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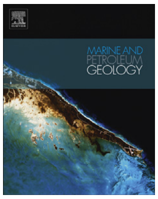

Research paper

# Fracture patterns and petrophysical properties of carbonates undergoing regional folding: A case study from Kurdistan, N Iraq

Abdullah Awdal [a, *], David Healy [b], G. Ian Alsop [b]

[a] GeoScience Limited, Falmouth Business Park, Bickland Water Road, Falmouth, Cornwall, TR11 4SZ, United Kingdom
[b] Department of Geology and Petroleum Geology, School of Geosciences, University of Aberdeen, Aberdeen, AB24 3UE, United Kingdom

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ABSTRACT

The Zagros-Taurus fold and thrust belt hosts a prolific hydrocarbon system. Most hydrocarbon reserves are stored in naturally fractured reservoirs and such fracture systems can therefore have a significant impact on reservoir performance. Fractures are one of the most important paths for fluid flow in carbonate reservoirs, and industrial geoscientists and engineers therefore need to understand and study fracture patterns in order to optimise hydrocarbon production. The observed fracture patterns in outcrops may have implications on fluid flow and reservoir modelling in subsurface reservoirs, and we have therefore undertaken a case study of fracturing associated with regional folding in Iraqi Kurdistan. In this area, some exploration wells currently target Upper Triassic dolostones (Kurra Chine Formation) and/or Lower Jurassic limestones and dolomitised limestones (Sehkaniyan Formation). In both units hydrocarbon production comes mainly from secondary porosity created by dolomitisation, dissolution and fracturing. Both formations have undergone multiple phases of deformation associated with burial, uplift, folding and thrusting. We investigate some fracture pattern characteristics and some petrophysical properties of these units using selected outcrops around the Gara, Ora and Ranya anticlines that form folds directly traceable for 25–70 km. Our outcrop data is compared with subsurface fracture and petrophysical datasets reported from wells in the nearby Shaikhan and Swara Tika Fields. The 1-2-3D fracture attributes collected from outcrops are fracture orientation, type, spacing, intensity, length and cross-cutting and abutting relationships. Fracture orientations show a clear relationship to the local fold axis in both the outcrop and subsurface, although in some cases they appear to relate more to the present day *in-situ* maximum horizontal stress direction or local strike-slip faulting. Three stages of fracturing are proposed: pre-folding, early-folding and post-folding fractures. In addition, we report petrophysical properties - porosity, permeability and acoustic velocity of both the Kurra Chine and Sehkaniyan formations in relation to their structural position within folds and faults and stratigraphic level. The highest porosities and permeabilities are recorded in the hinges and backlimbs of the Gara Anticline. The best reservoir quality (highest porosity and permeability) is often found in areas associated with replacement dolomite i.e. solution vugs and intercrystalline porosity. The Kurra Chine Formation displays similar trends in velocity-porosity data at both outcrop and the subsurface. However, the Sehkaniyan Formation displays lower acoustic velocity for a given porosity at outcrop compared to the subsurface.

## 1. Introduction

Fractures are one of the most important paths for fluid flow in carbonate reservoirs. Natural fracture systems can have a dramatic impact on reservoir performance and can act as permeable flow conduits or as baffles and seals (Bourne et al., 2000; Agosta, 2008). Outcrop analogue studies can improve understanding of some aspects of fracture distributions and their influence on fluid flow in fractured reservoirs (e.g. Antonellini and Mollema, 2000; Aydin, 2000; Nelson, 2001; Stephenson et al., 2007; Lacombe et al., 2011) and their influence on petrophysical properties such as porosity and velocity (Nemati and Pezeshk, 2005; Healy et al., 2015). However, the scaled outcrop data should be used with care in order to improve reservoir modelling and constrain uncertainties (Sharp et al., 2006; Wennberg et al., 2006; Barr

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[*] Corresponding author.
*E-mail address:* awdal@geoscience.co.uk (A. Awdal).

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et al., 2007; Lapponi et al., 2011). For example, the processes that have affected fracture generation at outcrop such as uplift, gas expansion, and erosion would not have occurred at depth, and is not therefore relevant to deeper reservoirs.

The Zagros mountain belt is a prolific petroleum province with several producing oil and gas fields (e.g. Cooper, 2007). Numerous outcrop analogue studies of fractured reservoirs have been undertaken, describing fracture patterns in the Zagros fold and thrust belt, especially in Iran (e.g. Wennberg et al., 2006; Ahmadhadi et al., 2008; Stephenson et al., 2007; Casini et al., 2011; Lacombe et al., 2011; Tavani et al., 2011). Reservoirs are mainly fractured carbonates developed at a variety of stratigraphic levels. Many studies show that fracture pattern is controlled by mechanical stratigraphy and petrophysical properties such as porosity (e.g. McQuillan, 1973; Huang and Angelier, 1989; Underwood et al., 2003; Nemati and Pezeshk, 2005; Wennberg et al., 2006). In a study of folded carbonate units in SW Iran, Wennberg et al. (2006) suggest that the spatial distribution of fractures is a multivariate problem, where fracture attributes such as orientation, length, spacing and apertures are functions of position within the fold, sedimentary texture and mechanical bed thickness. Fracture patterns could also be controlled by the evolution of fluid pressures during burial and evolution of the stress field during unroofing (uplifting).

