Architecture and sedimentary facies evolution in a delta stack controlled by fault growth (Betic Cordillera, southern Spain, late Tortonian)

Fernando García-García a,*, Juan Fernández b, César Viseras b, Jesús M. Soria c

a Departamento de Geología, Universidad de Jaén, Campus de las Lagunillas s/n, 23071 Jaén, Spain
b Departamento de Estratigrafía y Paleontología, Universidad de Granada, Campus de Fuentenueva s/n, 18071 Granada, Spain
c Departamento de Ciencias de la Tierra, Universidad de Alicante, 03080 Alicante, Spain

Received 27 July 2004; received in revised form 13 October 2005; accepted 31 October 2005

Abstract

Tectonic control is revealed in various ways (synsedimentary deformation structures, facies, architecture) in the coarse-grained delta systems that developed in the southeastern margin of the Guadix Basin, an intramontane basin in the central sector of the Betic Cordillera, Spain, during the late Tortonian (Miocene).

Vertical trends in the architecture of the deltaic succession (230 m thick) show changes in the stratal stacking pattern related to the variation in time in subsidence rates (in accommodation space). A period of high subsidence controlled by a normal growth fault began at the base of the succession, producing retrogradational units representing Gilbert-type delta systems onlapped by shallow platform calcarenites. A period of low subsidence followed, controlled by growth of a listric fault producing aggradational units representing shoal-water deltas capped by red algal biostromes. A non-subsidence period and decrease in accommodation space at the top of the succession (sediment supply remained constant) produced progradational deltas. The manuscript focuses on the part of the succession where the delta deposits show the effects of extensional tectonics, a listric growth fault and its rollover, on delta development. The progressive increase in accommodation space inherent in fault growth controlled the style of delta sedimentation in the river mouth. Gilbert-type deltas developed during periods of increase in subsidence rates and shoal-water deltas during periods of decrease in subsidence rates.

Horizontal trends in the architecture of the delta lobes show changes in the stratal stacking pattern affected by differential subsidence and pre-existing basin-floor topography. Periods of increase in subsidence rates near the fault scarp correlate with accommodation space kept constant, thinning of the units and shoal-water deltas development over the rollover, away from the fault scarp.

© 2005 Elsevier B.V. All rights reserved.

Keywords: Gilbert-type deltas; Shoal-water deltas; Normal growth fault; Rollover

1. Introduction

Tectonic effects not only influence the location of coarse-grained deltas in extensional basins, they also have a marked control on the external form, architecture and internal geometry of such deltas (Gawthorpe and Colella, 1990).

Fault growth is an important control on drainage development in modern extensional margins, but those links are difficult to establish in ancient basins. The stratigraphy of rift-related deposits rarely enables us to
make direct links with coeval structural controls, because faults located adjacent to synrift strata generally do not preserve evidence of their timing of activity in relation to depositional or erosional episodes (Gupta et al., 1999). This study is aimed at demonstrating the influence of growth faulting and the rollovers directly linked with the delta development in terms of architecture, type of delta and processes in a Tortonian coarse-grained delta stack.

The small coarse-grained deltas as here studied respond quickly to tectonic changes (Postma, 1990). A variety of deltaic systems changing from one to another type have been described in tectonic contexts (Colella, 1988; Postma and Drinia, 1993). The change in architecture of small-scale deltas controlled by faults, when sediment supply is kept constant, is related to the locus of delta deposition close to or away from the fault scarp and to subsidence rates. The objective of this paper is to describe the architecture and facies of delta systems during the different stages of fault growth and to establish the boundary conditions when and where a type delta (according the Postma’s classification, 1990) is changing to another type one and back again.

We compare, in terms of processes, the delta stack described in this example with some classical examples of Neogene delta stacking near normal faults, described from the Gulf of Corinth (Postma and Drinia, 1993), the Gulf of California (Dorsey et al., 1995, 1997) and from the Suez Rift (Gupta et al., 1999; Young et al., 2003).

2. Regional setting

The Guadix Basin is one of the Neogene–Quaternary basins located in the central sector of the Betic Cordillera (Fig. 1A). The Guadix Basin is an intramonotane basin formed in the late Tortonian during the neotectonic stage (late Miocene to Quaternary) of the cordillera, after the main tectonic movements that gave rise to the large structures the Betic Chain (main thrust and the second progradational (units 4 and 5) (Fig. 3).

