Marine and Petroleum Geology 68 (2015) 240–257

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Research paper

Sedimentological and isotopic heterogeneities within a Jurassic carbonate ramp (UAE) and implications for reservoirs in the Middle East

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A R T I C L E   I N F O

Article history:
Received 6 March 2015
Received in revised form
22 May 2015
Accepted 24 August 2015
Available online 2 September 2015

Keywords:
Bajocian
Musandam peninsula
Facies mosaic
Markov-chain analysis
Carbon isotope stratigraphy

A B S T R A C T

Carbonate rocks are major hydrocarbon reservoirs in the Middle East and across the world. Capturing the spatial distribution and dimensions of carbonate sedimentary facies is thus of interest for reservoir modelling and for the understanding of process sedimentology. Here we present data from a Middle Jurassic carbonate ramp outcropping on the Musandam Peninsula (Wadi Naqab, Northern United Arab Emirate of Ras-Al-Khaima), which serves as an analogue for the hydrocarbon bearing units in the subsurface of the Middle East with respect to stratigraphic age, lithofacies types, vertical stacking patterns and palaeogeographical setting. Seven closely spaced sections were logged across a 1900 × 1200 × 120 m fault-bounded outcrop offering a pseudo-3D view of the stratigraphy. Sections were correlated bed-by-bed by walking key surfaces and/or by using photopanels, to produce a detailed lithofacies map. Stable isotopes (carbon and oxygen) were measured from micrite samples in order to provide chemostratigraphic constraints. Ten lithofacies types were identified in thin sections and hand specimens, ranging from marls and mudstones to grainy oncolites and peloidal-ooidal grainstones. Beds are organised in a 'layer-cake' architecture, but individual bed thicknesses vary laterally. Lateral merging between different lithofacies types within beds is very common, resulting in a complex facies mosaic at the scale of the outcrop. Lithofacies types have a maximum probability of 40% of being continuous between logged sections with the highest frequencies of lateral variations occurring in the open, shallow part of the ramp, where maximum wave and current energy are indicated by facies. The vertical stratigraphic stacking pattern of the succession is characterised by metre-scale shoaling upwards parasequences. These are frequently capped by hardgrounds, interpreted as composite surfaces with depleted carbon and oxygen isotope values being evidence for frequent exposure during relative sea-level lowstand, followed by flooding and formation of a condensed hardground. The carbon isotope curves show a large amount of vertical 'isotope heterogeneity' reflected by meteoric diagenesis around hardground surfaces, and these are not always traceable laterally between the closely spaced neritic sections due to bias in sampling. However, if considering only the positive envelop of the carbon isotope curve and thus filtering out the meteoric diagenetic events, carbon isotope chemostratigraphy becomes possible and confirms a Bajocian age for the section. The main conclusion of the study is that maximum heterogeneity of facies at the scale of 100 m or less is expected in an environment of deposition with high wave energy. This has important implications for reservoir applications since rock facies often template flow units.

1. Introduction

Acquiring information on heterogeneities in carbonate systems helps to understand processes that govern sediment distribution within the carbonate depositional realm, and is thus crucial for subsurface applications. Multiple modern analogue studies have shown that carbonate facies distribution in the shallow marine

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http://dx.doi.org/10.1016/j.marpetgeo.2015.08.029
0264-8172/

environment can be very heterogeneous (Wilkinson et al., 1999; Rankey and Reeder, 2011; Harris et al., 2015; Purkis et al., 2015). The controlling factors on this distribution include, amongst others, sea-level fluctuations and climatic changes, changes in local hydrography and wind-energy, but also changes in carbonate precipitating biota, which are in turn controlled by their ecological requirements such as temperature, ocean chemistry and nutrient availability (Pomar and Kendall, 2007; Strasser and Védrine, 2009; Harris et al., 2015). Although modern analogues can deliver information on heterogeneities in carbonates, it remains unknown how comparable systems such as the Florida shelf or the Bahamas platform are to the vast epeiric carbonate ramps that existed, for example on the Arabian plate during much of the Palaeozoic and Mesozoic. While physical processes that govern carbonate accumulation will have remained unchanged, the main carbonate producing biota have changed through time (e.g. Pomar and Hallock, 2008), and the scale and configuration of the buildups is often very different.

Outcrop analogue studies play a crucial part in filling the gap between data provided by low vertical resolution seismic surveys, and the high-vertical resolution, 1D core analysis and are often better analogues regarding lithofacies types and the entire carbonate system, in comparison to modern analogues. Compared to siliciclastic systems however, the amount of quantitative carbonate-analogue data is still relatively scarce (Aigner et al., 2007). New studies have started to close this gap and also paved the way for more outcrop analogue research at the inter-well scale: for instance, carbonate outcrop analogue studies that include the systematic lateral mapping of facies and key stratigraphic surfaces exist from the Jurassic of Morocco (Amour et al., 2011; Christ et al., 2011), from Spain (Alnazghah et al., 2013) and from Oman and the United Arab Emirates, in the proximity of Middle Eastern reservoirs on Permian and Triassic (Zeller et al., 2011; Ahmadzamri et al., 2014) and Cretaceous outcrops (Immenhauser et al., 2004; Vaughan et al., 2004; Sattler et al., 2005; Grélaud et al., 2006, 2010; Rameil et al., 2010; Adams et al., 2011; Sena and John, 2013). No comparable studies have been published yet on outcrop-analogues for Jurassic reservoirs of the UAE, Qatar or Saudi Arabia, despite the fact that Jurassic carbonate reservoirs in the Middle East are of major economic importance (e.g. Alsharhan and Nairn, 1994, 2003; Sudarsana et al., 2009).

