A coarsening-upward megasequence generated by a Gilbert-type fan-delta in a tectonically controlled context (Upper Miocene, Guadix–Baza Basin, Betic Cordillera, southern Spain)

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Abstract

The 100 m thick succession at Bodurria of a Gilbert-type fan-delta constitutes an Upper Tortonian, coarsening- and thickening-upward megasequence. It lies unconformably on Triassic materials of the Alpujarride basement or on older Neogene materials of the basin infill, and is unconformably covered by the continental Pliocene.

The succession was deposited on one margin of an extensional basin, with active synsedimentary tectonics and rising sea-level. In these circumstances the accommodation space and the sediment supply increased throughout time. This determined the development of the coarsening and thickening upward megasequence, resulting from the vertical stacking of four smaller sequences which, in turn, were built up by stacking of Gilbert-type fan-delta units and were bounded by calcarenite facies deposited on a shallow shelf.

This sequential organisation and internal structure were controlled by the tectonic behaviour of the faults on the basin margin, in particular large-scale movements with intervals of stability, which respectively created accommodation space for the deltaic sequences and conditions for development of calcarenite shelf facies.

1. Introduction

There has been a growing interest in the study of fan-deltas in recent years, and much of what has been learnt about them is to be found in monographic issues (Nemec and Steel, 1988; Colella and Prior, 1990; Dabrio et al., 1991).

The location of fan-deltas on basin margins means that as depositional systems they are particularly sensitive to tectonic movements and changes in climate or in base level. For this reason they are an especially interesting object of investigation with regard to understanding basin evolution.

In the case of the Betic Neogene basins (Fernández et al., 1996a), this type of deposit is frequently found in association with mainly extensional-type margins, and several papers have been published on them in recent years. Some of these studies concentrate on the facies and sedimentary processes (Postma, 1984; Postma and Roep, 1985; Dabrio and Polo, 1988; Dabrio, 1990; Fernández et al., 1991), while others centre on the influence of base level variations on the internal structure of the resulting sedimentary body (Bardaji et al., 1990; Fernández et al., 1993).

The role played by tectonics in the definition of the general characteristics and emplacement of the fan-delta deposits has been examined from dif-
ferent points of view by several authors (Leeder and Gawthorpe, 1987; Colella, 1988; Gawthorpe and Colella, 1990; Roorsma, 1992). The present paper aims to concentrate on tectonic control of the origin and internal geometry of a coarsening and thickening upward megasequence (100 m thick), resulting from the successive stacking of Gilbert-type fan-delta units during the Late Tortonian in the Guadix–Baza basin (Betic Cordillera).

2. Geological setting

The Guadix–Baza basin (Fig. 1) is located in the central sector of the Betic Cordillera, on the contact between the South Iberian palaeomargin (External Zones) and the Alboran block (Internal Zones) (Sanz de Galdeano, 1990). It became defined at the beginning of the Late Miocene, and its fill presents a Tortonian marine unit and a Plio–Pleistocene continental unit separated by an angular-erosional unconformity (Fernandez et al., 1996a).

The marine unit includes the Morollon and Molicias Formations (Rodriguez-Fernandez, 1982), which correspond respectively to the Early and Late Tortonian. Both of these formations were deposited on a shallow shelf, with fans of layers towards the centre of the basin, and their sequential organization shows the respective retrogradational and progradational character of the formations as a result of sea-level behaviour during their deposition. The transgression during the earliest Tortonian (Fernandez and Rodriguez-Fernandez, 1991) and the regression of the latest Tortonian, involving a fall in sea-level of approximately 100 m (Vera and Rodriguez-Fernandez, 1988) are particularly well documented. In the northern area (Forruchu Formation, Soria, 1993), the aforementioned marine unit ends with restricted-shelf calcarenite facies of latest Tortonian in age. The latest Tortonian–earliest Messinian transgressive event, clearly known from other basins to the east (Guerra-Merchan, 1993), make up a marine depositional sequence of Late Tortonian age in the southeastern sector of the basin. Nevertheless, Goy et al. (1989) proposed an Early Pliocene age, for marine sediments underlying the fan-delta succession. This question and its paleogeographical implications have been widely analyzed in Guerra-Merchan (1993). The Bodurria Miocene materials fill a small depression which developed on the Alpujarride basement of limestones and Triassic dolomites, and which is located on the southern border of the basin (Figs. 1 and 2). Three units can be distinguished according to the facies: (a) conglomerates and red breccias, (b) conglomerates with oysters and reefs, and (c) conglomerates and sands with mega-cross-stratification, calcarenites and basin marls (Fig. 2).

