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Tectonic origin and evolution of a transverse drainage: the Río Almanzora, Betic Cordillera, Southeast Spain

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Abstract

The Río Almanzora forms one of the larger drainage systems within the Betic Cordillera, Southeast Spain. In its distal reaches, prior to joining the Mediterranean Sea, the Río Almanzora cuts across a major topographic barrier, the Sierra Almagro, forming drainage that is transverse to the regional geological structure.

The long-term drainage evolution of the Río Almanzora and its creation as a transverse drainage across the Sierra Almagro has been examined by reconstruction of an evolving basin-scale drainage network using a combination of the geological and geomorphological record. The early stages of drainage evolution (Late Miocene–Pliocene and Plio-Pleistocene) reveals the emergence of marine basins to the north and south of the Sierra Almagro and the development of unconnected drainage systems. This emergence records the development of the proto Río Almanzora on the south side of the Sierra Almagro as a prograding fan-delta and alluvial fan system. Expansion of this drainage network via incision and headward erosion across the Sierra Almagro took place during the Pleistocene. During the Early–?Mid-Pleistocene, the proto Río Almanzora became fully transverse across the Sierra Almagro and linked the endorheic Almanzora/Huercal-Overa basin with the Vera basin.

A tectonically induced lowering of regional base level is proposed for the incision, headward erosion and drainage network expansion that has resulted in the creation of the Río Almanzora as a transverse drainage. Differential uplift between the Huercal-Overa/Almanzora and Vera basins has resulted in southwards tilting and the creation of a regional gradient. The fluvial response to tilting was for incision into the steepened regional surface gradient via an increase in stream power.

The incision, headward erosion and drainage network expansion by the proto Río Almanzora and its creation as a transverse drainage appears to be part of a regional response by fluvial systems to differential uplift recorded throughout the Betic Cordillera of Southeast Spain during the Plio-Pleistocene.

Keywords: Transverse drainage; Pleistocene; Tectonics; Drainage evolution; Southeast Spain

1. Introduction

Within a geomorphological context, transverse drainages are rivers that cut across tectonically controlled geological structures such as faults, folds and orogenic mountain belts (Oberlander, 1985). They are frequently conspicuous within a landscape as they often occupy pronounced gorges or canyons that cut through prominent topographic barriers (e.g. Alvarez, 1999). Research into the origins and significance of transverse drainage has been prevalent in the geological and geomorphological literature since the late

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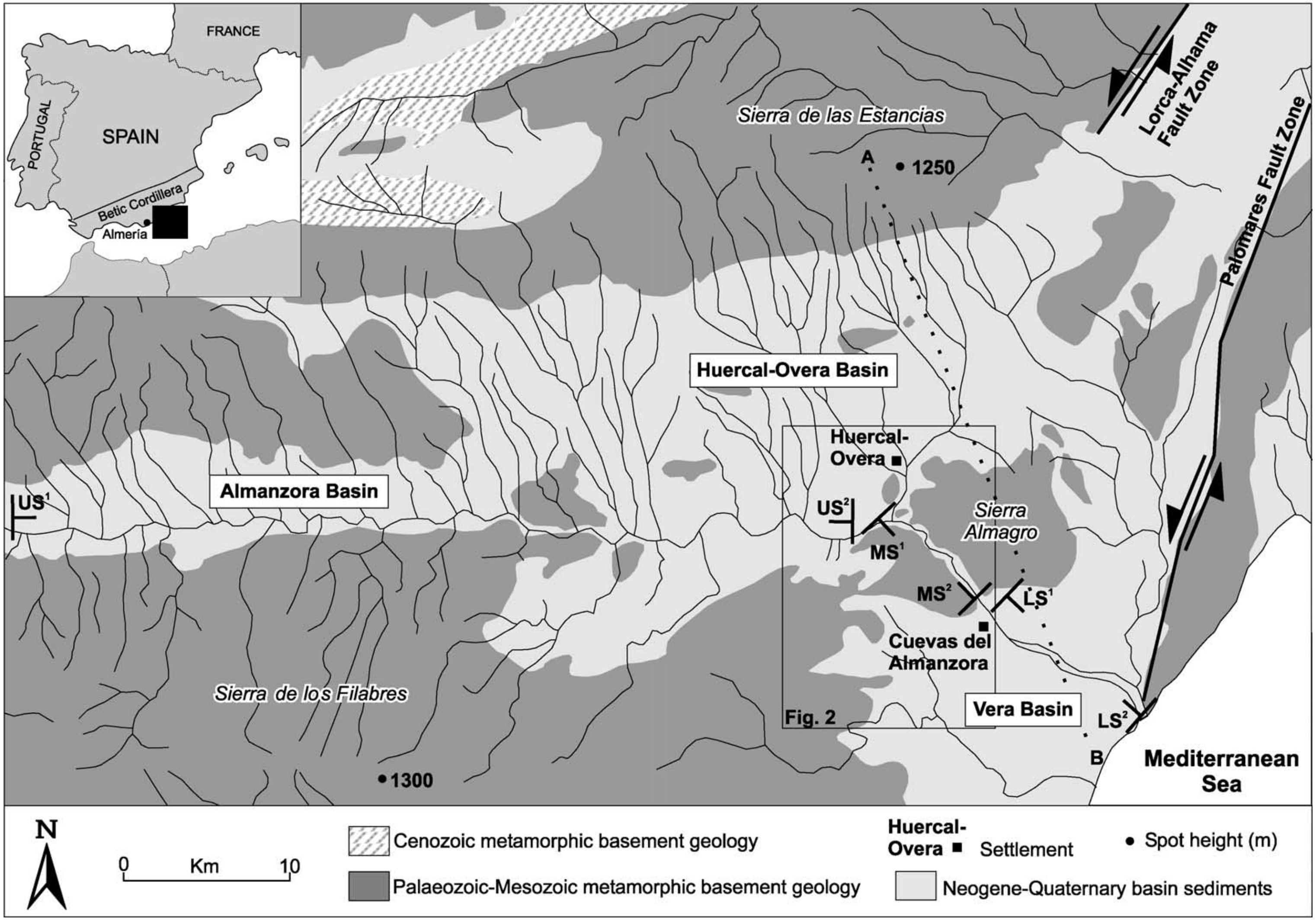


Fig. 1. General geological and geomorphological setting of the Río Almanzora within the Betic Cordillera, SE Spain. US$^{1-2}$ = upper sector; MS$^{1-2}$ = mid sector; LS$^{1-2}$ = lower sector. A–B = line of section in Fig. 9. Modified from IGME (1970a,b).

19th century following attempts in North America by Powell (1875) to explain down-cutting by the Colorado River and its tributaries into the uplifted Colorado Plateau. Since these early studies transverse drainage have been identified from most major mountain belt regions around the world (Oberlander, 1985; Harvey, 1987; Alvarez, 1999).

The creation of such discordant drainage is normally attributed to the following processes (see Oberlander, 1985; Summerfield, 1991 and references therein):

(1) antecedence—where a river exists prior to tectonic activity and incises into an uplifting surface as rates of incision keep pace with those of uplift,
(2) superposition—a river flowing over a young geological surface erodes the bedrock away and is lowered down onto an older more complex bedrock geology forming a drainage which is transverse to the structure,
(3) headward erosion and/or stream piracy—an actively incising and headward-eroding stream cuts back into and across an uplifted surface culminating in the beheading and re-routing of the drainage of a less active stream.

These mechanisms are themselves controlled by factors that are internal (e.g. geomorphic thresholds) or external (climatic change, eustacy, tectonism) to the fluvial system. Once established, transverse drainage often forms an important link between sedimentary and hydrological basins across structural highs; for example, connecting endorheic fluvial networks (internally drained) to create enlarged externally drained systems. Thus, knowledge of the origin and development of transverse drainage is essential to geomorphologists and geologists in order to enhance our understanding of the fluvial system, long-term landscape development and sedimentary basin evolution.

Within this paper, a contribution to understanding the creation and evolution of transverse drainage is made through analysis of the Río Almanzora, one of the larger drainage systems in southeast Spain (Fig. 1). In its distal reaches, prior to joining the Mediterranean Sea, the Río Almanzora cuts across a major topographic barrier, the Sierra Almagro, forming drainage that is transverse to the regional geological structure. A combination of the Late Miocene–Pleistocene sedimentary and geomorphological record is used to reconstruct the long-term drainage evolution. The evidence presented shows that the Río Almanzora links two previously isolated drainage systems, one endorheic, the second connected to the Mediterranean Sea. This linkage occurred during the Pleistocene, a feature which is common to landscape development within southeast Spain (e.g. Harvey, 1987; Silva et al., 1993; Mather, 1993a; Calvache and Viseras, 1997).

2. Transverse drainage within southeast Spain

The relief of southeast Spain is characterised by a series of low-lying Tertiary sedimentary basins bounded by uplifted blocks of Palaeozoic–Mesozoic basement (Fig. 1). This basin and range configuration typifies the Betic Cordillera; a major east–west orientated Alpine orogenic belt associated with the ongoing oblique collisional interactions between the African and Iberian plates (Sanz de Galdeano and Vera, 1992). Contemporary drainage routing within the Betic Cordillera tends to exploit the weaker sedimentary lithologies and follows the east–west synclinal axes of the small (ca. 40×40 km) fault controlled intermontane basins (e.g. Fig. 1). Despite these dominant trends, several examples of anomalous transverse drainages exist where streams abruptly change direction and cut across structurally controlled basement highs and mountain ranges of significant topographic relief (Harvey, 1987; Harvey and Wells, 1987).

