

Neogene strike-slip faulting in southeastern Spain: the deformation of the pull-apart basin of Abarán

H. C. van der Straaten
Uitgeeststraat 7, 1013 ZL Amsterdam, the Netherlands

Received 10 March 1992; accepted in revised form 28 October 1992

Key words: Betic Cordillera, Betic foreland, External Zone

Abstract

The Abarán Basin is interpreted as a Neogene pull-apart basin that developed along an east-striking right-slip fault zone in the thin-skinned fold-and-thrust belt of the Betic foreland (External Zone). Apart from showing well known strike-slip characteristics, the fault zone is typified by drag and imbrication along subvertical faults. Considerable right-slip faulting before, during and after basin development is demonstrated by the unconformable contact between the basin and its faulted 'basement', by the formation and deformation of the basin, and by the lateral separation between basin and hinterland.

The Abarán Basin shows a typical rhombic shape determined by synsedimentary faults. The fault configuration is interpreted as a releasing overstep: the northern and southern basin margin were controlled by two major right-hand stepping, east-striking right-slip faults connected by minor northwest-striking normal-oblique slip faults bounding the basin in the east and the west.

The progressive opening of the basin in response to the right-slip along the fault zone, generated lateral shear and extension parallel to the strike-slip basin margins throughout the sedimentation history. Right-slip led to en-echelon folds and progressive drag. Extension resulted in an overall deepening of the basin and activated normal faults.

Due to movements along normal faults dipping away from the basin centre, older sediments were torn apart while being tilted. The resulting depression in the centre of the basin was subsequently filled by younger sediments that accumulated next to older deposits. Repetition of this mechanism with basinward fault progradation, generated downlapping sediment packages that step over normal faults.

Introduction

The Abarán Basin is interpreted as a detached pull-apart basin that developed along a right-slip fault in the thin-skinned fold-and-thrust belt of the Betic foreland (SE Spain). With its modest size (10 × 4 km), good exposure and little disturbance by post-depositional faulting, the Abarán Basin provides a unique opportunity to document pull-apart deformation. Apart from showing well known strike-slip characteristics, the Abarán example sheds light up-

on some less known features, generally little discussed in literature, yet typical for strike-slip deformation. These are: the dominant role of drag and structural imbrication, and the oblique stacking of sediment packages that step over normal faults in extensional areas. In addition, the offset history of the right-slip fault could be reconstructed on the basis of the regional geology, the interpretation of the Abarán Basin and a neighbouring basin, and the lateral separation between basin fill and hinterland.

The present paper deals with the deformation by

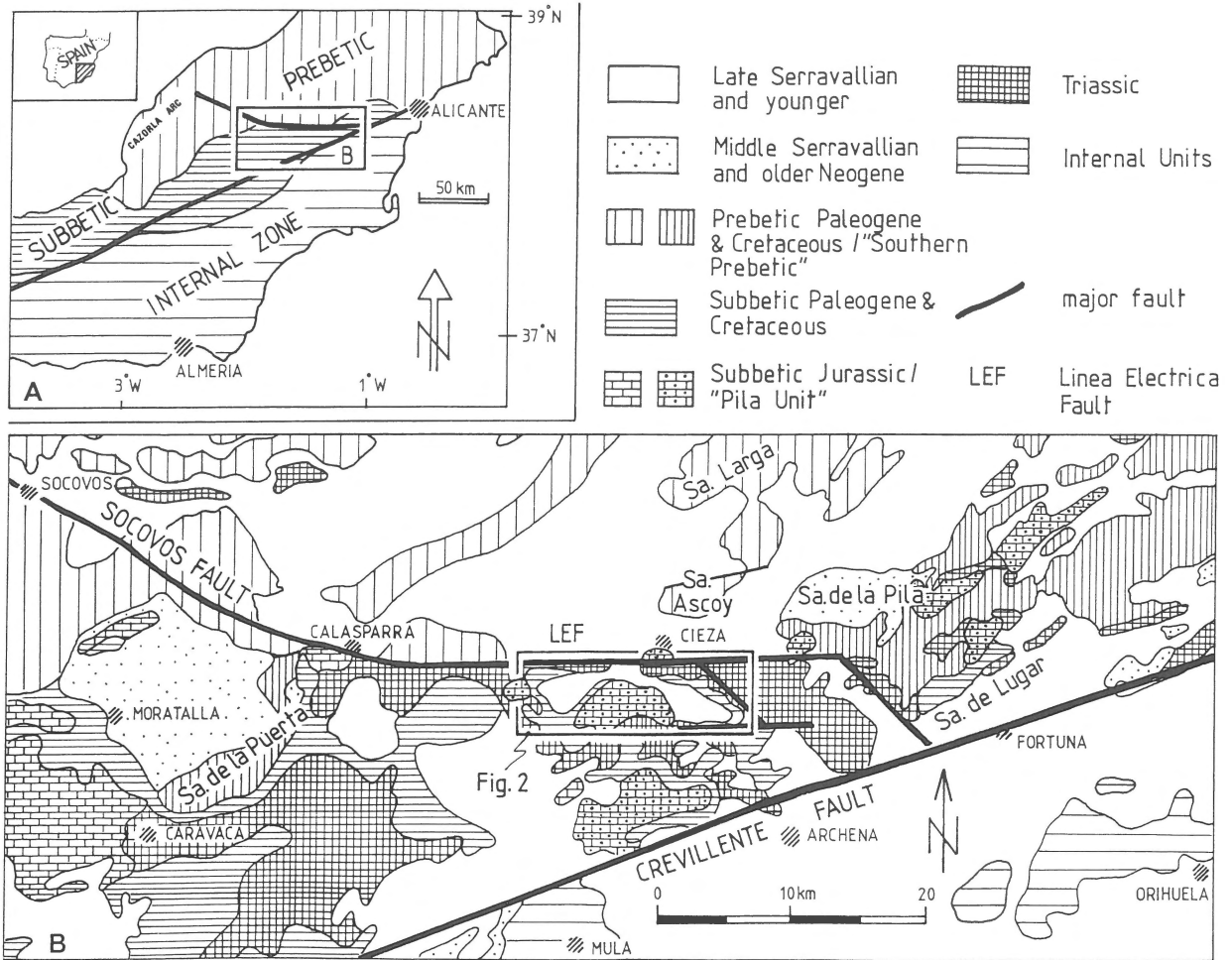


Fig. 1. Geological setting. A) Tectonic sketch map of the central and eastern Betic Cordillera. B) Geological map of the area of the Abarán Basin (modified after Baena Perez & Jerez Mir 1982). The 'Southern Prebetic' and the 'Pila Unit' correspond with the 'Prebetico Interno central and meridional' of Baena Perez & Jerez Mir (1982) and the 'Subbetico Medio-Septentrional' of Jerez Mir (1979), respectively.

right-slip faulting of the Abarán Basin and its pre-Miocene 'basement'. Basin sedimentation and post-depositional faulting separating basin and hinterland, will be discussed in Van der Straaten (forthcoming).

Geological setting

The Abarán Basin is situated in the northern part of the External Zone of the Betic Cordillera, the Alpine mountain belt in SE Spain. The External Zone is the foreland fold-and-thrust belt of the orogen

and consists of non-metamorphic sediments. Parallel SW-NE facies belts on a southeastward sloping passive continental margin prevailed during the Mesozoic and Paleogene. The fold-and-thrust belt was created by Miocene NW-SE compression (Jerez Mir 1979, Baena Perez & Jerez Mir 1982, Dercourt et al. 1986, Kenter et al. 1990).

The External Zone is subdivided into the Subbetic unit in the south and the Prebetic unit in the north (Fig. 1A). The Subbetic unit consists of Triassic to Miocene rocks characterized by Late Jurassic to Paleogene sediments of deep-marine origin. The unit is highly disrupted by overthrusting and strike-

slip faulting. Thrusting took place during the Miocene with final emplacement of the thrust slices in the middle to late Serravallian. The northern Subbetic is generally considered to consist of allochthonous thrust sheets overlying autochthonous Prebetic rocks. The exposed Prebetic unit due north of the Abarán Basin consists of neritic to continental deposits ranging in age from Aptian to Middle Miocene. Compression prevailed since the late Burdigalian and led to a major, late Serravallian orogenic phase that generated NE-trending folds and SE-dipping reverse faults (Paquet 1969, IGME 1974, 1975, Jerez Mir 1979, Garcia Hernandez et al. 1980, Baena Perez & Jerez Mir 1982, Kenter et al. 1990, Banks & Warburton 1991).

The relief created by late Middle Miocene compression, was flooded in late Serravallian times. Marine sediments accumulated during late Serra-

vallian to early Tortonian times in intramontane basins confined by structural highs (Montenat 1973, Baena Perez & Jerez Mir 1982, Kenter et al. 1990). These sediments include the fill of the Abarán Basin. They unconformably overlie older rocks deformed by Miocene compression. These older rocks are here referred to as the 'basement' of the Abarán Basin.

Although the Tortonian generally is considered to be 'post-orogenic', late- or post-orogenic deformation is reflected by faulting, local unconformities and rapidly subsiding basins (Montenat 1973, IGME 1974, Azéma 1977, Müller 1986). A tectonic regime of strike-slip faulting under NW-SE compression prevailed (Benavente Herrera & Sanz de Galdeano 1985, Montenat et al. 1987, Martin-Algarra et al. 1988).

The Abarán Basin developed along an east-strik-

Table 1. The Abarán basin fill (late Serravallian – early Tortonian) comprises three depositional sequences which in most places are separated by angular unconformities. Each sequence is characterized by a major, thick axial fill of sand-grade or finer grained delta deposits and a minor, thin lateral fill of gravelly talus deposits. The axial and lateral fills are in turn subdivided into facies associations, i.e. groups of associated lithologies.

