



## PRELIMINARY LATE QUATERNARY SLIP HISTORY OF THE CARBONERAS FAULT, SOUTHEASTERN SPAIN

JOHN W. BELL,<sup>1</sup> FALK AMELUNG<sup>2</sup> and GEOFFREY C. P. KING<sup>3</sup>

<sup>1</sup> Nevada Bureau of Mines and Geology, University of Nevada, Reno, NV 89557, U.S.A

<sup>2</sup> Institut de Physique du Globe, 5 rue René Descartes, Strasbourg 67084, France

<sup>3</sup> Institut de Physique du Globe de Paris, 4 place Jussieu, Paris 75252, France

(Received 6 November 1995; accepted in revised form 19 July 1996)

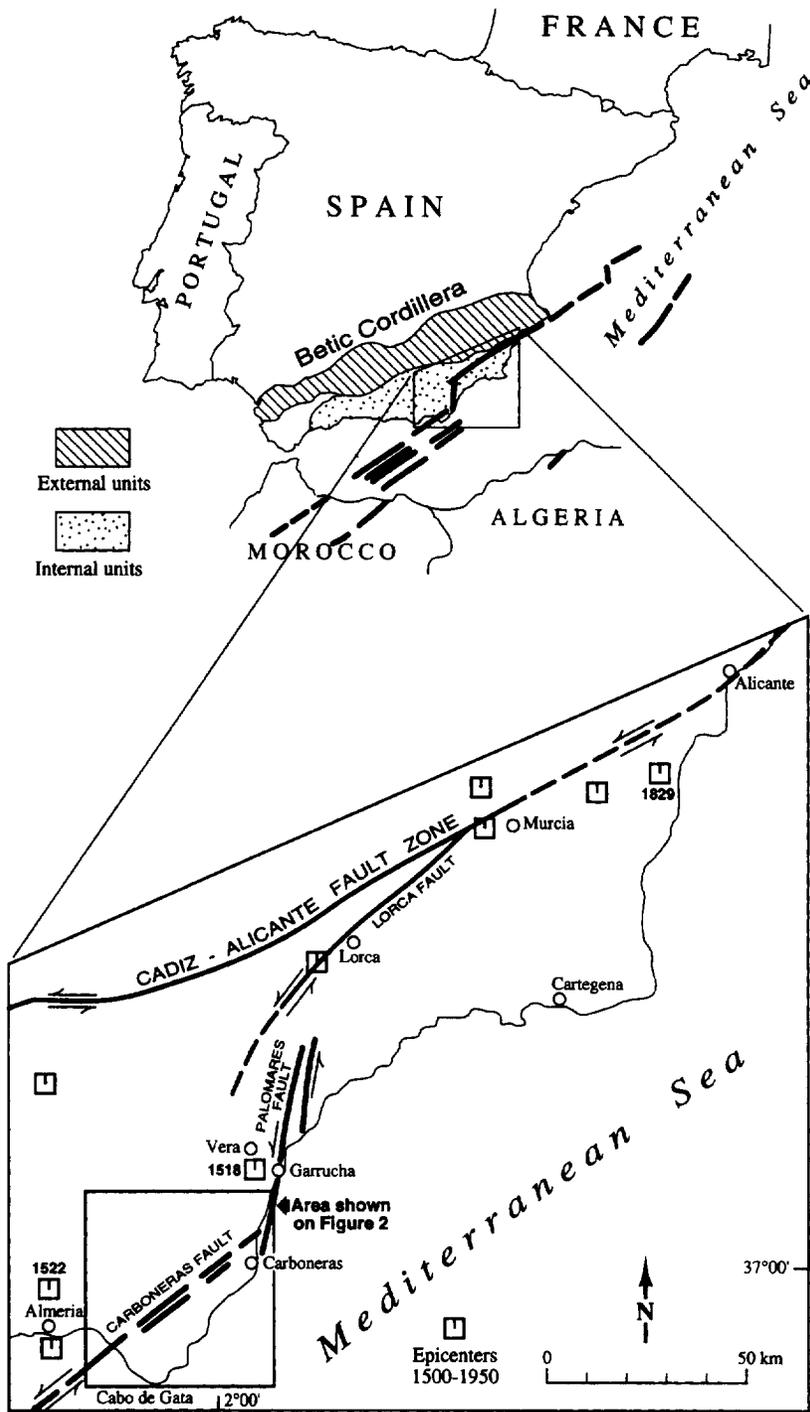
**Abstract**—The Carboneras fault is one of three principal Cenozoic strike-slip faults in the Betic Cordillera of southeastern Spain. In this study, we characterize the paleoseismic history of the Carboneras fault by examining the evidence for lateral offset of 85–180 ka Tyrrhenian marine terraces, by dating the left-lateral stream-channel offsets in La Serrata, and by postulating a late Holocene coastal uplift event. We define three Quaternary alluvial–geomorphic units that assist in constraining rates of fault slip. Qfo deposits are pre-Tyrrhenian in age (>100 ka); Qf deposits are post-Tyrrhenian in age (<100 ka); and Qfy deposits are Roman or post-Roman (<1–2 ka) in age.

Examination of the southern and northern segments of the Carboneras fault indicates that although Tyrrhenian marine terraces are vertically offset 5–10 m, no evidence for large lateral offset of the marine terraces is visible. In La Serrata, 80–100 m lateral stream-channel offsets are older than about 100 ka, and Würmian-age alluvial fans were deposited within these offset channels. Along Rio Carboneras, mapping and topographical profiling of Qfy deposits indicate that stream deposits were previously graded to a sea level 3–5 m higher than that at present. The correlation of the Qfy terrace with upraised bedrock beach platforms along the coast suggests that a regional tectonic uplift event occurred during the last 1–2 ka. Based on a <sup>14</sup>C age on charcoal from Qfy deposits, this event might have occurred since about AD 1475.

The Quaternary slip history of the Carboneras fault during the last 100 ka appears to be one of vertical uplift rather than strike-slip movement, in agreement with contemporary focal mechanisms. Maximum vertical slip rates during the last 100 ka are of the order of 0.05–0.1 mm/year. © 1997 Elsevier Science Ltd

### INTRODUCTION

Three major Quaternary sinistral faults are found within the Eastern Betic Cordillera of southeastern Spain: the Carboneras, Palomares and Alhama de Murcia (Lorca) faults (Fig. 1). These faults comprise part of a large left-lateral transcurrent fault system known as the Trans-Alboran fault zone (Bousquet, 1979; Larouzière *et al.*, 1988; Sanz de Galdeano, 1990; Silva *et al.*, 1993). The principal NE–SW and ‘conjugate’ NW–SE secondary faults originated during the Miocene. Since the mid-Miocene, the faults have been subjected to periodic rotation of the regional principal stress direction (Sanz de Galdeano, 1990): from NW–SE (during the



(after Bousquet, 1979)

Fig. 1.

Tortonian, 10–11 Ma) to N–S (during the late Tortonian–early Pliocene, 5 Ma) to NNW–SSE (from the late Pliocene through the Quaternary). Focal mechanisms from moderate-magnitude earthquakes in southern Spain have yielded modern compression axis directions similar to the inferred Quaternary directions (Bufo *et al.*, 1988).

The NNE-trending Carboneras, Palomares and Lorca faults comprise the Eastern Betic Shear Zone, and they collectively account for as much as 50–60 km of left-lateral offset since the late Miocene (Bousquet, 1979; Sanz De Galdeano, 1990). Historical records since about AD 1500 indicate that small- to moderate-magnitude seismicity is associated with this zone of faulting (Bousquet, 1979; Mezcuca *et al.*, 1984; Bufo *et al.*, 1988; Carreno *et al.*, 1989; Sanz de Galdeano *et al.*, 1995). The 1518 Vera and 1522 Almeria earthquakes (intensities  $\geq$  IX) occurred along the southwestern portion of this fault system (Fig. 1).

