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Depositional environments and sediment partitioning during early stage foreland basin thrusting: The Late Ilerdian-Early Cuisian Roda Sequence, South Pyrenean Foreland Basin (Spain)

Allard W. Martinius[1,2] and Cai Puigdefàbregas[3]
[1] Statoil ASA, Trondheim, Norway
[2] Technical University of Delft, The Netherlands
[3] University of Barcelona, Spain

The Late Ilerdian-Early Cuisian Roda Sequence spans approximately 3 Ma and formed in the South Pyrenean Foreland Basin (Spain). It is mapped in detail across the present-day Tremp-Graus, Ager and Ainsa sub-basins, and across the Boltaña Anticline into the Jaca sub-basin. The South Pyrenean Foreland Basin basin formed during the early stage of oblique collision of the Iberian Plate with the Eurasian Plate, and was bounded to the north by the Pyrenean chain and to the south by the Sierras Marginales. Within the basin, a time-sequenced series of curved thrusts developed (controlled by the location of inverted Mesozoic extensional faults) of which the Montsec thrust was decisive for the development of the Roda Sequence. This thrust sheet was displaced in a mostly southward direction and has an E-W orientation; it carried the Ilerdian-Cuisian sediments of the present-day Tremp-Graus and Ainsa sub-basins. It is well-expressed at the surface as well as partly buried by younger sediments. The Montsec thrust sheet is bounded east and west by the corresponding lateral ramps oriented SW-NW (Segre line), and SE-NW (La Fueba thrust system). Beyond the SE-NW oriented lateral ramp, the present-day Ainsa and Jaca sub-basins are located. The thrust had a significant influence on sediment dispersal patterns and the nature and location of depositional environments during the development of the Roda Sequence.

During the Late Ilerdian-Early Cuisian Roda Sequence, the South Pyrenean Foreland Basin was an approximately 50 km wide. The basin formed part of the paleo-Gulf of Biscay that extended significantly further eastward along the southern margin of the growing Pyrenees until the Catalan coastal ranges. In its eastern part, the basin was closed north of the Montsec Thrust but south of it, the basin continued eastward, and the Late Ilerdian-Early Cuisian Roda Sequence corresponds to the Ilerdian Sagnari-Corones delta sequence in the present-day Ripoll Basin (shallow carbonates and sandstones, and deeper marine marls) of the 'Lower Pedraforca Unit'. Intermittent compressional movements and thrust development at variable magnitudes in time and space imposed allogenic control during the development of the Roda Sequence. This resulted in 1) pluriform depth profiles in various directions across the foreland basin, and 2) a complex process-response of depositional facies in various parts of the basin. Along the northern margin, close to the Pyrenean chain, and in particular in the eastern section, a 'foredeep' developed with larger water depths than further south where the basin shallowed onto the actively moving Montsec Thrust. The Montsec Thrust became emerged during the Late Ilerdian-Early Cuisian and formed a topographic high, and a similar N-S water depth profile developed in the Ager sub-basin from the Montsec Thrust out to the Sierras Marginales. In the western section of the basin (the Jaca sub-basin), a more uniform foreland basin development is recognized. Therefore, progradational, retrogradational and aggradational patterns in the various time-equivalent depositional systems developed in response to the local A/S trend.

To describe the distribution of, and transitions between depositional environments as well as sediment dispersal patterns, four main depositional zones are defined: the Tremp-Graus sub-basin, the combined Ainsa and eastern part of the Jaca sub-basins, and the Ager sub-basin. These are discussed for two Roda Sequence time slices: the Late Ilerdian (53.5 Ma) and the Early Cuisian (52 Ma).

Roda Sequence time slice 1 – Late Ilerdian (53.5 Ma)

Tremp-Graus sub-basin

In the innermost eastern part of the Tremp-Graus sub-basin, small, shallow-water deltas prograded towards the SW to NW fed by minor rivers with a small catchment area. Extensive tidal flats and mixed siliciclastic-carbonate shallow-water environments were present along this eastern basin margin. Contemporaneously, further west, two main, several km wide and long, elongate and basin-margin hugging Gilbert-type deltas formed in deeper water. Granite derived siliciclastic sand, including carbonate and feldspars, was derived from the Pyrenean chain through braided fluvial systems flowing southwestward and located in the proto-Gurb and proto-Sis palaeovalleys respectively. Along the southern basin margin, carbonate platform deposits formed (Montrebei section).

The Roda Gilbert-type delta (fed through the proto-Sis palaeovalley) built out on an inner carbonate platform shelf with abundant life. At initiation of delta progradation, water depths several km's away from the basin margin are estimated to have been at around 40 to 60 meters and within the photic zone. Over time, increased southward directed sediment supply controlled rapid delta progradation (the Roda Sst Mbr). Main delta lobe progradation, compensational stacking and abandonment was controlled by allogenic processes at 4th order. During abandonment of the main delta lobes, rich, wave-resistant bivalve- and coral-dominated hardground fauna's developed suggesting water depths of around 5 to 10 meter. Autogenic processes and compensational stacking controlled the development of multiple sub-lobes constructing each main lobe. Sub-lobes responded quickly to fluctuating sediment input (magnitude and direction) and efficiently recorded high-frequency variations in the interplay of fluvial discharge variations, sedimentation rate and the creation of accommodation space. Strong longshore currents caused the deflection of delta lobes in a SE and SW direction due to complex tidal current rotational patterns, and lobe deposits interfingered basinward with distal delta front and prodelta to offshore siltstone deposition.

Elongate, laterally migrating lower delta-front attached tidal bars developed in the most distal parts of the Roda Gilbert-type delta lobes. These bars formed by dunes showing abundant and well-developed tidal bundles formed by strong regional W–NW directed ebb-dominant tidal currents and formed during high-frequency relative base level falls.

