Seismic Expression of Karst-Related Features in the Persian Gulf and Implications for Characterization of Carbonate Reservoirs*

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Abstract

Karstification can have a positive and negative effect on carbonate reservoirs. For example, dissolution during karstification can enhance inter- and intra-granular porosity and permeability, whereas cave collapse can generate mega-pores and completely alter reservoir geometry and continuity. Karst may also pose challenges to drilling due to the unpredictable and highly variable porosity and permeability structure of the rock, and corresponding difficulty in predicting drilling mud-weight. Some of the largest karst-related features are imaged by seismic reflection data, thus they can be mapped directly, improving carbonate reservoir characterization and allowing development of safer drilling programs. In this study we use time-migrated 2D seismic reflection data to determine the distribution, scale and genesis of karst in a 3 km thick, Jurassic-Miocene carbonate-dominated succession in the Persian Gulf. We map 34 near-circular karst features on the top-Turonian regional unconformity that marks the top of the Upper Cretaceous Sarvak Formation. These sinkhole-like features are 0.8–10.2 km in diameter and 15–80 m deep, and are onlapped by overlying Coniacian strata, thus constraining their age. Additional subsidence, driven by differential compaction above in the stratigraphic succession overlying the sinkholes, occurred until the Early Miocene. We interpret that a 1100 m thick poorly imaged interval developed immediately below the sinkholes is related to subterranean collapse or poor seismic imaging below the highly geologically and geophysically heterogeneous karstified surface. There is no relationship between sinkhole diameter and depth, suggesting that the sinkholes did not widen as they deepened. Instead, the distribution of sinkholes along pan-African fault trends or around salt domes suggest a formation mechanism of cave collapse associated with fluid movement along pre-existing fault or fracture networks. These data indicate that seismic-scale karst features may be deep, wide and areally widespread at specific stratigraphic levels, suggesting that sub-seismic-scale karstic features may be even more widespread. Our study indicates that seismic reflection data can and should be used to determine the extent and scale of karstification with the specific aim of improving the characterization of carbonate reservoirs.
1. Introduction

- Karstification positively and negatively impacts the quality of carbonate reservoirs.
- Dissolution can enhance inter- and intra-reservoir connectivity.
- Caves collapse can generate megapore systems.

2. Methods

- The study utilizes time-migrated 2D seismic reflection data to determine the distribution, scale, and genesis of karst in a 3 km thick, Jurassic-Miocene carbonate-dominated succession in the Persian Gulf.
- Reflection events were tied to well data from two nearby wells, IMD-1 and IE-1, to improve carbonate reservoir characterization and allow development of safer drilling programs.

3. Results

- The results show the presence of karst-related features, including caves and collapse structures, which widen and deepen downward.
- The features are distributed at depth, with eventual cavern collapse forming collapse structures.

Figure 3: Tectonostratigraphic column showing the units of interest in the Permian-Cretaceous.

**Overall Structure***

- **Stage I**: The Triassic section is made up of the Indosinian, Bathonian, and Callovian stages.
- **Stage II**: The Jurassic section consists of the Toarcian, Aalenian, and Bathonian stages.
- **Stage III**: The Cretaceous section includes the Aptian, Albian, and Cenomanian stages.

**Detailed Structure***

- **Stage I**: The Triassic section is characterized by the Indosinian, Bathonian, and Callovian stages.
- **Stage II**: The Jurassic section consists of the Toarcian, Aalenian, and Bathonian stages.
- **Stage III**: The Cretaceous section includes the Aptian, Albian, and Cenomanian stages.

**Event Curves***

- **Stage I**: The Triassic section is made up of the Indosinian, Bathonian, and Callovian stages.
- **Stage II**: The Jurassic section consists of the Toarcian, Aalenian, and Bathonian stages.
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**Marker Depths***

- **Stage I**: The Triassic section is characterized by the Indosinian, Bathonian, and Callovian stages.
- **Stage II**: The Jurassic section consists of the Toarcian, Aalenian, and Bathonian stages.
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**Topography***

- **Stage I**: The Triassic section is made up of the Indosinian, Bathonian, and Callovian stages.
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- **Stage III**: The Cretaceous section includes the Aptian, Albian, and Cenomanian stages.

**Erosion***

- **Stage I**: The Triassic section is characterized by the Indosinian, Bathonian, and Callovian stages.
- **Stage II**: The Jurassic section consists of the Toarcian, Aalenian, and Bathonian stages.
- **Stage III**: The Cretaceous section includes the Aptian, Albian, and Cenomanian stages.

**Deposition***

- **Stage I**: The Triassic section is made up of the Indosinian, Bathonian, and Callovian stages.
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**Sequence Boundaries***

- **Stage I**: The Triassic section is characterized by the Indosinian, Bathonian, and Callovian stages.
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- **Stage III**: The Cretaceous section includes the Aptian, Albian, and Cenomanian stages.

**Deposit Types***

- **Stage I**: The Triassic section is made up of the Indosinian, Bathonian, and Callovian stages.
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- **Stage III**: The Cretaceous section includes the Aptian, Albian, and Cenomanian stages.

**Significance***

- **Stage I**: The Triassic section is characterized by the Indosinian, Bathonian, and Callovian stages.
- **Stage II**: The Jurassic section consists of the Toarcian, Aalenian, and Bathonian stages.
- **Stage III**: The Cretaceous section includes the Aptian, Albian, and Cenomanian stages.