Numerous studies have examined patterns of long-term drainage evolution within southeast Spain (Harvey, 1987; Harvey and Wells, 1987; Mather, 1991; Viseras, 1991; Viseras and Fernandez, 1992; Mather, 1993a,b; Harvey et al., 1995; Mather and Harvey, 1995; Wenzens and Wenzens, 1995; Calvache and Viseras, 1997; Stokes, 1997; Mather, 2000a,b; Stokes and Mather, 2000; Mather et al., 2000; Stokes et al., 2002). While the occurrence of transverse drainage has been noted within several of these studies (e.g. Harvey, 1987; Harvey and Wells, 1987; Harvey et al., 1995; Mather and Harvey, 1995), there has been little detailed work on the origins of such drainage.

3. Geological and geomorphological setting of the Río Almanzora

The modern Río Almanzora has a catchment area of ca. 2600 km^2 and is some 100 km in length. Its course can be sub-divided into three geographical sectors: Upper, Mid and Lower (Fig. 1).

(1) *Upper sector*—this runs for ca. 80 km from west to east along the axis of the Almanzora basin (Fig. 1) and into the western part of the Huercal-Overa basin. The headwaters and associated tributaries within this sector lie in the uplifted basement highs of the Sierra de las Estancias to the north and Sierra de los Filabres to the south (Fig. 1). These sierras are major topographic barriers reaching maximum altitudes of ca. 1250 and 1300 m, respectively (Fig. 1). The mountains are composed of Palaeozoic–Mesozoic age metamorphic rocks that correspond to the major Betic nappe units, which form the basement geology for the region (Egeler and Simon, 1969; Weijermars, 1991). The Sierra de las Estancias is composed of metacarbonates, schists, quartzites and phyllites that belong to the Alpujárride Complex (IGME, 1970a). The Sierra de los Filabres is composed of metacarbonates, schists and gneisses that belong to the Nevado-Filábride Complex (IGME, 1970a,b). The main channel of the Río Almanzora is incised into weakly cemented Miocene marls, sandstones and conglomerates (IGME, 1978). The channel is positioned along the southern margin of the Almanzora basin abutting the uplifted metamorphic basement block of the Sierra de los Filabres (Fig. 1), possibly exploiting a faulted basin margin contact.

(2) *Mid sector*—this is located between the southern margin of the Huercal-Overa basin and the northern margin of the Vera basin (Fig. 1). It encompasses an area where the Río Almanzora turns southeast and cuts a 7-km transverse route within a deeply dissected valley across an uplifted basement high, the Sierra Almagro (700 m maximum altitude), a smaller subrange at the eastern end of the Sierra de los Filabres (Fig. 1). The basement lithologies of the Sierra Almagro form part of the Palaeozoic–Mesozoic Alpujárride Complex (metacarbonates, quartzites, phyllites, metabasites and evaporites) (Bicker, 1966; van Balen and van Bees, 1988; IGME, 1978).

(3) *Lower sector*—this represents the final course of the Río Almanzora. Here, on emergence from the Sierra Almagro, the Río Almanzora continues over a short 13-km distance through the lowland plains of the Vera basin to the modern Mediterranean coastline (Fig. 1). At the drainage outlet on the southern side of the Sierra Almagro, the Río Almanzora is cut down into Pliocene fluvial–deltaic conglomerates (IGME, 1975; Stokes, 1997). Away from the mountain front, the Río Almanzora is incised into weakly lithified Late Miocene–Pliocene shallow marine marls and sandstones (Völk, 1967; IGME, 1973, 1975; Stokes, 1997). In coastal areas, the final course of the Río Almanzora crosses transverse to one of the major structural features of the region, a sinistral strike-slip fault termed the Palomares Fault Zone (Weijermars, 1987).

The modern Río Almanzora is ephemeral and lacks flowing water for much of the year. This lack of water reflects the semi-arid climate of the region that annually receives 210–500 mm of rainfall and a winter–summer temperature range of 5–30 °C (Völk, 1973; Esteban-Parra et al., 1998). The main channel and tributaries contain a coarse grained gravel–cobble bedload which becomes mobile only during low frequency and high magnitude storm events (e.g. Thornes, 1974). Steep channel gradients combined with high bedload content have resulted in the development of within-channel braiding. The main valley course in the mid sector is characterised by high sinuosity valley–meanders (sinuosity: ca. 1.6) and localised straight reaches.

4. Approach

In order to address the question of the transverse nature of the Río Almanzora across the Sierra Almagro, it is necessary to reconstruct its long-term drainage evolution. Previous detailed studies of long-term drainage evolution in the region by Mather (1991), Mather and Harvey (1995) and Stokes (1997) have demonstrated that the origins of the modern drainage network can be traced back into the Late Miocene. These studies have successfully reconstructed an evolving basin-scale drainage network using a combination of the geological and geomorphological evidence.

A similar approach is adopted within this study whereby three temporal stages of drainage evolution for the Río Almanzora have been identified

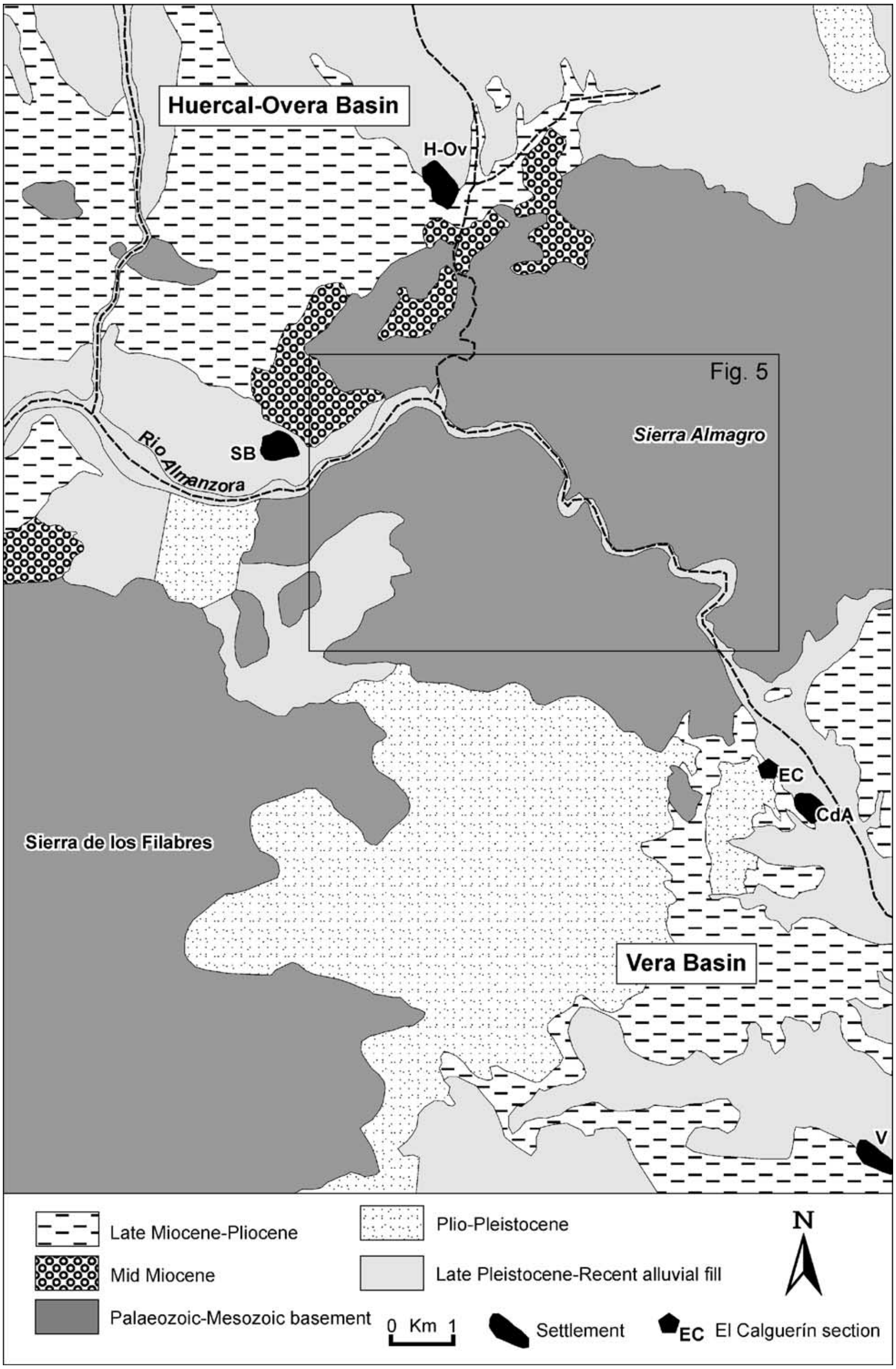


Fig. 2. Geological map of the transverse reach of the Río Almanzora across the Sierra Almagro and the sedimentary basins areas to the north and south (modified from IGME, 1973, 1978). SB = Santa Bábara; H-Ov = Huercal-Overa; CdA = Cuevas del Almanzora; V = Vera.

during: (1) the Late Miocene–Pliocene, (2) the Plio-Pleistocene and (3) the Pleistocene. These stages of drainage evolution are based upon key stratigraphic changes which record the final stages of sedimentary basin infilling from the Late Miocene through to the Early Pleistocene, followed by dissection of basins and mountain ranges during the Early to Late Pleistocene.

The study area for the reconstruction focuses upon the transverse reach of the Río Almanzora across the Sierra Almagro (the mid sector; Fig. 1), but also encompasses the sedimentary basin margin areas immediately to the north (Huercal-Overa and Almanzora basins) and south (Vera basin) of the Sierra Almagro (Fig. 1).

5. The Late Miocene–Pliocene

The Late Miocene–Pliocene stage of evolution can be reconstructed from sediments found within the mountain-front settings immediately to the south and north of the Sierra Almagro (Fig. 2).