Beyond the Gilbert-type deltas fed by the proto-Sis and Gurp palaeovalleys, southward and farther west into the basin, mud-prone offshore shelf sediments accumulated, developing a thick (up to 350 m thick) succession. Southward, carbonate deposition dominated and water depths shallowed onto the emergent Montsec Thrust. Westward, water depths gradually increased up to depths of approximately 80 m (the sub-photic zone; Yeba Marls in the Ainsa sub-basin). The transition from this shelf zone into deeper water environments was very gradual and smooth and located at the position where later in time the SE-NW orientation lateral ramp of the Montsec

Thrust (and associated minor thrusts) would develop. The transition zone was determined by the initial formation of the lateral ramp.

Ainsa and Jaca sub-basins
Above and west of the oblique Montsec lateral ramp, water depths increase further and slumps and thin turbidities developed (represented by the Yeba marls in the present-day Ainsa sub-basin) shedding sediment into the relative deepest and largest part of the foreland basin (the present-day Jaca sub-basin) where only marl deposition occurred.

Ager sub-basin
South of the Montsec Thrust, a thick succession of shallow-water tidal compound dunes (up to 6 m thick) was deposited suggesting a relatively high rate of accommodation space generation and a sedimentation rate that kept pace (the Baronia Fm). Compound dunes are formed by a highly bioturbated, muddy, fine grained sandstone with an open-marine *Cruziana* ichnofacies at the base, overlain by ripple-laminated sandstone that contains mud drapes, and capped by fine- to coarse-grained sandstones that contain both planar and trough cross-strata with unidirectional or bi-directional paleocurrent directions and occasional thin mud drapes on the foresets. Cross strata that formed by simple superimposed dunes dip in the same direction as the inclined master bedding planes within the compound dune, forming a forward-accretion architecture. The compound dunes alternate vertically with highly bioturbated muddy sandstones (up to 10 m thick) that represent the low-energy fringes of the dune fields or periods of high sea level when current speeds decreased. Compound dunes are 500–1000 m long in the direction of the current, and at least 350–600 m wide in a flow-transverse direction. The characteristics of this compound dune field and its strong tidal control are typical for a tidal strait depositional environment. Towards the west, the compound tidal dune field transitioned into a depositional environment dominated by carbonaceous silt and fine-grained sand with bedforms decreasing towards ripple fields. Towards the east, an opening towards the semi-enclosed but large present-day Ripoll Basin existed which was dominated by carbonate platforms during the Late Ilerdian (Cadí Fm) and deltaic and fluvial clastics (Corones Fm). This basin was large enough to develop rotational tidal currents that had to pass in and out through the Ager Strait.

Roda Sequence time slice 2 – Early Cuisian (52 Ma)

During the Early Cuisian, the paleobathymetry and paleomorphology of the South Pyrenean Foreland Basin changed mainly because of the ongoing collision and further development (southward movement) of the Montsec Thrust creating incipient relief. The asymmetric depth profiles in the area of the present-day Tremp-Graus sub-basin as well as the Ager sub-basin became less pronounced (overall shallowing) and less asymmetric.

Tremp-Graus sub-basin
In the eastern-most part of the Tremp-Graus sub-basin, tidal flats and low-gradient and shallow-water deltaic environments expanded westward. In the Isábena valley, a vertically stacked series of coarse-grained, thin but relatively small retrogradational fan-delta lobes developed in shallow water and hugging the paleocoastline (the Esdolomada Mbr). The fan-delta continued to be fed by rivers flowing through the proto-Sis paleovalley deriving sediment from a large catchment

area. In a direction perpendicular to the coastline, they were approximately 2 km wide and transitioned into sandy marl deposits. These were deposited contemporaneous with a series of thin (up to 6 m thick) elongated tidal sandstone bodies interpreted as detached tidal bars and up to 5 km long and 2 km wide. Bar crests were generally oriented northwest to southeast, parallel to the tidal palaeocurrents and to the nearby palaeoshoreline. Subaqueous tidal flat and shallow muddy shelf environments in between delta lobes and tidal bars, dominated by inter- to subtidal gastropod communities, were common.

Adjacent to this retrogradational fan delta and tidal bar system, relatively small, mixed siliciclastic-carbonate coarse-grained basin margin fringing river-dominated deltas existed (for example, in the Merli area). These had small catchment areas and well-developed shorefaces.

Ager sub-basin

South of the emergent Montsec Thrust, in the Ager sub-basin, the Baronia compound tidal dune field became moribund and the basin initially deepened. A sediment-starved marine shelf environment formed in which silty mudstone (the Passarella Fm) was deposited. Subsequently, the connection to the Catalan Basin closed and a series of relatively small basin margin-fringing deltas with mouth bars developed in the Ager Bight that prograded onto a silt- and mud-dominated shelf (the Ametlla Fm). Towards the west, these environments transitioned into a silty and bioclastic shelf.

A decrease in accommodation space, probably related to a phase of rapid thrust sheet displacement and uplift, caused a base level fall and created series of up to 35 m deep incised valleys. Continued subsidence related to thrusting initiated renewed flooding of the Ager sub-basin, landward stepping of the shelfal depositional system, and infilling of the incised valley; tidal bars were common. Coastal plain brackish-water environments subject to minor marine incursions developed towards the top of the Roda Sequence in the present-day Ager sub-basin. Macrofauna assemblages and inferred paleoenvironments are almost identical to those in the Tremp-Graus sub-basin.

Ainsa and Jaca sub-basins

In the area of the present-day Ainsa and eastern-part of the Jaca sub-basins thin and fine-grained turbidite layers, observed within the Yeba marls section, indicate a gradual deepening towards the west.