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Sedimentary models of coarse-grained deltas in the Neogene basins of the Betic Cordillera (SE Spain): Tortonian and Pliocene examples

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ABSTRACT

The Late Tortonian and Early Pliocene represent the two periods of greatest extension and sedimentary volume of the marine deltaic systems developing in the Betic Cordillera.

The complex palaeogeography of the Betic Cordillera during the Late Tortonian, consisting of marine intramontane basins surrounded by important reliefs (e.g. Sierra Nevada and Sierra de Filabres) and interconnected by narrow corridors, encouraged the development of very coarse-grained deltaic systems forming on basin margins and often controlled by tectonics. In this palaeogeographic setting, the Tortonian deltaic systems on the eastern boundary of the Granada Basin, the deltas of the Guadix Basin (Alicún, Lopera and Bodurria deltas) and the Alboloduy deltas in the Tabernas Basin developed. Delta building took place throughout a fourth-order (<1 m.a.) transgressive-regressive cycle, consisting of four tectonic systems tracts that include the deltas studied here - a transgressive systems tract controlled by a extensional tectonic regime (Alboloduy deltas and lower Bodurria deltaic sequences), a highstand systems tract (fan deltas in Granada and upper Bodurria deltaic sequences), a forced-regressive systems tract conditioned by regional tectonic uplift of the central sector of the Cordillera and a lowstand systems tract (small Gilbert-type deltas at Alicún, Lopera and the last Bodurria delta). The regressive phase of the cycle was conditioned by folding and uplift of the source area of the deltas.

During the Early Pliocene marine deltaic sedimentation in the Betic Cordillera was restricted to the peri-Mediterranean basins flooded by the earliest Pliocene transgression. After the Pliocene transgression the palaeogeography was characterised by different NW-SE oriented gulfs and bays bounded by mountain ranges such as Sierra de Gádor, located between the Andarax Corridor and the Campo de Dalías, basins in which the deltaic systems of Alhama de Almería and Adra respectively prograded. Catastrophic sedimentation events (storms and/or floods) recorded as erosion surfaces, backsets and accumulation layers of oysters and clasts with barnacles on the delta fronts played an important part in the construction (and destruction) of these deltas.

Shallow-water Gilbert-type deltas predominate among the examples selected. Palaeogeographic differences in the Tortonian and Pliocene encouraged the development of alluvial fans as feeder systems of the Tortonian deltas and high energy fluvial systems in the case of the Pliocene deltas. The relatively high tectonic subsidence of the basins in the Tortonian in comparison with the Pliocene affected the vertical accumulation of thick deltaic successions (up to 250 m) multiconstructed by several decametric sequences in the Tortonian, whereas the Pliocene deltas mainly developed horizontally. Some of the Tortonian deltaic sequences are capped by bioconstructed limestones such as coral reef patches, red algae biostromes and stromatolites, interpreted as facies of delta abandonment.

Key words: Betic Cordillera, coarse-grained deltas, forced regression, Neogene, tectonic-sedimentation relation

Modelos sedimentarios de deltas de grano grueso en las cuencas neógenas de la Cordillera Bética (SE de España): ejemplos tortonienses y pliocenos

RESUMEN

El Tortoniense superior y el Plioceno inferior representan los dos intervalos de tiempo durante los cuales el desarrollo de sistemas deltaicos marinos en la Cordillera Bética adquirió mayor importancia por extensión y volumen de sedimento.

La compleja paleogeografía de la Cordillera Bética durante el Tortoniense superior, representada por cuencas marinas intramontañosas rodeadas por importantes relieves (p. ej. Sierra Nevada y Sierra de Filabres) y conectadas entre sí por estrechos corredores favoreció el desarrollo de sistemas deltaicos de grano muy grueso adosados a bordes de cuenca, a menudo controlados por la tectónica. En ese contexto paleogeográfico se construyeron los sistemas deltaicos tortonienses del borde oriental de la Cuenca de Granada, los deltas de la Cuenca de Guadix (deltas de Alicún, Lopera y Bodurria) y los deltas de Alboloduy en la Cuenca de Tabernas. La construcción deltaica tuvo lugar a lo largo de un ciclo transgresivo-regresivo de cuarto orden (<1 m.a.) compuesto por cuatro cortejos sedimentarios controlados fundamentalmente por la tectónica, donde se integran los ejemplos deltaicos estudiados: un cortejo sedimentario transgresivo controlado por tectónica de tipo extensional (deltas de Alboloduy y deltas inferiores de Bodurria), un cortejo de alto nivel del mar (abanicos deltaicos de Granada, deltas superiores de Bodurria), un cortejo regresivo forzado por un levantamiento de escala regional del sector cen-

tral de la cordillera y un cortejo de bajo nivel del mar (pequeños deltas Gilbert de Alicún, Lopera y último delta de Bodurria). La fase regresiva del ciclo estuvo controlada por el inicio de la formación de los antiformes de gran radio que conforman la actual estructura de las sierras donde estaban instaladas las cuencas de drenaje de los deltas.

Durante el Plioceno inferior, la sedimentación deltaica marina en la Cordillera Bética quedó restringida a las cuencas perimediterráneas inundadas por la transgresión acontecida al inicio del Plioceno. La paleogeografía tras la transgresión pliocena quedó dibujada en diferentes golfos y bahías de orientación NO-SE limitados por sierras como Sierra de Gádor, situada entre el Corredor del Andarax y el Campo de Dalías, cuencas en las que progradaron los sistemas deltaicos de Alhama de Almería y Adra, respectivamente. Eventos de sedimentación catastrófica (tormentas y/o inundaciones) registrados en forma de superficies erosivas, backsets y capas depositadas en la llanura deltaica y posteriormente resedimentadas en los frentes deltaicos (lumaquelas de ostreidos y balánidos), jugaron un importante papel en la construcción (-destrucción) de estos deltas.

Los deltas Gilbert de aguas someras son los dominantes entre los ejemplos seleccionados. Las diferencias paleogeográficas entre el Tortoniense y el Plioceno favorecieron el desarrollo de abanicos deltaicos en el Tortoniense y deltas alimentados por sistemas fluviales de alta energía en el Plioceno. La relativamente alta subsidencia tectónica de las cuencas en el Tortoniense respecto al Plioceno condicionó la acumulación en la vertical de potentes sucesiones deltaicas (hasta de 250 m) multiconstruidas por varias secuencias de escala decamétrica en el Tortoniense, mientras que los deltas pliocenos se desarrollan fundamentalmente en la horizontal. Algunas de las secuencias deltaicas tortonienses aparecen limitadas a techo por bioconstrucciones carbonatadas tales como parches arrecifales de coral, biostromas de algas rojas y estromatolitos. Se interpretan como facies de abandono deltaico.

Palabras clave: Deltas de grano grueso, Cordillera Bética, Neógeno, regresión forzada, relación tectónica-sedimentación

Introduction

During the post-orogenic Neogene, numerous marine deltaic systems developed in the intramontane basins of the Betic Cordillera in different tectonic, eustatic and climatic settings. The Tortonian, in particular the Late Tortonian, and the Early Pliocene represent the periods when delta building was most prolific in these basins, as shown by the number of papers describing sedimentological aspects of examples of Tortonian and Pliocene deltas in the Betic Cordillera:

- Late Tortonian examples: Deltas on the eastern margin of the Granada Basin (Dabrio *et al.,* 1978; Braga *et al.,* 1990, García-García *et al.,* 1999), deltas in the Almanzora Corridor (Dabrio and Polo, 1988; Braga and Martín, 1988; Dabrio, 1990), and deltas in the Guadix Basin -some authors refer to this basin as the “Guadix-Baza Basin”- (Fernández and Guerra-Merchán, 1996; García-García *et al.,* 2000 and 2001; Soria *et al.,* 2003).
- Early Pliocene examples: Delta of the Abrioja Formation in the Andarax Corridor (Postma, 1984a and 1984b), Delta del Espíritu Santo in the Vera Basin (Postma and Roep, 1985), Delta de El Barranquete in the Almería Basin (Boorsma, 1992), Delta in the Polopos Corridor (Mather, 1993) and the Adra Delta in the Campo de Dalías and Alhama de Almería Delta in the Andarax Corridor (García-García *et al.,* 2003).

The main goals of this study are to: 1) establish the stratigraphic architecture and facies associations of the deltaic systems; 2) evaluate the role of the allocyclic controls -tectonic, eustatic and climatic events- in the deltaic sedimentation; 3) compare the deltaic systems to reveal global characteristics which contribute on existing models of coarse-grained deltas described in various monographs (Coleman and Prior, 1980; Nemec and Steel, Eds., 1988; Colella and Prior, Eds., 1990; Dabrio *et al.*, Eds., 1991; Chough and Orton, Eds., 1995; Marzo and Steel, Eds., 2000).

Geological setting

Betic Cordillera

The Betic Cordillera (southern Spain), together with the Rif (northern Africa), is the westernmost part of the circum-Mediterranean Alpine chain that originated after the closure of the Tethys Ocean, due to African-Eurasian plate convergence (Sanz de Galdeano, 1990). To the north it is bounded by the Iberian Massif (foreland domain) and to the south by the Alboran Basin. The Betic Cordillera comprises two main structural domains: the Internal Zones to the south, also known as the Alboran Block (Balanyá and García-Dueñas, 1986, 1987), and the External Zone or South-Iberian palaeomargin to the north. The Internal Zones made up of allochthonous stacking of major units separated by thrust faults. In much of the Cordillera, the Internal Zones are surrounded by the Campo de Gibraltar Complex or “Flysch” Trough, another allochthonous domain consisting of several tectonic units with complex structural relations (Martín Algarra, 1987). Both domains (Internal and External Zones) underwent convergence and collision processes that ended in the Early Miocene and gave rise to substantial crustal thickening.

During and after the collision, the Alboran Block was subjected to an extensional phase, dominated by detachment processes causing crustal thinning. The first of these extensional episodes took place during the Early Miocene, giving rise to the formation of the Alboran basin (Comas *et al.*, 1992; García-Dueñas *et al.*, 1992; Vissers *et al.*, 1995). Other extensional episodes occurred during the Middle Miocene, in particular the Serravallian episode, which was the direct cause of the destruction of the earliest (before Late Miocene) Neogene basins, of the present distribution of the complexes making up the Alboran Block and the palaeogeography of the most recent Neogene in the Cordillera.

Neogene-Quaternary basins

Internal Zones domain contain some of the Neogene-Quaternary basins where the deltas studied are located (Tabernas basin, Campo de Dalías and Andarax Corridor) whereas the basement of the rest of the basins (Granada and Guadix basins) is formed of pre-Miocene units from the Internal as well as from the External Zones (Fig. 1A).

The Neogene-Quaternary basins are intramontane basins in the central sector (Granada and Guadix basin) and the eastern sector of the Betic Cordillera (Tabernas basin, Campo de Dalías and Andarax Corridor). Tectonically, the basins are bounded by extensional and strike-slip fault systems that are responsible for significant uplift of the basin margins and subsidence of the basin itself (Sanz de Galdeano, 1990; Soria *et al.,* 1998). The mountains which constitute the margins of these basins are part of the Internal Zones and consist of antiforms which formed during the Late Neogene (Sierra Nevada, Sierra de Filabres, Sierra de Gádor, among others). The deltaic systems studied here are, in part, the sedimentary response to the folding and uplift of these mountains.

Tortonian and Pliocene deltas

The seven examples studied here -five Tortonian deltas and two Pliocene deltas- are located in different Neogene-Quaternary basins in the central and eastern sectors of the Betic Cordillera.

The five examples of tortonian deltas chosen for this study are: (1) the deltaic systems on the eastern margin of the Granada Basin (Granada deltas); (2) the Lopera and (3) Bodurria deltas on the southern margin and (4) Alicún delta on the northern margin of the Guadix Basin, and (5) the Alboloduy deltas on the northwestern margin of the Tabernas Basin (Fig. 1B). All these deltaic systems, except the Alicún delta fed by the subbetic material of the Montes Orientales (External Zones), have a common source area in the reliefs conforming the structural alignment of Sierra Nevada and Sierra de Filabres. From a structural point of view, these ranges are formed by two domes with preferential E-O axis (Martínez-Martínez *et al.,* 2002). These antiforms contain the folded rocks of two of the three stacked metamorphic complexes forming the Internal Zones of the Betic Cordillera, the Nevado-Filabride Complex in the nucleus and the Alpujarride Complex towards the edges of the sierras.

The two examples of Pliocene deltas chosen for study are those of Alhama de Almería and Adra at the northwestern margin of the Andarax Corridor and in the Campo de Dalías respectively (Fig. 1B). The drainage basins of the Pliocene deltaic systems were located on Sierra de Gádor mountains.

Stratigraphic setting

Late Tortonian

The deltaic systems studied in the Granada and Guadix basins represent depositional systems of the genetic units II and III of the six stratigraphic genetic units separated by Fernández *et al.* (1996) in the basin-fill sediments of the central sector of the Betic Cordillera. The deltaic systems studied in the Tabernas basin represent depositional systems of the genetic Unit II of the stratigraphic model proposed by Pascual (1997) for the Tabernas Basin in the eastern sector of the Cordillera (Fig. 2). All these units are bounded by basinwide discontinuities.

