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Research paper

Origin of the rudstone–floatstone beds in the Upper Jurassic Arab-D reservoir, Khurais Complex, Saudi Arabia

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ABSTRACT

Detailed description and analysis of cores from more than 50 wells through the Kimmeridgian Arab-D reservoir (Arab-D Member and upper part of the Jubaila Formation) in Khurais, Abu Jifan and Mazalij oil fields, are used to establish a consistent depositional model that represent a shift in the conceptual understanding of the Upper Jurassic carbonates of Saudi Arabia. The Jubaila Fm and Arab-D Mb conform to a shallowing upward carbonate-evaporite succession, in which three main carbonate facies-belts occur, capped by anhydrite.

The lower facies belt corresponds to the Jubaila Formation and consists of a series of eventites triggered by breaking internal waves; interbedded peloidal wackestones represents the background sedimentation, where neritic lime mud was churned by pellet-producing benthonic fauna. Eventites consist of a lower intraclastic rudstone–floatstone interval, a middle grainstone–packstone interval, and an upper barren mudstone interval. The middle facies belt is made of microbial-coral-stromatoporoid buildups. The upper facies belt consists of the following shallow water lithofacies with *Cladocoropsis*, green algae, foraminifers, peloids and oolitic grainstones, and oolitic cryptomicrobial mudstone to grainstone.

The stacking patterns of the internalites (internal wave deposits) in the Jubaila Fm suggests alternating periods with different internal waves activity, namely different strength and bathymetric position of the pycnocline, and intermittent production and accumulation of the neritic lime mud.

This interpretation represents a change to previous interpretations (turbidites and tempestites) and has important implications in both the perceptions of depositional processes in play, and the criteria behind stacking lithofacies into parasequences and sequences.

1. Introduction

Interbedded mudstone–wackestone, grainstone–packstone and floatstone–rudstone beds mostly comprise the upper part of the Jubaila Formation, in the lower part of the Arab-D reservoir Kimmeridgian) in Saudi Arabia. Commonly with erosive base and vertical grain-size differentiation, the rudstone/floatstone beds reflect the occurrence of episodic turbulence events (eventites, *sensu* Seilacher, 1982) in a depositional environment dominated by low-energy, mud-dominated sedimentation. These eventites consist of oncolitic–intraclastic-skeletal rudstone–floatstone with grainstone to packstone matrix.

The origin of these eventites and consequently the source of turbulence, have remained contentious. Some authors have favored storm-induced flows (Mitchell et al., 1988; Lindsay et al., 2006) or storm-induced turbiditic flows (Meyer and Price, 1993; Al-Awwad and Collins, 2013), whereas Meyer et al. (1996) and Lindsay et al. (2006) have proposed a combination of storms and base-level falls induced by sea-level cyclicity to explain the rhythmic nature of the lithofacies stacking pattern.

Among eventites, the sediments indicating the effects of turbulence events (Seilacher, 1982, 1991), tempestites and turbidites are the most frequently recognized, although internal wave deposits – referred to hereafter as internalites (Pomar et al., 2012) – are been increasingly recognized. As a product of turbulence events, the origin of the eventites share 1) an erosional phase – reflected by a basal erosion surface – and 2) a subsequent depositional phase that represents waning of the episodic turbulence.

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Differences between eventites derive from the different nature of the turbulence process and the resulting association of sedimentary structures.

Surface storm waves (SSWs) and associated currents (Ager, 1974) scour the coast and the shallow parts of the shelf, causing the eroded sediments to preferentially move in the direction of the prevailing wind. Seaward-directed, near-bottom currents may also locally develop on shorefaces associated with storms, causing sediment erosion and entrainment in near-coastal settings, which might lead to the formation of tempestites in deeper settings (Immenhauser, 2009). Fain et al. (2007) have suggested sediment transport in low-energy seas occurs primarily along-shelf, in the shallow water zone, with little cross-margin transport; whereas in higher energy environments, sediment resuspension and transport is subjected to stronger downwelling. As the wind strength decreases and the associated flows wane, sediment will be deposited across the shelf. The coarser sediment is deposited in erosional features and the fines are deposited where the waning storm surge was not strong enough for erosion Aigner, 1979).

Turbidites, which originate from turbidity currents (TC) in oceans and lakes, are inherent components of modern deep-sea fans, adjacent to the base of continental slopes in passive margins, and they are also found associated with river deltas. Turbidites are also common in ancient deep-water sandstone systems exposed in thrust-fold belts and other tectonically active settings, commonly associated with other types of gravity flows and contourites (Mutti and Ricci-Luchi, 1972; Shanmugam, 2000; Mutti, 1992). Turbiditic currents can move long distances downslope and are also common deposits associated with piggyback basins where they moved along the axis of the basin. Although several turbidite facies models exist, including other types of sediment-gravity flows (e.g., Bouma, 1962; Normark, 1970; Mutti and Ricci-Lucchi, 1972; Mutti, 1975; Walker, 1978; Stow and Shanmugam, 1980; Lowe, 1982; Shanmugam, 2000), the gradational character and internal structures are commonly related to the waning and waxing of flow modes. Sedimentation is seen as the result of flow deceleration in both time (waning of the catastrophic surge-type triggering event) and space (lateral expansion of the density flow or a change in the bathymetry gradient). The coarser lower portion of each cycle is interpreted to reflect deposition from the head and tail while fines represent deposition by settling of fines from suspension.