Analogue studies using outcrops sometimes suggest that ancient carbonates are preserved in a 'layer-cake' type architecture where pinch out and facies heterogeneities are rare (e.g. Borkhataria et al., 2005; Zeller et al., 2011; Pratt et al., 2012; Bendias et al., 2013), whereas in other examples large amounts of facies heterogeneity is documented, even on a relatively small scale and especially within shallow water depths (e.g. French and Kerans, 2004; Sattler et al., 2005; Bádenas et al., 2010; Amour et al., 2011; Christ et al., 2011; Alnazghah et al., 2013; Sena and John, 2013; Brandano and Loche, 2014). In this study, we focus on inter-well scale facies distribution within outcrops of Middle Jurassic shallow-water ramp deposits at Wadi Naqab, Emirate of Ras-Al-Khaima (UAE). Our work in Ras-Al-Khaima on a relatively small inter-well scale (1900 × 1100 × 120 m) outcrop allows us to capture sedimentological as well as isotopic heterogeneities, and provides the first published evidence of the complexity of facies distribution within Jurassic carbonate ramps of the Arabian Peninsula. The objectives of this study are to 1) provide new and quantitative constraints on the bedding and facies heterogeneities in an inner to middle ramp in the Middle East; 2) explore the links between facies distribution and process sedimentology in this setting, i.e. what controls the facies heterogeneities within carbonate ramps of the Middle East?; and 3) assess the vertical and lateral heterogeneity as well as usefulness of carbon isotopes as a chemostratigraphic constraint in this type of setting.

2. Geological setting

The outcrop is located close to the entrance of Wadi Naqab, which lies 13 km southeast of the city Ras Al-Khaimah in the Musandam Mountains (GPS coordinates of the outcrop: N 25° 42′ 20.1″; E 56° 03′ 15.5″).

The Musandam Mountains form the northern extension of the Oman Mountains and are composed of ~3 km-thick shallow-water carbonates (Maurer et al., 2009). The eastern margin of the Arabian Plate was tectonically passive during the Permian and the Mesozoic, but this period of quiescence was interrupted by two tectonic events, one during the Late Cretaceous when ophiolites were obducted, and the second one during the Plio- and Pleistocene when the Oman and Musandam Mountains were formed (Searle, 1988; Glennie, 2005). From the Cenozoic onwards the eastern margin of the Arabian platform is in an active continental setting and the plate is being subducted beneath the Eurasian Plate (Sharland et al., 2001).

The Jurassic section on the Musandam peninsula has a stratigraphic thickness of approximately 1300 m and forms the Musandam Group. It is divided in the Musandam Formation 1 to 3, for the Lower, Middle and Upper Jurassic respectively (Fig. 2). The Jurassic sedimentary record is near enough complete except for parts of the Toarcian and the Aalenian and the Tithonian (de Matos, 1997; de Matos and Walkden, 2000). The rock units were deposited in shallow water conditions on the northern margin of the Arabian Peninsula, with an open marine connection to the Neo-Tethys Ocean (Fig. 1B). This small oceanic basin was connected to the Palaeo-Tethys and was located between the Afro-Arabian platform in the southwest and a microcontinent in the northeast (de Matos, 1997; Glennie, 2005). The entire sedimentary package in Wadi Naqab extends in age from Permian in the eastern end of the wadi to Cretaceous at the wadi entrance in the west. The Bajocian section alone expands over 550 m (de Matos, 1997). Bajocian-aged strata partly crop out in a 'block' bound to the south and west by wadis and on its eastern side by an abandoned quarry. The Bajocian age was assigned by de Matos (1997) based on benthic formaminifera, stromatoporids, algae and on a single, equivocally classified ammonite. The studied stratigraphic interval can be examined in pseudo three-dimensions (Fig. 1C). The Cretaceous package overlies the Late Jurassic rocks at Wadi Naqab with a faulted contact, but no other obvious unconformity is visible within the sedimentary succession (de Matos, 1997).

3. Materials and methods

3.1. Field and petrographical analysis

Seven sections were measured around the Wadi Naqab 'block' outcrop, thus giving insight on the 3D distribution of facies (Fig. 1C). The stratigraphic thickness of sections ranges between 70 and 133 m. Four sections were logged on the eastern face of the outcrop within the abandoned quarry. One section was measured on the southern side of the outcrop and one on the other side of the wadi road also to the south of the 3D outcrop. The seventh corresponding log was produced on the western face of the outcrop. In total the study window covers an area of 1900 by 1200 m (Fig. 3). The Bajocian-aged rocks were logged bed-by-bed and examined in the field for their sedimentary features, fossil assemblages and texture. Textural classification of facies followed Dunham (1962) and Embry and Klovan (1971). The position of each section was mainly determined by the accessibility along the outcrop and the possibility to log it. A surface was chosen as reference datum (hardground II, top