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Fracture and in-situ stress patterns and impact on performance in the Khuff structural prospects, eastern offshore Saudi Arabia

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A B S T R A C T

We characterized natural fractures and in-situ stresses for exploration and prospect evaluation in nine periclinal structural traps, in the Eastern Province of Saudi Arabia, where several major gas discoveries were made in the deeply buried, Permian–Triassic Khuff Formation. Borehole image logs, oriented cores, seismic, gravity-magnetic data, and dynamic observations were used in the study. Two fracture systems were identified: a younger, major system, which enhances reservoir permeability and an older, minor, fully mineralized system. The older system consists of subordinate northerly striking extensional mesofractures, including joints and faults, which are fully mineralized by anhydrite and calcite. This mineralization occurred during an early diagenetic-phase. This system acted as paleo-fluid conduits, facilitating the occlusion of matrix porosity and deteriorating the reservoir quality in the immediate vicinity of the fractures. The younger system is regionally dominant, and includes mesofractures with persistent strike ranging from NE–SW to ESE–WNW irrespective of local structure. These younger fractures are nearly parallel to the present day maximum horizontal in-situ stress and perpendicular to the minimum horizontal in-situ stress, which are dominated by the Zagros plate tectonics. The development of this system commenced during the convergence of the Arabian and Eurasian plates (Late Cretaceous to Cenozoic) and culminated during the continental collision. The fractures are predominantly extension joints and hybrid (extensional-shear) fractures, and were facilitated by increases in pore pressure due to the oil placement and the subsequent cracking of this oil into gas. Hydrocarbon migration into the Khuff reservoirs was crucial in slowing down diagenesis and preserving both fracture apertures and matrix porosity. Therefore, most of the fractures in this system tend to be partly mineralized, mainly by carbonates, and/or coated with hydrocarbons. These fractures show channel-type apertures that enhance permeability and productivity of the Khuff by up to two fold. The channel apertures can endure operational changes in reservoir pressure with little or no reduction of their permeability. Critically stressed open fractures have no major role. Geomechanical analyses show that they are estimated to occur under the upper limits of differential stresses, within the margin of error of stress estimates. The static and dynamic observations show the permeability and productivity enhancement follows mechanical layering patterns. Production and pressure profiles in individual wells indicate lack of vertical communication (seal breach) across the different reservoir units. Similar pre-production pressure and hydrocarbons across the Khuff reservoir units is the result of normalization over geological time. Hydrocarbon migration across the anhydrite seals happened via episodic paleo-seismic pumping along faults with no sufficient vertical offset to permanently breach the reservoir seals.

1. Introduction

1.1. Study area

This study covers the Khuff reservoir in nine offshore structural traps of the Eastern Province of Saudi Arabia (Fig. 1).

1.2. Khuff carbonate reservoir (upper Permian to lower Triassic)

The Khuff carbonate reservoir is part of the Khuff Formation, which consists of shallow-water cyclic carbonate rocks (reservoirs) and evaporite rocks (seals). The reservoir is the deepest buried carbonate reservoir in the Arabian platform. It extends geographically beyond the study area (Al-Jallal, 1989), and within the Arabian plate as a whole it is estimated to hold in excess of 20% of the world non-associated gas reserves (Ameen et al., 2010). In the study area

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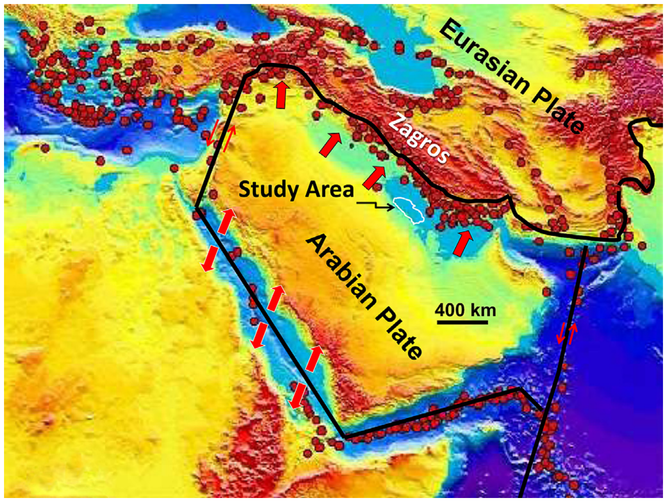