The character of Quaternary faulting and the strike-slip control of basin development around the Palomares and Lorca faults are discussed by Bousquet *et al.* (1975), Bousquet (1979), Harvey (1987), Silva *et al.* (1993, 1997). This study examines the evidence for late Quaternary activity along the Carboneras fault, the southernmost of the faults within the Eastern Betic Shear Zone. In order to determine the extent and timing of late Quaternary sinistral faulting, we examined three segments of the Carboneras fault: the El Cabo de Gata, the Rio Carboneras and the La Serrata segments (Fig. 2). Late Quaternary offset along the fault is indicated by displaced coastal marine terraces in the first two segments. In the third segment, prominent 80–100-m wide offset stream channels have been attributed to late Pleistocene strike-slip movement in several previous studies (Bousquet, 1979; Fournier, 1980; Goy and Zazo, 1986; Harvey, 1990).

## APPROACH

The approach we used to characterize the late Quaternary slip history of the Carboneras fault was three-fold: (1) we examined the evidence for lateral offset of radiometrically dated coastal marine terraces; (2) we measured and dated the amount of lateral fault slip associated with offset stream channels in La Serrata; and (3) we investigated the geomorphic and stratigraphic evidence for a recent coastal tectonic uplift event by mapping upraised stream terraces and beach platforms.

Using geomorphic and pedogenic criteria, we defined a sequence of mid- to late Quaternary surficial deposits that were used to constrain recency and rate of paleoseismic activity. This stratigraphic sequence was calibrated by the use of previous radiometric ages from marine coastal terraces and from  $^{14}\text{C}$  dating conducted during this study. We provide in this study new preliminary data suggesting that measurable sinistral faulting along the Carboneras fault is substantially older than previously believed, and that recent—possibly historic—vertical movement has occurred along the fault system resulting in several metres of broad coastal uplift.



Fig. 1. Location map showing the Trans-Alboran fault zone in the Betic Cordillera of southeastern Spain. The Betic Cordillera are divided into External and Internal Zones based on lithological, tectonic and paleogeographic criteria (Sanz de Galdeano, 1990). Principal epicenters for large historical earthquakes with intensity  $\geq$  VIII are shown for the coastal region between Almeria and Alicante (Bufo *et al.*, 1988).

## RESULTS

*Carboneras fault segments*

The Carboneras fault consists of three principal segments: southern, northern and central. Near El Cabo de Gata (Fig. 2), the southern segment of the fault can be traced discontinuously in Tertiary and Quaternary sediments, and at the coast it cuts Tyrrenian marine terraces formed during the last interglacial period (primarily oxygen isotope stage 5). The principal trace of the fault projects along Rambla de Morales, and several subparallel traces to the north extend offshore. In Rambla de Las Amoloderas (Fig. 3), a prominent, cemented NE-striking fault plane exposed in the wash cuts Tyrrenian terrace deposits and exhibits a normal displacement down to the southeast. Cumulative vertical offsets across the several sub-parallel traces are on the order of 5–10 m (Goy and Zazo, 1986), but no measurable horizontal offsets are visible.

The northern segment of the Carboneras fault bounds the southern margin of the Sierra Cabrera (Fig. 2), where the fault is marked by a NE-striking, strongly brecciated shear zone in

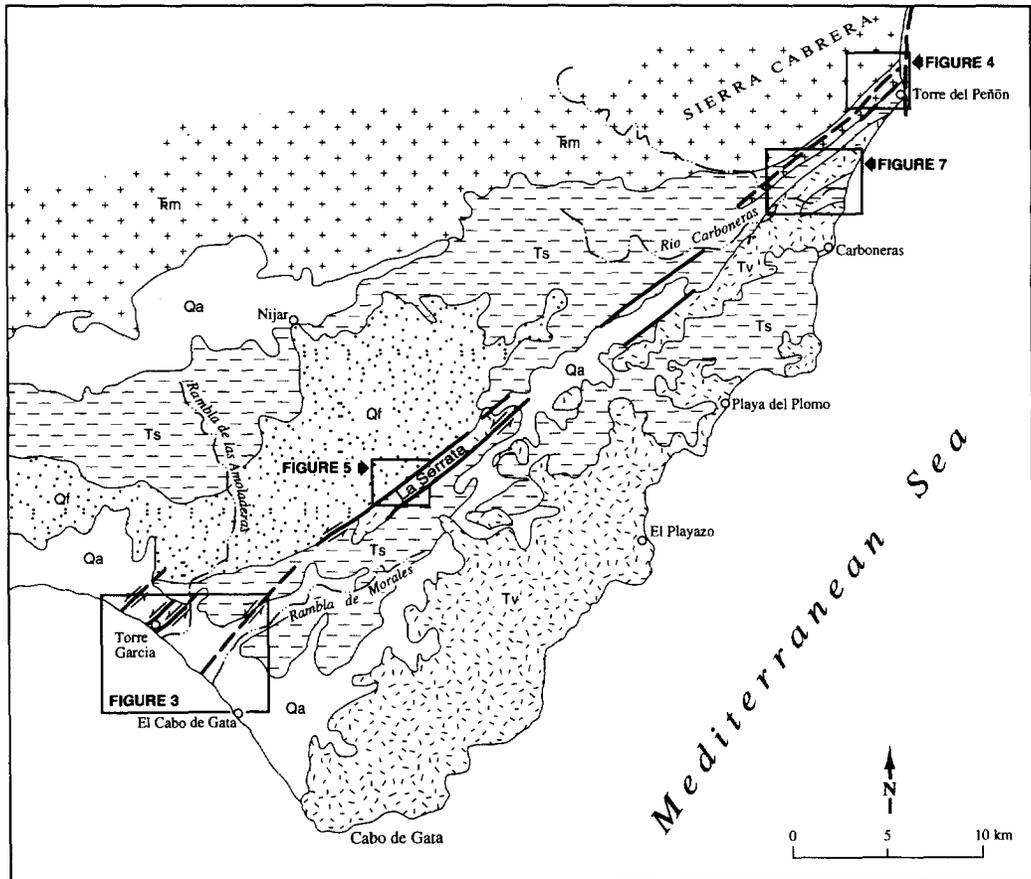


Fig. 2. Generalized geological map of the region of the Carboneras fault. Trm: metasedimentary rocks of Permo-Triassic age; Tv: volcanic rocks of probable Tertiary age; Ts: Tertiary sedimentary rocks; Qf: Quaternary alluvial piedmont deposits; Qa: Quaternary alluvium. (Modified from Almeria-Garrucha 1:200,000-scale geologic map sheet.)

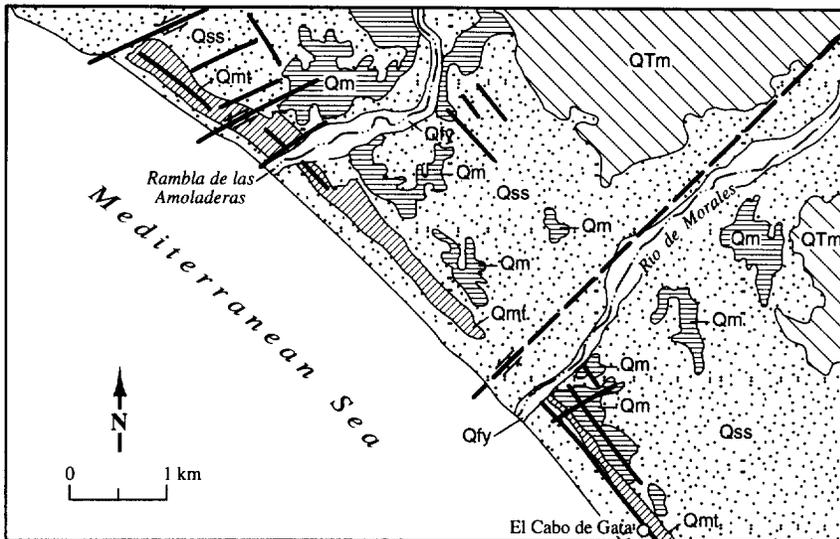


Fig. 3. Generalized geological map of the southern segment of the Carboneras fault near El Cabo de Gata. QTm: Plio-Pleistocene marine sedimentary deposits; Qm: pre-Tyrrhenian Quaternary marine terrace deposits; Qss: Quaternary alluvial and sedimentary deposits; Qmt: Tyrrhenian marine terrace deposits; Qfy: late Holocene stream alluvium. (Modified from Goy and Zazo, 1983.)

