Geometries and sedimentary heterogeneities in high sinuosity fluvial deposits: a case study from the Capella Formation (Middle Eocene, Graus-Tremp Basin)

Geometrías y heterogeneidades sedimentarias en depósitos fluviales de alta sinuosidad: Caso de estudio de la Formación Capella (Eoceno medio, Cuenca de Graus-Tremp)

Marc Gil-Ortiz[1, 4*], Luis Miguel Yeste[2], José Luis Cuevas[3, 4], Miguel López-Blanco[3, 4], Eider Rua-Alkain[3, 4], Patricia Cabello[3, 4] and César Viseras[2]

[1] Dpt. Mineralogia, Petrologia i Geologia Aplicada, Facultat de Ciències de la Terra, Universitat de Barcelona, c/Martí i Franquès s/n, 08028 Barcelona.
marc.gilortiz@ub.edu
[2] Sedimentary Reservoir Workgroup (SEDREGROUP). Dpto. Estratigrafía y Paleontología, Facultad de Ciencias, Universidad de Granada, Av. Fuente Nueva s/n, 18071 Granada.
lmyeste@ugr.es, viseras@ugr.es
[3] Dpt. Dinàmica de la Terra i de l'Oceà, Facultat de Ciències de la Terra, Universitat de Barcelona, c/Martí i Franquès s/n, 08028 Barcelona.
jcuevas@ub.edu, m.lopezblanco@ub.edu, eider.rualkain@ub.edu, pcabello@ub.edu
[4] Institut UB-Geomodels, Facultat de Ciències de la Terra, Universitat de Barcelona, c/Martí i Franquès s/n, 08028 Barcelona.
**Corresponding author*

ABSTRACT

The studied succession of the Middle Eocene Capella Formation in the Graus-Tremp Basin is characterized by high sinuosity fluvial deposits. The sedimentological logged section and the obtained outcrop digital model have allowed to identify up to 3 different facies associations. These include: 1) channel fill, 2) point bar and 3) overbank deposits, showing up to three different sand-prone geobody types. Vertically, the reservoir sand-prone geobodies are often disconnected one from each other by fine-grained facies, becoming potential vertical fluid flow barriers. However, horizontally, the geobodies are frequently connected due to channel incision over underlying sand-prone geobodies, as well as by contact of crevasse splays and point bars with the main channel fills. The exceptional outcropping conditions of the studied section, make this formation as an excellent outcrop analogue for similar fluvial reservoirs with comparable features in the subsurface.

Key-words: *Graus-Tremp Basin, Capella Formation, outcrop reservoir characterization, meandering river, sedimentary heterogeneity.*

RESUMEN

La sucesión estudiada en la Formación Capella del Eoceno medio en la Cuenca de Graus-Tremp, está caracterizada por depósitos fluviales de alta sinuosidad. El levantamiento de una columna estratigráfica y la elaboración de un modelo digital de afloramiento han permitido identificar hasta 3 asociaciones de facies distintas. Éstas incluyen: 1) relleno de canal, 2) point bar y 3) depósitos de desbordamiento, presentando hasta tres tipos de geocuerpos arenosos distintos. Verticalmente, los cuerpos arenosos con potencial de reservorio quedan frecuentemente desconectados por facies de grano fino, posiblemente creando barreras verticales para el flujo de fluidos. Sin embargo, en dirección horizontal, los geocuerpos a menudo se ven conectados debido a la incisión de los canales sobre cuerpos arenosos infrayacentes, así como por contacto de lóbulos de desbordamiento y point bars con los principales rellenos de canal. Las excepcionales condiciones de afloramiento de la sección estudiada la convierten en un excelente análogo aflorante de reservorios fluviales con características similares en el subsuelo.

Palabras clave: *Cuenca de Graus-Tremp, Formación Capella, caracterización de reservorio aflorante, río meandriforme, heterogeneidad sedimentaria.*

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Introduction

Fluvial deposits have been historically studied due to their potential as reservoirs in the subsurface (Cabello *et al.*, 2018; Colombera et al., 2017; Puig *et al.*, 2019; Yeste *et al.*, 2019, 2020).

