The Guadalentín Tectonic Depression, Betic Cordillera, Murcia

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Abstract

The tectonic Guadalentín Depression is an elongated Quaternary sedimentary basin generated by a system of left-lateral strike-slip faults on the eastern Betic Cordillera. The Lorca-Alhama de Murcia fault (LAF) is the most relevant structure, controlling the 100-km-long western margin of the depression with a prominent mountain front. Climatic conditions are semiarid, and sedimentation is dominated by alluvial fans. The interaction between tectonics, alluvial sedimentation, and climate results in the development of widespread tectonic landforms and alluvial fan surfaces with different degree of calcrete development. The variable morpho-sedimentary arrangements record different styles of faulting and uplift history on the range front faults. Large fans occur associated with the main gaps and step-overs between the different fault segments bounding the Quaternary basin (e.g. Lorca Fan). Telescopic fan sedimentation under limited distal aggradation eventually turned into distal trenching throughout the late Holocene. This geomorphic evolution constitutes a good example of the transformation of the ancient main fan-feeding channel into a true fluvial channel (present-day Guadalentín River) linked to a well-preserved Late Bronze geoarcheological record.

Keywords

Tectonic geomorphology • Mountain fronts • Alluvial fans • Drainage development • SE Spain

2.1 Introduction

The Guadalentín Depression (Murcia, SE Spain) constitutes one of the Quaternary sedimentary basins associated with the NE-SW active strike-slip fault system of the Eastern Betic Shear Zone (EBSZ; Larouzière et al. 1988; Silva et al. 1993). This tectonic depression, more than 100 km in length, is one of the most outstanding examples of recent tectonic landscapes in the Betic Cordillera, and the area of well documented historical and modern seismic activity (Mw 5.1, 2011 Lorca Earthquake; Alfaro et al. 2011). The depression is bounded by fault-controlled mountain fronts that provide evidence of significant Late Quaternary tectonic activity (Fig. 2.1) recorded by a large variety of tectonic landforms, mostly related to strike-slip faults (e.g. micro pull-apart basins, linear sag ponds, small pressure and shutter ridges, and offset drainages; Silva et al. 1992a, 1997, 2003; Silva 1994, 1996; Martínez-Díaz et al. 2012). Mountain front tectonic activity is well recorded by proximally trenched and distally aggrading alluvial fan sequences, whose stratigraphic and geomorphic relationships provide evidence of (a) their uplift history (Harvey 1984; Silva et al. 1992b);

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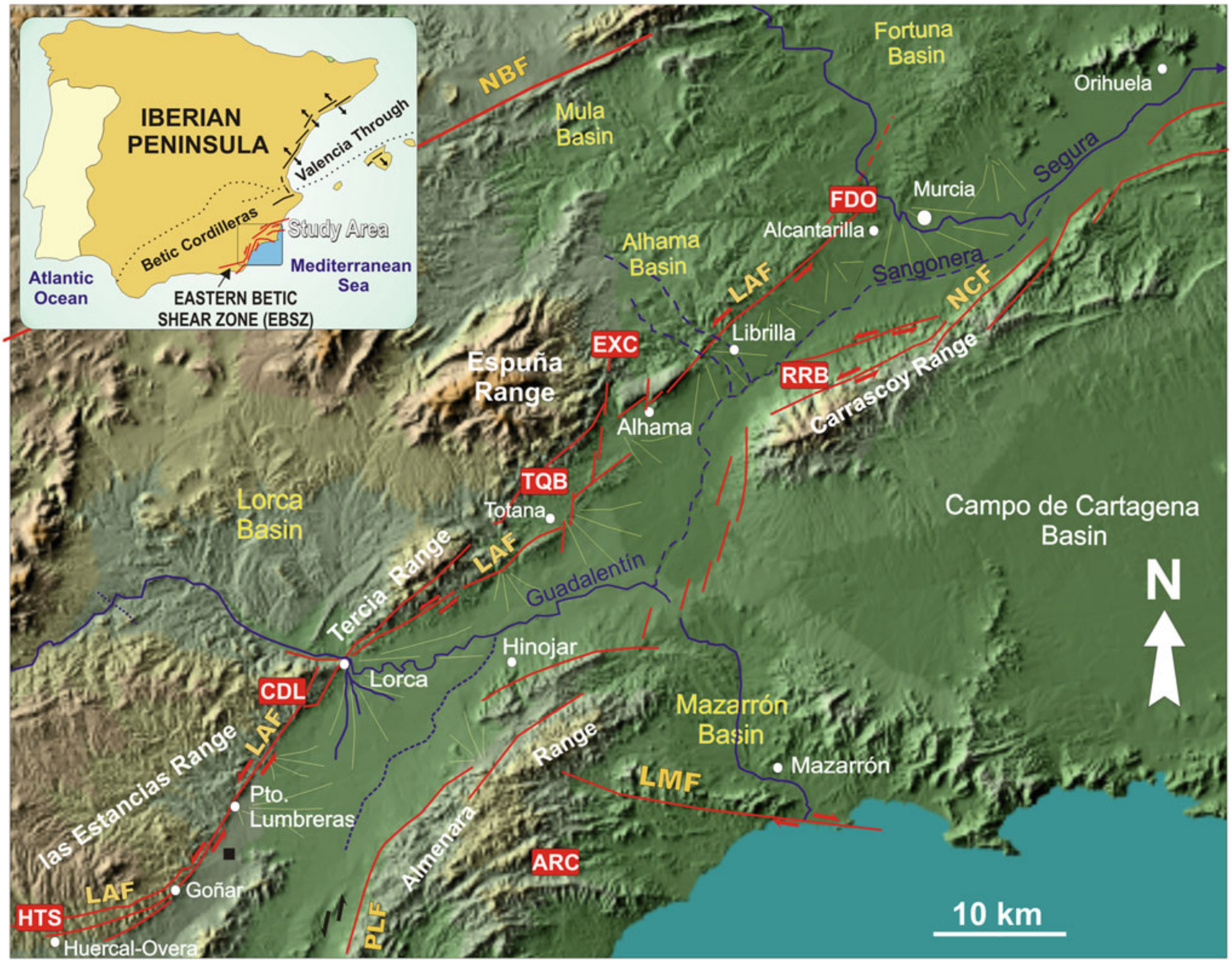