Permian and Triassic sedimentary and metasedimentary rocks. Near Rio Carboneras, the Carboneras fault is also a broad crushed zone cutting and folding metasedimentary terrain and Quaternary fill (Bousquet, 1979). North of Torre del Peñon (Fig. 4), the principal fault trace vertically displaces Tyrrhenian terraces about 5 m down to the north. North of the projected fault trace, the marine terraces are at sea level; south of the fault, they stand 5 m or more above sea level. No lateral displacement is visible in the exposed terrace sequence. Secondary, parallel splays of the Carboneras fault mapped in bedrock terrain west of Torre del Peñon pre-date the marine terraces (A. Harvey, 1995, written communication).

The Tyrrhenian marine terraces have been dated along this portion of the Spanish coastline by uranium-series analyses of the warm-water mollusc *Strombus bubonius* contained in the terrace deposits (Stearns and Thurber, 1965; Bernat *et al.*, 1978; Zazo and Goy, 1989; Hillaire-Marcel *et al.*, 1986; Zazo *et al.*, 1993). Three principal Tyrrhenian marine terraces have yielded numerous uranium–thorium–protactinium ages: T-I (ca 180 ka), T-II (ca 128 ka) and T-III (ca 95 ka). A fourth Tyrrhenian terrace (T-IV) estimated by Goy and Zazo (1986) to be 30–40 ka was later found to be about 85 ka (Hillaire-Marcel *et al.*, 1986). At El Cabo de Gata the full flight of stepped Tyrrhenian terraces is present, whereas at Torre del Peñon, only the two uppermost terraces are preserved. For this study, we have not differentiated between the marine terrace levels; we assume a nominal approximate age of 100 ka for the entire suite of Tyrrhenian terraces in order to divide Würmian and pre-Würmian alluvial deposits, and to estimate maximum fault slip rates.

The central segment of the Carboneras fault consists of two principal, parallel fault traces bounding a 1-km wide pre-Tertiary bedrock horst known as La Serrata (Figs 2 and 5). Based on field investigation, the most convincing evidence for Quaternary movement is along the northwest trace of the La Serrata horst where two smaller fault splays have formed a prominent

pressure ridge in bedrock and Quaternary alluvium. Northwest-flowing drainage from La Serrata has breached the pressure ridge, and several of the stream channels exhibit apparent left-lateral offsets ('bayonets') of as much as 100 m (Fig. 6).

#### *Quaternary alluvial deposits*

*Stratigraphic units*—In order to establish ages and rates of lateral slip along the Carboneras fault, we mapped three distinctive mid- to late Quaternary alluvial-geomorphic units; these units are, from youngest to oldest: Qfy, Qf and Qfo.

Qfy is a late Holocene alluvial fill contained within narrow terraces along present drainage channels. It is a brown to grey sandy silt (mud) forming prominent paired terrace surfaces standing a few metres above the modern stream channels. Recent agricultural terracing of the deposit suggests that the upper part of the unit may be cultural. Along Rio Carboneras, Qfy fill deposits characteristically consist of light grey sandy silts forming broad alluvial-fill terraces as much as 5 m high (Fig. 7).

Qf alluvial fan deposits form broad terraces in the principal drainages and compose the bulk of most mountain piedmonts, such as along La Serrata (Fig. 6). Qf soils typically exhibit a strongly reddened, textural argillic (Bt) horizon about 50 cm thick and a moderately strong calcic (Bk) horizon about 50–60 cm thick, having stage II to weak stage III secondary carbonate

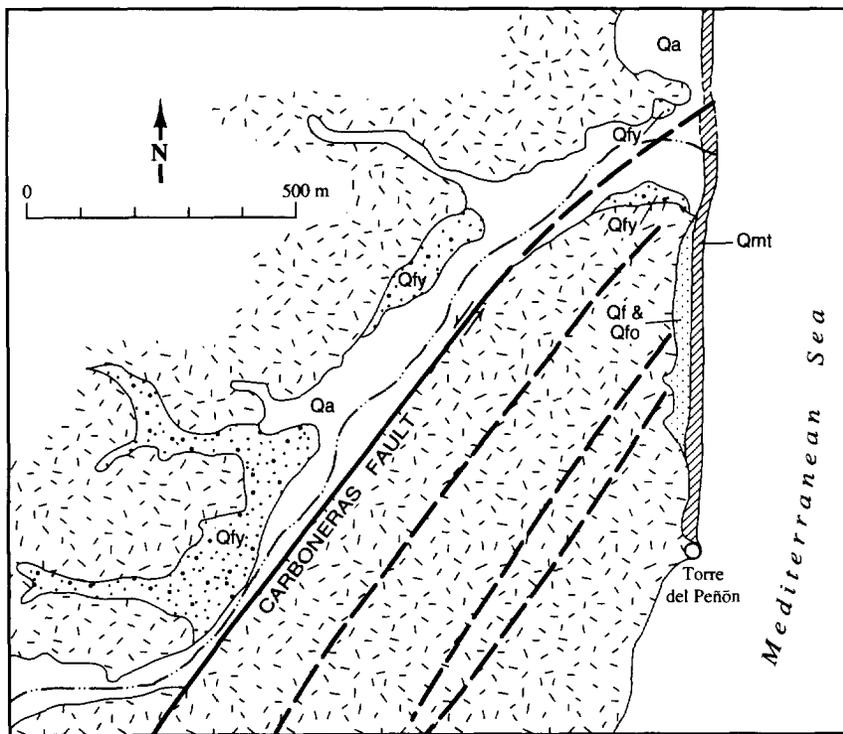


Fig. 4. Generalized geological map of the northern segment of the Carboneras fault zone. Tyrrhenian marine terraces are displaced 5 m down to the north by faulting. Qfo: pre-Tyrrhenian alluvial-fan deposits (>100 ka); Qmt: Tyrrhenian marine terrace deposits; Qf, post-Tyrrhenian alluvial-fan deposits; Qfy: late Holocene stream alluvium; Qa: modern stream alluvium.

development.

Qfo alluvial fan deposits are dissected remnants of once more extensive alluvial piedmonts. At La Serrata, they consist of irregularly shaped remnants buttressed and faulted against the pressure ridge. Qfo soils exhibit a strongly reddened, textural, truncated Bt horizon at least 30 cm thick overlying a strongly developed stage III–IV calcic (calcrete) horizon about 1 m thick.

*Ages of alluvial deposits*—Qfy soils have no visible pedogenic development, exhibiting A–C profiles (Fig. 8; Pedon #3). Qfy deposits have been extensively culturally modified, and thus the original soils, which would be otherwise indicative of age, are not well preserved. Nevertheless, the persistent lack of any pedogenic horizonation strongly suggests that the deposits are, at a maximum, no more than 1–2 ka in age.