Sequence	Fill	Facies association	Lithology	Interpretation
Upper	Axial	Prodelta 200–500m?	silty marlstones with fine, thin calcarenite beds	prodelta: hemipelagic silt and mud with distal turbidites
	Lateral	Margin south: 5 m	channelled pebble to boulder conglomerates	fault-talus of cohesive debris flow conglomerates
Middle	Axial	Prodelta 220m &	silty marlstones with fine, thin calcarenite beds	prodelta: hemipelagic silt and mud with distal turbidites
		Distal lobe 100m Proximal lobe min. 200m?	lobes of medium to coarse calcarenites embedded in silty marlstones	prodelta lobes of high-density and 'classical' turbidites in front of a submarine distributary
	Lateral	Margin south: 5 m north: 15–40m	coarse reef debris calcarenites and channelled boulder conglomerates	reef- and fault-talus of cohesive debris flow conglomerates
Lower	Axial	Gilbert Delta 280m	largely structureless, massive (pebbly) calcarenites with channel-shaped bodies of pebble- to cobble conglomerates	Submarine foresets (30–150m) of Gilbert-type deltas composed of small-scale mass flows and mud from suspension. Conglomerate bodies are slump scars filled by gravelly debris flows
	Lateral	Margin northeast: 20–30m southwest: 0–10m	algal-bryozoal boundstones, coarse reef debris calcarenites and monomict boulder conglomerates	algal reefs with reef- and fault-talus of cohesive debris flow conglomerates

ing right-slip fault zone and overlies a Subbetic 'basement' strongly affected by faulting. The fault zone runs along the Subbetic-Prebetic boundary between Calasparra and Cieza and continues farther eastward to the Sierra de la Pila. The fault zone is bounded in the north by the 'Linea Electrica Fault' of Jerez Mir (1979), the eastern extension of the 'Socovos Fault' of Sanz de Galdeano (1983) (Fig. 1B).

The fill of the Abarán Basin shows an overall fin-

ing and deepening upward trend in which three sedimentary units can be recognized based on abrupt changes in lithology (Table 1). Younger units show finer grained and more distal facies and each unit is bounded by angular unconformities which are commonly associated with slide or debris flow deposits (megabreccia facies), probably representing seismites. The units reflect distinct depositional episodes separated from each other by pulses of tectonic subsidence and will be called 'sequences'.

Table 2. Overview of the main rock types of the 'basement' of the Abarán Basin, based on IGME (1974, 1975). See also Paquet (1969), Hoedemaeker (1973), Azéma (1977), Jerez Mir (1979, 1981), Garcia Hernandez et al. (1980), and Baena Perez & Jerez Mir (1982). 'Basement' refers to Mesozoic-Tertiary sediments deformed by Miocene (pre-late Serravallian) compression. With 'foliation' is meant a discontinuous, streaky banding in gypsiferous rocks, caused by squeezing and stretching parallel to the plane of major simple shear.

Age	Lithology	Deformation
<i>Neogene</i>	silty marlstone, skeletal algal or (sandy) lithoclast packstone, and conglomerate	plastic (marl) & brittle (limestone)
<i>Prebetic Paleogene</i>	skeletal algal packstone with larger foraminifera	brittle: imbricated & brecciated
	red, continental silt with shallow marine, larger foraminifera limestone interbeds	brittle?
<i>Cretaceous</i>	massive, shallow marine dolomite and limestone	brittle: imbricated, brecciated; large open folds
	white or multi-coloured, mica-bearing sand and shallow marine carbonate ('Utrillas' facies)	brittle?
<i>Subbetic Paleogene</i>	green, pelagic marlstone	plastic: folded and disintegrated
	light grey pelagic calcilitite, calcisiltite and marlstone with thick calcarenite turbidites	plastic and brittle: broken or folded; small isoclinal folds with axial cleavage
<i>Cretaceous</i>	light grey pelagic calcilitite, calcisiltite and marlstone ('Capas Blancas' facies)	idem
	dark grey, pelagic marlstone with thin sandstone turbidites	plastic: tightly folded or disintegrated into slicken-sided, conchoidal chips
<i>Jurassic</i>	predominantly massive dolomite and limestone	brittle: fault-breccias or horizontal slabs unaffected by deformation
<i>Triassic</i>	green to dark grey basic intrusive	brittle: generally heavily faulted
	multi-coloured gypsum and gypsiferous silt with thin carbonate and sandstone interbeds	highly plastic: tightly folded; 'foliation banding' with lenses of more brittle rock
	massive or thick-bedded, black to dark grey carbonate with small angular pores	brittle: fault-breccias or large fragments unaffected by deformation
	red, mica-rich silt- and sandstone with ripple-lamination	large fragments unaffected by deformation

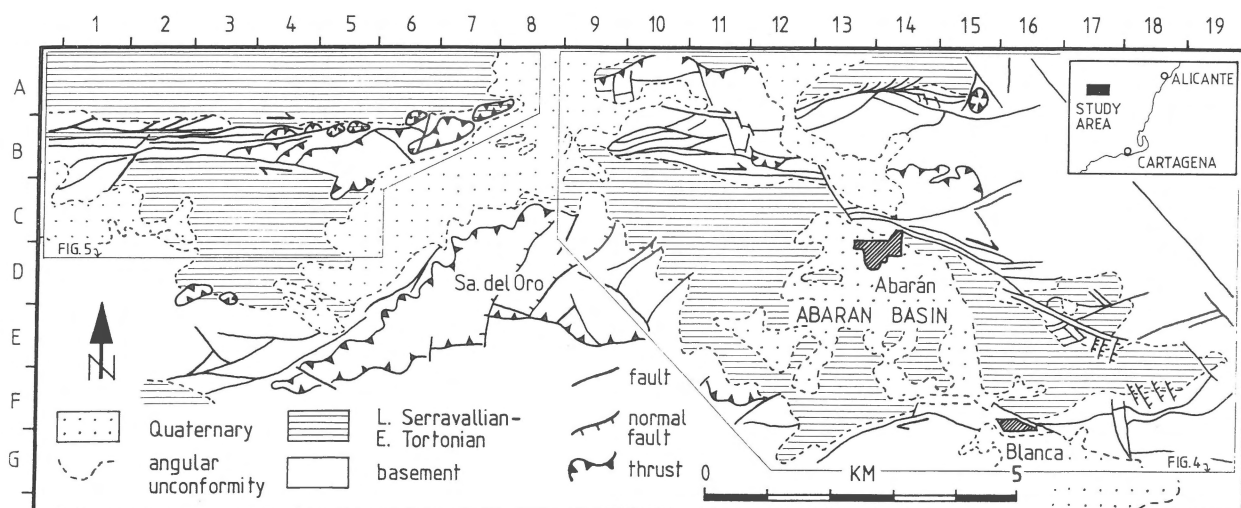


Fig. 2. Structural map of the study area (modified after Van der Straaten 1990a). Location of study area marked in Fig. 1B. 'Basement' refers in this paper to non-metamorphic, Mesozoic-Tertiary sediments deformed by Miocene (pre-late Serravallian) compression.

Each sequence shows an axial fill of sand-grade and finer grained delta sediments and a lateral fill of fault- and reef-talus conglomerates.

Basement deformation under right-lateral shear

The exposed 'basement' directly adjacent to the Abarán Basin consists of Subbetic rocks of Triassic to Miocene age, deformed and highly disrupted by faulting and shear along the east-striking fault zone (Figs 1B, 2). Basin deposits are far less deformed than the 'basement' and their basal unconformity generally truncates structures in the fault zone generated by strike-slip. Although the Prebetic 'basement' north of the Abarán Basin is generally not affected by the fault zone, large fragments of Prebetic rock are incorporated in the fault zone in the area northwest of the Abarán Basin, close to the contact with the Prebetic unit. The Linea Electrica Fault (LEF) delimits the fault zone in the north. The LEF zone refers to the narrow E-W deformation zone parallel to the LEF, running directly north of the Abarán Basin (Figs 1B, 2: B/1–15).

The fault zone consists of a tectonic mixture of a variety of rocks of Triassic to Miocene age. Triassic gypsum or gypsiferous sediment predominates and

forms a plastic matrix with 'floating' tectonic fragments of other, more brittle rocks ranging from pebble-size to blocks of kilometre-scale. Each type of rock reacted differently to the right-lateral shear. Plastic types are folded or sheared along the major fault planes; more brittle rocks either occur as unaffected blocks of various sizes, or as tectonic breccias. Brittle rocks have locally been imbricated. A highly simplified overview of the rock types, their approximate ages and their way of deformation, is presented in Table 2.

Fault zone characteristics

'Basement' deformation in the study area (Fig. 2) is characterized by:

- 1) Major subvertical faults trending roughly E-W with, in map view, linear and curvilinear traces in an anastomosing pattern. Individual fault planes show lateral variation in attitude. Locally, dip reversals occur (Figs 3–7).
- 2) Predominantly steeply dipping and east- to southeast-striking minor fault planes with generally oblique-slip or strike-slip slickensides. The slip data reveal a conjugate set of E-W to