Figure 1. Location of the study area (solid white line) superimposed over the Arabian Plate. Solid black lines indicate plate boundaries, red arrows indicate plate relative movement, and red dots indicate surface locations of epicenters of earthquakes along the plate boundaries. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the Khuff is divided in the subsurface, into four members: Khuff A, B, C, and D, from younger to older, respectively. Khuff C and D are of Permian age; Khuff A and B are of Triassic age (Ameen et al., 2010, Fig. 2). The formation represents the earliest period of major carbonate sedimentation caused by marine transgression on the Arabian plate onto a vast, east-facing, arid ramp. This commenced with the Late Permian rifting along the Zagros (opening of the Neotethys Ocean) and continued into the Early Triassic. For detailed description see the comprehensive work done on both outcrop and subsurface sections (Powers et al., 1966; Al-Jallal, 1989, 1995; Al-Dukhayyil, 1997; Wender et al., 1998; Al-Eid, 2000; Ziegler, 2001; Al-Aswad, 2007).

The source rock for the gas and condensate in the Khuff reservoir in Saudi Arabia is the basal organic-rich hot shale of the Qusaiba Member of the Silurian Qalibah Formation (Carrigan et al., 1998; Worden et al., 2004). The non-associate gas in the Khuff is produced by simple depletion drive. The gas is produced by expansion of the gas. The onshore Khuff reservoir has weak aquifer support and includes condensates in some traps (Ismail M. Buhidma, personal communication, 2013). However for the offshore traps, we do not have enough production history to make that assessment.

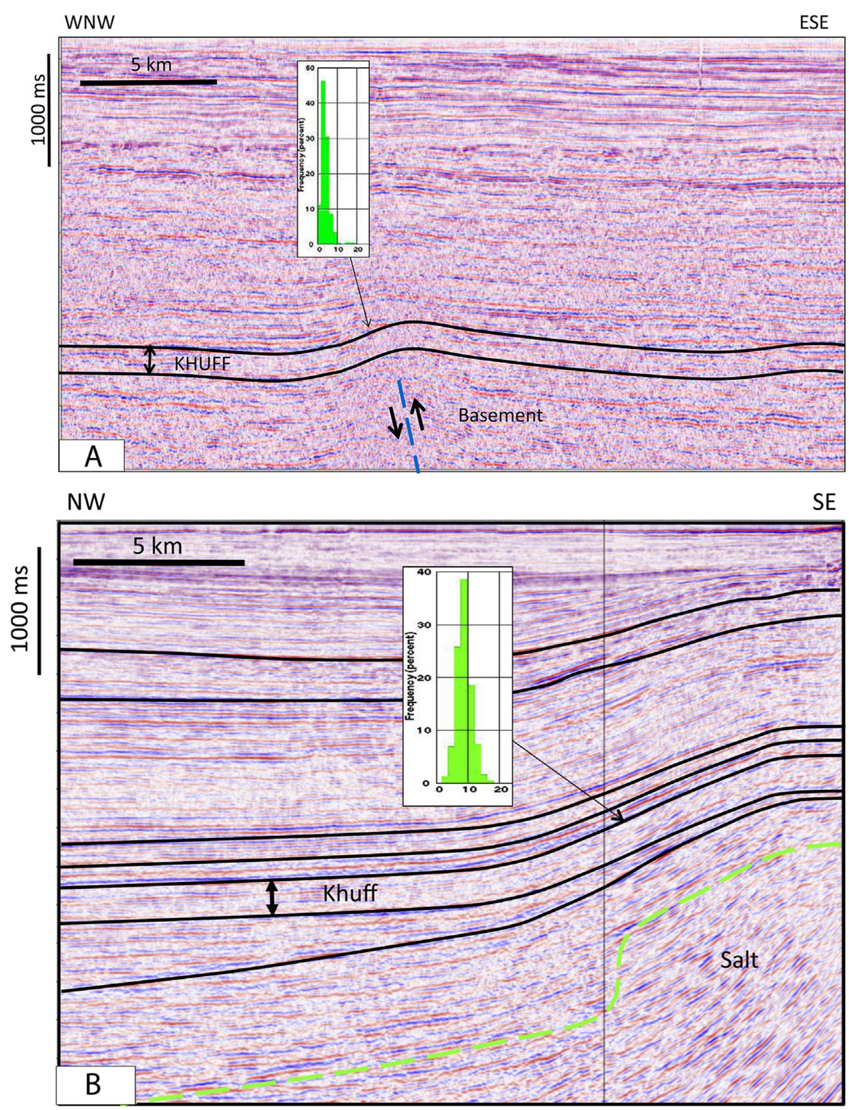

Figure 2. Traveltime, seismic cross sections of gentle, basement-rooted fold (A) and salt-cored periclinal fold (B) structural traps in the Khuff reservoir. The histograms show the structural dip of the steep limbs within the Khuff sequences.