The conglomerates and red breccias form a discontinuous unit with a maximum thickness of around 15 m, and are thought to have been deposited in small alluvial cones. The conglomerates with oysters and reefs lie unconformably on this unit. They vary in thickness from 10 to 20 m and were deposited in a shallow marine environment probably including beaches. Both units were locally preserved following irregularities of the basement.

The conglomerates and sands with mega-cross-stratification (6–30 m in scale), calcarenites and marls are the best represented unit in the area of study. The minimum thickness of the unit is 100 m and it lies unconformably on the Alpujarride basement or on the more ancient materials of the Neogene basin fill mentioned above.

A group of continental materials made up of conglomerates and red sands (alluvial fan deposits) lies on the materials of the Bodurria Miocene and is separated from them by an unconformity extending throughout the entire basin (Fernandez et al., 1996a). This group belonging to the Guadix Formation has a subhorizontal position and Plio–Pleistocene age (Viseras, 1991; Fernandez et al., 1996b).
3. Stratigraphic framework

The fan-delta deposits constitute a coarsening and thickening upward megasequence approximately 100 m thick, made up of four smaller sequences of increasing thickness, bounded by shelf calcarenites (Fig. 3 and Fig. 4). Each of these sequences contains several fan-delta units separated by surfaces which are erosional towards the basin edge and conformable towards the centre.

Sequence I (Fig. 5). This is made up of three intervals: a, b and c. Interval ‘a’ is characterised by steeply inclined (30°) foresets beds approximately 25–30 cm thick, whose corresponding top- and bottomsets cannot be observed. It ends with an intensely deformed bed of medium sands a few centimetres
thick, which wedges out towards the upper part of the foresets in the same way as the basin facies deposited on it. Interval 'b' is not as thick as 'a' and the beds of the low-angle foresets are joined to their respective topsets and bottomsets. The contact with the lower interval is erosional in proximal areas and conformable in distal areas. Interval 'c' presents similar characteristics to 'b' and ends with a calcarenite level. The three intervals are organised in a thinning and fining upward sequence.
Fig. 3. Internal geometry and sequential organisation of fan-delta deposits. The Gilbert-type fan-delta succession at Bodurria constitutes a coarsening and thickening upward megasequence consisting of four smaller, fining upward sequences. Sequences I and II are the result of the stacking of three delta lobes, sequence III consists of a single lobe and sequence IV consists of a single lobe prograding three times at different directions. In all cases the internal geometry is indicative of the relation between supply and subsidence at each moment of the stratigraphic succession.

Sequence II (Fig. 5). This sequence is also made up of three intervals. Intervals 'a' and 'b' show characteristics similar to the corresponding intervals in sequence I. Interval 'c' is made up of high-angle foresets wedging out rapidly towards the centre of the basin, where they come into contact with a gravel bed (80 cm thick) with coarsely imbricated boulders (55 cm). This bed wedges out and its grain size decreases towards land, as a consequence of the reworking by coastal processes of a debris flow bed.

The sequence ends with a bed of calcarenites (50 cm) wedging out towards land, and eventually disappears where the layers rise in the foresets.

Sequence III (Fig. 5). This is a thicker sequence than I and II, made up of a single interval of sigmoidal beds which permit a gradual change from the topset, through the foreset, to the bottomset. It ends towards the top with a layer of calcarenites approximately 15 m thick which wedges out towards land in an onlap structure. Cross-bedding caused by sandwaves migrating towards land (N180E) is present locally.

