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# Architecture and stacking patterns of lower-slope and proximal basin-floor channelised submarine fans, Middle Eocene Ainsa System, Spanish Pyrenees: An integrated outcrop–subsurface study

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ABSTRACT

An integrated outcrop and subsurface study of the Middle Eocene (Lutetian) Ainsa System, Ainsa Basin, Spanish Pyrenees, was undertaken to characterise the proximal depositional environments of sandy channelised submarine fans, interfan and slope deposits, the results of which are presented here for the first time as a coherent synthesis and interpretation. It is unique for any drilling programme in coarse-grained deep-marine clastic sediments as it documents the facies, architecture, and evolution of the proximal parts of three structurally confined and channelised sandy lower-slope and proximal basin-floor submarine fans (Ainsa I, II and III fans). Eight wells were drilled through ~220–250 m of stratigraphy with typical inter-well spacing of ~400–500 m, with seismic lines, wireline logs, essentially continuous coring, sandstone petrography, micropalaeontological and palynomorph analyses. The fans show a lateral stepwise migration away from a growth anticline that formed the lateral basin margin on the side of the growing Pyrenean orogen. Unlike the Ainsa I Fan, the Ainsa II and III fans appear to have an essentially non-erosive base overlain by at least several metres of relatively unconfined sandy deposits interpreted as pre-channel proximal-lobe deposits. Submarine channels erode into these proximal-lobe deposits, typically 5–30 m deep and hundreds of metres wide (~100–600 m). The channels are associated with composite erosional surfaces, local m-scale scouring, and pebbly lag deposits, suggesting substantial sediment bypass in the early stages of channel evolution, but with later channel abandonment and filling by finer-grained deposits. This process of channel incision, bypass and likely backfill appears to have occurred many times during the main growth phase of the sandy submarine fans, and with only one channel active at any time. Well correlations and mapping, including using bio-events, suggest the presence of levée–overbank deposits. Candidate lateral accretion packages suggest that there was an increase in channel sinuosity upwards from the Ainsa I, II and III fans, probably linked to an overall decrease in seafloor gradients; supported by the presence of many tens of metres of essentially undeformed marlstones of very fine-grained, thin- to very thin-bedded turbidites in the upper parts of the Ainsa System.

Depositional architecture was controlled by a combination of syn-sedimentary tectonics fashioned by seafloor growth structures, climate change (affecting seafloor environmental conditions that controlled bioturbation intensity) and probably autocyclic (intrafan) processes (that were probably responsible for individual channel elements). Local accommodation was controlled by intra-basinal tectonics and the interplay between erosional and depositional processes, including irregular seafloor topography created by cohesive debris flow and slide deposits (MTDs/MTCs). We also show that post-depositional thrusting and folding has created locally complex geometrical relationships within the fans and interfan deposits, which could not have been resolved without careful outcrop and subsurface mapping, logging and correlation.



**Contents**



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## 1. Introduction

There are few detailed studies utilising an integrated outcrop and subsurface study of proximal deep-marine, channelised, clastic systems. There have, however, been such studies of the more distal and finer-grained parts of deep-water systems (e.g., Permian Karoo foreland-basin systems in the European Union-funded 2001–2004 Nomad Project, South Africa, Johnson et al., 2001; Grecula et al., 2003a,b; Hodgson et al., 2006; Luthi et al., 2006; Brunt et al., 2013a,b), the Upper Carboniferous Ross Sandstone, western Ireland (Haughton and Shanon, 2013), and the Miocene Mount Messenger Formation, Taranaki, New Zealand (Browne and Slatt, 2002; Kamp et al., 2004; Browne et al., 2005; Field, 2005). Also, there are many detailed outcrop studies of ancient channelised deep-marine systems, e.g., the Permian Brushy Canyon (Batzle and Gardner, 2000; Carr and Gardner, 2000; Gardner and Borer, 2000; Gardner et al., 2003), and the Upper Cretaceous Cerro Toro and Tres Pasos formations (Shultz and Hubbard, 2005; Crane and Lowe, 2008; Armitage and Stright, 2010).

Many of the recent publications on the deep-marine sediments of the Ainsa Basin and in particular the Ainsa System, the focus of this paper, have tended to consider aspects of reservoir modelling (e.g., Fernandez et al., 2004; Falivene et al., 2006a,b, 2007; Arbués et al., 2007), some with an emphasis on seismic modelling (Benevelli et al., 2003; Bakke et al., 2008), rather than their detailed sedimentology and stratigraphy (but for detailed studies of bioturbation at outcrop and in core, see Heard and Pickering (2008), Heard et al. (2008) and Heard et al. (2014)). Together with a review of what is known about the Ainsa System, the paper bridges the gap between studies that emphasise reservoir modelling of the system and detailed sedimentological and stratigraphical descriptions and interpretations. A secondary but nevertheless important aspect of this paper is to modify and revise the stratigraphy of the Ainsa System from that of Pickering (2005) and Pickering and Corregidor (2000, 2005), in the light of more recent fieldwork. In particular, the recognition that most submarine slopes (and therefore fans such as those in the Ainsa Basin) are likely to contain abundant evidence of supercritical flows; since for a reasonable friction factor ($f = 0.02$), Komar (1971) concluded that turbidity currents would be supercritical on slopes >0.5°, a value exceeded on many basin-margin slopes and on the upper parts of submarine fans, particularly small-radius fans in tectonically-active margins. Thus, much of the Ainsa System should contain sedimentary structures linked with supercritical turbidity–current flow, including "cyclic steps", where flows

**Table 1**
GPS locations and distances between wells (see Fig. 1 for map positions).

| Well Pair | x-coord (m) | y-coord (m) | z-coord (m) | |
|---|---|---|---|---|
| A4 well | 265316.81 | 4697963.84 | 597.61 | Distance between A4 well and A3 well (in 3-D) = 670.78 m |
| A3 well | 265136.46 | 4698609.14 | 565.86 | Bearing between A4 well and A3 well = 344.39 |
| | | | | Vertical angle between A4 well and A3 well = −2.713 |
| A3 well | 265136.46 | 4698609.14 | 565.86 | Distance between A3 well and A2 well (in 3-D) = 2308.88 m |
| A2 well | 264502.58 | 4700829.3 | 571.63 | Bearing between A3 well and A2 well = 344.07 |
| | | | | Vertical angle between A3 well and A2 well = 0.143 |
| A2 well | 264502.58 | 4700829.3 | 571.63 | Distance between A2 well and A1 well (in 3-D) = 532.38 m |
| A1 well | 264293.95 | 4701318.93 | 584.28 | Bearing between A2 well and A1 well = 336.92 |
| | | | | Vertical angle between A2 well and A1 well = 1.362 |
| A1 well | 264293.95 | 4701318.93 | 584.28 | Distance between A1 well and L1 well (in 3-D) = 926.05 m |
| L1 well | 263705.07 | 4702031.93 | 535.15 | Bearing between A1 well and L1 well = 320.45 |
| | | | | Vertical angle between A1 well and L1 well = −3.041 |
| L1 well | 263705.07 | 4702031.93 | 535.15 | Distance between L1 well and L2 well (in 3-D) = 394.17 m |
| L2 well | 263377.89 | 4702247.25 | 579.4 | Bearing between L1 well and L2 well = 303.35 |
| | | | | Vertical angle between L1 well and L2 well = 6.446 |