3. Stratigraphic architecture

The deltaic succession, about 230 m thick, is made up of five delta units separated from one another by unconformities (Figs. 1C and 2). Each delta unit consists of several delta single delta lobes. Two stratal pattern trends can be recognized in the delta units—the first retrogradational to aggradational (units 1 to 3) and the second progradational (units 4 and 5) (Fig. 3).

3.1. Retrogradational to aggradational units (units 1 to 3)

3.1.1. Unit 1

The first unit is approximately 70 m thick and contains Gilbert-type delta systems retrogradationally stacked (Fernández and Guerra-Merchán, 1996). The single lobes are onlapped by platform calcarenites that distally give way to hemipelagic marls. The vertical trend in delta architecture shows clinoform geometry varying from oblique-tangential clinoforms at the base of the unit to sigmoidal higher in the unit.
Fig. 1. (A) Location of the Guadix Basin (GB) at the north of Sierra Nevada (SN) in the Betic Cordillera. (B) Position of the studied area within the Guadix Basin. (C) Geological map of the study area (after Fernández and Guerra-Merchán, 1996, modified).
Fig. 2. Panoramic view and line drawing of the studied cross-section (see Fig. 1C for location) with the differentiation of the five deltaic units (1–5) bounded by unconformities. Locations of the stratigraphic logs (a–f) of Fig. 4 are shown.
3.1.2. Unit 2
Unit 2 is approximately 60 m thick and was deposited nearer to the basin margin than unit 1, from which it is separated by an angular unconformity. It contains three coarsening- and thickening-upward minor sequences, representing aggradational shallow-marine deltas that distally give way to onlapping platform calcarenites.

3.1.3. Unit 3
The geometry of this unit is wedge shaped, with a thickness of nearly 60 m near the basin margin thinning to 30 m basinward about 500 m away from the basin margin. This unit contains aggradational, shoal-water delta systems capped by red algae biostromes. Some shoal-water delta lobes change distally to Gilbert-type profile lobes (Fig. 3).

3.2. Progradational units (units 4 and 5)
This is represented by the last two deltaic units, both of which display a progradational stacking pattern. The depocentres moved toward the centre of the basin.

3.2.1. Unit 4
This unit, about 45 m thick, is represented by progradational delta lobes overlying an erosional surface suggesting a slide scar. The deltas developed both oblique and oblique-tangential clinoforms.

3.2.2. Unit 5
The first deposits of unit 5, overlying the basin marls, are represented by a bed of outsized clasts (some up to 2 or 3 m in diameter). It could be interpreted as the progradational infill of a slump scar. The geometry and extent of the clinoforms clearly differentiate two construction phases in this unit. The first led to extensive oblique-tangential clinoforms, becoming wedge-shaped distally. The second construction phase led to a small Gilbert-type deltaic lobe with sigmoidal clinoforms, increasing basinward in thickness from 7 to 15 m.

4. Facies associations of the delta deposits
Lithologically, the succession consists of deltaic conglomerates and sandstones with clinoforms 5–45 m high that distally give way to platform calcarenites and hemipelagic marls (Fig. 4). Three types of shallow-water and coarse-grained deltas, according to Postma’s (1990) delta classification, have been recognized in the deltaic succession. They are characterized by their delta front dip: classic Gilbert-type deltas (steeply inclined delta front), shoal-water deltas (gently inclined delta front) and Gilbert-type profile (intermediate dipping delta front).

