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TILTING NEOTECTONICS OF THE GUADIAMAR DRAINAGE BASIN, SW SPAIN

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ABSTRACT

The Guadiamar river flows from the southern Iberian Massif to the Guadalquivir foreland basin, SW Spain. Its drainage basin displays asymmetries in the stream network, the arrangement of alluvial terraces and the configuration of the trunk river valley. The stream network asymmetry was studied using morphometric measures of transverse topographic symmetry, asymmetry factor and drainage basin shape. The alluvial terraces were studied through the lithologic logs of more than a hundred boreholes and field mapping. The morphometric methods demonstrate a regional tectonic tilting toward the SSE, causing both the migration of the Guadiamar river toward the east and the migration of the Guadiamar tributaries toward the southwest. As a consequence of the Guadiamar river migration, an asymmetric valley developed, with a steep eastern margin caused by river dissection, and a gentle western margin where the main alluvial deposits are found. The ages obtained using the ^{14}C analysis of samples from several alluvial deposits show that the river migration, and thus tilting, has occurred during the Holocene as well as earlier in the Quaternary. This interpretation revises the Guadiamar longitudinal fault assumed by previous studies. Copyright © 2003 John Wiley & Sons, Ltd.

KEY WORDS: tectonics; drainage basin; asymmetry; Holocene

INTRODUCTION

The Guadiamar river in SW Spain (Figure 1) has a marked asymmetric drainage basin (Figure 2). This asymmetry is illustrated by three different geomorphic features: (1) the shape of the stream network, with the river flowing close to the eastern drainage basin boundary and all the major tributaries coming from their right margin; (2) the terrace arrangement, with the terraces stepped from W to E; and (3) the shape of the alluvial valley, which has a continuous scarp along the eastern margin, parallel to the river, while forming a gentle surface in the opposite side.

Similar asymmetric drainage basins have been attributed to longitudinal faults (Keller and Pinter, 1996; Schumm *et al*., 2000; Burbank and Anderson, 2001), for instance, the Madison river, SW Montana (Leeder and Alexander, 1987; Leeder and Gawthorpe,1987; Alexander and Leeder, 1990), the Carson river, Nevada (Leeder, 1993), and the Big Creek river in the Lower Mississippi drainage basin (Schumm and Spitz, 1996). In these cases tilting of a sunken fault block and the consequent channel shift down-dip cause asymmetry of the stream networks and the development of a fault scarp.

Earlier studies by Viguier (1977) and Armijo *et al*. (1977) also associate the Guadiamar river with a longitudinal fault, known as the Guadiamar fault (Figure 1). This is a NNE–SSW normal fault, active from the Late Neogene, which separates a western sunken block, where the greatest area of the drainage basin is developed, and an eastern uplift block, where only minor tributaries are found (Figure 1). This fault has been accepted in later studies by Goy *et al*. (1994), Zazo *et al*. (1999), Salvany and Custodio (1995), and Salvany *et al*. (2000a). However, it has never been investigated in detail nor justified.

The purpose of this study is to know the origin of the Guadiamar drainage basin asymmetry and its possible relationship with the assumed Guadiamar fault. The study is mainly based on morphometric methods, from 1 : 20 000 topographic maps, as well as on the geomorphology of the Guadiamar terraces established by Salvany *et al*. (2000a) from a number of surface and borehole data.

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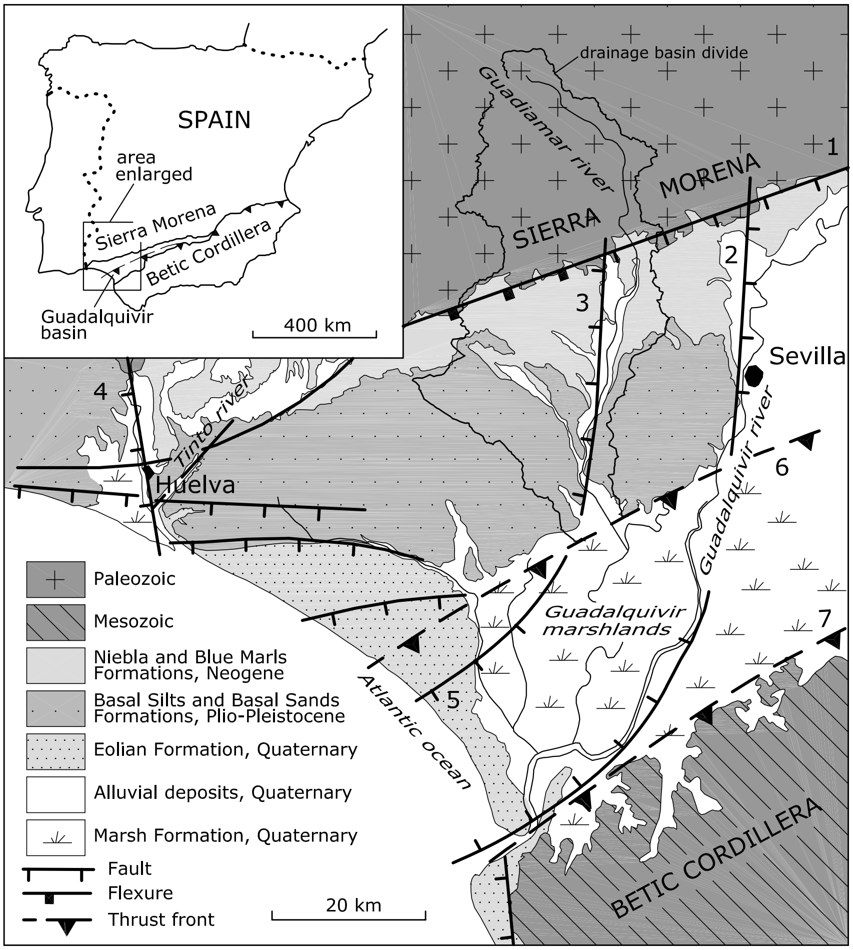

Figure 1. Geological map of the Lower Guadalquivir basin, showing the location of the Guadiamar drainage basin. The main assumed faults affecting Neogene and Quaternary deposits are indicated, after Armijo *et al*. (1977), Goy *et al*. (1994) and Salvany and Custodio (1995): 1, Guadalquivir fault; 2, Lower Guadalquivir fault; 3, Guadiamar fault; 4, Huelva fault; 5, Matalascañas fault. Dashed lines indicate the Olistostrome front (6) below the Plio-Quaternary deposits, and the Subbetic front (7)

GEOLOGICAL SETTING

Bedrock

The Guadiamar drainage basin extends over two geologic domains (Figures 2 and 3): the Palaeozoic massif of Sierra Morena and the Tertiary basin of Lower Guadalquivir.

Sierra Morena is the southern part of the Iberian Massif that occupies the central and northwestern area of Spain and Portugal (Figure 1). It is made up of a wide variety of Palaeozoic rocks such as plutonic rocks (granites as well as diorites and gabbros), metamorphic rocks (slates, schists and hornfels), volcanic rocks (dacites and basalts) and volcano-sedimentary rocks (Figure 2). The whole area has a complex Hercynian structure of faults and folds, with a WNW–ESE trend.

The Lower Guadalquivir basin is the southwestern part of the major Guadalquivir basin, which is an elongated SW–NE basin bounded by the Sierra Morena to the north and the Betic Cordillera to the south (Figure 1). It consists of Miocene, Pliocene and Quaternary deposits.

