Response of Quaternary fluvial systems to differential epeirogenic uplift: Aguas and Feos river systems, southeast Spain

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ABSTRACT
The geomorphic expression of two fluvial systems, the Rio de Aguas and the Rambla de los Feos, in southeast Spain reflects their adjustment to differential epeirogenic uplift and local tectonic activity during the Quaternary. Regional uplift of a depositional marine surface resulted in the development of a southward-flowing drainage network during late Pliocene–early Pleistocene time. Disruption of this consequent drainage began as the Alhamilla-Cabrera Sierras and the Sorbas basin were differentially uplifted relative to the surrounding basins. The ancestral Feos drainage responded by incision across the uplift through a combination of superimposition and antecedence. Differential uplift of the Sorbas basin enhanced headward erosion of strike-oriented drainages and promoted capture of the ancestral Feos drainage by the Rio de Aguas during the late Pleistocene. Stratigraphic relations and soil development indicate that epeirogenic uplift and local tectonics, together with climatic fluctuations, have influenced the development of the drainage systems throughout the Quaternary.

INTRODUCTION
River systems of the eastern part of the Betic Cordillera of southeast Spain show discordance with structure; many rivers cut across major axes of Neogene and Quaternary uplift. The Betic Cordillera evolved in response to the relative motions of the European and African plates from Jurassic to Miocene time (Bourrouilh and Gorsline, 1979; Smith and Woodcock, 1982), and during the Pliocene it underwent epeirogenic uplift and deformation (Rios, 1978; Postma, 1984). Numerous studies have demonstrated continuing Quaternary tectonism (Dumas et al., 1978; Estevez and Sanz de Galdeano, 1983), but none have addressed its impact on landscape evolution. The river systems developed on an emergent Pliocene marine depositional surface, from which they became superimposed onto underlying rocks. Since the late Pliocene, deformation of this surface and differential epeirogenic uplift of up to 600 m have occurred. The river systems have incised across major axes of uplift and, by capture, have locally adjusted their patterns to the underlying structures.

In this paper we examine the influence of differential uplift on the Quaternary geomorphic history of the Rambla de los Feos, which was formerly the main stem of the Rio de Aguas and which drained the Neogene Sorbas basin before crossing the uplift of the Alhamilla and Cabrera Sierras (Fig. 1).

NEOGENE AND QUATERNARY GEOLOGIC SETTING
Mountain ranges of the Betic Cordillera, composed largely of Palaeozoic to Triassic metamorphic rocks, are separated by Neogene sedimentary basins. During sedimentation the Sorbas basin was connected to neighboring basins to the east, west, and south (Fig. 1), but the southern link became restricted with the uplift of the Sierra de Alhamilla (Postma, 1984). The basin fill is dominantly of upper Miocene marine clastic sediments that unconformably overlie pre-Miocene basement. Within the upper Miocene sequence, the lower (Tortonian) sediments are folded into east-west–oriented folds and are overlain unconformably by the upper (Messinian) sediments. These Messinian rocks are characterized, as elsewhere in the western Mediterranean, by evaporite deposits (Rouchy and Pierre, 1979; Cita, 1982), thick beds of gypsum, which now form a prominent escarpment near El Río (Fig. 2).

Unrestricted marine conditions returned during the latest Messinian and the Pliocene (Addicott et al., 1978). Messinian-Pliocene limestone was deposited across the axis of the Sierras de Alhamilla and Cabrera, northwest of Polopos (Fig. 2). During the late Pliocene, uplift and emergence of this limestone established a regional slope to the south which became the surface on which the drainage was established. The age of this limestone is therefore significant in relation to the initiation of the drainage pattern. Roep et al. (1979) and Weijermars et al. (1985) suggested an early Messinian (pregypsum) age.
equivalent to reef limestones in the Almeria basin, but Megias (in Dabrio et al., 1985) suggested a latest Messinian (postgypsum) or Pliocene age, equivalent to shallow-marine and shoreline deposits near Sorbas (Roep et al., 1979). In the area north of Cantona (Fig. 2), the relations are obscure; however, our field investigations suggest the presence of two limestones, one above and one below the gypsum, confirming a latest Messinian (postgypsum) or Pliocene age for marine continuity across the Alhamilla-Cabrerax axis.