5.1. Southern margin of the Sierra Almagro

The southern margin of the Sierra Almagro is characterised almost entirely by Pliocene sandstones and conglomerates up to 80 m in thickness that lie unconformably on metamorphic basement (Völk, 1967; IGME, 1973, 1975; Stokes, 1997). The lithologies and stratigraphic relationships are well exposed at a key locality called "El Caguerín" located ca. 1.5 km to the northwest of the town of Cuevas del Almanzora along the northern margin of the Vera basin (Fig. 2).

5.1.1. The Cuevas Formation

At El Calguerín, the lower 40 m of the stratigraphic succession is characterised by beige–yellow coloured sandstones with intercalations of gravel–pebble conglomerates that form part of Cuevas Formation (Fig. 3). The Cuevas Formation is an Early to Mid-Pliocene stratigraphic unit which has been dated biostratigraphically using micropalaeontology (Völk, 1967; Fortuin et al., 1995). Sedimentation is interpreted to have taken place within a near-shore shallow marine shelf/beach setting, based upon facies distributions and macro-fossil faunal content (Stokes, 1997). Table 1 summarises the key sedimentary characteristics of the Cuevas Formation.

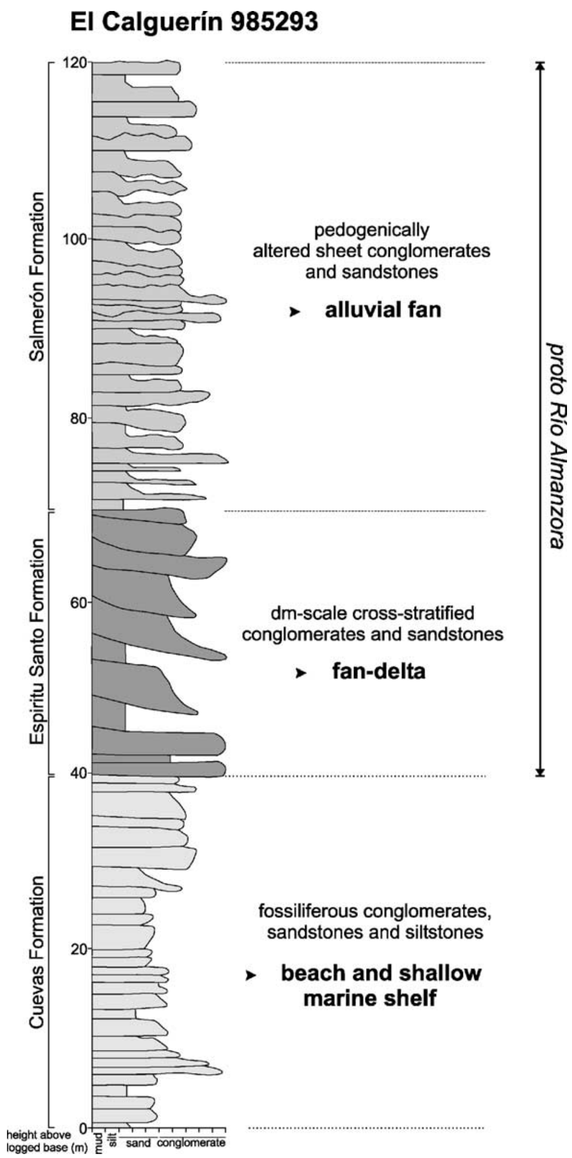
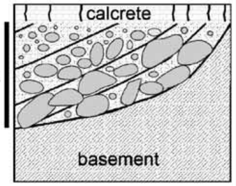
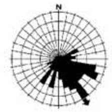
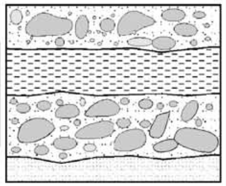
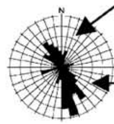
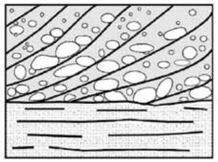
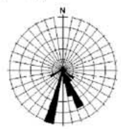


Fig. 3. Graphic sedimentary log from the El Calguerín section (grid reference 985293, Mapa Militar de España, 1992). The log (modified from Stokes, 1997) illustrates the marine to continental transition along the northern margin of the Vera basin, marked by the progradation of fan-delta and alluvial fan sediments. These sediments provide the first evidence for fluvial inputs from the proto Río Almanzora into the Vera basin. See Fig. 2 for the location of the El Calguerín section.

Table 1
Summary of key geological and geomorphological attributes for each of the stages of drainage evolution

		Sedimentary style	Sedimentary processes and environment	Provenance	Palaeocurrents	Type locality (Mapa Militar grid reference)
Pleistocene	Terrace record	- m-scale planar cross stratified gravel–boulder conglomerates with subordinate sandstones - Mean D_{max} = 0.575 m 3 m 	- point bar lateral accretion within a meandering river system	Alpujárride Complex =72%, Nevado-Filábride Complex = 28%	n =111 	Level 3* – 968328 (* representative type locality for all terrace levels - see Table 2 for individual level type localities)
Plio-Pleistocene	Salmerón Formation	- interbedded red coloured sheet conglomerates, sandstones and siltstones - Mean D_{max} = 0.11 m 3 m 	- pedogenically altered debris flow and sheetflood deposits within an alluvial fan setting	Alpujárride Complex = 100%	n = 125 	Northern margin: Santa Bárbara – 914337 Southern margin: El Calguerín – 985293
Late Mio-Pliocene	Espíritu Santo Formation	- dm-scale planar cross-stratified gravel–boulder conglomerates - Mean D_{max} = 0.69 m 40 m 	- sediment gravity flows within a Gilbert-type fan-delta	Alpujárride Complex = 100%	n = 13 	El Calguerín – 985293
	Cuevas Formation	- bedded beige–yellow sandstones	- near shore, shallow marine shelf and beach	N / A	N / A	El Calguerín – 985293

5.1.2. The Espíritu Santo Formation

A 30-m thick succession of conglomerates conformably overlies the Cuevas Formation sandstones at the El Calguerín section (Fig. 3). These sediments correspond to the Mid–Late Pliocene Espíritu Santo Formation (Völk, 1967; IGME, 1973, 1975). Typically, these conglomerates are texturally immature; comprising poorly sorted angular cobble–boulder sized clasts (mean $D_{max} = 0.69$ m) that consists of a mixture of mica-schist, phyllite, metacarbonate and metabasite lithologies (Table 1). The conglomerates are arranged into planar cross-stratified units (Fig. 4) that show a dominant sediment transport direction to the S to SW (Table 1). Individual foresets can reach up to 30 m in height and have an asymptotic relationship with underlying Cuevas Formation sandstone units (Fig. 4).

Stokes (1997) argues that the cross-stratified conglomerates have been deposited as a series of Gilbert-type fan-delta lobes that have built out via sediment gravity flows into a low energy marine environment. The textural immaturity of the conglomerates suggests a local sediment source that is transport limited. The south to southwesterly sediment transport direction implies material being shed from the nearby Sierra Almagro to the north. The mica-schist, phyllite, metacarbonate and metabasite clast provenance of the conglomerates are typical of the Alpujárride Complex that crops out within the Sierra Almagro (Bicker, 1966; van Balen and van Bees, 1988). Stokes (1997) has demonstrated that a single fan-delta body was present and that it was fed from a drainage outlet on the southern side of the Sierra Almagro positioned

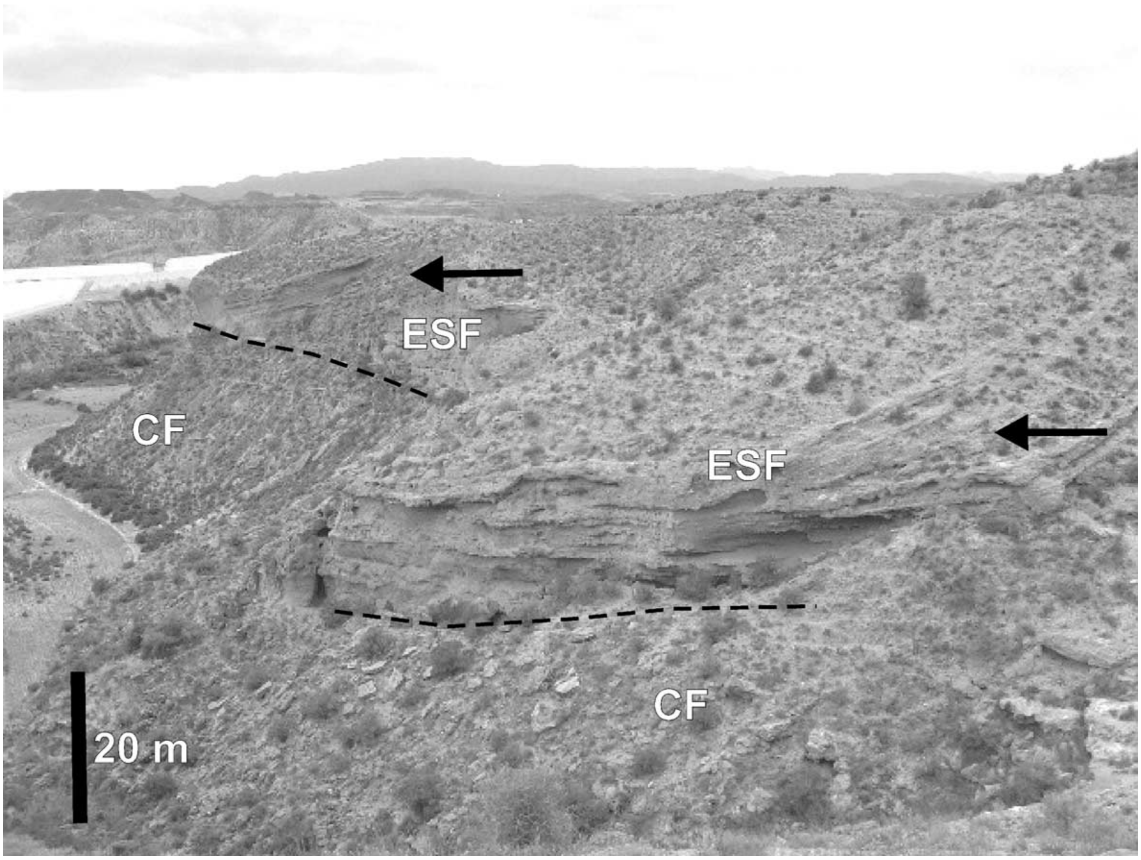


Fig. 4. View looking west to Pliocene Cuevas Formation (CF) and Espiritu Santo Formation (ESF) sediments exposed in the El Calguerín region (grid reference: 987284; Mapa Militar de España, 1992). Note the steeply dipping foresets (arrowed) that correspond to progradation of a Gilbert-type fan-delta. The foresets overlie lower angle bottomset beds that mark the transition between the Cuevas and Espirítu Santo Formations. Topset beds of the Salmerón Formation are not exposed at this locality.