Fig. 2.1 Geomorphological and tectonic setting of the Guadalentín Depression. Blue: main drainage systems related to the Guadalentín River. *Red* main strike-slip fault systems controlling major range fronts. *Yellow* location of the main Late Neogene sedimentary basins. *White* main ranges and localities of the region. *LAF* Lorca-Alhama de Murcia Fault; *PLF* Palomares Fault; *NCF* North Carrascoy Fault; *LMF* Las Moreras Fault; *NBF* North Betic Fault; *HTS* horse-tail splay termination of the LAF; *CDL* Contractional duplex of Lorca; *TQB* triangular Quaternary pull-apart basins; *EXC* extensional system of Canacarix; *RRB* El Romeral Rock-Bar fault; *FDO* fault die-out at surface

(b) the progressive development of the drainage network during the Late Quaternary (Harvey 1990, 1997); (c) and the transition from alluvial to fluvial systems in the semi-arid SE Spain during historical times (e.g. Bronze Age; Silva et al. 1996, 2008; Calmel-Avila 2002). Additionally, the depression constitutes a remarkable example of a semi-endorheic environment drained artificially in very recent historical times and affected by severe flooding events (López-Bermúdez et al. 2002). The preserved Late Holocene alluvial landforms and sedimentary sequences within the depression provide a high-quality geoarchaeological record illustrating the relationships between human populations and drainage changes since the early Bronze to Medieval times (Silva et al. 2008).

2.2 Geological and Geographical Setting

The Guadalentín Depression is located in the central sector of the EBSZ. This is a crustal-scale structure defined by a set of post-orogenic NE-SW left-lateral strike-slip faults in the eastern Betic Cordillera, such as the Lorca-Alhama de Murcia (LAF), Palomares (PLF), and North-Carrascoy (NCF) faults (Fig. 2.1). These faults have been affected by successive transtensional and transpressional activity from the Late Neogene to the present time (Bousquet 1979; Larouzière et al. 1988). Tectonic activity generated the elongated Guadalentín Depression bounded by prominent fault-controlled mountain fronts from the Middle Pleistocene (Silva et al. 1993, 2003). The main range fronts are

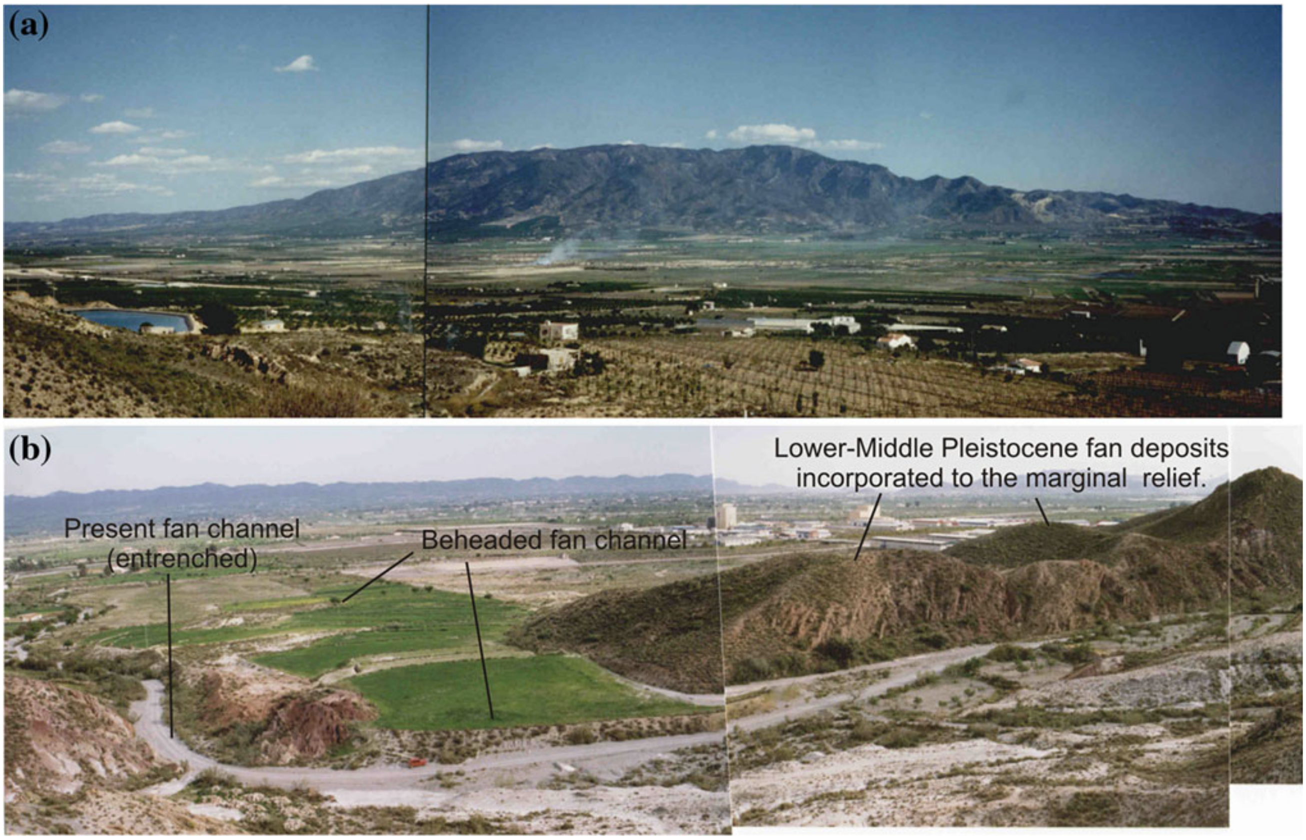

Fig. 2.2 **a** Panoramic view of the North Carrascoy mountain front and related alluvial fan systems. **b** Panoramic view of a beheaded channel along the left-lateral Puerto Lumbreras-Lorca fault segment (*LAF*) south of Lorca city. Note *red car* in the deflected channel bed for scale (Burruezo fan, location in Fig. 2.5)