We believe that Qfy deposits are equivalent to the Liotor Alluvium of Vita-Finzi (1964, 1976), a ubiquitous, post-Roman alluvial fill found throughout the western Mediterranean region. They may also be in part correlative with unit D of Harvey and Wells (1987). In southeastern Spain, Vita-Finzi (1976) reported  $^{14}\text{C}$  ages ranging between 419 and 853 years BP. In this study, we dated detrital charcoal taken from a 1-m depth in Qfy deposits along Rio Carboneras (Fig. 7) that yielded a  $^{14}\text{C}$  date of  $390 \pm 60$  years BP (Laboratory No. Beta-84855). The corrected

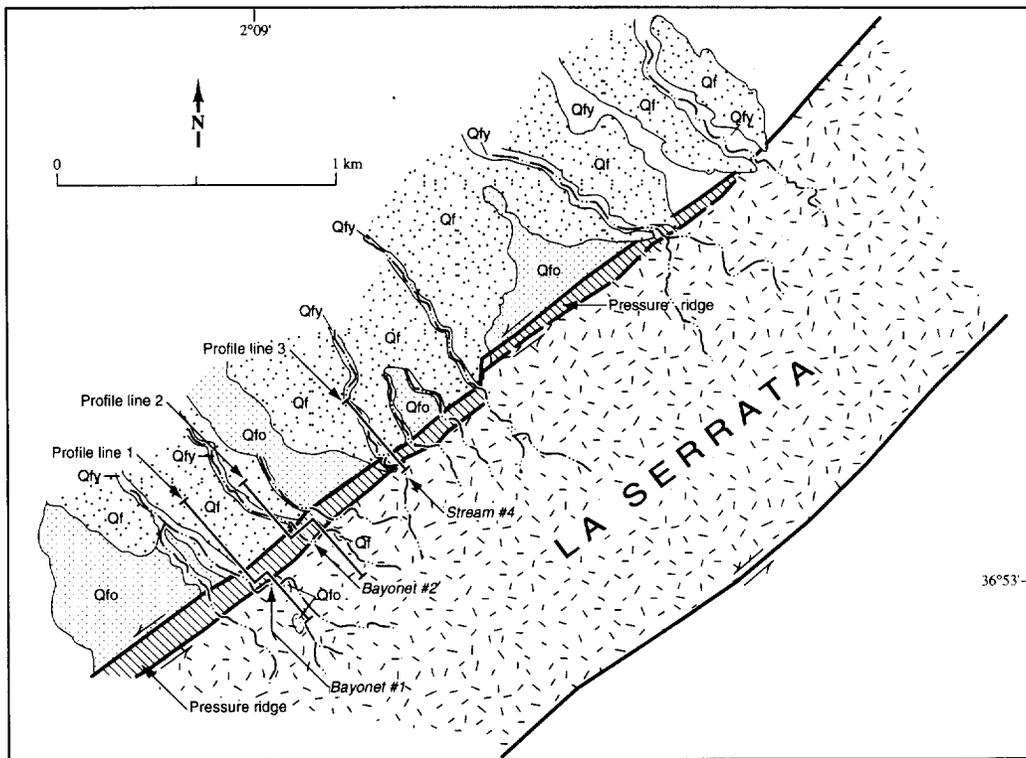


Fig. 5. Generalized surficial geological map of the northwestern flank of La Serrata showing offset stream channels (bayonets) and location of topographic profile lines. Qfo: pre-Tyrrhenian alluvial-fan deposits (>100 ka); Qf: post-Tyrrhenian alluvial-fan deposits (<100 ka); Qfy: late Holocene stream alluvium (<1–2 ka).

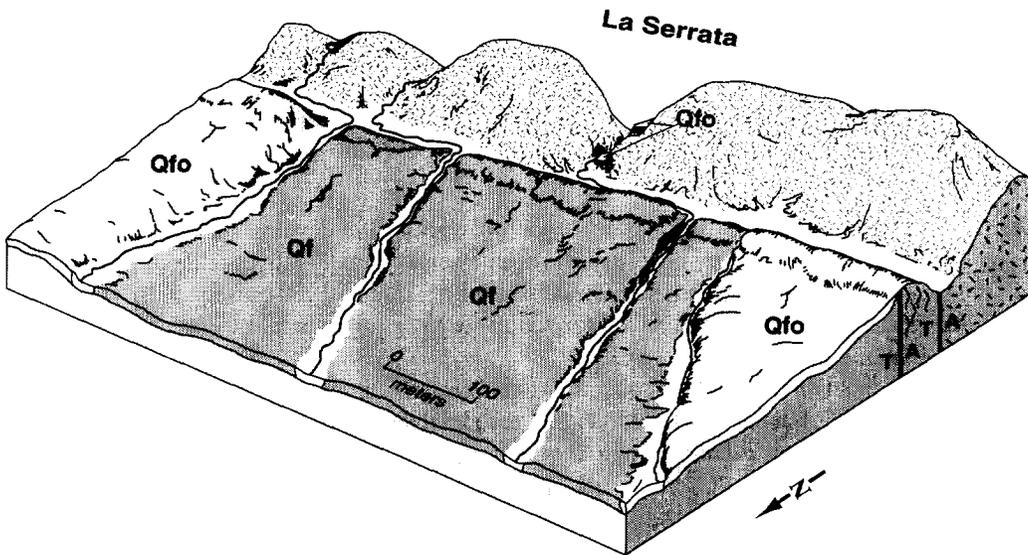


Fig. 6. Three-dimensional isometric drawing of the northwest flank of La Serrata showing the three offset stream channels, the piedmont alluvium relations, and the location of the principal fault traces. See Fig. 5 for abbreviations.

calendric age is AD 1475 with a  $2\text{-}\sigma$  range between AD 1425 and 1650.

We estimate numerical ages for the Qf and Qfo alluvial fans based on previous soil geomorphic studies and on the stratigraphic relations we found between soils and the Tyrrhenian terraces. In general, the broad alluvial Quaternary piedmonts which occur along the mountain ranges throughout the Betic Cordillera are believed to be products of the colder, drier glacial periods (Harvey, 1984; Lhenaff, 1986; Harvey and Wells, 1987). These alluvial-piedmont deposits alternate in sequence with the marine interglacial terrace deposits (Goy and Zazo, 1986, 1989).

Soil morphology provides a useful criterion for distinguishing and dating alluvial piedmont deposits. Three age-related types of calcium carbonate crusts (*croûtes calcaires*) are recognized in southeastern Spain (Dumas, 1969; Fournier, 1980; Harvey, 1984; Harvey and Wells, 1987; Silva *et al.*, 1992): (1) weak calcretes (stage II) of late Pleistocene age; (2) mature ( $\sim 1$  m) calcretes (stage III–IV) of mid-Pleistocene age; and (3) massive ( $\geq 1$  m) calcretes (stage IV and greater) of early Pleistocene age. The stage II calcretes are believed to be of probable Würmian glacial age ( $< 100$  ka), and the more strongly developed crusts to be pre-Würmian in age. The massively cemented calcretes are commonly inferred to be of Rissian age, hundreds of thousands of years old (*cf.* Harvey *et al.*, 1995).

The morphology and thickness of the argillic Bt horizon is also a useful criterion for distinguishing and dating soils (Birkeland, 1984). Properties such as rubification, texture, clay film development, structure and consistence may be quantified for comparing and correlating soils. For example, under similar arid climatic conditions in the western Basin and Range Province of the U.S.A., soils exhibiting Bt and Bk horizons comparable in morphology and thickness to those we found in Qf are of late Pleistocene (Würmian) age (Bull, 1991). The translocation of clay and depth of carbonate movement indicate that they have been subjected to at least one pluvial episode; they are thus at least 35 ka in age.

*Calibration of soil age*—Two kilometres north of the town of Carboneras near the mouth of Rio Carboneras (Fig. 7), we mapped a Qf deposit which post-dates (overlies) the 100-ka Tyrrhenian terraces. We use this soil to calibrate and establish a maximum age of the Qf fans. North of Torre del Peñon (Fig. 4), Qfo-age alluvial fans pre-date (are truncated by) the Tyrrhenian terraces, and thus they are older than 100 ka. Harvey (1987) also described Qf-age fans overlying marine terrace deposits at this location. These relations are consistent with the respective Würmian and pre-Würmian ages suggested for these soils by previous workers.