Table 2
Summary of key geological and geomorphological attributes for each of the Pleistocene terrace/strath levels

		Terrace / Strath	**Fluvial / valley planform (Fig. 5)**	**Height range and incision (Fig 3)**	**Sedimentology and inferred channel planform**	**Provenance**	**Soils** (calcrete classification after Machette et al., 1985)	**Type locality** (Mapa Militar grid reference)
Early Pleistocene ↑ ↓ Late Pleistocene	**Level 1**	mainly straths some terraces - rare	- unknown planform pattern - mean gradient = 0.02	325–275 m	**Description** - gravel–boulder conglomerates - sub-angular to sub rounded clasts - D_{max} = 0.6 m - poor to moderate sorting - lack notable structures (i.e. cross stratification) -southeasterly palaeocurrent **Process Interpretation** - unknown fluvial barforms	Nevado-Filábride Complex = 45% Alpujárride Complex = 55%	N/A	971321
	Level 2	terrace - common	- degraded meandering - estimated sinuosity = 1.8 - mean gradient = 0.016	295–200 m - incised by 75 m below Level 1	**Description** - gravel-boulder conglomerates - sub-angular to rounded clasts - - poor to moderate sorting - 3 m high lateral accretion surfaces Level 2 D_{max} = 0.7 m Level 3 D_{max} = 0.5 m Level 4 D_{max} = 0.5 m southeasterly palaeocurrent **Interpretation** - lateral accretion by bank attached barforms within a meandering valley	Nevado-Filábride Complex = 23% Alpujárride Complex = 77%	N/A	944344
	Level 3	terrace - common	- degraded meandering - mean gradient = 0.013	245–175 m - incised by 50 m below Level 2		Nevado-Filábride Complex = 31% Alpujárride Complex = 69%	- B horizon stripped - laminar calcrete stage 4-5	968328
	Level 4	terrace - widespread	- well-developed meandering - estimated sinuosity = 2.7 to 4.2 - mean gradient = 0.006	185–125 m - incised by 45 m below Level 3		Nevado-Filábride Complex = 12% Alpujárride Complex = 88%	-B-horizon 7.5 year 5/6 bright brown - nodular / laminar calcrete stage 2-3	974313

approximately at the same outlet point as the modern Río Almanzora.

5.2. Northern margin of the Sierra Almagro

The northern margin of the Sierra Almagro comprises Late Miocene and Pliocene sediments that unconformably overlie metamorphic basement and Mid-Miocene (Serravalian) continental conglomerates (IGME, 1978; Briend et al., 1990; Mora-Gluckstadt, 1993). Away from the Sierra Almagro mountain front in more central basin areas to the north are Late Miocene–Early Pliocene beige–yellow sandstones and grey marls of marine origin (IGME, 1978; Briend et al., 1990; Mora-Gluckstadt, 1993). There is no evidence for any Mid–Late Pliocene (Espíritu Santo Formation equivalent) sediments to the north of the Sierra Almagro in the Almanzora/Huercal-Overa basin.

The Mid-Miocene (Serravalian) continental conglomerates are interpreted to be of alluvial origin (Mora-Gluckstadt, 1993) and represent continental drainage development prior to the temporal scope of this study and appear to have no direct palaeogeographic relationship to the modern Río Almanzora and its ancestral form. The Late Miocene–Early Pliocene sandstones and marls are of more relevance to this study. Recent studies suggest that the sandstones represent deposition within near-shore shallow marine/beach conditions while the marls correspond to deeper water offshore areas (Briend et al., 1990; Mora-Gluckstadt, 1993). The absence of Mid–Late Pliocene (Espirtu Santo Formation equivalent) sediments along the northern side of the Sierra Almagro may suggest that the Almanzora/Huercal-Overa basin was an emergent continental basin dominated by erosion at that time.

5.3. Synthesis

The Late Miocene–Pliocene sediments exposed along the southern and northern margins of the Sierra Almagro (Fig. 2) suggest the presence of an emergent topographic relief during late Miocene–Pliocene times. The Early–Mid Pliocene Cuevas Formation sandstones to the south and Late Miocene–Early Pliocene sandstones and marls to the north demonstrate the existence of near-shore shallow marine shelf/beach environment around the margins of the Sierra Almagro. Most importantly, these sediments *do not* show any evidence for fluvial sediment inputs into the shoreline areas.

It is not until the Mid–Late Pliocene Espíritu Santo Formation times that the first evidence for fluvial inputs into shallow marine shoreline areas are recorded. These fluvial inputs occur only along the southern side of the Sierra Almagro in the Vera basin where the cross-stratified boulder conglomerates of the Espíritu Santo Formation indicate southwards progradation of a small (area = ca. 1.7 km^2) Gilbert-type fan-delta body over Early–Mid Pliocene shallow marine shelf sediments of the Cuevas Formation. The positioning of the fan-delta body adjacent to the modern drainage outlet that suggests that the stream feeding the fan-delta may have been a precursor to the modern Río Almanzora. However, it is not clear whether the fan-delta feeder stream was transverse across the entire Sierra Almagro range at this point in time. Indeed, a transverse drainage linking the Vera and Huercal-Overa/Almanzora basins is unlikely due to the following reasoning based upon the previously outlined sedimentary characteristics:

(1) There is no evidence for fluvial routing from the Almanzora/Huercal-Overa basin southwards into and across the Sierra Almagro during Espíritu Santo Formation times.
(2) The provenance of the Espíritu Santo Formation fan-delta sediments (Table 2) is exclusively of locally derived Aplujarride Complex lithologies. A transverse drainage with a catchment area *beyond* the Sierra Almagro would be expected to supply some extrabasinal sediment (e.g. Nevado-Filábride Complex basement material from the west and reworked Mid-Miocene clasts) to the fan-delta.
(3) The textural immaturity of the Espíritu Santo Formation fan-delta sediments (Table 2) suggests a *localised* sediment source from a small, steep catchment area. A transverse drainage would have a much larger catchment area and therefore would supply sediment with a greater textural maturity due to the greater transportation distance of sediment.
(4) The small size of the fan-delta body (delta lobes covering ca. 1.7 km^2: Fig. 2) suggests the presence

of a small catchment area feeding the fan-delta. A transverse drainage with a larger catchment area would supply larger amounts of sediment and would therefore be expected to build a bigger fan-delta.

6. The Plio-Pleistocene drainage record

The Plio-Pleistocene drainage record is documented within sediments of the Salmerón Formation. These sediments are located along the northern and southern margins of the Sierra Almagro (Völk, 1967; IGME, 1975, 1978; Stokes, 1997: Fig. 2) where they are characterised by an interbedded succession of red and grey coloured conglomerates, sandstones, siltstones and evaporites up to 60 m in thickness. Dating of the Salmerón Formation is difficult due to a lack of datable material, although (Wenzens, 1992a) has used an electron spin resonance (ESR) technique on shallow marine and travertine carbonates in the Vera basin to date the lower and upper boundaries at 2.3 and 1.6 Ma, respectively.

6.1. The southern margin of the Sierra Almagro

Along the southern margin of the Sierra Almagro, the Salmerón Formation comprises an extensive interbedded succession of conglomerates with subordinate sandstones, siltstones and evaporitic deposits. In mountain-front areas, the Salmerón Formation lies unconformably on metamorphic basement of the Alpujárride Complex. Away from the Sierra Almagro mountain front, the Salmerón Formation forms either a conformable contact or slight angular unconformity with the underlying Espíritu Santo Formation. This relationship is demonstrated within the El Calguerín section (Fig. 3). Here, the conglomerates are texturally immature (mean $D_{max} = 0.11$ m) and have sheetform geometries (Table 1). Palaeocurrents are radial but dominantly towards the south (Table 1). Clast provenance is characterised by mica-schist, phyllite, metacarbonate and metabasite lithologies (Table 1).

Stokes (1997) has interpreted the Salmerón Formation along the southern margin of the Sierra Almagro to represent deposition by sheetflood and debris-flow processes within a series of alluvial fan bodies that terminated in an evaporitic playa lake. Remnants of dissected alluvial fan morphologies (ca. 5 km^2) can be identified from aerial photograph analysis of the area (Stokes, 1997; Mather et al., 2000). Clast provenance together with southerly palaeocurrent directions suggests a local Alpujárride Complex sediment source with transport towards the centre of the Vera basin away from the Sierra Almagro mountain front.