Sequence IV (Fig. 3). This is the thickest sequence of all (30 m) and also has the largest grain size (80 cm max.) It is made up of a single interval, which in turn is made up of three units separated by reactivation surfaces (Fig. 3). These three units show a proximal to distal increase in the angle of inclination of the beds, and represent three phases of progradation at different directions of a deltaic lobe.

The areal distribution and thickness of the four sequences described above differed during their development (Fig. 6). Outcrop conditions do not permit a detailed reconstruction of the spatial distribution of each sequence; however, the data on palaeocurrents obtained from the foresets allow reconstruction of the main entry points of materials to the basin and
the progradation directions of deltaic lobes. It can be said that during the development of the first sequence at least three entry points existed, in relation to which small lobes formed, which prograded only slightly towards the centre of the basin, so that they probably did not come to coalesce. The same situation continued during deposition of the second sequence, although here the lobes which developed were more extensive, at least during intervals ‘a’ and ‘b’, eventually coalesced. During the development of the third sequence, sediment supply to the basin was predominantly channelled through two points, whereas during deposition of the fourth sequence supply to the system took place in a single point.

The foregoing remarks allow us to visualize the basin filling in this area as follows:

After the intra-Tortonian tectonic event, the newly created relief began to be drained towards the basin. The drainage network was at first not highly evolved, so that numerous small streams connected with depressed zones of the basin margin, whose detailed palaeogeography is complex. Thus small outlet lobes developed that did not undergo significant progradation. The evolution of the drainage network gradually caused the number of sediment entry points to decrease, although the amount of materials supplied by each of these points increased, thus resulting in the creation of a smaller number of lobes, which were, however, more extensive. The homogeniza-

Fig. 5. Detail of the internal geometry of fan-delta sequences I, II, and III. In sequences I and II can be observed the nature of the contact between superposed lobes (erosional-conformable in proximal-distal direction), the retrogradational trend in lobe stacking and the evolution of thickness and inner structure. In sequence III the sigmoidal nature of the beds and their perfect preservation are noteworthy. The shelf calcarenites show uneven development in the different sequences, but in all cases they increase towards the top. All these characteristics are indicative of the relation between supply and subsidence and the tectonic behaviour of the basin margin at all times. \(a, b, c\) = intervals of each sequence; \(Ch\) = channel; \(T\) = topset; \(F\) = foreset; \(B\) = bottomset.

Regarding the internal organisation, the foresets consisting of massive conglomerates show rapid wedging as a result of the deposit of lobes by gravitational flows. Towards more distal parts these flows became more fluid and deposition took the form of successive avalanches causing low-angle cross-bedding, in which elementary coarsening-upward or coarsening-fining-upward sequences can be recognised. These were a consequence first of the shearing effect on the base and then of the deposit of the fine fraction during the phase of the waning flow.

The distal parts of the foresets and bottomsets rarely contain lenticular bodies of conglomerates related to slipping mechanisms from higher, very steeply sloping parts of the foresets (comparable to those described by Postma and Roep, 1985).

4. Facies analysis

The fan-delta deposits are made up of clast-supported conglomerates and sands. The foresets are made up of beds varying in thickness from 3 m in the upper part, where they dip approximately 30°, to 0.5 m in the transition zone to the bottomset. A decrease in maximum grain size towards the bottomset from cobble to pebble and a larger proportion of sand can also be detected. The conglomerates are clast-supported in this direction, whereas towards distal parts they change to sands with pebbles.

The entire process was modified by numerous tectonic pulses.
Another characteristic feature of some coarse beds of the foreset is the presence of water escape structures similar to those described by Postma (1984) in the Abrioja fan-delta. The bottomsets are represented by subhorizontal beds normally less than 1 m thick, made up of sands with pebbles and microconglomerates. They represent the distal parts of the foresets, where the fossil contents (red algae, corals, bryozoa, lamellibranchia) and their degree of preservation is higher. The topsets are formed by layers of clast-supported conglomerates approximately 3 m thick. They normally present erosional bases and channel fill fining-upward sequences.