developed along the LAF reaching elevations above 900 m a.s.l. This fault comprises three large segments expressed as distinctive range fronts (Fig. 2.1), which also correspond to the main structural and seismic segments (Silva et al. 1992a, 1996, 1997, 2003; Martínez-Díaz et al. 2003, 2012). The Puerto Lumbreras (Estancias Range) and Lorca-Totana (La Tercia and Espuña ranges) fronts are mainly developed on Palaeozoic metamorphic rocks (dominantly schists and marbles) of the Alpujárride and Maláguide Betic complexes, but also on the terrigenous and marly formations of the ancient Late Neogene Lorca Basin (La Tercia Range). The Alcantarilla front (Alhama Range), with lower elevations, is entirely developed in these erodible sediments. To the east, the Almenara (PLF) and NCF range fronts are mainly underlain by more resistant metamorphic rocks of the Nevado-Filábride and Almágride Betic complexes (Fig. 2.2). Deformed marly Neogene sediments locally occur along the fault traces. Only the northern portion of the Almenara front (Hinojar Range) is entirely developed on sedimentary Neogene terrains and is the only fault displaying a landscape dominated by erosional features, indicating the lower degree of tectonic activity (Silva et al. 2003).

The depression is currently drained by a ca. 80-km-long axial fluvial system, the Guadalentín River, which flows into the Segura River in the vicinity of Murcia city (Fig. 2.1). The Guadalentín River is an ephemeral and flashy fluvial system slightly incised (7–17 m) into the Holocene fill of the depression (Fig. 2.3; Silva et al. 2008). This torrential rambla has produced major damaging floods in historical and recent times (i.e. López-Bermúdez et al. 2002), related to high-intensity convective storm events typical of the Mediterranean environments (López-Gómez and López-Gómez 1987). However, the most significant drainage systems in this zone are the numerous channels and large gullies (ramblas) that feed the small and steep alluvial fans developed at the foot of the mountain fronts (Harvey 1990; Silva et al. 1992b). Most of the fan systems are characterised by proximal trenching and distal aggradation from at least the Late Pleistocene, but also currently in relation to storms events. In most cases, the fan channels are disconnected from the axial drainage, which constitutes the base level (Guadalentín River). Endorheic conditions prevail in the central and southern sector of the depression, where only some inter-fan channels are connected to the axial drainage causing incision on distal fan surfaces related

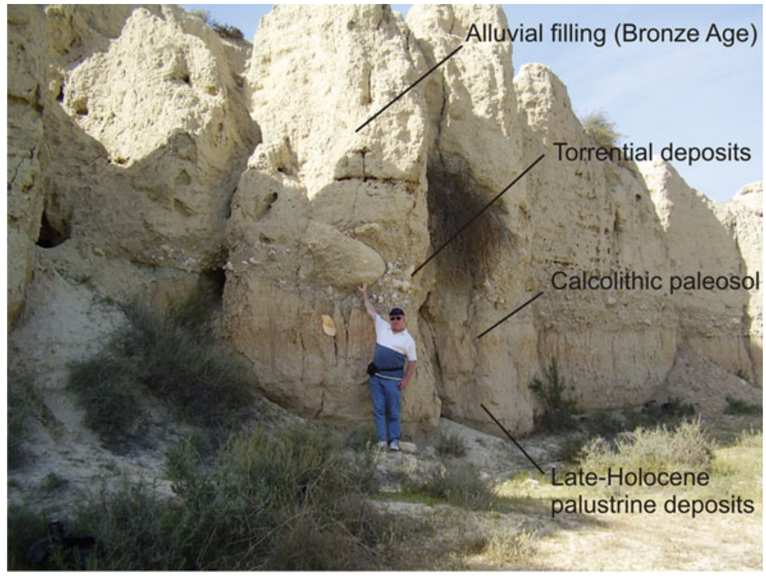

Fig. 2.3 Upper part of the Holocene fill within the northern sector of the Guadalentín Depression (Rambla de Algeciras). Note the big boulders recording torrential activity. The *yellow cap* indicates the position of the Calcolithic soil horizon, a characteristic stratigraphic marker in this sector of the depression. Photo courtesy of Mary Ivonne Calmel-Avila (2002)

to headward erosion. Only in the northern sector of the depression, along the Alcantarilla Range front, through-fan dissection occurs and ancient fan and inter-fan channels are properly integrated in the regional drainage network as tributaries of the trunk Guadalentín River (Fig. 2.1). In this sector, aggressive headward erosion favours the development of badland landscapes within the depression and on its margins.

2.3 Geomorphology

2.3.1 Tectonic Landforms

The largest tectonic landforms developed in the Guadalentín Depression correspond to the mountain fronts associated with the main faults bounding the depression. The 80-km-long LAF is the main fault on the NW margin of the Guadalentín Depression (Fig. 2.1). This oblique-slip fault has accommodated significant left-lateral (8–20 km) and vertical displacement from the Messinian to the present day (Weijermars 1987; Silva et al. 1997). The Quaternary vertical slip rate has been estimated at 0.8–0.4 mm/yr (Silva et al. 2003; Masana et al. 2004). The fault is subdivided into several morpho-structural segments separated by significant erosional gaps through which the main drainages enter into the Guadalentín Depression (Silva 1994), forming large fans such as the Lorca fan, whose apex is located in the gap between the Lorca and Totana fault segments (Fig. 2.4). To the north, the Segura River fan at Murcia City is developed at the surface termination of the LAF (Fig. 2.1). However, Quaternary tectonic activity on the fault-controlled range fronts promoted the development of many small- to medium-size alluvial fans fed by minor rambla systems (Fig. 2.5). The main morphological features associated with the range front faults include the following (Silva 1994, 1996; Silva et al. 1997, 2003):

