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Environmental and sequence stratigraphic implications of anhydrite textures: A case from the Lower Triassic of the Central Persian Gulf

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ABSTRACT

The Lower Triassic Kangan Formation in the Persian Gulf (South Pars Gas Field) and its adjacent areas are composed of carbonate–evaporite sequences. These sediments were deposited in a shallow marine homoclinal ramp. Study of the anhydrite-bearing intervals shows various structures and textures. The anhydrite structures are mainly bedded, massive, chicken-wire and nodular type and the main textures are felted, sparse crystal, needle shape, lath shape, equant and fibrous. Pervasive and poikilotopic cement together with replacement and porphyroblastic gypsum are accounted as the most common diagenetic features in anhydrite. Evaluation of anhydrite occurrences and features support both primary and secondary formations. The nodular to chicken-wire anhydrite formed under synsedimentary sabkha conditions, whereas anhydrite cements occurred during the late stages of diagenesis (shallow burial stage). Massive to bedded anhydrite could have been formed under subaqueous conditions or originated by coalescing and continued growth of anhydrite nodules in the sabkha zone. Anhydrite fabrics impose a significant control on the reservoir quality of the Kangan carbonates at the South Pars Gas Field. Thick massive and bedded anhydrite could have been formed as an intraformational seals and anhydrite cements occluded pore spaces and reduced the poroperm values. The sequence stratigraphic analysis revealed two depositional sequences in the studied intervals, which are composed of TST and HST. Investigation of anhydrite throughout depositional sequences indicates a change in the content and style of anhydrite texture. Anhydrite content (volume) decreases upward through transgressive system tract (sea-level rise) whereas, it enhances during highstand system tract (sea-level fall). Pervasive and poikilotopic anhydrite cements together with replacement by anhydrite are prevalent features during transgressive and early highstand system tract. At the late HST, with a progradational stacking pattern, anhydrite value increases and felted, radial, equant, crystalline and mosaic texture are the most common anhydrite fabrics. Sequence boundaries that indicate maximum sea level fall and exposure of successions are marked by the broad anhydrite deposits with massive to bedded and chicken-wire structures and various textures that located in late HST package. There is an unambiguous relationship between the microfacies associations, the evaporite textures, and the sea-level fluctuations. This relationship could lead to a predictable pattern that can be of use as a general guide for the sequence stratigraphic interpretations in the area.

1. Introduction

Evaporite deposits provide efficient seals for many hydrocarbon reservoirs and yield a wealth of paleogeographic, paleoclimatic and paleoenvironmental information. They commonly occur interbedded with carbonates and form an important component of the stratigraphic section in the Iranian portion of the Middle East. In spite of their abundance and close association with hydrocarbon-bearing carbonate reservoirs, there are very few studies that combine the description and occurrence of evaporite textures, with a sequence stratigraphic interpretation.

Anhydrite fabrics (including structures, textures and diagenetic features specially anhydrite cements) have influenced the reservoir quality of Permo-Triassic carbonates of Upper Dalan–Kangan formations, the main reservoir at the South Pars Gas Field, offshore Iran. More than 60% of the reservoir rocks in this supergiant gas field are dolomitic that are associated with evaporites (Ehrenberg, 2006; Rahimpour-Bonab et al., 2010). These anhydrites that occur in close association with the above mentioned dolomites, reflect the influence of hypersaline depositional conditions on both calcium sulphate precipitation and dolomitization (Ehrenberg,

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2006). The anhydrite component can have a negative effect on reservoir quality in tidal-flat, lagoonal and shoal environments. However, Lucia and Ruppel (1996) and Lucia (1999) noted that replacive nodular and poikilotopic anhydrite had only a minor influence on poroperm values in the South Cowden carbonates (West Texas). Lucia et al. (2004) showed that anhydrite fabrics might enhance reservoir quality, as well. Therefore, appraisal of effects of anhydrite fabrics on reservoir quality is significant and complex. On the other hand, excellent hydrocarbon accumulations occur in many ancient evaporite-related basins. Seals and traps of such accumulation are, in many cases, controlled by the stratigraphic distribution of carbonate–evaporite facies transitions (Sarg, 2001). Evaporites may occur in each of the systems tracts within the depositional sequences. This depositional system responds to relative sea-level changes in different ways (Emery and Myers, 1996; Catuneanu, 2002, 2006). The study of sequence stratigraphy provides information on the depositional environment, sea-level fluctuation and hydrology of restricted basins (Tucker, 1991). Several authors have studied diagenesis, sedimentary environment and sequence stratigraphy of the Permo-Triassic succession (Dalan and Kangan Formations and their equivalents in the Arabian platform) (e.g. Al-Jallal, 1995; Strohmenger et al., 2002; Alsharhan, 2006; Ehrenberg et al., 2007; Insalaco et al., 2006; Moradpour et al., 2008; Maurer et al., 2008, 2009; Peyravi et al., 2010; Esrafili-Dizaji and Rahimpour-Bonab, 2009; Koehrer et al., 2010, 2011; Rahimpour-Bonab et al., 2009, 2010; Tavakoli et al., 2011), but very few studies were focused on the evaporite textures and their relationships with the sea level fluctuations. The main goal of this paper is to present a case study that defines the relationships between anhydrite fabrics and the sequence stratigraphy of the Kangan Formation.

