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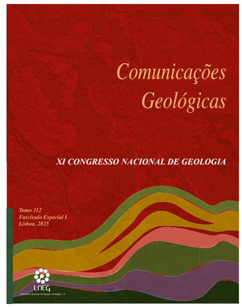
# Heterogeneity of the mixed siliciclastic-carbonate deposits of the upper Cabo Carvoeiro formation (Lower-Middle Jurassic), Lusitanian Basin, Portugal




# Heterogeneidade da sucessão siliciclástico-carbonatada do topo da formação de Cabo Carvoeiro (transição Jurássico Inferior-Médio), Bacia Lusitânica, Portugal

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**Abstract:** The upper CC5 member of the Cabo Carvoeiro Formation (Toarcian-Aalenian(?)) of the Lusitanian Basin is characterized by grainstone facies with quartz grains, ooids and intraclasts. These facies are observed exclusively at Peniche, contrasting with the hemipelagic marly sediments of coeval outcrop sections in the basin. A detailed facies scheme reveals the relative local heterogeneity of the succession on outcrops, while the analysed subsurface data helps to better understand its regional heterogeneity. Lateral facies variability on outcrop is observed to occur through gradation, interfingering or pinching-out geometries. Coeval sections in the analysed offshore wells are generally characterized by micritic mudstone facies, which might transition laterally into the Peniche grainstones through similar geometric relationships based on the existing conceptual model. The relative heterogeneity of this sedimentary system is defined in this study by integrating outcrop and subsurface data, allowing for its perception at different observation scales.
**Keywords:** Carbonate heterogeneity, petrographic analysis, outcrop-subsurface correlation, Jurassic, Portugal.

**Resumo:** O topo do membro CC5 da Formação do Cabo Carvoeiro (Toarciano-Aaleniano(?)) na Bacia Lusitânica caracteriza-se por fácies grainstone com intraclastos, oóides e grãos de quartzo. Estas observam-se exclusivamente em Peniche, contrastando com os sedimentos margosos hemipelágicos das secções coevas da bacia e as fácies micríticas das sondagens offshore. Um esquema de fácies detalhado revela a heterogeneidade da sucessão em afloramento, sendo que os dados de sondagem ajudam a definir a heterogeneidade do sistema à escala regional. Em afloramento, a variabilidade lateral de fácies ocorre através de gradação, interdigitação ou bizelamento de corpos. As secções coevas das sondagens analisadas caracterizam-se na generalidade por fácies micríticas mudstone. Estas passam lateralmente às fácies grainstone de Peniche através de relações geométricas semelhantes, de acordo com o modelo concetual. A heterogeneidade do sistema descreve-se através da análise integrada de dados de afloramento e subsuperfície, permitindo a perceção dessa variabilidade a diferentes escalas.
**Palavras-chave:** Heterogeneidade de depósitos carbonatados, análise petrográfica, correlação afloramento-subsuperfície, Jurássico, Portugal.

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## 1. Introduction

The upper CC5 member of the Cabo Carvoeiro Formation (Toarcian-Aalenian(?)) in the Lusitanian Basin is characterized by a succession of mixed carbonate-siliciclastic sediments defined as grainstones with intraclasts, ooids, bioclasts and quartz grains (*e.g.* Wright and Wilson, 1984; Duarte and Soares, 2002; Duarte, 2007; Barata *et al.*, 2021). This succession was deposited within a complex tectonic context and strongly influenced by the uplift and exposure of the Berlengas block to the west (*e.g.* Wilson *et al.*, 1989; Rasmussen *et al.*, 1998).