In particular, meandering fluvial channels present a high degree of sedimentary heterogeneity (Gil Ortiz and Colombo, 2014; Cabello *et al.*, 2018; Colombera et al., 2017; Yeste *et al.*, 2020, 2024a), becoming a challenge for subsurface management in terms of reservoir connectivity (Cabello *et al.*, 2018).

In order to accomplish this commitment, this work deals with meandering river deposits of the Capella Formation (Fm.), present in the Foreland South-Pyrenean basin.

The Middle Eocene Capella Fm. was defined by Garrido and Megías (1968) as a detrital sedimentary unit in the Graus-Tremp basin. This succession has been studied by very few authors in the past (Cuevas Gozalo *et al.*, 1985; Atkinson, 1986; Cuevas-Gozalo 1989; Yeste *et al.*, 2024b) and is characterized by nicely preserved high sinuosity fluvial to fluvio-tidal deposits. This framework provides room for a detailed study under different applied purposes.

In that sense, this study aims to carry out a geometric characterization of several geobodies present in this formation, as well as to identify the sedimentary heterogeneities that may constitute potential baffles and barriers in terms of reservoir vertical and lateral connectivity.

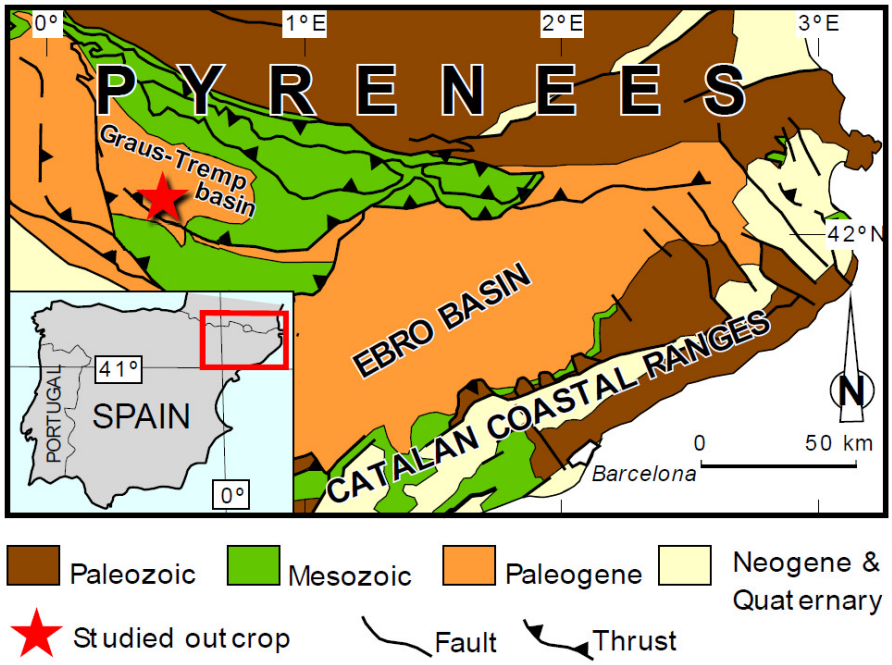

Fig. 1.- Study area with a regional geological mapping of the main units outcropping in the Southern Pyrenees. The approximate location of the sedimentological log is also highlighted with a red star.

Fig. 1.- Área de estudio con la cartografía geológica regional de las principales unidades aflorantes en los Pirineos meridionales. La localización aproximada de la columna estratigráfica está también marcada con una estrella roja.

The results of this study are intended to be used as outcrop analogues for equivalent depositional environment deposits and provide a tool for subsurface management in large-scale carbon, capture and storage, as well as hydrogen injection and storage projects.

The study area is located southward Isábena river, nearby Laguarres and approximately 5 km far from Capella, at the "Barranco del Estaball" outcrop (Fig. 1).

Geological setting

The Pyrenean orogen was formed from the Late Cretaceous to the Early Miocene as a consequence of the convergence between the Iberian and Eurasian tectonic plates. A foreland basin system was developed to the south of the developing mountain chain in response to flexural subsidence. The evolution and shortening of this orogen resulted in a series of sub-basins bounded by major structures. These basins preserved several syn-tectonic units deposited in a wide range of depositional environments, from non-marine to deep marine clastic and carbonate settings.

