, remnants of planation surfaces mapped in both papers in the area southwest of Monreal del Campo, at heights between 1050 and 1300 m asl, are considered as Late Oligocene to Early Miocene pediplains by Casas & Cortés (2002, fig. 15) (S4, S5 and S6 in their nomenclature), whereas they are interpreted as Late Pliocene to Quaternary karstic corrosion surfaces (A, B, C and D) by Gracia, Gutiérrez & Gutiérrez (2003). These remnants were previously attributed to Late Miocene–Early Pliocene pediplains: the Fundamental Erosion Surface of the Iberian Chain (Peña *et al.* 1984) and the Border Surface of Neogene Basins, S3 (Gutiérrez & Gracia, 1997). With respect to the integrated geological evolution of the area (erosion, tectonics, sedimentation), the first paper states that the erosional lowering would have developed prior to the main infilling, Neogene in age, of the internally drained Teruel basin (Late Miocene to Early Pliocene in age: Alcalá et al. 2000; Alonso & Calvo, 2000), whereas the second paper implicitly considers the stepped corrosion surfaces as subsequent to post-sedimentary extensional faulting and tilting of those Neogene deposits.

According to our results, the thickness of Pliocene–Quaternary deposits in the central Jiloca depression, although not comparable with other contemporaneous graben of the Mediterranean domain, cannot be considered as 'insignificant' (as assessed by Cortés & Casas, 2000). This thickness reaches 50 to 75 m in several areas. These values are similar to those of the Calatayud and Teruel graben, where Plio-Quaternary clastic sediments cover discontinuous areas and usually do not exceed 60 m in thickness (the only exception is an Upper Pliocene alluvial deposit located 13 km south of Teruel, which attains some 120 m). In some areas, the geometry of the sedimentary filling shows structural control (sharp thickening related to extensional faults bounding the graben). Coarse clastic deposits are abundant within it, mainly close to the basin edges, and a number of alluvial fans can be recognized in association with fault scarps. All these features are common in tectonic graben, whereas they cannot be easily explained in the framework of an erosional depression, as discussed in the following paragraphs.

The northern and southern sectors of the Jiloca depression have unambiguous structural control, bounded by the Calamocha and Concud faults, respectively. Both faults have measurable throws, since they displace the near-horizontal, uppermost lacustrine carbonate deposits (Early Pliocene in age: Alcalá *et al.* 2000; Alonso & Calvo, 2000) of the Calatayud and Teruel basins, respectively (Figs 2, 3). The Calamocha fault shows such lacustrine limestones at 880–920 m asl in its hangingwall, in contact with Palaeozoic slates and Lower Miocene conglomerates of the footwall (Venta de los Céntimos, site 4 in Figs 2, 3b; IGME, 1983*a*). Although this unit does not appear in the footwall close to site 4, it could be either (a) approximately coeval with clastic deposits cropping out at Llano de la Lastra (site 5 in Figs 2, 3b; IGME, 1983*a*), or (b) eroded while an unconformity underlying those clastic deposits was developed. This unconformity lies at 1060–1080 m asl, which indicates a minimum throw of 160–180 m (although it could be larger, depending upon the interpretation of fault history and erosion of sedimentary infilling during Miocene times).

Figure 8. Concud fault cropping out in an artificial trench 3 km north of Teruel. M – Turolian (Upper Miocene) lacustrine carbonates of the Teruel basin. Q – Middle Pleistocene alluvial fan deposits (site 8 in Fig. 2).

The Concud fault shows Lower Pliocene carbonates at 920–940 m asl in its hangingwall near Concud (site 6 in Figs 2, 3c), lying unconformably beneath the Upper Pliocene and Pleistocene red clastic sediments of the Jiloca graben (IGME, 1983*d*). In the footwall, the same unit forms a structural plain at 1180–1200 m asl (Celadas, site 7 in Fig. 2). This suggests a post-Early Pliocene vertical offset of about 250 m. An independent calculation can be made as well for Pleistocene times; the Concud fault offsets a fluvial terrace of the Alfambra river by some 40 to 60 m (Moissenet, 1985; Simón and Soriano, 1993). Calcareous tufa from the terrace has provided Th/U ages between 169 000 ± 10 000 and 116 000 ± 4000 years BP (Arlegui *et al.* 2004*a*) (see Fig. 8).