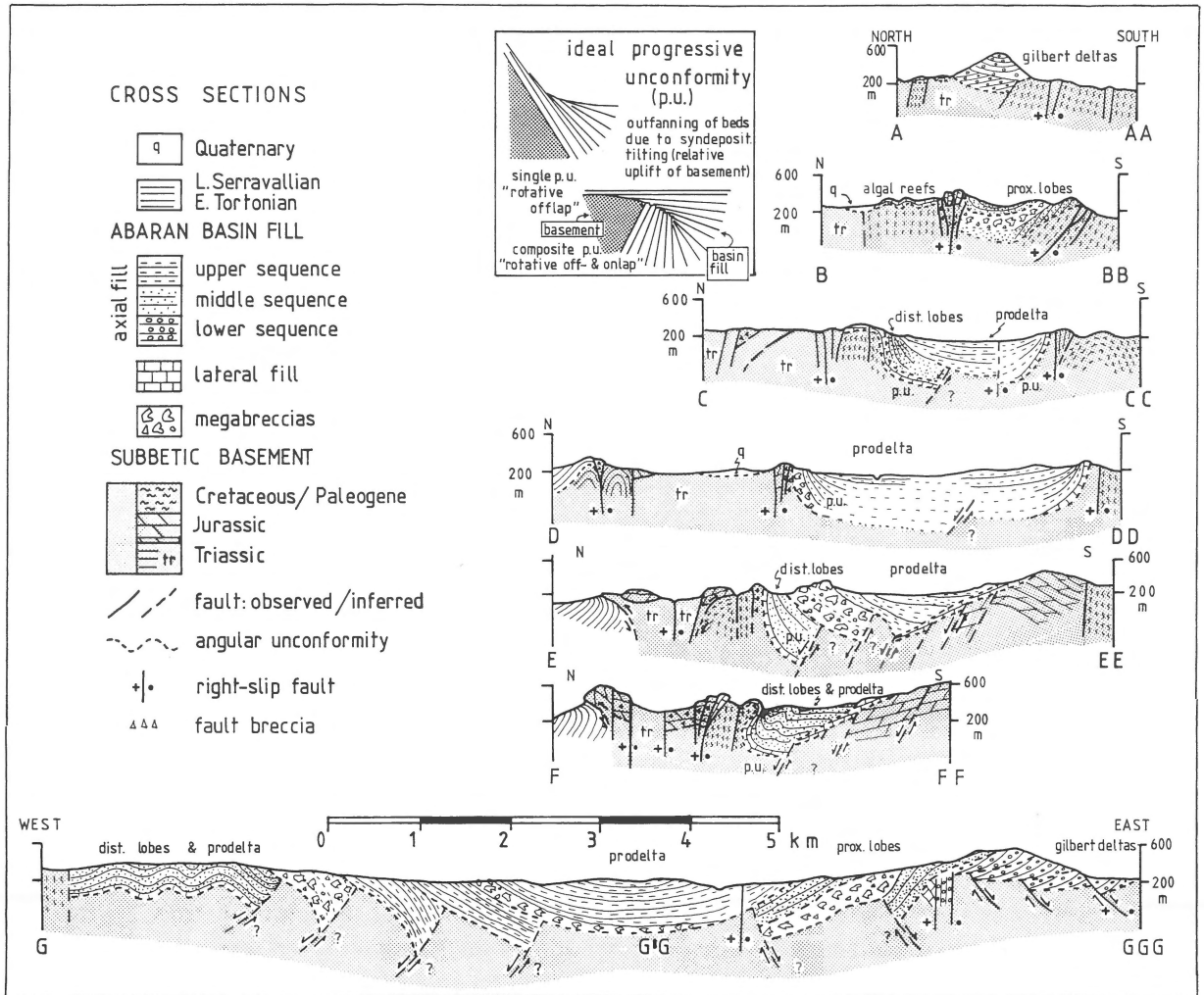


Fig. 3. Cross-sections of the Abarán Basin and adjacent 'basement' (modified after Van der Straaten 1990a). Normal faults under the western basin fill are inferred from faults in the 'basement' of the Sierra del Oro. Note that if the beds do not terminate against 'basement', the thickness of the basin fill would be anomalously large (>2 km) in respect to basin-size. Progressive unconformities along the margins of the Abarán Basin are denoted with 'p.u.'; the structure is explained by the inset (after Riba 1976). Traces of cross-sections are shown in Fig. 4.

- NW-SE right-slip and N-S left-slip faults (Fig. 6).
- 3) Folds with steeply inclined to vertical axes generated by drag (Figs 4, 5). Beds approaching a fault swing round and tend to parallel the fault. The drag indicates right-slip on E-W faults and left-slip on N-S faults (Figs 7A-E, 7G).
- 4) En-echelon fold series with subhorizontal east-to northeast-trending axes (Figs 4, 5) that are

- restricted to the area adjacent to the major E-W faults. The folds form elongate domes, steeply dipping at their extremes. Most are at an angle of about 20° to the major faults (Fig. 6).
- 5) Structural imbrication, including imbricate fans and duplexes (terminology of Woodcock & Fischer 1986, cf. larger-scale strike-slip structures of Crouch 1979 and Boukadi et al. 1986). The stratigraphy of the 'basement' is locally repeat-

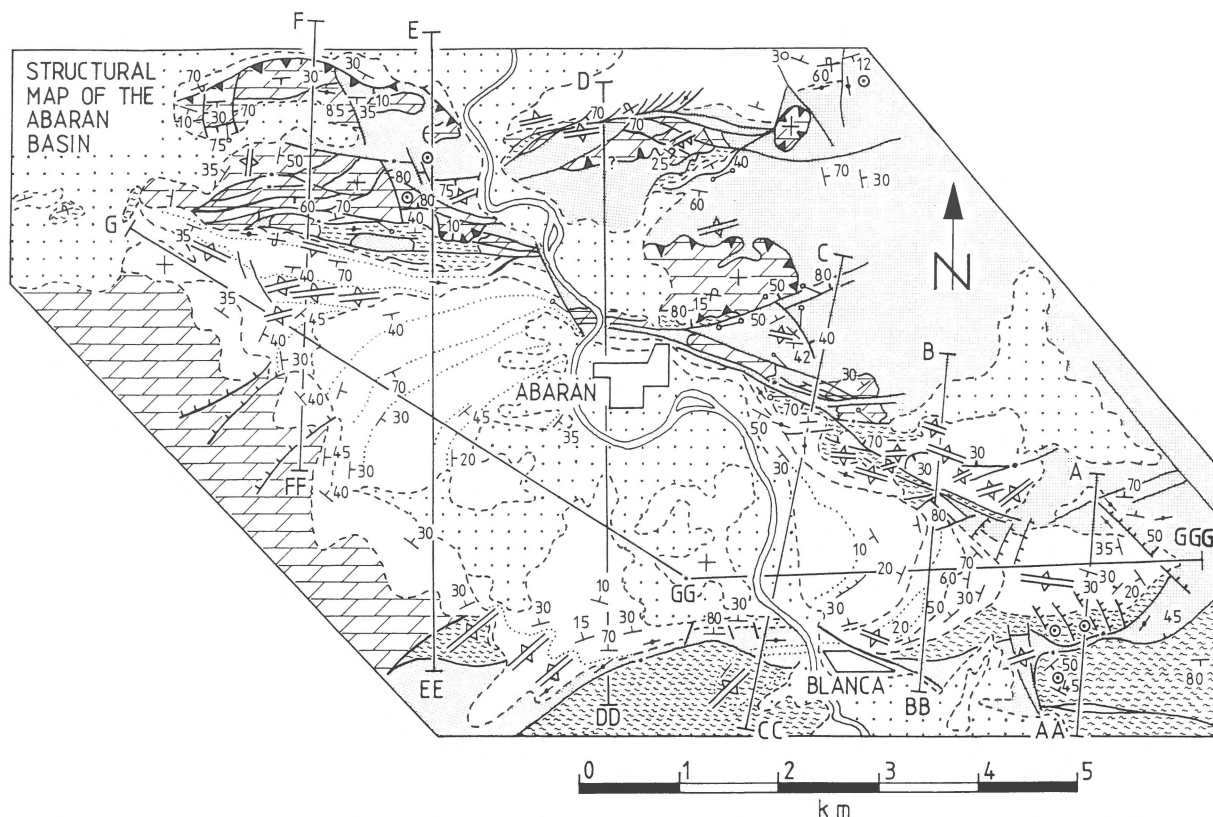


Fig. 4. Structural map of the Abarán Basin. The profiles A-AA to G-GGG are shown in Fig. 3. Location indicated in Fig. 2, legend in Fig. 5.

ed due to imbrication of steeply dipping strata along subvertical faults that splay off from major E-W faults (Figs 4, 5, 7E-F). Locally, faults splay off and rejoin forming duplexes in map view (Figs 4, 7E).

- 6) Subvertical, strongly sheared E-W bedding parallel to the fault zone (Figs 3–5). The Triassic gypsiferous deposits show a discontinuous banding or ‘foliation’, which coincides with the original bedding and is interpreted as the result of important simple shear, parallel to the major fault planes. The banding commonly encloses lens-shaped fragments, up to metre-scale and composed of more brittle rocks.
- 7) Minor thrust faults and associated overturned folds that affect Tortonian sediments and therefore postdate the major late Serravallian compressive phase. South-dipping faults and north-facing folds dominate along the northern mar-

gin of the LEF zone; some north-dipping faults and south-facing folds are present along its southern margin. Downward, the thrust faults are bounded by, or steepen into, subvertical E-W faults (Figs 3–5).

The LEF zone is interpreted as a right-lateral strike-slip fault zone. The nature of the major faults is characteristic for strike-slip faulting (cf. Reading 1980, Christie-Blick & Biddle 1985). The general E-W subvertical orientation and sheared appearance of the more plastic rocks suggest major shear. Additionally, the striae on larger fault planes and the orientation and nature of striated minor shear planes, document strike-slip along predominantly E-W trending faults (Fig. 6).