The studied stratigraphic interval corresponds to the informal subunits CC5c to CC5e (Barata *et al.*, 2021), has a minimum thickness of 160 m and is observed exclusively at Peniche,

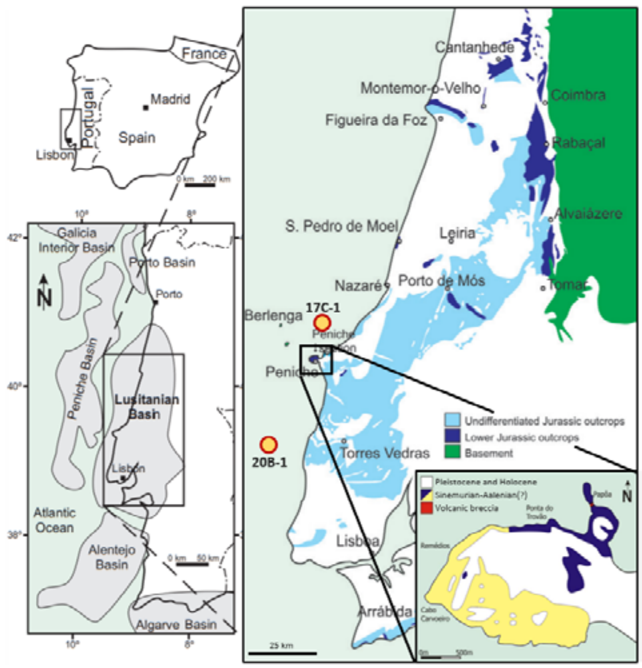


Figure 1. Simplified geological map of the Lusitanian Basin and Peniche (based on Camarate França et al., 1960; Duarte et al., 2017).

Figura 1. Mapa geológico simplificado da Bacia Lusitânica e de Peniche (baseado em Camarate França et al., 1960; Duarte et al., 2017).

located approximately 80 km to the north of Lisbon (Figura 1). It is characterized by grainstone facies, contrasting with the hemipelagic marls and marly limestones of the coeval S. Gião and Póvoa da Lomba formations generally found in outcrops from the Lusitanian Basin (*e.g.* Duarte, 1997, 2007; Duarte *et al.*, 2001). This study aims to characterize the local and regional relative heterogeneity of the upper CC5 member through an integrated stratigraphic and petrographic analysis of outcrop and offshore well data.

## 2. Geological setting

The Toarcian-Aalenian(?) Cabo Carvoeiro Formation is divided into five members (CC1 to CC5; Figura 2; Duarte and Soares, 2002; Duarte, 2007). The upper CC5 member is defined by a succession of mixed carbonate-siliciclastic sediments deposited during an overall regressive phase (Duarte, 1997, 2007; Duarte and Soares, 2002; Duarte *et al.*, 2017; see also Duarte *et al.*, 2001; Azerêdo *et al*., 2014) under the influence of ongoing tectonics associated with the Atlantic opening and active horst system leading to the progressive uplift of the Berlengas basement block (*e.g.* Wright and Wilson, 1984; Wilson *et al.*, 1989; Rasmussen *et al.*, 1998). The CC5 member has been subdivided into five informal units (CC5a to CC5e) with similar thicknesses of 40 to 45 m (Figura 2; Barata *et al.*, 2021).

Sub-units CC5c to CC5e are characterized by grainstone facies containing intraclasts (lithified carbonate fragments), ooids (micritic and quartz nuclei), bioclasts (echinoderm fragments, bivalves, gastropods and foraminifera) as well as extraclasts (quartz grains). Grain sorting is variable and clasts are generally very well-rounded (Barata *et al.*, 2021). Unlike the underlying units, no marly layers are observed (Wright and Wilson, 1984; Duarte *et al*., 2010; Barata *et al.*, 2021). The exposed units generally show planar bedding, but cross-bedding and lateral thickness variations are observed, with lateral facies variability occurring through abrupt to gradual transitions, interfingering or pinching-out geometries (Wright and Wilson, 1984; Barata *et al*., 2021). These data reflect an evolution from sedimentation in relatively low energy, deeper water environments to higher energy and shallower water environments adjacent to the uplifted Berlengas block (Barata *et al*., 2021).