In the study area, the Mio-Pliocene deposits form a thick sequence of marine deposits, which dips a few degrees toward the south and cover unconformably the Palaeozoic south of Sierra Morena. This sequence is

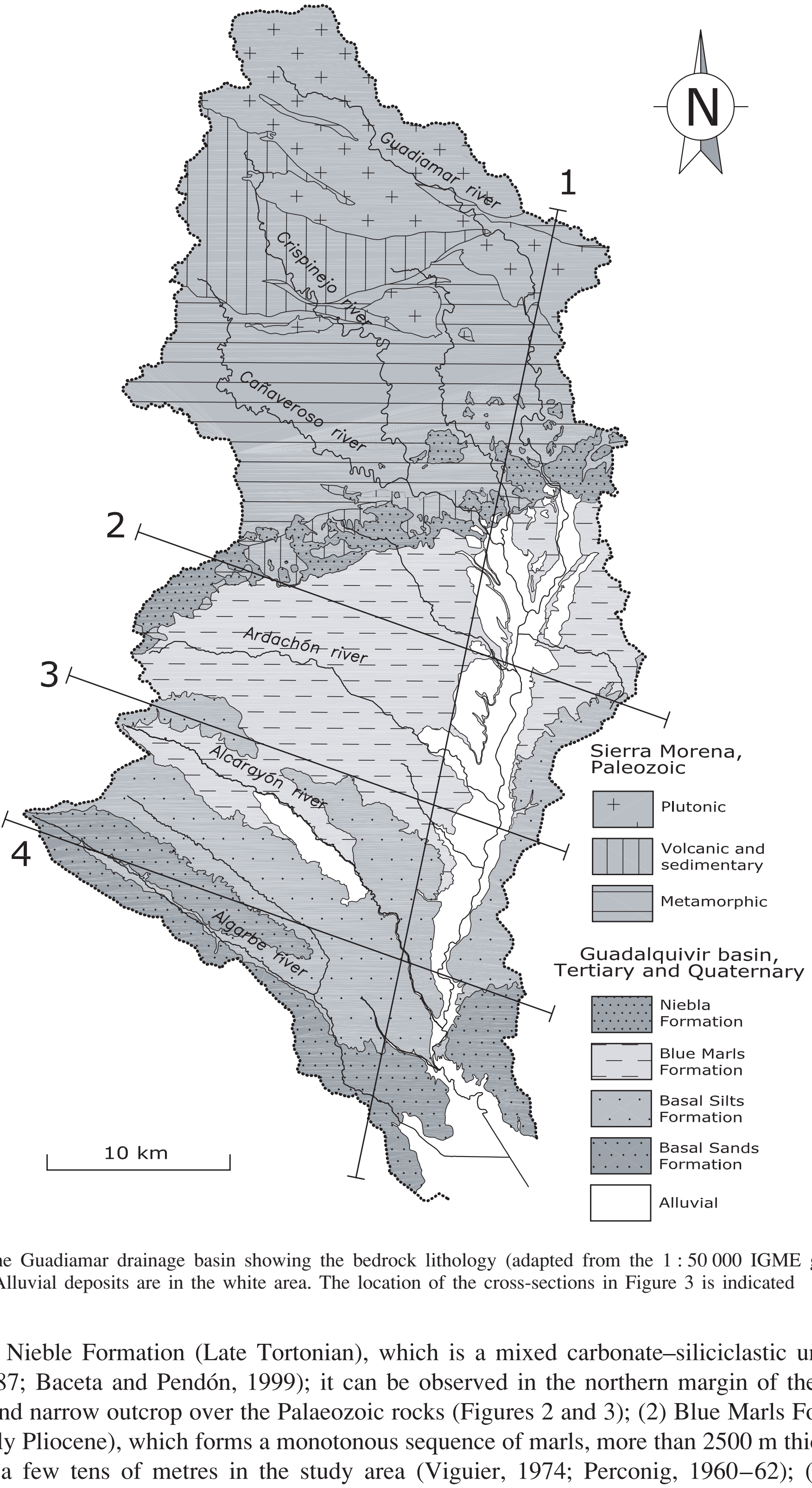

Figure 2. Map of the Guadiamar drainage basin showing the bedrock lithology (adapted from the 1 : 50 000 IGME geological maps). Alluvial deposits are in the white area. The location of the cross-sections in Figure 3 is indicated

made up of: (1) Nieble Formation (Late Tortonian), which is a mixed carbonate–siliciclastic unit 15 m thick (Civis *et al*., 1987; Baceta and Pendón, 1999); it can be observed in the northern margin of the basin, where it forms a long and narrow outcrop over the Palaeozoic rocks (Figures 2 and 3); (2) Blue Marls Formation (Late Tortonian to Early Pliocene), which forms a monotonous sequence of marls, more than 2500 m thick in the basin centre but only a few tens of metres in the study area (Viguier, 1974; Perconig, 1960–62); (3) Basal Silts Formation (Pliocene), which is made up of marly silt, fine sand and sandstone of yellow or grey colour and a

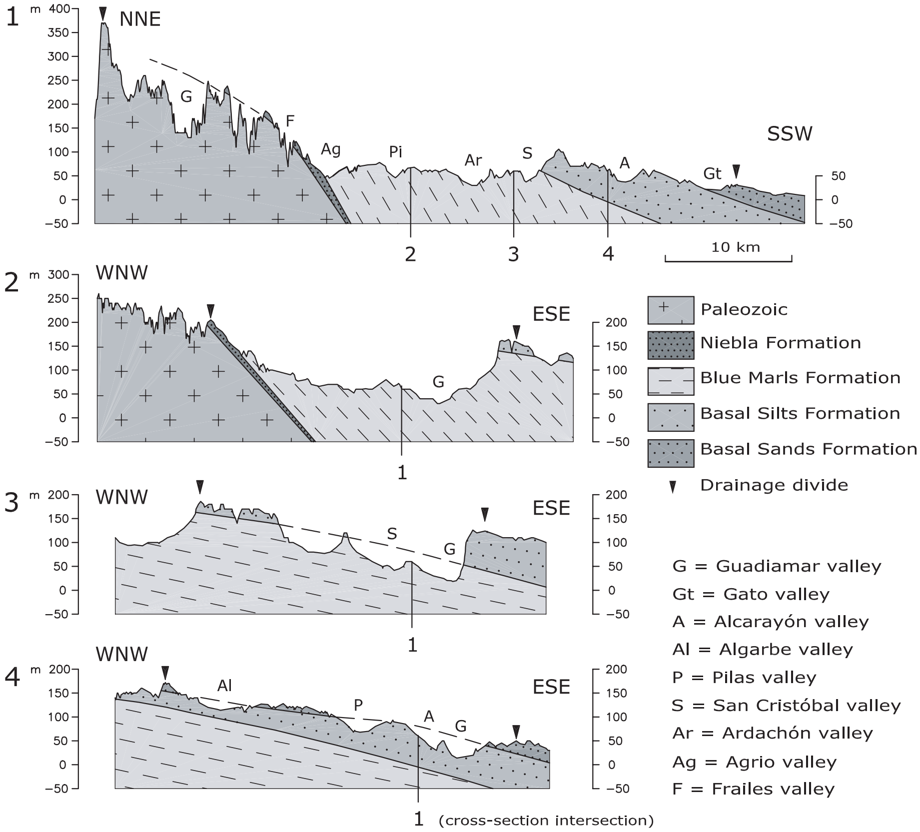

Figure 3. Geological cross-sections through the Guadiamar drainage basin (see Figure 2 for locations)

thickness of some tens of metres (IGME, 1976, 1977); and (4) Basal Sands Formation (Pliocene–Pleistocene?), which is made up of reddish sand and gravel deposits, with subordinate clay, silt and shell layers, several tens of metres thick (Salvany *et al*., 2000b).

Quaternary deposits cover the Mio-Pliocene formations unconformably (Figure 1). They consist of: (1) Marsh Formation (Upper Pleistocene and Holocene), which is a sequence more than 20 m thick of clayey deposits of dark grey colour and develops southward of the Guadiamar valley outlet (Salvany and Custodio, 1995; Zazo *et al*., 1999); and (2) alluvial deposits (Pleistocene to present), which are located on the floor and margins of the Guadiamar valley and some tributaries (Agrio and Alcarayón rivers, see below; Salvany *et al*., 2000a).

Structural setting

The Guadalquivir basin is the northern foreland basin of the Betic Cordillera, related to the convergent boundary between the African and Eurasian plates. The Sierra Morena is the northern passive margin of the Guadalquivir basin (Figure 1).