(a) the development of a terminal horsetail splay (HTS) in the southern termination of the LAF south of the locality of Puerto Lumbreras. Pleistocene tectonics generated a staircased topography in the range front, affecting the oldest fan surfaces and previous Plio-Pleistocene sedimentary sequences.
(b) the splitting of the basin-bounding fault into branches between Lorca and Alhama de Murcia, giving place to a set of intervening contractional duplexes (e.g. Lorca CDL), triangular strike-slip basins (TQB), and small pull-apart zones in which the Pleistocene fan surfaces are deformed and faulted. Strike-slip activity of the fault generates kilometric pressure ridges, linear tectonic ridges, beheaded fans and channels, as well as a small-scale horst and graben topography (Figs. 2.2, 2.5, 2.6).
(c) the development of linear mountain fronts with low sinuosity ($Smf < 1.5$) and low valley-floor width-to-valley height ratios ($Vf < 0.6$), in which the occurrence of metre- to decametre-scale channel offsets and deflections are common. Other minor tectonic landforms are also frequent, such as shutter ridges, beheaded fans, and flexures on fan surfaces, illustrating the dominant Late Pleistocene strike-slip activity on the fault (Fig. 2.5). Only the northern fault segments of the LAF (Librilla-Alcantarilla) and PLF (Hinojar) display high sinuosity values ($Smf > 2.0$) and valley-floor width ratios ($Vf > 0.8$), indicating the prevalence of erosion over tectonics in this sector of the depression.
(d) the development of younger N–S trending normal faults intersecting the main fault zones has a major role in the

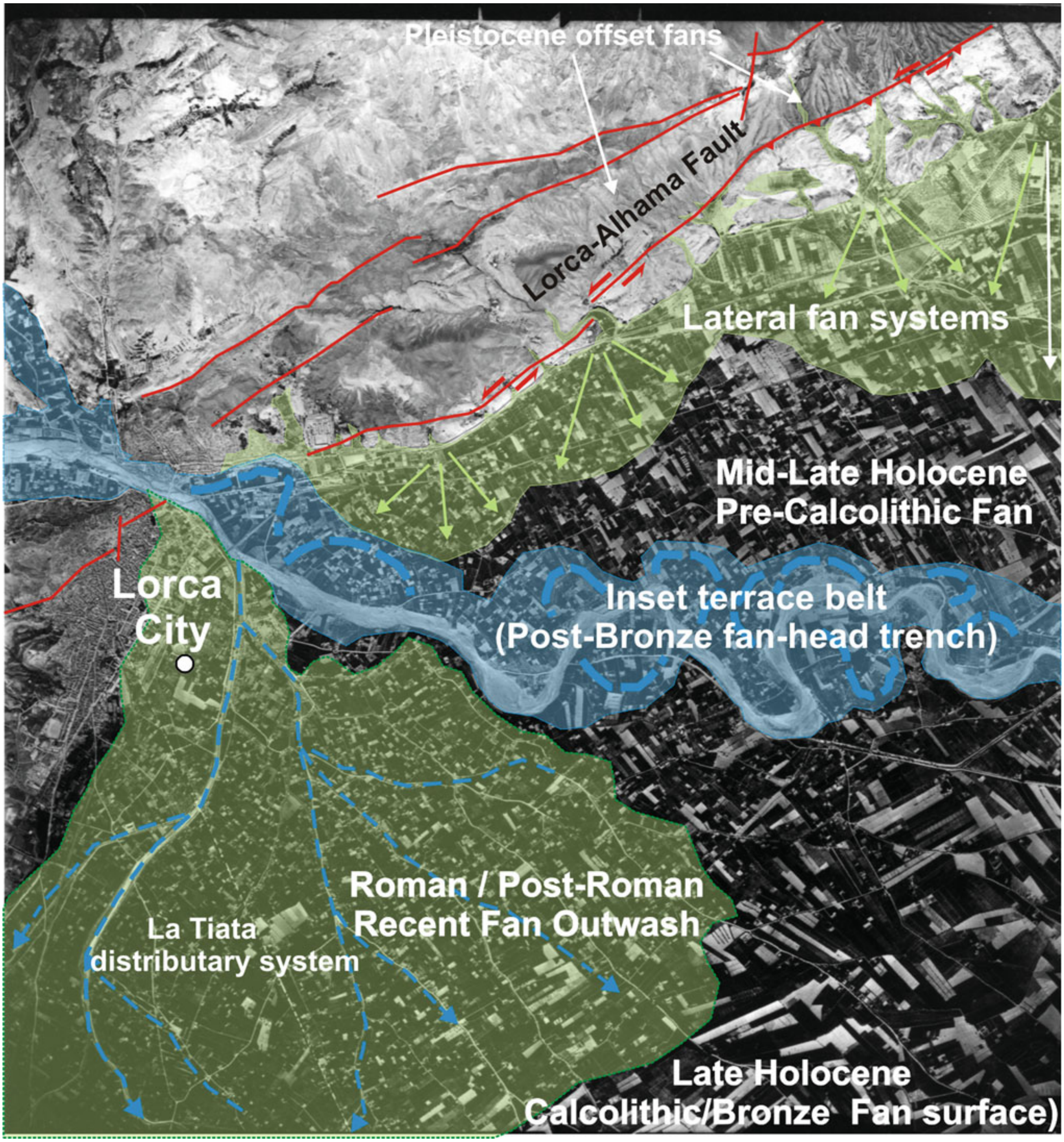

Fig. 2.4 Aerial photograph taken in 1953 (1:30,000 scale) showing the modern and ancient surfaces of the Lorca fan in the proximal sector. The terraces associated with the present-day rambla dissecting the fan surface are indicated in blue and holds an overall post-Bronze Age working as the primary fanhead trench incised in the Late Holocene fan surface. Green-coloured zones depict modern (Roman and post-Roman) fan lobes. Note fault branching and offset fan surfaces in the NE upper quadrant [modified from Silva et al. (2008)]

landscape development from Late Pleistocene to Holocene times, leading to the generation of a transverse micro-horst and graben topography and controlling in some cases the geometrical arrangement of the most recent fan sequences (Fig. 2.7).