The right-lateral sense of the fault zone is clearly illustrated by drag, striae and structural imbrication. Right-slip along major E-W faults is supported by the orientation of the associated en-echelon

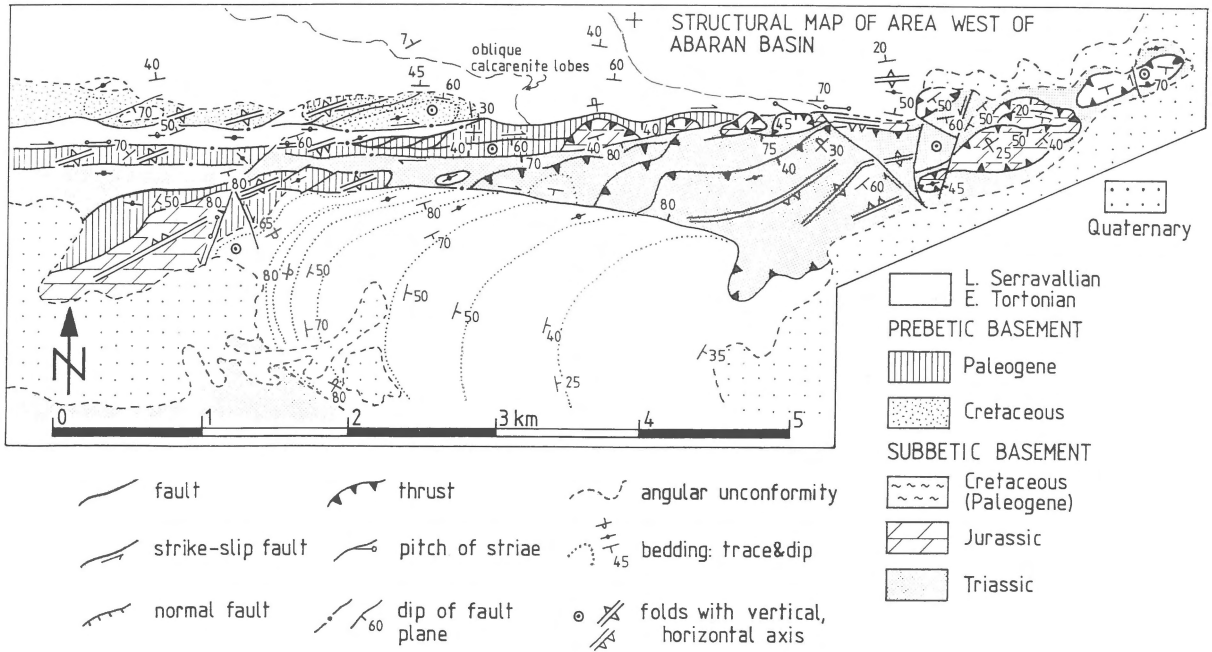


Fig. 5. Structural map of area west of Abarán Basin. Location marked in Fig. 2. Fold symbols: two teeth in same direction indicate overturned fold. Bedding: symbols shown in legend above 45° dip symbol indicate vertical beds and overturned beds, respectively.

folds, and by the conjugate sets of right- and left-slip fractures, that conform with the configuration of synthetic and antithetic shears in an E-W right-slip fault zone (Fig. 6; cf. Wilcox et al. 1973, Barlett et al. 1981).

'Positive flower structures', as defined by Biddle & Christie-Blick (1985), are suggested by: 1) north- and south-facing overturned folds along the northern and southern margin of the LEF zone, respectively; 2) thrusts along the LEF zone margins dipping towards the centre of the zone, bounded by or steepening downwards into vertical faults; 3) upward diverging fault splays; and 4) convex-upward fault planes (Figs 3–5).

Dating

Since most late Serravallian to early Tortonian deposits unconformably overlie the LEF zone and truncate structures related to the E-W right-lateral shear, the initiation of the fault zone must predate

these deposits. The right-lateral sense of major E-W fractures suggests that the fault zone relates to NW-SE compression that reigned in Early Miocene and later times. According to Jerez Mir (1979) the LEF showed its major activity during the Early Miocene; Sanz de Galdeano (1983) postulates a Middle to Late Miocene activity of the Socovos Fault.

Synsedimentary right-slip is obvious from the deformation of the Abarán Basin. After deposition of the late Serravallian to early Tortonian sediments, movement along the LEF zone continued. This is indicated by the separation of the Abarán Basin from its north-easterly hinterland, by lithological mismatches in Tortonian sediments across the zone (Van der Straaten 1992), and by faulting of such sediments along the zone (Fig. 5).

The LEF zone and the early Tortonian deposits are intersected by younger NW-SE faults. A major one crosses the central Abarán Basin and runs from Abarán to Blanca (Fig 2: B/13 to F-G/16, Figs 4, 8). It affects the youngest basin fill and displaces the ba-

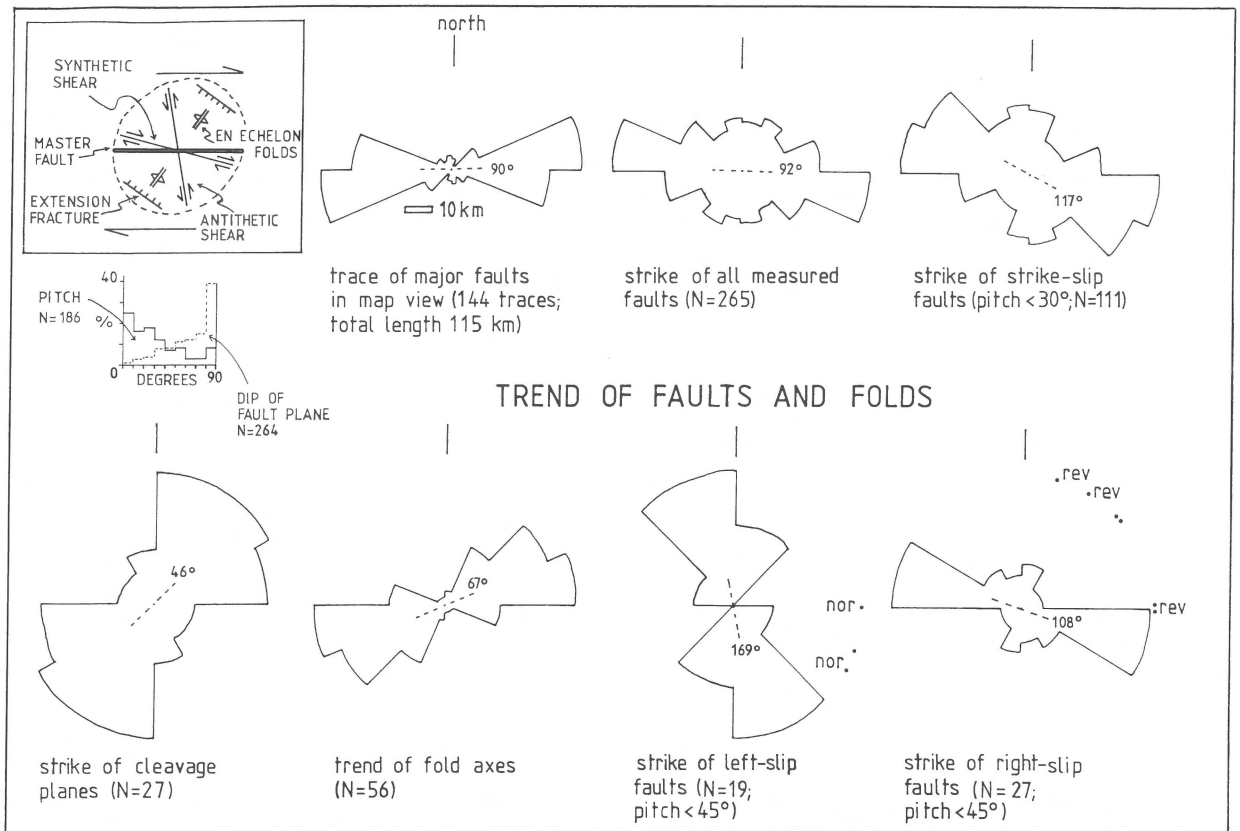


Fig. 6. Trends of faults and folds. The rose diagrams show the trends of fault planes, fold axes and cleavage planes measured in the areas of Figs 4 and 5. Dashed lines and numbers in the centre of the diagrams denote the mean trend (longest eigenvector). Pitch refers to the acute angle between striae and fault plane strike. The strikes of single normal and reverse faults with a pitch larger than 45° , are marked in the two lower right diagrams by 'nor.' and 'rev.', respectively. The inset presents the expected angular relation between structures in right-lateral shear under ideal conditions (inset after Christie-Blick & Biddle 1985).

sin margins and associated major faults in a right-lateral way. Offset, drag and striae document right-slip. The fault coincides with a right-slip fault described by Müller (1986), active during Pliocene times under N-S compression.

Along the northwestern margin of the Sierra del Oro, NE-SW trending subvertical faults are present. Although their actual relation with the LEF zone is hidden by Quaternary deposits, the faults appear to displace the LEF zone in a left-lateral manner (Fig. 2: F/4 to A/9). Similarly oriented left-slip faults west of the Abarán Basin cut off major E-W faults (Fig. 2: B-C/1-2 & B/6; Figs 5, 7A, 7D).

The NE-SW left-slip and NW-SE right-slip faults are considered a conjugate set postdating both the

Abarán Basin and the LEF, and reflecting N-S shortening. This tectonic regime coincides with the Pliocene N-S compression and E-W extension postulated by Montenat et al. (1987) and is in agreement with the conjugate fault set in Neogene deposits described by Benavente Herrera & Sanz de Galdeano (1985).

In conclusion, the right-slip along the E-W fault zone probably started during the Early or Middle Miocene and stopped before the end of the Pliocene. The Abarán basin fill documents significant right-slip before and after the late Serravallian to early Tortonian basin development, and the fault zone was obviously also active during this development.

