Quantitative Sedimentological and Structural Study of a Lower Cretaceous Analogue Outcrop, Qishn Formation, Central Oman*

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Abstract

Outcrops of the Barremian-Aptian Qishn Formation in the Huqf region are laterally continuous over at least 1 km, and minimally deformed, providing geometric information on sedimentary systems and system tracts at the inter-well scale. These carbonates could be excellent outcrop analogues for the Upper Kharaib and Lower Shu’aiba oil reservoirs in the Interior Oman basins.

The study focuses on the facies geometries and fracture patterns of shallow-water carbonates in a shallow burial context. It presents outcrop-based quantitative data of facies and fractures distribution from a 1,000 m long and 500 m wide butte in a sequence stratigraphic framework. A bed-by-bed sampling of six 30 meters-thick outcrop sections provides material for geochemical and petrographic analysis. Fractures were measured on a 1,500 m window and whenever possible, on bedding planes, and their type, orientation, spacing were studied.

The stratigraphic architecture shows a general layer-cake pattern. Two types of grainstone bodies were recognized based on their different geometries and positions in the depositional profile. The high-energy subtidal shoal facies present a high degree of vertical and lateral heterogeneity. One-meter thick by tens of meters wide cross-stratified rudstones pass laterally into tabular floatstones and rudstones. Tidal flats beds are laterally irregular, as they are occasionally cut by 10 meters wide 30 cm deep storm scours infilled with carbonate mud.

Quantitative data on fracture distribution reveal that lithology has acted as a major control on fracture density. Mudstone and wackestones present widely spaced sets of non-stratabound fractures whereas grainstones are saturated with stratabound fractures of a single set only.

The outcomes of this study could be used to reduce uncertainties on facies geometries and fracture distribution of storm influenced peritidal carbonate models. This study is part of the Qatar Carbonate Carbon Storage Center funded jointly by Qatar Petroleum, Shell and the Qatar Science & Technology Park.
II. Quantitative sedimentological study

ii.a. Sequence stratigraphy

- Discontinuity surfaces
  - Section O
  - Section R
  - Section C1
  - Section C2
  - Section M
  - Sequence types
  - Facies associations
  - Interpretation

Facies of FA2 and FA1: evolution from oyster floatstones (O) to high-energy gravestones (H6) to Facies TA5 and TB5.

Facies of FA5, well-developed coral biostrome grading into a bioturbated oolitic rich packstone clogged by wackestones with increasing amounts of reworked material and decreasing oolitic content.

Facies of FA6: high diversity fauna wackestones coarsening up to wavy and thin-beded gravestones.

Facies of FA2: fluviatile with open marine fauna (H6) grade into cross-stratified grainstones (H5) clogged by floatstones and rudstones (H4 and H6) and occasionally preserved thin lenses of nites in situ (H5).

Catch-up sequence composed of intertidal facies overlie by supratidal facies, records a complete proggradation facies sequence with occasional phases of erosion.

Catch-down sequence composed of an incomplete shallowing-upward succession of subtidal facies subby submarine erosion; records a truncated progradational facies sequence.

Catch-down sequence composed of subjacent facies overlie by supratidal facies and characterized by the absence of intertidal facies, records an incomplete progradational facies sequence.

Give-up sequence composed of deep subtidal facies deposited below the FWB and above the SMB; the lithofacies succession records gradually increasing subtidal influence as the platform shoaled.

Give-up sequence composed of shell subtidal facies deposited below the FWB, the carbonate sand bar propagation is followed by stabilization and development of rudists biostromes that are reworked and deposited in the vicinity of the bar.

II.b. Quantitative distribution of heterogeneities

1. Shoal Complex

- Shoal bodies modeled in Petrel

- Block diagram to scale showing subtidal dunes distribution

- The shoal complex is composed of discontinuous shoal bodies embedded in offshore facies.
- We recorded 10 symetric to slightly asymmetric carbonate sand waves roughly migrating to the SW.
- The thicker and wider shoal bodies are interpreted to be related to periods of high accumulations and high carbonate system dynamics.

2. Storm scours

- Conceptual shape with size ranges

- 11 storm scours were identified on marine erosion surfaces.
- Scours are interpreted to be substrate incisions formed by high-energy currents during storms and to get infilled by carbonate sediment during the waning phases of storms.
- The widths and thicknesses of storm scours occurring in the same depositional environment are linearly correlated.