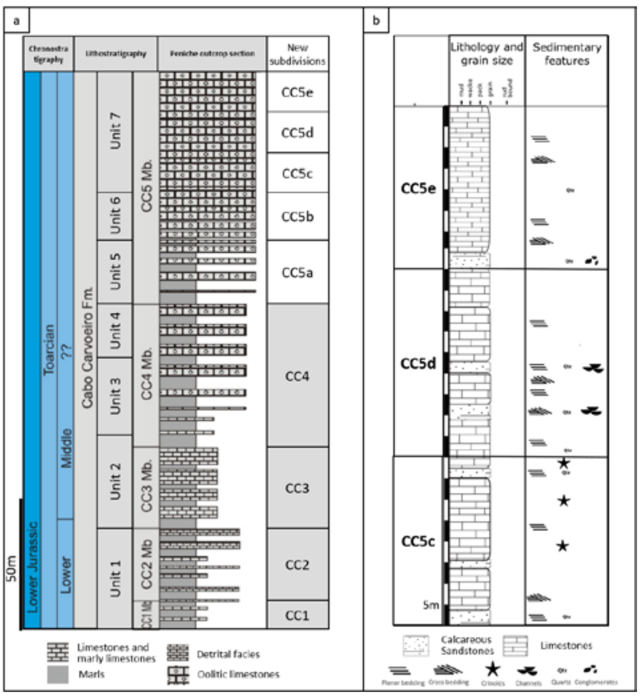


Figure 2. a: Lithostratigraphic column of the Cabo Carvoeiro Formation, showing the equivalence between the units of Wright and Wilson (1984), members of Duarte and Soares (2002) and the informal sub-units for the CC5 member (Barata et al., 2021). b: Detailed representation of the CC5c to CC5e informal sub-units.

Figura 2. a: Coluna litostratigráfica para a Fm. do Cabo Carvoeiro, mostrando a correspondência entre as unidades de Wright e Wilson (1984), os membros de Duarte e Soares (2002) e as subunidades informais do mb. CC5 (Barata et al., 2021). b: Detalhe das subdivisões informais CC5c a CC5e.

## 3. Material and methods

Outcrop analysis was carried out along an approximately 4 km sector of the western-to-southern margins of the Peniche peninsula exposing the CC5 member (Figura 3), focusing on the informal sub-units CC5c to CC5e. Depositional facies were defined in a previous study based on a semi-quantitative analysis of 107 outcrop thin sections (Barata *et al.*, 2021).

This study analyses and integrates reports, wireline logs, and cuttings from the 17C-1 and 20B-1 offshore wells (ENMC/UPEP, 1976a, b). A total of 63 thin-sections from cuttings in both offshore wells were analysed. Facies were described following the classification scheme of Dunham (1962), using modifier terms where required (*e.g.* Lokier and Junaibi, 2016). The resulting facies classification was integrated and presented in a stratigraphic correlation panel, including

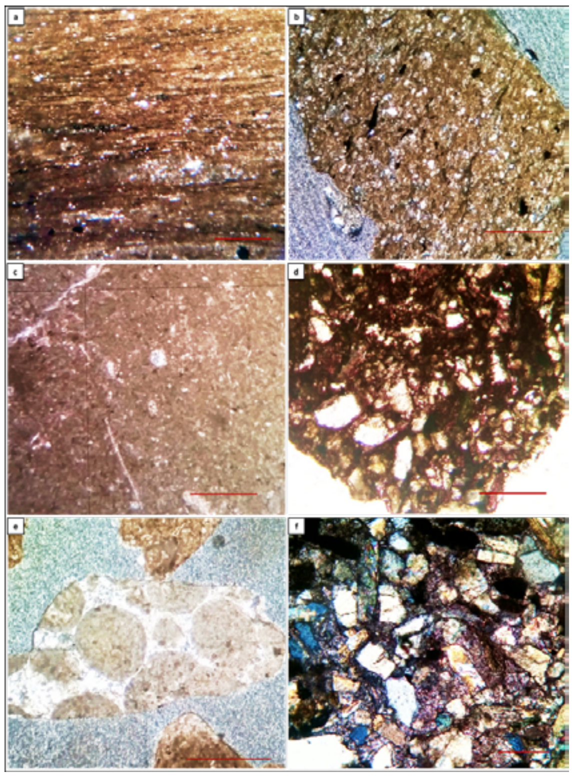


Figure 3. Samples from the 17C-1 well, showing examples of the recognized facies types. a: Laminated micritic mudstone (FTa, 1030 m); b: Weakly laminated micritic mudstone (FTb, 950 m); c: Micritic mudstone (FTc, 930 m); d: Micritic wackestone-packstone with quartz (FTd, 990 m); e: Oo-intraclastic grainstone (FTe, 830 m); f: Calcareous sandstone (FTf, 970 m). Red bars = 500 µm.