According to Stokes (1997), the Salmerón Formation represents the initiation of a consequent drainage network, developed onto the topography created by the underlying shallow marine and fan-delta sediments of the Cuevas and Espíritu Santo Formations in the Vera basin. Within the El Calguerín region, the conformable stratigraphic transition between the Espíritu and Salmerón Formations is significant because it demonstrates a progressive change in sedimentary style from fan-delta (Espíritu Santo Formation) to alluvial fan (Salmerón Formation). This progressive change supports the fact that a drainage outlet from the Sierra Almagro was probably maintained throughout the Mid to Late Pliocene and into the Pleistocene feeding both fan-delta (Espíritu Santo Formation) and alluvial fan bodies (Salmerón Formation).

6.2. The northern margin of the Sierra Almagro

The occurrence of Salmerón Formation sediments on the northern side of the Sierra Almagro is limited. Interbedded red coloured conglomerates and sandstones with sheetform geometries (width/depth ratio >15:1) are exposed within an abandoned road cutting adjacent to the Almería-Murcia motorway near to the village of Santa Bárbara (Fig. 2: grid reference = 914337; Mapa Militar de España, 1974). The conglomerates are texturally immature and are characterised by palaeocurrents to the NW and a clast provenance dominated by metacarbonate with subordinate amounts of mica-schist and phyllite (Table 1).

Stokes (1997) has interpreted these sediments to have been deposited by debris-flow and sheetflood processes within an alluvial fan environment. The palaeocurents to the NW suggest sediment transport away from the Sierra Almagro mountain front into the Almanzora/Huercal-Overa basins. The dominance of metacarbonate clasts suggests a local sediment source derived from the Alpujárride Complex within the Sierra Almagro.

6.3. Synthesis

The alluvial style of sedimentation depicted by the Salmerón Formation records the onset of full continental conditions in the basins to the north and south of the Sierra Almagro for the period of the Plio-Pleistocene. During this time, alluvial fans developed in mountain-front areas where texturally immature sediment from debris-flow and sheetflood processes were locally derived from catchment areas developed in the Sierra Almagro as demonstrated by the Alpujárride Complex clast provenance of the alluvial fan sediments (Table 1). Palaeocurrents suggest sediment transport away from the Sierra Almagro to the north and south into the Huercal-Overa/Almanzora and Vera basins, respectively (Table 1). These data imply that a transverse drainage across the Sierra Almagro, linking the Huercal-Overa/Almanzora and Vera basins was not yet present.

Wenzens and Wenzens (1995), together with Garcia-Melendez et al. (this volume) have reported Salmerón Formation sediments within the northern and southeastern regions of the Huercal-Overa basin. The sediments are thought to represent a mixture of braided river and fluvial fan type processes (Garcia-Melendez et al., this volume). The sedimentary style, together with palaeocurrent and clast provenance data indicate that an endorheic drainage was routed towards the eastern margins of the Huercal-Overa basin during Salmerón Formation times (Wenzens and Wenzens, 1995; Garcia-Melendez et al., this volume).

Along the southern side of the Sierra Almagro, the Salmerón Formation alluvial fan sediments within the El Calguerín section are important because they form the topset beds to the underlying Espíritu Santo Formation Gilbert-type fan-delta (Fig. 3). These alluvial fan sediments demonstrate that a drainage outlet was being maintained during the Plio-Pleistocene. The stream feeding the alluvial fan in the El Calguerín region probably corresponded to a precursor of the Río Almanzora but one that was not yet transverse.

7. The Pleistocene drainage record

The Pleistocene drainage record is documented by a series of inset river terrace and erosional strath landforms that are cut into metamorphic basement. These landforms can be traced across the Sierra Almagro and can be correlated with comparable Pleistocene landforms within the Vera and Almanzora/Huercal-Overa basins (Völk, 1979; Wenzens, 1991, 1992a,b; Wenzens and Wenzens, 1995; Stokes, 1997). Dating using electron spin resonance (Wenzens, 1992a), together with a disconformable (basin centre) and inset (basin margin) stratigraphic position in relation to the Salmerón Formation within the Vera basin (Stokes, 1997; Stokes and Mather, 2000) suggests that the terrace record across the Sierra Almagro is younger than 1.6 Ma.

Recent low water levels within the dammed Río Almanzora valley across the Sierra Almagro have enabled access to previously submerged or inaccessible landforms. This has allowed mapping and sedimentary analyses of the Pleistocene landforms to be undertaken. A fluvial terrace and erosional strath sequence of four levels has been identified across the transverse reach of the Sierra Almagro (Fig. 5). The precise dating of such Pleistocene landforms in southeast Spain is often difficult due to a lack of datable material or the landforms being beyond the maximum age limit of most suitable dating techniques. Sequences are therefore correlated and assigned to a relative stratigraphic framework on the basis of landform altitude and the degree of soil development (e.g. Harvey and Wells, 1987; Harvey et al., 1995, 1999).

A down-valley long profile (Fig. 6) illustrates the correlation of the landforms within the transverse reach across the Sierra Almagro. Level 1 is the highest and oldest unit, while Level 4 is the lowest and youngest. Table 1 summarises the morphological, sedimentary and soil characteristics of each of the landform levels. Fig. 7 shows a panoramic view of the landforms within the transverse reach across the Sierra Almagro. Key similarities and differences between these characteristics are highlighted below in order to establish the sedimentary processes operative and drainage routing during the Pleistocene.

7.1. Landform sequence

Level 1 is the least well preserved part of the landform sequence (Figs. 5 and 6 and Table 2). It is composed primarily of straths and very rare terraces that are developed onto metamorphic basement. Lev-

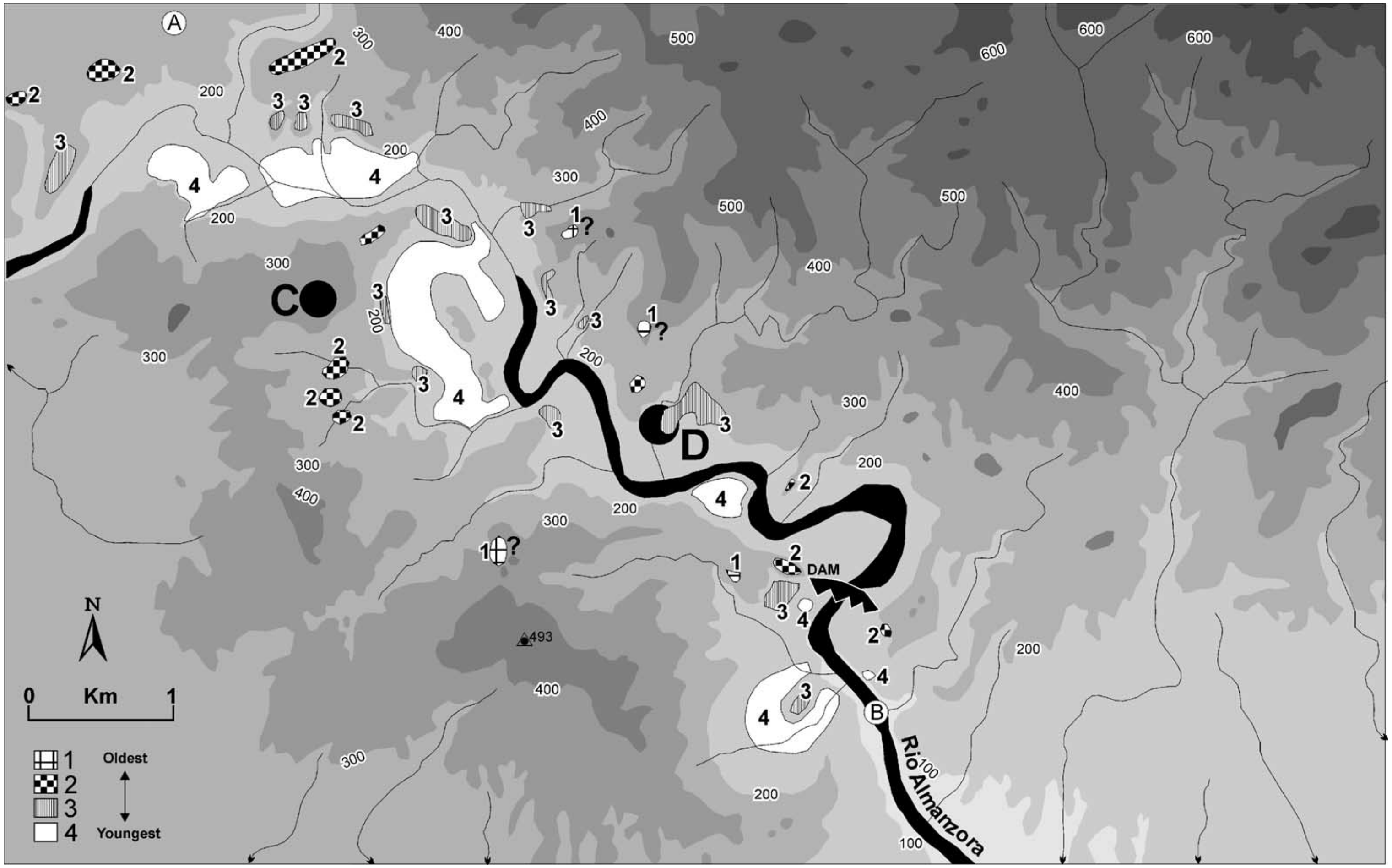


Fig. 5. Distribution of Pleistocene terrace/strath landforms within the transverse valley of the Río Almanzora. (A–B) denotes the start/end points of Fig. 6. Points (C) and (D) are the locations of Figs. 7 and 8, respectively.