The Guadalquivir basin started to develop during the Late Tortonian time, after the main orogenic events (Sanz de Galdeano, 1990). The Pliocene was an extensive phase characterized by the development of normal faults in the Guadalquivir basin and strike-slip faults in the Betic domain (Benkhelil, 1976; Viguier, 1977; Armijo *et al*., 1977). After this phase a new contraction started around the time of the Pliocene–Pleistocene boundary, which continues to the present as demonstrated by the recurrence of earthquakes of moderate to high magnitude in the Betic Cordillera and the surrounding areas (Sanz de Galdeano and López-Casado, 1988; Camacho and Alonso-Chaves, 1997; Morales *et al*., 1999).

Neogene and Quaternary deposits are affected by faults and folds. Viguier (1977) and Armijo *et al.* (1977) identify a long NE–SW flexural fault, which follows the northern boundary of the basin (the Guadalquivir fault), and other transverse faults of near N–S direction (Lower Guadalquivir, Guadiamar and Huelva faults, Figure 1). From the morphogenetic analysis, Flores-Hurtado and Rodríguez-Vidal (1994) interpret Quaternary tilting towards the SE of several crustal blocks bounded by areas of structural weakness. The larger and eastern block (Condado Block) extends from the Tinto to the Guadiamar valleys (Figure 1), which they interpret as two tectonic alignments. Later studies (Goy *et al*., 1994, 1996) describe other minor faults in the Atlantic coast, which controlled the sedimentary deposition during the Quaternary. Also, in the Subbetic units Benkhelil (1976) describes folds from 30° N to 60° N associated with small reverse faults in some small basins filled with Neogene and Quaternary deposits. As a whole these normal faults originated during the Pliocene extensional episode and moved again during Quaternary compression as strike-slip or reverse faults.

THE GUADIAMAR DRAINAGE BASIN

Stream network

The Guadiamar river is a tributary of the Guadalquivir river (Figure 1). It is nearly 100 km long, drawing from the Sierra Morena at 480 m over sea level to the Guadalquivir marshlands close to sea level.

The Guadiamar drainage basin (Figure 4) has an area of 1200 km^2 and a length and width respectively of 65 and 29 km. The long profiles of the Guadiamar river and its tributaries display typical concave graded profiles (Table I). When the river flows over Tertiary rocks the main gradient is between 0·5 and 1 per cent, with a maximum slope of 2·12 per cent at the Ardachón river, while in the Palaeozoic rocks the mean gradient is 1 to 2 per cent and exceeds 17 per cent in the headwaters of the Guadiamar and Cañaveroso rivers. Significant changes of slope are rare, and are always related to changes in the lithology. This feature is specially shown by the Guadiamar long profile (Figure 5). It clearly displays three sections: an upper area where the river flows over hard plutonic rocks of Sierra Morena, where the main slopes are found; an intermediate area where the river flows over less hard metamorphic rocks with a slope average of 0·79 per cent; and a lower area over soft Tertiary rocks with a slope average of 0·1 per cent. There are rapid slope changes between each area, especially between the upper and intermediate areas where there is a step with up to 5 per cent slope.

Alluvial terraces

Between Aznalcóllar and the Guadalquivir marshlands, the Guadiamar river and the Agrio tributary flow over a continuous alluvial deposit consisting of four terraces (Figure 6). These terraces are: T3 (upper terrace), T2 (intermediate terrace), T1 (lower terrace) and T0 (current terrace). The geometry of these terraces is well constrained with more than 100 hydrogeological boreholes (Salvany *et al*., 2000a). Each terrace (except for T0) is associated with a single fining upward sedimentary sequence ranging from less than 30 cm coarse gravels at the base to sand at the surface. There is a gradual transition between gravels and sand with frequent sand and gravel alternations in the middle of the sequence. Upstream, gravels dominate and sand is rare, while downstream, from Sanlúcar, the sand becomes dominant and thicker (Figures 6 and 7). Near the Guadiamar valley outlet, the sands of the T1 and T2 terraces grade into silt and clay, and gravels extend beyond the Guadiamar valley below the marsh deposits.

Terrace T3 is mainly developed in the northern half of the valley and is found in both sides of the river valley (Figure 6). There it is always separated from T2 by Blue Marls. South to Sanlúcar T3 is found only on the west side of the river where it is in contact with T2. South to Aznacázar it disappears. Its deposits are widely eroded, thus making it difficult to describe their original geometry and thickness.

Terrace T2 is well represented in both sides of the Agrio valley but it is only found on the west side of the Guadiamar valley. It forms a continuous scarp, up to 4 m high, in the upper Guadiamar and Agrio valleys. To the south the scarp height decreases progressively and becomes discontinuous. Alluvial deposits vary in thickness downstream from 12 to 25 m. The bottom valley has a slope of 0·16 per cent.

Terrace T1 is continuous in both the Agrio and Guadiamar valleys. Their alluvial deposits fill a bottom flat valley with a slope of 0·14 per cent. The thickness of these deposits varies downstream from 8 to 16 m.

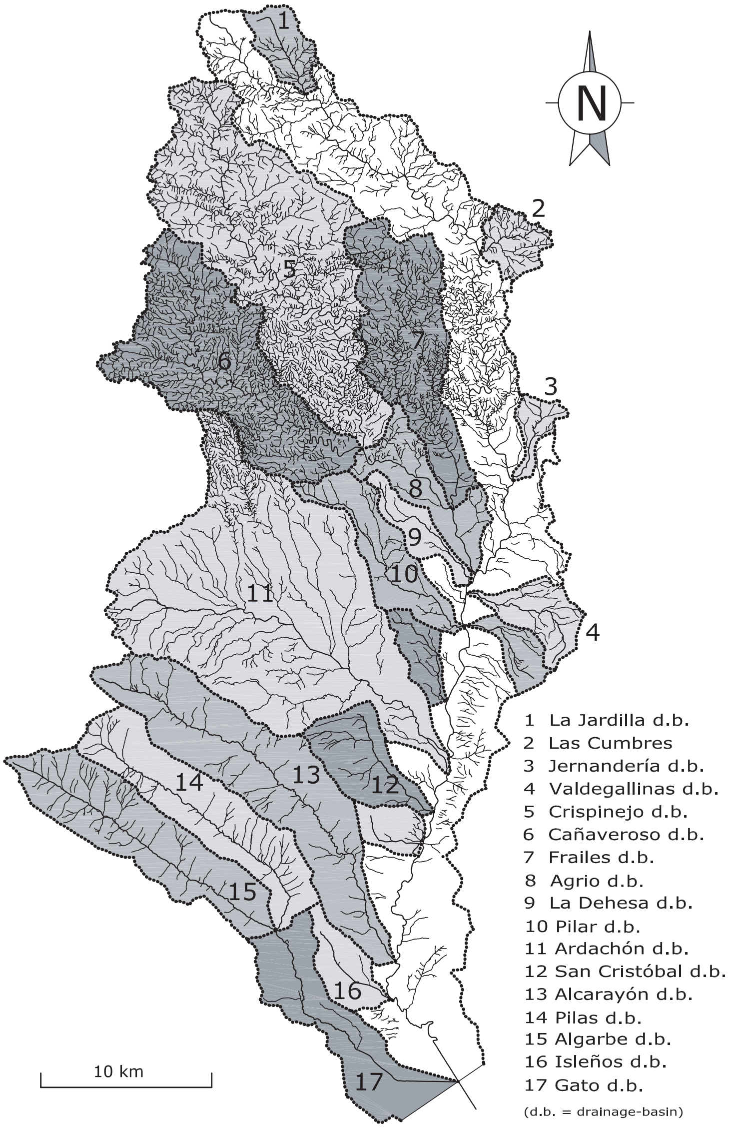

Figure 4. Guadiamar drainage basin and those of its principal subbasins

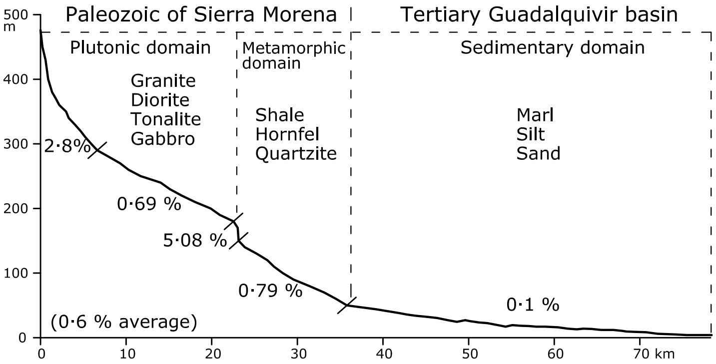

Figure 5. Long profile of the Guadiamar river showing the relationship between the slope and the bedrock lithology