The deltaic sediments are Late Tortonian in age, corresponding to the *Discoaster quinqueramus* biozone or biozone NBN-12 in accordance with the biozonation of Martín Pérez (1997). They represent the last marine deposits in the basins of the central sector of the Cordillera, before they eventually became continental at the end of the Tortonian (Rodríguez-Fernández, 1982).

Early Pliocene

The Alhama de Almería and Adra deltas developed during the Early Pliocene, in accordance with the biostratigraphic data of Fourniguet and Le Calvez (1975), Aguirre (1995) and Pascual (1997). Both exam-

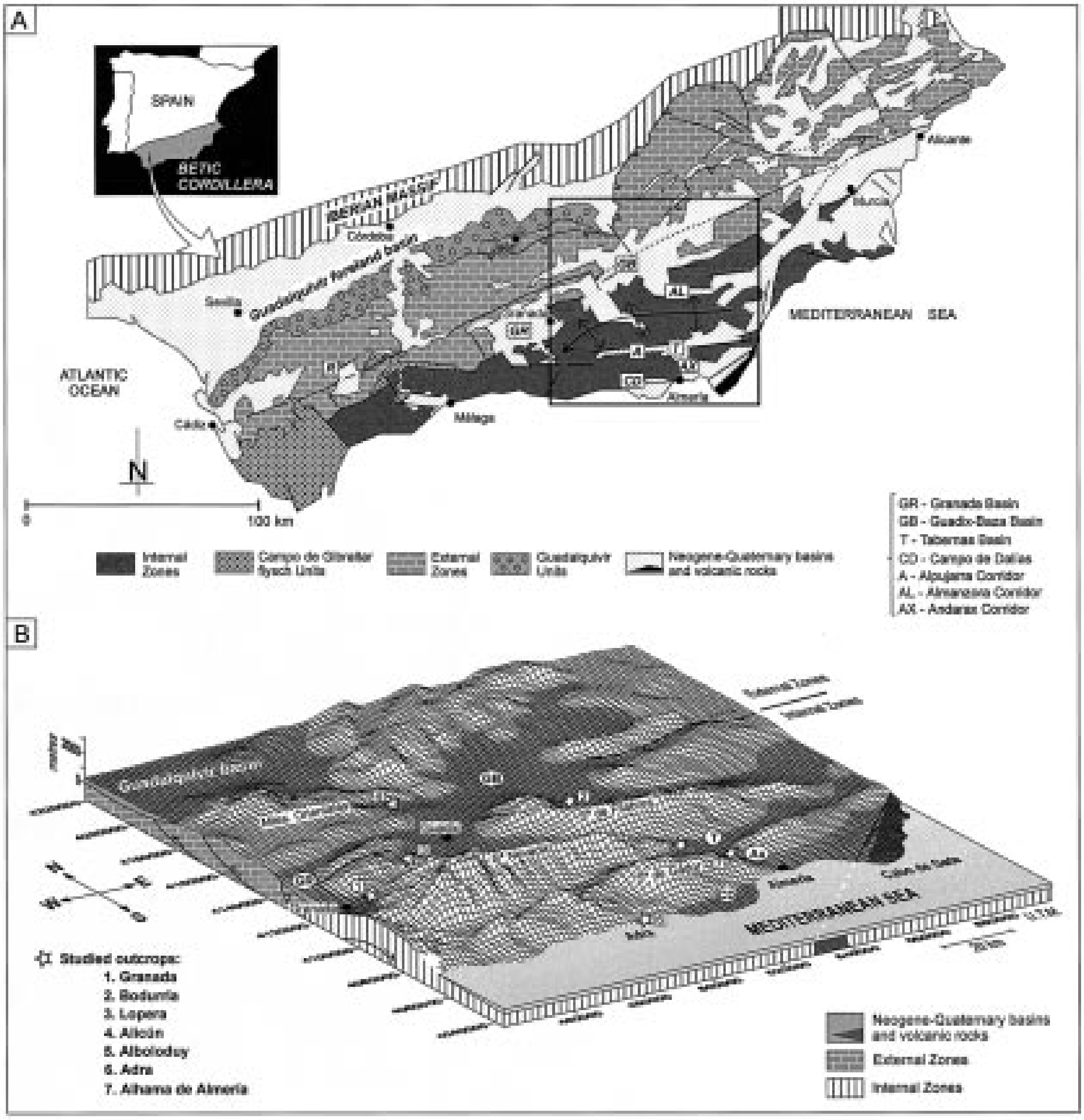

Fig. 1.A. Geological map of the Betic Cordillera and situation of some of the Neogene-Quaternary basins of the central and eastern sectors of the Cordillera, B. Digital model of relief in the sector of the Betic Cordillera shown in Figure A, where the outcrops studied are located

Fig. 1.A. Mapa geológico de la Cordillera Bética y situación de algunas de las cuencas neógeno-cuaternarias del sector central y oriental de la cordillera, B. Modelo digital del relieve del sector de la Cordillera Bética enmarcado en la figura A, donde se localizan los afloramientos estudiados

ples form part of the unit informally defined as Pliocene 1 by Montenat (1990) and Aguirre (*op. cit.*) or Pascual's genetic unit VII (*op. cit.*) (Fig. 2). The deltaic sediments were deposited in a marine setting in some of the peri-Mediterranean basins of the Betic Cordillera that were flooded by the rise in sea level occurring at the beginning of the Pliocene.

Stratigraphic architecture and sequential organisation

Deltaic succession on the eastern margin of the Granada Basin

The 250 m thick deltaic succession on the eastern margin of the Granada Basin consist of five deltaic sequences (I to V) bounded by unconformities. The clinoforms decrease upward in height from 180 m in the first to 15 m in the last deltaic sequence. The decrease of the clinoforms height, calculated approximately as the vertical distance between the average surfaces of the topset and bottomoset, reflects the shallowing of the basin. The deltaic sequences show a progradational stratal pattern to the west. The total horizontal displacement of the brinkpoints from the first to the last sequence surpasses 3 km, implying an equivalent amount of coastline displacement towards the basin center.

Bodurria deltaic succession

The 230 m thick Bodurria deltaic succession on the southeastern margin of the Guadix Basin also consists of five coarsening-upward sequences (I-V) of decametric height, bounded by angular and syntectonic progressive unconformities (Fig. 3A). The deltaic succession unconformably overlies the Alpujarride limestone and underlies alluvial deposits of the continental basin-fill. The first three sequences (I-III) show a retrogradational stratal pattern, whereas the last two present a progradational stratal pattern. The delta lobes making up each of the lower deltaic sequences (I-III) are capped by onlapping carbonate beds (Fig. 3B). The last delta lobes of the succession (Sequence V) are located 3 km away from the basin margin overlying the pelagic basin deposits of the underlying sequences up to (Fig. 3C).

Alicún and Lopera Deltas

The Alicún and Lopera deltaic deposits occupy the

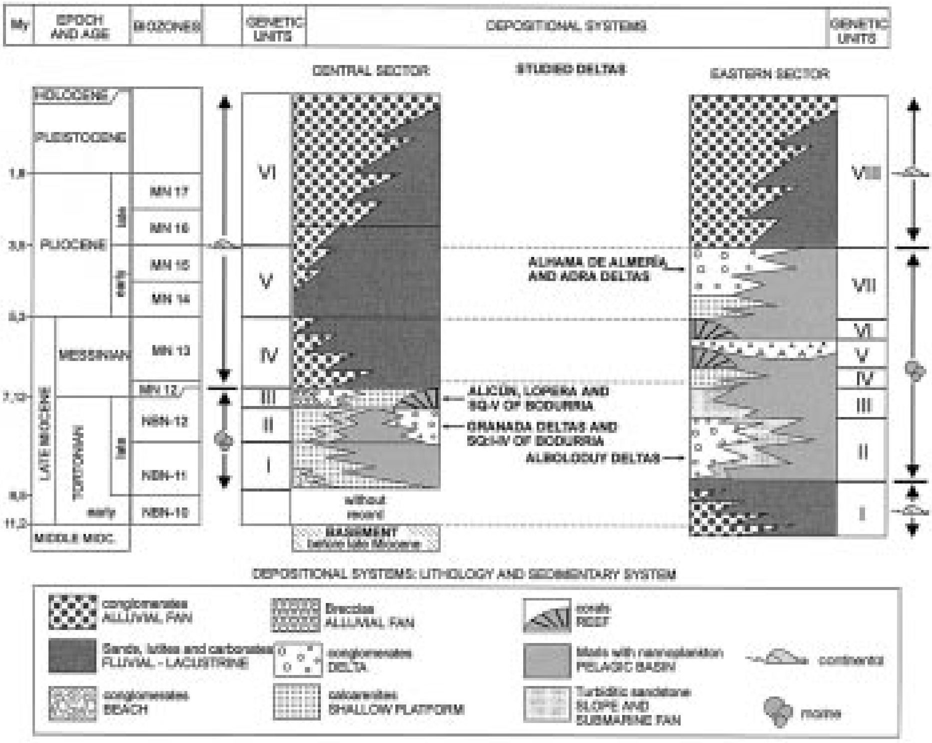

Fig. 2. Synthetic columns representative of the sedimentary filling of the Neogene-Quaternary basins in the central and eastern sectors of the Betic Cordillera with most representative depositional systems, including the delta systems studied, whose stratigraphic position is marked (figure drawn following the geochronology of Cande and Kent, 1992; Berggren *et al.* 1995, the biostratigraphy of Martín Pérez, 1997 and allostratigraphic units defined by Montenat *et al.* 1987; Pascual, 1993; Soria *et al.*, 1998 and 1999)

Fig. 2. Columnas estratigráficas sintéticas del relleno sedimentario de las cuencas neógeno-cuaternarias del sector central y oriental de la Cordillera Bética con los sistema deposicionales más representativos, entre ellos los sistemas deltaicos estudiados, cuya posición estratigráfica aparece señalada (figura realizada a partir de la geocronología de Cande y Kent, 1992; Berggren et al. *1995, biostratigrafía de Martín Pérez, 1997 y unidades aloestratigráficas diferenciadas por Montenat* et al. *1987; Pascual, 1993; Soria* et al.*, 1998 y 1999)*

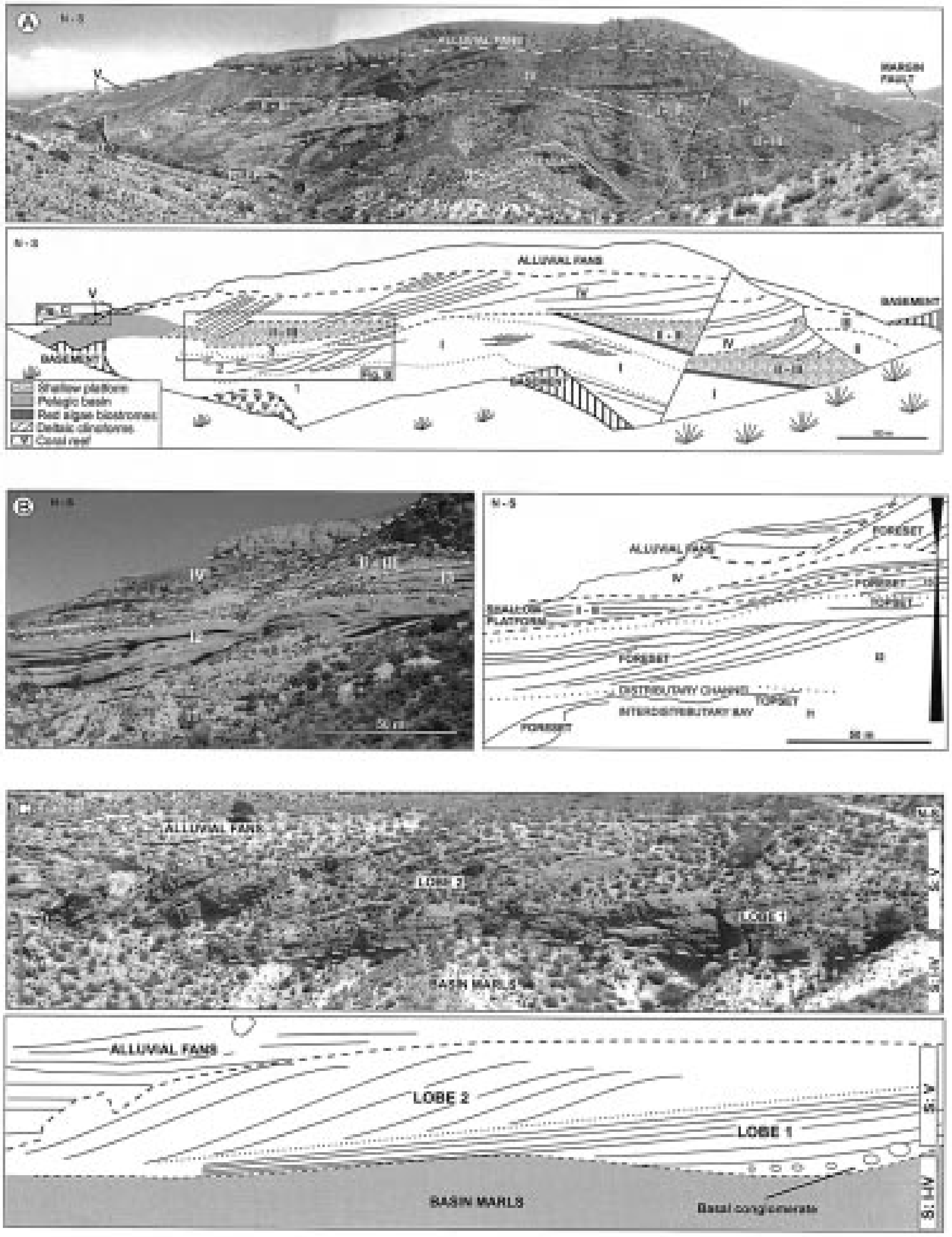

Fig. 3. Tortonian deltas at Bodurria: A. Photomosaic and line drawing of the studied cross-section of Bodurria with differentiation of the five deltaic sequences (I-V) bounded by unconformities and some of the smaller deltaic sequences making up sequence I (1-3). The situations of figures 3B and 3C are shown, B. Photograph and line-drawing of sequence I (S:I) arranged in three stacked minor sequences (I1-I3), C. Panoramic view and line-drawing of the two lobes of deltaic sequence V which prograded over basin marls. The distal part of the oblique-tangential clinoforms of the lower lobe lying on the basal conglomerate and the sigmoidal clinoforms of the upper lobe can be seen

