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HIGH SINUOSITY BEDROCK CHANNELS: RESPONSE TO RAPID INCISION - EXAMPLES IN SE SPAIN

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Resumen: Tres tipos de canales fluviales de alta sinuosidad, encajados en el sustrato rocoso, pueden reconocerse en la zona de Almería en el SE de España: (A) Meandros encajados o en crecimiento; (B) Zonas de rápida propagación de la incisión; y (C) Meandros encajados abandonados. Su desarrollo se encuentra relacionado con incrementos en el gradiente longitudinal de los arroyos durante el proceso de encajamiento en respuesta a (i) Tectónica regional, (ii) Deformaciones tectónicas locales, así como otros factores causantes de cambios de nivel de base locales, como pueden ser (iii) obturación o modificación del drenaje inducida tectónicamente, (iv) capturas fluviales, y (v) variaciones del nivel del mar. Los patrones de incisión más complejos provienen de la combinación de dos o más de los procesos anteriormente mencionados. La duración del proceso de encajamiento, en particular aquellos relacionados con cortes de meandro (Tipo C), ha sido establecida a partir de las secuencias de terrazas fluviales. Las tasas de incisión altas no solo controlan la morfología de los canales, sino que también inciden en su ensamblaje geomorfológico final e inestabilidad. Así mismo, su impacto sobre el paisaje se encuentra relacionado con la velocidad de propagación de la erosión remontante ligada a diferentes ondas de incisión. Aunque no sean características totalmente diagnósticas, la distribución y propiedades de los meandros encajados en el sustrato rocoso pueden ser utilizadas para deducir la distribución espacial de los factores causantes de cambios en el gradiente de los canales, en especial de aquellos relacionados con la actividad tectónica.

Palabras clave: Meandros encajados, geomorfología tectónica, captura fluvial, nivel de base, tasas de incisión, SE España.

Abstract: Three types of high sinuosity bedrock channels are recognised from the Almeria region of southeast Spain: (A) simple incised or ingrown meanders, (B) zones of rapid incisional migration; (C) incised meander cutoffs. Their distributions are related to gradient increases during incision in response to (i) regional tectonics, (ii) local tectonic deformation, and other causes of local base-level changes following (iii) tectonically-induced drainage ponding and breaching, (iv) river capture, (v) eustatic sea-level change. The more complex patterns of incision result from combinations of two or more causes of gradient steepening. The timing of incision, and particularly of cutoffs (Type C), has been assessed through consideration of the terrace sequence. Greatest rates of lateral erosion coincide with periods of maximum net incision. High incision rates control not only the morphology of incising bedrock channels, but also have implications for geomorphic coupling and instability, their spatial effects depending on the headwards propagation rates of incision waves. Although not totally diagnostic, the distribution and properties of incised bedrock channels can be used to infer spatial patterns of the factors causing gradient change, especially those related to tectonic deformation.

Keywords: incised meanders, tectonic geomorphology, river capture, base-level, incision rates, SE Spain.

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1. Introduction

Despite their common occurrence, there has been very little modern research on incised or ingrown bedrock meanders. They are widespread on rivers incised into uplifted plateaux: for example on the Colorado and other rivers incised into the Colorado Plateau, USA, on the Middle Rhine, the Mosel and their tributaries, incised into the Rhine Plateau, Germany, and on many of the rivers incised into the Massif Central in France. Textbook material stresses the possibility of inheritance from alluvial meanders, either by simple incision or by ingrowing and increasing in sinuosity during incision (Thornbury, 1954), but there is some doubt about the mechanisms (Leopold et al., 1964). What modern work there is (Schumm et al., 1987), stresses tectonic causes, but again is equivocal on mechanisms. The examples given above all come from areas of late Neogene to Quaternary uplift, but other causes of base-level change may be underlying causes for incision leading to the development of bedrock meanders.

There has been more work on the response of alluvial channels to tectonically-induced gradient changes, especially in terms of channel pattern response (Russ, 1982; Burnett and Schumm, 1983; Ouchi, 1985; Schumm et al., 1987, 2000; Gomez and Marron, 1991). The general concensus appears to be that tectonically-induced gradient steepening may lead to heightened channel activity, resulting in accelerated erosion either by incision or by lateral erosion, and an increase in sinuosity (Keller and Pinter, 1996).

The same trends could be expected on bedrock meanders. Whatever the underlying cause, a gradient increase, could lead to an increase in stream power and concurrent rapid incision and lateral migration into erodible bedrock. Ultimately, negative feedback resulting from increased sinuosity could be expected to reduce stream power and thereby reduce the tendency for incision and lateral migration. However, some of the published work, based both on flume experiments (Gardner, 1983; Schumm et al., 1987) and on field observations (Gardner, 1975) suggests that the reverse can be the case. On the rivers of the Colorado Plateau the incised meanders coincide with zones where the rivers flow updip, in contrast to steeper less sinuous canyons where they flow downdip. This suggests that incised meanders are a response to intermediate gradients, whereas vertical incision dominates steeper gradient reaches.

This paper examines the distribution of various styles of high sinuosity bedrock channels in the Almeria region within the eastern Betic Cordillera of southeast Spain first by a regional survey, then by detailed case studies. Finally the extent to which that distribution reflects the patterns, causes and rates of incision is assessed.

2. Styles of high sinuosity bedrock channels

Three styles of high sinuosity bedrock channels have been recognised within the field area, their distributions mapped and considered in relation to the range of possible causes of rapid incision.

The three styles can be defined as follows (Fig. 1):

A: Zones of tortuous, highly sinuous ingrown meanders. These are defined as reaches of incised

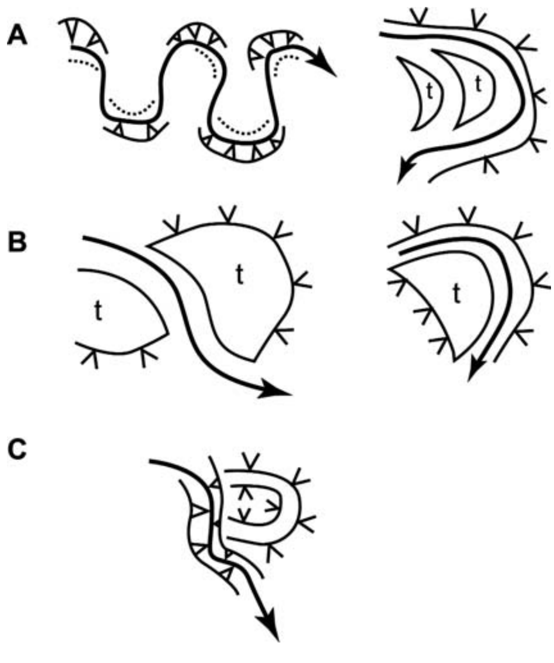

Figure 1. Styles of high sinuosity bedrock channels, for explanation see text.

Figura 1. Tipos de canales meandriforems en roca, ver texto para la explicación de detalles.

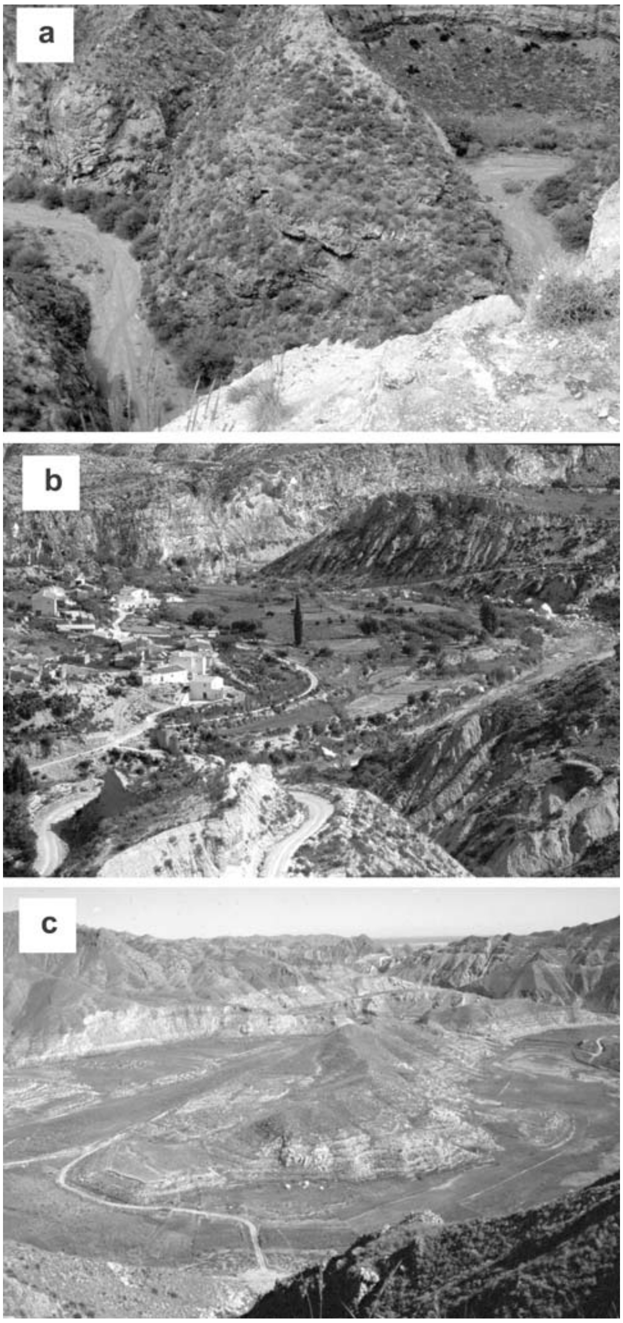

Figure 2. Styles of high sinuosity bedrock channels, illustrated from the Almeria region a) Type A: incised meandering bedrock channel, headwaters of Rambla Lanujar, Tabernas, b) Type B: Evidence of rapid incisional migration: Rio Aguas, near Los Perales 2 km upstream of La Herreria, c) Type C: Cutoff incised meander: Rio Almanzora, NW of Cuervas de Almanzora (locations shown on Fig. 3).

Figura 2. Tipos de canales meandriformes en roca, con ejemplos de la Región de Almería. A) Tipo A: Canal meandriforme encajado en roca, cabecera de la Rambla de Lanujar, Tabernas; b) Tipo B: Evidencia de rápida migración de la incisión, Río Aguas en las cercanias de Los Perales 2 km aguas arriba de La Herrería; c) Tipo C: Meandro encajado abandonado, Río Almanzora, NW de Cuevas de Almanzora (localizaciones en Fig. 3).

meandering bedrock channels, where for a downvalley distance equivalent of at least three meander bends, the limbs of the meanders run at right angles or more to the downvalley direction (Figs. 1a, 2a). Two variants can be distinguished, one where there is little or no preservation of terraces on the slipoff slope, the other where there is preservation of terrace remnants on the slipoff slope indicating a progressive increase in sinuosity during incision, ie. a classic ingrown meander form.

B: Zones of rapid incisional lateral migration (preserved as high sinuosity zones in the terrace sequence or floodplain). The bedrock valley walls are scalloped, indicating the presence of meanders from which the channel may have migrated away, leaving behind terrace or floodplain remnants (Figs. 1b, 2b).

C: Incised meander cutoffs. These are expressed by abandoned incised meander loops preserved as incised arcuate terrace remnants (Figs. 1c, 2c).

All three types are common throughout the field area and are clearly evidence of rapid lateral erosion during incision.