Standardized field properties were described for the Qf soil at La Serrata (Fig. 8; Pedon #1) and for the post-100 ka alluvial-fan soil overlying the coastal terraces (Pedon #5). Using the field properties of rubification, texture, structure and consistence, we calculated quantitative soil property indices according to Harden (1982). The La Serrata Qf soil yielded a Harden soil development index of 24.1, and the coastal post-Tyrrhenian (<100 ka) soil yielded a Harden index of 34.9. Harden (1982) found soil property indices to range up to about 160 for soils estimated to be about 600 ka in age. The indices calculated here would, therefore, correspond to a late Pleistocene age of less than 100 ka based on correlation with the Harden (1982) soils. Harvey and Wells (1987) determined a Harden soil development index of 36.5 for fluvial deposits in the Sorbas basin (25 km northwest of Carboneras) that may be correlative with Qf deposits. The similarity of the Pedon #1 and #5 indices indicates that Qf deposits at La Serrata are younger than 100 ka.

*Topographic profiles*—In order to investigate the geomorphic evidence for tectonic movement,

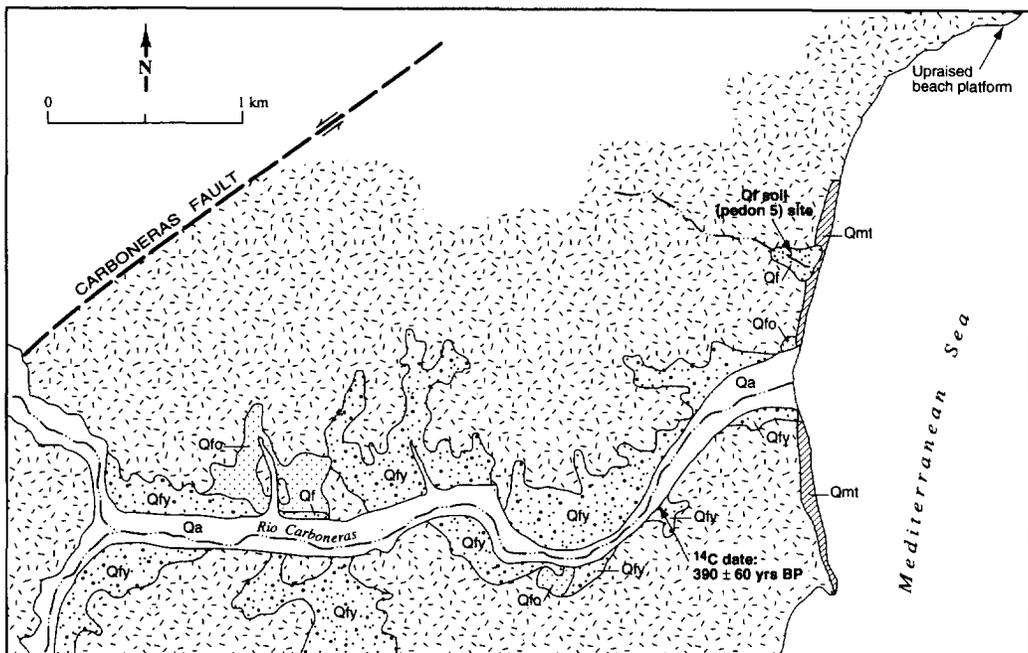


Fig. 7. Generalized surficial geological map of the lower portion of the Rio Carboneras drainage showing alluvial deposits, the location of the  $^{14}\text{C}$  and Qf soil calibration sites, and the location of the upraised beach platform. Qfo: pre-Tyrrhenian alluvial-fan deposits (>100 ka); Qm: Tyrrhenian marine terrace deposits; Qf: post-Tyrrhenian alluvial-fan deposits (<100 ka); Qfy: late Holocene stream alluvium (<1–2 ka); Qa: modern stream alluvium.

we used a Wild theodolite equipped with an electronic distance meter to precisely survey the longitudinal gradients of the La Serrata Qf and Qfo fan surfaces and the fluvial Qfy terrace

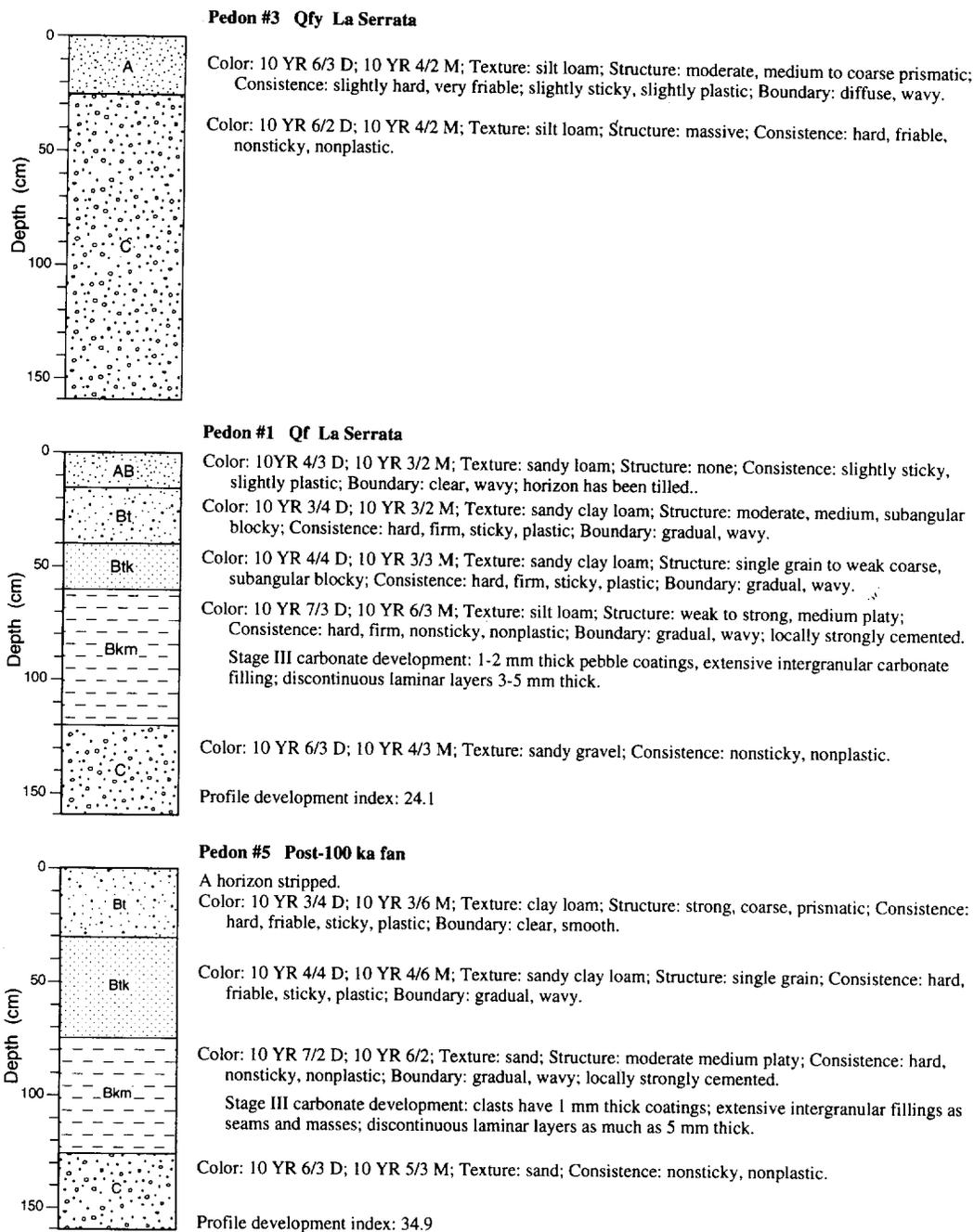


Fig. 8. Representative pedon descriptions for Qf and Qfy deposits.

remnants along Rio Carboneras (Fig. 5). At La Serrata we assumed that the paleofan gradients were related to conventional channel-fan dynamics (cf. Harvey, 1990). We argue that any fault displacement post-dating the deposition of Qf and Qfo would be indicated by disrupted fan profiles through the 80–100 m wide bayonets. The terrace elevations are plotted as a function of linear along-stream distance through the bayonets, and any significant lateral displacement would produce a flat profile gradient, that is, the fan surface profile would be flattened or 'stretched out' by lateral offset.