During the Pliocene, folding of the sedimentary sequence in the Sorbas basin occurred along east-west axes, and regional uplift of the area began. A Messinian to early Pliocene regression marine sequence was followed by terrestrial deposition, first by fine coastal plain sediments, then in late Pliocene to early Quaternary time by a coarse fluviatile gravel sequence (Weijermars et al., 1985). This gravel sequence records the establishment of a regional fluvial network draining southward across the Sorbas basin toward the Almeria/Carboneras basin (Fig. 1). Younger Quaternary deposits are all of terrestrial origin and include alluvial-an sediments (Harvey, 1984) and river-terrace gravels. Quaternary marine deposits occur only near the present coast in the neighboring Vera and Almeria basins (Ovejero and Zazo, 1971; Zazo et al., 1981).

Continued folding of the basin sediments occurred during the Quaternary, and differential uplift of up to 600 m is evidenced by Pliocene marine rocks that crop out at elevations from near sea level to about 600 m. The Sorbas basin was uplifted relative to the surrounding basins; maximum differential uplift was in the southern part of the basin and along the Alhamilla-
Cabrera axis. Evidence for continuing uplift along this axis can be seen in the study area, where Quaternary terraces of the Feos near Cortijada los Arojos (see below and Figs. 3, 4) have been faulted by the Cabrera boundary fault. This fault merges with the Carboneras strike-slip fault system which has demonstrably disturbed Quaternary as well as Neogene rocks (Dumas et al., 1978; Bousquet, 1979).

EVALUATION OF THE AGUAS AND FEOS RIVER SYSTEMS

The river systems of the Sorbas basin developed during the Quaternary by incision from the uplifted Pliocene marine surface into the underlying rocks. They show three types of incised drainage pattern: centripetal, transverse, and subsequent (Fig. 2). The main headwater streams of the Aguas system drain the Sierra de los Filabres and form a centripetal pattern converging toward Sorbas in the basin center (Fig. 1).

The southern part of the basin is drained by the Lucainena/Carboneras system, many of whose headstreams, including the Feos, form transverse reaches crossing the axis of the uplifted Alhamilla-Cabrera ranges (Figs. 1, 2). North of Peñas Negras a topographic gap separates the Feos/Carboneras drainage from the modern Aguas system, which suggests that the upper Aguas formerly flowed into the Feos to form a major tributary of the Carboneras river (Figs. 1–3).

The Rio de Aguas downstream of El Rio (Fig. 2) is a subsequent stream, aligned with a band of weak, deeply dissected upper Miocene marls (Fig. 2). To the north of the basin the central reach of the Rambla de los Costancos occupies a similar position. In the center of the basin, headwater streams of the Aguas are incised less than 40 m into lower Quaternary gravels, but near Sorbas the depth of incision increases to more than 90 m, and canyons are formed in Pliocene-age rocks. The channel gradient steepens as the Rio de Aguas crosses the gypsum escarpment near El Rio (Fig. 3), and the depth of incision increases to more than 130 m. From this point the channel is trenchled in a deep canyon, in gypsum, and downstream in upper Miocene calcarenite.

High-level terrace gravels can be traced from above the Aguas near El Rio through the gap into the Feos valley (Fig. 3, sites e and f). The upper Feos valley is characterized by low hills, capped by cemented Quaternary gravels that rest unconformably on folded Miocene rocks. These terrace gravels can be traced through the trans-mountain section to Cortijada los Arojos and from there onto Miocene and Pliocene rocks of the Carboneras valley (Figs. 2, 4).

Terrace Sequence

The terrace remnants between El Rio and Cortijada los Arojos have been assigned relative ages (stages A–D; A is the oldest) on the basis of sedimentology, lateral continuity, height differences between horizontally eroded bases, and...

Figure 3. Terrace remnants of Aguas-Feos system from El Rio to Cortijada los Arojos. Rose diagrams show paleocurrent directions measured from clast imbrication by 10° classes, expressed as percent; inset shows stratigraphic relations at buried soil site. Below: height-range diagram with inferred grouping of terrace stages A–C.
degree of soil development. Heights were measured by profiling from the valley floor; detailed soil profiles were described by procedures given by Birkeland (1984).

Stage A–C deposits are conglomeratic and strongly cemented throughout; modal clast sizes are 10–20 cm (b axis). The deposits are stratified with interbedded sand lenses. Prominent clast imbrication is common. Terrace remnants range from thin veneers to accumulations more than 20 m thick. In places, the deposits show well-developed soils that have thick Bt, Bk, and K horizons (stage II to stage III carbonate accumulation; nomenclature after Gile et al., 1966) (Wells and Ritter, unpub. data) or that are characterized by well-developed calcrete crusts (Dumas, 1969). Soil-profile thickness in these deposits typically exceeds 2.0 m, and Bt or Bk horizons are present that are more than 80 cm thick and display 2.5 YR coloration.