3. Study area: Almeria (Causes of rapid incision)

The study area (Fig. 3) comprises a series of uplifted mountain ranges, dominantly of basement schists, separated by intra-montane sedimentary basins, composed of a wide range of dominantly marine Neogene sedimentary rocks (Sanz de Galdeano, 1990; Weijermars, 1991; Mather et al.,

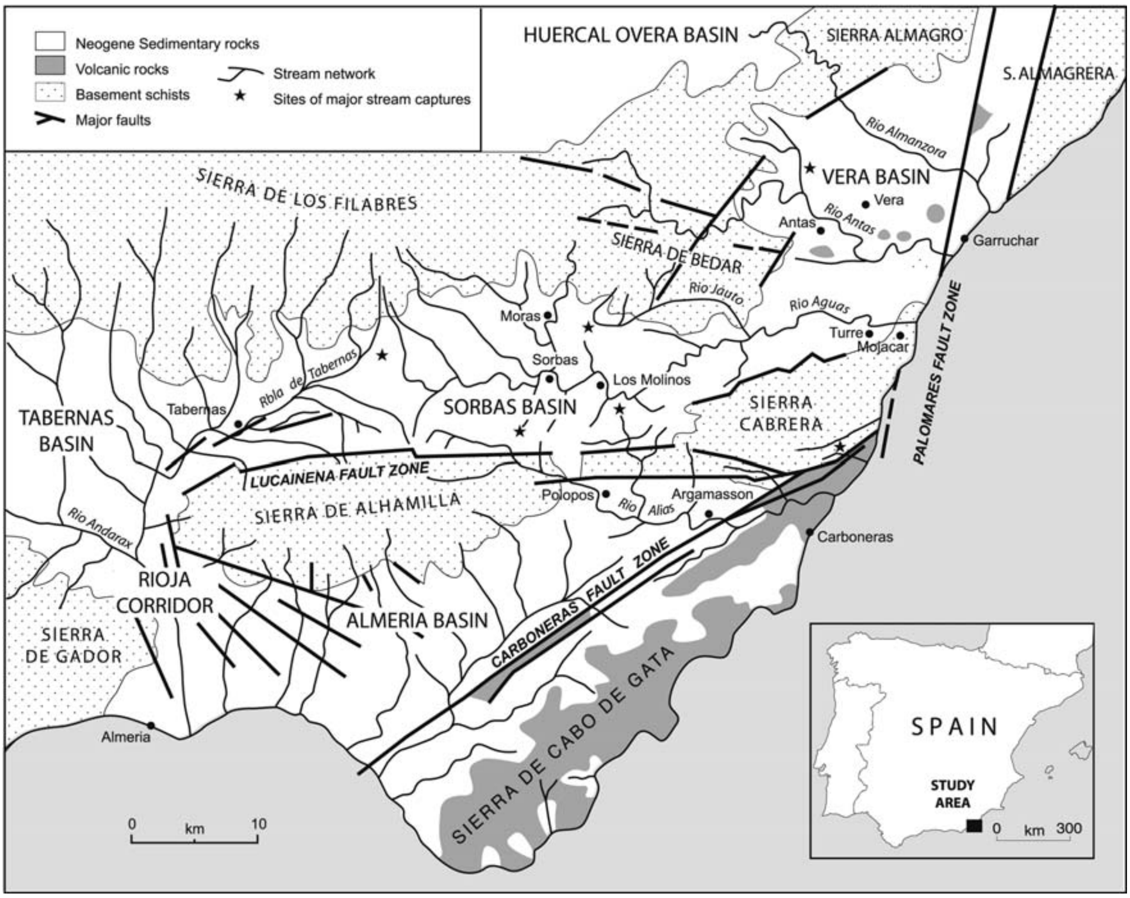

Figure 3. Almeria region: Main geological units, and locations.
Figura 3. Unidades geológicas principales de la Región de Almería, ilustrando las localidades citadas en texto.

2001). Since the Upper Miocene the regional tectonic patterns have been defined by a series of left-lateral strike-slip faults (Fig. 3), which have continued to be active to varying degrees throughout the Quaternary (Bousquet, 1979; Bell et al., 1997; Mather and Stokes, 2001; Silva et al., 2003). During the Late Miocene the mountains were differentially uplifted, first the Sierra de los Filabres, then the Sierras Alhamilla and Cabrera (Fig. 3), but the basins were still marine. By the early Pliocene the basins had begun to be emergent, with the Tabernas and Sorbas basins emergent by the early Pliocene and the Vera and Almeria basins emergent by the late Pliocene (Fig. 4) (Braga et al.,2003; Martin et al., 2003). The patterns of differential uplift created differential tectonically-induced gradients, directing the drainage from the Tabernas basin into the tectonic low of the Rioja Corridor, the Sorbas drainage through a structural low between the Sierras Alhamilla and Cabrera, and the Vera drainage centripetally and to the east (Fig. 4) (Harvey, 1987, 2001, 2006; Mather, 1991; Harvey and Wells, 1987; Harvey et al., 1995; Mather and Harvey, 1995). Rapid incision took place into the uplifted Neogene sedimentary rocks, especially in response to the steeper gradients and where the underlying Neogene rocks were weak marls or turbidites, as in the western Tabernas basin or in the central Vera basin.

During early drainage development, drainage patterns were modified by river capture, especially in the southwest of the Sorbas basin and between

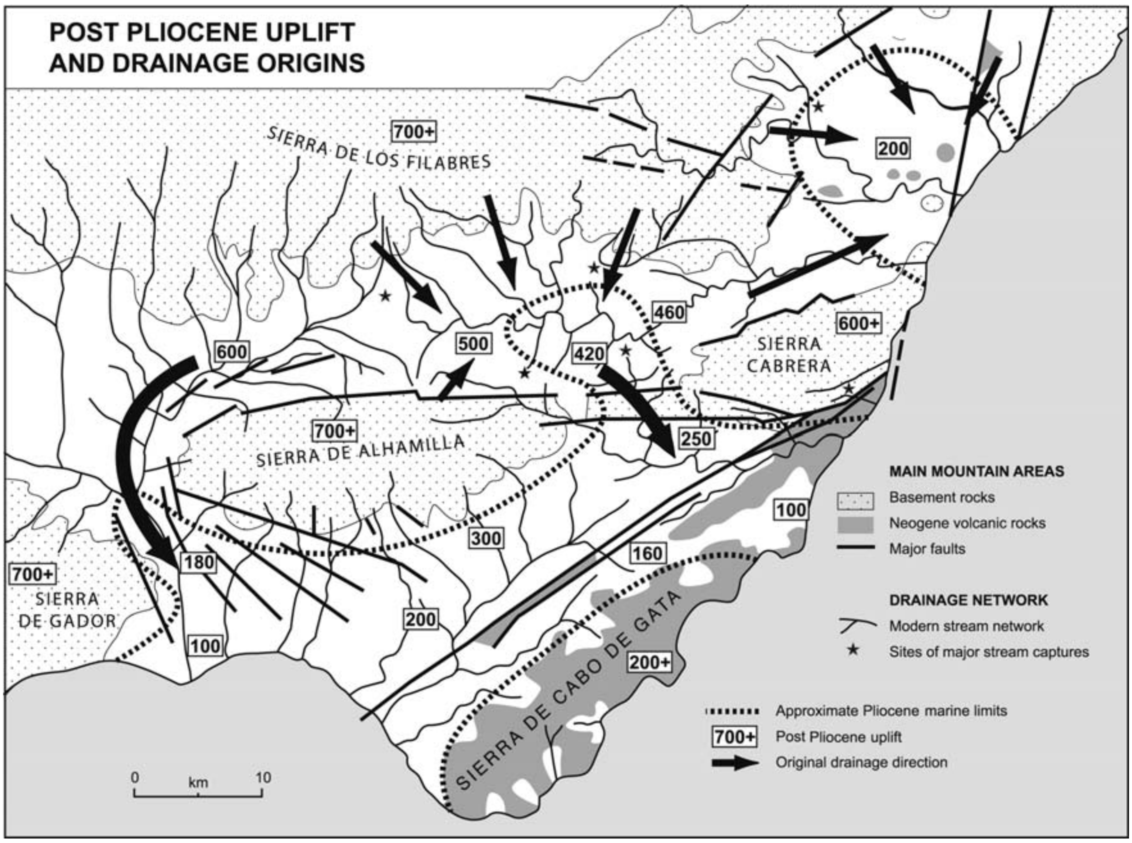

Figure 4. Almeria region: uplift patterns and drainage origins: Differential uplift patterns since the Lower Pliocene derived from Braga et al. (2003) and Martin et al. (2003); drainage origins from Harvey and Wells (1987), Harvey (1987, 2006), Mather (1991), and Mather and Harvey (1995).

Figura 4. Patrones de elevación y origen del drenaje en la región de Almería. Los patrones de elevación diferencial desde el Plioceno Inferior obtenidos de los trabaos de Braga et al. (2003) y Martín et al. (2003); Origen del drenaje tomado de Harvey and Wells (1987), Harvey (1987; 2006); Mather (1991) y Mather y Harvey (1995).

the Sorbas and Tabernas basins (Harvey, 1987; Mather, 1991; Mather and Harvey, 1995; Mather, 2000a). The most significant river capture took place during the Late Pleistocene by the lower Aguas, Vera basin drainage, cutting back along the outcrop of the weak Abad marl, and capturing the proto Aguas/Feos drainage of the Sorbas basin (Fig. 5) (Harvey and Wells, 1987; Harvey et al., 1995; Mather and Harvey, 1995). This not only diverted the Sorbas drainage east into the Vera basin, and beheaded a major tributary of the Rio Alias (Maher, 2006; Maher et al., 2007), but caused a major fall of base level and a major incision wave in the Sorbas basin. The response was accelerated incision of the river system upstream from the capture point (Stokes et al., 2002), destabilisation of the valley walls by landslides (Hart et al., 2000) and badland development (Harvey, 1987, 2006), the triggering of a number of headwater captures (Mather, 2000b), as well as accentuating the development of high sinuosity bedrock channels (see below and Harvey, 2005, 2006). The timing of the capture has been dated, through U/Th dating of the last pre-capture terrace of the Aguas/Feos to 70-80 ka (Candy et al., 2004), recently partially confirmed by OSL dating of the younger Alias terraces (Maher, 2006).

In addition to the continuation of the patterns of differential regional uplift during the Quaternary, there has been more localised tectonic activity on individual structures (Fig. 5) (Mather and Stokes, 2001). These include the regional controlling faults, especially the Palomares fault (Weijermars, 1991), the Carboneras fault (Bell et al., 1997; Maher, 2006; Maher and Harvey, in press), and the Lucainena fault system (Harvey and Wells, 1987). In the latter two cases the movement has been primarily vertical. There has also been movement along smaller faults or growth folds within the basins, both of which appear to reflect movement of underlying basement faults (Fig. 5). These are important in the Tabernas basin (Harvey, 2006), one of which has been a major active structure since the upper Miocene (Haughton, 2001), and in

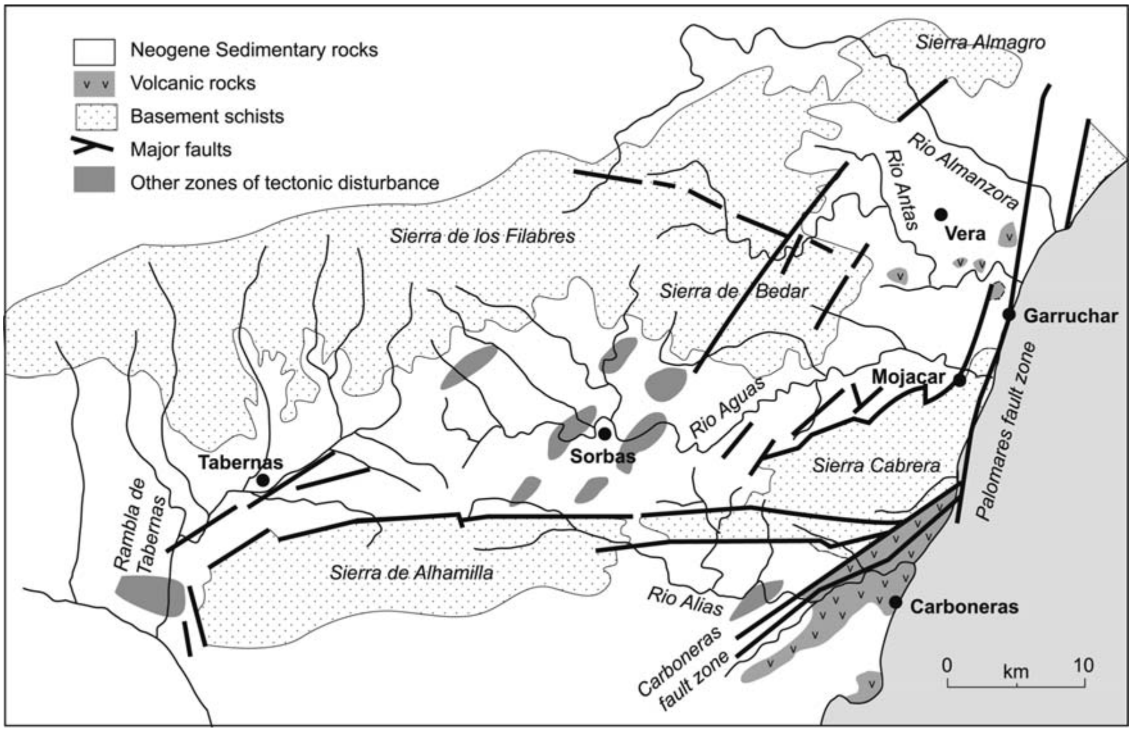

Figure 5. Study area: Quaternary tectonics.
Figura 5. Tectónica Cuaternaria de la zona de estudio.

several zones running NNE-SSW through the Sorbas basin (Mather, 1991; Mather and Westhead, 1993; Maher, 2006). In two cases tectonic deformation caused Late Pleistocene ponding of the drainage. In the west of the Tabernas basin the drainage was ponded upstream of the growth fold (Harvey et al., 2003). At Urra, east of Sorbas, the Aguas was ponded where it crosses one of the zones of tectonic disturbance within the Sorbas basin, however the extent to which this was due solely to tectonics or complicated by the presence of underlying gypsum is uncertain (Mather et al., 1991; Harvey, 2001, 2006). On breaching, the rivers incised rapidly.