At La Serrata the best preserved profiles were found in streams 1, 2 and 4. Due to data scatter each terrace profile was constructed using a best-fit line, which we assume reasonably approximates to the original alluvial fan gradient. Some data points lie  $\pm 1$  m off the reconstructed profiles; this data scatter may be real, but our field observations suggest that much of it is due to cultural modification.

At stream 1 [Fig. 9(A) and (B)], the gradients of profiles on the Qf and Qfo fan surfaces are similar with Qf inset a few metres below Qfo. The modern stream has incised to bedrock and displays a series of prominent knickpoints, particularly where it descends through the pressure ridge. A projection of fan profiles upstream through the pressure ridge indicates that two upstream terrace remnants are of Qfo age. Both of these profiles indicate that little to no displacement has occurred since Qfo time.

At stream 2 [Fig. 9(C)], the profile of the right-bank Qf fan surface is projected through the bayonet to an upstream fan remnant containing a Qf soil. This profile also indicates that no significant fault displacement has occurred since Qf time.

At stream 4 [Fig. 9(D)], which lacks a bayonet, the Qf profile provides further evidence that little fault offset has occurred since the deposition of Qf; the profile is linear and continuous through the fault zone. It indicates that no detectable vertical displacement ( $> 1$  m) has occurred and that no lateral 'stretching' of the profiles has occurred since the deposition of Qf.

Along the Rio Carboneras, (Fig. 7), we surveyed Qfy remnants along the lower 1 km of the drainage, and we reconstructed paleostream profiles. Here, we assumed that the Rio Carboneras was hydraulically graded to the Mediterranean Sea during Qfy deposition, as it is at the present. The results indicate that the right-bank terrace profile is closely parallel to the present channel gradient [Fig. 10(A)]. The left-bank profile, although similar in the upstream portion, is substantially higher in elevation in the downstream portion. We attribute this difference to cultural terracing and irrigation of the left-bank terrace which is evident at several locations.

## DISCUSSION

### *Lack of evidence for significant late Quaternary sinistral slip*

Several lines of evidence suggest late Quaternary slip along the Carboneras fault is dominantly vertical, rather than strike slip. We found little evidence for lateral offset of 85–180-ka Tyrrhenian terraces at either end of the Carboneras fault where it extends offshore (Figs 3 and 4). Near Cabo de Gata, Tyrrhenian terraces are vertically offset by as much as 10 m, and north of Carboneras, the marine terraces are vertically offset about 5 m, although part of this offset may be related to movement on the nearby Palomares fault (A. Harvey, 1995, written communication). If a vertical to horizontal slip ratio of 1:20 is assumed for the Carboneras fault based on slickenside data (Fournier, 1980), as much as 100–200 m of left-lateral offset in the marine terrace sequence should be evident. The lack of such large lateral offsets suggests that other factors, such as conjugate normal faulting or change in structural style, may be controlling

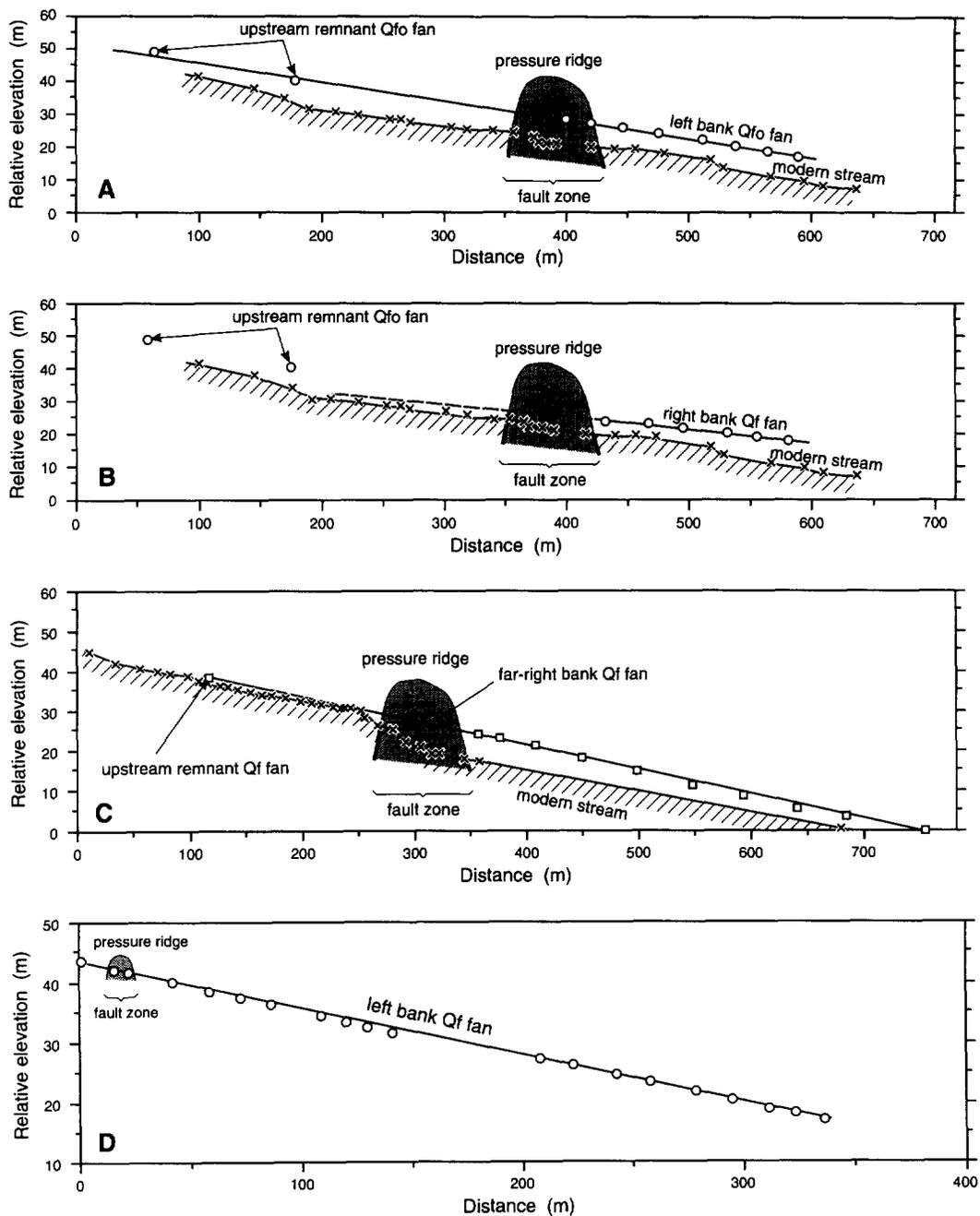


Fig. 9. Topographic profiles surveyed on alluvial-fan surfaces extending through the Carboneras fault zone. (A) Profile along Bayonet #1 showing reconstruction of Qfo fan gradient and modern stream channel gradient. (B) Profile along Bayonet #1 showing reconstruction of Qf fan gradient and modern channel gradient. (C) Profile along Bayonet #2 showing reconstruction of Qf fan gradient and modern channel gradient. (D) Profile along Stream #4 showing reconstruction of Qf fan gradient.

late Quaternary movement along the fault.