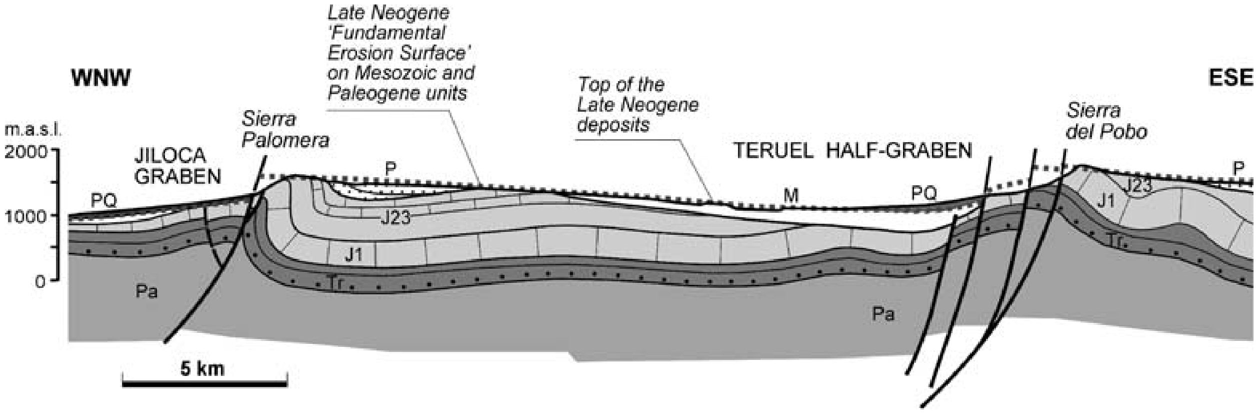

Figure 9. Schematic morphostructural cross-section showing the interpretation of the tilted block between the Jiloca depression and the Teruel half graben, and the calculated throw at the Sierra Palomera fault. Vertical scale ×2; same legend as in Figure 3. See location in map of Figure 2.

In the central segment of the Jiloca depression, the offset at the Sierra Palomera fault cannot be calculated in the same way since no appropriate recent sedimentary marker is available. Gracia, Gutiérrez & Gutiérrez (2003) admit that it is very difficult to estimate the structural throw in the folded Jurassic units. Nevertheless, they use the interpretation of Cortés & Casas (2000), which is opposed to a significant throw at this fault, as a basis for their hypothesis of corrosion-driven lowering. Casas & Cortés (2002) are even in doubt about the existence of the fault, based on the observation that the lateral termination of the Sierra Palomera anticline is not clearly displaced. Nevertheless, in that area, Jurassic materials do not show continuous outcrop along the fold hinge, so it is not possible to assess whether the fold is broken or not. Visual inspection of the geological map (IGME, 1983*b*) suggests that, in fact, the stratigraphic contacts are offset between both fold limbs (although this could also be caused by another transverse, NNE–SSW-striking fault). In such a situation, the eventual geometric continuity of the fold can be interpreted only by graphic interpolation in cross-section, a subjective procedure that does not lead to a unique solution. In particular, a hectometric-scale post-folding throw between both limbs is compatible with the geometry of the outcropping units (Fig. 3a).

In our opinion, there are three arguments which point to a vertical displacement of the Sierra Palomera fault larger than those of Calamocha and Concud faults:

(a) This would be consistent with a 'logical' morphostructural setting for the whole extensional structure; it is unlikely that the extreme segments of the Jiloca graben (Calamocha and Concud faults) underwent more deformation than the central segment (Sierra Palomera fault).

(b) The morphological scarp is higher (up to 300 m; 450 m for the whole mountain front) than those of the Calamocha and Concud faults (maximum scarp heights of 140 and 120 m, respectively).