Figura 3. Amostras da sondagem 17C-1, mostrando exemplos das fácies identificadas. a: Mudstone micrítico laminado (FTa, 1030 m); b: Mudstone micrítico levemente laminado (FTb, 950 m); c: Mudstone micrítico (FTc, 930 m); d: Wackestone-packstone micrítico com quartzo (FTd, 990 m); e: Grainstone oo-intraclástico (FTe, 830 m); f: Sandstone carbonatado (FTf, 970 m). Barras vermelhas = 500 µm.

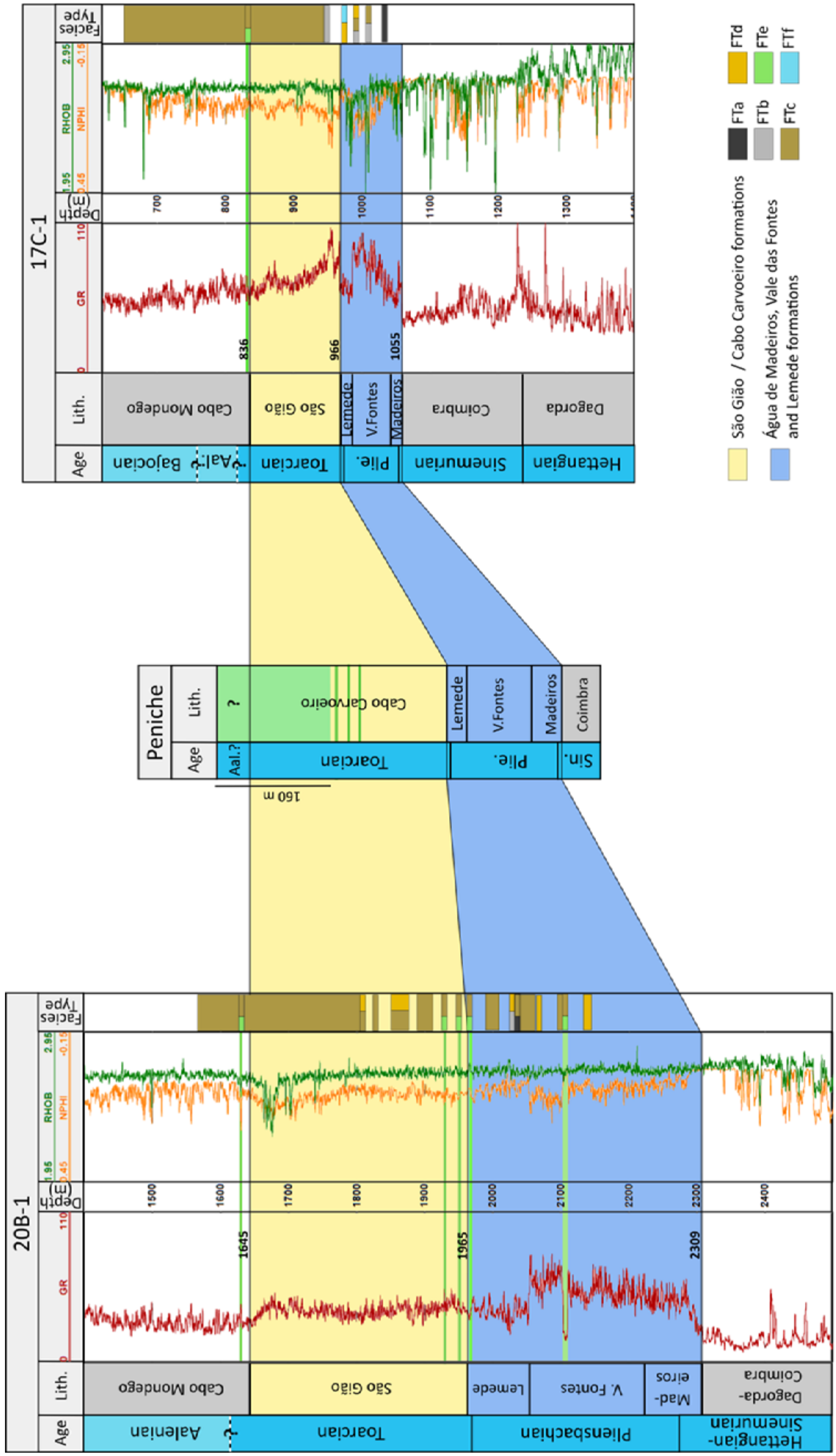


Figure 4. Outcrop to subsurface correlation panel. Lithostratigraphy based on Duarte and Soares (2002), Azerêdo et al. (2003) and Duarte et al. (2010). Pliensbachian sub-divisions in 17C-1 from Sêco et al. (2018) and applied to 20B-1 through well log correlation (ENMC/UPEP 1976a, 1976b). Madeiros: Água de Madeiros Fm.; V. Fontes: Vale das Fontes Fm. FT: facies type. See Figure 1 for locations.

Figura 4. Painel de correlação afloramento-subsuperfície. Litostratigrafia baseada em Duarte e Soares (2002), Azerêdo et al. (2003) e Duarte et al. (2010). Subdivisões do Pliensbaquiano em 17C-1 baseadas em Sêco et al. (2018) e aplicadas a 20B-1 através da correlação de diagrafias (ENMC/UPEP 1976a, 1976b). Madeiros: Água de Madeiros Fm.; V. Fontes: Vale das Fontes Fm. FT: facies type. Ver Figura 1 para localizações.

outcrop data.

## 4. Results

The intervals equivalent to sub-units CC5c-CC5e in the analysed wells generally show the presence of micritic mudstone facies, while grainstones are rare or non-existent. The petrographic analysis performed on thin-sections from cuttings from the 17C-1 and 20B-1 offshore wells allowed for the identification of facies types, which are described here.