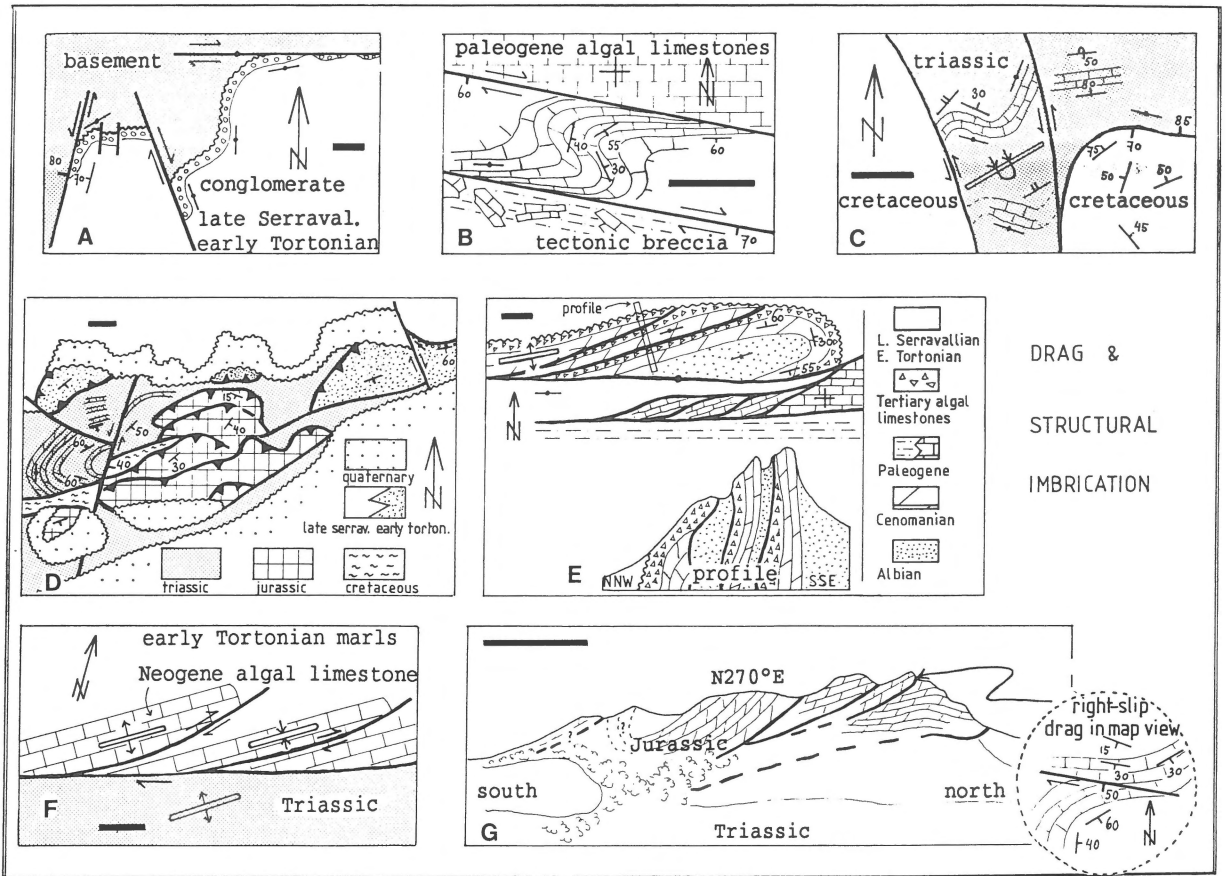


Fig. 7. Examples of drag and structural imbrication. Locations of maps and profiles are indicated by co-ordinates of Fig. 2. Solid bars approximate 100 m. A) Faulted and dragged Neogene deposits (B/1–2). B) Right-slip drag (B/3). C) Overturned synform affected by left-slip drag (F/17–18). D) Northward thrusting and conjugate set of strike-slip faults post-dating the E-W right-slip fault zone (B/6–7). E) Steeply ENE-plunging anticline generated by right-slip drag with 'imbricate fans' and 'strike-slip duplexes' (terminology of Woodcock & Fischer 1986) (B/2–3). F) Right-slip imbrication and small en-echelon folds (A/13–14). G) Thrust plane with right-slip drag (AB/7).

Basin structure

The structure of the Abarán Basin, shown in Figs 3, 4 and 8, will be discussed using the following thematic framework: 1) faults and faulted margins, 2) unconformities, 3) folds and drag, and 4) tectonic downlap. The reader is reminded that an overview of the sequences and their lithology (facies association), used in the section below, is presented in Table 1.

Faults and faulted margins

The *Northern margin* of the basin is formed by the LEF zone which is dominated by major E-W right-slip faults. The middle sequence partly seals the faults and unconformably overlies east-striking, subvertical 'basement' rocks strongly sheared parallel to the fault zone. Syndimentary activity on the E-W faults is indicated by the proximal talus deposits (lateral fill of the middle sequence) and by progressive unconformities. Right-slip during basin development is expressed by en-echelon folds and progressive drag.

The *northeastern margin* is formed by subvertical

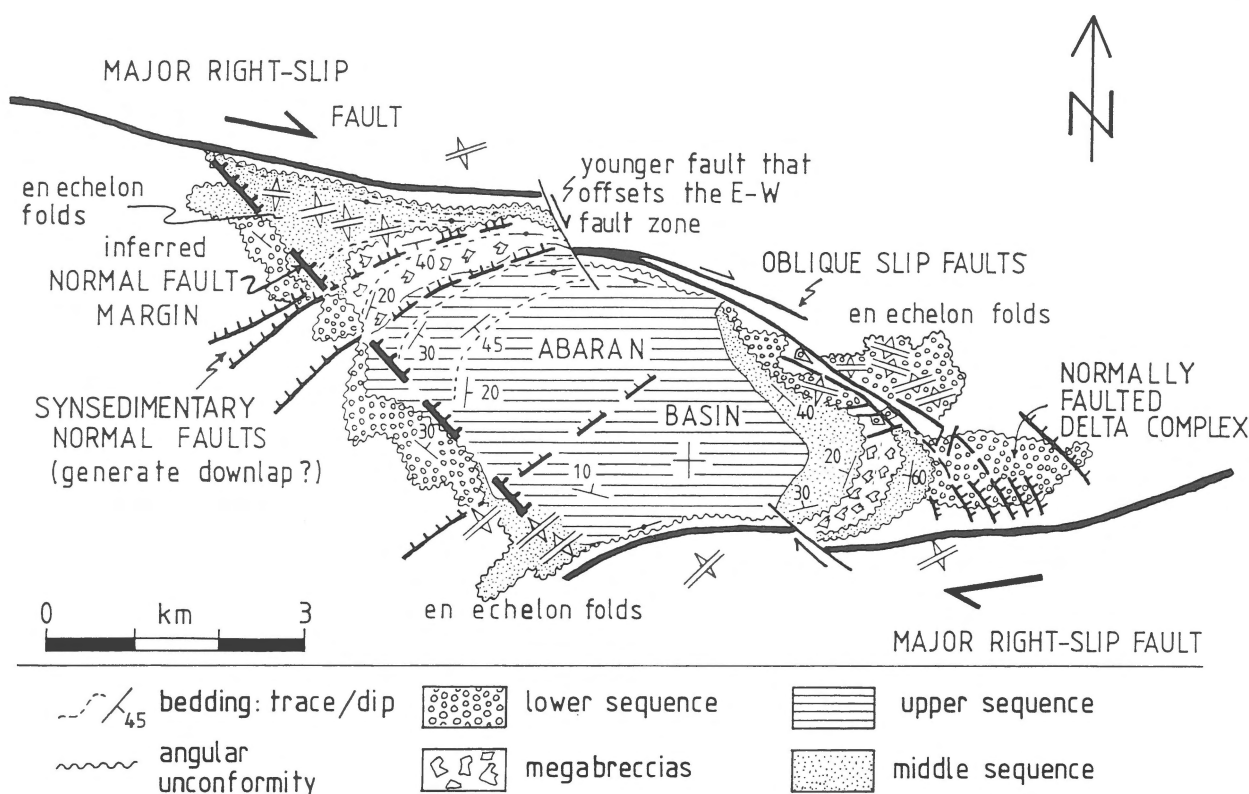


Fig. 8. Structural sketch map of the Abarán Basin (after Van der Straaten 1990a).

faults that splay off from the LEF zone in the north. The splays change orientation from WNW-ESE in the north to NW-SE in the south. Still further south, they pass into synsedimentary normal faults that control the eastern margin. The lower sequence is strongly faulted. It is locally incorporated in the WNW-ESE fault zone branch and occurs as tectonic fragments amidst highly disrupted 'basement'. The middle sequence truncates faults and fault-related structures and is less affected. En-echelon folds and striae on major fault planes suggest right-slip. Progressive unconformities associated with translational slides, document a relative subsidence of the basin during sedimentation (see section 'Unconformities').

The *eastern margin* is dominated by synsedimentary normal faults that affect the Gilbert delta association of the lower sequence. Faults dip east and become progressively younger towards the basin centre. Most trend NNW-SSE, but some trend NNE-SSW.

The *southern margin* is formed by an east-striking fault zone that comprises steeply dipping to sub-vertical faults. Curvilinear traces, variable dip, and vertical beds sheared parallel to the major faults, suggest its strike-slip nature. Small en-echelon folds indicate right-slip. The deformation style and the parallelism with the LEF zone agree with right-slip along the southern margin.

The *southwestern margin* of the basin is formed by the Sierra del Oro, which represents a distinct paleo-high above the Tortonian sea, as documented by onlap and proximal conglomerates with only clasts from this Sierra (lateral fill of the lower and middle sequence). The on the whole rectilinear contact between the 'basement' of the Sierra and the basin, and the discrepancy between the north-westerly trend of this contact and the long series of monotonously east-dipping basin sediments, reveal that this contact is probably formed by a NW-SE fault. The inferred marginal fault may be related to NW-SE faults that intersect the Jurassic rocks of the

Sierra del Oro (IGME 1974). The fault contact is, however, concealed by onlapping sediments.

Unconformities

The angular unconformities in the Abarán Basin are shown in Figs 2, 4 and 8. Some aspects need further discussion.

The *basal unconformity* is remarkable, because the 'basement' is overlain by the lower sequence in the east and southwest and by younger deposits in the other parts of the basin. The lower and middle sequence appear to be completely absent in the central area where, judging from observations along the northern and southern basin margins, the upper sequence lies on 'basement' (Figs 3, 8).

The nature of this unconformable relation is explained as follows. Older deposits originally formed a continuous cover that was split due to the E-W extension inside the basin, creating a depression floored by 'basement' in its central part. Older deposits once present in the central part, thus moved aside making room for younger sediments to be deposited directly on the 'basement' (see section 'Tectonic downlap'). The faults that terminate the middle sequence near Abarán and Blanca are proof that the phenomenon is not generated by onlap (Figs 4, 8).

Apart from the major basal unconformity, several *internal unconformities* are present. In the eastern part of the basin, the lower and middle sequence are separated from each other by an angular unconformity. The margin association of the lower sequence is heavily faulted and folded and unconformably covered by the middle sequence, that is also strongly deformed in its lower part. The proximal lobe association shows an angular unconformity accompanied by megabreccias. Towards the northwest the unconformity merges into the lower-middle sequence boundary.

In the western part of the basin, a major unconformity between the middle and the upper sequence is also accompanied by megabreccias. The unconformity truncates about 300 m of middle sequence sediments, and is considered the result of progressive tilting, whereby younger beds eventu-

ally truncated older beds (cf. 'composite progressive unconformity' in Fig. 3).