(c) The eastern wall of the Sierra Palomera fault corresponds to a tilted block whose outline is defined by the uppermost lacustrine carbonate deposits of the Teruel basin (Early Pliocene in age: IGME, 1983*c*) and, westwards, by a vast planation surface which truncates Mesozoic and Palaeogene materials up to Sierra Palomera (Fig. 9). Both (sedimentary and morphological) markers are in continuity with each other and show a quite consistent slope (about 2 % along a distance of 18 km), which suggests that they made a single near-horizontal marker in Early Pliocene times. Such a relationship would allow the identification of the planation surface as the Fundamental Erosion Surface of the Iberian Chain (Peña *et al.* 1984). The final geometry of the morphostructure involves a tectonic uplift of Sierra Palomera of about 350–400 m relative to the bottom of the Teruel depression. This value should not be too different from the uplift relative to the bottom of Jiloca depression; in fact, it is similar to the height of the Sierra Palomera scarp.

The evolution model proposed by Casas & Cortés (2002), based on the continuity of compressive folding structures of the Iberian Chain up to Plio-Quaternary times, is hardly compatible with the extensional framework above described. From the methodological viewpoint, the basic problem of that model relates to the criteria used for mapping and correlating erosion surfaces. Elevation with respect to sea level of the observed remnants has been considered as an absolute, so that seven planation surfaces have been defined on the basis of a cumulative curve of elevation (Casas & Cortés, 2002, fig. 3c). Height differences between successive nested planation surfaces range between 50 and 100 m, but the region has undergone recent hectometric-scale offsets on large normal faults; throws of 200 to 300 m have been explicitly admitted by Cortés & Casas (2000) in Late Miocene limestones at the central and southern sectors of the Teruel graben. In such a situation, it seems quite difficult to establish reliable correlations between planation surfaces based on absolute altitudinal criteria.

The Jiloca depression constitutes a well-defined geological unit showing consistent structural and sedimentary features, as well as a noteworthy geomorphological unit which provides a sharp contrast with the surrounding uneven landscape (Fig. 1b). Its nearly N–S trend is clearly oblique to folding structures and lithological domains of the bounding Mesozoic and Tertiary materials, and fits the orientation of the recent extensional stress field in the region (Simón, 1989; Herraiz *et al.* 2000; Arlegui *et al.* 2004*b*). It is neither an area of soft lithologies nor a synclinal structure. Thus, in opposition to the model by Casas & Cortés (2002):

(a) This elongated area was not particularly prone to erosional lowering during Palaeogene to Middle Miocene times. It seems contradictory to invoke differential erosion to explain the Sierra Palomera morphological scarp, while such a mechanism is not considered for other fold limbs fully eroded below the floor of the Jiloca depression. Some morphological scarps are parallel to fold limbs, as in Palomera and Concud, because the faults are also parallel to those limbs. These normal faults were probably ancient reverse, fold-related faults which underwent negative inversion during the Neogene extension. Nevertheless, the first-order folds are clearly oblique to the overall nearly N–S trend of the depression; their traces can be linked from one margin to the other and the impervious Upper Triassic materials at their cores give rise to hydrogeological segmentation of the basin.

(b) This elongated area would also not have shown a particular tendency to sedimentary infilling during Late Pliocene and Quaternary times if tectonic subsidence had not occurred. In contrast to the Calatayud and Teruel basins, it was not a sedimentary domain during Miocene time (we should remember that the materials of such ages found at its northern and southern sectors correspond, respectively, to those basins). However, the whole area became a sedimentary basin during and after Late Pliocene time, with a strong, continuous tendency to infilling during the Quaternary, over a time scale when the entire region underwent fluvial incision. Even at present, some alluvial fans at the eastern margin are active and show a fresh morphology (Fig. 5d) that constitutes a conspicuous anomaly within the framework of regional landscape evolution.