One of these sub-basins is the Graus-Tremp basin, an E-W oriented trough developed on the top of the Montsec thrust in the south-central Pyrenees.

The sedimentary record of the Graus-Tremp basin includes a series of non-marine to shallow marine deposits from the Paleocene up to the Oligocene. One of the main sedimentary units in this basin is the Middle Eocene Capella Formation (Cuisian-Lutetian), a non-marine to marginal marine succession, which constitutes the focus of this study.

Data and methods

A particular outcrop was selected due to the outstanding exposure conditions at the "Barranco del Estaball" (Fig. 1). This outcrop is encased in the middle part of the Capella succession according to previously measured section by Cuevas-Gozalo (1989).

An 80 m stratigraphical column was logged (Fig. 2) identifying and measuring different lithologies, grain sizes, sedimentary structures, bioturbation types and degrees.

In addition, a digital outcrop model (DOM) was built from photogrammetry with a remotely piloted aircraft system (RPAS). The RPAS used was a DJI Mavic 3 Enterprise, provided by the Drone Unit at the Scientific Instrumentation Center of the University of Granada. For the DOM, the Agisoft Metashape™ software was used, a specifically designed tool for drone-based mapping.

The virtual outcrop model was used to complement the traditional outcrop study and sedimentary logging with a digital characterization of the main geobodies identified in the outcrop, providing geometrical data, such as dimensions and shapes, and an estimation of connectivity among them.

Results

The stratigraphic section and the DOM at the "Barranco del Estaball" outcrop, allowed to identify at least three different facies associations, including:

Channel fill

Three different lenticular geobodies were identified in the logged section (Fig. 2). These are characterized by a fining-upward succession of coarse- to medium-grained sandstones with erosive base and common mud clasts associated with this base and occasional micro-conglomeratic lags. Thickness of these packages oscillates between 40 cm to almost 5 m and their lateral extension usually exceeds 50 m (Fig. 3). The main primary sedimentary structures present grade from moderate to high energy trough cross-bedding at the base to lower energy ripple cross-lamination to the top. Bioturbation in these geobodies is common, mostly associated with *Taenidium* ichnofossils, restricted to the uppermost part of the channel fill, denoting a decrease in the energy of the system and/or abandonment of the channel.

The interpretation of this facies association corresponds with waning fluvial discharge on channels, according to the lenticular shape of the geobody, erosive base with conglomeratic lags, fining-upward grain-size trend and sedimentary structures found in these deposits.

Point bar

This facies association was not apparently logged but clearly identified in the DOM (Fig. 3). It is characterized by fine to medium-grained sandstones with large-scale epsilon cross bedding and ripple cross-lamination. Characteristic silty cm-thick layers bound individual sigmoids. Measured vertical thickness of stacked sigmoidal packages is around 6 m, with a