Other facies associated with the fan-delta deposits are: “Fine sands and silts with oyster banks and intercalated channelled conglomerates”; locally these show horizontal lamination and are yellowish and
reddish in colour. They are found associated with topsets and the upper parts of foresets and are interpreted as interdistributary bay deposits. 'Sandy marls' are found in thin beds (20–30 cm) intercalating the bottomset layers and the distal parts of foresets and represent the autochthonous deposit in the basin. 'Bioclastic calcarenites' are better developed in relation to sequences II and III, forming an onlap structure with the latter. These are bioclastic sandstones containing remains of red algae, bryozoans, corals, benthic foraminifera and bivalve fragments. They are almost always horizontally laminated, rarely cross-bedded due to sandwave migration in a shelf environment.

5. Discussion

The stratigraphic succession studied here is located to the extreme southeast of the Guadix–Baza basin, and fills a small, markedly asymmetrical depression. In a global context of eustatic sea-level fall (Late Tortonian), the tectonic movements of the border faults created the main topographic and bathymetric differences and thereby also the source areas and depocentres for sedimentation. The episodic character of these movements affected the stacking pattern of the different units and therefore also the resulting stratigraphic architecture.

Deltaic sedimentation began in a shallow marine environment. Large-scale movements of the border faults increased the depth of the environment and created ideal conditions for the deposit of Gilbert-type deltaic lobes.

The coarsening and thickening upward megasequence studied here is made up of four smaller sequences of increasing thickness towards the top. Sequence I (Fig. 5) is made up of three intervals whose thickness decrease towards the top, while the inclination of the foreset beds decreases in the same direction, and a certain retrogradational trend is also observed. This evolution in the thickness of each interval and the dipping of the foreset beds indicate decrease in depth. The thickest interval 'a' (1 in Fig. 7) is the result of the stacking of several lobes characterised by sequences thinning upwards because of lateral migration. The sandy bed at the top of each of these elementary sequences represents the phase of abandonment of the corresponding lobe.

The steeply inclined foresets were built by turbulent gravitational flows, mainly supplied with sediment accumulated on the topset. The less thick intervals 'b' and 'c' (2 and 3a in Figs. 7), which are characterised by sigmoidal beds, were formed by the simultaneous progradation and aggradation of a lobe in a shallower environment and with a lower degree of slope than interval 'a', whose supply was provided by stream flows.

The nature of the contact between the successive intervals (erosional in the proximal parts) reveals phases of slowing in the tectonic subsidence and probable stability of the base level of the streams, which prevented vertical aggradation in the high parts of the foreset and in the topset, and favoured the development of oblique contacts bounded by bypass surface, that transferred the sediment towards deeper areas (Colella, 1988; Gawthorpe and Colella, 1990). The change from one interval to the next is preceded by a tectonic reactivation as revealed by the abundant deformation structures in the last layers of the previous interval, and the activity of synsedimentary faults towards the basin edge and behind the first foresets (2 in Fig. 7).

Sequence I is therefore the result of the stacking of several deltaic units in a tectonic regime characterised by an initial large-scale slip event, followed by smaller slip events separated by periods of calm. The sediment supply/tectonic subsidence ratio evolved in such a way that depth and accommodation space decreased with time, and so too did the thickness of the corresponding intervals and the style of sedimentation.

Another large-scale movement of the border faults created enough space for the stacking of another shallowing sequence (sequence II). Intervals 'a' and 'b' of this sequence are not substantially different to those of sequence I, and an identical mechanism can be assumed for their generation. Interval 'c' (3b in Fig. 7), represented by a not very extensive lobe with steeply sloping foresets, can be interpreted in connection with a period of instability, which caused an increase in depth on the margin and stimulated the gravitational avalanche mechanisms, some of which penetrated to the bottomset.