Table I. Morphometric values obtained from the Guadiamar river and its main tributaries

Drainage basin	Surface area (km^2)	Stream long profile		River length (km)	Drainage Basin Shape $Bs = Bl/Bw$	Asymmetry Factor $AF = 100Ar/At$	Transverse Topographic Symmetry Factor	
		Range of slope (%)	Average slope (%)				T	bearing
Guadiamar river	1200	17·85–0·06	0·6	92·23	1·87	81·5	0·64	79
Algarbe-Gato rivers	103·2	1·25–0·07	0·46	36·82	4·40/2·67	39·7/60·3	0·20/0·20	213/140
Pilas river	54·0	1·69–0·53	0·65	18·18	3·79	32·5	0·35	219
Isleños river	14·6	1·11–0·05	0·79	6·37	2·12	57·4	0·24	104
Alcarayón river	89·6	2·04–0·34	0·58	30·46	4·93	51·4	0·23	163
San Cristobal river	24·5	0·51–0·13	0·42	8·27	1·90	78·7	0·52	51
Ardachón river	193·1	2·12–0·22	0·47	25·90	1·72	35·4	0·24	118
Pilar river	28·6	6·25–0·35	1·00	15·61	3·58	36·5	0·44	161
Agrio river	25·7	*	*	11·96	2·38	39·3	0·29	143
Cañaveroso river	90·1	17·09–0·93	2·05	30·48	2·38	58·7	0·28	123
Crispinejo river	140·0	13·24–0·70	1·63	39·20	2·53	47·3	0·33	146
Frailes river	62·3	10·47–0·66	1·38	25·39	3·07	40·2	0·24	188

* River slope largely modified by mining works.

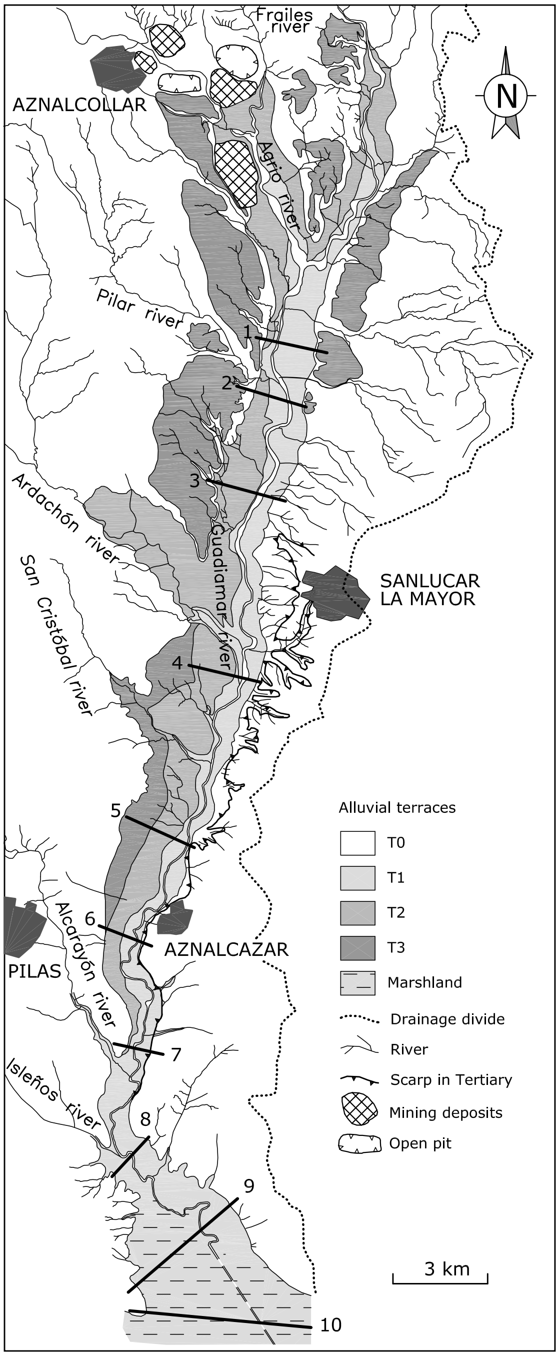

Figure 6. Geomorphologic map of the Guadiamar alluvial valley. The location of the cross-sections in Figure 7 is indicated

T0 or the current terrace is an erosive terrace with no deposits of its own and cuts through T1. In the Agrio valley and the upper half of the Guadiamar valley, T0 is 50 to 200 m wide and it is bounded by a scarp 1 to 1·5 m high. In this area the river channel is sinuous and rarely floods the marginal flood plain. South of Sanlúcar, T0 becomes a single narrow channel, 20 to 50 m wide, which downcuts progressively up to 5 m below the T1 surface.

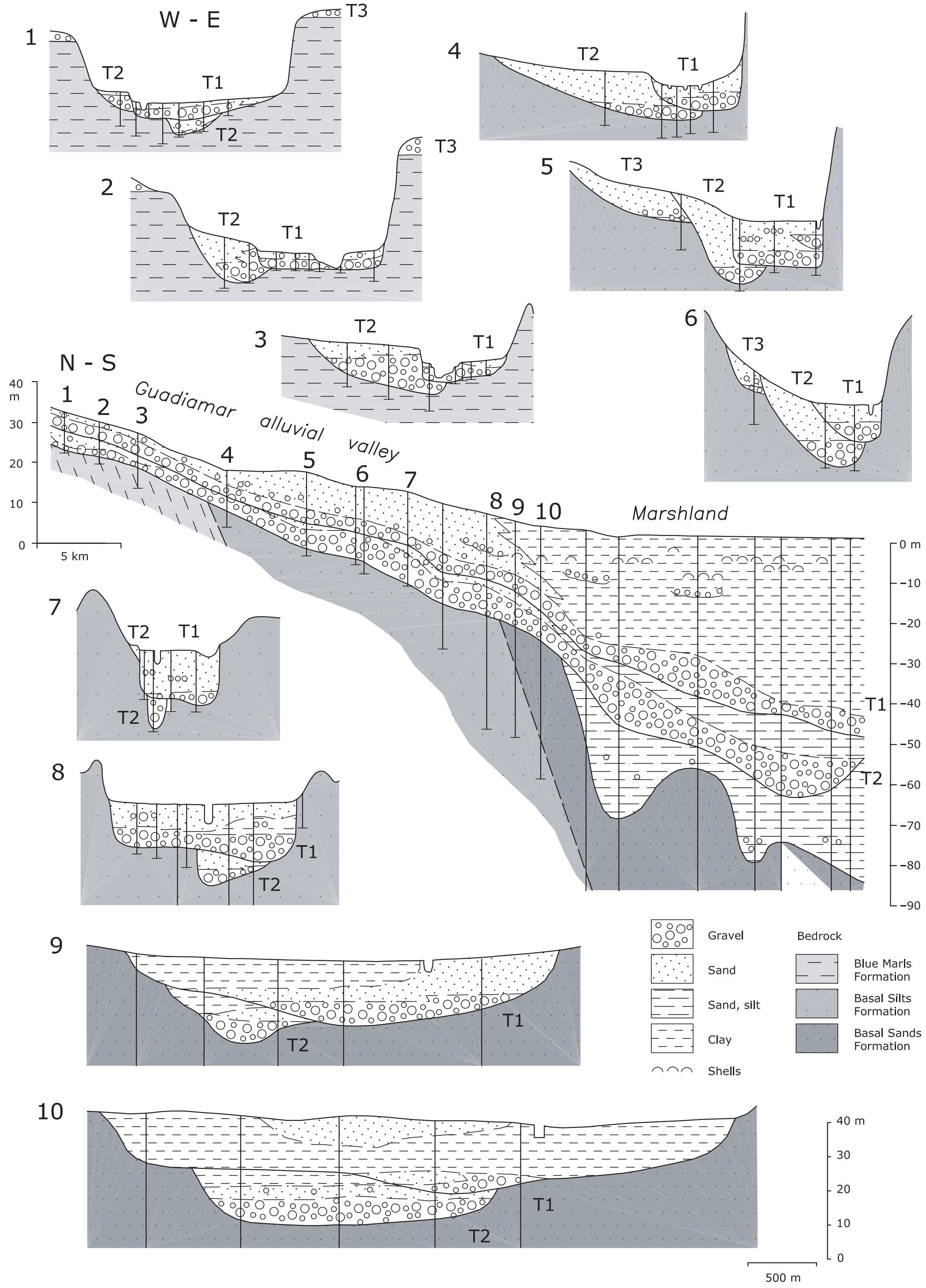

Figure 7. Longitudinal and transverse cross-sections of the Guadiamar alluvial terraces. Sections are obtained using borehole data (vertical lines). See Figure 6 for locations