Fig. 3. Deltas tortonienses de Bodurria: A. Panorámica e interpretación del corte geológico de Bodurria en el que se han diferenciado las 5 secuencias deltaicas (I-V) y algunas de las secuencias deltaicas de orden menor que componen la secuencia I (1-3). Se muestra la situación de las figuras 3B y 3C, B. Panorámica e interpretación de la secuencia I (S: I) en la que se diferencian 3 secuencias de orden menor (I1-I3), C. Panorámica e interpretación de los dos lóbulos de la secuencia deltaica V que progradaron sobre margas de cuenca pelágica. Del lóbulo inferior aparece la parte distal de las clinoformas oblicuo-tangenciales dispuestas sobre el conglomerado basal y del lóbulo superior se reconocen las clinoformas sigmoidales

same stratigraphic position and are located respectively on the northern and southern margins of the Guadix Basin. They form part of the third of the genetic units (Unit III) into which Fernández *et al*. (1996) separated the Guadix basin-fill sediments. Both systems directly unconformably superposed on the turbiditic slope of the last shallow platform-slope sigmoid and on the pelagic-basin marls of the underlying stratigraphic genetic unit (Unit II).

Alboloduy deltaic succession

The 100 m thick Alboloduy deltaic succession on the western margin of the Tabernas Basin consists of five deltaic sequences between 10 and 20 m thick. The stacking of the deltaic sequences shows an aggradational stratal pattern directly overlying coastal plain deposits. Some of the deltaic sequences are capped by carbonate beds on which the clinoforms of the overlying deltaic lobe downlap. The deltaic succession lies unconformably on red conglomerates alluvial fans and underlies marls alternating with sand and conglomerates interpreted as submarine fans.

Alhama de Almería and Adra Deltas

The Alhama deltaic deposits lie on shallow platform bioclastic sandstones that interfinger distally with silts recording the earliest Pliocene transgression. The wedge-shaped geometry of the deltaic and platform deposits represents a syntectonic progressive unconformity. The deltaic unit varies in thickness from 5 m in proximal areas to 30 m in distal areas. It shows a progradational stratal pattern to the east.

The Adra deltaic deposits uncoformably overlie the Alpujarride basement. The contact is a stepped unconformity dipping to the south. The deltaic unit varies in thickness to 80 m and several deltaic lobes or progradation units bounded by erosional surfaces can be distinguished in it. The stratal pattern is progradational and the trajectory of the brinkpoints line is stationary, descending ultimately among the last delta lobes with a fall of some 25 m.

Sigmoidal, oblique (Fig. 4A) and oblique-tangential are the three types of geometry recognised in delta clinoforms. All three can be showed in the clinoforms of a single delta due to temporal variations in the supply/accommodation space ratio. The geometry of the clinoforms in the delta of the Alhama transversal system varies from sigmoidal to oblique geometries. The irregular physiography of the basin bottom revealed the clinoforms variation in height gave way to local variation in accommodation space (Fig. 4B). Where the delta migrated over small depressions, sporadic increase of the accommodation space ocurred forming sigmoidal clinoforms. When it migrated over areas where the basin bottom was more elevated, oblique geometries developed (Fig. 4C).

Sedimentological analysis

Individualised analysis of the deltaic examples

Deltaic succession on the eastern margin of the Granada Basin

The deltaic systems are very coarse-grained fan deltas, with the exception of the last deltaic sequence represented by small fluvial Gilbert-type deltas. The deltas evolve from large deep-water fan deltas (200 m deep according to the height of the clinoforms of sequence I) several kilometres in radius (up to 5 km) to small deltaic systems (100 m radius) prograding in a very shallow sea (15 m deep for sequence V). Reef patches were established on the brinkpoint of some of the clinoforms of sequences I to IV (Braga *et al.,* 1990). The type sequence of these deltas is coarsening-upward, with isolated conglomeratic lobes alternating with silts and sand lobes. Convex-up geometry bodies consisting of amalgamated conglomeratic lobes appear at top of the sequece (Fig. 5A).

Bodurria deltaic succession

Each of the sequences (I-V) is made up of deltaic systems interfinger distally to shallow platform systems and pelagic-basin marls. Several types of deltas make up the sequences: Fluvial Gilbert-type deltas (S: I and V), Gilbert-type fan deltas (S: IV and V) and shoal-water type deltas (S: III). The deltas of sequences I and III are capped by carbonate deposits: platform calcarenites on the deltas of sequence I and red algae biostromes on the deltas of sequence III. The red algae biostromes have been interpreted to represent intervals of reduced siliciclastic input into the basin which records time of delta abandonment. A bed containing large boulders of Alpujarride limestone appears at bottom of the last delta (S: V) which progrades over pelagic-basin marls.

Alicún and Lopera Deltas

Both the Alicún and Lopera deltas are small deltaic

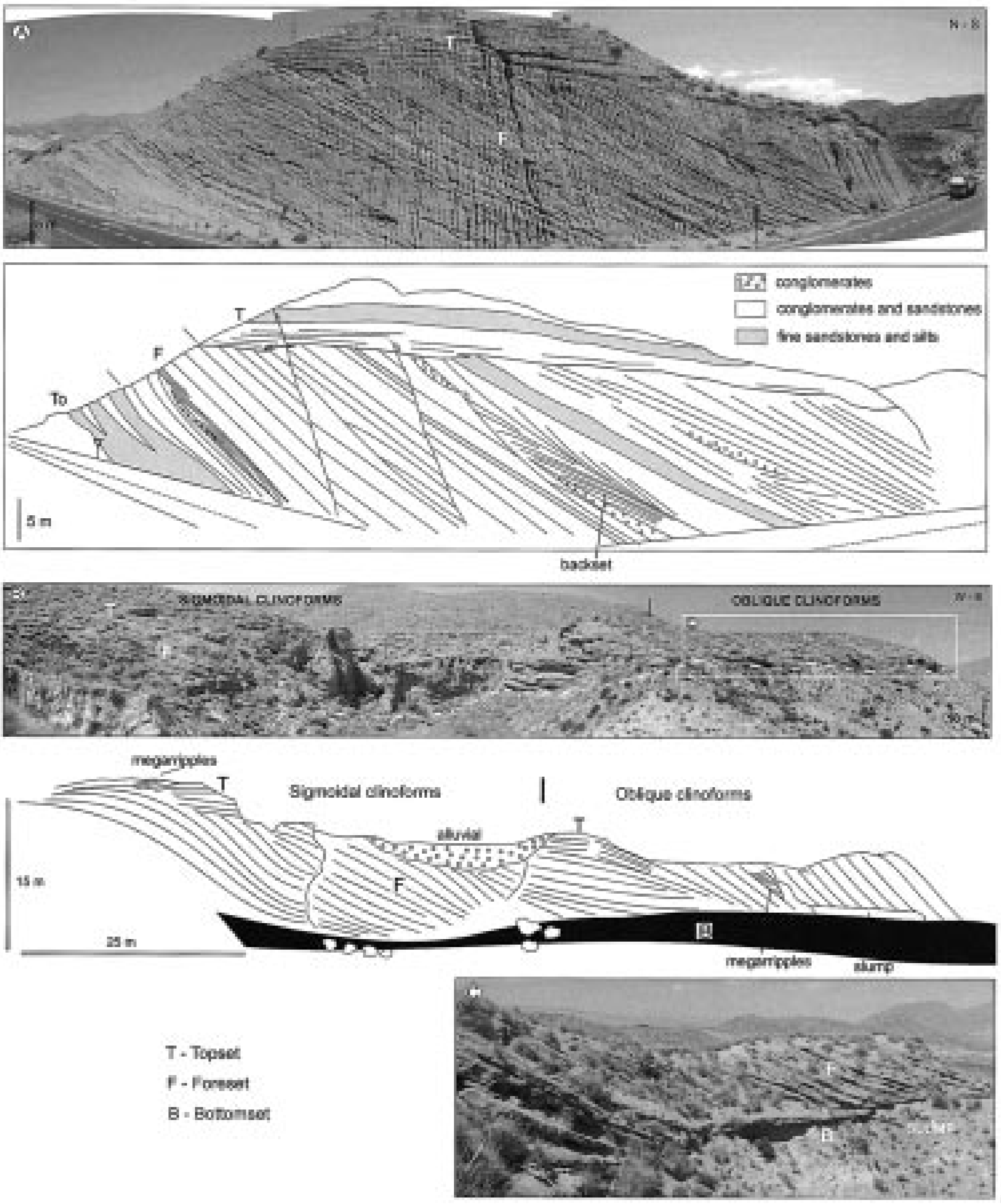

Fig. 4. Pliocene deltas at Alhama de Almería. A. Panoramic view and line-drawing of the longitudinal delta showing the oblique geometry of the clinoforms (T: topset; F: foreset; To: toeset; b: backsets), B. Panoramic view and line-drawing of the transverse delta showing sigmoidal and oblique forms, C. Detail of the oblique clinoforms of figure 4B with and intercalated slump layer

Fig. 4. Deltas pliocenos de Alhama de Almería. A. Panorámica e interpretación del delta longitudinal que muestra la geometría oblicua de las clinoformas (T: topset*; F:* foreset*; To:* toeset*; b:* backsets*), B. Panorámica e interpretación del delta transversal que muestra clinoformas sigmoidales y algunas oblicuas, C. Detalle de las clinoformas oblicuas de la figura 4B con una capa de* slump *intercalada*

systems with Gilbert-type geometry prograding to the northeast (Fig. 5B).

The Alicún delta, located in the northwestern sector of the Guadix Basin, is a deltaic system that shifts distally and laterally to shallow platform deposits. In some cases, channelized volcanic conglomerates occur at the base of the platform deposits associated with a stage of intense erosion of the outcropping basement in the basin margin. The five main phases of delta progradation separated by erosional surfaces are correlated with five phases of aggradation in the shelf. The delta clinoforms decrease in height (from 30 m the first to 5 m the last) revealing the shallowing of the basin. The decrease in basin accommodation is interpreted as a result of the passive filling. At the foot of the erosional scars bounding each of the five deltas's progradational units there is a conglomeratic lobe, which implies an origin as resedimentation of downslope destabilised foreset beds.

On the southwestern margin of the Guadix basin the Lopera deltaic system that prograded up to 3 km to the northeast. It consists of clinoforms less than 15 m in height.

Alboloduy deltaic succession

Two deltaic systems alternate in this deltaic complex: a longitudinal system whose deltas prograded to the west filling a Tortonian marine bay, and a transveral system whose deltas prograded to the south. The longitudinal system (Sequences I to IV) consists of wave-dominated Gilbert-type deltas fed by a river eroding the red conglomerates of the underlying stratigraphic unit. The topset deposits of these deltas are characterised by morphological segregation of the clasts. Discoidal clasts of schists imbricated landward overlie spherical quartzite clasts, suggesting the development of gravel beaches. Reef patches cap both interdistributary bay silts (Fig. 5C) and inactive distributary mouth bars in the plain delta. Some of deltaic sequences are capped by calcarenite beds consisting of colonies of branching red algae interpreted as deltaic abandonment deposits. The skeletal association of the calcarenites (red algae, bryozoan, bivalves, brachiopods, echinoderms) is characteristic of the typical spectrum of the "bryomol association" of temperate carbonates. Stromatolithic limestones also precipitated in the interdistributary bay sediments of the delta plain. The deltas of the transversal system (part of Sequence I and Sequence V) are smaller in size and present characteristics of very coarse-grained deltas common in fan deltas. Their drainage basins were on the nearby reliefs of Sierra Nevada.

Alhama de Almería and Adra Deltas

The Alhama deltaic complex consists of two deltaic systems that interfinger distally: one whose migration direction is parallel to the main directions of the Andarax Corridor, from northwest to southeast (longitudinal system) and the other from west to east (transversal system). The longitudinal system is represented by a Gilbert-type delta with oblique clinoforms, fed by a fluvial system with the source area in the reliefs of Sierra Nevada, as indicated by the lithology of the clasts and the palaeocurrents towards southeast. The most representative facies of this delta are the frequent backset beds in the foreset (Fig. 5D). The transversal system is represented by a Gilbert-type fan delta with sigmoid clinoforms and source area in Sierra de Gádor, as shown by the eastward palaeocurrents and the clasts lithology.