A third cause of rapid incision relates to local base-level change following Quaternary eustatic sea-level changes of the Mediterranean Sea. Along the coast up to elevations of 5-8 m, are preserved remnants of raised beaches formed during the last Interglacial highstand (OIS 5, 125-110 ka) (Goy and Zazo, 1986; Goy et al., 1986), and occasional remnants of much older beaches at about 25-30 m (probably dating from OIS 9, 300-350 ka; Goy and Zazo, 1986; Goy et al., 1986). During the intervening glacial low sea levels, and where the offshore gradients were sufficiently steep, rivers incised channels to below modern sea level. At the mouth of the Rio Alias the bases of aggradional terraces pass below the modern river channel, indicating deep incision related to falling sea levels, followed by aggradation and burial of the incised channels (Maher, 2006).

The overall picture is one of sustained incision in response to regional uplift, punctuated by short term climatically-induced aggradation during Pleistocene cold phases. The result is a region-wide system of river terraces (Harvey, 2001, 2006). This picture is complicated locally by accelerated rates of incision in response to (i) spatial variations in the resistance of the underlying lithologies, including both basement schists and Neogene sedimentary rocks, (ii) spatial variations in regional patterns of uplift, and tectonically induced original gradients, (iii) local Quaternary tectonic deformation, including the effects of incision following ponding, (iv) changes of local base level resulting from river capture, and (v) changes in base level resulting from Quaternary sea-level change.

4. Regional patterns of high sinuosity bedrock channels

The occurrence of high sinuosity bedrock channels in the Vera, Sorbas, Tabernas and the northern parts of the Almeria basins, within the drainages of the lower Rio Almanzora, the Rios Antas, Aguas and Alias and the Rambla de Tabernas was initially mapped from air photos and 1:25000 topographic maps, followed up by field checking of the most significant areas. The results are summarised by type of incised channel (A, B, C, see Fig. 1) on Figure 6.

The Rio Almanzora is a large river system sourced on the northern flanks of the Sierra de los Filabres and in the Huercal Overa basin. It enters the northern part of the Vera basin via an incised reach through the Sierra Almagro. Through this transverse reach there are a number of cutoff incised meanders (type C), preserved within the terrace sequence (Stokes and Mather, 2003). Within the Vera basin there is evidence of rapid lateral migration (Type B) preserved in the younger terraces and the floodplain.

The Rio Antas also rises in the northern Filabres (within the Sierra de Bedar) and flows across the central part of the Vera basin. Through the lower part of the basement reach and at the basin margin the river system has undergone Quaternary tectonically-induced base-level change (Stokes, 1997; Stokes and Mather, 2000). Between Antas and Vera, at some stage, probably in the late Pleistocene the lower Antas captured the Vera drainage, triggering a wave of incision. All three types of high sinuosity bedrock channels are present in the middle and lower Antas drainage. Incised meander cutoffs (type C) are present in the middle reaches incised into basement; simple tortuous incised meanders (Type A) occur on some of the tributaries, both on basement and within the Vera basin; and within the Vera basin on the lower reaches there is evidence of rapid lateral migration (Type B).

The Rio Aguas is the main drainage of the Sorbas basin, fed largely from the Sierra de los Filabres, but in its lower course, fed also from the Sierra Cabrera. As indicated above, radical drainage reorganisation took place c 80 ka, through the capture of the original southward draining

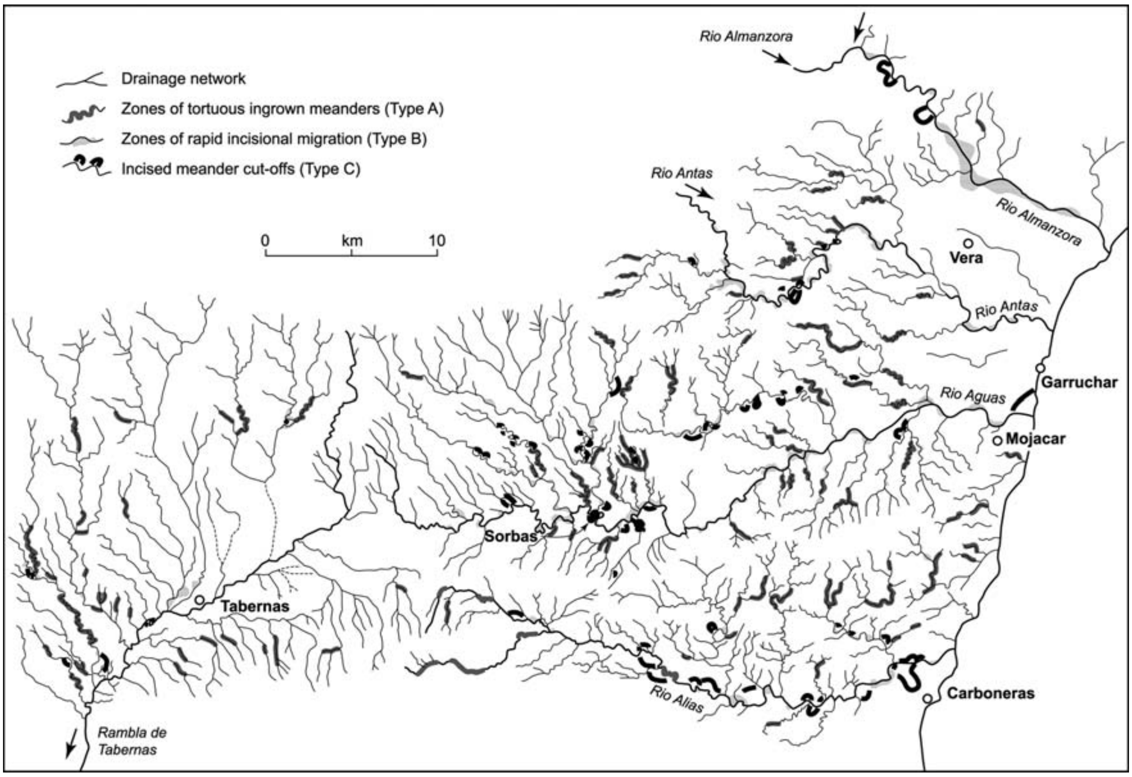

Figure 6. Study area: Distribution of high sinuosity bedrock channels.
Figura 6. Distribución de los canales meandriformes encajados en roca en la zona de estudio.

Aguas/Feos system by the lower Aguas, diverting the drainage east into the Vera basin, and triggering a major wave of incision into the upper part of the basin. Selected reaches on the upper part of the Aguas system will be discussed in detail below, but a general summary is given here. High sinuosity bedrock channels occur in several distinct zones within the Aguas drainage. Many of the southern tributaries, rising on the northern flank of the Sierra Cabrera, show type A sinous channels, but there are occasional cutoff meander loops (type C). Other clusters, again dominantly of type A, occur in the Filabres headstreams. The Rio Jauto, which collects many of these headwaters, has numerous cutoff meanders (type C), located particularly on the south side of the river. This suggests some structural flexuring, and although the Jauto sits obliquely across a set of basement faults, there is no obvious reason for these patterns. The lowest terraces and floodplain of the lower Aguas show evidence of rapid lateral migration (type B), and right at the coast is evidence of an older channel running north from Mojacar towards the sea at Garrucha.

It is the upper part of the Aguas system, within the Sorbas basin that shows the greatest concentration of high sinuosity bedrock channels, and it is from this area that detailed examples will be described below. All three types (A,B,C) are common within a zone of approximately 12 km upstream of the capture site at Los Molinos (see above), and incorporating the zone affected by incision upstream of the late Pleistocene ponding (see above) at Urra.

The Rio Alias drains the southern margins of the Sorbas basin, where its headwaters represent headwards capture of older Sorbas drainage (Mather, 2000a). It then crosses the Sierra

Alhamilla in a canyon through Polopus, aligned along the Lucainena fault zone, and flows across the northern part of the Almeria basin, collecting tributaries primarily from the Sierra Cabrera. One of these northern tributaries is the Feos, the beheaded transverse remnant of the Aguas/Feos proto Sorbas drainage (Maher, 2006; Maher et al., 2007). Midway through the northern part of the Almeria basin the Alias crosses the Carboneras fault zone (Maher, 2006; Maher and Harvey, in press). It enters the sea just north of Carboneras. High sinuosity bedrock channels are common throughout, with simple incised meanders on the headstreams, particularly within the Sierras Alhamilla and Cabrera. They also occur on the Cabrera streams that drain directly to the sea north of the Rio Alias, between Carboneras and Mojacar. The most noticeable incised bedrock channels on the Alias are numerous meander cutoffs (type C), clustered in several zones. In the uppermost part of the drainage there has been local drainage reorganisation through minor capture and channel abandonment around a fault zone (Maher, 2006). Downstream of the canyon reach near Polopos, there are several meander cutoffs (type C), suggesting local tectonic influence. In the same fault zone on the Feos (Harvey and Wells, 1987) are areas of rapid lateral migration (type B) and one cutoff meander loop (type C), relating to the larger pre-capture river. Further downstream there are meander cutoffs just upstream of the Carboneras fault zone, and clear indications of fault deformation of the terrace sequence (Maher and Harvey, in press). Finally, in the zone of the lowermost Alias, directly affected by Quaternary sea-level change (Maher, 2006) there are several large cutoff loops (type C).

The Rambla de Tabernas is the main drainage of the Tabernas basin, fed from the north by the Sierra de los Filabres and from the south by the Sierra de Alhamilla. The drainage has been subject to rapid incision, both over the Quaternary as a whole, in response to the initial steep tectonically-induced gradients (see above), and in response to Late Pleistocene, post-ponding incision in the lower part of the basin. High sinuosity bedrock channels are common in some of the headstreams, but particularly where rapid incision has taken place through the Upper Miocene basin marl and turbidite sedimentary rocks. Most common are simple incised meanders (type A) but cutoffs (type C) also occur.

5. Case studies: The Rio Aguas

5.1 Incision sequence

Through most of the Aguas (Harvey and Wells, 1987; Mather et al., 1991; Harvey et al., 1995) and Alias river systems (Maher, 2006) the Quaternary river terraces have been mapped and correlated using soil profile characteristics, including horizon development (after Harden and Taylor, 1983), B-horizon colour (after Hurst, 1977), mineral magnetics (Harvey et al., 1995; J. Hannam pers. comm.), and pedogenic carbonate status (after Gile et al., 1966; Machette, 1985). The chronosequence has since been age-calibrated using U/Th dating (Kelly et al., 2000; Candy et al., 2004, 2005) and OSL dating (Maher, 2006; B. Mauz, pers. comm.). For this paper several reaches of high sinuousity bedrock channels within the Aguas system have been mapped in detail within the context of the terrace sequence. These data allow the timing of phases of rapid incision, rapid lateral migration, and particularly of meander cutoff formation to be age constrained.

Regional aggradation within the Sorbas basin ceased with the deposition of the Gochar formation, probably more the 1M years ago (Mather, 1991), by which time sustained regional uplift was already underway, and both synsedimentary and post-sedimentary deformation occurred, particularly in the zones of local deformation shown on Figure 5 (Mather and Westhead, 1993; Mather and Stokes, 2001). The degraded remnant depositional surface that marks the culmination of "Gochar" deposition (Stokes et al., 2002), can still be traced in the modern landscape, forming the interfluves and extensive low-relief zones within the north and west of the Sorbas basin.

The developing drainage network, forming the proto-Aguas system, became incised below the level of this surface. The incision was temporally variable, whereby the overall trend of incision during the Quaternary was punctuated by periods of aggradation, resulting in alluvial terraces within the valley system (Harvey, 2006). These can be traced over wide areas and appear to be dominantly the response to climatically-generated periods of sediment excess, coincident particularly with late Quaternary cold phases (Harvey, 1987, 2006; Candy et al., 2004, 2005). The terraces have been mapped and labelled, according to the scheme developed by Harvey and Wells (1987), and elaborated and developed by Mather et al. (1991) and Harvey et al. (1995), with the sequence of older terraces on which red soils are well developed labelled A-C in descending sequence, and the younger terraces labelled Terrace D, split, where appropriate, into D1, D2 and D3 in descending order of age. The capture of the proto-Aguas/Feos by the lower Aguas (see above) took place between terraces C and D, so that Terraces A, B and C from the upper Aguas can be traced south from the capture site, whereas Terraces D and E follow the course of the modern Aguas towards the east. The best current estimates of the age of the terrace depositional surfaces are given in Table 1.