The LAF has been active throughout the entire Quaternary period, but early transpressive tectonics favoured the development of mountain fronts from the Lower Pleistocene (Silva 1994). Conversely, tectonic activity since the Late Pleistocene seems to be controlled by pure strike-slip

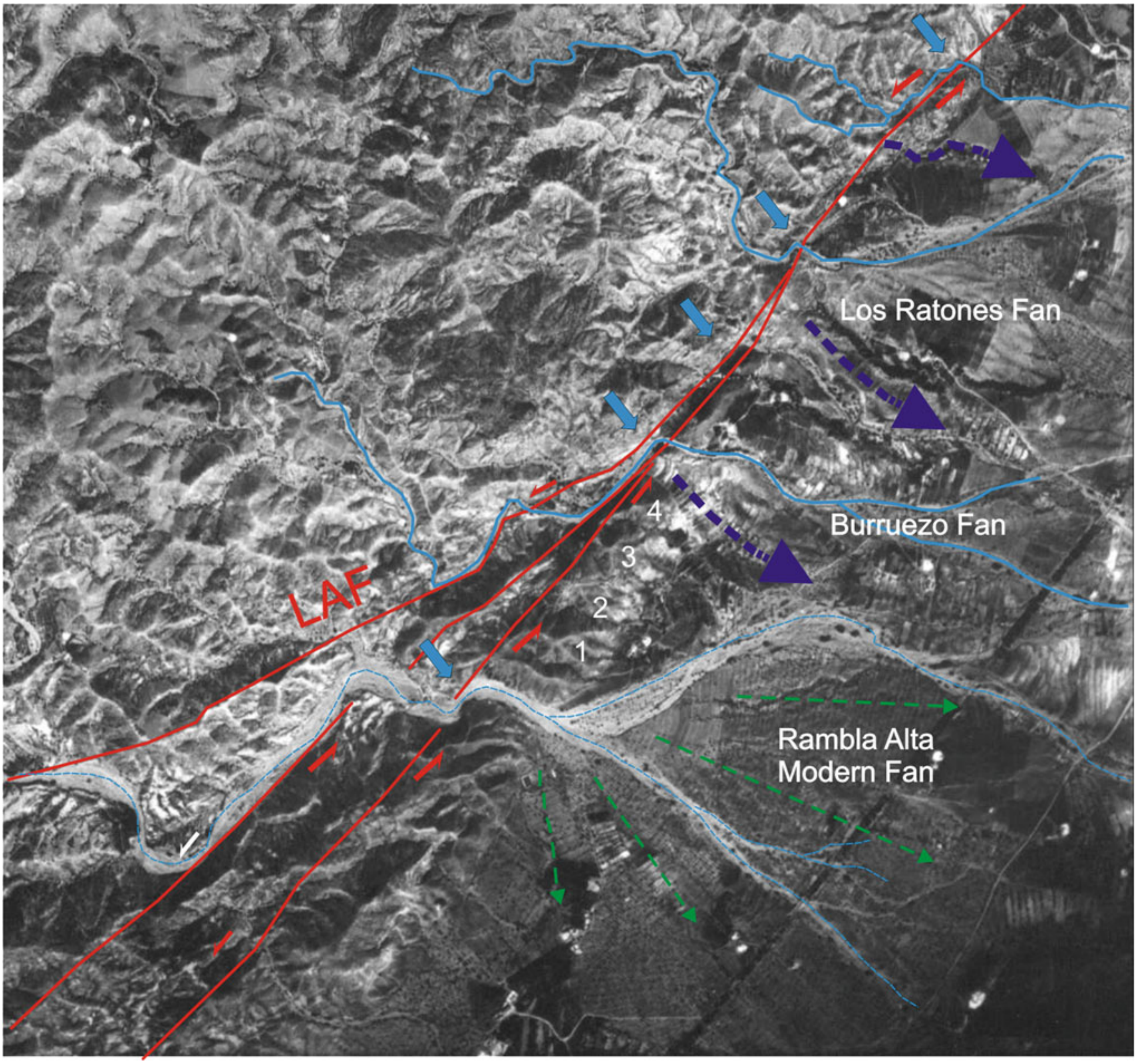

Fig. 2.5 Aerial photograph taken in 1953 (1:30,000 scale) showing left-lateral channel offsets and deflections along the LAF south of Lorca City. Note the Burruezo fan and beheaded channel shown in Fig. 2.2. *Blue arrows* indicate major channel deflections and offsets with bayonete-like pattern. Numbers (1–4) indicate the position of Lower–Middle Pleistocene fan lobes incorporated into the marginal relief due to fault activity

faulting and local transtensive tectonics (Silva et al. 1997). Paleoseismological investigations carried out via trenching north and south of Lorca city reveal two recent faulting events with loose bracketing ages (830–2130 BC and 1760 BC–1650 AD) and ascribed to large earthquakes with estimated magnitudes of 6.5–7.0 Mw (Masana et al. 2004; Ortuño et al. 2012), but with apparently minor geomorphic impact. In contrast, in the Librilla zone, the entire pre-Bronze Age Holocene sedimentary sequence is tilted more than 30° at its contact with the El Romeral Rock-Bar fault, a transverse fault zone probably belonging to the southern branch of the LAF, but buried by Late Holecene deposits. (Calmel-Avila 2002). The geoarcheological record around the El Romeral Rock-Bar indicates fault activity during the Late Calcolithic–Early Bronze transition (2700–2400 BC) along the southern branch of the LAF (Silva et al. 2008). Some synsedimentary liquefaction features in sediments corresponding to the Roman period (200 BC–90 AD) around the Totana–Librilla sector also suggest the occurrence of seismic activity during this time (Silva et al. 2008;