The deltaic lobes of Adra prograded to the south in a Pliocene marine bay with steeply slope coast characterised by cliff and gravel beach environments similar to the present. The geometries of the clinoforms vary cyclically from oblique, built up of coarse grain conglomerates, to sigmoid, built up of smaller size conglomerates and sands. The most characteristic facies are found in the foresets and are represented by oysters accumulation beds (Fig. 5F), clasts with attached barnacles (Fig. 5E) and backset beds. Occasionally, these deposists filled erosional surfaces bounded the deltaic progradation phases.

Comparative analysis of deltas: sedimentological synthesis

Delta types

Because of the predominant grain size of the sediment, all the deltas studied can be classified as coarse-grained deltas developed in shallow-water sea. Most of the deltas have a Gilbert-type profile, apart from the deltas in Bodurria sequence III, which are shoal-water type deltas with development of distributary mouth bars. This case is an excellent example for study since, although the characteristics of supply and distributary channel are maintained, it can be seen how a delta's profile can vary as the basin characteristics change where the distributary channel deposits its supply. Thus, shoal-water type deltas become Gilbert-type deltas with the local increase in gradient and accommodation space at the mouth of the distributary channel.

The high-energy characteristics of the feeder systems of the deltas mean that the latter are mainly dominated by the dynamic of the feeder system. The deltas in the longitudinal system at Alboloduy are the only ones in which the wave action is predominant, causing the development of gravel beaches in the delta plain.

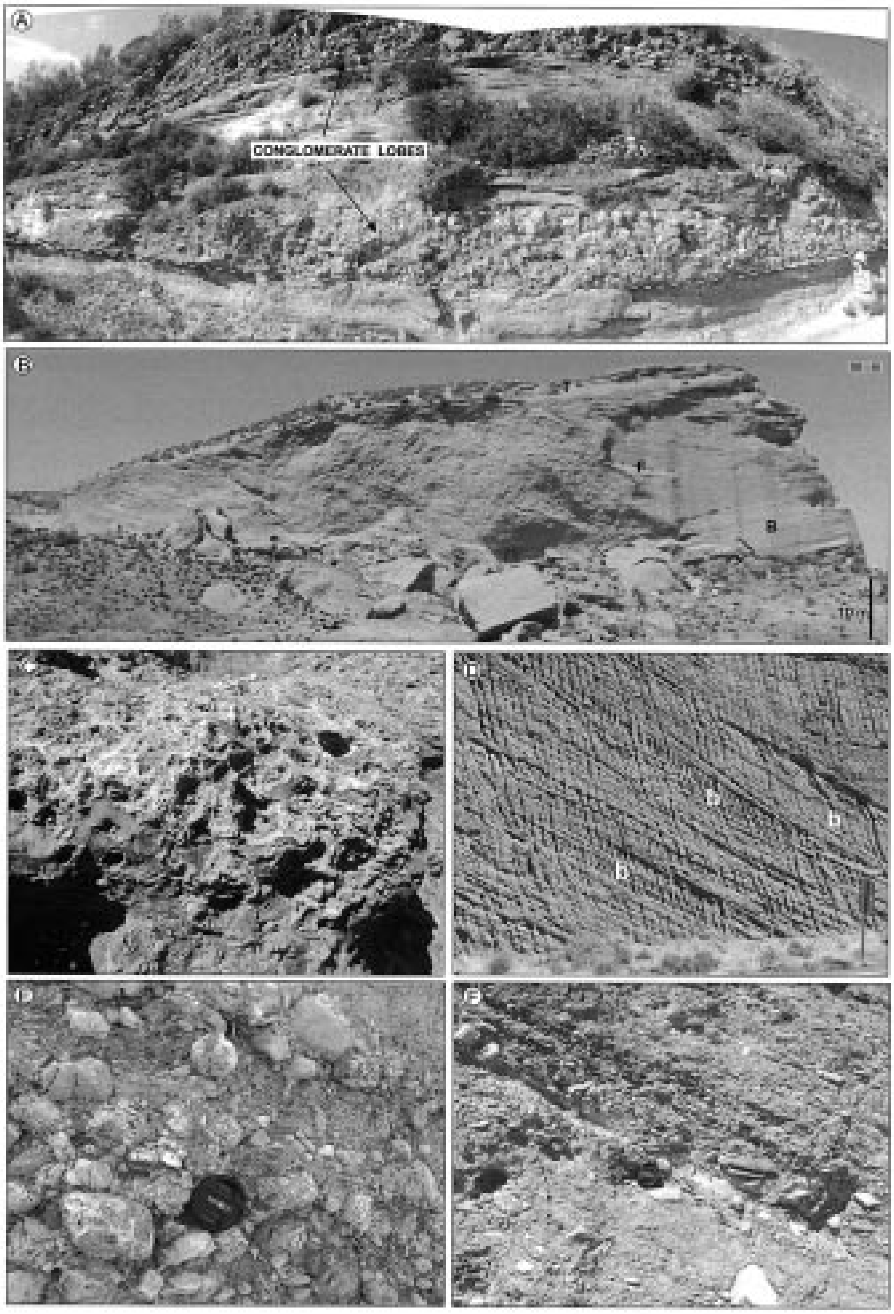

Fig. 5. A. Granada delta: coarsening sequence in the distal delta front where isolated conglomerate lobes intercalate between silts and sands (person to show scale in lower right). At top of the sequence is a body consisting of amalgamated conglomerate lobes, B. Gilbert-type delta at Alicún (T: topset; F: foreset; B: bottomset), C. Alboloduy deltas: reefal patch where corals grew on the soft substratum of grey, interdistributary bay silts, D. Alhama deltas: backset beds (b) in the foreset, E. Adra deltas: foreset bed with barnacles attached to most of the clasts, F. Adra deltas: accumulation layer of oysters imbricated with the foreset slope (sea to the right)
Fig. 5. A. Deltas de Granada: secuencia granocreciente en el frente deltaico distal donde lóbulos aislados de conglomerados se intercalan entre limos y arenas (persona como escala en la parte inferior derecha). A techo de la secuencia aparece un cuerpo formado por lóbulos conglomeráticos amalgamados, B. Delta Gilbert de Alicún (T: Topset*, F:* Foreset*, B:* Bottomset*), C. Delta de Alboloduy: parche arrecifal en el que los corales crecieron sobre el sustrato blando representado por limos de bahía interdistributaria, D. Delta de Alhama: estratificaciones cruzadas inclinadas contrapendiente (b:* backset*) en el* foreset*, E. Delta de Adra: capa del* foreset *con balánidos adosados a la mayoría de los clastos, F. Delta de Adra: capa de ostreidos imbricados a favor de la pendiente del* foreset *(mar hacia la derecha)*

Sediment lithology and its influence on deltaic processes

Regarding the source area lithologies, we can divide the examples studied into deltas fed by mainly carbonate rocks (limestone, dolomite, marble) and those fed by metamorphic rocks, mainly schist and quartzite. The source area of the former are the Triassic rocks of the Alpujarride Complex (deltas in Sequence V at Granada, deltas in Sequence I and V at Bodurria, tranverse delta at Alhama and initial stages of the Adra delta) or the External Zones of the Cordillera (Alicún delta), whereas the latter were supplied by the erosion of Palaeozoic and Permo-Triassic rocks from the Nevado-Filabride Complex. Schists predominate in the reliefs of Sierra Nevada and Sierra de Filabres, whereas in Sierra de Gádor the predominant rocks are carbonate rocks. Since schists are more easily eroded than carbonate rocks, the reliefs of Sierra Nevada and Sierra de Filabres represent more efficient source area than Sierra de Gádor for supply of the deltas developing at their feet. This efficiency can be seen in the Pliocene deltas of Adra and Alhama de Almería, whose deltaic lobes developed at the feet of Sierra de Gádor, but whose carbonate clasts are minority. Schists and quarzites from more distant ranges (Sierra Nevada and Filabres) and with a “softer” behaviour under erosion are the predominat lithologies in these deltas. The fact that these ranges were distant from the Pliocene coastline meant that some of the Pliocence deltas were fed by rivers (braidplains or solitary rivers), whose transport efficiency is higher if the feeder systems are alluvial fans, e.g., the longitudinal fans of Alhama and the Espiritu Santo delta in the Vera Basin.

The soft behaviour of schists under erosion, particularly in damp conditions, encourages the formation of an important volume of fine fraction, which, in turn, allows the predominance of deposits from matrix-supported flows and, therefore, cohesive debris flows, as is the case of the Granada deltas. In deltas fed by carbonate clasts, the deposits from cohesionless debris flows predominate, with fluidal flows especially on the delta plain. As the matrix/clasts ratio increases, so too does the viscosity of the debris flows, with greater capacity to transport large blocks. This is why the deltas fed from source areas of schists present greater heterogeneity of grain-size, with the appearance of outsized clasts, than deltas fed by limestones and dolomites.

Lithofacies and deltaic subenvironments

The dominant lithofacies in the deltas studied are gravels matrix-supported and can be found either chaotically, with no grading, or with inverse grading. These facies (Gms and Gmi-Table 1) are representative of delta plains and delta fronts of very coarse-grained deltas, such as Granada. The beds with convex-up geometry are interpreted as conglomeratic lobes originating in the freezing of cohesive or cohesionless debris flows from the alluvial system.

The river or braidplain deltas developed bodies and facies appropriate to fluidal flows in the delta plain. In cases such as the Lopera Delta, the deltas in the first three sequences of Bodurria, the longitudinal deltas of Alboloduy and Pliocene deltas, the delta plain is dominated by distributary channels (Gci facies), fine, interdistributary bay facies and the development of distributary mouth bars. In some cases, such as the deltas of the third sequence at Bodurria, the occasional deltaic lobe at Alboloduy and the Pliocene deltas, lagoon or marsh facies developed (Fsc facies).

Backset beds (Gb) predominate on the fronts of the Pliocene deltas.

The prodelta lithofacies became homogenised in all the deltas and are dominated by silts from suspension settling and sands deposited by low density turbidity currents (Sm and Shl facies). At the foot of erosion surface on the delta front at Alicún there are conglomeratic lobes with Gmi facies intercalated between fine prodelta lithofacies.

Deltaic abandon facies were only recognised in the deltas of the three first sequences at Bodurria and in the Alboloduy deltas. In both cases, these are deltas deposited in transgressive contexts, which favours preservation of these facies. The cessation of sediment supply to the delta was used to develop bioconstructions or carbonate precipitation caused by high biota concentrations (Cl, Ca, Cr and Cn facies).

Biofacies associated with the various deltaic subenvironments

The highest concentrations of fossils is found on the lower delta plain, in both interdistributary bay and lagoon subenvironments, where the organisms proliferated due to the low sediment supply rate.

In the lagoon subenvironments, the brackish water encouraged development of algae, a context in which stromatolithic limestones deposited with charophytes (Bodurria and Alboloduy deltas). Abundant root traces also appear in these subenvironments, maturing in anoxic conditions into layers of coal or dark and sulphurous clays. These conditions can favour the opportunistic nature of stromatolites.