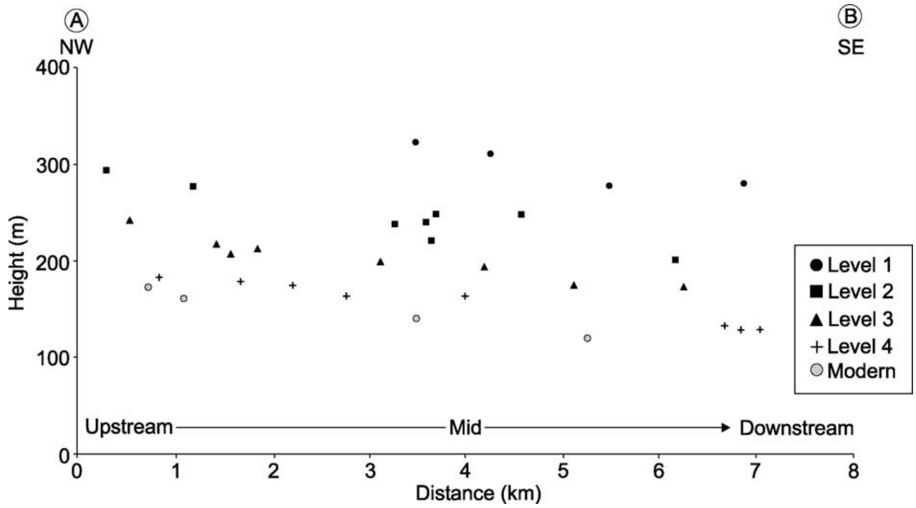


Fig. 6. Down-valley long profiles of Pleistocene terrace/strath landforms and the modern Río Almanzora. The profiles are taken from within the transverse reach illustrated in Fig. 5 (Sections A–B). Downvalley distance is measured along the modern valley.

els 2, 3 and 4 are preserved mainly as terraces. Each of these levels is incised by between 45 and 75 m below the base of the previous terrace (Fig. 6 and Table 2). Level 4 is the most commonly preserved part of the landform sequence (Figs. 5 and 6). Within the northwestern region of the transverse valley (Figs. 3 and 6), Levels 2–4 are inset into low-lying hills of Mid-Miocene (Serravalian) sediments that separate the Sierra Almagro from the main lowland area of the Huercal-Overa basin.

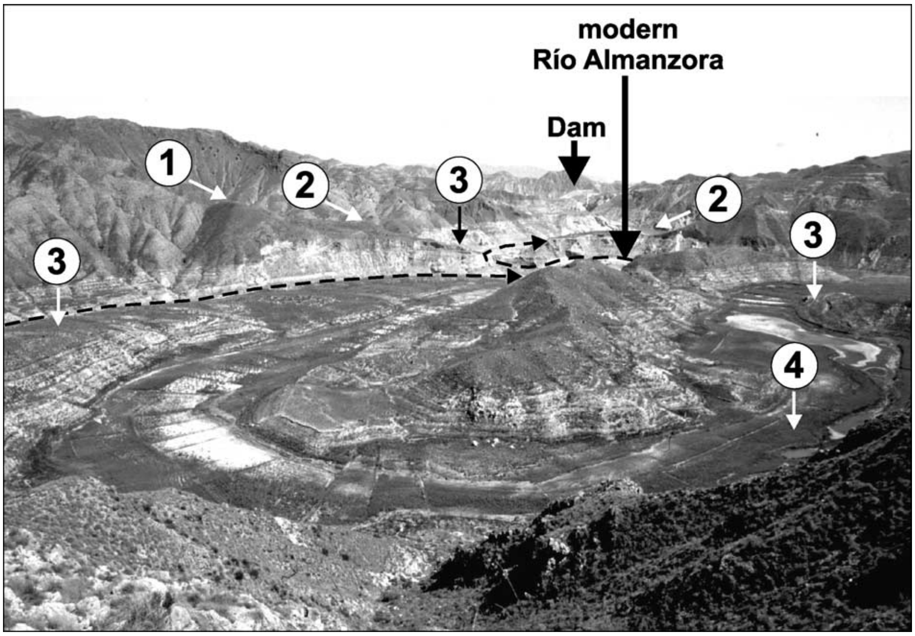


Fig. 7. Panoramic overview of the transverse valley looking southeast across the Sierra Almagro. Numbers 1 to 4 illustrate key elements of the Pleistocene terrace/strath landform sequence. Note the presence of the spectacular Level 4 meander loop. See Fig. 5 for photo location.

Mapping the landform sequence reveals a clustering of terrace fragments within Level 2 in central areas of the transverse valley adjacent to the abandoned village of Los Orives (Fig. 5). Within Level 4, the terrace configuration is more continuous and reveals a series of extensive sinuous patterns in central and southeastern areas of the transverse valley (Fig. 5). The Level 2 clustering pattern is interpreted as a degraded abandoned meander loop with an estimated sinuosity of 1.8 (Table 2). The more continuous sinuous terrace patterns observed in Level 4 are also abandoned meander loops with sinuosities of between 2.7 and 4.2 (Table 2).

7.2. Terrace sediments and soils

The Level 1 terrace sediments are characterised by textually immature gravel–boulder conglomerates that are quite massive and lack any degree of organisation (Table 2). Levels 2, 3 and 4 are characterised by large-scale (up to 3 m high) cross-stratified gravel–boulder conglomerates (Fig. 8). Clasts greater than 0.5 m in diameter are common (D_{max} = 0.5 to 0.75 m), many of which are well rounded and show clear imbrication. Cross-stratification often builds out from channel-like erosive surfaces cut into metamorphic basement (Fig. 8). Clast imbrication is typically oblique to the cross-stratification and reveals a dominant transport direction towards the south (Table 2). Clast provenance is typically characterised by a variety of metamorphic bedrock lithologies including quartzites, phyllites, metacarbonates and metabasites (56–88%: Table 2), together with amphibole mica-schists and tourmaline gneisses (12–44%: Table 2). The upper surfaces of the Level 1 and 2 terraces lack any preserved soil. Laminar and nodular calcrete development is however observed in Levels 3 and 4 (Table 2), overlain on Level 4 by a brown B-horizon (Table 2).

The terrace sediments are interpreted to be of fluvial origin based upon on their observed textural features and sedimentary structures. The coarse-grained nature and poor-moderate sorting of these sediments suggests transport as bedload with a high sediment to water ratio within a high-energy fluvial system. The cross-stratification is interpreted as lateral accretion from bank-attached bar forms. The previously described high sinuosity planform pattern (Section 7.1) implies that the terrace sediments probably represent lateral accretion by a bank-attached bar within a meandering valley.

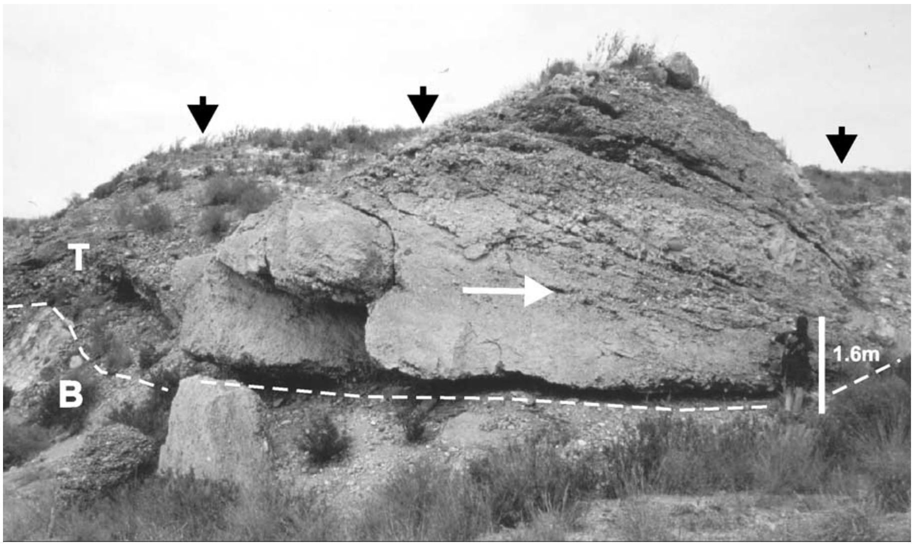


Fig. 8. Typical Pleistocene terrace sedimentology characterised by ca. 3-m high cross-stratified boulder conglomerates (T). These sediments infill an erosive channel form (dashed line) cut into metaamorphic basement (B). The sediments represent a bank attached bar form that has built out via lateral accretion (white arrow). Palaeoflow comes out of the photo obliquely from left to right. Black arrows mark flat upper surface of the river terrace. This example is taken from an exposure of the Level 3 terrace (grid reference 968328: Mapa Militar de España, 1974).