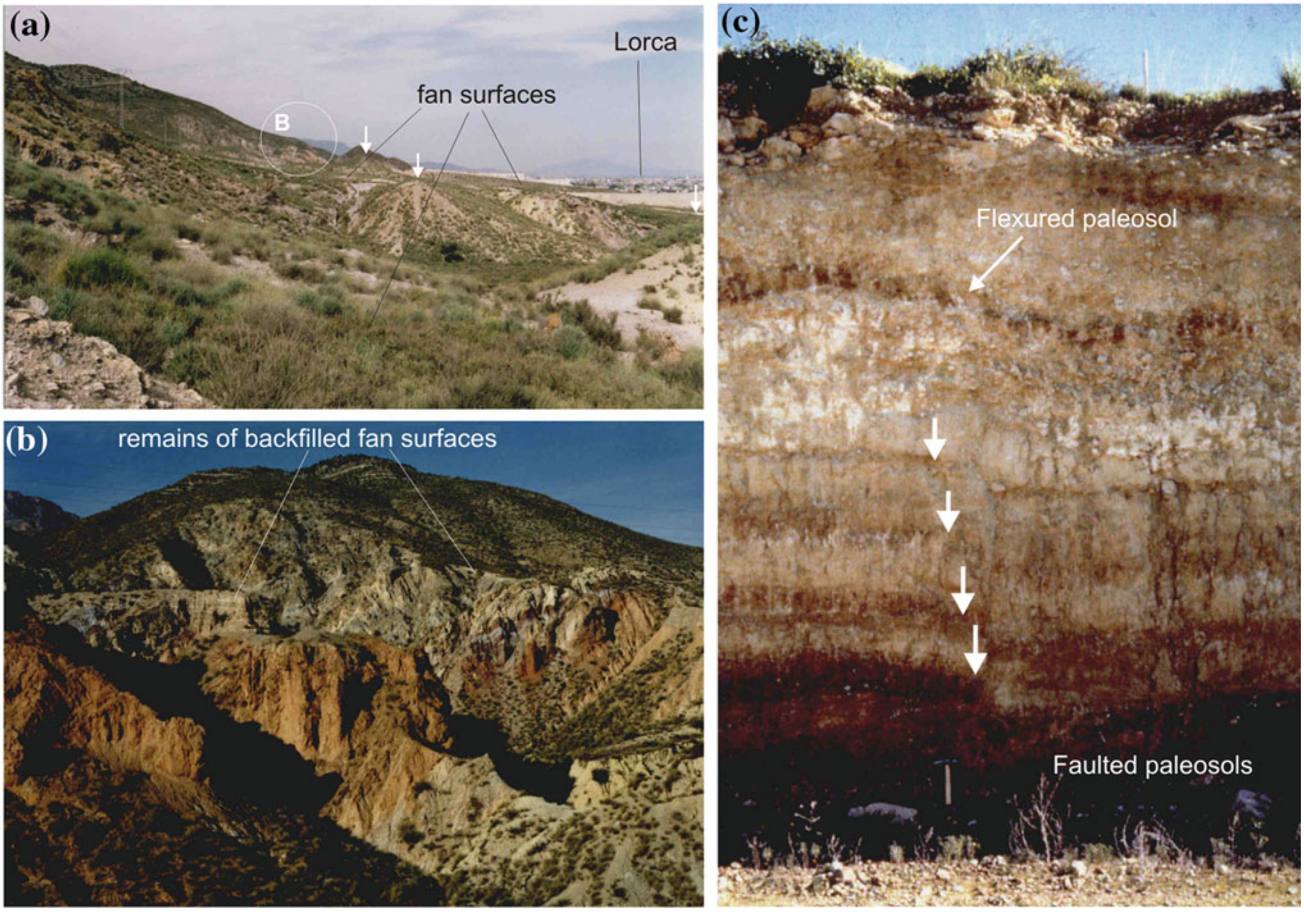

Fig. 2.6 Some characteristic tectonic landforms in the Guadalentín Depression. **a** Pressure and shutter ridges developed along the LAF south of Lorca city. Note the interaction of the fault zone with the alluvial fan surfaces of the second depositional phase (backfilling). **b** View of the LAF zone south of the Lorca city (see location in Fig. 2.6a) with remains of backfilled fan units on the fault zone. **c** Recurrent displacement of Middle to Late Pleistocene alluvial paleosols in the Palomares fault (*PLF*) at the southern sector of the Guadalentín Depression

Calmel-Avila et al. 2009). In addition to this probable paleoseismic evidences, historical records indicate at least three main seismic events with intensities of VIII-VII MSK (1679, 1784, and 1818 AD) similar to that occurred on May 2011. No surface faulting has been reported for any of the historical events, but significant rockfall events are the most widespread secondary environmental effects (Alfaro et al. 2011).

2.3.2 Alluvial Fan Systems

Alluvial fans are the most extensive landforms in the Guadalentín Depression. Small to medium fan systems develop along the foot of the main mountain fronts, while large fans (i.e. Lorca, Nogalte, Lebor, Algeciras, and Librilla) are associated with drainages that take advantage of gaps between different fault segments and range fronts (Figs. 2.1, 2.4). Alluvial fans in this region record a complex Pleistocene history (Harvey 1990; Silva et al. 1992b) with (a) early periods dominated by aggradation, followed by (b) fan-surface stabilisation and calcrete formation (Alonso-Zarza et al. 1998), and eventually (c) fan-head trenching and distal aggradation (Silva et al. 1992b). Different alluvial fan sedimentary styles controlled by variables such as mountain front geomorphology, lithology, and degree of tectonic activity have been identified. Silva et al. (1992b) recognised three main depositional alluvial fan sequences along the entire Guadalentín Depression (Fig. 2.7).