	Lithofacies	Description	Interpretation	Subenvironment
GRAVELS	Disorganised gravels (Gms)	Metres thick (50 cm to 7 m); pebble to boulder-sized and some outsized clasts (70 cm – 3 m); matrix-supported (medium-coarse sand), sometimes clast-supported; massive or with faint inverse grading; poor sorting	Debris flow (Lowe 1976, 1982)	Delta plain and proximal delta front
	Inverse grading conglomerates (Gmi)	50 cm to 2 m thick; little lateral continuity; pebble, cobble and, exceptionally at top, boulder-sized gravels; matrix-supported; clear base; lens shaped bodies with convex-up tops and flat bases	Cohesionless debris flow (Postma, 1983, 1984, 1986; Nemec, 1990; Kim et al., 1995)	Delta plain and delta front
	Normal grading conglomerates (Gn)	Approximately 1 m thick decreasing laterally, normal grading; clast-supported; erosional base	Channel fill (Miall, 1977, 1978)	Distributary channel (Delta plain)
	Reworked conglomerates (Gw)	Conglomerate layers, pebble-sized clasts with relative textural and mineralogical maturity (quartzites dominant); clast-supported; boring in carbonated clasts	Conglomeratic deposits in very shallow environments reworked by wave action	Beach (Delta plain)
	Cross-stratified conglomerates (Gp)	Thickness of about 1 m in bodies with seaward bedding; alternating layers in foresets with normal grading; clast-supported; cross-stratification	Distributary channel-mouth bar	Delta plain – delta front (Breakpoint)
	Bucket conglomerates (Gb)	Imbricated and clast-supported; cross-bed dipping against slope; erosional base	Bucket filling slump scars (Postma, 1984a; Postma and Roep, 1985; Massari and Parea, 1990)	Proximal delta front
SANDS	Massive sandstone (Sm)	Tabular layers ranging from 10 cm to 1 m thick; homogeneous yellow sands; occasionally with normal grading and horizontal lamination; fine to medium grain size with good sorting; disperse clasts and rip-up mud clasts; vertical burrowing	High or low density turbidity current - Bouma sequence- (Bouma, 1962; Middleton and Hampton, 1976; Lowe, 1982); sandy debris flow (Lowe, 1976)	Distal delta front - prodelta
	Silty sandstone (Sld)	2 to 50 cm thick; grey and poorly sorted; diffuse grading; massive or with diffuse horizontal lamination; disperse pebble-sized clasts	Traction carpets or High or low density turbidity currents (Bouma, 1962; Middleton and Hampton, 1976; Lowe, 1982)	Prodelta
LUTITES	Sandy silt (Fsc)	5 to 20 cm thick; dark brown colour; mottling; root traces; lignite	Suspension settling on interdistributary bay areas with development of vegetation in low energy conditions	Interdistributary bay – lagoon (Delta plain)
CARBONATES	Calcarenite (Ca)	Thickness varying from 0.5 to 4 m, medium to coarse sand with isolated pebble-sized clasts; abundant microfauna, often broken; lamellibranchs (oysters and pectinaceans), echinoids, brachiopods, solitary corals, halimeda algae and red algae	Siliciclastic grains cemented by the macrofauna produced carbonate	Platform
	Algal limestone (Cr)	Tabular layers varying from 0.5 to 8 m thick with lateral continuity for several tens of metres; grainstone texture; red algae (particularly as rhodoliths, also with branching morphology) and macrofauna (lamellibranchs - clamis dominant with lesser amounts of oysters, echinoids, solitary corals and brachiopods)	Red algae biostromes	Delta plain or platform
	Microbial limestone (Cl)	Tabular packets 10 to 20 cm thick; stromatolithic-type algal lamination; charophytes	Carbonate precipitation caused by green algae and cyanobacteria	Interdistributary bay – lagoon (Delta plain)
	Reefal limestone (Cs)	Dome shaped reef patches 2 to 4 m thick and several tens of metres lateral extension; framestone texture; composed of corals and other organisms (coralline algae, stromatolites, lamellibranchs, brachiopods, etc.)	Carbonate precipitation caused by coral activity	Coral reef

Table. 1. Lithofacies used in the description of the sedimentary environments
Tabla. 1. Cuadro de litofacies utilizado en la descripción de los ambientes sedimentarios

In the interdistributary bay subenvironments, different types of bioconstructions appear built up on the soft substratum of the fine lithofacies. Once again, the low energy conditions of sediment supply and the shallow water, as well as protection from wave activity, led to the development of coral reef patches where sea water tempeture was high (Alboloduy deltas) and oyster mounds (Bodurria deltas). In both cases growth of large oyster specimens (*crassostreas sp.* among others) was very common. Distribution of associations of different oyster species in the deltas was controlled by the grain-size of the substratum on which they grew, as proposed by Jiménez *et al.* (1991). The reef patches constructed by corals also colonised the hard substrata that represent the top of the inactive distributary mouth bars on the delta plain (Alboloduy deltas) and deposits originating in debris flows on the plain and delta front built up on large blocks of schists (Granada deltas).

On the delta front, the most common fossils are oysters and barnacles attached to the clasts. Other lamellibranchs, such as *pectinacea*, are also common on the delta front, but linked to layers of sand lithofacies. The oyster specimens found in the sand layers of the delta front affected by processes of liquefaction-fluidification (Alboloduy deltas) are large in size. The mobile substratum encouraged laminar growth of valves. Much of the macrofauna found at the delta front originated in resedimentation from the lower delta plain or the upper delta front (Adra delta).

The most delicate shelled macrofauna appear in the prodelta, since coarse grained sediments rarely reach this far. The predominant macrofauna in the prodelta subenvironment are fine-shelled gastropods and pectinacea among the lamellibranchs. In the prodelta subenvironments of the Alicún delta there are layers with high concentrations of brachiopods. The fact that some of the brachiopod specimens are buried in megaripple and sandwaves indicates reworking and probable accumulation by currents or storm waves.

Finally, although not directly linked to deltaic sedimentation, biostromes of serpulids with some lamellibranchs represent biofacies developed in transgressive contexts with maximum sea flooding in the Pliocene deltas of Alhama and Adra. Equivalent bioconstructions have been described in present deltaic environments in which nutrient concentrations is high. Other accumulations of organisms are those that formed at the top of some delta lobes and have been interpreted as deltaic abandon facies. In this case, red algae biostromes (Bodurria and Alboloduy deltas) and coral reefs (Granada and Alboloduy deltas) represent the most characteristic facies:

- Coral reefs: The coral appearing in connection with the deltas are grouped together forming reef patches, which developed on the lower or submerged delta plain deposits and the upper part of the delta front. If a reefal talus developed as well as the reefal framework, the latter extends over the submerged delta plain and the former on the proximal delta front. The reefal patches located on layers of the proximal delta front occasionally lie unconformably on slump scars (e.g., the last reefal patch in deltaic sequence IV at Granada). In spite of the turbidity supposed for the water, the diversity of coral genera in the reefs is considerable (*Porites, tarbellastreae,...*). Some of the genera in theory more vulnerable to turbidity, such as *tarbellastreae* and *platygyra*, settled on fine, interdistributary bay sediments in some of the deltaic sequences at Alboloduy. The reefal patches developed during periods of decreased sediment supply to the delta (e.g., patches located at the top of the inactive distributary mouth bars at Alboloduy) or occupied positions lateral to the main supply entry point (e.g. reef patches in interdistributary bay subenvironments at the Alboloduy outcrop).
- Red algae biostromes: The red algae adopted very diverse forms in the deltaic deposits, generally conditioned by the energy of the environment. In high energy contexts due to wave action, the algae are massive or appear as rhodoliths. This is the case of the red algae biostromes colonising the topset of the shoal-water deltas of Bodurria. On the other hand, in low energy contexts connected to depths of 10 to 20 metres, such as the calcarenite beds separating some deltaic sequences at Alboloduy, the algae take on branching morphologies.
- Alternating reef corals and red algae beds (Alboloduy deltas example): at the Alboloduy deltaic succession coral reef patches and red algae calcarenites in association with other temperate water organisms (foraminifera, briozoa, lamellibranchs...). Both biofacies are repeated at the top of the deltas, sometimes in the same delta. In these cases, the red algae calcarenite bars appear on the reef patches and just below the next delta. The corals colonised subenvironments of the topset and, therefore, developed in very shallow sea conditions. At top some show traces of emersion. In order to explain the development of colonies with branching forms, the red algae calcarenites would have developed at more depth. According to this interpretation of the cyclical nature of the coral and red algae, on outcrop scale the reefal carbonates would be associated with stable sea level conditions and the red algae carbonate with stages of deepening. On a global scale, deposits of tropical and temperate carbonates are respectively associated with highstand and lowstand sea level in response to glacio-eustatic cycles. At the Alboloduy deltaic succession, however, this cyclical nature responds to deep-water changes controlled by local tectonics.

Palaeogeographic context of the deltas

Late Tortonian

The complex palaeogeography of the Betic Cordillera during the Late Tortonian, represented by marine basins surrounded by important reliefs (e.g., Sierra Nevada and Sierra de Filabres) and interconnected by narrow corridors encouraged development of coarse-grained delta systems attached to basin margins often controlled by tectonics.

One of the most significant palaeogeographic changes that occurred during deltaic sedimentation was the marine disconnection from the sea of the Granada and Guadix Basins due to a fall in sea level (analysed below) between allostratigraphic units I and II (Fig. 6). In the Granada basin the sea was restricted to the centre of the basin. Basins of the eastern sector such as Lorca and Fortuna were also affected. In these basins, as in Granada, the fall in sea level caused their confinement and the deposit of evaporites (Garcés *et al.,* 1998). This event of restriction of the basins, which gave rise to the so-called "Tortonian salinity crisis" in the basins of the eastern sector of the Betic Cordillera has been dated in the Fortuna Basin to 7,8 m.a. (Krijgsman *et al.,* 2000). Extrapolation of this age to the central sector sets 7,8 m.a. as the age of the forced regression systems tract and the beginning of the lowstand systems tract, i.e., the age of the deltas at Alicún, Lopera and the first deltaic sequence at Bodurria. In the Guadix Basin the coastline migrated northwards and eastwards. The southwestern sector of the basin remained communicated with the north and west of the basin through a sea corridor where the Lopera delta prograded. To the East of the basin, in the Bodurria sector, the Guadix Basin was connected to the Mediterranean through the Almanzora Corridor (Guerra-Merchán, 1992). To the north, in the Alicún sector, the basin communica-

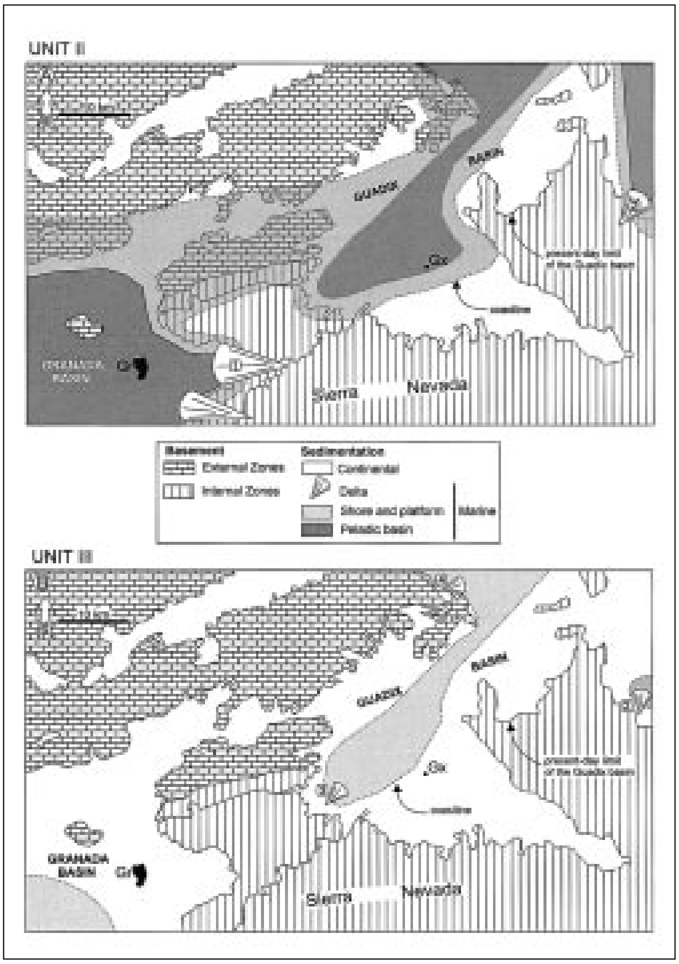

Fig. 6. Palaeogeography of the Guadix Basin and eastern sector of the Granada Basin: A. During deposit of Unit II, prior to the forced regression caused by tectonics, and B. During deposit of Unit III, immediately after the forced regression (Gr: Granada; Gx: Guadix). 1. Granada deltas, 2. Bodurria deltas, 3. Lopera delta, 4. Alicún delta. See figure 1 for geological setting in the Betic Cordillera

Fig. 6. Paleogeografía de la Cuenca de Guadix y sector oriental de la Cuenca de Granada: A. Durante el depósito de la Unidad II, previa a la regresión forzada por la tectónica, y B. Durante el depósito de la Unidad III, inmediatamente posterior a la regresión forzada (Gr-Granada; Gx-Guadix). 1. Deltas de Granada, 2. Deltas de Bodurria, 3. Delta de Lopera y 4. Delta de Alicún. Ver encuadre geológico dentro de la Cordillera Bética en la figura 1

ted with the Guadalquivir Basin. This connection of the Guadix Basin with a basin under oceanic (Atlantic) influence is shown by the sandwaves that migrated on the coetaneous platform to the Alicún delta from northwest to southeast by the action of currents under oceanic influence.

Towards the end of the Tortonian, the basins in the central sector of the Betic Cordillera became definitively continental (Guadix and Granada Basins) and disconnected from the Mediterranean and Atlantic (Soria *et al.,* 1999).

Early Pliocene

During the Early Pliocene, two arms of the sea penetrated east and west of the Sierra de Gádor, repectively constituting the Adra Bay and Andarax Corridor (Fig. 7). In comparison with the present coastline, the sea reached 5 km inland in the Adra Bay and at least 20 km in the Andarax Corridor.