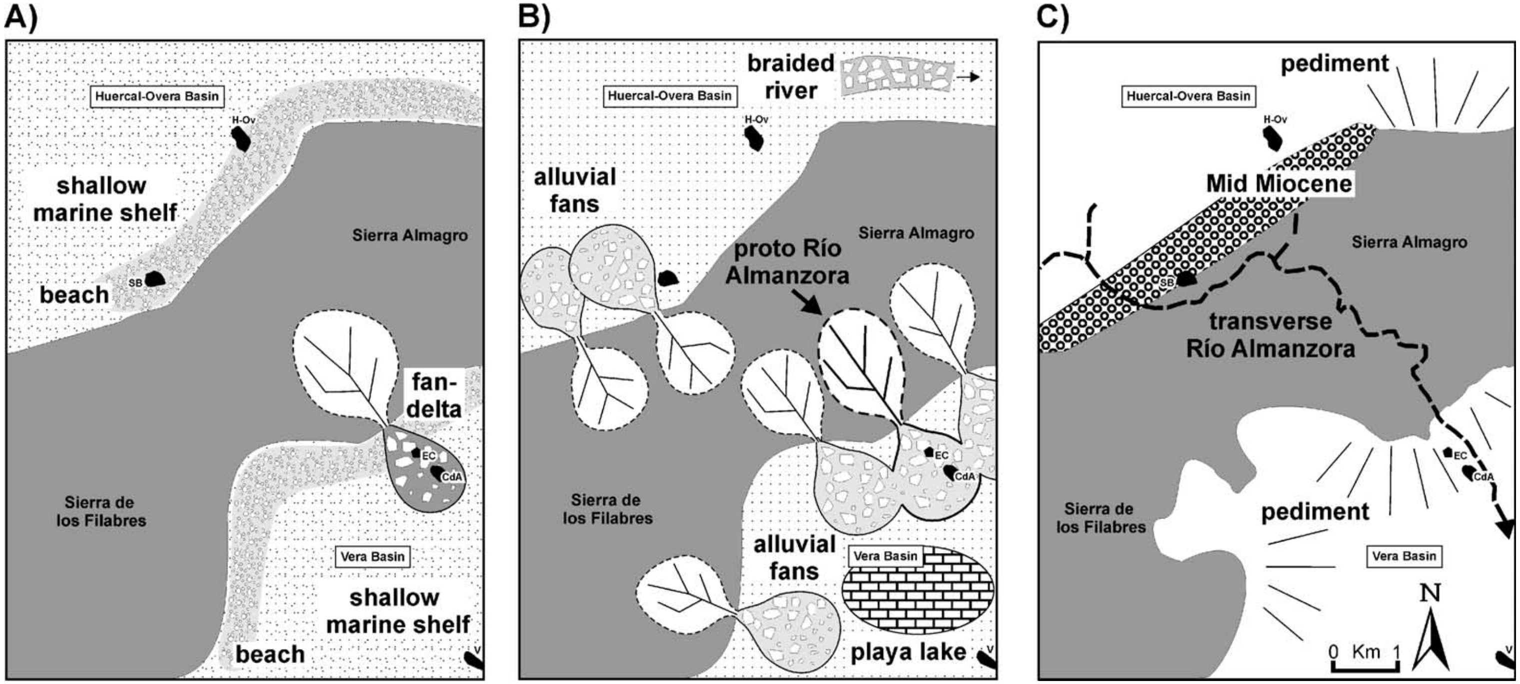


Fig. 9. Palaeogeographic reconstructions for each of the stages of drainage development: (A) Late Miocene–Pliocene, (B) Plio-Pleistocene and (C) Pleistocene. See text for full explanation. Note the inclusion of the Mid-Miocene (Serravalian) outcrop in order to demonstrate how an expanding drainage system would rework Nevado-Filábride Complex-rich sediments into the Pleistocene terrace sediments once the Río Almanzora became fully transverse. Maps compiled from data presented within this paper together with the studies of Briend et al. (1990), Mora-Gluckstadt (1993), Wenzens and Wenzens (1995), Stokes (1997), Garcia-Melendez et al. (this volume).

Clast provenance indicates two possible sediment sources: (1) Alpujárride Complex (quartzites, phyllites, metacarbonates and metabasites), and (2) Nevado-Filábride Complex (amphibole mica-schist and tourmaline gneiss). The Alpujárride Complex material dominates the provenance signatures for all of the terrace levels (56–88%: Table 2) and is most likely to be locally derived via hillslopes in the Sierra Almagro. In contrast, the Nevado-Filábride Complex material is less common within the terrace sediments (12–45%: Table 2). Its presence is interesting since the Nevado-Filábride Complex is absent from the Sierra Almagro. The nearest occurrence is several tens of kilometres to the west in the Sierra de los Filabres (IGME, 1970a,b). An alternative probable source could be via reworking of Mid-Miocene (Serravalian) sediments along the northern margin of the Sierra Almagro that is dominated by Nevado-Filábride Complex material (Mora-Gluckstadt, 1993).

7.3. Synthesis

The Pleistocene landform sequence across the Sierra Almagro provides the first evidence for the existence of a southwards flowing drainage linking the Almanzora/Huercal-Overa basins with the Vera basin. These landforms provide the first clear evidence for the occurrence of a transverse drainage that closely corresponds to an ancestral Río Almanzora. Levels 2–4 record the progressive incision by the transverse drainage across the Sierra Almagro (Figs. 6 and 7). The planform distribution (Fig. 5) and sedimentology (Fig. 8 and Table 2) of these levels record a meandering valley pattern that was cut and filled via lateral accretion within a high-energy fluvial system. The presence of Alpujárride and Nevado-Filábride Complex material within the terrace sediments (Table 2) suggests local sediment derivation from (1) the Sierra Almagro and (2) from reworking of Mid-Miocene (Serravalian) sediments along the northern side of the Sierra Almagro. The latter is of particular importance as this is the first indication of material being derived from the sedimentary basins to the north of the Sierra Almagro. Indeed, the spatial occurrence of Levels 2–4 along the northern side of the Sierra Almagro suggests drainage routing primarily from the southwestern part of the Huercal-Overa basin and the Almanzora basin.

8. Long-term drainage evolution (palaeogeographic model)

Table 1 outlines the key geological and geomorphological attributes for each of the previously described stages of drainage evolution. On the basis of these data, a series of palaeogeographic reconstructions have been made that trace the long-term drainage evolution of the Río Almanzora (Fig. 9).

8.1. Late Miocene–Pliocene

- Shallow marine shelf conditions in the basins to the north and south of the Sierra Almagro during Cuevas Formation times (Late Miocene–Early Pliocene).
- Southwards progradation of a Gilbert-type fan-delta into the Vera basin during Espíritu Santo Formation time (Mid–Late Pliocene). The fan-delta was supplied with coarse-grained, texturally immature, Alpujárride Complex material from a drainage outlet on the southern side of the Sierra Almagro.

8.2. Plio-Pleistocene

- Emergence and establishment of continental conditions within the basins to the north and south of the Sierra Almagro during Salmerón Formation time (Late Pliocene–Early Pleistocene). The Almanzora and Huercal-Overa basins appear to be endorheic.
- Coalescent, mountain-front alluvial fans are supplied with coarse grained, texturally immature Alpujárride Complex material from the Sierra Almagro.
- Maintenance of a drainage outlet on the south side of the Sierra Almagro feeding an alluvial fan body in the El Calguerín region of the Vera basin.

8.3. Pleistocene

- Connection of the basins to the north and south of the Sierra Almagro via the establishment of a high energy, meandering drainage system across the Sierra Almagro during the Early–?Mid-Pleistocene.

- The appearance of Nevado-Filábride Complex material within the terrace sediments suggests the reworking of mid Miocene sediment from the southern western part of the Huercal-Overa basin and expansion westwards into the Almanzora basin.

These palaeogeographic reconstructions show that a transverse drainage was not fully created until the final stage of drainage evolution during the Pleistocene. The earlier stages of drainage evolution reveal unconnected marine basins (Late Miocene–Pliocene) that switched to continental conditions (Plio-Pleistocene). The critical evidence for the existence of a proto Río Almanzora prior to its creation as a transverse drainage is recorded within the Vera basin. Here, the switch from marine to continental conditions records the initiation (fan-delta) and maintenance (alluvial fan) of a drainage outlet on the south side of the Sierra Almagro in the El Calguerín region. To the north of the Sierra Almagro, the switch from marine to continental conditions within the Huercal-Overa/Almanzora basins simply reveals Plio-Pleistocene drainage routing northwards and eastwards away from the Sierra Almagro mountain front. That drainage appears to lack any connection to the south with the Vera basin and therefore has no direct relationship to the proto Río Almanzora on the south side of the Sierra Almagro.

9. Controlling factors for the creation of transverse drainage

Having reconstructed the long-term drainage evolution of the Río Almanzora, the factors which have resulted in its creation as a transverse drainage can now be considered. Typically, transverse drainage can be formed by the following mechanisms: (1) antecedence; (2) superposition or (3) headward erosion.

9.1. Antecedence

The creation of a transverse drainage via antecedence involves surface uplift and requires fluvial incision to keep pace with uplift. Tectonic activity in the form of differential surface uplift has taken place within the study area since the Late Miocene. However, for antecedence to work a fluvial connection between the Huercal-Overa/Almanzora and Vera basins would need to have been present from the Late Miocene onwards. This is not the case since the basins did not become connected across the Sierra Almagro until the final stage of drainage evolution during the Pleistocene. Antecedence is therefore an unlikely mechanism for the creation of the Río Almanzora as a transverse drainage.

9.2. Superposition

The creation of a transverse drainage via superposition requires a river that is flowing over a young geological surface to erode onto an older, more structurally complex bedrock geology. This mechanism would require the structurally complex metamorphic basement of the Sierra Almagro to be overlain by at least a thin sedimentary cover of Late Miocene–Pliocene age. A southwards flowing drainage would then need to remove this sedimentary cover and to superpose itself onto and across the metamorphic basement of the Sierra Almagro. Superposition is deemed unlikely in this case due to:

(1) There is no evidence for any remnants of Late Miocene–Pliocene sediments within the transverse reach of the Río Almanzora or across the modern Sierra Almagro. It is therefore unlikely that the Sierra Almagro was buried by Late Miocene–Pliocene sediments.
(2) Reconstruction of shoreline zones around the margins of the Sierra Almagro during the Late Miocene–Pliocene stage suggests that the Sierra Almagro was present as an emergent topographic relief and that the basins to north and south were unconnected and formed separate depocentres. Indeed, Neogene palaeogeographic reconstructions of the study area all suggest that the Sierra Almagro has existed as an emergent topographic relief since the Mid-Miocene (Völk, 1967; Alvado, 1986; Briend et al., 1990; Guerra-Merchán and Serrano, 1993; Mora-Gluckstadt, 1993).

Superposition is however a mechanism that has been invoked for other transverse drainages in the region (e.g. the Aguas–Feos system of the Sorbas basin: Harvey and Wells, 1987; Harvey et al., 1995; Mather and Harvey, 1995).