The first depositional phase, dominated by cemented debris-flow conglomerates with thick calcrete profiles at the surface (Alonso-Zarza et al. 1998), can be assigned to the Middle Pleistocene (>330 ka) (Sohbati et al. 2011; Ortuño et al. 2012). This syntectonic sequence displays a cumulative wedge-out with a proximal offlap arrangement related to continuous uplift along a range front controlled by oblique-slip faults. These oldest fan surfaces have a

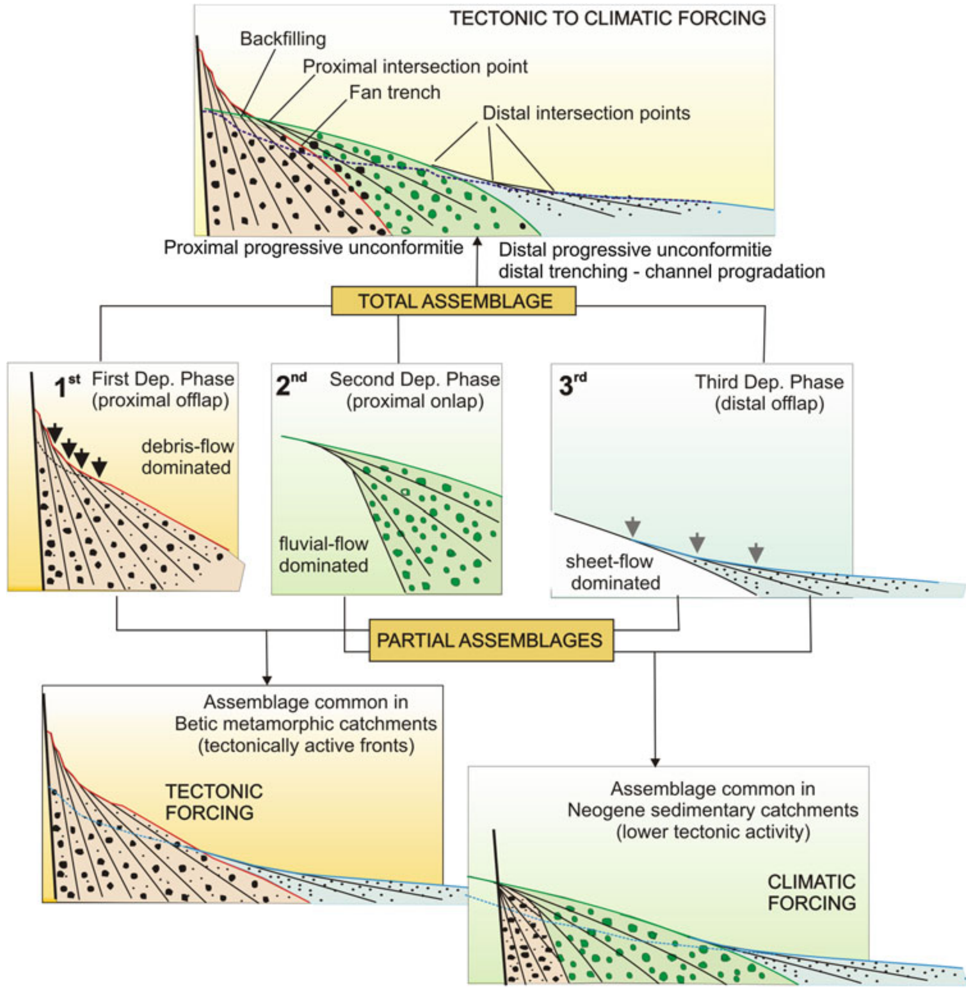

Fig. 2.7 Stratigraphic and morphological arrangement of alluvial fan bodies along the margins of the Guadalentín Depression recording tectonic and climatic forcing during deposition of the three main Middle Pleistocene–Holocene morpho-sedimentary units [modified from Silva et al. (1992b)]

dominant geomorphic expression in the southern horse-tail splay termination of the LAF (Goñar sector) and in the proximal zones of the intervening strike-slip triangular basins developed in the branched central sector of the LAF, between Lorca and Alhama de Murcia.

The second depositional phase comprises debris flow and alluvial gravel and sand facies with a proximal onlap arrangement recorded by proximal fan aggradation and backfilling in the mountain front catchments. Fan surfaces of this phase display some degree of cementation, but no true calcrete development (Alonso-Zarza et al. 1998). Recent numerical dates (Sohbati et al. 2011; Ortuño et al. 2012) allow assigning this phase to the Middle–Late Pleistocene, with ages from ca. 290 to 106–107 ka BP. The final development of these fan surfaces by means of proximal onlap aggradation and backfilling can be preliminary assigned to the last interglacial period (OIS 5). Fan surfaces of this second depositional phase dominate the mountain front piedmonts in the southern and central sectors of the depression. Proximal onlap aggradation can be interpreted as a progressive attenuation of tectonic uplift along the range fronts.

The third depositional phase mainly comprise sandy to gravely sheet flood deposits, with inset fluvial-like gravel channels generated by distributary systems. This phase is characterised by the development of proximal fanhead trenches and distal aggradation, with the progressive down-fan migration of intersection points and the formation of telescopic fan systems prograding onto the playa-lake and palustrine environments located in the centre of the depression. Available chronological data (OSL, Th/U, C14) from geoarchaeological (Calmel-Avila 2000, 2002; Silva et al. 2008) and paleoseismic research (Martínez-Díaz et al. 2003; Masana et al. 2004; Ortuño et al. 2012) allowed a finer subdivision of the third depositional fan sequence into several Late Pleistocene (<100 ka BP), Early Holocene, Bronze, Roman, Muslim, and historically recent phases of distal fan aggradation (Silva et al. 2008). Detailed analyses of the larger fans generated during the Holocene (e.g. Lorca Fan; Fig. 2.4) indicate that palustrine environments and fan aggradation prevailed until at least 2500–2300 BC (Early Bronze Age) in the southern and central sectors of the depression. Major intrabasinal fluvial incision started from the Late Bronze Age, when significant headward erosion reached the central sector of the Guadalentín Depression between Librilla and Totana (Fig. 2.3), achieving an entrenchment of up to 17 m (Calmel-Avila 2002). However, semi-endorheic conditions remained in the central zone of the depression upstream (Totana zone, Fig. 2.1) until the sixteenth to seventeenth centuries. In this zone, the ancient palustrine environments were fragmented by fluvial dissection evolving into smaller ephemeral playa-lake systems, occasionally flooded by the Guadalentín River (Silva et al. 2010a, b).