Stage D deposits postdate those mapped as Stage C and include two groups. The older group is made up of river-terrace, fan, and colluvial deposits that are not cemented but are locally capped by thin, weakly developed calcrete crusts. Soils developed on these deposits are typically less than 1.5 m thick and display Btk horizons that are less than 50 cm thick and have 5.0 YR coloration (Wells and Ritter, unpub. data). Stage II carbonate accumulation is typical. Younger noncrusted, friable terrace and colluvial deposits display weakly developed soils (Bwk horizons, 10 YR coloration, and stage I carbonate accumulation). Modal clast size of the fluvial gravels of both groups of stage-D deposits does not exceed 5 cm (b axis).

Fluvial gravels of stages A–C were deposited by the ancestral Aguas, which drained south from El Rio into the Feos basin. Palaeocurrent measurements based on clast imbrication (a-b plane) at three sites in stage-A gravels and one in stage-C gravels confirm a north-to-south flow direction (Fig. 3). This drainage passed from the present-day Aguas into the Feos drainage through the gap south of El Rio (Fig. 3). Since capture, the Aguas has incised by more than 80 m below the gap. Approximately 24 m of cemented gravels on top of Miocene marls are exposed by postcapture tributary incision in the floor of the gap. These gravels are allocated to stage C and display north-to-south paleocurrents (Fig. 3).

These stage-C gravels in the floor of the gap place the capture between stages C and D. This is supported by changes in the sedimentology of the gravels from stages A to C to stage D. Not only is there a marked reduction in clast size, perhaps related to a reduction in transport capability, but significant changes also occur in clast lithology. In gravels of stages A–C in the transmountain reach (Fig. 4), the most distinctive clast lithology is a biotite granite gneiss, a lithology with no mapped local source in the Alhamilla-Cabra range. The only major source area is in the higher grade metamorphics of the Sierra de los Filabres to the north (Fig. 1). One stream, currently draining the Sierra de los Filabres into the Sorbas basin, the Cinta Blanca (Fig. 2), is dominated by clasts of the biotite granite gneiss (over 50% are clasts of this type). In the transmountain reach, gravels of stages A–C have a 10%–15% component of this lithology. Stage-D gravels have little to no granite-gneiss clasts but are dominated by local schists and sedimentary rocks. This accords with a major change in headwater source area by stream capture after stage-C gravel deposition.

**Age of Terrace Sequence and the Capture Event**

The age of stage A–D gravels ranges from early Pleistocene to Holocene, on the basis of stratigraphic relations, soil-profile development, and one radiocarbon date. Preliminary observations suggest that stage-A deposits may correlate with the last phases of the late Pliocene to early Pleistocene fluvial gravel sequence. All the younger deposits are set into or are topographically lower than these deposits. Only one radiocarbon date has been obtained; charcoal in the upper part of younger stage-D deposits near Cortijada los Arojos (Fig. 4) has been dated at 2310 +80/–90 B.P. (DIC-3331 [Dior Corporations Laboratory, Cincinnati, Ohio]). This date supports the interpretation from soil-profile data that younger stage-D deposits are Holocene.

At the capture site, stage-C gravels in the floor of the gap represent the last stage of throughflowing drainage. A well-developed soil occurs on these deposits (Fig. 3) and is buried by colluvium that shows little soil development. The buried soil displays a Bt horizon at least 80 cm thick and a Bk horizon with stage II to stage III carbonate accumulation. By using four properties derived from field descriptions of the soil profile (rubification, texture, structure, and clay-film character) and assuming maximum development values from Harden (1982), a Harden Index of soil-profile development has been calculated for this soil. If we assume a similarity between Quaternary southeast Spanish and southern Californian, xeric inland and coastal climates, a soil-profile index of 36.5 suggests a period of soil development, prior to burial by the colluvium, of several tens of thousands of years (Harden and Taylor, 1983).

Where stage-C terraces are capped by exposed calcrete crusts, crustal thickness, induration, and complexity of secondary cementation would, according to the criteria used by Dumas (1969) and Dumas et al. (1978), suggest a pre-Würm or, at the youngest, an early Würm age for stage-C gravels.

In the loop area (Fig. 4), a meander cutoff occurred between stages B and C. In the abandoned meander, stage-D fan deposits bury stage-B gravels. Both there and 1 km to the south, stage-D deposits are capped by a soil less well

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**Figure 4.** Morphological map and selected surveyed profiles in trans-mountain reach of Feos valley between Peñas Negras and Cortijada los Arojos.
developed than that on stage-C gravels at the capture site and a weak calcareous crust similar to that ascribed to Würm age by Dumas (1969) and Dumas et al. (1978).