Terrace chronology

Six samples of organic matter (wood and charred material) were analysed for ^{14}C age (Table II); five samples from T1 and one from T2. The age-values obtained from the top of T1 are 305, 310 and 285 years BP. These values come from upper sand deposits near cross-sections 2 and 3 (Figure 7). A fourth sample 10 m below the top of T1 near cross-section 6 gave a value of 4990–5035 years BP. A fifth sample 13 m below the top of T1 and near cross-section 7 gave a value of 1717 years BP. Only one sample from T2 was dated and comes from 1 m below the top between cross-sections 1 and 2, and gave an age of 6285 years BP. Thus, both T1 and T2 are Holocene in age. It was not possible to date T3 as no organic matter is found, but it probably belongs to the Pleistocene.

ANALYSIS OF DRAINAGE BASIN SYMMETRY

Study methods

In order to describe the type and amount of asymmetry of the studied drainage basin two quantitative morphometric methods are used: the Transverse Topographic Symmetry Factor (Cox, 1994) and the Asymmetry Factor (Keller and Pinter, 1996).

The Transverse Topographic Symmetry Factor (T) is a method that evaluates the amount of asymmetry of a river within a basin and how this asymmetry varies in length. We divide the river into segments of the same length (2 km in this case) (Figure 8A). The basin midline would be the location of a river symmetrically placed with regard to the basin divide. It is calculated regarding the larger axis of the basin, which extends from the outlet of the basin to the most distal point in the headwater (Figure 8A). For each segment, T is the ratio of the distance from the basin midline to the active meander-belt midline (D_a) and to the basin divide (D_d): $T = D_a/D_d$. This value varies between 0 and 1, which represent respectively the minimum and maximum asymmetry of a segment. It can be represented as a two-dimensional vector with a length equivalent to D_a/D_d, and a direction perpendicular to the segment that indicates movement of the segment (as well as the river) with regard to the basin midline.

This method quantifies the mean migration direction for all streams of a given, and larger order, thus allowing discrimination between preferred stream migration as a consequence of internal fluvial processes or as a consequence of external forces. It was applied by Cox (1994) to the southwestern Mississippi Embayment where there are some asymmetric drainage basins related to fault-block tilting.

The Asymmetry Factor (AF) evaluates the asymmetry of a drainage basin. It is defined as $AF = 100(A_r/A_t)$, where A_r is the area of the basin to the right of the trunk stream and A_t is the total area of the drainage basin. When $AF = 50$, the drainage basin is perfectly symmetric, while values greater or less than 50 belong to asymmetric basins. This method was developed to detect tectonic tilting at drainage basin scale or larger areas and was applied by Hare and Gardner (1985) to the Nicoya Peninsula (Costa Rica). They described some drainage basins which flow parallel to the limb of a faulted half-dome. AF is 49·8 if the drainage basin flows in the dome margin where tilting was less important but up to 75 in the inner dome area where tilting was higher.

As a complementary method, a measure of Drainage Basin Shape (B_s) was also used. B_s quantifies the planimetric shape of a basin to the distance between the two most distal points in the basin (Ramírez-Herrera, 1998). It is defined as $B_s = B_l/B_w$, where B_l is the length of the basin, measured from its outlet to the most distal point in the drainage divide, and B_w is the width of the basin measured across the short axis. The index reflects differences between elongated basins with high values of B_s, and more circular basins with low values. Basins with elongated shapes are characteristic of tectonically active areas, where the stream was primarily downcutting. This method was applied to analyse drainage basins near to mountain fronts where active tectonics were found, such as in the Mojave desert of California (Bull and McFadden, 1977) and in the Acambay Graben in the Mexican volcanic belt (Ramírez-Herrera, 1998).

Results and interpretation

The Transverse Topographic Symmetry Factor method applied to the Guadiamar drainage basin is shown in Figure 8B and C. Two different areas can be distinguished: (1) a southern area, equivalent to the region with

Table II. Samples and ^{14}C ages in the Guadiamar alluvial deposits (data from Salvany *et al*., 2000a, reproduced by permission of Geotemas)

Sample	Material	Location		Laboratory and number	Conventional ^{14}C age (years BP)	$^{13}C/^{12}C$ (‰)	^{14}C calibrated age (years BP)	Age (years BP)
		Terrace	Depth					
3	charred	T1	1·5 m (outcrop)	Beta-132184	270 ± 60	–25·4	430–285	305
4	charred	T1	1 m (outcrop)	Beta-132185	290 ± 60	–22	440–290	310
5	wood	T1	9–10 m (borehole)	Beta-132186	4430 ± 60	–28	5265–4880	5035/5005/4990
6	charred	T1	1·5 m (outcrop)	Beta-132187	210 ± 70	–23·5	305–0	285
7	charred	T2	1 m (outcrop)	Beta-136255	5470 ± 40	–23·9	6295–6270	6285
8	wood	T1	13 m (borehole)	Beta-132188	1800 ± 60	–30·4	1815–1625	1715