Although Middle Pleistocene fan development was favoured by tectonic activity on the basin-bounding faults, Late Pleistocene to Holocene sedimentation was mainly controlled by climate, and fans in the Murcia region evolved under very limited distal aggradation and proximal trenching (Harvey 1990, 1997). The most important factor in recent alluvial fan dynamics is the effectiveness of rainstorm events, controlling the production of sediment and run-off in the mountain catchments, as well as the generation of new distal fan lobes with telescopic arrangement (Silva et al. 2008). Data from significant flood events which occurred in the Guadalentín Depression indicate that precipitation events of 286 mm may produce peak-discharge values of 3,090 m^3/s, and sediment supply to individual large-sized fans (e.g. Nogalte Fan) can reach volumes of 813 m^3, ultimately accumulated in the distal fan segments (López-Bermúdez et al. 2002). More than 200 flood events have been documented since 1482 AD within the Guadalentín Depression, and some references to major floods during Roman and Muslim times are also available (Camarasa-Belmonte 2002).

2.4 Evolution

The Eastern Betic Shear zone was generated by an overall N–S compression related to the crustal-scale indentation processes associated with the development of the Aguilas Arc from the Middle Miocene until the Quaternary (Larouzière et al. 1988; Silva et al. 1993; Bardají et al. 2003). Late Neogene activity along this large transcurrent zone gave rise to intense magmatic phenomena and to the formation of transtensive and transpressive marine basins of various types (Larouzière et al. 1988). These Neogene basins (i.e. Lorca, Hinojar, Mazarrón, and Mula-Fortuna basins) developed on both sides of the present Guadalentín tectonic depression, where ancient Betic metamorphic paleomassifs were located (Fig. 2.1; Silva et al. 1993). Neogene basins were affected by progressive uplift from the Messinian giving place to the deposition of thick evaporite sequences in the western basins (Lorca and Mula-Fortuna) induced by the significant sea level drop that occurred at the end of the Messinian (Montenat et al. 1990). Important paleogeographical changes took place across the entire area from the Late Pliocene onwards. During this period, the stress field rotated to a NNW–SSE orientation, causing the dislocation, differential uplift, and a generalised inversion of the Late Neogene basins (Montenat et al. 1990; Silva et al. 1993).

The development of the current landscape started in the Late Pliocene, with the formation of a large sedimentary trough (Guadalentín Depression) in a zone previously occupied by the ancient Betic paleomassifs. The uplifted Neogene formations were incorporated into the marginal reliefs and mountain fronts, underlying the catchments that fed the Plio-Quaternary alluvial fan sequences. The landscape within these ancient sedimentary zones is dominated by erosional landforms including cuestas and mesas developed in the more resistant lithologies and extensive badlands in the marly and silty Late Neogene sequences (Silva 1994). The oldest late Pleistocene alluvial fan sequences are also incorporated into the mountain fronts and tectonic push-ups generated along the LAF (Fig. 2.6), recording continuous uplift and left-lateral slip during the early Quaternary (Silva et al. 2010a, b; Silva and Bardají 2012). Local rotation of the stress field to N170E associated with the development of complex tectonic structures (duplexes, step-overs, bends, and branching) within in the fault zone, especially in the complex central sector of the fault (Martínez-Díaz 2002), took place during the Lower–Middle Pleistocene transition (Silva et al. 2010a). This new tectonic scenario gave place to the rearrangement of the mountain front morphology, faulting of ancient fan sequences, and new sedimentary assemblages in Middle to Late Pleistocene alluvial fan sequences (Silva et al. 1992b, 2010b). From a geomorphological point of view, the development of the tectonic landforms associated with the alluvial fan sequences and strike-slip tectonics preserved in the piedmont areas dates from this period. Most of the mountain front uplift was achieved during the Pliocene and Early Pleistocene (>85 %), while the remaining vertical displacement (<15 %) can be assigned to the Middle Pleistocene. During this last phase, dominant strike-slip tectonics, and limited uplift, controlled the geomorphological development of mountain fronts and associated alluvial fan sequences. This interpretation is supported by offset key stratigraphic markers and the geomorphic and stratigraphic relationships of the alluvial fan sequences along the fault zones (Silva et al. 1992b, 2010a, b). From the Late Pleistocene, the geomorphological evolution has been mainly controlled by climate, inducing the generation of fanhead trenches and progressive distal fan progradation related to the aridification of the area during the Late Holocene (Calmel-Avila 2002). These climatic conditions favoured the progradation of the fan channels towards basin centre and extrabasinal capture processes that promoted the transformation of ancient alluvial systems into confined fluvial systems, leading to the present-day drainage network and the fragmentation of ancient palustrine systems in basin centre (Silva et al. 1996, 2008; Bardají et al. 2003).

2.5 Conclusions

The Guadalentín tectonic Depression is an elongated Quaternary sedimentary basin generated by left-lateral oblique faults on the eastern Betic Cordillera. The 100-km-long LAF is the main basin-bounding structure, comprising several segments and the associated mountain fronts. Climatic conditions are semiarid, and alluvial fans are the dominant sedimentary environment. The interaction among tectonics, climate, and alluvial sedimentation results in the development of a wide range of tectonic landforms and extensive alluvial fan surfaces with different degree of calcrete development and variable morpho-sedimentary assemblages. The latter record the different styles of faulting and uplift history on the range front faults. Large fans are associated with major gaps between fault segments at the basin margin (e.g. Lorca Fan). Their progressive development under limited distal aggradation throughout the Late Holocene constitutes a nice example of the transformation from alluvial to fluvial channel systems linked to a well-preserved Late Bronze geoarcheological record.

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