At La Serrata, the 80–100-m wide offset stream channels are tectonic, but they are early to mid-Quaternary in age. Based upon stratigraphic evidence and the reconstruction of paleofan gradients through the fault zone, we conclude that the left-lateral offsets occurred before about 100 ka and possibly much earlier. Exposures along the fault trace indicate that Qf, and locally Qfo, deposits are unfaulted. Reconstruction of Qf fan gradients also indicates that the fan surfaces have not been measurably offset by vertical or horizontal displacement since their deposition. We conclude that these units were deposited within drainages exhibiting pre-existing lateral offsets. The age of these lateral offsets is not precisely known, but strongly developed calcretes of pre-Qfo ( $\geq 100$  ka) are offset, and the lateral faulting thus appears no younger than mid-Quaternary in age. Field evidence also indicates that there has been little vertical slip along the La Serrata segment since the deposition of Würmian-age ( $< 100$  ka) Qf fans. No scarps are visible in Qf alluvium, and the longitudinal profiles of Qf fan gradients through the fault zone indicates that Qf fan surfaces have not been visibly offset or deformed.

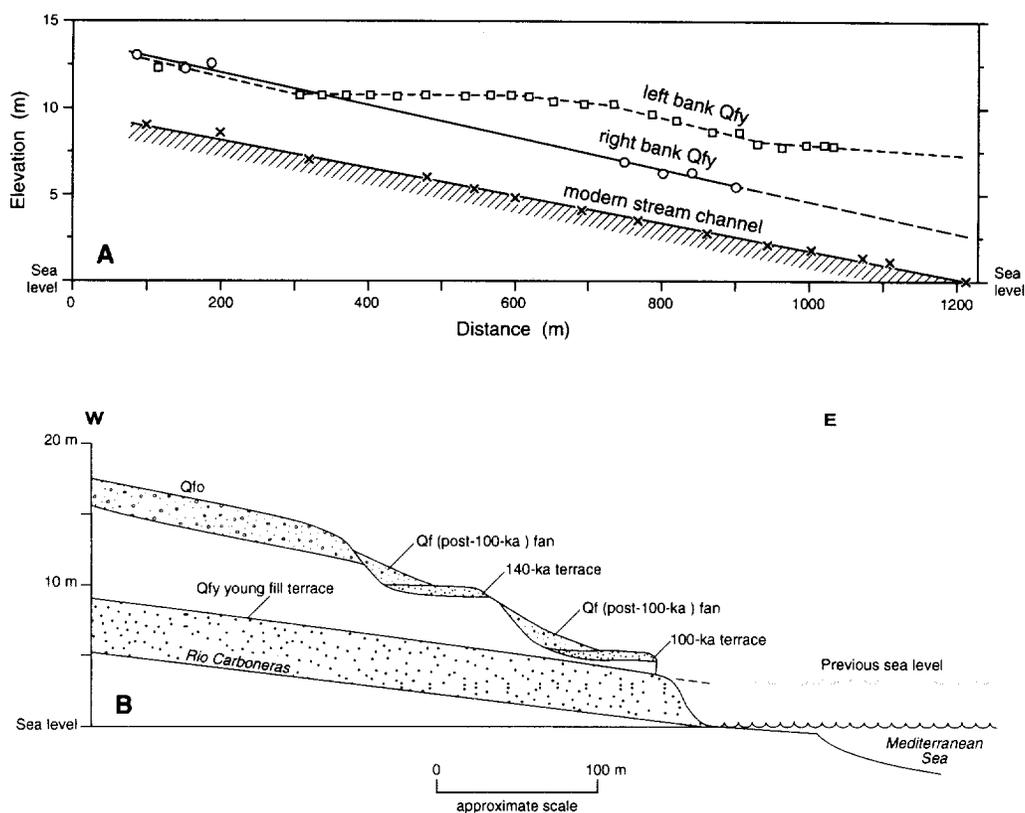


Fig. 10. Topographic and cross-section relations of surficial deposits along the lower portion of the Rio Carboneras. (A) Topographic profiles along left- and right-bank terrace gradients of Qfy and modern stream channel gradient. (B) Schematic cross-section of surficial relations between Rio Carboneras deposits and coastal marine terrace deposits of Tyrrhenian age (dated at *ca* 100 and 140 ka). Qfo: old alluvial fan deposits ( $> 100$  ka); Qf: alluvial fan deposits younger than Tyrrhenian terraces ( $< 100$  ka); Qfy: late Holocene stream alluvium. Note that the top of the Qfy terrace is graded to a previous sea level approximately 3 m higher than modern sea level.

### *Evidence for late Holocene coastal uplift*

At several localities along the coastline between Cabo de Gata and Carboneras (Fig. 2), we found geomorphically fresh bedrock beach platforms elevated at heights of 2–3 m above modern sea level. We believe that these raised beach platforms, together with stream profile data along Rio Carboneras, indicate that late Holocene tectonic uplift has occurred along the coast. At Playa del Plomo (Fig. 1), bedrock platforms elevated 3 m above modern sea level are notched into vertical beach cliffs, and they have only been slightly eroded since emergence. North of Rio Carboneras (Fig. 7), a similar raised beach platform is visible along the coastline.

Along Rio Carboneras, we found that Qfy terrace surfaces project to a coastal base level 3–5 m above modern sea level [Fig. 10(B)]. The paleostream profile reconstructed for Qfy deposits is parallel to the modern stream profile, indicating that stream hydraulics [drainage area and channel slope-width relations (cf. Harvey, 1990)] have remained unchanged. The Qfy stream gradient also projects close to the same height as the raised bedrock beach platform found 2 km north of the channel profile (Fig. 7). The projection of the Qfy terrace to a height above modern sea level and the presence of an upraised beach platform indicate that either sea level was higher during the late Holocene or that the coast has been uplifted.

Previous studies of worldwide sea level generally indicate that sea level during the mid- to late Holocene has not been higher than present (Hopley, 1978; Field *et al.*, 1979; Kennett, 1982). More recently, Pirazzoli (1991) presented a compilation of sea level data from the central Mediterranean region which shows that sea level has not been higher than present during the last 4–5 ka.

Our study of paleostream gradients along the Rio Carboneras strongly suggests that several metres of uplift has occurred during the late Holocene along the coast near Carboneras. Supporting this conclusion are the similar stratigraphic relations found in other principal coastal drainage channels. At El Cabo de Gata, several major washes contain Qfy fill terraces 1–2 m high. At El Playazo, a Holocene stream terrace containing Roman or post-Roman pottery stands 2 m above sea level. At Playa del Plomo, a 3-m thick Holocene terrace fill can be traced to a raised bedrock beach platform. Based upon the  $^{14}\text{C}$  age of  $390 \pm 60$  years BP we obtained for Qfy deposits along Rio Carboneras, we believe that a tectonic event has probably occurred since about AD 1475 and that it uplifted the coastline between El Cabo de Gata and Carboneras. Although the precise age of this event is not known, it could be related to either the 1518 Vera or the 1522 Almeria earthquakes.

### SUMMARY

We conclude that late Quaternary slip rates along the Carboneras fault have been relatively low, and that they have been dominantly vertical in nature. The prominent 80–100-m left-lateral Quaternary stream offsets at La Serrata occurred earlier than about 100 ka, and they are possibly much older. Laterally offset alluvial fans containing massive calcretes are estimated to be hundreds of thousands of years in age. If we assume an age of 500 ka for these ancient Quaternary fans, we calculate an approximate early to mid-Quaternary sinistral slip rate of 0.2–0.3 mm/year. Maximum late Quaternary vertical slip rates estimated from displaced Tyrrhenian marine terraces (*ca* 100 ka) are on the order of 0.05–0.1 mm/year.

We do not at this time know which segments, if any, of the Carboneras fault have contributed to the late Holocene coastal uplift. The late Quaternary pattern of tectonic movement along the coast appears to be complex. Although we found no evidence for late Quaternary lateral offset along the Carboneras fault, vertical offsets of as much as 10 m are measured at the coast, and

the long-term regional trend of tectonic movement along the coast appears to be one of uplift. The 128-ka Tyrrenian (T-II) terrace at El Cabo de Gata formed at an interglacial sea level 10–20 m below the present level (Bernat *et al.*, 1978). It now stands 5–10 m above sea level at most locations along the Almeria-Carboneras coastline, clearly illustrating the long-term vertical uplift trend. This trend is also consistent with focal mechanisms determined for recent earthquakes which show regional E–W tensional stresses producing normal displacements on NE-striking fault systems (Bufoin *et al.*, 1988).