In our opinion, the thickness, geometry and age of the Jiloca sedimentary infill also raises serious difficulties for the model of Gracia, Gutiérrez & Gutiérrez (2003). Briefly, that model implies that the Jiloca depression underwent some 300 m of differential erosional lowering by karstic corrosion during Late Pliocene and Quaternary times (about 3 Ma), while it accommodated coeval clastic sediments up to 75 m thick. Interaction of both processes had to be necessarily complex. In a first approach, Gracia, Gutiérrez & Gutiérrez (2003) solve the problem of coeval erosion and filling by considering that deepening of the polje progressed by dissolution processes acting beneath the alluvial cover (kryptokarstic corrosion). It is easy to understand such a process when the limestone is overlain by a thin veneer of the products of its own weathering, mainly in vegetated regions where water enriched in CO_2 from rotting organic matter is present ('subsoil corrosion' as defined by Gams, 1978). The case of 'suballuvial corrosion' (solution beneath permeable non-calcareous surface deposits: Gams, 1978) is quite different. It is admitted that many alluvial or lacustrine deposits are pervious and do not seal off the bottoms of the poljes, so that solution persists beneath these covers and the poljes continue to deepen as well as extend laterally (Gams, 1978; Fabre & Nicod, 1982; Jennings, 1985). There are, however, some questions relative to the rates and geological evidence for such processes in the Jiloca depression that should be discussed in detail.

Corrosion of limestone beneath the alluvium cover is controlled by three main parameters: water flow, available CO_2, and carbonate content of the alluvial cover (the smaller the latter, the more CO_2 is available for limestone solution: Fabre & Nicod, 1982). The consensus is that about 70 % of limestone dissolution takes place within 10 m of the surface, with a range of variability of 50 to 90 %, depending on lithology and other factors (Atkinsons & Smith, 1976; Ford & Williams, 1989). The alluvial infill of the Jiloca depression shows a high content of calcareous gravel and conglomerate (about 35–40 % from borehole logs) that should undergo dissolution before water reaches the bedrock. This would drastically reduce the amount of carbonate that could be dissolved from Mesozoic limestone and dolostone at a depth of several tens of metres. Solutional lowering rates on bare limestone surfaces have been estimated within the range of 12 to 42 mm/ka (data compiled by Ford & Williams, 1989; Bono & Percopo, 1996). Under surface corrosion at the highest rate, more than 7 Ma would be required for a topographic deepening of 300 m as stated by Gracia, Gutiérrez & Gutiérrez (2003). With suballuvial corrosion acting at medium rates beneath a carbonate-rich cover 20–60 m thick, the time would be much longer.

On the other hand, if such extremely intense and widely distributed kryptocorrosion processes actually occurred, they should have been recorded as collapse structures within Plio-Quaternary deposits, both at the surface (alluvial dolines) and at depth (collapse funnels and other similar structures). 'The poljes are drained underground through swallow holes or ponors … Where the floor is covered with drift or alluvium, alluvial dolines form by collapse of alluvium into the fissures and these absorb the overflow water from the polje' (Sweeting, 1972, p. 194). Such a scenario is not confirmed by geological observations. Examples of karstic collapse structures have been described in fluvial terraces of the neighbouring Teruel and Calatayud basins, related to dissolution of underlying Neogene evaporites (Moissenet, 1985; Gutiérrez, Peña & Sánchez, 1985; F. Gutiérrez, unpub. Ph.D. thesis, Univ. Zaragoza, 1998). Nevertheless, no vestige has been found within the Jiloca depression.

It could be admitted that the topographic steps at both margins of the Jiloca depression may not be due in their entirety to tectonic subsidence. Pediplanation processes prior to graben development did not result in a single erosion surface. The Fundamental Erosion Surface of the Iberian Chain (Peña *et al.* 1984) is inset in relation to an older surface preserved, for instance, on the highest reliefs of Sierra de Albarracín, and it splits into two main stepped surfaces in certain areas (S_2 and S_3 surfaces of Gutiérrez & Gracia, 1997). This situation makes the accurate evaluation of tectonic offsets difficult, but it does not invalidate the overall conclusions about recent vertical deformation obtained by numerous authors based on geometrical reconstruction of such surfaces (Birot, 1959; Riba, 1959; Simón, 1983, 1984, 1989; Peña *et al.* 1984; Gracia, Gutiérrez & Leránoz, 1988; Gutiérrez & Gracia, 1997).