The palaeogeographic axis of both arms of the sea was southeast to northwest, so that they were exposed to wave action generated by easterly winds and protected from westerly wave action. At present westerly storms are more violent and so it is the waves from the west that mainly erode and rework the coastal sediments. During the Early Pliocene the situation must have been similar. Thus, the Alhama deltas and the initial phases of construction of the Adra delta, both protected from westerly storms, show no signs of important storm action. There is little evidence of the influence of important storms in the Alhama deltas and initial phases of the Adra delta construction if we compare with the abundant slump scars, most of them linked to wave actions, of the last phases of Adra delta or the abundant slumps of the La Abrioja delta (Postma, 1984a y b). In these cases, these deltas occupy more external positions less protected from mainly westerly storms. At Adra the accumulations of lamellibranchs associated with storm sand layers and the abundant slump scars in the foresets of the last delta lobes show the lack of protection from westerly storms. Postma (1984a) refers to heavy storms capa-

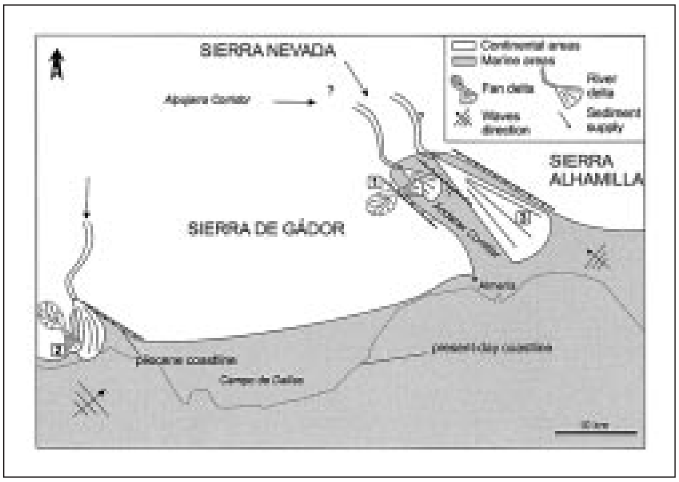

Fig. 7. Paleogeographical map of sectors close to Sierra de Gádor during Early Pliocene with Alhama (1), Adra (2) and Abrioja (3) deltas. See figure 1 for geological setting in the Betic Cordillera

Fig. 7. Mapa paleogeográfico de los sectores próximos a Sierra de Gádor durante el Plioceno inferior con los deltas de Alhama de Almería (1), Adra (2) y Abrioja (3). Ver encuadre geológico dentro de la Cordillera Bética en la figura 1

ble of generating waves that reworked the upper part of the foresets as possible causes of the abundant slumps in the La Abrioja delta. If we consider the palaeogeographic situation of the La Abrioja delta in relation to Alhama deltas, their greater exposure to westerly storms is evident.

Sequential stratigraphy

The deltaic systems were built over two transgressive-regressive cycles occurring throughout the late Tortonian and Early Pliocene. Specifically, the deltaic structures were formed mainly during the regressive stages of these cycles.

Tortonian deltas

Qualitative and quantitative analysis of the Late Tortonian transgressive-regressive cycle

The deltaic systems of the Late Tortonian developed throughout a fourth-order transgressive-regressive cycle lasting less than 1 m.a. The cycle began with sea flooding of the Neogene Basins of the Betic Cordillera during zone NBN-11 and ended when the basins of the central sector (Granada and Guadix) became continental before the end of zone NBN-12, according to the biostratigraphy by Martín Pérez (1997).

The Tortonian delta systems studied here are distributed in four systems tracts, one transgressive systems tract and three regressive systems tracts. In chronological order, from more ancient to more modern (following the terminology of Posamentier *et al*., 1988 and 1992, and Hunt and Tucker, 1992), these are: Transgressive systems tract (TST), Highstand systems tract (HST), Forced regressive wedge systems tract (FRWST) and Lowstand wedge systems tract (LWST).

A. Transgressive phase

This phase began with the transgression that flooded the Granada and Guadix Basins and the Tabernas Basin at the beginning of the Late Tortonian (Rodríguez-Fernández *et al.,* 1999).

Of all the deltaic successions studied here, the only one showing a generally transgressive tendency is at Alboloduy, in the Tabernas Basin. This stage is represented in the other basin margins by retrogradational platforms which evolved distally to basin marls (Rodríguez-Fernández, 1982). The Alboloduy deltaic succession began with coastal plain deposits on a continental unit of alluvial fans and ended with the extension of basin marls intercalated with sand and conglomerates deposited by the submarine fans described by Kleverlaan (1989). The bathymetric evolution throughout the deltaic succession reveals alternation of regressions linked to the progradation of each of the deltaic sequences, sometimes culminating in emersions (some reef patches at top of the deltas show microkarstification features), limited by transgressive events. These transgressive events are related to deepenings that created accommodation space necessary for the progradation of a new deltaic sequence. Some transgressive events were recorded by calcarenite beds with a large accumulation of branching red algae colonies which capped the deltaic lobes.

The lower part of the Bodurria deltaic succession (sequences I to III) also shows this transgressive evolution in its retrogradational stratal pattern. The transgression associated with sea flooding of this sector occurred before the deltaic deposit and is recorded as cliff and coastal deposits and two coral reef patches.

B. Regressive phase

Two phases of normal regression have been distinguished, separated by a relative sea level fall leading to a forced regression. The first phase of normal regression is recorded in the Granada deltaic succession and in deltaic sequence IV at Bodurria, as well as in the progradant platform-slope systems (Unit II of the Granada and Guadix Basins). At the end of this first regressive phase a sea level fall occurred that has been estimated as 200 m in the Lopera sector (Fig. 8). This relative sea level fall and the subsequent forced regression are represented by different stratigraphic and sedimentary features: an unconformity surface separating the basin marls of allostratigraphic unit II, below, from the deltaic deposits of unit III; a basal conglomerate related to this unconformity surface (e.g., volcanic clast channels beneath the Alicún delta), and a forced regression wedge systems tract (following the terminology of Hunt and Tucker, 1992) or a lowstand fan systems tract (LFST, following Posamentier *et al.,* 1988) represented by the lower lobe of deltaic sequence V at Bodurria.

In the central sector of the Cordillera, the Lopera and Alicún deltas and the upper lobe of the last deltaic sequence at Bodurria (Unit III in the Guadix Basin) prograded in a very shallow-water sea about 15 m deep, causing a normal regression that would have

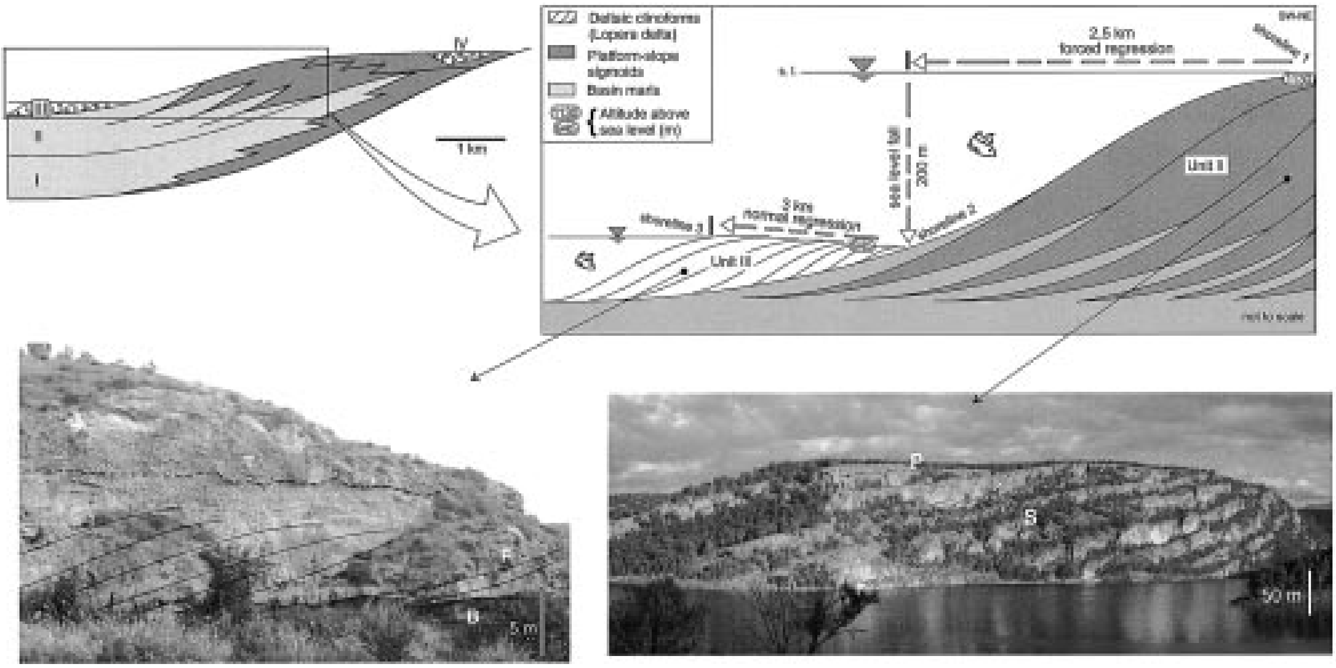

Fig. 8. Synthetic stratigraphic diagram of the south-western sector of the Guadix Basin (upper figure) and quantitative analysis of the normal and forced regressions in which Unit II (P-platform; S-turbiditic slope in left photo) and Unit III (Lopera delta: T-topset; F-foreset; B-bottomset, right photo) are involved. Note different scale of photos

Fig. 8. Esquema estratigráfico sintético del sector suroccidental de la Cuenca de Guadix (figura superior) y análisis cuantitativo de la etapa regresiva en la que están involucradas la Unidad II (P-plataforma; S-talud turbidítico en la foto izquierda) y la Unidad III (Delta de Lopera: T-topset*; F-*foreset*; B-*bottomset*, en la foto derecha). Obsérvese la diferencia de escala entre las dos fotos*

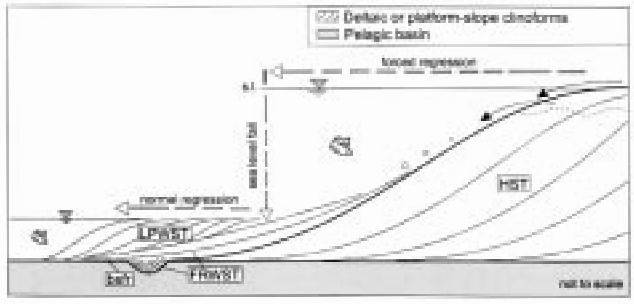

Fig. 9. Synthetic diagram of the systems tract involved in the regressive stage recorded in the basins of the central sector of the Cordillera following the terminology of Posamentier *et al.* (1988) and Hunt and Tucker (1992). HST-Highstand systems tract; bsfr-basal surface of forced regression; FRWST-Forced regressive wedge systems tract and LPWST-Lowstand prograding wedge systems tract

Fig. 9. Esquema de síntesis de los cortejos sedimentarios que intervienen en la etapa regresiva registrada en las cuencas del sector central de la cordillera a partir de la terminología usada por Posamentier et al. *(1988) y Hunt y Tucker (1992). HST-Cortejo de alto nivel del mar; bsfr-superficie basal de la regresión forzada; FRWST-Cortejo de cuña de regresión forzada y LPWST-Cortejo de cuña progradante de bajo nivel del mar*

concluded when the Granada and Guadix Basins became continental. These last marine deltas of both basins represent the lowstand systems tract. These systems tracts can be found at the base of and detached of the last platform-slope sigmoid or delta clinoform of the highstand systems tract (Fig. 9). In the terminology of Ainsworth and Pattison (1994) this would represent a detached lowstand systems tract (LSTd).

Correlation between global sea-level changes (Exxon curve, Haq et al. 1988) and the local sea-level changes: eustatic control

The transgressive systems tract described began with a transgression of regional scale and ended with a maximum flood surface, represented by the maximum extension of the basin marls. This tract can be correlated to the transgressive systems tract of the third-order TB 3.2 cycle of the Exxon curve (Haq *et al.*, 1988), characterised by eustatic rise on a global scale (Fig. 10).

The highstand systems tract described can be correlated to the highstand systems tract proposed by Haq *et al.* (1988) for the third-order TB 3.2 cycle of the Exxon curve characterised on a global scale by a highstand sea level. However, after the highstand systems tract, there ceases to be any highstand systems tract a relative fall in sea level occurred in the sectors studied here, which is not represented on the global curve, in which the highstand systems tract continues until the Tortonian-Messinian boundary. However, a lowstand systems tract has been recognised in the sector studied, after the sea level fall (forced regression wedge and lowstand systems tracts) and before the Tortonian-Messinian boundary. On the Exxon curve, the sea level fall that concludes cycle TB 3.2 is later, occurring after the beginning of the Messinian.

Pliocene deltas

The Pliocene deltas prograded during the regressive phase of a transgressive-regressive cycle that began with the regional transgression that flooded the peri-Mediterranean basins at the beginning of the Pliocene. The beginning of this third-order cycle is recorded in the Alhama de Almería outcrop, while the end of the cycle is recorded in the Adra deltaic complex.

The transgressive systems tract is represented by a shallow platform system attached to the Sierra de Gádor in the Alhama sector. Biostromes of serpulids and lamellibranchs mark the maximum flood surface.

The highstand systems tract is represented by the progradation of the Adra and Alhama deltas. In the progradation, the deltas caused regression of the coastline to less than 5 km at Adra and a similar distance at Alhama. The end of Pliocene deltaic sedimentation at Adra is proof of a regression forced by a fall in sea level of several tens of metres (30 m) between the two last deltaic lobes. The foregoing suggests that the lowstand systems tract is represented in the Adra deltaic system and, specifically, by the most modern of the Early Pliocene deltaic lobes. According to the terminology of Ainsworth and Pattison (1994), this would represent a detached lowstand systems tract (LSTd), as it is attached to the last of th deltaic lobes forming the highstand systems tract.