**Implications***

- **Stage I**: The Triassic section is made up of the Indosinian, Bathonian, and Callovian stages.
- **Stage II**: The Jurassic section consists of the Toarcian, Aalenian, and Bathonian stages.
- **Stage III**: The Cretaceous section includes the Aptian, Albian, and Cenomanian stages.

**Conclusion***

- The study highlights the importance of understanding karst-related features in carbonate reservoirs for improved reservoir characterization and drilling safety.

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**References***

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**Supplementary Information***

- **Stage I**: The Triassic section is characterized by the Indosinian, Bathonian, and Callovian stages.
- **Stage II**: The Jurassic section consists of the Toarcian, Aalenian, and Bathonian stages.
- **Stage III**: The Cretaceous section includes the Aptian, Albian, and Cenomanian stages.
3. Results Cont’d.

- Using detailed contour maps (Figure 8) and line-by-line inspection of the dataset, we highlight several features.
  - Features expressed as vertical, sub-circular columns of chaotic reflections capped by downslope-decreased depresions that are imprinted on overlying strata, spanning the Jurassic to Upper Cretaceous succession (Figure 9).
  - Top Maastrichtian deflections are typically located vertically above the largest deflection features (Figure 12).
- Weak positive correlation between the width and depth of features on each specific horizon (Figure 11), top Aptian features > top Turonian features.
- Weak correlation between the width and depth of features on each specific horizon (Figure 11), top Aptian features > top Turonian features.
- The arrows mark the point where the lines cross. Both uninterpreted and interpreted lines are shown. The feature deforms horizons from the top Maastrichtian-deflections are typically located vertically above the largest deflection features (Figure 12).
- Top Maastrichtian deflections are typically located vertically above the largest deflection features (Figure 12).

![Graph showing the variation in depth of the features with changing width, on the top Maastrichtian reflection. Weak correlation between width and depth is noted. The red circle indicates the depth at which the features are located.](image)

![Map showing the thickness variation in the top Callovian-top Turonian seismic package between the top Callovian and top Turonian reflections.](image)

![Map showing the Thinning of the seismic package between the top Callovian and top Turonian reflections (Figure 13, see also Figures 9 and 10) observed beneath the feature.](image)

- Figures 9 and 10 are marked by black boxes. Similar thinning observed in the seismic package between the top Callovian and top Turonian reflections (Figure 14, see also Figures 9 and 10).

![Map showing the Thinning of the seismic package between the top Callovian and top Turonian reflections (Figure 13, see also Figures 9 and 10).](image)

![Map showing the Thinning of the seismic package between the top Callovian and top Turonian reflections (Figure 14, see also Figures 9 and 10).](image)

- Overlain black stars in part (b) indicate the locations of mapped pipe-like features, correlating to areas of Maastrichtian depression. Larger features have associated Maastrichtian depressions (Figure 14 above, right).
3. Results Cont’d.

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- Features most common in the southern part of the dataset, close to the South Pars Field (Figure 15, see also Figure 14).
- Three subtle linear trends are observed on Figure 15, associated with faults A and B (Figure 16) and fault K (Figure 17).

Figure 16: Top structure map of the Top Rhaetian reflection, with associated fault cuts marked in pale grey. Structures discussed in the text are arrowed and labeled. Black stars mark the locations of mapped pipe-like features.

5. Conclusions & Implications

- Features are collapse sinkholes, formed by three phases of epigenetic karstification.
- Phase 1: generated caverns c. 300m below the contemporaneous free surface that collapsed to form sinkholes in overlying strata and enlargement and weight removal.
- Phase 2: Exposure of the pre-Palaeocene surface at Late Turonian to end-Aptian (Figure 18) increased the width and depth of the sinkholes at these levels.

3. Results Cont’d.

- Weak relationship between sinkhole density and pre-existing tectonic features suggesting that faults acted as conduits to focus fluid flow at depth.
- Karstification can have both a positive and a negative effect on the porosity and permeability of a reservoir:
  - Positive effect: increased porosity and permeability due to dissolution and collapse of caverns.
  - Negative effect: reduction in porosity and permeability due to dolomitization and cementation.

4. Interpretation

- Features are collapse sinkholes, formed by three phases of epigenetic karstification.
- Phase 1: generated caverns c. 300m below the contemporaneous free surface that collapsed to form sinkholes in overlying strata and weight removal.
- Phase 2: Exposure of the pre-Palaeocene surface at Late Turonian to end-Aptian (Figure 18) increased the width and depth of the sinkholes at these levels.

5. Conclusions & Implications

- Results of integrated micro- and macro-scale seismic, and well-log analyses indicate the presence of variable scales of karst features present in the study area.
- Karst features are distributed across all lithofacies, with the most significant features observed in the Upper Sarvak Formation.
- Karst features are associated with major tectonic structures, such as faults and anticlines, and their distribution is controlled by the tectonic framework of the studied area.
- Karst features have implications for reservoir development and exploration, including porosity and permeability enhancement and reduction, as well as potential reservoir connectivity and flow pathways.

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- References:

In summary, 43 pipe-like zones of detected and downwarped discontinuous events are observed in the dataset, extending from the top Callovian to the top Turonian reflection events. Occasionally these zones and the associated downslope reflection are expressed at the top Maastrichtian reflections, a vertical distance of 1600-2100 m. On the top Turonian and top Aptian reflections there is no weak linear relationship between dip angle and dip angle density, although the features are, on average, wider and deeper on the top Aptian reflection than on the top Turonian reflection. In summary, and becomes shallower upwards. The width-depth relationship is less pronounced on the top Turonian reflection and is not present for the features at the top Callovian reflection. Marked thinning occurs in the Jurassic section beneath the pipe-like features.