The implications for the chronology are that the Aguas-Feos capture took place after deposition of stage-C gravels in the late Pleistocene but prior to deposition of the Würm-age, older stage-D gravels. The younger stage-D deposits have been dated as Holocene.

**DISCUSSION**

We believe that the Pliocene-Quaternary development of the Aguas and Feos river systems is related to the Neogene and Quaternary tectonic development of the Sorbas basin and epirogenic uplift of the Alhamilla-Cabreriza Sierras. The original, presumably late Pliocene, drainage directions were centripetal to the Sorbas basin and southward across the present Sierra de Alhamilla-Cabreriza uplift (Fig. 1). Changes in the vertical and spatial position of the rivers reflect adjustments to Pliocene-Quaternary differential uplift.

**Evidence for Local Tectonic Disturbance of the Terrace Sequence**

The remnants of stages A–C are too fragmentary for the reconstruction of accurate stream profiles for each stage with a view to identifying differential distortion, as has been done for river terraces in North America (Reeves, 1985; Rockwell et al., 1984). However, stage-terrace correlations indicated on the height-range diagram suggest an arching, similar to that described by Schumm (1986), of the A–C terrace sequence between the capture site and the loop area (Fig. 3, sites e–g). This arching might be in response to an extension of the diapiric uplift at the western end of the Sierra Cabrera (Fig. 1). Continued uplift of the Alhamilla-Cabreriza terraces relative to the Carboneras lowland is suggested by the convergence of terrace profiles apparent through the southern part of the field area (Fig. 3, sites g and h) and is demonstrated by stage-B terrace gravels at Cortijada los Arojos, which have been displaced 3.6 m by the Cabreriza boundary high-angle reverse fault (Fig. 4, section 4). Earlier movement along this fault may account for the height differences between stages A and B terraces north and south of the fault (Fig. 4).

**Regional Fluvial Adjustments**

During epigenetic uplift, consequent southflowing streams were superimposed on the Pliocene marine cover over the underlying Miocene sediments and older metamorphic rocks. The ancestral Aguas-Feos became the master stream draining the uplifted Sierra de los Filabres and the Sorbas basin. During the Quaternary, uplift of the Alhamilla-Cabreriza Sierras continued, raising the overlying Messinian and Pliocene rocks to elevations in excess of 600 m above sea level, and local downwarping and folding occurred within the Sorbas basin. As uplift occurred, rivers of the Lucainena-Carboneras system, including the Aguas-Feos river, progressively incised into the underlying rocks. Therefore, both superimposition and antecedence were involved in creating the transverse river patterns (Fig. 1). Terrace stages A, B, and C represent successive stages in this development.

The regional differential uplift of the Sorbas basin, in relation to neighboring basins to the east and to the west, has accentuated the aggressive development of subsequent streams originating from these directions. In the west, the headstreams of the Rambla de los Molinos have captured basal drainage at the expense of the Aguas system (Figs. 1, 2), but most important of all has been the lower Aguas, working headward along the strike of weak upper Miocene marls to capture the former Aguas-Feos river near El Rio. Capture occurred during the late Pleistocene after deposition of the stage-C gravels and left the Feos valley as a beheaded remnant of the former master drainage.

Height differences between the major terraces of the Aguas-Feos fluvial system, though modified by neotectonics, must relate to episodic incision during the Quaternary. However, as each terrace stage (A–C) has in at least one locality an aggradational thickness of 20 m, there were major periods of aggradation between periods of incision. Throughout the drier parts of the western Mediterranean basin, periods of Quaternary alluvial aggradation are generally associated with dry glacial climatic phases (Rohdenburg and Sabelberg, 1973; Harvey, 1984; Lennard, 1986). Hence, the aggradation and dissection sequence of the Aguas-Feos river system may partly reflect Quaternary climatic fluctuations but within a spatial framework determined by tectonic activity.

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**ACKNOWLEDGMENTS**

Wells was supported by the Visiting Scholars Fund of the University of Liverpool and a research grant from the Research Allocation Committee, University of New Mexico. We thank P. J. Brechot for critical comments on the manuscript. L. D. McFadden for his comments on the soil-profile data and interpretation; the staff of the drawing office and photographic sections of the Department of Geography, University of Liverpool, for producing the drawings; and J. B. Riser and Michael Harvey for field assistance.

Manuscript received December 29, 1986
Manuscript revised March 30, 1987
Manuscript accepted April 17, 1987

GEOLOGY, August 1987

693