Table 1. Best age-estimates for the alluvial terraces of the Rio Aguas. Nomenclature from Harvey and Wells (1987), and elaborated and developed by Mather et al. (1991) and Harvey et al. (1995). Dates based on U/Th dates on pedogenic carbonates (Kelly et al., 2000; Candy et al., 2004, 2005), OSL dates (B. Mauz, pers. comm.), and one Holocene 14C date (Harvey and Wells, 1987).

Tabla 1. Edad estimada para el sistema de terrazas del Río Aguas. La nomenclatura de los niveles de terraza esta basada en la propuesta por Harvey and Wells (1987), posteriormente refinada y desarrollada por Mather et al. (1991) y Harvey et al. (1995). Las edades se encuentran basadas en dataciones U/Th de carbonatos edáficos (Nelly et al., 2000; Candy et al., 2004, 2005), determinaciones OSL (B. Mauz, com. pers.) y una edad 14C Holocena (Harvey and Wells, 1987).

End-Gochar surface	>1Ma?
Terrace A	>300 ka
Terrace B	200 ka
Terrace C	80 ka
Terrace D1	40 ka
Terrace D2	20-15 ka
Terrace D3	12-10 ka
Terrace E (Holocene)	2 ka

Nomenclature from Harvey and Wells (1987), and elaborated and developed by Mather et al. (1991) and Harvey et al. (1995), Dates based on U/Th dates on pedogenic carbonates (Kelly et al., 2000; Candy et al., 2004, 2005), OSL dates (B. Mauz, pers. comm.), and one Holocene ^{14}C date (Harvey and Wells, 1987).

Terrace elevations, derived from previous work (Harvey et al., 1995), demonstrate the spatial variations in incision through the basin (Table 2; Fig. 7). Above the capture site there was steady incision into the Gochar surface through terraces A-C. As would be expected from long term incision following uplift of the headwaters, successive terrace profiles are mildly divergent downstream. Following the capture, incision worked rapidly headwards from the capture site into the upper parts of the basin, to give markedly incised valley cross profiles (Stokes et al., 2002). The depth of this lower incision decreases up the system, as successive nickpoints became stalled during the headwards propagation of the incision wave (Harvey, 2002). Below the capture site there is no continuity of the older terraces with those from upstream. There is however a zone on the valley side below which no well developed red soils occur (Fig. 7), which can be traced downvalley to grade into the lowest of the lower Aguas terraces that carries a red soil. Clast provenance analysis of the gravels in this terrace suggests that it was sourced locally, rather than from the Sorbas basin upstream, and therefore appears to pre-date the capture (Harvey et al., 1995). Furthermore, because Terrace C in the upper Aguas basin, the last terace formed before the capture, is also the youngest to support an extensive well developed red soil, it would appear that the lower limit of red soils and the terrace described above probably represent the lower Aguas valley immediately before the capture. If this is the case then the pre- and post- capture profiles of the lower Aguas are markedly concave downstream, with both pre-capture incision and post-capture adjustment focussed on the zone between the capture site and La Herreria (Fig. 7).

By combining the age estimates and elevations (Tables 1, 2), a crude estimate of the relative rates of incision can made (Table 3). These are net estimates measured from terrace surface/reconstructed profile to terrace surface, rather than taking into account the total incision prior to burial by the terrace deposits. That is attempted later for three sites where sufficient field evidence is available. These results have to be treated with caution, firstly

Table 2. Terrace elevations (m): (for locations see Fig. 7). Pre-incisional surface: Upstream of Sorbas (a) relates to degraded remnant Gochar depositional surface (>1Ma); (b) eroded gypsum surface, tectonically depressed? in Urra area; (c) eroded gypsum surface, tectonically elevated? in Los Molinos area; (d) eroded edge of valley incised below gypsum plateau. Terrace A (>300 ka), (e) remnant tectonically elevated near Los Molinos. Terrace B (200 ka). Terrace C (80 ka), (f) Equivalent in lower Aguas valley – Last pre-capture terrace, lowest elevation with "red" soils. Terrace D - where subdivided in three levels: Terrace D1(40 ka); Terrace D2 (20-15 ka);Terrace D3 (12-10 ka); (g) dominant post-capture terrace in lower Aguas Valley.

Tabla 2. Altitud (en metros) de los niveles fluviales respecto al nivel del mar (para localización ver Fig. 7). Superficie pre-incisión: Aguas arriba de Sorbas (a) relacionada con retazos muy degradados de la superficie deposicional de la fm. Gochar (> 1 Ma); (b) Superficie erosiva sobre yesos, tectónicamente hundida (?) En la zona de Urra; (c) Superficie erosiva sobre yesos elevada tectónicamente (¿) en la zona de Los Molinos; (d) paleovalle erosivo encajado sobre la superficie erosiva de los yesos. Terraza A (> 300 ka), (e) retazo de terraza tectónicamente elevado en las cercanías de Los Molinos. Terraza B (200 ka). Terraza C (80 ka), (f) Equivalente en el Valle inferior del Río Aguas – Ultima terraza pre-captura con "suelos rojos" a menor altitud. Terraza D – subdividida en tres niveles: Terraza D1 (40 ka); Terraza D2 (20-15 ka); Terraza D3 (12-10 ka); (g) nivel de terraza post-captura dominante en el Valle inferior del Río Aguas.

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Above Moras	520a	507	496	488		478		474
Below Moras	500a	480	472	464		452		438
Sorbas	455a	436	408	392	380	368	358	348
Urra	420b?	430	395	375	350	340	320	310
Los Molinos	440c	430e	380	360		330		250
Capture site								
La Herreria	390d			250f		200g		175
Los Giles	370d			190f		170g		140

1. Pre-incisional surface: Upstream of Sorbas (a) relates to degraded remnant Gochar depositional surface (>1ma); (b) eroded gypsum surface, tectonically depressed? in Urra area; (c) eroded gypsum surface, tectonically elevated? in Los Molinos area; (d) eroded edge of valley incised below gypsum plateau.
2. Terrace A (>300 ka), (e) remnant tectonically elevated near Los Molinos.
3. Terrace B (200 k).
4. Terrace C (80 ka), (f) Equivalent in lower Aguas valley - Last pre-capture terrace, lowest elevation with "red" soils.

5, 6, 7 Terrace D - where subdivided, 5: Terrace D1 (40 ka), 6: Terrace D2 (20-15 ka), 7: Terrace D3 (12-10 ka); (g) dominant post-capture terrace in lower Aguas Valley.

8. Elevation of modern channel.

because the age control is variable. The timing of the end of Gochar deposition and the beginning of incision is unknown; an estimate of one million years is used. Furthermore, no remnants of this surface are preserved to the east of the area; the depth of the incised valley below extensive eroded bedrock surfaces is assumed to be equivalent to the depth of incision below the Gochar surface. The age of Terrace A is unknown, other than it is greater than 300 ka; and an estimate of 500 ka is used here. The other dates are more precise (Candy et al., 2004, 2005). Furthermore, tectonic deformation has not been taken into account, so would add an error particularly in the deformed zones, and particularly to the elevations of the older surfaces.

Despite these limitations, the results do show some interesting patterns (Table 3). The total depth of incision increases irregularly downvalley. When divided into pre- and post-capture incision the effects of the capture are clear. In the upper valley pre-capture incision is 30-40 m, of which 15-20 m occurred between terraces A-C, and about 20 m occurred after the capture at much accelerated incision rates. Downstream, the effect of the capture

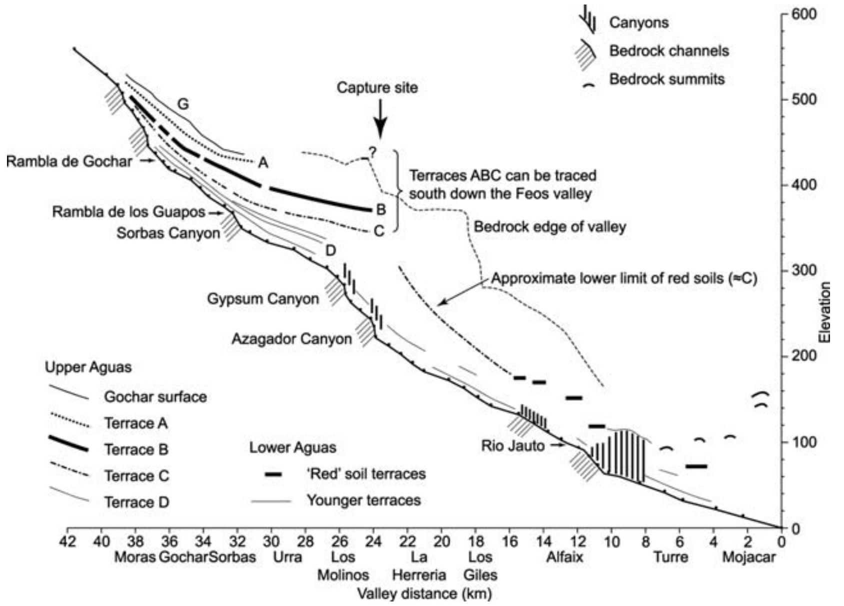

Figure 7. Rio Aguas: long profile, terrace relationships and spatial/temporal variations in incision (adapted from Harvey et al., 1995; Harvey, 2001).

Figura 7. Perfil longitudinal del Río Aguas mostrando las relaciones entre niveles de terraza y variaciones espacio/temporales (adaptado de Harvey et al., 1995 y Harvey, 2001).

Table 3. Relief between successive terrace surfaces (m): estimated net incision rates over the periods (m ka-1), given in brackets, based on duration of incision calculated as the age difference between the surfaces. P: Pre-incision surface, is Gochar depositional surface at Moras and Sorbas, eroded gypsum surface at Los Molinos and downstream (assumed equivalent in elevation and age to Terrace A). A, C, Terraces; M, Modern valley floor.

Tabla 3. Relieve (m) generado entre los sucesivos niveles de terraza A, C y el canal fluvial actual (M). Las Tasas de incisión asociadas a cada uno de los periodos (m ka-1), entre paréntesis, están basadas en la duración de la incisión calculada en función de la diferencia de edad entre las distintas superficies fluviales. P: La superficie pre-incisión corresponde a la superficie deposicional de la fm. Gochar en las zonas de Moras y Sorbas, y a la superficie erosiva sobre yesos en la zona de Los Molinos y aguas abajo de ella (asumiendo que es equivalente en altitud y edad al nivel de terraza A).

1. Incision period	Total	P-C	A-C	C-M
2. Estimated duration (ka)			420	80
Locations				
Moras	50-60	30-40	15-20	c20
			(0.040-0.045)	(0.2-0.3)
Sorbas	c110	c60	40-50	c40
			(c0.1	(>0.5)
Los Molinos	190	c80	c70?	>100
			(0.17)	(>1.3)
La Herreria-Los Giles	>215		>150	>50
			(0.15-0.2)	(0.6-0.9)

1. Surfaces, P: Pre-incision surface, is Gochar depositional surface at Moras and Sorbas, eroded gypsum surface at Los Molinos and downstream (assumed equivalent in elevation and age to Terrace A). A, C, Terraces; M, Modern valley floor.
2. Estimated durations (ka) between surfaces A, C, M.