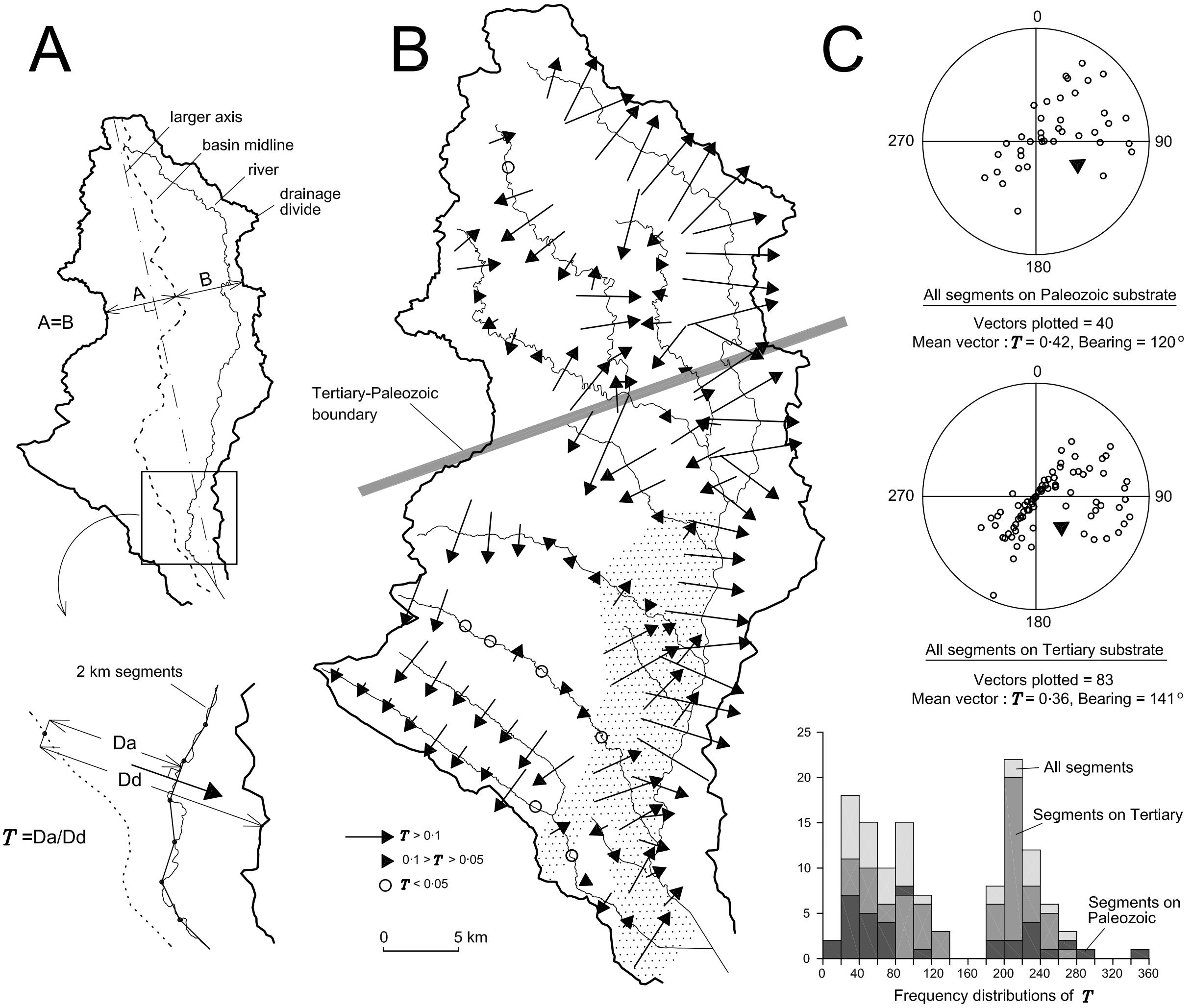

Figura 8. (A) The Transverse Topographic Symmetry method after Cox (1994). (B) Basin asymmetry vectors for the Guadiamar river and tributaries in the Guadiamar drainage basin. The Tertiary–Palaeozoic boundary (dark line) separates a southern area where *T*-vectors show a uniform trend and a northern area where these trends are variable. The dashed area in the western margin of the Guadiamar river indicates the change of direction of the tributaries' *T*-vectors. (C) Polar plots and frequency diagram of asymmetry vectors. At centre, magnitude = 0; at margin, magnitude = 1. Triangle indicates the mean vector for the data

Tertiary bedrock with *T*-vectors generally showing a uniform trend, and (2) a northern area with Palaeozoic bedrock and variable *T*-vectors.

In the first area, *T*-vectors of the Guadiamar river itself have a similar direction and high values (*T*-average = 0·64). This implies that the Guadiamar river has migrated uniformly and largely to the east. This migration to the east is also coherent with the terrace arrangement and the scarp developed on the opposite margin of the terraces. Terraces are clearly stepping to the east indicating that the Guadiamar alluvial deposits also migrated to the east. The palaeovalley floor of Terraces T1 and T2 also shows this trend. Thus, T1 palaeovalley floor is, in all studied cross-sections, aligned to the east in comparison with T2 palaeovalley floor (Figure 7). The scarp would be a consequence of lateral cutting associated with the stream migration to the east.

On the other hand, the *T*-vectors of the Guadiamar tributaries display a main SW direction and have a different size (Table I). Upstream, the larger tributaries (Pilar, Ardachón, Alcarayón, Pilas and Algarbe-Gato rivers; Figure 4) display SW *T*-vectors and high *T*-values, while downstream *T*-values decrease and eventually change their direction to the northeast. Short tributaries (San Cristóbal and Isleños rivers, Figure 4) display NE *T*-vectors

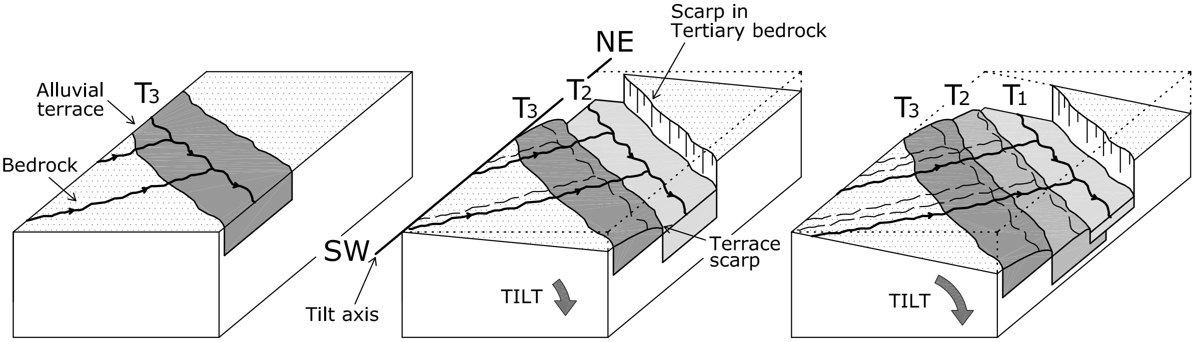

Figure 9. Stream migration pattern caused by tectonic tilting interpreted for the Guadiamar drainage basin. Tilting is oblique to the trunk river and tributaries forcing both to migrate at the same time. As a result of the trunk river migration, alluvial terraces migrate and an erosive scarp occurs by lateral cutting in the opposite margin

following the same tendency as the lower part of the larger tributaries. Generally, this arrangement suggests that tributaries migrated uniformly to the SW. However, close to the Guadiamar river (pointed area in Figure 8B) this trend changes and takes an opposite direction.

The Transverse Topographic Symmetry Factor method shows a uniformly lateral migration of all streams. This evidences a direct influence of external forces (tectonics, changes in the bedrock resistance, climate) as fluvial processes influence the migration of different streams independently (Beaty, 1962; Cox, 1994; Wende, 1995). No relationship is found between the bedrock trends and the stream migration directions, and climate does not appear to be a plausible explanation for drainage asymmetry. On the contrary, tectonics seem to reasonably explain the stream migrations.

The stream network in the Tertiary area may be seen as a consequence of SSE tilting of the drainage basin (Figure 9). Tilting following this direction can explain the simultaneous migration of both the Guadiamar river, to the east, and the tributaries, to the southwest. As suggested by Cox (1994), the most probable tilt direction is that indicated by the mean vector magnitude obtained from the basin segments measured. In this case that would be 141° N, for the Tertiary area (Figure 8C). The change of migration direction close to the Guadiamar river is not well understood. The change may be controlled by the erosive trace of the Guadiamar river during its migration to the east conditioning a different stream response when the tributaries cross this zone of migration.

In the area of Palaeozoic bedrock, *T*-vectors of the Guadiamar river display a similar arrangement to that of the area above implying that the eastern migration occurred throughout all the river. The tributaries formed on Palaeozoic bedrock (Cañaveroso, Crispinejo and Frailes rivers; Figure 4) do not have a clear migration trend. This is interpreted as a significant influence in stream migration bedrock. This contrast in lithology is only present in the Sierra Morena and not in the Tertiary basin.

The Asymmetry Factor displays a wide range of values (Table I). The *AF* of Algarbe (39·7), Pilas (32·5), Ardachón (35·4), Pilar (36·5), Agrio (39·3) and Frailes (40·2) tributaries (Figure 4) have similar low values, which are consistent with a uniform tilting SSE of the Guadiamar drainage basin. However, other tributaries seemingly do not follow this tendency. This is understandable as the Asymmetry Factor is sensitive to the direction of the asymmetry and some drainage basins display changes of direction throughout the river or have an opposite direction throughout the river with regard to the first referred drainage basins. Thus, the SW asymmetry of the Gato, Alcarayón and Cañaveroso rivers changes downstream from SW to NE and both asymmetries compensate giving a lower *Ar*-value and subsequently a lower Asymmetry Factor (closer to 50). On the other hand, rivers such as the Guadiamar, Isleños and San Cristóbal that have an E or NE asymmetry will always give higher *AF*-values than those with a SW asymmetry. The Asymmetry Factor is a good method to compare drainage basins where the asymmetry has the same direction in each individual basin as well as among them.