Progressive unconformities are present along the northern, the northeastern and central-southern margin of the basin (Figs 3, 9). The term 'progressive unconformity' refers to the fanning of the beds in profile along the basin margin due to basin subsidence relative to its borders (Riba 1976). Since the margin subsides less than central parts of the basin, beds become tilted. The fanning expresses a progressive decrease of tectonic tilt in younger deposits and demonstrates the synsedimentary nature of the deformation. If the movements are exclusively vertical, tilting is around a horizontal axis parallel to the basin margin. Bedding strike remains fixed and the fanning is only apparent in vertical cross-sections. Tilting around non-horizontal axes results in a fanning of the beds in map view.

Along the northeastern basin margin, the middle sequence shows a prominent progressive unconformity with beds striking parallel to the margin (Fig. 9). The structure is accompanied by translational slides and expresses downfaulting of the basin floor along synsedimentary NW-SE faults that control this margin. In the western part of the basin, the fanning of the beds in profile is less obvious. The structure is combined with a progressive change in the strike of the beds, forming a fanning in map view. This configuration is ascribed to a combination of synsedimentary right-slip drag and basin subsidence due to the E-W extension.

Folds and drag

Small folds with a maximum lateral extent of a few hundreds of metres (Fig. 4), are present exclusively along the basin margins in the lower and middle sequence. They are commonly arranged en-echelon. Their subhorizontal axes of a general E-W to SW-NE orientation commonly plunge rather steeply at the end of the fold. The restriction of the folds to areas adjacent to major faults along the basin margins, shows the genetic relation of the two. Their occurrence, arrangement and orientation, are characteristic for en-echelon folds that develop in relation to right-slip systems (Fig. 6). Most folds are fossil-



Fig. 9. Progressive unconformity. Subvertical beds of the lateral fill of the lower sequence are unconformably overlain by beds of the distal lobe association of the middle sequence that show a single progressive unconformity (rotative offlap, see Fig. 3). View towards the E; location D/15 in Fig. 2.

ized by internal unconformities, which documents their syndepositional nature.

In the western part of the basin, en-echelon ENE-WSW folds are restricted to the middle sequence, and make an angle of ca. 15° with N095E faults along the northern margin. Along the northeast margin, another concentration of small folds occurs along faults trending N120E. Here, folded deposits of the lower sequence are unconformably overlain by an unfolded middle sequence. Fold orientation varies from N030E to N110E (mean ca. N080E). The wide variation in orientation is thought to be the result of the intense faulting which generated individual tectonic blocks floating in a plastic matrix of gypsum and marls. The deposits lost coherence and adopted variable orientations. Along the southern margin, controlled by an E-W fault zone, the middle sequence shows several en-echelon folds trending N050E.

Apart from these small, strike-slip-related en-echelon folds, the basin displays an east-west oriented, basin-wide syncline which plunges towards

the basin centre from both its ends. The syncline is thought to express basin subsidence. The structure, and especially its axial plunge, was probably enhanced by drag due to the E-W lateral shear and by the downfaulting of the basin in its eastern and western parts.

In the western part of the basin, the beds assume on approach of the LEF zone an orientation parallel to this zone. This configuration is here referred to as '*progressive drag*'. A similar situation is found in the concurrent basin west of Abarán (Fig. 2:B-D/2-5; Fig. 5) which shows in its central part a series of steeply east-dipping sediments (dips of 90 to 40°) over a distance of ca. 3.5 km. Approaching the northern margin, beds converge and swing round to parallel the subvertical, east-striking right-slip fault that delimits and truncates the basin fill. Bedding shows a prominent fanning in map view and the sediments are sheared and dragged along the fault over a distance of at least 1 km.

The bedding configuration of the Abarán Basin and the coeval basin due west, resembles drag along

strike-slip faults in the LEF zone, as illustrated in Figs. 7B-E and 7G. The prominent southward divergence of the beds reveals that older beds have been influenced more than younger beds. Although the configuration is similar to the progressive unconformities mentioned above, the progressive change in bedding strike demonstrates a significant horizontal slip component. Strike-slip shear combined with tilt due to basin subsidence, will tend to rotate structures in a vertical position. Older beds will therefore dip more steeply than younger beds resulting in an additional fanning of the beds in profile.

The basinwide syncline is accompanied in the east by a similar progressive change in bedding strike. This change may represent drag along the southern faulted margin. Alternatively, it may be inherited from the local basin geometry in combination with the complex stacking of sediment lobes. Interpretation as drag is supported by the change in orientation of the channelled boulder conglomerates in the proximal lobe association, from NW-SE to N-S towards the south.

Tectonic downlap

In the west, the central basin fill forms a monotonously east-dipping series (Figs 3G, 4). Beds terminate against the southwestern margin, where they onlap the Jurassic 'basement' of the Sierra del Oro. Consequently, progressively younger beds overlie 'basement' in an eastward direction, which explains the anomalously large, apparent cumulative thickness of the series of more than 2000 m. The eastward dip of about 40° of prodelta marlstones with a westward sediment transport, shows that the bedding configuration does not represent depositional downlap of sediments with a steep primary dip, but suggests a tectonic origin.

Northwest-dipping normal faults offset the overturned Subbetic thrust slice of the Sierra del Oro and are covered by the Abarán basin fill (IGME 1974). Given the final emplacement of Subbetic thrust masses in the middle to late Serravallian (IGME 1974), faulting occurred in the period mid-

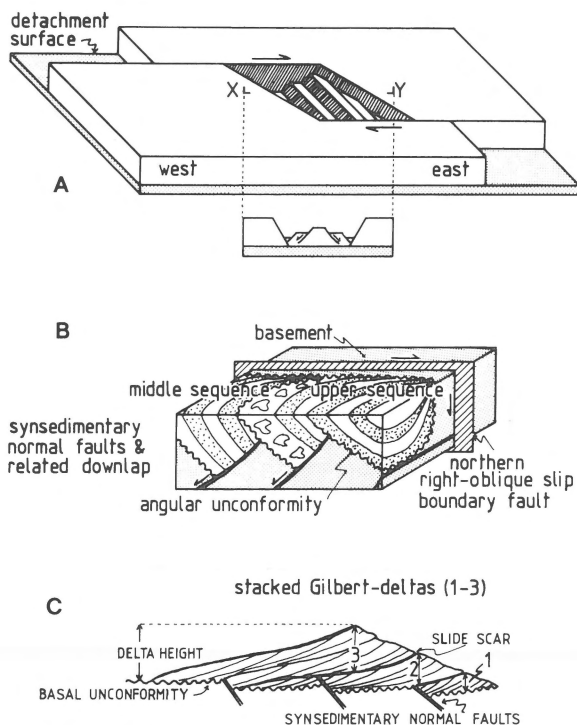


Fig. 10. Rigid, detached pull-apart basin and tectonic downlap (after Van der Straaten 1990a). A) Cartoon of the Abarán Basin as a rigid, detached pull-apart basin. B) Tectonic downlap in the western part of the basin: faulting, related tilt and tectonic transport away from the basin centre generate down- and overlapping sediment packages. C) Imbricate stacking of Gilbert-deltas stepping over normal faults.

dle Serravallian – early Tortonian. Faults with a similar trend affect the lateral fill of the lower sequence and are covered by the axial fill of the middle and upper sequence. Based on the above arguments, NW-dipping synsedimentary normal faults are inferred that laterally extend beneath the basin fill. They are considered to be related to the downlap as shown on Fig. 3G.

An interpretation of the phenomenon is given in Figs 10A and 10B. The right-slip along the E-W fault zone led to basin extension and generated NE-SW trending normal faults. As a result of the normal faulting, older deposits were torn apart and moved aside while being progressively tilted. Consequently, younger deposits accumulated laterally next to, rather than upon the older basin fill, creating down- and overlapping sediment packages. The combina-

tion of downlap, normal faulting and lateral migration of the older sediments away from the basin centre, is here referred to as 'tectonic downlap'.

The tectonic downlap is inferred in the western part of the basin, but can actually be seen in the Gilbert delta association in the east (Fig. 10C; Van der Straaten 1990a), where normal faults affect older deltas and are fossilized by younger ones. These normal faults dip away from the basin centre and become younger towards it. A major downthrow along the faults is followed by the formation of a delta prograding partly over 'basement' and partly over downfaulted and slightly tilted older deltas. The increasing delta height reflects considerably deeper water after each faulting event.

Overstep mechanisms and faulting history

The Abarán Basin interpreted as releasing overstep

The Abarán Basin is situated in an east-trending fault zone with right-slip before, during and after basin development. The basin shows a rhombic geometry determined by the configuration of the faults along its margins (Fig. 8). Given the configuration and nature of the bounding faults and their synsedimentary activity, the basin is interpreted as a releasing overstep formed by two right-hand stepping, major E-W right-slip faults connected by NW-SE normal-oblique slip faults. Synsedimentary deformation is evidenced by older beds faulted, folded and tilted more than younger beds and by intrabasinal unconformities. Synsedimentary faulting includes vertical and lateral displacement, leading to basin subsidence and E-W basin extension.

Basin subsidence is illustrated by the three depositional sequences in progressively deeper facies, bounded by angular unconformities, and by progressive unconformities associated with translational slides. The sequences reflect depositional episodes separated by pulses of tectonic subsidence. Actual downfaulting of the basin is documented by synsedimentary normal faults. Syndepositional right-slip along the E-W basin margins is indicated by en-echelon folds, by strike-slip striae on

fault planes, and progressive drag. Growth of the basin in E-W direction in response to the right-slip is thought to be reflected in 'tectonic downlap', i.e. the oblique stacking of sedimentary units related to normal faulting (section 'Tectonic downlap').

Inherent to the releasing overstep interpretation, the Abarán Basin is considered a pull-apart basin (cf. Crowell 1974, Aydin & Nur 1982, Mann et al. 1983). Biddle & Christie-Blick (1985: 380) define a pull-apart basin as 'A basin formed by crustal extension at a releasing bend or overstep along a strike-slip fault zone'. The Abarán Basin conforms to this definition. Extension is, however, considered to be restricted to the sediment pile above a Triassic detachment horizon.