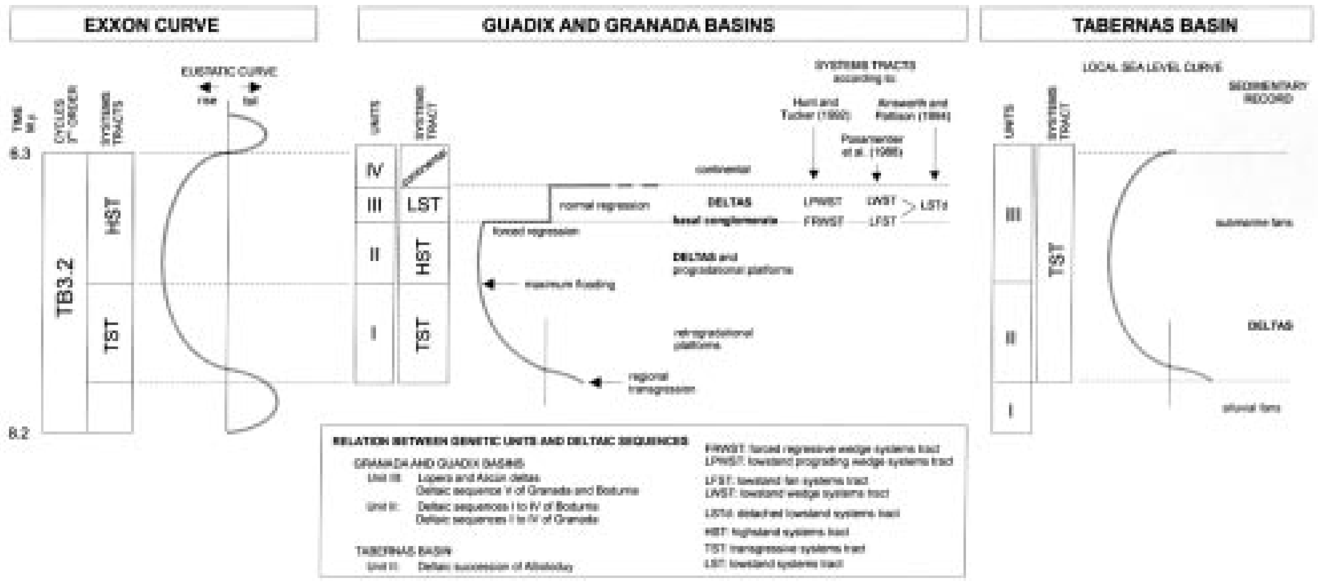

Fig. 10. Correlation between global sea-level changes (Exxon curve, Haq *et al.* 1988) and the local sea-level changes during Tortonian based on data obtained in study of deltaic systems and other contemporary depositional systems in the Guadix, Granada and Tabernas Basins

Fig. 10. Correlación entre cambios globales del nivel del mar (Exxon curve, Haq et al. *1988) y cambios locales del nivel del mar durante el Tortoniense a partir de los datos obtenidos del estudio de los sistemas deltaicos y otros sistemas deposicionales coetáneos en las cuencas de Guadix, Granada y Tabernas*

Tectono-sedimentary reconstruction

Tortonian deltas

Tectonics controlled the Tortonian deltaic sedimentation. The transgressive phase recorded in the Bodurria and Alboloduy deltaic successions and the forced regression event recorded in the Guadix Basin represent the most direct manifestations of, respectively, extensional and compressive tectonics on the deltaic sedimentation.

Transgressive phase controlled by extensional tectonics

The Alboloduy deltaic succession and the lower part of the Bodurria succession (deltaic sequences I to III) show evidence of important tectonic subsidence.

The transgressive phase of the Bodurria deltaic succession (sequences I-III) occurred in an extensional context as shown by the presence of normal faults, listric growth faults, rollovers and syntectonic unconformities expanding towards the basin margin.

In the Alboloduy succession, the calcarenite beds that cap the Gilbert-type deltas are interpreted to represent intervals of reduced siliciclastic input into the basin which records time of delta abandonment. The underlying and just-deposited Gilbert-delta plain (represented by topset strata) was drowned and submerged by a pronounced rise relative sea level that created the accommodation space filled by the overlying delta lobe. Angular unconformities bounding some delta sequences, liquefaction slides in the delta front and synsedimentary faulting reveal that the local tectonic subsidence could be the mechanism responsible for the repetitive, cyclic stratigraphy of the stacked Gilbert-type deltas and the capping carbonate beds in the Alboloduy succession. Episodic fault-controlled subsidence in a context of eustatic rise caused the transgressive events which happened between successive delta sequences.

Forced regression conditioned by regional tectonic uplift

As already described above, one of the last phases of the regressive stage in the Guadix and Granada Basins is a forced regression, with which the Alicún and Lopera deltas and the last deltaic sequence at Bodurria begin. The fact that this relative sea-level fall does not correspond with a eustatic fall implies that the regression linked to the fall was forced by tectonic factors. Tectonic uplift was on a regional scale, as it was not restricted to the central sector of the cordillera (Granada and Guadix Basins).

The study of the deltaic systems originating as a result of this regional uplift shows that the response varied from one sector to another. At Alicún, the basement and basin did not lift as a single block, but the normal faults on the margin caused differential uplift. Thus, the basement and, with it, the platform systems developed prior to the delta underwent more uplift than the bottom of the basin where the delta was to form. The normal faults compensated part of the uplift by causing a relative subsidence of the basin. This situation led to intense erosion of the platform deposits prior to the delta, which are now practically absent from the sector, the fall in sea-level and the forced regression recorded in the basal conglomerate, after which the Alicún delta prograded (Fig. 11). At Bodurria and Lopera, unlike Alicún, there were no faults acting between the deltas and platform-slope systems of the highstand systems tract (Unit II of

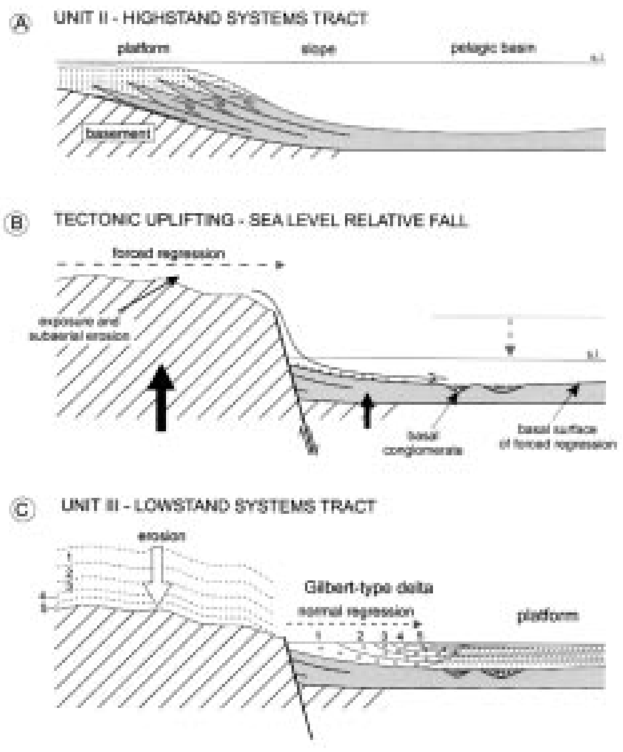

Fig. 11. Relation between tectonics on northern margin of Guadix Basin, the forced regression and subsequent development of the Alicún delta

Fig. 11. Relación entre la tectónica del borde norte de la Cuenca de Guadix, la regresión forzada y el posterior desarrollo del delta de Alicún

Guadix Basin) and the deltas of the lowstand systems tract (Unit III). In both sectors the two systems tracts responded as a single block to the regional uplift already referred to as the cause of the forced regression. Even with a similar response, the two sectors differ, however, in the values of the sea-level fall. Because of the difference in height between the clinoforms of the HST and LST systems after the sea-level fall, it can be calculated that the fall was 200 m in the south-western sector of the Guadix Basin (Lopera) and 50 m in the south-eastern sector (Bodurria). After the sea-level fall and the subsequent forced regression, two deltas prograded, one in each sector, on basin marls in a 10 to 20 m deep sea. The differential response to the same regional uplift event is more proof confirming the structuring in more than one block of the Guadix Basin before became continental.

Main regional tectonic events occurring throughout the record of the deltaic sedimentation

There follows a correlation of the main tectonics events described in the Betic Cordillera during the Tortonian and the deltaic sequences studied (Fig. 12).

Galindo-Zaldívar *et al*. (1993 and 1996) described the action of high-angle normal faults to the West of Sierra Nevada, in some cases listric faults, striking NW-SE on the eastern margin of the Granada Basin and associated to which rollovers were caused. These faults, active since the Late Miocene, have the same orientation as the basin margins on which the deltaic systems studied in the Guadix Basin are installed. Normal faults have also been documented in association with these deltas, mainly in the Bodurria sector, causing extension towards the North-East, whereas those described in the Granada Basin produced extension towards the South-West. The aforementioned authors proposed a reactivation in the Tortonian of the extenisonal detachment between the Alpujarride Complex (hanging wall) and the Nevado-Filabride Complex (footwall) that had been active in the Middle Miocene. The normal faults and rollovers of the Bodurria sector would be associated to this extensional stage.

A stage of compressive forces in the cental sector of the Cordillera has been documented and is known as the intra-Tortonian compressive event (Estévez *et al.,* 1982). Recent biostratigraphic studies have shown that this event occurred in the Late Tortonian (Rodríguez-Fernández *et al.,* 1999). It coincided with the compressive stage recorded in the deltaic successions. At Bodurria, the compressive event is located between the deposits of sequences III and IV. A second, Uppermost Tortonian compressive event was responsible for the fall in sea-level and the subsequent forced regression concluding with the formation of the Alicún and Lopera deltas and the last of the Bodurria deltas. This second compressive event involved exhumation of material of Alpujarride

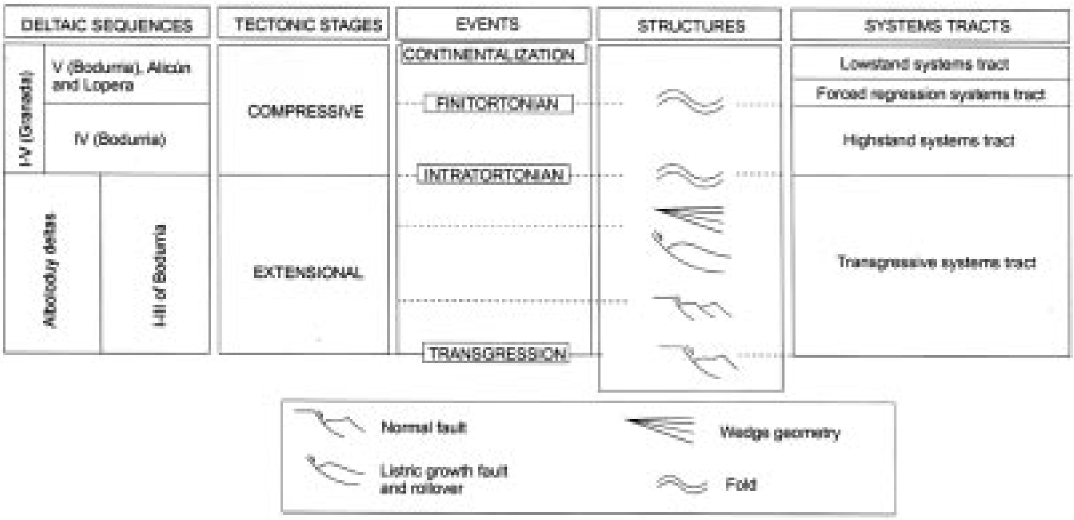

Fig. 12. Relation between tectonic activity and development of deltaic sequences and systems tracts in Tortonian examples
Fig. 12. Cuadro que muestra la relación entre la actividad tectónica y el desarrollo de secuencias deltaicas y cortejos sedimentarios en los ejemplos tortonienses

Complex forming part of the reliefs of Sierra Nevada and Sierra de Filabres on which some of the studied deltas are built (Granada, Lopera, Bodurria and Alboloduy). The Alpujarride Complex was eroded during the extensional stage (sequences I to III) at Bodurria, but its presence in the clasts of the deltas of the compressive stage is scarce (sequence IV at Bodurria) or non-existent (Granada deltas) as against the Nevado-Filabride clasts (material constituting the internal sector of Sierra Nevada and Sierra de Filabres). However, at the end of the compressive stage (last deltaic sequence in Granada) and especially after the forced regression (last deltaic sequence at Bodurria) the Alpujarride materials were again heavily eroded. Apart from this important dismantling of the Alpujarride Complex, the underlying deltaic sequences located closest to the basin margins were also eroded. On the basis, therefore, of the study of the composition of the clasts supplying the deltaic sequences, we can observe a normal and reverse unroofing sequence in Sierra Nevada and Sierra de Filabres (following terminology by Colombo, 1994) (Fig. 13). The normal unroofing sequence is first fed by clasts from the erosion of the upper complex (Alpujarride), as can be seen in the three first Bodurria sequences and Granada Unit I, followed by erosion of the lower complex (Nevado-Filabride), as seen in Bodurria sequence IV and the first four deltaic sequences at Granada. After this normal unroofing sequence, there occurred a reverse unroofing sequence in which, after erosion of the lower complex, the upper complex was again eroded, including the basin margin sediments, as evident in sequence V at Granada and Bodurria. Studies carried out using fission tracks conform this hypothesis (Clark *et al.,* 2002). This reverse unroofing sequence is consistent with a tectonic pulse at the end of the Tortonian which began or accelerated formation of the large radius antiform that makes up the present structure of the Sierra Nevada and Sierra de Filabres reliefs. Using fission tracks in zircons analysed in rocks from the Nevado-Filabride Complex, Johnson *et al.,* (1997) dated the beginning of the uplift of Sierra Nevada to 9-8 m.a. B.P.