Facies type a (FTa): Laminated micritic mudstone. Micritic mudstone texture with very thin dark-coloured laminations. Scattered, unidentifiable, silt-sized (under 16 µm) skeletal grains and a few planktonic foraminifera are observed (Figura 3a).

Facies type b (FTb): Weakly laminated micritic mudstone. Lamination is not as clear as in FTa. Micritic mudstone texture, with higher volume of unidentifiable, silt-sized skeletal grains than in FTa (coarser-sized, with 30 to 60 µm). Silt-grade coarse to sand-grade very fine quartz grains are observed (Figura 3b).

Facies type c (FTc): Micritic mudstone. Mudstone texture with micritic matrix and scattered unidentifiable skeletal grains with variable size (silt-grade to sand-grade, up to around 100 µm). Calcite-filled fractures are observed (Figura 3c).

Facies type d (FTd): Micritic wackestone-packstone. Poorly to very poorly sorted quartz grains supported by a micritic matrix (Figura 3d).

Facies type e (FTe): Oo-intraclastic grainstone. Variable relative volumes of moderately sorted sand-grade fine to coarse-sized micritized intraclasts and radial ooids. Interparticle space is fully occluded by granular to blocky calcite cements with inequigranular xenotopic crystallization fabrics. Micritized particles mostly show point-contact to no contact (Figura 3e).

Facies type f (FTf): Calcareous sandstone. Abundance of poorly-rounded, poorly-sorted, mostly fine-grained (to medium-grained) quartz grains. Contains a few identifiable micritic intraclasts and granular spar cement (Figura 3f).

