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Research paper

Sedimentary heterogeneity and petrophysical characterization of Barremian tsunami and barrier island/inlet deposits: The Aliaga outcrop as a reservoir analogue (Galve sub-basin, eastern Spain)

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ABSTRACT

The present study examined two sandstone deposits in the Aliaga outcrop as a reservoir analogue over a distance of 200-m-long and attempted to establish a correlation between sand facies and the petrophysical properties of the sandstones in order to investigate the reservoir heterogeneity. The Aliaga reservoir analogue represents the upper part of Camarillas Fm., deposited during the Barremian synrift phase of the Galve sub-basin (Iberian Basin, Spain). It is characterized by a transitional sedimentary interval from sandy-dominant deposits to carbonate-dominant deposits, which were deposited under the same palaeoenvironmental conditions (in relation to systems of back-barrier sedimentation).

The description of the Aliaga outcrop provided here consists of lithological descriptions of two sandstone deposits: a tsunami and a barrier island/inlet, at both mesoscopic (decimetres to tens of metres) and microscopic scales (millimetres to centimetres). Both deposits recognized at the basin scale were described in terms of sand grain size, sand sorting and cementation; further cores were drilled along outcrop to collect samples for porosity and permeability measurements.

Both sandstone reservoirs are the result of different sedimentary processes that determined facies characteristics, as the different petrophysical properties observed in these deposits. Consequently, the sedimentary process controls the heterogeneity of the sandstones facies and thus, the sand heterogeneity controls the distribution of the petrophysical properties. The classification of sand facies in terms of sand sorting seems to be more appropriate for describing sand heterogeneity; accordingly, petrophysical parameters in both deposits were also influenced by sand sorting.

The sand facies and petrophysics heterogeneity of the described deposits can be hierarchically ordered. First-order heterogeneity is related to the basin scale, second-order heterogeneity is related to genesis and the conditions of sediment deposition, and third-order heterogeneity is related to synsedimentary faults and/or post-sedimentation events.

1. Introduction

Sedimentary heterogeneity on sandstone deposits depends on the scale and the phenomenon that is been investigated (Cushman, 1997; Bachu et al., 2007; Frykman, 2009). The sedimentary heterogeneity into reservoir models are usually expressed by the distribution of low-permeability structural or diagenetic features, such as faults, breccia or deformation bands (Eaton, 2006), or by the attribution of low-permeability facies, such as mud drapes or shale layers (Asharf, 2014; Issautier et al., 2014). However, detailed studies on outcrops have showed the impact of the textural features of the reservoir sandstone, such as grain-size distribution, sorting index, net to gross (percentage of clay and/or silt) and rock texture, on the spatial distribution of the petrophysical properties, such as porosity, permeability or capillarity entry pressure (Hornung and Aigner, 1999; Klingbeil et al., 1999; Heinz et al., 2003; Sun et al., 2007; Ambrose et al., 2008; Huysmans et al., 2008; Frykman et al., 2013).

The challenge in building geological models for reservoir studies is the integration of different scales of heterogeneity with the most relevant petrophysic characteristics that impact the fluid

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flow into the reservoir (Corbett and Potter, 2004). The high resolution of sedimentary heterogeneity of reservoir or groundwater models improves the accuracy for prediction the behaviour of fluid flow, principally in clastic sedimentary systems where petrophysical parameters (porosity and/or permeability) are commonly correlated with specific sandy lithofacies (Hornung and Aigner, 1999; Heinz et al., 2003; Huysmans et al., 2008; Norden et al., 2010; Pyrcz and Deutsch, 2014). Reservoir models are often constructed at the field scale (from tens to hundreds of square kilometres) and practical limits on the size of reservoir models for post-studies of flow simulation are often imposed (AAPG wiki). The outcrop scale is a bridge between seismic and core scales, as the outcrop represents the scale of individual bedforms (metre to hundred of metres) and laminae (millimetre to metre) (Yoshida et al., 2001).

Sedimentary heterogeneity at the outcrop scale provides access to observe rock with relatively straightforward observation and sampling and with the large-scale features limited by the extent of the outcrop exposure (Pyrcz and Deutsch, 2014). The geomodel built from outcrop provides the reservoir and top seal heterogeneity and architecture, which is necessary to investigate the dynamic influence of the main intra-body heterogeneities into reservoir flow-simulation studies (Robinson and McCabe, 1997; Dalrymple, 2001; Tye, 2004; Wood, 2004; Ekeland et al., 2008). Therefore, analogous outcrop studies supply detailed geological information that can help to elucidate the geological gaps of local zones in the reservoir model, as well as they should be useful in defining the spatial variability of reservoir properties (White et al., 2004). There are some significant limitations to outcrop information. Firstly, the data is typically 2-D (Lantuéjoul et al., 2005) and present some observational bias. Consolidated rock is often preserved in outcrop while less-consolidated rocks (e.g., shales) are eroded and, if dominant, prevent the formation of outcrops in the first place. Also, weathering and unloading of the rocks may change the outcrop exposure and obscure observation of features relevant in the in situ state (Pyrcz and Deutsch, 2014).