On the other hand, some of the low surfaces mapped by Gracia, Gutiérrez & Gutiérrez (2003) at the western margin of the Jiloca depression (surfaces E–H) could have effectively developed by karstic corrosion during an early polje stage, soon after the beginning of tectonic subsidence and essentially prior to alluvial Plio-Quaternary sedimentation. They may represent a first erosional response to deformation at the western edge of the Jiloca basin. In such a framework, they could develop by rim-corrosion (Roglic, 1964) along the contact between the limestones of the basin margins and previously deposited impervious materials, either marls of Unit 1 (Upper Miocene–Lower Pliocene?) or the lowermost lutites of Unit 2 (Upper Pliocene). Under the same mechanism, the Sierra Palomera scarp could retreat eastwards with respect to the fault trace. Nevertheless, the overall present-day topography is basically a consequence of the recent extensional structure, as in numerous poljes where the structural setting dominates the morphogeny and karst erosion has only a limited contribution (Jakucs, 1977).

6. Conclusions

The Jiloca depression is a tectonic graben with hectometric-scale offsets at its bounding faults, hectometric-scale morphological scarps, and decametric-scale thickness of the sedimentary infill. It constitutes a well-defined geological and geomorphological unit, whose nearly N–S trend crosses folds and lithological domains of the central Iberian Chain and fits the orientation of a recent (Late Neogene to present day) stress field. The overall depression is neither an area of soft lithologies able to undergo differential erosional lowering, nor a syncline area providing space for sedimentary infilling during post-orogenic times. In our opinion, there is no evidence to support the hypothesis of an exceptional polje, 700 km^2 in area and undergoing 300 m of erosional deepening, while the tectonic control on both the topography and the sedimentary filling is fairly well supported by data.

The central Jiloca depression contains an Upper Pliocene to Pleistocene sedimentary sequence made up of alluvial fan, pediment mantle and episodic palustrine deposits. The compiled borehole information shows that it has an irregular thickness, usually ranging from 20 to 60 m and locally exceeding 75 m. These deposits overlie a puzzling carbonate unit, whose precise age and sedimentology remain unknown. We hypothesize that it could represent the record of an early stage of basin development (Late Miocene–Early Pliocene?), not identified up to the present from surface geology.

NW–SE-striking faults at the western basin boundary (Santa Eulalia and Cella faults) control the geometry of the infill, which suggests synsedimentary activity. Unfortunately, the lack of available data from the neighbourhood of the Sierra Palomera fault hinders assessment of its recent activity. Nevertheless, geological and geomorphological evidence for tilting of the Sierra Palomera–Alfambra block, together with the active alluvial fans close to the Sierra Palomera mountain front, and the morphology of the prominent scarp itself, suggest a hectometric-scale post-Early Pliocene slip on the Sierra Palomera fault.

Geometry, thickness, facies distribution and age of the sedimentary infill are consistent with a tectonic basin developed within the framework of the Neogene–Quaternary extensional evolution of eastern Spain. These sedimentary features, as well as the lithological grain and the evidence of hectometric-scale offsets on the large faults, are hardly compatible with the hypothesis of erosional deepening as the main mechanism for explaining the Jiloca topographic depression.

A partial contribution of erosional lowering to the development of the Jiloca depression should not be ruled out. Pediplanation processes prior to graben development did not result in a single erosion level but in a sequence of at least three surfaces: the high surface of Sierra de Albarracín, Fundamental Erosion Surface (Peña *et al.* 1984), Border Surface of Neogene Basins, S_3 (Gutiérrez & Gracia, 1997). The topographic steps at both margins of the Jiloca depression may therefore be partially due to erosion, and an ancient, gentle topographic depression could have formed between Sierra de Albarracín and Sierra Palomera by

Late Neogene times. Within this scenario, the lower corrosion surfaces mapped by Gracia, Gutiérrez & Gutiérrez (2003) at the western margin of the Jiloca depression might be related to an early polje inset in relation to Late Neogene pediplains and mainly prior to alluvial Plio-Quaternary sedimentation. This is compatible with the essentials of the regional morphotectonic scheme drawn after four decades of continuous research (Birot, 1959; Riba, 1959; Simón, 1983, 1984, 1989; Peña *et al.* 1984; Gracia, Gutiérrez & Leránoz, 1988; Gutiérrez & Gracia, 1997), in which the relative roles of erosion and deformation have been pondered and progressively clarified. In our opinion, the arguments provided by Cortés & Casas (2000), Casas & Cortés (2002) and Gracia, Gutiérrez & Gutiérrez (2003) are not solid enough to substantially change that scheme.

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