4.1. Classic Gilbert-type delta systems
4.1.1. Description
This facies association is represented by lobes with well defined clinoforms ranging in height from 5 m to 30 m. Coarse-grained deposits show variable grain size and can be divided into two types: sandy-conglomerates and conglomerates. The three geometric elements making up Gilbert-type deltas (topset, foreset and bottomset) are clearly distinguished (Fig. 5A). The deltaic clinoforms have slopes ranging from 20° to 30° in the upper parts, the angle decreasing from the brinkpoint to the subhorizontal layers of the bottomsets. Their geometry varies from oblique-tangential to sigmoidal.
Fig. 4. Correlation diagram between several stratigraphic logs of the deltaic succession from south, next to the basin margin (log f) to north (log a) (1–5: deltaic units; T—topset, F—foreset, B—bottomset).
Fig. 5. (A) Photograph and line drawing of the unit 1 showing a classic Gilbert-type delta system (1a–1c) bounded by calcarenites (dotted line) showing a retrogradational stratal pattern. Unit 4 and the Pliocene alluvial fans overlie shallow platform calcarenites of the units 2–3. (B) Fine-grained interdistributary bay/delta plain sediments overlain by a distributary channel. The channel is overlain by foreset beds of the next classic Gilbert-type delta lobe. (C) Beds of conglomerate with normal grading in a Gilbert-type foreset.
The topsets have coarsening and thickening-upwards sequences, equivalent to those described for the delta plain of shoal-water deltas. The channel height ranges from 1 to 3 m and the channels fill are fining-upward (Fig. 5B). The foresets consist of conglomerates with both matrix-supported and clast-supported fabrics. They may be normally graded (Fig. 5C) or inversely graded, and the larger clasts are commonly located in the upper or lower part of the foresets, depending on whether they are associated with matrix-supported or clast-supported fabrics. Erosional scars and upward-coarsening small conglomerate lobes are locally observed, respectively in the upper and lower parts of some steeply sloping foresets. The scars are filled with cross-stratified, imbricated conglomerates dipping against the slope. Sandy layers with ripple cross-lamination and tabular cross-bedding are more abundant in the topsets and bottomsets of the prograding bodies.

The bottomsets are represented by horizontal layers in which sand, and local pebbles, alternate with burrowed, marly silts. The fossil content (red algae, bryozoa and oysters) is abundant here and well preserved.

Depth ratio at the river mouth is 0.1 to 0.2.

4.1.2. Interpretation

The topsets have minor mouth bar-crevasse channel sequences built out in interistributary bays with characteristics equivalent to those of shoal-water deltas described below.

The foresets were built out by gravitational avalanches of alternating cohesive and cohesionless debris flows. The steep slope may, in some cases, have caused instability of the upper part, leading to avalanches of coarse material down the slope, where it was deposited in the topset as lobes showing inverse grading because of basal shearing. The scour left in the foresets could have caused hydraulic jumps in later avalanches, forming backsets filling scours interpreted as due to the turbulence developed in the hydraulic jump (Massari, 1996). Postma and Roep (1985) described similar processes for Pliocene Gilbert-type deltas in Southeast Spain. Backsets could be created by the development of strong turbulence, which accompanies the formation of a hydraulic jump and not controlled by any pre-existing scour.

4.2. Shoal-water delta systems

4.2.1. Description

For description, of these, deposits have been divided into a siliciclastic unit and a carbonate unit overlying the former (Fig. 6A).

The siliciclastic unit consist of upward-coarsening sequences, 5 to 15 m thick in the delta plain where four facies can be distinguished from bottom to top: (1) mottled silts and clays, with root traces and a few thin layers of lignite, (2) sand containing marine gastropods and wavy lamination, (3) beds of seaward cross-stratified conglomerates 2 to 3 m thick and (4) channelized pebble-conglomerates 1.5 m thick with sharp erosional base. Occasional layers (10–15 cm) of carbonates, with algal lamination, charophytes and root traces, are locally associated. The delta front inclination ranges from 2° to 5°. It consists of coarsening and thickening sequences 3 to 4 m thick (Fig. 6B) of normally graded conglomeratic beds 25 to 30 cm thick (Fig. 6C). Rare outsized clasts are located at the bed tops. Angular pebble-conglomerates with clast-supported fabrics fill the delta front beds. The prodelta is represented by massive pebbly sandstone alternating with silty layers. Burrows and symmetrical ripples occur. Depth ratio (ratio channel depth/basin depth following Postma, 1990) at the river mouth is 0.4 to 0.5.

Tabular beds of red algae represent the carbonate unit capping the siliciclastic deposits. They overlie openwork gravels consisting of very rounded and imbricated quartzite clasts. Red algae occur both in the form of rhodoliths (similar to those described by Braga and Martin, 1988, in equivalent environments situated 30 km to the east), and also as massive, branching morphologies, in which case they form biostromes. These algal beds are up to 8 m thick and extend laterally for up to 100 m. The siliciclastic content and grain size decrease upwards within these beds.