The tributaries of the right margin of the Guadiamar river have in general drainage basins of moderate to great elongate shapes (B_s-average of 2·9) and are all oriented SE (Table I). B_s-values reach a maximum elongation shape for the Alcarayón (4·93), Pilas (3·79) and Algarbe (4·40) drainage basins. Lower B_s-values correspond to the Ardachón and San Cristóbal basins with values equal to 1·72 and 1·9 respectively. Generally, these values are larger than those obtained by Ramírez-Herrera (1998) and Bull and McFadden (1977). We interpret the high values obtained as due to tectonic tilting which causes the elongate shape of the drainage basins as the effect of the eastward Guadiamar river migration. The relatively lower B_s-values of the Ardachón and San Cristóbal drainage basins reflect a certain lithologic control, as they flow over the Blue Marls. Thus, it is concluded that tilting tectonics may have caused the elongation of the drainage basin shape.

DISCUSSION

As stated in the introduction, before this study was carried out, the Guadiamar river was related to a longitudinal fault active during Plio-Quaternary time. However, the morphometric analysis described above allows us to reinterpret this river as having originated by tilting neotectonics not influenced by any other fault. The lack of a fault also agrees with the surface and subsoil observations recorded in this study. On the one hand, the geological cross-sections through the Guadiamar valley, obtained from geological mapping data (Figure 2), show a continuous bedrock structure from one side of the valley to the other, without any fault displacement (sections 3 and 4 in Figure 3). In addition, no typical fault geomorphic features were identified from the aerial photography and field study.

On the other hand, the depositional structure of the Basal Sands Formation below the Lower Guadiamar valley and the northern Guadalquivir marshlands does not show any fault across the area presumably affected by the Guadiamar fault (Salvany *et al*., 2000b). This Formation has a progradation structure toward the SW, following the axial direction of the Guadalquivir basin. Without deformation, it would form a gentle depositional dip toward the SW. However, the complete sequence is dipping several degrees toward the south, suggesting a tectonic deformation occurring during or after the deposition. This deformation can be explained as a SSE tilting affecting the original SW depositional dip. Thus, the Basal Sands Formation reveals not only the non-existence of any fault but the existence of a SSE tilting similar to that interpreted for the Guadiamar drainage basin. It is reasonable to consider both as the same tilting. If this were true, it would imply that the tilting of the Guadiamar drainage basin extends beyond its limits and has a wide regional character. This agrees with the SE-SSE tilting described by Flores-Hurtado and Rodríguez-Vidal (1994) and Rodríguez-Ramírez (1998), which took place in the coastal area of the Lower Guadalquivir.

Following the flexural and gravity models of Van der Beek and Cloetingh (1992) the regional tilting affecting Pliocene–Holocene deposits can be interpreted as a result of the deformation of the Hercynian basement. These authors explain that the SE dipping of the Guadalquivir basement is the flexural response of the Iberian lithosphere to the loading exerted by the thrust sheets of the Internal Zone of the Betic Cordillera during the Neogene compression. Furthermore, minor thrustings of the thin continental crust toward the NW over the southern part of the Iberian Massif took place during the Quaternary (Galindo-Zaldívar *et al*., 1997). Further, recent and current field stresses (Galindo-Zaldívar *et al*., 1993; Camacho *et al*., 1999) have a well-defined NW–SE subhorizontal compressional trend, which also agrees with a SSE tilting such as that which affected the Guadiamar drainage basin. Similar relationships between tilting at a regional scale affecting drainage basins and movements of crustal blocks was also described by Adams (1980) in the United States midcontinent.

Another structure crossing the Guadiamar drainage basin is the Guadalquivir fault with NE–SW strike (Figure 1). This structure was not identified in the studied area. The boundary between the Sierra Morena and the Guadalquivir basin seems to be a gentle flexure that would be the beginning of the Hercynian basement tilting. This is well illustrated by the Niebla Formation deposits that are scattered over the Palaeozoic rocks forming a discontinuous thin layer increasing in dip toward the south, until they are buried by the Blue Marls (Figures 2 and 3). The resulting gentle fold has a NE–SW strike corresponding to the tilt axis.

There is one last structure that should be analysed, that is the Matalascañas fault (Figure 1), which was interpreted by Salvany and Custodio (1995) as the prolongation toward the south of the Guadiamar fault. This earlier study dealt with the lithostratigraphy of the Plio-Quaternary deposits of the Lower Guadalquivir basin. The authors interpreted the existence of a N–S vertical fault (Matalascañas fault) as explaining the rapid lateral change found between an eastern sedimentary domain, where sands of deltaic and aeolian origin are dominant, and a western domain, made up mainly by gravels and clays of alluvial and lagoon-marsh origin. They suggested that both Matalascañas and Guadiamar faults belong to the same structure (Matalascañas–Guadiamar fault), which crossed the basin from its northern margin to the Atlantic coast and is currently covered in its southern part by the Guadalquivir marshland deposits. The study was a first approximation to the Plio-Quaternary stratigraphy from the lithologic correlation of several selected boreholes. A more recent revision of the Plio-Quaternary stratigraphy with the aid of new boreholes (J. M. Salvany *et al*., unpublished work) suggests that the lithologic change between both sedimentary domains could be better explained as a change of sedimentary environment. Stratigraphic data over this southern area is still scarce. However, from the available data it is nowadays difficult to maintain the Matalascañas fault, specially if the Guadiamar fault becomes uncertain.

CONCLUSIONS

The study of the stream network of the Guadiamar drainage basin using the Transverse Topographic Symmetry Factor (T), the Asymmetry Factor (AF) and the Drainage Basin Shape (Bs) allows interpretation of the asymmetry of this basin as the result of tectonic tilting. The data are consistent with a SSE tilting, oblique to the N–S direction of the Guadiamar river and the NW–SE direction of their major tributaries. Tilting caused both the Guadiamar stream migration toward the east and the tributaries' migration toward the SW. The Guadiamar stream migration to the east caused the subsequent migration of their alluvial deposits forming three terraces stepped over their western margin, while in the eastern margin the lateral cutting developed a long erosive scarp.

This interpretation revises the Guadiamar longitudinal fault assumed by previous studies. It is important to note that both tectonics, although different (longitudinal faults and regional tilting), can cause similar geomorphic responses and that this would be taken into account in the interpretation of the asymmetry of drainage basins.

The ^{14}C ages obtained from samples of alluvial deposits of two terraces demonstrate active tectonics during the Holocene and probably earlier, but it is not clear when it started.

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REFERENCES

Adams J. 1980. Active tilting of the United States midcontinent: geodetic and geomorphic evidence. *Geology* **8**: 442–446.

Alexander J, Leeder MR. 1990. Geomorphology and surface tilting in an active extensional basin, SW Montana, USA. *Journal of the Geological Society, London* **147**: 461–467.

Armijo R, Benkhelil J, Bousquete JC, Estévez A, Guiraud R, Montenat Ch, Pavillon MJ, Philip H, Sanz de Galdeano C, Viguier CI. 1977. Les résultats de l'analyse structurale en Espagne. In: L'histoire tectonique récent (Tortonien à Quaternaire) de l'Arc de Gibraltar et des bordures de la mer d'Alboran. *Bulletin de la Societé Géologique de France* **19**: 591–594.

Baceta JI, Pendón JG. 1999. Estratigrafía y arquitectura de facies de la Formación Niebla, Neógeno superior, sector occidental de la cuenca del Guadalquivir. *Revista de la Sociedad Geológica de España* **12**: 419–438.

Beaty ChB. 1962. Asymmetry of stream patterns and topography in the Biterroot Range, Montana. *Journal of Geology* **70**: 347–354.

Benkhelil J. 1976. *Etude néotectonique de la terminaison occidentale des Cordillères Bétiques*. PhD thesis, Université de Nice.