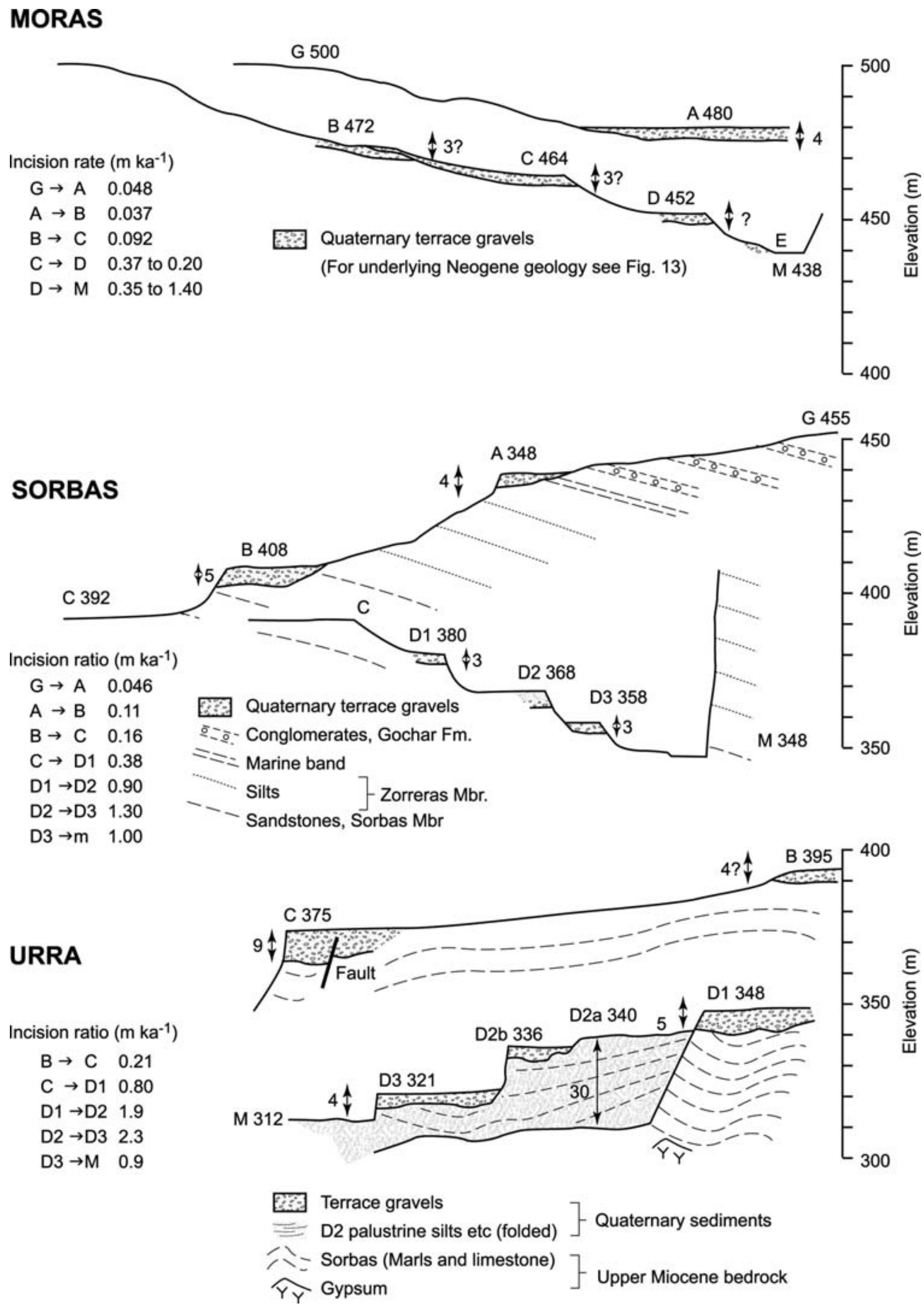

Figure 8. Schematic representations of incision sequences, represented by terraces at a) Moras, b) Sorbas, c) Urra. (adapted from Harvey, 2001; Stokes et al 2002). Estimated terrace ages updated from Kelly et al., 2000; Candy et al., 2004, 2005).

Figura 8. Representación esquemática de las secuencias de incisión representadas por los niveles de terraza de a) Moras, b) Sorbas, y c) Urra (adaptado de Harvey, 2001 y Stokes et al., 2002). Las edades estimadas de las terrazas actualizadas de Nelly et al. (2000) y Candy et al. (2004; 2005).

becomes even more pronounced with more than half the post-Terrace A incision at Sorbas occurring after the capture, at rates about five times those before the capture. This is even more apparent at the capture site at Los Molinos, with a total of 180 –190 m of incision, more than 100 m occurring after the capture at overall rates almost 10 times the pre-capture rates. Beyond the capture site the late Pleistocene incision rates are less. Even further downstream Schulte (1998, 2001) and Schulte et al. (in press) have dated a travertine deposit near Alfaix, using U/Th dating. Although their interpretation of the terrace relationships with the upper Aguas differs from that presented here, the overall incision rate for the lower Aguas during the late Pleistocene (30 m in 169 ka; ie. c 0.18 m ka^{-1}) accords with the patterns suggested here. Downstream of a pronounced nickpoint at Alfaix the incision has been complicated by the effects of base-level change in response to eustatic changes of sea level (Schulte et al., in press).

The overall incision rates presented on Table 3 are of the same order of magnitude as the regional uplift rates calculated by Braga et al. (2003). A mean post-Gochar incision rate of c 0.2 m ka^{-1} (ie. 200 m Ma^{-1}), for the past million years over much of the basin is of the same order of magnitude as the mean post-Lower Pliocene (3.6 Ma) uplift rate of c 100 m Ma^{-1}, especially if the uplift was concentrated in say the c 1.5 Ma between the mid Pliocene and the mid Pleistocene, in which case the uplift rate would be nearer to 200 m Ma^{-1}.

More important for the purposes of this paper is to estimate incision rates nearer to the actual rates that would have occurred, rather than the net rates expressed by terrace elevations alone. This can be done from information derived from field exposures for the three sites for which the morphological implications are considered in the next section. At Moras (Fig. 8a) the Quaternary terraces are cut into folded uppermost Neogene and lower Pleistocene sedimentary rocks, culminating in the Plio-Pleistocene Gochar conglomerates. Terraces A and C are well exposed; B and D less so, so that by and large true incisional depths to the base of the terrace sediments can be used to calculate incision rates nearer to the real rates than was done in the previous section. Even these incision rates are minimum estimates in that incision may have been occurring for only part of the time. As shown earlier the incision rates accelerate through time especially after Terrace C. The incision wave, generated by the capture, has propagated up into the canyon a few km upstream from Moras. Because only one D-age terrace is present here, and it is uncertain to which sub-stage it should be attributed, the range of possible C-to-D and D-to-Modern incision rates have been quoted (Fig. 8a), in both cases much higher than the pre-C rates.

The same trends can be identified further downstream at Sorbas (Fig. 8b), but there Terrace D can be subdivided into its three constituent parts (D1-3), and although exposures are poor and elevations are difficult to estimate, the high rates of incision from D1 to D2 to D3 are obvious.

The sub-stages of Terrace D are best seen at Urra (Fig. 8c), previously described by Mather et al. (1991) and Harvey (2001), and dated by Candy et al. (2005). Terrace D1 is a gravel terrace that follows the first post-capture (ie. post-Terrace C) massive dissection phase. Further dissection then followed, cutting the valley to below modern river level. The system then became ponded and c 30 m of fine sediments (D2) accumulated, culminating in the D2a depositional surface. Fluvial activity resumed, cutting the D2b surface into the D2a sediments, followed by rapid incision prior to deposition of the D3 fluvial gravel sediments. Finally there was rapid incision of the D3 terrace down to modern river level. The causes of this complex sequence have been discussed elsewhere (Mather et al.,1991; Harvey, 2001), and may involve interaction between (i) incision in response to the capture-induced base-level change (ii) local tectonic disturbance, and (iii) gypsum dynamics, possibly through solution, more likely by deformation in relation to faulting. That discussion is beyond the scope of this paper; suffice it to say that four periods of very rapid incision can be identified, by the dissection of the C, D1, D2, and D3 terraces at 60-40 ka, 30-20 ka, 15-12 ka and post-10 ka respectively.

5.2 Examples of response to rapid incision

Sorbas

The full terrace sequence, representing incision over much of the Quaternary, is present in the

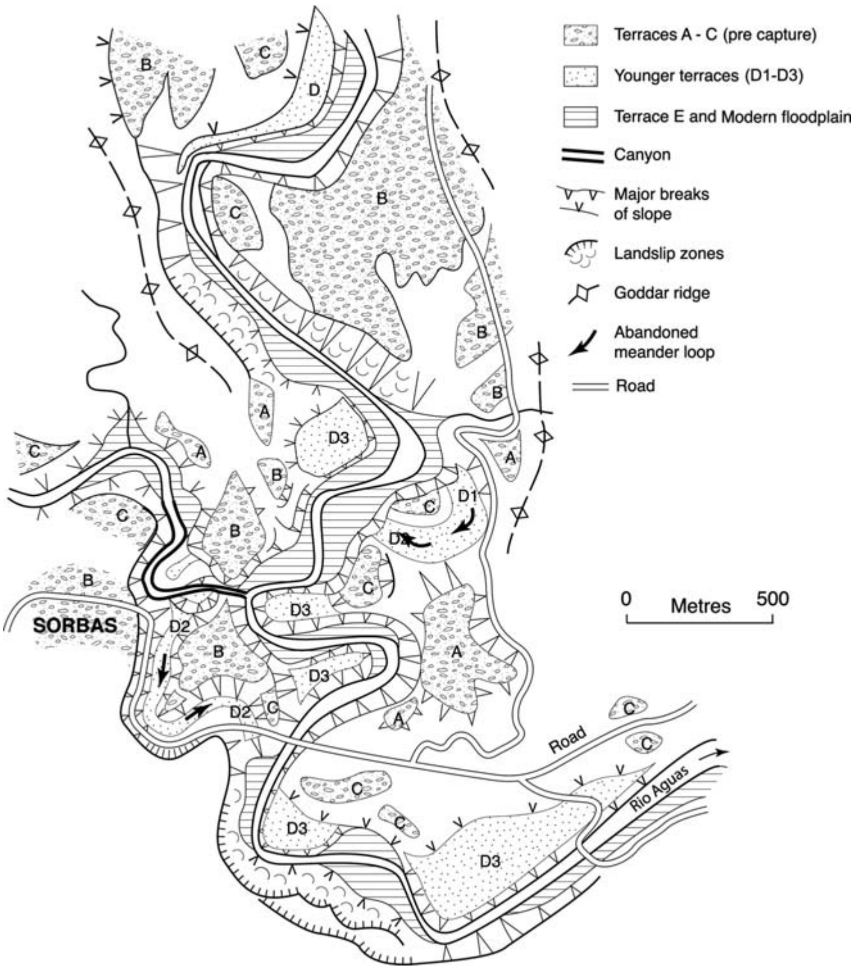

Figure 9. Sorbas area: terrace sequence and incised meander cutoffs; adapted from Harvey et al., 1995; Harvey, 2001.

Figura 9. Secuencia de terrazas y meandros encajados abandonados en la zona de Sorbas (adaptado de Harvey et al., 1995, Harvey, 2001).

Sorbas area (Fig. 9), from which the sequence of palaeo-valley morphologies can be reconstructed. The valleys of both the Ramblas de Sorbas from the north and de Guapos from the west, which join at Sorbas to form the Aguas, are bounded by low ridges preserving remnants of the Gochar surface. Terraces A, B, and C are remnants of wide palaeo valley floors, cut into this surface, created by long periods dominated by lateral channel migration, punctuated by shorter periods of incision.

A major change was triggered by the incision wave that followed the Aguas/Feos capture. The rapid incision after Terrace C caused increasing valley confinement and the development of incised meanders, preserved in the terrace D remnants. In three extreme cases (Fig. 9) incised meander cutoffs occurred during the incision phases, the first NE of Sorbas (Fig. 9) is an ill defined cutoff that postdates Terrace C. The second, just a little further to the NE very clearly occurred during the D1-D2 incision. The third was more complicated. The original confluence of the Ramblas de Sorbas and Guapos was south of the site of Sorbas village. These two courses were maintained until Stage D2.