2. Geological setting and stratigraphy

In Iran, evaporites are present in the sedimentary successions of four major horizons: (1) Hormoz series of Precambrian age; (2) Permo-Triassic deposits (Upper Dalan and Kangan Formations); (3) Upper Jurassic deposits, and (4) Tertiary evaporites (Nabavi, 1976; Darvishzadeh, 1991; Rahimpour-Bonab et al., 2007). The Lower Triassic Kangan Formation (Stratigraphic committee of Iran, 1976; Szabo and Kheradpir, 1978) is mainly composed of carbonate (limestone and dolostone) and evaporite successions in the Persian Gulf and adjacent areas (Fig. 1a and b). The shallow marine carbonate–evaporite of Kangan Formation were deposited over Dalan Formation and covered by Dashtak Formation. The Upper Dalan along with Kangan Formations compose a single reservoir, which is the largest non-associated gas reservoir of the world (containing around 20% of global gas conventional reserves) (Rabbani, 2001; Aali et al., 2006). A regional unconformity, which separates the Dalan from the Kangan Formation, shows important changes in the depositional conditions (Szabo and Kheradpir, 1978; Kashfi, 1992; Sharland et al., 2001; Rahimpour-Bonab et al., 2009). During the Permo-Triassic time interval, due to sea-level fluctuations, a thick sequence of carbonate associated with evaporites accumulated in these areas (see Fig. 2).

The South Pars Gas Field formed during regional epirogenic movements of the Qatar Arch. This field and its southern extension, the North Dome, are part of the huge NNE–SSW trending Qatar Arch structural feature. The Qatar arc is a large regional high that has had a fundamental influence on the tectonic pattern of the Gulf. The Arch is located in the interior platform of the Arabian Plate and bounded by the Zagros folded belt to the north and northeast. This uplifted arch has influenced the geology of the region since Palaeozoic times and divided the Persian Gulf into two distinct sedimentary basins, one to the northwest and the other to the southeast, each with its own sedimentary regimes and styles of hydrocarbon reservoirs (Sharland et al., 2001). This basin is composed of the lithostratigraphic units that include the source rocks and reservoirs of Late Permian and Early Triassic age, as well as some cap rocks (Aali et al., 2006).

Stratigraphic successions similar to the carbonate–evaporite units of the Kangan Formation occur in many parts of the world (especially in the Middle East and the Persian Gulf area). These successions may form good reservoirs or seals in the different intervals. More or less similar successions from the Persian Gulf and Zagros area are Fars Group, Sachun Formation and Umm Er Radhuma Formation at Tertiary, the Upper Jurassic Arab Formation and the Hith Anhydrite. The worlds comparable examples include the Ordovician Bauman, the Ordovician Red River Formation of the Williston Basin, the Devonian of Western Canada and Western Australia, the Permian of West Texas, the Zechstein in the North Sea area and the Jurassic sedimentary rocks of the Gulf of Mexico (Alsharhan and Kendall, 2011). Warren and Kendall (1985) and Warren (2006) proposed evaporative sabkhas of the Trucial Coast as a modern analogue for these types of successions.

3. Paleogeography and paleoclimatology

During the Late Permian to Middle Triassic time, a new passive margin developed in Neo-Tethys. The Arabian Plate is interpreted as an essentially peneplaned ENE-dipping platform (Ziegler, 2001). With the northward drift of the Plate, low-latitude warming occurred (Ziegler, 2001). The paleolatitudes for the Khuff platform were about 20–25°S for the Late Permian and 20–17°S for the Early Triassic (Stampfli, 2000; Angiolini et al., 2003; Insalaco et al., 2006). This places the platform in an arid to semi-tropical climatic belt. Moreover, this suggests that at a large-scale, the Upper Khuff system evolved from a more arid system during the Late Permian, to a more sub-tropical climate during the Early Triassic as the system drifted northwards (Insalaco et al., 2006).

On the other hand, geological evidences (e.g. Parrish, 1993) and modeling studies (e.g. Wilson et al., 1994) suggest that the Late Permian to Early Triassic was a time of global climate change from icehouse to greenhouse mode (e.g. Al-Jallal, 1995; Kidder and Worsley, 2004; Brayard et al., 2006; Galfetti et al., 2007). Thus, at this time, the climatic setting was warm and arid and evaporative-hypersaline conditions may have been widespread (such as present day Persian Gulf) (Strohmenger et al., 2002). Similar to the other parts of the Middle East, the Late Permian to Early Triassic sedimentation in the Persian Gulf took place in a shallow marine environment (Berberian and King, 1981; Alsharhan and Naim, 1997; Alsharhan, 2006; Insalaco et al., 2006). These conditions are attested by domination of evaporite–carbonate platforms, abundance of anhydrite and early evaporite-related dolomite (Alsharhan and Kendall, 1994; Insalaco et al., 2006; Maurer et al., 2008, 2009; Koehrer et al., 2010, 2011). Alsharhan and Kendall, 2003 suggested that the arid conditions during the Late Permian and Early Triassic times and the association of dolomite and anhydrite indicate hypersalinity and sabkha conditons.

4. Methods and materials

This study is based on the data from four exploration appraisal wells in the South Pars Gas Field. More than 700 samples were collected at intervals ranging from 0.3 to 1 m, from which stained thin sections were prepared for petrographic studies. All thin sections were half-stained with Alizarin Red-S and blue dyed. Facies associations and their depositional environments were determined based on the core and petrographic criteria and comparison with