3. Depression infills

- Conceptual shape with size ranges

- 20 depression infills were identified on subaerial exposure surfaces.
- Depression infills are interpreted to be dissolution features on tidal flats created during subaerial exposure that got infilled by carbonate mud during the following transgression.
- Depression infills are clustered and their widths and thicknesses are poorly correlated.
III. Quantitative fracture study

III.a. Fracture characteristics

1. Orientations

The fractures are extentional and subvertical. They take two forms:

Stratobound joints
- closely spaced joints trend NW-SE and are constrained to individual beds from the 5th and 6th facies;
- most of the stratobound joints are closed but some have mm-scale apertures infilled with calcite cement or micrite mud.

Throughgoing joints
- throughgoing joints strike in several directions but predominantly to the N-S;
- throughgoing joints develop in thick mechanical units composed of several beds;
- most of the throughgoing joints are closed but some are infilled with calcite cement.

Plan view showing stratobound joints

Plan view showing the hook geometry of one joint terminations

Rose diagram of orientations for throughgoing joints

III.b. Quantification of the distribution of fractures

1. Fracture saturated beds

Histogram of spacing for stratobound joints from N140 set

Suggested petrography of the grain-supported facies at the time of fracturing (Aptian-Albian)

Microphotographs of the 5th facies:
- Marine bioclastic limestone
- Marine equidistant calcite cement
- Fossil assocaited with sea SA

Brazilian test for the grain-supported facies

Tensile strength, Moller&Hawkes (1971)
- Tensile strength, D: t: dimensions of the core P: Maximum load
- Grain-supported rock tensile strength
  \[ \sigma = 0.65 \times 10^6 \text{ MPa} \]
- Mud-supported rock tensile strength
  \[ \sigma = 2.09 \times 10^6 \text{ MPa} \]

Using the link between spacing distribution and fracture saturation established by Rives et al. (1992) and the study of the diagenetic history we draw the following conclusions on the fracture's density relationship with lithology:

- The joint spacing distribution of the stratobound joints fits a log-normal distribution law. The grain-supported beds are saturated with respect to extensional fractures of the N140 set.
- The joint spacing distribution of the throughgoing joints fits a negative exponential distribution law. The thick mechanical units composed of mud-supported and grain-supported beds are undersaturated with respect to extensional fractures.
- During the Aptian, grain-supported facies are cemented and the number of grain boundaries and the competence of the beds is increased. The mud-supported facies was, on the contrary, little altered by diagenesis and remained ductile.
- The tensile strength measured on present day lithologies show that grain-supported rocks accommodate less strain than mud-supported rocks and deform in a brittle manner.

2. Fracture under-saturated beds

Histogram of spacing for throughgoing fractures from the N75 set

Petrography of the mud-supported facies at the time of fracturing (Aptian-Albian)

Microphotograph of the Or facies:
- Shell fragments
- Micrite

Brazilian test for the mud-supported facies

III.c. Timing of fracture development

The same joint system was observed at Wadi Baw and Wadi Jarrah and their distribution is not affected by folds and faults (Bertotti et al., 2005). These systems are related to a regional rather than local stress fields and therefore have a regional character as already argued by Bertotti et al. (2005).

The extensional fractures that trend N140 were formed under a low horizontal differential stress when the least compressive stress c3 was oriented NE-SW. Compatible with this interpretation is the occurrence of a fold within the study area, with an axis oriented NE-SW and interpreted to be associated with Late Cretaceous NNW-SEE shortening related to the northwards migration of the Indian plate.

The extensional fractures that trend N190 were formed later, under a larger horizontal differential stress when the least compressive stress c3 was oriented W-E. The development of these fractures are associated with a N-S shortening that can relate to the emplacement of the Sakib Arch or to the opening of the Gulf of Aden during the Cenozoic.

Figure 3: Simplified geological map of the Haushi-Huf area adapted from Piel et al. (1994). Dominant fracture sets measured in this study are indicated.

- In the Lower Cretaceous perritidal environment of the Neo-Tethys ocean, sediment redistribution processes, mainly by storms, result in inter-well scale heterogeneities.
- Inter-well scale heterogeneities comprise carbonate sand dunes of a subtidal shoal complex, storm scours and depression infills occurring at erosional and exposure discontinuity surfaces.
- Fracture spacing and orientation is strongly controlled by the primary facies and subsequent diagenesis.

III.d. Conclusions and recommendations

Conceptual distribution of heterogeneities

Discontinuity surfaces
- 8
- 300 m
- 3.5
- 20 m
- Facies sequence types
- Subtle Strike-slip sequences
- Hostatal Surfaces such as reservoirs
- Subtle orientational stick-slip sequences

Fracture sets
- N140
- N75
- N190
- NW
- SW

Features such as:
- linear features and faults
- Fracture orientation (N-S)
- Figure 4: Distribution of fracture sets.