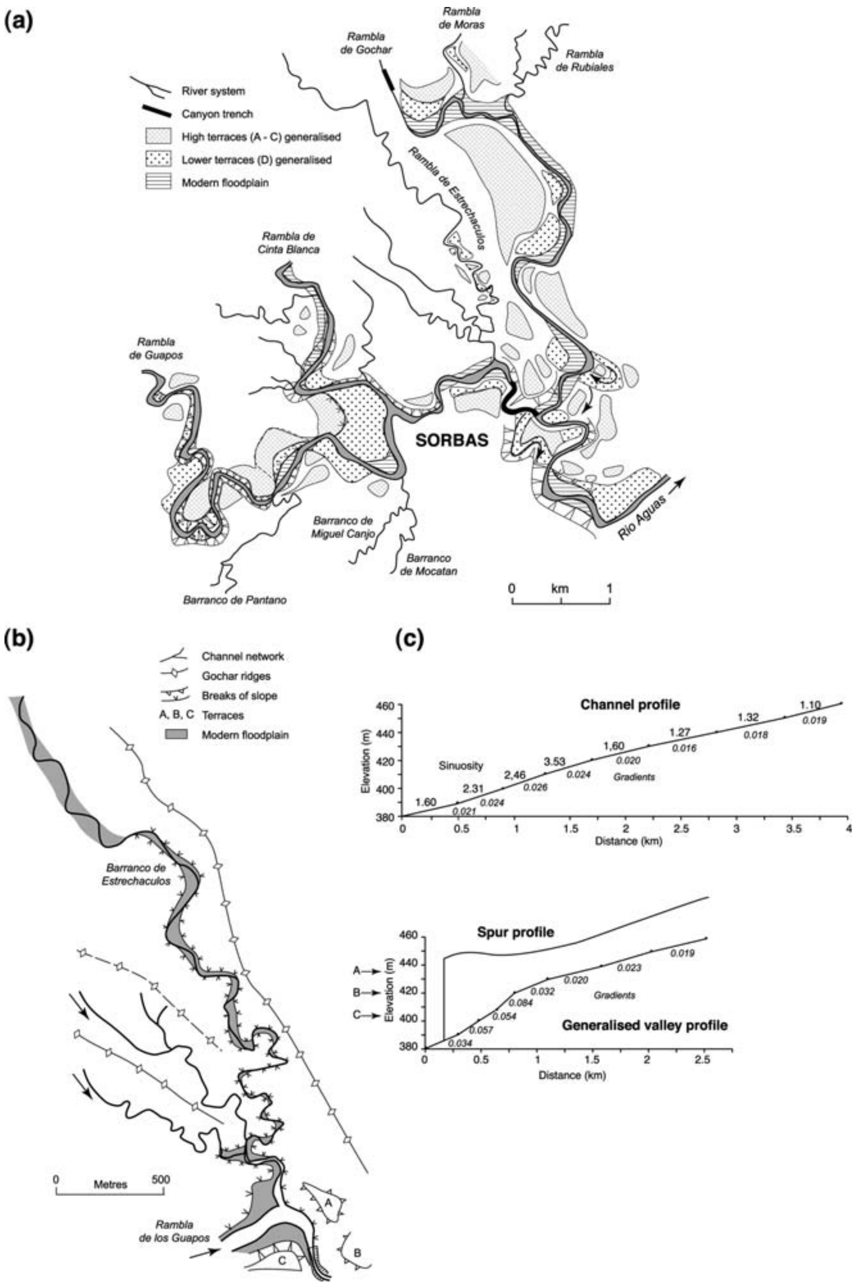

Figure 10. Incised meanders on small oversteepened tributary streams: a) Distribution of incised meanders on oversteepened tributary streams, resulting from incision of the main channels: the Ramblas de Sorbas and de Guapos, north and west of Sorbas respectively; b) Rambla Estrechaculos: incision sequence (plan view mapped from air photographs); c) Rambla Estrechaculos: profile (derived from 10 m contours on the 1:10000 map), also shown are reach sinuosities and gradients.

Figura 10. Meandros encajados desarrollados en sistemas tributarios de elevada pendiente: a) Distribución de meandros encajados en sistemas tributarios resultado del encajamiento de sus canales principales: Las Ramblas de Sorbas y de Guapos, al norte y este de Sorbas respectivamente; b) Secuencia de episodios de incisión en la Rambla de Estrechaculos (esquema realizado a partir de fotogramas aéreos); c) Perfil longitudinal de la Rambla de Estrechaculos (a partir de mapas topográficos 1:10.000) mostrando los tramos sinuosos y gradientes asociados.

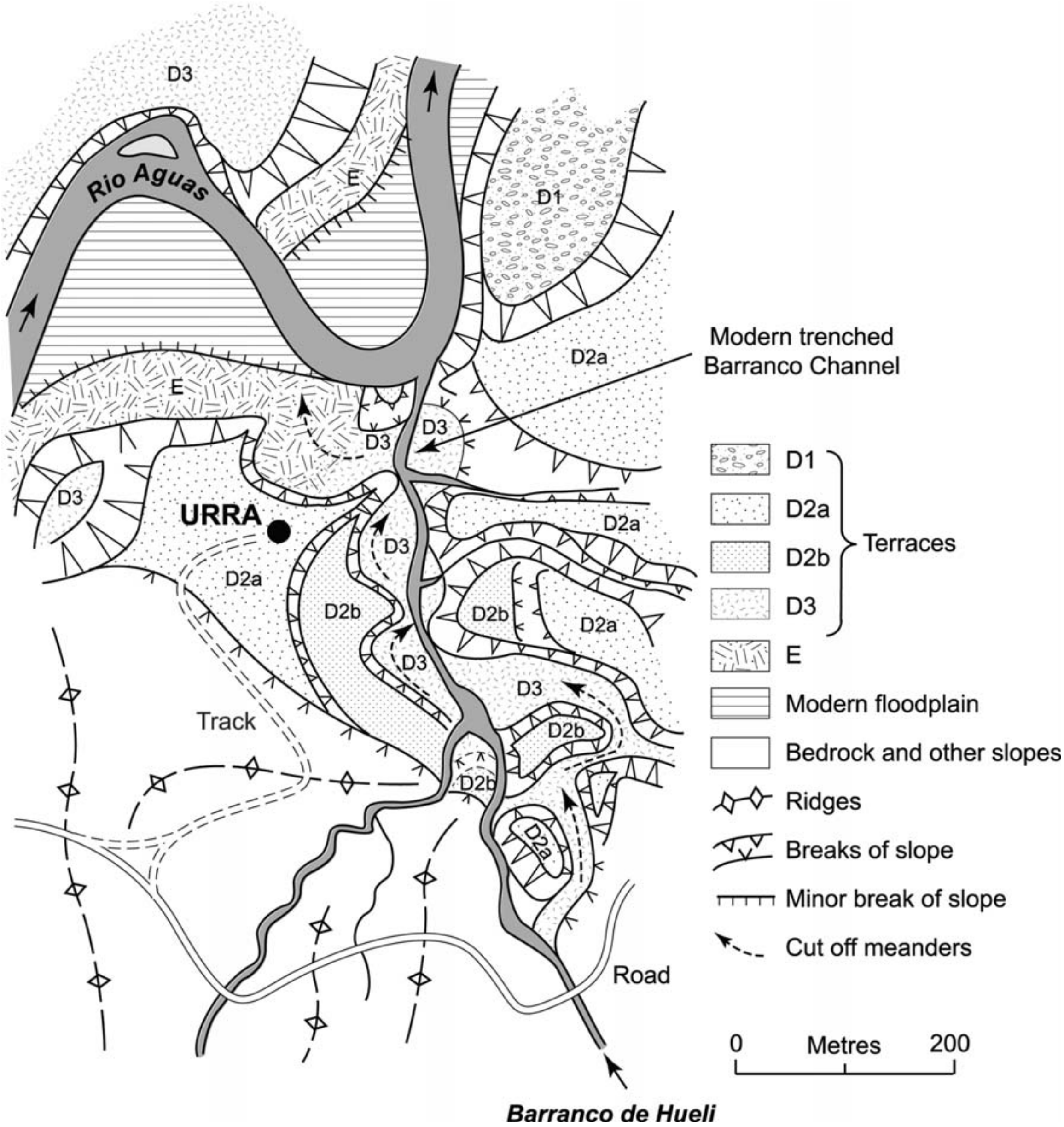

Figure 11. Urra area: terrace sequence and incised meander cutoffs; adapted from Mather et al., 1991; Harvey, 2001.

Figura 11. Secuencia de terrazas y menadros encajados abandonados en la zona de Urra (adaptado de Mather et al., 1991; Harvey, 2001).

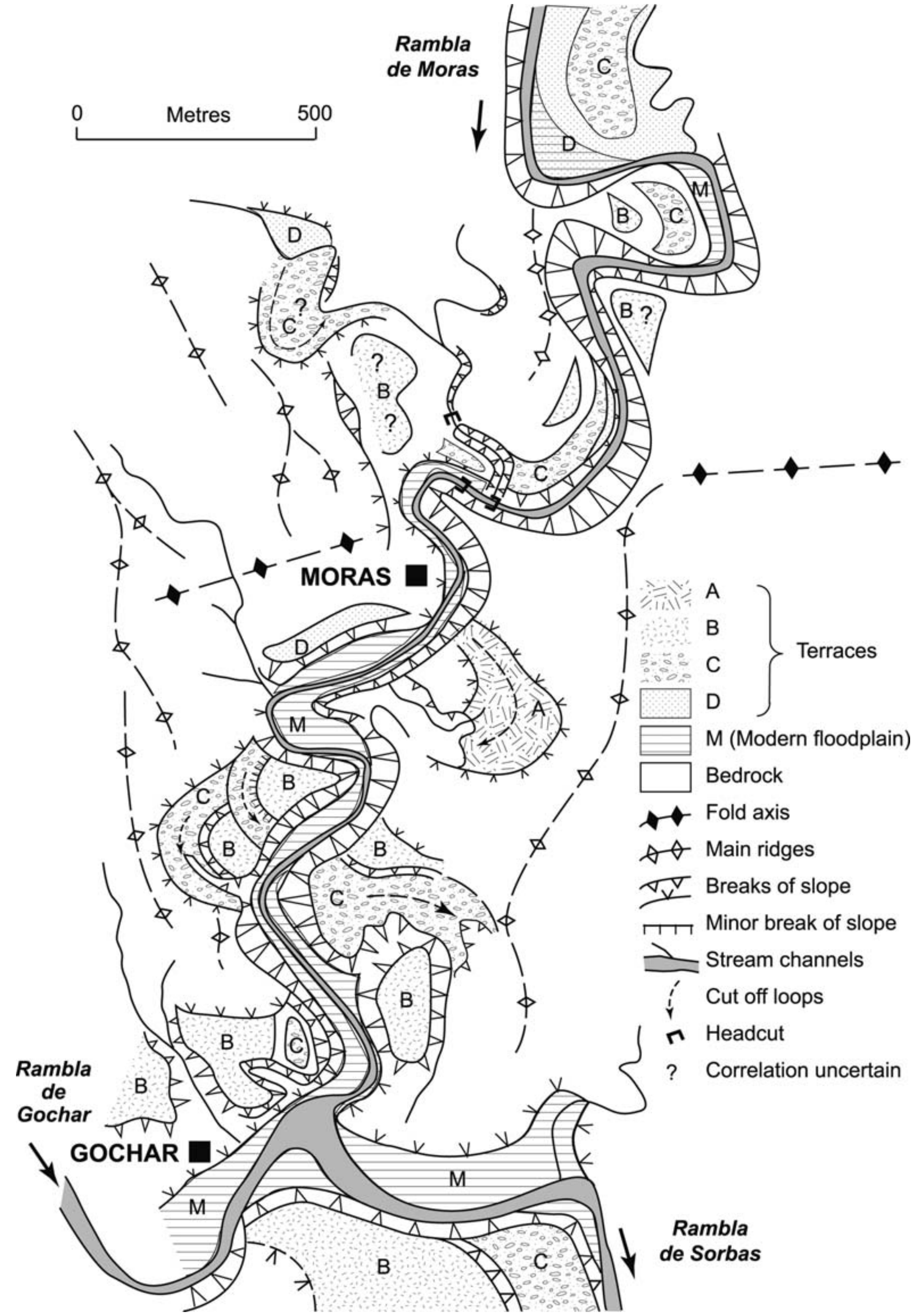

Figure 12. Moras area: terrace sequence and incised meanders (adapted from Harvey et al., 1995; Harvey, 2001).
Figura 12. Secuencia de terrazas y meandros encajados en la zona de Moras (adaptado de Harvey et al., 1995; Harvey, 2001).