Bull WB, McFadden LD. 1977. Tectonic geomorphology north and south of the Garlock fault, California. In *Geomorphology in Arid Regions. Proceedings of Eighth Annual Geomorphology Symposium*, Doehring DO (ed.). State University of New York: Binghamton; 115–138.

Burbank DW, Anderson RS. 2001. *Tectonic Geomorphology*. Blackwell Science: Massachusetts.

Camacho MA, Alonso-Chaves FM. 1997. Sismicidad en el límite de placas entre Eurasis y Africa al SW de Iberia, desde 1984 a 1994. *Geogaceta* **21**: 51–54.

Camacho MA, García-Navarro E, Fernández C, Alonso-Chaves FM. 1999. Paleoesfuerzos en las cuencas de antepaís en la parte noroccidental del arco de Gibraltar (Mioceno superior-actualidad). *Geogaceta* **25**: 59–62.

Civis J, Sierro FJ, González-Delgado JA, Flores JA, Andrés I, Porta J, Valle MF. 1987. El Neógeno marino de la provincia de Huelva: antecedentes y definición de las unidades litoestratigráficas. *Paleontología del Neógeno de Huelva*, Universidad de Salamanca: 9–21.

Cox RT. 1994. Analysis of drainage basin symmetry as a rapid technique to identify areas of possible Quaternary tilt-block tectonics: an example from the Mississippi Embayment. *Geological Society of America Bulletin* **106**: 571–581

Flores-Hurtado E, Rodríguez-Vidal J. 1994. Rasgos morfotectónicos del interfluvio costero Guadiana-Guadalquivir (Golfo de Cádiz). In *Geomorfología en España*, Arnáez J, García-Ruiz JM, Gómez-Villar A (eds). Sociedad Española de Geomorfología: Logroño; 13–19.

Galindo-Zaldívar J, González-Lodeiro F, Jabaloy A. 1993. Stress and palaeostress in the Betic-Rif cordilleras (Miocene to the present). *Tectonophysics* **227**: 105–126.

Galindo-Zaldívar J, Jabaloy A, González-Lodeiro F, Aldaya F. 1997. Crustal structure of the central sector of the Betic Cordillera (SE Spain). *Tectonics* **16**: 18–36.

Goy JL, Zazo C, Dabrio C, Lario J. 1994. Fault-controled shifting shoreline in the Gulf of Cádiz since 20 ky BP. *1° Simpósio sobre a margem continental Ibérica Atlantica*, Universidade de Lisboa: 24.

Goy JL, Zazo C, Dabrio CJ, Lario J, Borja F, Sierro F, Flores JA, 1996. Global and regional factors controlling changes of coastlines in Southern Iberia (Spain) during the Holocene. *Quaternary Science Reviews* **15**: 773–780.

Hare PH, Gardner TW. 1985. Geomorphic indicators of vertical neotectonism along converging plate margins, Nicoya Peninsula, Costa Rica. In *Tectonic Geomorphology*, Morisawa M, Hack JT (eds). Allen and Unwin: Boston; 75–104.

IGME. 1976. *Mapa Geológico de España 1 : 50·000, hoja 983, Sanlúcar La Mayor*. Servicio de Publicaciones del Ministerio de Industria: Madrid.

IGME. 1977. *Mapa Geológico de España 1 : 50·000, hoja 1001, Almonte*, Servicio de Publicaciones del Ministerio de Industria: Madrid.

Keller EA, Pinter N. 1996. *Active Tectonics, Earthquakes, Uplift and Landscape*. Prentice Hall: New Jersey.

Leeder MR. 1993. Tectonic controls upon drainage basin development, river channel migration and alluvial architecture: implications for hydrocarbon reservoir development and characterization. In *Characterization of Fluvial and Aeolian Reservoirs*, North CP, Prosser DJ (eds). Special Publication 73. Geological Society: London; 7–22.

Leeder MR, Alexander J. 1987. The origin and tectonic significance of asymmetrical meander-belts. *Sedimentology* **34**: 217–226.

Leeder MR, Gawthorpe RL. 1987. Sedimentary models for extensional tilt-block/half-graben basins. In *Continental Extensional Tectonics*, Coward MP, Dewey JF, Hancock PL (eds). Special Publication 28. Geological Society: London; 139–152.

Morales J, Serrano I, Jabaloy A, Galindo-Zaldívar J, Zaho D, Torcal F, Vidal F, González-Lodeiro F. 1999. Active continental subduction beneath the Betic Cordillera and the Alborán Sea. *Geology* **27**: 735–738.

Perconig E. 1960–62. Sur la constitution géologique de l'Andalousie occidentale en particulier du bassin du Guadalquivir (Espagne méridionale). *Bulletin de la Société Géologique de France*, Livre a la mèmoire du Prof. P. Fallot: 229–256.

Ramírez-Herrera MA. 1998. Geomorphic assessment of active tectonics in the Acambay Graben, Mexican volcanic belt. *Earth Surface Processes and Landforms* **23**: 317–332.

Rodríguez-Ramírez A. 1998. *Geomorfología del Parque Nacional de Doñana y su entorno*. Ministerio de Medio Ambiente, Organismo Autónomo Parques Nacionales: Madrid.

Salvany JM, Custodio E. 1995. Características litoestratigráficas de los depósitos plio-cuaternarios del bajo Guadalquivir en el área de Doñana: implicaciones hidrogeológicas. *Revista de la Sociedad Geológica de España* **8**: 21–31.

Salvany JM, Carrera J, Bolzicco J, Bernet O, Mediavilla C, Mantecón R. 2000a. Geometría y edad de los depósitos aluviales de los ríos Agrio y Guadiamar entre Aznalcóllar y las marismas del Guadalquivir (Huelva-Sevilla). V Congreso Geológico de España, Alicante. *Geotemas* **1**: 285–290.

Salvany JM, Carrera J, Mediavilla C, Jaén M, Vázquez-Suñé E, Castro A, Manzano M. 2000b. Litoestratigrafía y paleogeografía de los depósitos pliocuaternarios del margen NO de las marismas del Guadalquivir (Huelva-Sevilla). V Congreso Geológico de España, Alicante. *Geotemas* **1**: 291–297.

Sanz de Galdeano C. 1990. Geologic evolution of the Betic Cordilleras in the western Mediterranean, Miocene to the present. *Tectonophysics* **172**: 107–119.

Sanz de Galdeano C, López-Casado C. 1988. Fuentes sísmicas en el ámbito bético-rifeño. *Revista de Geofísica* **44**: 175–198.

Schumm SA, Spitz WJ. 1996. Geological influences on the Lower Mississippi River and its alluvial valley. *Engineering Geology* **45**: 245–261.

Schumm SA, Dumont JF, Holbrook JM. 2000. *Active Tectonics and Alluvial Rivers*. Cambridge University Press: Cambridge.

Van der Beek PA, Cloetingh S. 1992. Lithospheric flexure and tectonic evolution of the Betic Cordillera (SE Spain). *Tectonophysics* **203**: 325–344.

Viguier C. 1974. *Le Néogène de l'Andalousie Nord-Occidentale (Espagne): histoire géologique du Bassin du bas-Guadalquivir*. PhD thesis, Université Bordeaux.

Viguier C. 1977. Les grands traits de la tectonique du Basin neogene du Bas-Guadalquivir. *Boletín Geológico y Minero* **88**: 39–44.

Wende R. 1995. Drainage and valley asymmetry in the Tertiary Hills of Lower Bavaria, Germany. *Geomorphology* **14**: 255–265.

Zazo C, Goy JL, Dabrio C, Civis J, Baena J. 1985. Paleogeografía de la desembocadura del Guadalquivir al comienzo del Cuaternario (provincia de Cádiz, España). *Actas I Reunión del Cuaternario Ibérico*, Lisboa: 461–472.

Zazo C, Dabrio C, González A, Sierro F, Yll EI, Goy JL, Luque L, Pantaleón-Cano J, Soler V, Roure JM, Lario J, Hoyos M, Borja F. 1999. The record of the latter glacial and interglacial periods in the Guadalquivir marshlands (Mari López drilling, SW Spain). *Geogaceta* **26**: 119–122.