This study attempts to investigate the correlation between the characteristics of sandy facies and their petrophysical parameters, such as porosity and permeability, at the outcrop scale in the Aliaga reservoir analogue (Early Cretaceous Galve Sub-Basin, eastern Spain, Fig. 1). Two sandstone bodies were the main targets of this study. They deposited under the same palaeogeographical context but in relation to different sedimentary processes, one representing a tsunami deposit and the other a barrier-island/inlet deposit. Both deposits were studied in detail at both mesoscopic (metre to hundred of metres) and microscopic (millimetre to centimetres) scales for identifying heterogeneities in relation with the different involved sedimentary facies. Porosity and permeability measurements were made for the different sandy facies and results are compared and discussed in the context of the sedimentary processes involved during deposition in each deposit. A discussion on the different orders of heterogeneity and their control is also included.

2. Geological setting

The Aliaga outcrop of the Barremian Camarillas Fm. studied as reservoir analogue is located in the Cretaceous Galve sub-basin, which is situated in the Iberian Chain, in central–eastern Iberia (Fig. 1A). The NNW–SSE elongate Galve sub-basin (40 km long and 20 km wide) was a western marginal sedimentation area of the Maestrazgo Basin, which was developed during the Late Jurassic–Early Cretaceous rifting that affected Iberia (e.g., Salas and Casas, 1993; Capote et al., 2002; Antolín-Tomas et al., 2007). The activity of two main fault sets, one trending NNW–SSE (e.g. the Alpeñés, Ababuj, Cañada Vellida, and Miravete faults) and the other trending ENE–WSW (the Campos, Santa Bárbara, Aliaga, Camarillas and Remenderuelas faults) (Fig. 1B) determined the Early Cretaceous extensional structure of the Galve sub-basin (Soria, 1997; Liesa et al., 2000; Soria et al., 2001; Navarrete et al., 2013a, 2014).

The structure of the studied region shows the superimposition of two mainly Palaeogene, orthogonal fold-and-thrust structural trends, one striking NNW–SSE (e.g., Aliaga-Miravete Anticline, Camarillas-Jorcas Syncline, Fig. 1C), and the other WSW–ENE (Camarillas and Remenderuelas faults, Fig. 2). Both structural trends represent the rejuvenation and inversion of normal faults, basically inherited from Mesozoic extensional and/or post-Variscan fracturing (Guimerà et al., 1996; Soria, 1997; Liesa et al., 2004, 2006). Present-day morphotectonics are the result of extensional deformation that began on the eastern margin of the Iberian Peninsula during the mid-Miocene, related to rifting in the Valencia Trough (Álvaro et al., 1979).

Synrift sedimentation in the Galve sub-basin spans the late Hauterivian to the early Albian (Soria, 1997; Soria et al., 2000; Salas et al., 2001; Liesa et al., 2004, 2006; Peropadre, 2012), and comprises the following units (Fig. 1D): (1) an alluvial and lacustrine series (El Castellar Fm.; Soria, 1997) that records the transition from initial rifting to rift climax (Liesa et al., 2006; Meléndez et al., 2009); (2) red clays and sandstones (Camarillas Fm.) recently interpreted as deposited in a transitional continental-to-marine sedimentary system. This transitional system is composed of tidal mud flat with tidal channel deposits at the base, changing upward into barrier island and lagoon deposits (Navarrete, 2015); (3) marls and limestones (Artoles Fm.) rich in calcareous algae, planktonic foraminifera and molluscs, interpreted as a shallow marine to transitional carbonate system (Salas, 1987; Soria, 1997); (4) a series of siliciclastic and/or carbonate marine platforms (Morella, Chert, Forcall, Villarroya de los Pinares and Benasal Fm.) characteristic of Aptian sedimentation (e.g., Vennin and Aurell, 2001; Peropadre et al., 2008; Peropadre, 2012); and (5) a late Aptian–early Albian transitional siliciclastic series with coal beds (Escucha Fm.; Rodríguez-López et al., 2009).

The studied sediments belong to the Camarillas Fm., which constitutes one of the most important thickest sedimentary units to be deposited in the Galve sub-basin during the Barremian synrift phase (Soria, 1997) (Figs. 1D and 2). This unit exhibits large thickness variations (150–800 m) that are related to extensional faulting (Soria, 1997; Navarrete et al., 2013a,b; Navarrete, 2015) that occurred at the climax of Cretaceous rifting (Liesa et al., 2004, 2006; Navarrete et al., 2013a).

Concretely, the studied sediments in the Aliaga outcrop are included into the upper part of the Camarillas Fm., in a transition interval with the uppermost Artoles Fm. In this interval, Navarrete et al. (2013a) distinguish two stages of back-barrier sedimentation (Figs. 2 and 3). Stage 1 is characterised by extensive back-barrier mud flat deposits, with tidal creeks and minor washover fans, interbedded with lagoonal carbonates; while Stage 2 includes washover fan deposits interbedded with lagoonal carbonates, well-developed ebb- and flood-tidal deposits and the complete absence of back-barrier tidal mud flats and associated channels.

Below the stage 1 sediments, an exceptional tsunami deposit (up to 3 m thick) has been identified and studied in detail by Navarrete et al. (2014). Its is a multiple-bed deposit made of sandstones and, locally, conglomerates that shows some fining-upwards facies successions sequences, which correspond to incursions and outflows of the tsunami wave train (Fujiwara, 2008; Navarrete et al., 2014). The tsunami sediments accumulated on onshore back-barrier mudflats with lagoon deposits covering and filling exceptionally dinosaur footprints (described below).