4.2.2. Interpretation

For interpretation these deposits are divided in two units, siliciclastic and carbonate. The former have been interpreted as shoal-water delta (cf. Postma, 1990) deposits. In the interistributary bay subenvironment of the deltas, the fine sediments represent suspension settling, which is periodically interrupted by the input of coarse siliciclastic deposits through distributary channels feeding distributary channel-mouth bars which prograded seaward. The stromatolite layers represent temporary interruptions of sediment supply. The facies of the delta front beds suggest deposition from gravitational avalanches recording periods of river floods during which bedload sediment is deposited just beyond the river mouth into the basin and is not wave reworked. Symmetrical ripples in the shallow prodelta deposits indicate that the depositional environment was to a certain extent controlled by wave action.
Fig. 6. (A) Shoal-water deltaic lobe capped by a red algae biostrome (basin margin to the right). Location of picture B is shown. (B) Coarsening-upward sequence of shoal-water delta front (scale bar is 2 m long). (C) A detail of picture B showing a normally graded bed in the shoal-water delta front (camera lens cover - 5 cm diameter—for scale). (D) Gilbert-type delta profile (basin margin to the right).
The siliciclastic unit is capped by a carbonate unit represented as red algae biostromes, which colonized the top of the delta deposits during periods of delta abandonment. Wave reworking evidenced by open work quartzite gravels (gravel beaches?). Algal colonization of the top of the delta lobes and decrease of the siliciclastic content from bottom to top of the algal beds could be related to delta abandonment, accompanied by starvation of terrigenous sediment supply. These horizons could be also interpreted as transgressive intervals, recording times of sediment starvation during which the underlying delta-top was drowned and submerged, as has been interpreted elsewhere (Gupta et al., 1999).

4.3. Gilbert-type profile delta systems

4.3.1. Description

The three geometric elements making up Gilbert-type deltas (topset, foreset and bottomset) can be distinguished (Fig. 6D). The deltaic clinoforms show sigmoidal geometries 10 to 12 m height.

The topsets consist of channelized pebble-conglomerates 2 to 3 m thick with sharp erosional bases. The channel fill is fining-upward. Foreset inclinations range from $10^\circ$ to $13^\circ$. Foresets consist of normally graded conglomeratic beds. Angular and bored pebble-conglomerates with clast-supported fabrics that distally give way to sandstones form the delta front beds (2 to 20 cm diameter). These beds alternate with normally graded oysters beds. Bottomsets are absent.

Depth ratio at the river mouth is 0.2.

4.3.2. Interpretation

The facies of foreset beds suggest deposition from gravitational avalanches of cohesionless debris flows recording periods of river floods during which bedload sediment is deposited just beyond the river mouth into basin. Fossil beds in the delta front represent resedimented oysters and barnacles coming from the delta plain and emplaced by catastrophic floods. Absence of bottomsets could be related to high sediment supply and rapid delta progradation.

The characteristics of these delta lobes show both shoal-type and Gilbert-type delta features so they are interpreted as shoal deltas with Gilbert-type profiles.

5. Role of fault growth in delta development: architecture and processes

In the delta succession, tectonic control is revealed in various ways: synsedimentary deformation structures, facies, architecture and clast provenances.

5.1. Margin faults

The first three units are characterized by retrogradational/aggradational stacking pattern controlled by the behaviour of the margin faults. Their activity would have caused the tectonic subsidence necessary for the growth of accommodation space to exceed the stacking pattern sedimentation rate, thus leading to a retrogradational-aggradational stacking pattern. The platform calcarenites onlapping the single delta lobes represent the transgressive-abandonment stage subsequent to the delta development. Retrogradational stacking of delta units has been noted from other extensional basins related to a progressive basin expansion (cf. Postma and Drinia, 1993). A listric growth fault occurred between the second and third deltaic units as can be inferred from the rollover geometry of unit II, which was responsible for the wedge-shaped geometry of the third unit, synchronous with fault activity. The most reliable tectonic effects in the sedimentation are stratigraphic variations in tilting described in coarse-grained delta deposits (cf. Gawthorpe and Colella, 1990).