9.3. Headward erosion

The creation of a transverse drainage via headward erosion requires an actively incising and headward-eroding stream to cut back into and across an uplifted surface. The occurrence of fan-delta and alluvial fan sediments on the south side of the Sierra Almagro supports the presence and maintenance of a drainage outlet during the Late Miocene–Pliocene and Plio-Pleistocene stages of drainage evolution. The textural immaturity and clast provenance of these sediments suggest a localised source from the Sierra Almagro. Headward erosion by the drainage outlet feeding the fan-delta and alluvial fan would create a transverse drainage that connected the basins north and south of the Sierra Almagro. The connection probably took place at some point between the Plio-Pleistocene and Pleistocene stages of drainage evolution (Early–?Mid-Pleistocene). The occurrence and changes in Nevado-Filábride clast provenance of the transverse drainage fluvial sediments (Table 1) provide some critical evidence for an ongoing expansion of the drainage network during the Pleistocene. There is no clear evidence from the landform sequence for stream piracy and re-routing of the Pleistocene Huercal-Overa/Almanzora basin drainage once the Río Almanzora became transverse. However, there are reports of Late Pleistocene capture of drainage from the south/southeast of the Huercal-Overa basin (Wenzens and Wenzens, 1995).

10. Controls of headward erosion

The long-term drainage evolution of the Río Almanzora and its creation as a transverse drainage has taken place over a time scale of some 5 Ma. The catchment area of the modern Río Almanzora is ca. 2600 km^2 and for the proto Río Almanzora would have been considerably smaller. At these spatial scales, the influence of climatic change typically operates over temporal scales of $<10^4$ years (Blum and Tornquist, 2000). While climatic change has been used to explain episodic changes in fluvial system behaviour within the Quaternary of southeast Spain (e.g. Harvey, 1987) the longer term sustained regional patterns of incision can thus clearly be attributed to tectonics (e.g. Mather and Harvey, 1995) and associated relative base-level changes. Superimposed on this are the impacts of eustatic changes in sea level. The discussion below will consider the consequences of (a) eustatic sea-level lowering versus (b) regional tectonics for long-term drainage evolution of the Río Almanzora.

10.1. Sea-level change

Sea level acts as the lower limit within a terrestrial landscape and represents a base level below which rivers cannot erode. Typically, fluvial systems will respond to sea-level lowering by incision (Leopold and Bull, 1979; Schumm, 1993; Harvey et al., 1999). Thus, a lowering of sea level could contribute to the development of the Río Almanzora as a transverse drainage, since its base level is the Mediterranean Sea. Within the study area, sea-level fluctuations have been recorded in relation to Pleistocene cyclic global climate cooling/warming episodes (Shackleton, 1987). With the onset of global cooling since the Pliocene, global sea level has fluctuated in a cyclical manner but has shown an overall-lowering trend of some 50 m (e.g. Haq et al., 1987). This progressive lowering could account in part for headward erosion and network expansion during development of the Río Almanzora as it responded to a progressive base-level lowering. However, the amount of incision recorded by the transverse Río Almanzora (typically >100 m) is far in excess of that which could be accommodated by the eustatic sea-level fluctuations.

10.2. Regional tectonic activity

Active tectonics, via differential uplift and subsidence, can stimulate incision within fluvial systems by steepening geomorphic gradients and increasing the stream power of the fluvial system (Holbrook and Schumm, 1999). Within the study area, tectonic activity in the form of differential uplift has been a major factor in the generation of topography (Harvey, 1987; Silva et al., 1993). Since the Mid-Miocene, an approximate north–south compressive regime has affected the study area in relation to the ongoing collision between the African and Iberian plates (Montenat and Ott D'Estevou, 1999). The compression is taken up along major strike-slip fault zones such as the Palomares and Lorca-Alhama faults (Weijermars, 1987; Silva et al., 1993; Keller et al., 1995; Bell et al., 1997) and as a consequence has created regional topographic gradients (Harvey, 1987; Mather and Harvey, 1995). This is particularly evident within the nearby Sorbas basin. There, tectonic elevation of the Sorbas basin in relation to its southern and eastern neighbours (Almeria/Nijar and Vera basins) has resulted in accelerated fluvial incision and river captures during the Late Miocene to Pleistocene (Harvey and Wells, 1987; Harvey et al., 1995; Mather and Harvey, 1995; Mather, 2000a,b; Stokes et al., 2002).

Within the study area, a pronounced regional topographic gradient is present from north to south across the Sierra Almagro (Fig. 10). The creation of this regional gradient can be explained by differential uplift between the basins on either side of the Sierra Almagro and can account for why the Río Almanzora has developed into a transverse drainage.

The differential uplift and therefore creation of a regional gradient, can be described in both quantitative and qualitative forms. Quantitative estimates for tectonic elevation of the Almanzora/Huercal-Overa basin over the Pliocene–Recent suggests average surface uplift rates in excess of >50 m Ma^{-1} (calculated by time averaged elevation of Pliocene marine deposits above modern sea level). This compares with much lower rates of < 20 m Ma^{-1} for the Vera basin (Stokes, 1997). Therefore, since the Late Miocene–Pliocene, an approximate southwards tilting has taken place.

Pliocene–Recent amounts of dissection can provide a qualitative approximation of differential surface uplift within the study area. Within the Vera basin, Pliocene–Recent dissection is typically < 100 m (Stokes, 1997), in contrast to dissection of < 150 m for the Almanzora/Huercal-Overa basins (Wenzens and Wenzens, 1995). These differences in dissection reflect differential uplift, with the highest amount of dissection corresponding to the highest amount of tectonic elevation.

The creation of a regional topographic gradient by tectonic activity would have increased stream power and changed regional and local base levels. Heightened stream power would have stimulated incision and headward erosion from the Vera basin, northwestwards across the Sierra Almagro into the Almanzora/Huercal-Overa basin thus creating a transverse drainage. Once the transverse drainage was established, headward erosion would have continued westwards into the Almanzora basin in response to the ongoing tectonic activity.

The tilting model is further supported through estimation of river terrace and strath gradients across the Sierra Almagro. The higher and older levels record relatively steep mean gradients (0.020 to 0.016). In comparison, the lower and younger levels record relatively low mean gradients (0.013 to 0.006). While some caution should be used with these gradients due to the fragmentary nature of the landform record, these best estimates do suggest that tilting has continued during the Pleistocene after the Río Almanzora became a transverse drainage.

Of major significance is the timing of the creation of the Río Almanzora as a transverse drainage. This

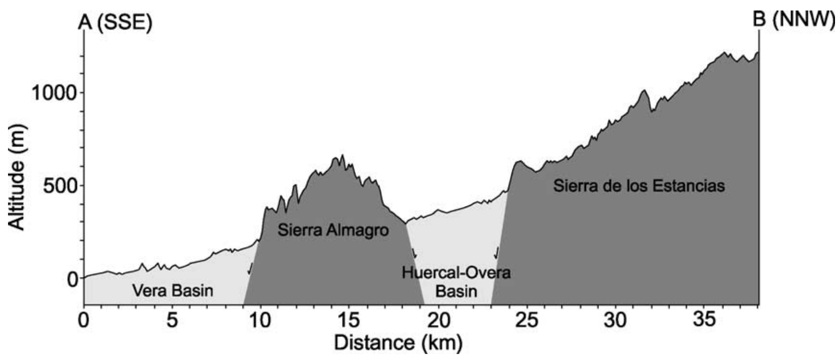


Fig. 10. Regional topographic gradient of the study area created by differential uplift and southwards tilting. The development of the gradient has resulted in incision, headward erosion and drainage network expansion. This tectonically induced regional surface gradient has created and maintained the Río Almanzora as a transverse drainage throughout the Pleistocene–Recent. See Fig. 1 for the location of the section line.

study suggests that the connection between endorheic basins across the Sierra Almagro via incision, headward erosion and drainage network expansion took place between the Plio-Pleistocene and Pleistocene stages of drainage evolution (possibly during Early–?Mid-Pleistocene). Similar spatial and temporal patterns of incision and drainage network expansion are recorded within several studies of long-term drainage evolution throughout southeast Spain (e.g. Harvey and Wells, 1987; Silva et al., 1993; Calvache and Viseras, 1997; Stokes, 1997). These patterns are clearly part of a regional phenomenon that corresponds to a marked increase in tectonic activity during the Plio-Pleistocene (Mather, 1991; Mather and Westhead, 1993; Silva et al., 1993; Stokes, 1997; Stokes and Mather, 2000).

11. Conclusions

1. Through the integration of geological and geomorphological data, the long-term drainage evolution of the Río Almanzora spanning some 5 Ma has been established.
2. The evidence clearly demonstrates that the Río Almanzora was created as a transverse drainage during the Early–?Mid-Pleistocene.
3. The mechanism for its creation as a transverse drainage is via headward erosion of a drainage outlet in the El Calguerín area on the south side of the Sierra Almagro.
4. The headward erosion was driven by differential uplift between the Huercal-Overa/Almanzora and Vera basins resulting in the creation of a southwards dipping regional gradient.
5. Once established as a transverse drainage, the Río Almanzora provided an external connection to the Mediterranean Sea for a previously endorheic basin (the Huercal-Overa/Almanzora basin).
6. The continued expansion of the Río Almanzora catchment area has enabled incision to keep pace with uplift. The Río Almanzora having been initiated by headward erosion has therefore maintained its transverse course via antecedence.

The long-term drainage evolution of the Río Almanzora provides valuable insights into the origins of transverse drainage within tectonically active areas. The mechanisms invoked for the origin of this case study have important implications for similar drainages that are common across southern Spain.

Acknowledgements

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