Pliocene deltas

Unlike the thick Tortonian deltaic successions of Granada, Bodurria and Alboloduy, the effects of tectonics on deltaic sedimentation are not so evident in the Pliocene deltas. The reduced tectonic subsidence during the Early Pliocene encouraged horizontal building of deltaic examples instead of the vertical construction of some of the Tortonian successions such as Bodurria and Alboloduy. This difference is due to greater creation of accommodation space on the Tortonian basin margins than in the Pliocene basins. During the Tortonian tectonic subsidence on basin margins was more active than in the Pliocene, which caused the differences in large scale architecture of the deltaic succession in the two periods. Heller *et al.,* (1988) suggested a model for foreland basins which could also be used to explain the differences between the Tortonian and Pliocene deltaic successions in the intramontane basins of the Betic Cordillera. The model proposes that coarse-grained sediments supplied by montainous fronts tend to be trapped mainly near basin margin in periods of maximum subsidence and that the more extensive progradation of clast wedges takes place during periods of tectonic stability.

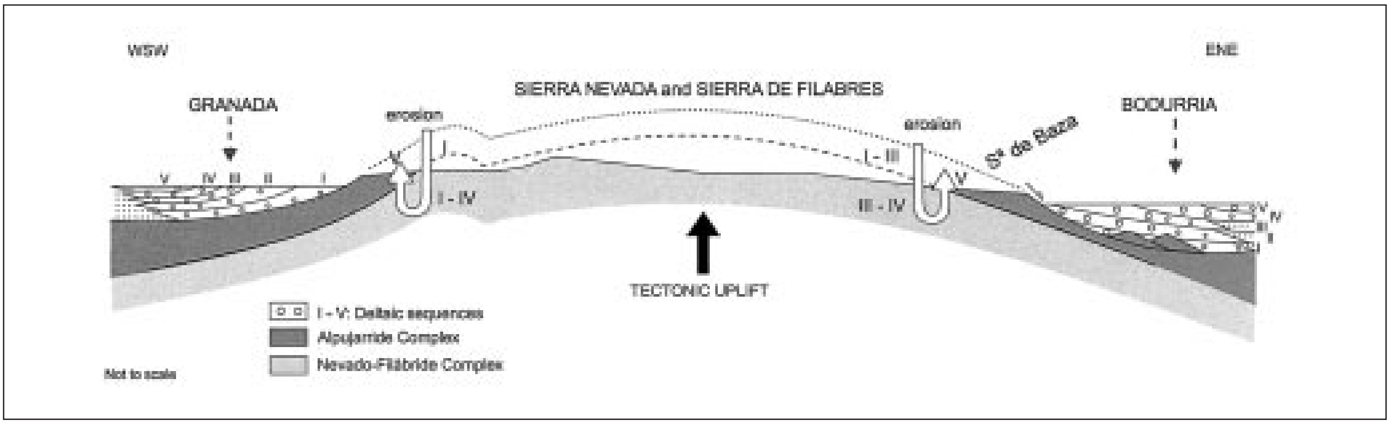

Fig. 13. Synthetic geological cross-section relating the sequences (I-V) of the deltaic systems of Granada and Bodurria and course of erosion in source areas feeding each of the sequences

Fig. 13. Corte geológico simplificado que relaciona las secuencias (I-V) de las sucesiones deltaicas de Granada y Bodurria y la trayectoria seguida por la erosión de los materiales del área fuente que alimenta cada una de las secuencias

At the same time as the formation of the transgressive systems of the Early Pliocene, there was an uplift pulse in Sierra de Gádor, shown in the sediments as a syntectonic unconformity in the Alhama sector and the progradational stratal pattern of the platform deposits of the transgressive systems tract underlying the delta deposits.

Climatic control

The small coarse-grained deltas with small drainage basins are the most sensitive to climatic variations (Postma, 2001). Climatic conditions can be recorded in sediments on a scale of changes forced by orbital phenomena, i.e., on the Milankovitch scale, or on a scale of short-term (high frecuency) catastrophic events. The Pliocene deltas at Alhama and Adra share the characteristics of the deltas that Postma (2001) proposed as a record sensitive to climatic change.

A pattern of geometrical variation in the deltaic clinoforms has been recognised in the Alhama and Adra deltas, beginning with oblique and ending with sigmoidal clinoforms. These cycles are fining-upward, with larger size in the oblique than in the sigmoidal clinoforms.

The deltas with oblique clinoforms are associated with high values of the relation between sediment supply volume and accommodation space available in the topset. Consequently, the cycles of geometrical change from oblique to sigmoidal clinoforms observed in the Alhama and Adra deltas imply a reduction in the sediment supply/accommodation space ratio. This reduction could be caused by the decrease in sediment volume supplied by the distributaries observing the size of the clasts supplied to one and other type of clinoform. Since the association of larger grain sizes with oblique and smaller sizes with sigmoidal clinoforms indicates decrease in the energy of the distributary systems. Since there is no evidence of a tectonic origin and the stationary trajectory of the brinkpoints line indicates a stand sea level, the climatic factor seems to have been responsible for this high-frecuency cyclicity. The higher energy stages of the distributaries imply more water-flow for erosion and transport of the larger clasts. On the other hand, stages of lower energy in the distributaries coinciding with sigmoidal deltaic clinoforms would be associated with periods of less water-flow in the distributaries. From this point of view, each fining-upward cycle of geometrical variation from sigmoidal to oblique clinoforms would imply a decrease in water-flow in the distributaries.

Another indicator of climatic control in these deltas -mainly the Adra delta- more specifically catastrophic events such as floods or storms, are the frequent accumulation layers of oysters or clasts with barnacles on the delta front. The origin of these layers is related to physical phenomena of reworking, indeed, the oysters are imbricated downslope and the barnacles are upside down on the clasts. These organisms would have developed on the subaqueous deltaic plain or on the upper part of the delta front and were resedimented throughout the delta front by storms and/or floods. Both storms and floods are manifestations of high-frecuency catastrophic events of a climatic natute. The frequent layers of backsets appearing in the foresets and caused by violent, turbulent and erosive flows could be related to flood events, as suggested by Massari and Parea (1990) in their analysis of these structures in wave-dominated deltas in southern Italy. Both the lamellibranch accumulations and the backset beds fill slump scars in the foreset.

Conclusions

The following points summarise the most significant aspects of the description and discussion of the data examined througout this study. These aspects correspond to the sedimentological, stratigraphic and basin analysis objectives set out for the study of deltaic systems.

The most significant contributions on the sedimentology of the deltas studied are as follows:

- Most of the deltaic systems analysed, whether Tortonian or Pliocene, are classified as Gilbert-type deltas because their deposit took place in shallow seas and they were supplied by high energy systems (alluvial fans or braided rivers) from steeply sloping margins. The deltas at Alicún, Lopera, sequences I, IV and V at Bodurria sequence V in Granada, sequences I to IV at Alboloduy and the Adra and Alhama deltas are classic Gilbert-type deltas. The deltaic systems in the eastern part of the Granada Basin evolved from mouth-bar type deep-water deltas (Sequence I), to Gilbert-type deltas (Sequence V). At Bodurria, the deltas of sequence III evolved distally from shoal-water type deltas to Gilbert-type deltas because of local variations in accommodation space tectonically controlled.
- The facies associations in the deltas differ widely from one example to another depending on the characteristics of the feeder systems and the reworking of the sediment by waves and longsho-

re currents action. Very coarse-grained fan deltas such as those in Granada are basically conditioned by the high energy of their feeder system. These systems are highly efficient in transporting the coarse fraction of the sediment to distal zones in the form of lobes at the mouth of gullies. The predominant processes are sediment gravity flows, ranging from debris flows on the proximal delta front to high density turbidity currents on the distal delta front and prodelta. Other deltas, such as the longitudinal system at Alboloduy, fed by lower energy systems and dominated by wave action, concentrate most of the coarse fraction as beaches on the topsets.

- Beds of carbonate lithofacies, generally organic carbonates, were deposited on the delta topsets, mainly in connection with periods of delta abandon. Stromatolithic limestones formed in the lagoon or interdistributary bay subenvironments and red algae biostromes, bioclastic calcarenites and, above all, reef patches also formed. The reef patches colonised the deposits of the submarine delta plain of the Granada and Alboloduy deltas prograding in a tropical sea.
- The facies in the foresets of the Pliocene deltas, especially the Adra Delta, dominated by accumulation layers of lamellibranchs and clasts with attached barnacles as well as backset beds, indicate high energy flows that reworked the topset deposits and caused turbulence downslope from the foresets. It is suggested that the origin of these deposits was related to catastrophic sedimentation due to storms and/or floods, whose role was very important in the construction and destruction of these deltas.
- The geometry of the clinoforms in the Pliocene deltas varies from oblique to sigmoidal because of the decrease in sediment supply and local variations in accommodation space caused by the irregular physiography of the basin bottom on which they migrated.

The most significant aspects of stratigraphy and basin analysis are as follows:

- The complex palaeogeography of the Neogene-Quaternary basins of the Betic Cordillera during the Late Tortonian in the form of intramontane basins (Granada, Guadix, Tabernas basins, etc) flooded by the sea, encouraged the development of very coarse-grained marine deltaic systems lying against steeply sloping margins in most of these basins. During the Early Pliocene marine deltaic sedimentation was limited to the basins affected by the transgression occurring at the beginning of the Pliocene, which were basically the peri-Mediterranean basins (Campo de Dalías, Almería Basin, Andarax Corridor, among others).
- The creation of accommodation space due to tectonic subsidence on the basin margins and rejuvenation of reliefs during the Late Tortonian caused the development of vertically multiconstructed deltaic successions (Granada, Bodurria and Alboloduy). During the Early and Middle Pliocene, however, tectonic subsidence was minimal and the deltaic systems built up horizontally, filling the accommodation space created in gulfs and bays flooded by the transgression at the beginning of the Pliocene.
- At the end of the Tortonian, before the Granada and Guadix Basins became continental, a sea-level fall occurred between Units II and III of these basins. This fall has been quantified as 200 m in the south-western sector of the Guadix Basin. This sea-level fall did not coincide with a eustatic fall, but occurred as a result of regional uplift causing a tectonically forced regression.
- The forced regression affecting the central sector of the Betic Cordillera was recorded by an unconformity surface between the basin marls of Unit II and the deltaic deposits of Unit III, by channelled basal conglomerates fed by large blocks and by a forced regression systems tract. After the forced regression, small deltaic systems with Gilbert-type profiles prograded in the shallow seas remaining in the Granada and Guadix Basins (Alicún and Lopera deltas and the last deltaic sequence at Bodurria), leading to the normal regression into a very shallow-water basin.
- Apart from eustatic control, the Tortonian deltaic systems were also affected by local and regional tectonics, the latter causing the sea-level fall and associated forced regression. The Bodurria and Alboloduy deltaic successions are where tectonics left the most impression. Thus, although the Bodurria succession was deposited in a highstand sea level, an extensional tectonic phase caused the transgressive megasequence formed by the three first stacked deltaic sequences with a retrogradational stratal pattern. Normal faults and rollovers affected the sediments of the first deltaic sequences. The extensional trend of the margin is also clear in the migration of the source areas shifted from external to internal sectors of the chain. A tectonic inversion took place in the last two deltaic sequences, recorded as a progradational stratal pattern in the deltas and migration of their drainage basins from the internal to external sectors of

the chain. This migration marks the beginning of the folding of the Sierra Nevada, creating the large wavelength anticline characterising their present structure.

- The stacking of Gilbert-type delta lobes in the Alboloduy deltaic succession, the progradation direction of the delta lobes parallel to the basin margin and the alternation of low-energy temperata carbonates and tropical carbonates can be explained by the tectonic subsidence controlled by normal faults.
- Delta development was conditioned by palaeogeographic factors such as the position of the coastline as regards the reliefs, the source areas of the deltas, and behaviour under mechanical erosion of the main lithologies making up these reliefs. In the Late Tortonian the position of the coastline at the foot of abrupt reliefs consisting of easily eroded lithologies supplying large volumes of clasts and fine sediment (e.g., Sierra Nevada and Sierra de Filabres) encouraged the creation of abundant fan deltas fed by cohesive debris flows. In the Early Pliocene the coastline was located at the foot of reliefs whose lithologies were more resistant to mechanical erosion and therefore supplied less clasts and fine sediment (e.g. Sierra de Gádor). In these cases, the deltas were fed by "softer" reliefs located far from the coastline and separated from it by bypass plains, allowing development of deltas fed by fluvial plains or solitary rivers.

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