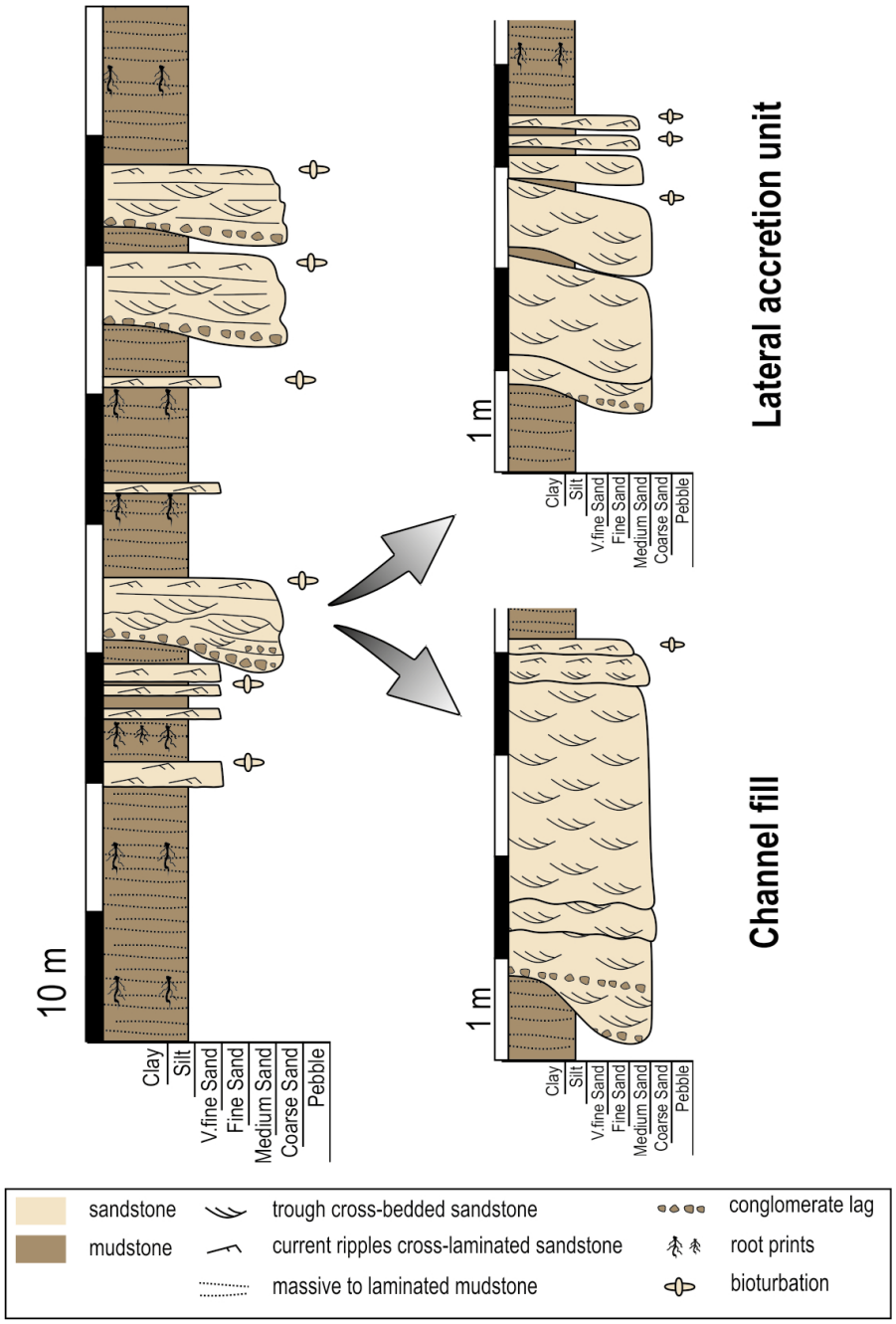

Fig. 2.- Synthetic stratigraphic column of the logged section in the study area (left). See also at the right side of the figure, a closer view of the channel fill interpretation (below) and the point bar (above) connected to this channel infill body, showed in Figure 3.
Fig. 2.- Columna estratigráfica sintética de la sección medida en el área de estudio (izquierda). Véase también en la parte derecha de la figura, una vista cercana de la interpretación del relleno de canal (abajo) y la point bar (arriba) conectada a este cuerpo de canal, mostrados en la Figura 3.

lateral extension of more than 60 m (Fig. 3). Bioturbation at the uppermost part of these geobodies is common, often associated with *Taenidium* ichnofossils.

The interpretation for this facies association is point bar deposits according to lateral accretion surfaces with silty laminae bounding individual bars, possibly related with periods of waning energy after point bar deposition. Sedimentary structures and typical fining-upward trend of these packages supports also this interpretation.

Overbank

This facies association is mainly formed by ochre silt to clay-rich deposits with a characteristic modified fabric by root traces and carbonate nodules (Fig. 2). Bioturbation is common in some of these sandy packages, being *Taenidium* and *Arenicolites* the most frequent ichnotaxa.

The interpretation for this facies association is low-energy non-confined deposits in a nonmarine environment with an advanced level of pedogenesis. This fine-grained material would come from overflowing in channels during flood events.

Despite of being a facies association dominated by fine-grained sediment, there are several cm-thick sand-prone packages, with planar base and convex top (Fig. 3), and with common occurrence of ripple cross-lamination (Fig. 2), extending for several tens of metres.

These are interpreted as crevasse splay deposits associated with breaching of channel levees during high energy floodings.

Discussion

After previous sedimentological characterization, the studied section of the Capella Fm. is defined as a highly heterogeneous succession, in terms of sedimentary geobodies and lateral and vertical connectivity.