The phase of stability and decrease in supply at the end of this sequence brought about the reworking of the gravels at the top of interval 'c', with the
incipient development of a conglomeratic beach and deposit of calcarenites towards the centre in shallow conditions.

Sequence III, made up of a single interval, was deposited in a regime of rather active subsidence, with increasing depth and supply, which favoured the development of large-scale sigmoidal units related to the simultaneous progradation and aggradation of a Gilbert-type deltaic lobe. During the build-up of this lobe, shallowing took place and the coast line migrated landwards, as also did the shelf calcarenite facies. As the terrigenous supply to the basin decreased, the calcarenite facies moved towards land, eventually creating an authentic shelf with development of sandwaves migrating towards land. The physiography of the basin would at this time have been that of a shallow shelf connected to land by a conglomeratic coast.

The deposition of sequence IV on this shelf was preceded by important tectonic activity, as revealed by both the large-scale movements of the border faults, and the fracturing of the calcarenite shelf itself (Fig. 3). Accommodation space was created in these circumstances, the reliefs were rejuvenated and the drainage systems reactivated, thus causing an important inflow of sediments and allowing the formation of lobes which prograded and migrated rather quickly.

The megasequence described above is the result of the stacking of four smaller sequences, built up by the stacking of Gilbert-type fan-delta units and bounded by calcarenites deposited in a shallow shelf. This megasequence reveals a situation of rising sea-level, with the creation of accommodation space and increasing sediment supply towards the top. The tectonic regime on the basin margin was the most...
significant control factor on the stacking pattern of the sequences and the different types of sedimentary units, and therefore also on the internal organisation of the resulting stratigraphic succession. Large-scale slips separated by periods of calm created the accommodation space for the deltaic sequences and the conditions for development of the calcarenite shelf facies which separates them. Smaller tectonic pulses favoured the stacking of deltaic lobes with differing internal geometry depending on depth and/or subsidence, separated by oblique contacts (Colella, 1988) in the proximal areas.

The synsedimentary activity of the border faults can clearly be demonstrated by: (a) abundant deformation structures located at the top of the sequences and/or intervals; (b) tilting of beds in the border zone, behind the foresets created at the beginning of each sequence; (c) the retrogradational character of the sequences reproduces a retreat of the coastline related to the activity of border faults in the same direction. All these observations show that the changes in sea-level during deltaic sedimentation were controlled tectonically.

6. Conclusions

The Late Tortonian coincides with an important period of relief uplift, reactivation of drainage systems and development of fan-deltas in numerous Neogene basins in the Betic Cordillera. A good example of this is the Gilbert-type fan-delta sequence which developed in the extreme southeast of the Guadix–Baza basin, in the vicinity of Bodurria.

The Bodurria fan-delta succession constitutes a coarsening and thickening upward megasequence deposited on an extensional-type basin margin with active synsedimentary tectonics and rising sea-level resulting from important tectonic subsidence. In these circumstances the available accommodation space and the sediment supply to the basin increased with time.

The keys to the interpretation of the sequential organization and the internal geometry of the succession studied here lie in the tectonic behaviour of the border faults: large-scale tectonic movements of the faults prior to the deposit of each sequence created the required topographic and bathymetric conditions for development of Gilbert-type fan-delta lobes.

The evolution of the drainage network also had an effect by modifying the position and number of sediment entry points to the basin, the quantity of materials supplied at each point, and consequently the size of the resulting sedimentary body and its internal structure.

The sediment supply/subsidence ratio determined the pattern of lobe stacking and their internal geometry. Thus, at the beginning of each sequence, with a high ratio, the lobes prograded and migrated laterally, whereas towards the top, where the ratio was low, the lobes prograded and aggraded vertically. Moreover, the phase of stability produced erosional contacts, whereas the longer periods of calm, with scarce sediment supply, allowed the establishment of a better developed calcarenite shelf towards the upper part of the succession.

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