5.2. Subsidence rates

The vertical trend in the architecture shows changes in the stratal stacking pattern related to decrease in subsidence rates and, hence, accommodation space. A period of high subsidence controlled by normal faults began at the base of the succession, producing the retrogradational units 1 and 2, representing Gilbert-type delta systems onlapped by shallow platform calcarenites. The presence of thick, vertically stacked Gilbert-type fan-delta successions has been used in tectonically active basins to infer direct tectonic control and very rapid subsidence and sedimentation rates (Dorsey et al., 1995). A period of low subsidence followed, controlled by a listric growth fault, producing aggradational unit 3, representing shoal-water deltas capped by red algae biostromes. A non-subsidence period and decrease in accommodation space at the top of the succession related to uplift of the basin margin, with sediment supply remaining constant, produced progradational deltas higher in the succession (units 4 and 5).

5.3. Geometry

This focuses on the part of the succession where the delta deposits show the effects on delta development of extensional tectonic, normal faults and a listric growth fault and its rollover (Fig. 7). The listric growth fault
which affected the deposits of unit 3 was the most influential structure in the stratigraphic architecture and in the sedimentation of the deltaic succession (Fig. 8A). The listric fault strike is NW–SE. Unit 2 deposits located on the hanging wall were folded in a rollover whose radius is 300 m. Unit 3, synchronous with fault activity, shows a typically wedge shaped geometry, increasing in thickness near the fault scarp and decreasing away from the scarp. Sedimentary evidence of the fault activity synchronous with unit 3 is seen in the horizontal and vertical trends in deltaic sedimentation style (Fig. 8B).

5.3.1. Horizontal trend

Depth ratio at the river mouth decreased from 0.5 away from the scarp fault to 0.2 near the scarp fault. Gently inclined delta fronts (shoal-water deltas) developed away from the fault scarp, evolving to steep inclined delta fronts (Gilbert-type delta profiles) near the fault scarp. Shoal-water deltaic lobes developed in the proximal areas and on the rollover top away from the fault scarp (Fig. 8C). Gilbert-type delta profiles developed in the local accommodation created between the scarp of the normal listric growth fault and the rollover (Fig. 8D).

5.3.2. Vertical trend

Depth ratios at the distributary river mouth of the shoal-water deltas persisted through time, maintained by slow steady sea-level rise. When the activity of the growth fault ceased, filling by the Gilbert-type deltaic lobes of the local accommodation space related to the fault was completed and the shoal-water deltas formed (Fig. 8E). When palaeo-bathymetric differences disappeared, the development of shoal-water deltas spread over the smoothed sea-floor topography.

The progressive increase in accommodation space inherent in fault growth controlled the style of deltaic sedimentation in the river mouth. Gilbert-type deltas developed during periods of increasing in subsidence rates or near the fault scarp and shoal-water deltas during periods of decreasing in subsidence rates or away the fault scarp. During the periods of increasing in subsidence rates near the fault scarp, basin depth and accommodation space remained more or less constant over the rollover. There, away from the fault scarp,
Fig. 8. (A) Panoramic view of unit 2, folded as a rollover and overlain by unit 3 forming a divergent fill expanding towards the basin margin (to the right). (B) Panoramic view of unit 3 with the differentiation of shoal-water deltaic lobes towards the margin (to the right) (C) changing distally to Gilbert-type delta profile (D). (E) Interpreted cross-section showing the evolution of the deltaic lobes of Unit 3 controlled by a listric growth fault. Shoal-water deltaic lobes developed on the basement and on the rollover where the accommodation space was reduced and a Gilbert-type delta profile developed where the listric fault caused local growth in the accommodation space.
basin infilling occurred by progradation of shoal-water deltas.

6. Discussion

We have described the architecture and sedimentary facies of a delta stack deposited during a third-order highstand sea-level at a tectonically active margin. The delta stack consists of five delta units controlled by fourth-order tectonic variations. Two tectonic phases have been recognized from the sedimentary fill. A progressive basin expansion controlled by a fault growth is recorded by the retrogradational stacking of the first three delta units. Then, after the extensional phase, the margin became dominated by compression, recorded by progradational delta units (units 4 and 5).