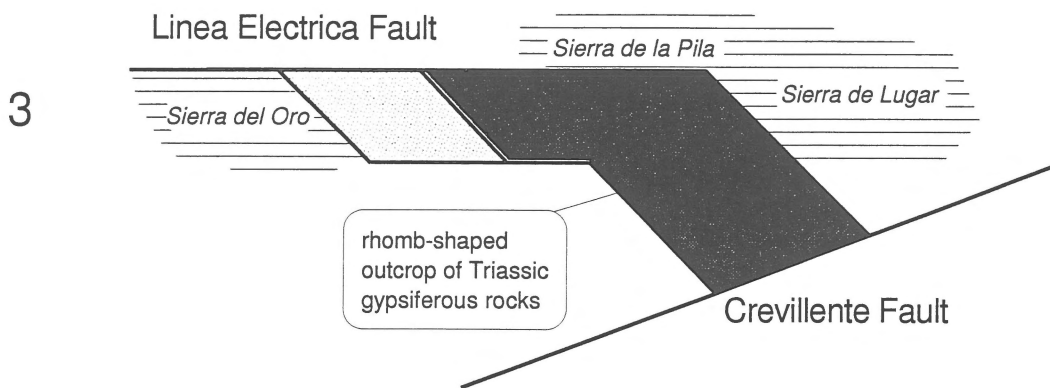
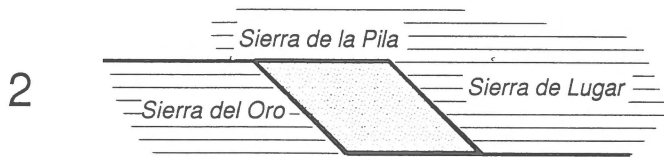
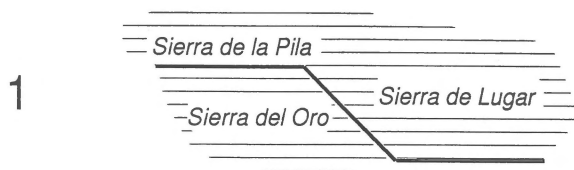
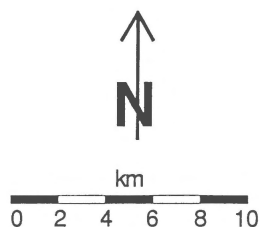
Depth of overstep

The interpretation of the Abarán Basin as a detached pull-apart basin developed along a right-slip fault (LEF) in a thin-skinned fold-and-thrust belt, is based on the following arguments.

The deformation of the External Zone is normally thought to be detached (Jerez Mir 1979, Baena Perez & Jerez Mir 1982, Banks & Warburton 1991). Moreover, the western extension of the LEF, the Socovos Fault, terminates where the Paleozoic metamorphic basement emerges from under the Mesozoic cover and does not affect this basement (Baena Perez & Jerez Mir 1982).

An additional argument forms the 35 to 40 km of shortening of the Prebetic southwest of the Socovos Fault in the 'Arc of Cazorla', which is a thin-skinned feature above a décollement horizon of Triassic gypsum, situated 100 km WNW of Abarán (Baena Perez & Jerez Mir 1982, Nobel & Rondeel 1988, Banks & Warburton 1991). According to Baena Perez & Jerez Mir (1982), this amount of shortening corresponds with the total displacement along the Socovos Fault. North of the Socovos Fault and the LEF no significant shortening took place relative to the pre-Triassic basement (Nobel & Rondeel 1988, De Ruig 1990). Here, folding and reverse faulting led to local contraction, but did not result in a net shortening, because of diametrically opposed tec-

EVOLUTION OF THE
ABARAN BASIN IN
MAP VIEW



A

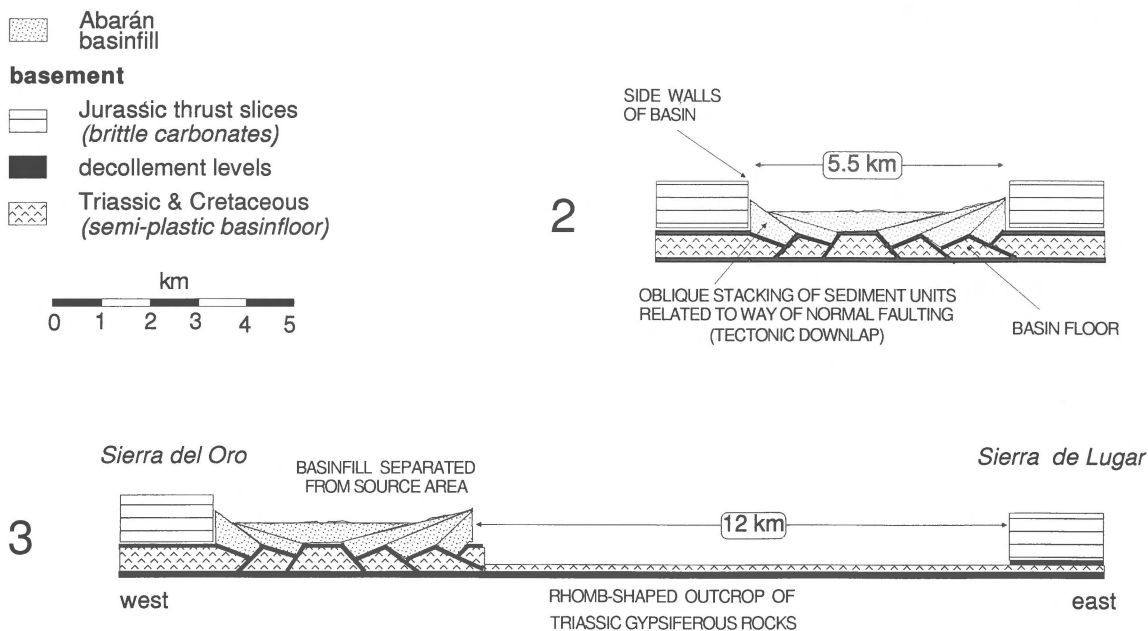
Fig. 11. Evolution model of the Abarán Basin, in map view (A) and in cross section (B). The cartoons show three stages: 1) a continuous thrust-slice formed by the Subbetic Jurassic of the Sierra del Oro, Sierra de la Pila and Sierra de Lugar; 2) breaking up of the thrust-slice and the opening of the Abarán pull-apart basin with lengthening of the basin floor by plastic stretching or detachment, and by normal faulting; 3) post-depositional, detached displacement along the Linea Electrica Fault, separating the basin from its northeasterly hinterland.

tonic transport directions. These conflicting tectonic movements were compensated by ruptures in the sediment cover (Frank Nobel, pers. comm. 1987). The detached shortening south of the LEF and Socovos Fault thus totally accounts for the assumed right-slip along these faults. No subsurface information is available for the Abarán Basin. Yet, some speculative conclusions can be drawn about the depth of deformation. The relation between basin and ‘basement’ allows suppositions about the depth of the overstep and the process of basin formation.

The lateral fill on the Jurassic rocks of the Sierra del Oro reveals that this Sierra was an emerged, detritus-giving ‘basement’ block with a northwest-trending margin that bordered the basin in the

southwest. In the northeast, the basin fill is bounded by NW-SE faults. Although the actual basin margin is not exposed here, a similar northwest-trending boundary block of Jurassic Subbetic is inferred from talus deposits, clast composition, and the present-day topography of the Pila-Lugar relief (Fig. 1; Van der Straaten 1992). With an exception in the extreme west, the basin fill along the northern and southern margins rests exclusively on a tectonic mixture of Triassic and Subbetic Cretaceous rocks and not on Jurassic Subbetic. The geological map of IGME (1974) and personal field observations (Fig. 4) reveal that this Triassic-Cretaceous ‘basement’ normally underlies the Jurassic thrust slices. The situation suggests that – apart from the SW and NE

B EVOLUTION OF THE ABARÁN BASIN IN CROSS SECTION



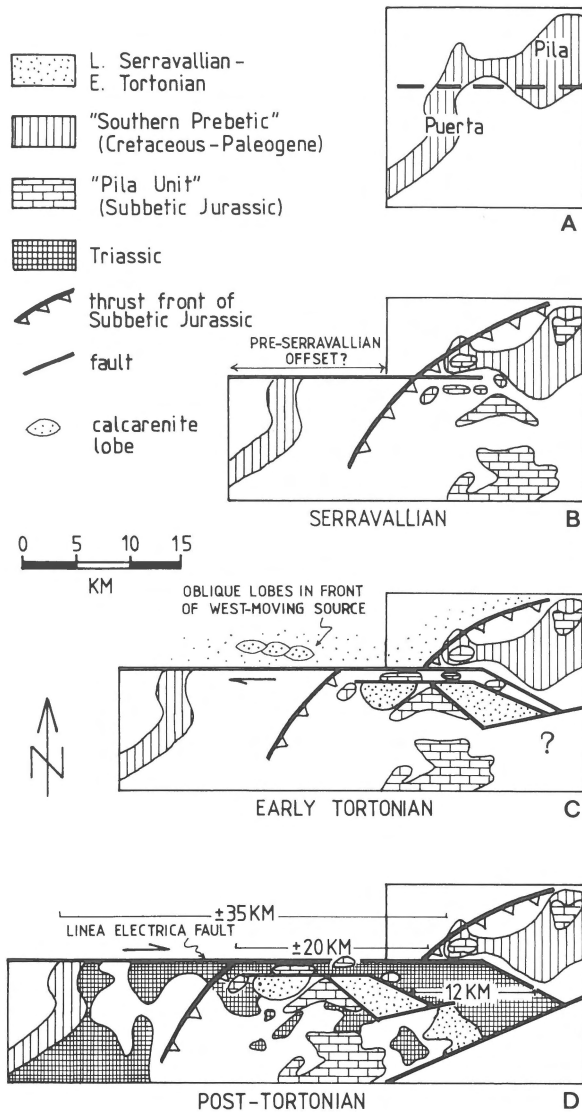
margin – the basin is underlain by Triassic-Cretaceous ‘basement’ usually present below the Jurassic thrust slice.