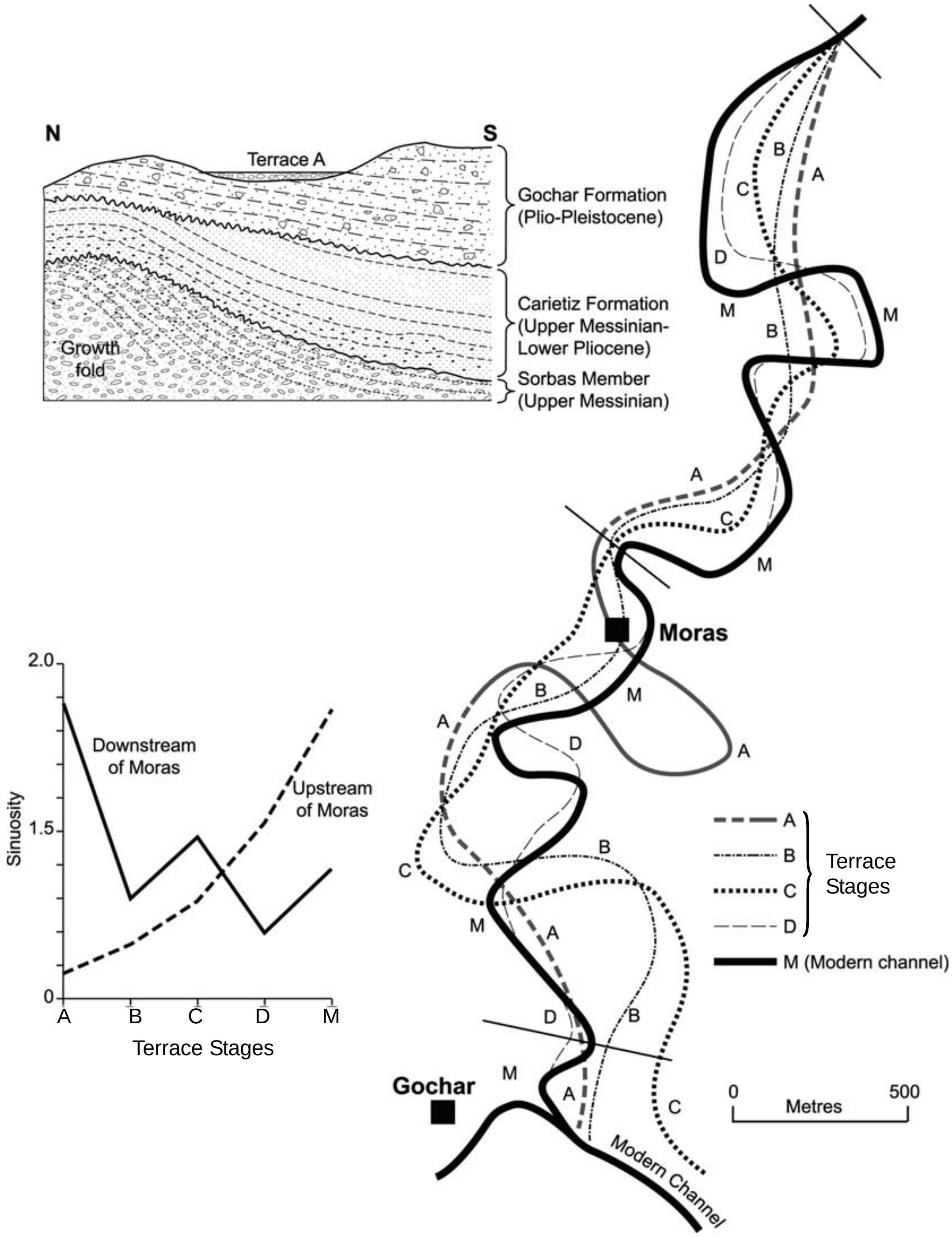

Figure 13. Moras area: reconstructed channel patterns in relation to the growth fold; growth fold shown on the left; progressive change in sinuosities of reaches upstream and downstream of Moras shown on the right.

Figura 13. Reconstrucción del patron del canal principal de la Rambla de Moras en relación con el crecimiento de un pliegue. El crecimiento del pliegue se ilustra en la izquierda del gráfico. El cambio progresivo en sinuosidad del canal aguas arriba y abajo de Moras se ilustra a la derecha.

But, during post-D2 incision back-to-back incising meanders of the two streams intersected one another upstream of the site of Sorbas villlage. Effectively, the Rambla de Sorbas captured the Rambla de Guapos, which abandoned its D2 valley, isolating the location of Sorbas village, and accounting for its spectactular site. The deep canyon of the Guapos NW of Sorbas village (Fig. 9) accounts for the foreshortened and steepened course of the captured Guapos. It is clear that both of these incised meander abandonments were brought about by accelerated lateral activity *during* incision (ie. between terrace phases).

Small tributary junctions

An indication of how the mechanism operates is provided by the morphology of many of the junctions between small tributaries and the incised main channels of the Ramblas de Sorbas and Guapos upstream of Sorbas (Fig. 10a). The gradients of the tributaries steepen towards the falling local base level of the incising (and often laterally migrating) main channel. As the tributaries steepen and incise, unit stream power is enhanced, promoting lateral migration, resulting in tortuous incised meanders in the oversteepened reach. This would tend to reduce gradients and stream power, and thereby can be regarded as a form of adjustment to the local base-level change created by the incising main river.

Figure 10b shows plan and profile views of one of these streams, the Barranco de Estrechaculos, tributary to the Rambla de Guapos upstream of Sorbas. The plan view shows the increasing sinuosity of the incised meanders on the tributary stream as it approaches the tributary junction. Two profiles are shown, one of the channel itself, and one showing the theoretical gradient that would be equal to the valley gradient if the effect of sinuosity is disregarded. The second of these shows gradients of around 0.02 in the upper less sinuous reach, increasing to over 0.05 as the stream approaches the main river. This gives an indication of the degree of gradient steepening resulting from the base-level change. The difference between the two profiles shows the degree of adjustment resulting from the increased sinuosity from around 1.2 in the upper reach to over 2.5 through the steeper reach. Channel gradients of the upper reach average 0.018, and increase to an average of only 0.025 in the lower reach.

Urra

An extraordinary cluster of incised meanders and incised meander cutoffs occurs at Urra, east of Sorbas, on the Barranco de Hueli just upstream of the confluence with the Rio Aguas (Fig. 11), within the zone of D1, D2, D3, and E terrace development (see also Fig. 8c). After burial of the landscape by the D2 fine sediments to form the D2a depositional surface, the fluvial network became re-established and cut down to the D2b surface, then rapidly down to a few m above modern stream level. In doing so, it created the highly sinuous incised meandering D3 course. The modern course has cut off three of these incised meanders. The possibility that these cutoffs were human-dug has been considered, however this seems unlikely. The modern channel is deeply incised into D3 sediments, which appear to be latest Pleistocene or earliest Holocene in age (Candy et al., 2005). There is only a limited amount of younger sediment within the Barranco, but the Terrace D3 palaeo valley-floor of the most downstream cutoff grades down to Terrace E of the Rio Aguas. This suggests that cutoff took place during the incision of the Aguas below the Terrace D3 valley floor (early Holocene?), and therefore probably before any significant human modification of the valley floor.

Moras

The examples presented so far have all considered the development of incised meanders as responses to local base-level change induced by the Aguas/Feos capture or by the complex causes of incision expressed by the D1, D2, D3 terrace sequence at Urra. The Rambla de Moras (Fig. 12), a northern headstream of the Aguas, shows evidence of a response to interaction between the capture-induced incision wave and local tectonic activity. There are contrasting styles of incised meanders upstream and downstream of Moras village (Fig. 12), with simple ingrown meanders upstream and a complex pattern of cutoff meanders downstream. The development can be traced through the sequence of terrace development, and, because it affects

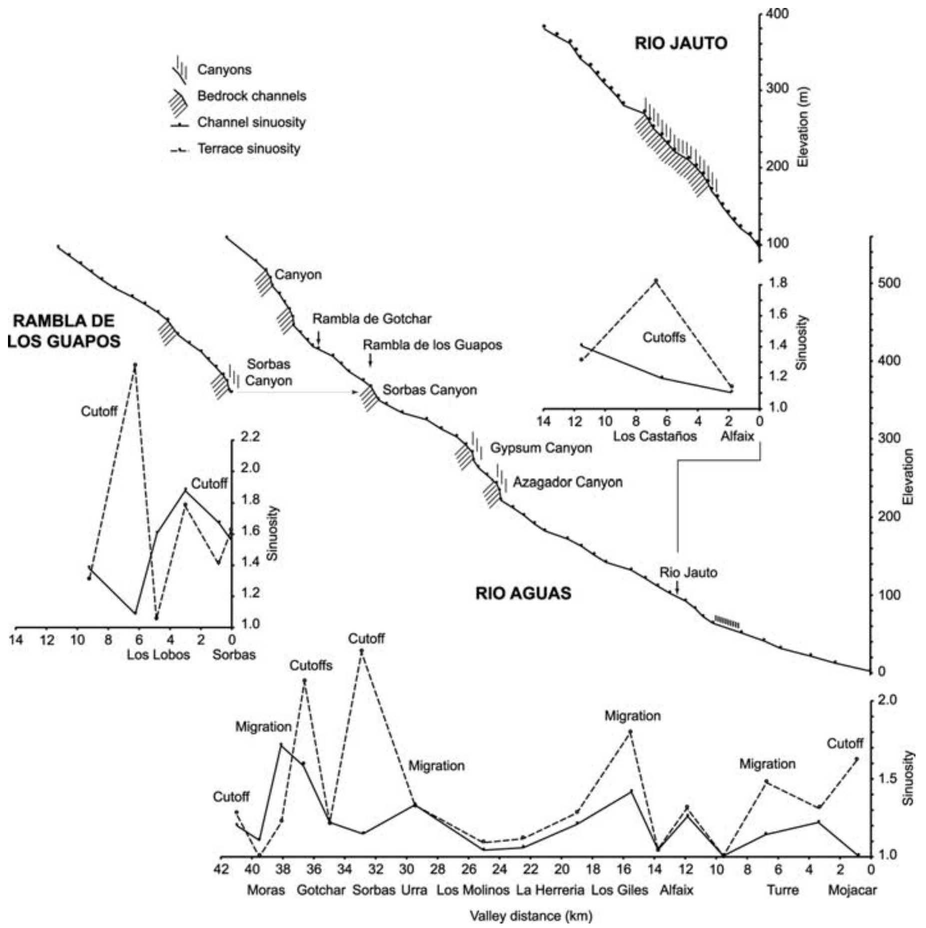

Figure 14. Rio Aguas system: Long profile, channel and terrace sinuosity.
Figura 14. Perfil longitudinal, sinuosidad del canal y de las terrazas del Río Aguas.

Terraces A-C, it is clear that incised meandering had developed long before the accelerated incision associated with the post Terrace C headwards propagation of the Aguas/Feos capture-induced incision wave.

There are sufficient terrace remnants to enable reconstruction of the sequence of palaeo-stream courses with reasonable confidence (Fig. 13). These suggest that in the upstream reach ingrowing meanders had already begun to develop by Terrace B times, the channel showing a consistent increase in sinuosity from the reconstructed Terrace A course through Terraces B, C and D to the modern channel (Fig. 13). The reach downstream of Moras shows evidence of lateral migration leading to cutoff incised meanders for each of the Terraces A, B, C, with consequent variations in sinuosity through the period (Fig. 13). It is only with the capture-induced accelerated incision after Terrace C that the channel effectively becomes locked into its stable planform.

A possible cause of the differences between the two reaches lies in the effects of ongoing Quaternary tectonics. A growth fold lies under the village of Moras (Fig. 13), with its axis running approximately ENE-WSW, so that the downstream reach runs downdip, and the upstream reach runs more or less strike parallel. The anticline probably lies above a blind basement fault, and has been intermittently active since the late Messinian. It causes an intra-formation unconformity within the upper Messinian Sorbas Mbr., that peters out laterally, another at the top of the lower Pliocene Moras Mbr. of the Carietiz Fm. (Mather, 1991), and tilts the Plio-Pleistocene Gochar formation to the south. Locally this formation is also affected by Quaternary faulting. There is further supportive evidence that this area had been a local topographic high forming a shoreline zone during deposition of both the Sorbas Mbr. (Martin et al., 1993; Braga and Martin, 2000) and the Carietiz Mbr. (Mather, 1991).

It seems likely that Quaternary regional uplift was sufficient to trigger incision, together with slow lateral migration and the development of incised meanders. South of the axis of the growth fold local deformation on the fold increased the effective uplift and the gradient sufficiently to accentuate lateral migration during incision to a degree that allowed cutoff of incising meanders to occur.

5.3 Changes in Sinuosity

In the Moras area changes in sinuosity have been shown to reflect the style of the development of incised meanders. Two measures of sinuosity have been derived for the main rivers within the Aguas river system as a whole (Fig. 14), calculated over valley reaches of 50 m elevational increments (as for the long profile, plotted on Fig. 7), and taking the valley distance as the centreline of the late Quaternary valley floor, defined by rock valley edge and including D-age terraces or their equivalents. The first measure is the modern channel sinuosity, defined as the modern channel distance divided by the valley distance (defined above). The second measure is the terrace sinuosity, approximating to the maximum palaeo-sinuosity, taking the line of maximum sinuosity as the centre line of palaeochannels, generally of Terrace D or equivalent age, once flowing through cutoffs or against arcuate valley walls, and dividing that measurement by the valley distance (defined above).

Zones of high terrace sinuosity indicate zones of past lateral migration and cutoff (high sinuosity channels of Types A, C; see Fig. 1). Zones where the channel sinuosity is higher than the terrace sinuosity indicate zones of tortuous ingrown meanders. The zones of low values for both terrace and channel sinuosities include steep entrenched rock-bound gorges through the more resistant lithologies. In these zones rock resistance appears to be too great to allow the development of rapid lateral migration during entrenchment.

6. Discussion

6.1 Regional patterns in relation to controls

The regional survey and the case studies within the Rio Aguas system have highlighted some of the temporal and spatial controls on the development of incised bedrock meanders. Lateral erosion during incision, leading to the development of high sinuosity bedrock meanders is closely associated with periods with high rates of incision. The regional distribution shown on Figure 6 appears to relate directly to zones where gradients have been steepened by rapid changes in local base levels.