## 5. Discussion

Although the analysed succession on outcrop is characterized by grainstone facies across the whole section, a relative heterogeneity has been observed and described by applying the subfacies scheme presented by Barata *et al.* (2021). Heterogeneity at a more extensive, regional scale is more pronounced, as these shallow-water, high-energy facies exposed on the Peniche outcrops are practically absent in the coeval intervals of the studied wells, where micritic mudstone facies prevail in coeval sections. In the nearby 17C-1 and 20B-1 offshore wells, north and south of Peniche, respectively (Figura 1), the observed oo-intraclastic grainstone facies type FTe are similar to the high-energy facies type FT3 of Barata *et al*. (2021) (oo-intraclastic grainstone with quartz extraclasts), which characterize the Peniche outcrops succession. However, facies type FTe occur in very limited intervals in these wells and it is only identified in cuttings originating from certain stratigraphic levels (Figura 4). Most of the interpreted Toarcian interval in both wells is generally characterized by micritic mudstone facies, with low to moderate presence of siliciclastic material. While the grainstone interval of the upper CC5 member has an estimated minimum thickness of 160 m on outcrop, in the analysed wells only thin grainstone intervals with thicknesses of less than 40 m are observed.

This regional facies variability is interpreted to be influenced by tectonic factors affecting the morphology of the basin, as well as by hydrodynamics and submarine currents (see discussion in Barata *et al.* (2021)). This succession results from localized, line-source sedimentation associated with the Berlengas basement block uplift (Barata *et al.*, 2021). The effects of this continued structural activity and uplift of the Berlengas block are interpreted to be stronger in the area closer to the Nazaré transfer fault and in the vicinity of Peniche. This is reflected in the decreasing thickness of the Pliensbachian-Toarcian interval from well 20B-1 towards Peniche and well 17C-1, to the north (Figura 4), in response to the associated decrease in overall accommodation space. In this case, the exposure and erosion of the Berlengas basement block would have been more substantial in the region closer to this transfer fault, which would result in the deposition of the eroded sediments in geographically localized fans and infralittoral prograding wedges, as observed in and around the Peniche area (*e.g.* Wright and Wilson, 1984; Barata *et al.*, 2021). However, this is a hypothesis that requires further testing.

The high-energy sediments observed at Peniche are interpreted to transition laterally and gradually into the micritic mudstones observed at the well locations, through interfingering or pinching-out geometries over moderate distances, relating to the depositional architecture of the interpreted infralittoral prograding wedge setting (Barata *et al.*, 2021). Based on the available data, the infralittoral prograding wedges characterizing the Peniche grainstone succession do not extend regionally beyond the well locations (40-45 km to the south or 15-20 km to the north).

Understanding these strong regional facies heterogeneities is of high relevance to the analysis of dynamic reservoir systems, such as in the context of petroleum systems or carbon capture and storage projects. Such variabilities potentially promote the development of stratigraphic traps, as the grainstone facies with strong reservoir potential transition laterally into the micritic mudstone facies, which would behave as baffles to fluid flow and promote the accumulation of fluids within the grainstone facies, in similarity to the scenario hypothesized for the inner ramp Middle Jurassic units towards the centre of the Lusitanian Basin (Azerêdo *et al.*, 2020).

## 6. Conclusions

The heterogeneity of the upper CC5 member of the Cabo Carvoeiro Fm. is perceived differently at different scales. A detailed subfacies scheme reveals the local relative heterogeneity of the grainstone succession. At the same time, an integrated analysis with nearby offshore well data allows for observations on the regional lateral facies variability. The grainstone facies of the Peniche outcrops change laterally into predominantly micritic mudstones at the well locations, interpreted to occur through gradation, interfingering or pinching-out geometries associated with the depositional architecture of infralittoral prograding wedges. Integrating outcrop and well data within a regional stratigraphic framework provides relevant information regarding the regional thickness variability of the analysed stratigraphic interval, which increases towards the south. This type of multi-scale integrated analysis is essential to different kinds of geological studies, such as the analysis of reservoir systems, where defining heterogeneities is vital to understanding their dynamic behaviour.

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