The vertical trend in bathymetry, suggested by the characteristics of the base of the studied succession comprising alluvial fan deposits, corals and the first three delta units showing the transition from shallow deltas to platform deposits and hemipelagic marls (see synthetic column of Fig. 7), are similar to those predicted by theoretical fault-growth models (Schlische, 1991) and to those described in the sedimentary fill of extensional basins (Postma and Drinia, 1993; Young et al., 2003). Those models describe the natural transitions from alluvial to deep-marine facies.

The differential response of delta systems to fault growth is related to the structures linked to the fault growth, rollovers or the growth of folds. A rollover is a structural barrier that substantially modifies the delta progradation transverse to the basin and encourages delta progradation laterally, parallel to the fault and the rollover. Individual delta units show convergence and thinning towards the fold crest, and divergence and expansion towards the basin margin and the fault scarp. At the same time, onlap of platform calcarenites onto the rollover flank gently dipping basinwards demonstrates that the rollover crest represents a structural barrier. High sedimentation rates in the area between the steep rollover flank (southern flank) and the fault scarp in contrast with sediment starvation on the gentle rollover flank (northern flank). The rollover represents a passive structure in relation to synsedimentary delta processes contrasting to fold growth which can progressively rotate and incorporate the deltas into fold limbs (Gupta et al., 1999).

The delta architecture provides a signature of the fault activity. During the early stage of fault growth, retrogradational units representing vertically stacked Gilbert-type delta systems (delta unit 1) imply direct tectonic control, with very rapid subsidence and high sedimentation rates required to maintain the gentle slope and accommodation space necessary for development this type of delta, following Dorsey et al. (1995). During the intermediate stage, aggradational units representing shoal water-type deltas (delta unit 3) imply lower rates of subsidence, coupled with lower rates of sediment supply during red algae biostromes construction, to maintain the gentle slope and accommodation space necessary for development this type of delta. Higher rates of sediment supply to shoal deltas would encourage exposure during their development but no exposure signatures can be recognized. During the later stage of fault growth, strongly progradational deltas (delta units 4 and 5) imply low rates of subsidence or no subsidence, coupled with high sediment supply as in the transfer zone of the Suez Rift coarse-grained delta described by Young et al. (2000).

7. Conclusions

Field studies of the architecture and sedimentary evolution of the late Tortonian extensional marginal fill of an intramontane basin in the Betic Cordillera (Gaudix Basin) show a delta succession made up of five delta units. Progressive basin expansion is recorded by a retrogradational stacking of the first three delta units. Local variations of subsidence, and variations in subsidence rates related to normal growth faults, controlled the horizontal and vertical trends, respectively, in the architecture and facies of the deltas. A variety of delta types developed, with Gilbert-type deltas at the base and in the middle of the succession (units 1 and 3) developed near the fault scarp or during periods of high subsidence rates, and shoal-water deltas developed away of the fault scarp or during periods of low subsidence rates. Shoal-water type deltas change to Gilbert-type deltas and back again due to variations in accommodation space controlled by variations in local subsidence and subsidence rates. Near the fault scarps the accommodation space progressively increases and over the rollover the accommodation space is remains constant.

In the same way that the presence of thick, vertically stacked Gilbert-type fan-delta successions have been used in tectonically active basins to infer direct tectonic control and very rapid subsidence and sedimentation rates (Dorsey et al., 1995), it may be possible to use the presence of thick, vertically stacked shoal water-type delta successions in tectonically active basins to infer low rates of subsidence with low sediment supply to maintain the gently slope and accommodation space necessary for development this type of deltas.
Spatial variability of delta type is linked to the location near or away from the fault scarp and onto the rollover, whereas the vertical variability of the delta type is linked to variation in fault growth rates.

For improvement in understanding the control of fault growth on basin fill architecture in extensional margins, modeling studies should take into account vertical and horizontal variations in delta type.

Acknowledgements

This research was supported by projects CGL 2005-06224 of the Ministerio de Educación y Ciencia-FEDER, BTE2001-2872 and Research Group RNM0163 of the Junta de Andalucía. The paper has greatly benefited by the constructive comments of Dr. K.A.W. Crook and two anonymous reviewers, and it had previously benefited by the comments of Dr. F. Massari and Dr. P. Haughton.

References