In this case, the vertical connectivity of the geobodies is often interrupted by overbank fine-grained deposits. However, in some cases, channel incision helps to connect some of these sand-prone levels by truncating down into the muddy section. Thus, vertical connectivity of potential reservoir intervals seems to be often guaranteed, at least in some points along and across the section.

Despite of the fact that many of these geobodies are apparently disconnected one to each other, the DOM has proved the lateral connection of many sandy intervals by means of lateral migration of point bars (Fig. 3), which are eventually in contact with the main channel feeding the system. Furthermore, usually thin crevasse splay deposits encased into the overbank matrix, provide lateral connectivity of the main channels with other channel, point bar and crevasse deposits, becoming an excellent assistant in the lateral connectivity of these meandering fluvial systems.

Conclusions

Three different facies associations were identified for the Middle Eocene Capella Fm. in the "Barranco del Estaball" outcrop; these include: 1) channel fill, 2) point bar and 3) overbank deposits. These facies associations can be framed into a non-marine high sinuosity fluvial depositional environment.

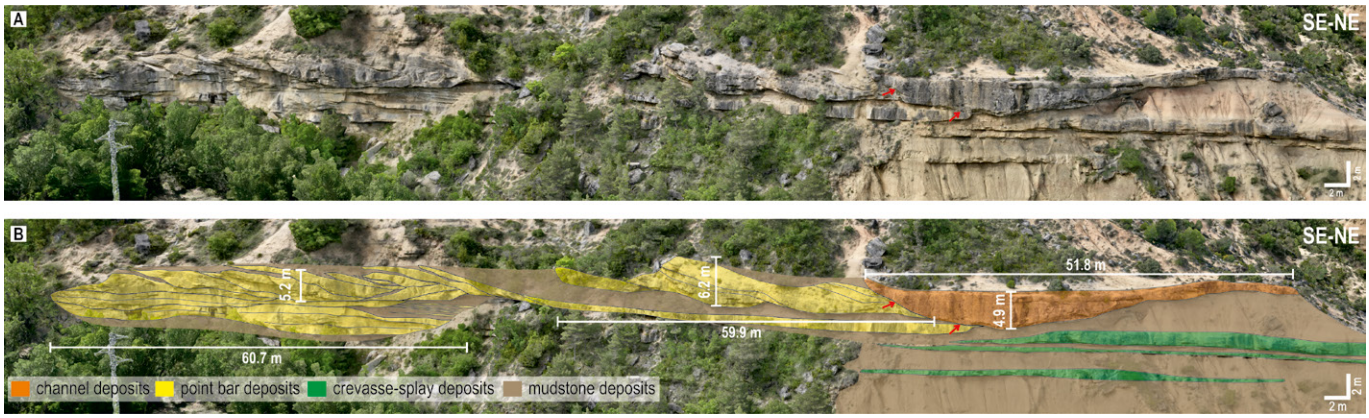

Fig. 3.- SE-NE oriented section of basal fluvial channel and associated point bar and crevasse splay deposits. See how channel incision helps to vertically connect potential reservoir intervals, originally disconnected one from the others. See also point bars to the left (red arrows) and crevasse splays to the bottom right, help to laterally connect sand-prone intervals. Vertical and lateral scale is 2 m showed in the bottom right-hand corner of the image.

Fig. 3.- Corte orientado SE-NE con el canal fluvial basal y depósitos asociados de point bar y lóbulo de desbordamiento. Ver como la incisión del canal ayuda a conectar verticalmente intervalos potenciales de reservorios, originalmente desconectados los unos de los otros. Ver también las point bars a la izquierda (flechas rojas) y los lóbulos de crevasse en la parte inferior derecha, ayudan a conectar intervalos ricos en arena. La escala vertical y horizontal son 2 m y se muestra en la esquina derecha inferior de la imagen.

The DOM allowed to identify up to three different sand-prone geobody types, including channels, point bars and crevasse splays. The dimensions of these geobodies seems to be controlled by the geobody type.

Excellent exposition of this outcrop allows this section of the Capella Fm. to be used as an outcrop analogue for similar subsurface high sinuosity fluvial deposits.

Authors contribution

The authors have contributed with the field work, data analysis and interpretation of the results, as well as in the manuscript preparation.

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