The impact of internal waves (IWs) in the sedimentary record has remained largely unrecognized until recent times (e.g., Baird and Brett, 1986; Gao and Eriksson, 1991; Gao et al., 1998; He and Gao, 1999; Shanmugam, 2003; He et al., 2008; Pomar et al., 2012), despite the fact that internal waves are ubiquitous in most oceans and lakes (Apel et al., 2007). Progressive increase of interest in internal waves has been induced by their impact in anthropogenic activities (acoustic modifications, movement of remotely operated vehicles and divers, submarine wrecks, large stresses on offshore oil-drilling rigs, etc), and by scientific interest (dissipation of tidal energy, mass transport and momentum, turbulence and mixing in the thermocline, vertical exchange of nutrients and heat, distribution of larvae, across-shore transport of plankton and contaminants, etc.) (Inall et al., 2001; Apel, 2002; Scotti and Pineda, 2004; Jackson and Apel, 2004). Yet, studies on the impact of internal waves on sediment re-suspension and transport are still not very abundant.

Internal waves arise by perturbations that disturb the hydrostatic equilibrium between gravity and buoyancy at the pycnocline. Perturbation can be caused by storms, wind-stress fluctuations, tsunamis, interaction of tidal currents with topography, and other processes that are still poorly documented (Staquet and Sommeria, 2002; Santek and Winguth, 2007). In contrast to tempestites and turbidites, internal waves create episodic high-turbulence events and remobilize the sediment at the depth where the pycnocline intersects the sea floor. This depth commonly occurs at mid-shelf settings — when pycnocline is dependent on seasonal thermocline — or deeper on the continental slope — when dependent on the permanent thermocline (LaFond, 1962; Thorpe, 2005; Butman et al., 2006). Difficulties in recognizing internalites arises from their potential mixing with turbidites on slopes and basins, and the potential mixing with tempestites in shallower settings. Nevertheless, in carbonates the distinction is more conspicuous owing to the bathymetric dependence of many carbonate constituents.

The differentiation between the types of eventites is important to precisely reflect the geologic architecture and its impact in the reservoir plumbing system (Fig. 1). For example, in a storm-dominated shelf, tempestites would form layers that thicken updip to the shoreface lithofacies. In a turbiditic system the best permeability layers would occur in sequences whose stacking reflects the organization of lobes and channels, but would be detached from the shoreline lithofacies. In an internalites shelf model, grainy permeable layers would occur in sets, detached from the shoreline and encased in mid-ramp muds.

This paper analyzes the eventite beds in the upper part of the Jubaila Formations and lower part of Arab-D Member and proposes they are internal wave deposits, to latter discus the implications on the sequence development in the lower part of the reservoir, and the bearing of this on reservoir correlation models. Outcomes of this study could potentially be implemented in future three-dimensional modeling of porosity, permeability, diagenesis, structural and other petrophysical parameters within the reservoir, and guide reservoir production and management efforts.

The study uses a data set of more than 50 cored wells from the Khurais Complex, located about 160 km east of the Saudi capital, Riyadh. Khurais, Abu Jifan, Mazalij and adjacent fields are referred to as the "Khurais Complex", a term that used to refer to the industrial complex that was built, in 2008 to process the hydrocarbon production of these field and later became synonymous with them (Fig. 2). Cores were described at a high-resolution, 10-cm scale, to capture subtle lithofacies variations, break down key geologic factors and processes that caused these variations and determine how they interacted to control the paleoenvironment of deposition. Analysis of numerous thin sections complemented this study, which was carried out in Saudi Aramco's Exploration Core Laboratories, Dhahran, Saudi Arabia and in the laboratories of the University of the Balearic Islands, Palma de Mallorca, Spain.

2. Geological setting and stratigraphy

Oil was discovered in Saudi Arabia in the Upper Jurassic Arab Formation, the world's most prolific oil-bearing interval, in 1938 (Barger, 1984; Sorkhabi, 2008; Stegner, 2007). The Upper Jurassic clean grainstones of the Arab-D limestone forms the major oil-producing reservoir in a number of super-giant fields on the Arabian plate (Durham, 2005). The excellent porosities and permeabilities of the Arab-D are sandwiched between organic-rich mudstones of the Jurassic Hanifa and Tuwaiq Mountain formations below and the non-porous anhydrite seals of the Arab and Hith Formations above (Durham, 2005). The remarkable lateral extent of the Jurassic source-reservoir-seal sandwich is what makes the Arabian plate's petroleum system unequaled (Sorkhabi, 2010). Arabian Jurassic oils were trapped in expansive structural traps, such as the En Nala anticline of the Ghawar Field, the world's largest oil field, and the Khurais-Burgan Anticline of Khurais Field, Saudi Arabia's second largest onshore oil field, which were charged by extensive areas of source rock (Alsharhan, 1993; Sorkhabi, 2011). These structures are characterized by gentle dips, which make