Figure 15 shows the distribution of high sinuosity bedrock channels in relation to the potential causes of rapid changes in gradient. Regional tectonics are the most obvious underlying cause, with rapid incision most likely associated with zones of steep tectonically-induced gradient, reflecting the regional uplift patterns (Fig. 4; Zone 1, Fig. 15). The most common distribution is of simple incised bedrock meanders (Type A – Fig. 1) on small streams draining the flanks of the uplifted mountain ranges. Some of these are faulted mountain-front zones, others are simply tilted. These streams are mostly cut into fissile schists, but on the northern flank of the Sierra Cabrera also involve a wide range of other rocks. Where larger rivers are cut into uplifted basement notably the Rios Almanzora, Antas, and Jauto, the incised channels show greater complexity, and more evidence of lateral migration, including abandoned cutoffs (Types B, C - Fig. 1). The lower reaches of the larger rivers within Neogene sedimentary rocks, but away from the coasts (Rios Almanzora, Antas, Aguas: Zone 2, Fig. 15) show evidence of lateral migration during incision (Type B – Fig. 1).

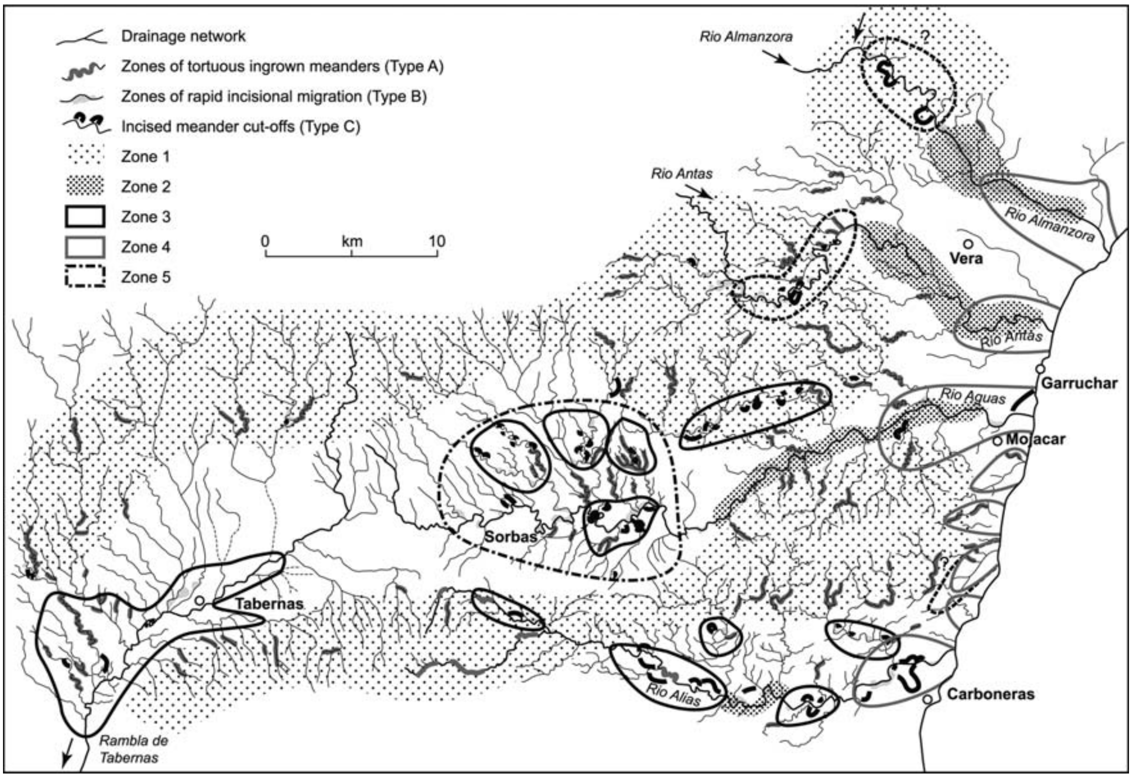

Figure 15. Study area: Distribution of high sinuosity bedrock channels (shown on Fig. 6) in relation to local controls on incision rates. Zone 1: Affected by differential regional uplift of basement; Zone 2: Affected by differential regional uplift of Neogene basins; Zone 3: Affected by Quaternary and ongoing local tectonic deformation, including active faults, growth folds, and zones of uplift causing ponding and breaching; Zone 4: Affected by eustatic marine base levels; Zone 5: Affected by river capture.

Figura 15. Distribución de canales meandrifrmes encajados en roca en el área de estudio (Ver Fig. 6) en relación a los controles locales de las tasas de incisión. Zona 1: Afectados por elevación regional diferencial del basamento; Zona 2: Afectados por elevación regional diferencial de las cuencas neógenas; Zona 3: Afectados por tectónica cuaternaria y actual, incluyendo crecimiento de pliegues, zonas de elevación provocando obturaciones y aperturas del drenaje; Zona 4: Afectados por cambios eustáticos del nivel de base marino; Zone 5: Afectados por procesos de captura fluvial.

Where other factors have accentuated or modified regional uplift patterns to produce rapid changes in local base levels, more complex incision patterns have resulted. Quaternary and ongoing tectonic deformation (Zone 3, Fig. 15) includes situations where the larger rivers cross active fault zones notably where the Alias crosses the Luicainena and Carboneras fault zones (Maher, 2006; Maher and Harvey, in press), but also includes where the proto Aguas/Feos crossed the Lucainena fault zone (Harvey and Wells, 1987), and possibly, though the details are not known, where the Jauto, Antas and Almanzora cross fault zones within the basement rocks. Similarly where streams cross growth folds, as at Moras, and elsewhere in the northern part of the Sorbas basin, cutoffs are common (Type C – Fig. 1). This is especially true where localised uplift caused ponding then breaching during the Quaternary as at Tabernas and Urra.

Marine base-level controls are also important (Zone 4, Fig. 15), and tend to produce complex incised patterns, especially on the Aguas and Alias,

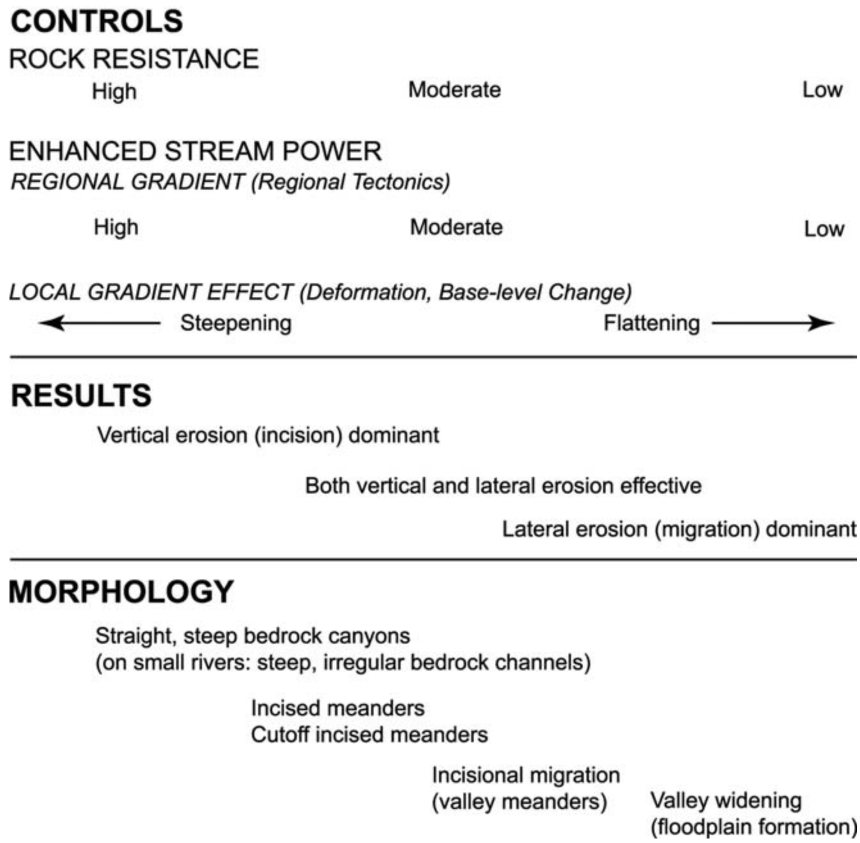

Figure 16. Schematic representation of the effects of rock resistance and enhanced stream power (through increased gradients) on erosional regime and resulting morphology in bedrock channels.
Figura 16. Representación esquemática del efecto de la resistencia de las rocas y el "stream power" magnificado (por incrementos de gradiente) en regímenes erosivos y su impacto sobre la morfología de canales en roca.

but the most abundant cutoffs are associated with the capture-induced base-level fall upstream from the Aguas/Feos capture (Zone 5, Fig. 15). Cutoffs are especially abundant where the capture-induced incision interacts with the ponding/breaching-induced incision at Urra, or the tectonically-enhanced incision at Moras.

In summary, simple regional tectonic tilting tends to produce simple incised meanders (Type A – Fig. 1) on small headwater streams, with more active lateral migration on the larger rivers (Type B – Fig. 1). However in the situations where regional tectonic tilting combines with a local cause of accelerated base-level fall the patterns are more complex and often involve complex sequences of meander cutoffs (Type C – Fig. 1).

The general explanation would appear to be that the greater the incision rate, the more complex the development of incised meander morphology. If this is the case, it appears to be the opposite of what has been demonstrated on rivers of the Colorado plateau (Gardner, 1975, 1983; Schumm et al., 1987), where greater gradients are associated with steeper but straighter incised rivers and incised meanders occur primarily on sections of less steep gradient. A more complex explanation would seem to be more appropriate, involving consideration of the relationships between stream power and rock resistance, in a manner not unlike that in the concept of critical power in alluvial channels (Bull, 1979). For high sinuosity bedrock channels to develop both vertical and lateral erosion must occur; the balance between the two depending not only on rock resistance but also on the relationship between gradient and discharge (Fig. 16).

Under conditions of high rock resistance and steep gradients on small streams, incision would be slow, irregular and primarily vertical. On larger rivers under these conditions, incision would be vertical, leading to canyon formation, within which the stream course would be steep and more or less straight. Where rock resistance was less, perhaps with lower stream power (lower gradients?) lateral erosion might develop concurrently with incision, leading to the suite of incised sinuous channel forms described in this paper. With larger rivers and lower gradients lateral activity might dominate, leading to floodplain formation and the switch from a bedrock channel to an alluvial channel within a confined rock valley. Where rock resistance is low, lateral activity might dominate very early in the sequence, allowing a rapid increase in valley width and the switch to alluvial channel morphology, without the development of incised bedrock meanders.

There would appear to be a continuum of channel response to gradient increase. Where the gradient change is small, irregular low sinuosity bedrock channels may dominate, as erosion progresses perhaps to be transformed into alluvial channels. With higher gradients high sinousity bedrock channels may develop and persist. Under higher gradients still, especially where rock resistance is high, vertical incision may dominate, resulting in steep, low sinuosity bedrock channels.

6.2 Implications

Two important properties of all types of base-level triggered incision have important implications for the geomorphology of the incised zone, affecting not only the fluvial landforms themselves but local hillslope-to-channel coupling within the system (Harvey, 2002). First is the rate of incision; second is whether headwards propagation of the incised reach takes place, and if so, the rate of propagation of the nickpoint to form an incision wave (Garcia et al., 2003). Net incision rates are difficult to estimate meaningfully, but rates of between 0.2 and >1.3 m ka^{-1} for the post-capture incision on the Aguas (Table 3) allowed the development of incised bedrock channels and allowed incision to dominate the late Quaternary evolution of the Aguas valley (Harvey, 2001). Incision-wave propagation rates are even more difficult to determine and subject to a wide range of errors and uncertainties. For this region evidence is present for six incision waves, related to base-level changes in response to sea-level change (Rios Aguas and Alias), capture (Aguas/Feos at Los Molinos), fault movement (Rio Alias at Argamasson: Maher, 2006; Maher and Harvey, in press), and tectonically-induced ponding and breaching (Tabernas and Urra). These nick points generated by base-level changes of 25-100m, have propagated distances of 4-12 km over timescales ranging between15 and 80 ka. Although these estimates are very crude, they do give an indication of the rate at which zones of landscape destabilisation in this area propagate headwards from a point of base-level change. As they propagate they stimulate the development of a range of incisional morphologies including badlands, landslides and canyons as well as sinuous bedrock channels (Harvey, 2007).

The sinuous bedrock channels of the Almeria region appear to be responses to four sets of controls over base levels and incisional river gradients: regional tectonics, zones of local tectonic deformation, river capture, and direct base-level change related to eustatic sea levels, and to breaching after drainage ponding. Each type of high sinuosity bedrock channel has distinctive spatial characteristics reflecting the style of gradient change. While the distributions are not absolute, the indications are that in any one region they could be used as indicators of the spatial characteristics of tectonic or other base-level influences on the evolution of the fluvial system.

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