*Acknowledgements*—This study was in part funded by the desertification project of the European Community. The authors thank Rolando Armijo, Bertrand Meyer, and Armando Cisternas for helpful discussions, and Peter Talling and Adrian Harvey for manuscript review. The study was conducted while the senior author was on sabbatical leave as a visiting researcher at the Institut de Physique du Globe, Strasbourg, France.

#### REFERENCES

- Bernat M., Bousquet J.-C. and Dars R. (1978)  $I_0/U$  dating of the Ouljian stage from Torre Garcia (Spain). *Nature* **276**, 302–303.
- Birkeland P. W. (1984) *Soils and Geomorphology*. Oxford University Press, New York.
- Bousquet J.-C. (1979) Quaternary strike-slip faults in southeastern Spain. *Tectonophysics* **52**, 277–286.
- Bousquet J.-C., Dumas B. and Montenat C. (1975) Le décrochement de Palomares: décrochement Quaternaire sénestre du Bassin de Vera (Cordillères Bétiques orientales, Espagne). *Cuad. Geol. Univ. Granada* **6**, 113–119.
- Bufoin E., Udias A. and Mezcua J. (1988) Seismicity and focal mechanisms in south Spain. *Bull. seism. Soc. Am.* **78**, 2008–2024.
- Bull W. B. (1991) *Geomorphic Responses to Climatic Change*. Oxford University Press, New York.
- Carreno E., Martinez-Solares J. M., Sanchez-Venero M., Bufoin E., Herraiz M., Pro C., Udias A., Gallart J., Cisternas A., Rivera L., Gaulon J., Patau G. and Phillip H. (1989) Microseismicity surveys of the fault-systems of S.E. Spain. *Rev. Geofisica* **45**, 117–122.
- Dumas M. B. (1969) Glacis et croûtes calcaires dans le levant espagnol. *Ass. Géogr. Fr. Bull.* **375–376**, 553–561.
- Field M. E., Meisburger E. P., Stanley E. A. and Williams S. J. (1979) Upper Quaternary peat deposits on the Atlantic inner shelf of the U.S. *Bull. geol. Soc. Am.* **90**, 618–628.
- Fournier M. (1980) Le bassin de Nijar-Carboneras (Cordillères Bétiques) néotectonique; étude des diaclases. Ph.D. Thèse, Université Paris VII.
- Goy J. L. and Zazo C. (1983) Cartografía y memoria del Cuaternario de la Hoja (1059), El Cabo de Gata. Mapa Geológico de España, 1:50,000, 2 ser., Instituto Geologica y Minero de España.
- Goy J. L. and Zazo C. (1986) Synthesis of the Quaternary in the Almeria littoral, neotectonic activity and its morphologic features, western Betics, Spain. *Tectonophysics* **130**, 259–270.
- Goy J. L. and Zazo C. (1989) The role of neotectonics in the morphologic distribution of the Quaternary marine and continental deposits of the Elche Basin, southeast Spain. *Tectonophysics* **163**, 219–225.
- Harden J. W. (1982) A quantitative index of soil development from field descriptions: examples from a chronosequence in central California. *Geoderma* **28**, 1–28.
- Harvey A. M. (1984) Aggradation and dissection sequences on Spanish alluvial fans: Influence on morphological development. *Catena* **11**, 289–304.
- Harvey A. M. (1987) Patterns of Quaternary aggradational and dissectional landform development in the Almeria region, southeast Spain: a dry-region, tectonically active landscape. *Die Erde* **118**, 193–215.

- Harvey A. M. (1990) Factors influencing Quaternary alluvial fan development in southeast Spain. In: *Alluvial Fans: a field approach* (Rochocki A. H. and Church M. eds.), John Wiley and Sons, New York. pp. 247–269.
- Harvey A. M. and Wells S. G. (1987) Response of Quaternary fluvial systems to differential epeirogenic uplift, Aguas and Feos river systems, southeast Spain. *Geology* **15**, 689–693.
- Harvey A. M., Miller S. Y. and Wells, S. G. (1995) Quaternary soil and river terrace sequences in the Aguas/Feos river systems: Sorbas basin, southeast Spain. In: *Mediterranean Quaternary River Environments* (Lewin J., Macklin M. G. and Woodward J. C. eds), pp. 263–281. Balkema, Rotterdam.
- Hillaire-Marcel C., Carro O., Causse C., Goy J. L. and Zazo C. (1986) Th/U dating on *Strombus bubonius* bearing marine terraces in southeastern Spain. *Geology* **14**, 613–616.
- Hopley D. (1978) Sea level changes on the Great Barrier reef. *Phil. Trans. R. Soc. Lond.* **A291**, 159–166.
- Kennett J. (1982) *Marine Geology*. Prentice-Hall, Englewood Cliffs, New Jersey.
- Larouzière F. D., Bolze J., Bordet P., Hernandez J., Montenat C. and Ott d'Estevou P. (1988) The Betic segment of the lithospheric Trans-Alboran shear zone during the late Miocene. *Tectonophysics* **152**, 41–52.
- Lhenaff R. (1986) Héritages morphoclimatiques et environnements du Quaternaire moyen méditerranéen. *Ass. Géogr. Fr. Bull.* **63**, 21–30.
- Mezcua J., Herraiz M. and Buforn E. (1984) Study of the 6 June 1977 Lorca (Spain) earthquake and its aftershock sequence. *Bull. seism Soc. Am.* **74**, 167–179.
- Pirazzoli P. A. (1991) *World Atlas of Holocene Sea-level Changes*. Elsevier Oceanography Series, 58, Amsterdam.
- Sanz de Galdeano C. (1990) Geologic evolution of the Betic Cordilleras in the western Mediterranean, Miocene to the present. *Tectonophysics* **172**, 107–119.
- Sanz de Galdeano C., Casado C. L., Delgado J. and Peinado M. A. (1995) Shallow seismicity and active faults in the Betic Cordillera. A preliminary approach to seismic sources associated with specific faults. *Tectonophysics* **248**, 293–302.
- Silva P. G., Goy J. L., Somoza L., Zazo C. and Bardaji T. (1993) Landscape response to strike-slip faulting linked to collisional settings: Quaternary tectonics and basin formation in the eastern Betics, southeastern Spain. *Tectonophysics* **224**, 289–303.
- Silva P. G., Goy J. L. and Zazo C. (1992) Structural and geometrical features of the Lorca-Alhama strike-slip fault. *Geogaceta* **12**, 7–11.
- Silva P. G., Goy J. L., Cari Z., Lario J. and Bardaji T. (1997) Paleoseismic indications along 'aseismic' fault segments in the Guadalentín depression (SE Spain). *J. Geod.* **24**, 105–115.
- Stearns C. C. and Thurber D. L. (1965) Th-230-U-234 dates of late Pleistocene marine fossils for mediterranean and Moroccan littorals. *Quaternaria* **VII**, 29–42.
- Vita-Finzi C. (1964) Synchronous stream deposition throughout the Mediterranean area in historical times. *Nature* **202**, 1324.
- Vita-Finzi C. (1976) Diachronism in Old World alluvial sequences. *Nature* **263**, 218–219.
- Zazo C. and Goy J. L. (1989) Sea-level changes in the Iberian peninsula during the last 200,000 years. In: *Late Quaternary Sea-level Correlation and Applications* (Scott D. B., Pirazzoli P. and Honing G. eds), pp. 27–39. Kluwer Academic Publishers.
- Zazo C., Goy J. L., Dabrio C. J., Bardaji T., Somoza L. and Silva P. G. (1993) The last interglacial in the Mediterranean as a model for the present interglacial. *Global & Planet. Change* **7**, 109–117.