Based on these considerations, the basin is interpreted as a depression bordered at its NE and SW margins by fault-controlled blocks of Jurassic carbonates that were originally juxtaposed and formed a continuous Subbetic thrust slice, as shown in Figs 11A-B and 12C-D. With the opening of the overstep, the Jurassic blocks were torn apart, creating the depression of the Abarán Basin, floored by ‘basement’ that emerged from below the disrupted thrust slice. These assumptions imply that the Abarán Basin formed in respect to the Jurassic thrust slice a ‘clean’ pull-apart and that the separation between the NE and SW margin equals the amount of right-slip along the major E-W boundary faults.

Complete detachment occurred, however, at a level deeper than the sole of the Jurassic thrust slice. This is indicated by normal faults that involve the Triassic-Cretaceous ‘basement’ at the southern

margin of the basin (Figs 3, 4). Normal faults in the Gilbert delta association of the lower sequence, suggest a minimum subsidence due to normal faulting in the order of 250 m. Normal faults penetrating the Triassic-Cretaceous ‘basement’ for at least 400 m, are required to construct the basin profile of Fig. 3G. A speculative estimate for the depth of the overstep therefore is the thickness of the Subbetic thrust slice, ranging from 400 to 1000 m (IGME 1974, 1975, Baena Perez & Jerez Mir 1982), added to the amount of cumulative subsidence due to normal faulting in the underlying ‘basement’. Hence, the total depth of the overstep is in the order of 650 to 1400 m. Downfaulting of the Triassic-Cretaceous ‘basement’ caused the basin fill to drop below the level of the thrust sole. Consequently, the postulated detached post-depositional displacement of the basin fill (Van der Straaten 1992) must have been at a deeper level. The above tentative interpretation is presented in Fig. 11.

Rodgers (1980) and Hempton & Dunne (1984)



←

Fig. 12. Model for offset history of the Linea Electrica Fault. A) Cretaceous – Late Eocene: Pre-LEF situation with a continuous ‘Southern Prebetic’ facies belt formed by the Sierra de la Pila and the Sierra de la Puerta. (B) Late Eocene – late Serravallian: Pre-Serravallian right-slip along LEF zone of about 14 km (??) with a more or less continuous slab of Subbetic Jurassic rocks thrust over the fault zone during Serravallian times. (C) Late Serravallian – early Tortonian: Breaking up of thrust slab due to continued right-slip along LEF zone, with marine sedimentation in strike-slip basins (Abarán Basin and its neighbouring basin due west) that were progressively opened in response to 9 km syn-depositional right-slip. (D) Early Tortonian – Pliocene: After sedimentation had stopped in the early Tortonian, the entire Abarán Basin moved about 12 km westward, as part of a larger, detached lithological block, leaving behind a rhomb-shaped outcrop of gypsiferous deposits that had acted as a detachment horizon.

The extensive Triassic outcrops south of the LEF and west of the ‘Subbetic Jurassic thrust front’ (D) may have been formed by ‘pull-apart stretching’ also. If this occurred during or after the development of the Abarán Basin, the amount of displacement along the LEF since the late Serravallian will be larger than in this model, implying a smaller offset in the period before.

to extension by normal faulting in an area between two major overstepping strike-slip faults, indicates a releasing overstep formed by fault segments that interact and merge at depth into a single fault, whereby the slip on the one segment is passed on to the other (Segall & Pollard 1980, Aydin & Nur 1985). Theoretical studies indicate that significant interaction should occur between two parallel strike-slip faults that are separated by less than twice the depth of faulting (Christie-Blick & Biddle 1985). In the Abarán case, the fault configuration indicates significant interaction between two major overstepping strike-slip faults that show a separation of about 4 km, suggesting that the faults penetrate at least 2 km in depth.

An exploration well and a seismic line SW of Calasparra demonstrate that here the pre-Triassic metamorphic basement is at a depth of about 5 km (Banks & Warburton 1991), thus confining the depth of the inferred Triassic detachment surface.

Faulting history of the LEF

suggest for pull-apart basins in general that basin depth is a function of basin length parallel to the major strike-slip faults. Hempton & Dunne suggest that the basin depth D relates to length L as: $D = 0.26 + 0.08 \times L$. Rodgers predicts for an initial pull-apart basin with length L a maximum depth of $D_{\max} = 0.15 \times L$. Since the Abarán Basin shows a fault-parallel length of 5.5 km, the equations predict a basin depth of 700 to 825 m.

The separation of interacting fault segments is usually considered to be related to the depth of the fault (e.g. Barlett et al. 1981, Naylor et al. 1986, Woodcock & Fischer 1986). Basin subsidence due

Considering the pull-apart nature of the Abarán

Basin and its original location adjacent to the Sierra de la Pila and the Sierra de Lugar (Fig. 11; Van der Straaten 1992), some speculative remarks can be made about the offset history of the LEF (Fig. 12A-D).

The pull-apart origin leads to an offset of ca. 5.5 km during the fill of the Abarán Basin in the late Serravallian to early Tortonian. This is the amount of overlap of the major E-W right-slip faults along the northern and southern margins of the basin. The separation between proximal, monomict boulder conglomerates (lateral fill of the middle sequence) and their probable sediment source in the 'basement', supports this amount of displacement. Coeval sediments due west of the Abarán Basin (Figs 2, 5) are considered to have been deposited in another strike-slip basin and probably document 3.5 km additional right-slip. The deposits are dragged along the northern boundary fault over a distance of at least 1 km (Fig. 5), giving a minimum amount of slip. The probable total offset on the LEF during late Serravallian – early Tortonian times therefore amounts to up to 9 km or even more if 'pull-apart stretching' occurred west of the study area.

Faulting continued after the filling of the basin. The displacement of the Abarán Basin from an area due south of the Sierra de la Pila to its present location has been estimated at 12 km (Van der Straaten 1992), which leads to a probable total displacement of at least 21 km since late Serravallian times.

The Jurassic carbonates exposed in the Sierra de la Pila, Sierra del Lugar (Fig. 1B) and Sierra del Oro (Fig. 2) are considered to be allochthonous Subbetic rocks thrust towards the northwest. These rocks and those exposed in the LEF zone more to the west (Fig. 2: B-C/1) belong to the same 'Pila Unit' (Fig. 1B). Remarkably, the westernmost outcrops north of the LEF lie about 20 km east of the westernmost outcrops south of the LEF. There are no indications that this situation was brought about by total erosion or rapid subsidence and subsequent burial of formerly existing thrust slices of the Pila Unit. The Subbetic outcrops may originally have formed one large, more or less continuous thrust complex with a roughly NE-SW trending front, displaced by the fault zone in later times. If this as-

sumption is valid, then the displacement along the fault zone since the emplacement of the thrusts approximates 20 km. This amount agrees with the ca. 21 km offset since the late Serravallian mentioned above.

Another element which may allow to establish the offset along the LEF zone is the stratigraphical similarity between the Prebetic rocks of the Sierra de la Pila and those of the Sierra de la Puerta (Hoe-demaeker 1973, Baena Perez & Jerez Mir 1982; see 'southern Prebetic' in Fig. 1B). This similarity documents that the sediments of both Sierras did not accumulate far apart. Their present separation suggests a total displacement on the LEF of about 35 km. This matches the above-mentioned amount of detached shortening in the Prebetic cover south of the Socovos Fault and the LEF.

Conclusions

The Abarán Basin developed along an E-W right-slip fault zone and is interpreted as a pull-apart basin (releasing overstep) defined by two right-hand stepping, major E-W right-slip faults connected by NW-SE normal oblique-slip faults. Inherent to the pull-apart interpretation, the right-slip along the E-W 'master' faults along the northern and southern basin margins is accommodated by extension parallel to the master faults, which resulted in subsidence inside the overstep.

The step-wise opening of the basin led to the development of three sequences, bounded by angular unconformities, in a progressively deeper and marine environment. Extension activated synsedimentary normal faults trending highly obliquely to the major right-slip faults. Due to this normal faulting, older basin sediments were progressively tilted and torn apart creating a depression in the central basin fill. Younger sediments occupied this depression and accumulated largely next to the older ones (tectonic downlap). The way of normal faulting, 'gapping' of older sequences, and tectonic downlap, suggest that the older basin deposits were pulled apart indeed, as illustrated in Fig. 10B-C, by displacement away from the basin centre.

The Abarán pull-apart was restricted to the sedi-

mentary cover above a Triassic detachment level. The depth of the Abarán Basin was probably in the order of 650 to 1400 m. The LEF zone probably penetrates 2 to 5 km in depth and does not affect the Paleozoic metamorphic basement.

The total offset along the LEF zone probably is of the order of 35 km. This displacement is interpreted to have taken place as follows (Fig. 12A-D):

- approximately 14 km (?) in the period Late Eocene – late Serravallian, probably during Early/Middle Miocene times under a tectonic regime of NW-SE compression;
- 9 km in the late Serravallian and early Tortonian, during the opening and filling of the Abarán Basin and another strike-slip basin due west;
- 12 km during the early Tortonian to Pliocene when the entire Abarán Basin moved as part of a larger detached block, leaving behind an 'empty' pull-apart between the basin and its northeastern sediment source area.

The total offset of 21 km since the late Serravallian corresponds with the distance between the westernmost outcrops of Subbetic Jurassic rock directly north and south of the LEF.

Acknowledgements

The study on the Abarán Basin has been carried out at the Vrije Universiteit te Amsterdam (The Netherlands) and fits in a broader research project on the External Zone of the Betic Cordillera. Publication has been made possible by the 'Fonds Structurele Geologie' of the Universiteit van Amsterdam. The paper covers a considerable part of my PhD thesis (Van der Straaten 1990b) and benefited from critical comments and helpful suggestions by Sierd Cloetingh, John Platt, Harm Rondeel and Wolfgang Schlager. Warner ten Kate and Harm Rondeel supported me in the field. Directional data have been analyzed and plotted using computer programs by Jan Diderick van Wees. I thank them all most kindly.

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