The fracture patterns and petrophysical properties of potential carbonate reservoirs are investigated within Iraqi Kurdistan, as represented by the Sehkaniyan Formation (Lower Jurassic) and the Kurra Chine Formation (Upper Triassic) (Fig. 1a, b, 2). The outcrop fracture datasets are mainly collected in E–W trending structures and nearby subsurface oil fields. These localities are chosen because of the outcrop exposures of the studied units. In this paper, we focus on the potential control that regional anticlines may exert on the fracture patterns and petrophysical properties of folded and fractured carbonates. Reservoir units are analysed in outcrops around regional folds comprising the Gara, Ora and Ranya anticlines, and in the subsurface within the Shaikhan and Swara Tika oil fields (Fig. 1a, b). The Gara Anticline is studied because it is regarded as viable outcrop analogue to the nearby Shaikhan and Swara Tika fields, whereas the Ora and Ranya anticlines were selected as supplementary outcrops as they exhibit good exposures of the Kurra Chine and Sehkaniyan formations, respectively.

## 2. Geological setting

### 2.1. Tectonics

The Zagros-Taurus fold and thrust belt is situated along the NE margin of the Arabian Plate. It has developed as a consequence of the oblique collision between the Arabian and the Eurasian plates (Homke et al., 2004, 2009), reflecting gradual closure of the Neo-Tethys Ocean mainly during Late Cretaceous–Cenozoic times (Talbot and Alavi, 1996). The onset of Arabian–Eurasian plate collision, and associated folding and thrusting of the Zagros Orogeny started in the Oligocene and is still active (Fard et al., 2006). The Zagros orogenic belt in Kurdistan can be divided into five distinct structural zones, that from the NE hinterland to the SW foreland, and are named the: Zagros Suture, Imbricated Zone, Highly Folded Zone, Foothill Zone and Mesopotamian Foreland Basin (Jassim and Goff, 2006) (Fig. 1a). The Imbricate and Highly Folded zones are characterised by major surface-breaching, mainly SW-verging thrust-related anticlines, whereas major folds above blind thrusts characterise the Foothill Zone (Awdal et al., 2013). The orientation of fold axes in the study area varies from NW–SE Zagros (e.g. Ranya Anticline) to WNW–ESE Taurus trends (e.g. Gara and Swara Tika anticlines) (Fig. 1b).

The structural style of the Zagros-Taurus fold and thrust belt in Iraqi Kurdistan is characterised by thin- and thick-skinned tectonics (Kubli and McKenna, 2013), and is segmented due to the interaction of the exposure level and variations in decollement levels along strike (Granath and Odell, 2014). The stratigraphy is dominated by competent to incompetent carbonate units interbedded with detached intervals of incompetent siliciclastic rocks often bearing evaporite beds. The main thin-skinned detachment levels occur in the Lower Fars (Neogene), the Gercus-Kolosh (Palaeogene), the Jurassic, and the Baluti (Upper Triassic). In addition, thick-skinned detachment levels are likely to occur at one or more deeper levels within the Palaeozoic (e.g. Ora Shale) (Granath and Odell, 2014). This stratigraphic architecture sets up a structural style composed of ramps cutting across the competent carbonates, and flats running along incompetent units (Al-Breefkani, 2008; Granath and Odell, 2014). Duplexes are formed by a group of ramps and comprise narrow repeated fault slices that build structural relief. The floor thrust is the lower detachment below the duplex, whereas a possible passive roof fault is the upper detachment which isolates the duplex from an overlying carapace of less deformed rocks (Al-Breefkani, 2008; Granath and Odell, 2014). In south-eastern Iraqi Kurdistan, the surface structures are decoupled from the more complex subsurface structures by multiple thrust sheets. Folding, faulting and uplift of early formed thrust sheets took place during progressive structural thickening of the orogenic wedge. The orogenic wedge itself is characterised by a stack of nappes and hinterland-dipping, connecting splay duplexes (Banks, 2013). Basement blocks are possibly involved in the thick-skinned tectonic phase and there is most likely reactivation along some of the pre-existing Late Cretaceous extensional faults (Kubli and McKenna, 2013).

Gara and Shaikhan are asymmetrical double-plunging anticlines with N-directed vergence and WNW–ESE and E–W orientated fold axes, respectively. Conversely, Swara Tika is an asymmetrical double-plunging anticline (i.e. pericline) with S-directed vergence and a WNW–ESE orientated fold axis. The Ora Anticline is an asymmetrical, cylindrical and open fold with S-directed vergence and E–W orientated fold axis. The Ranya Anticline is asymmetrical with NE-directed vergence and a NW–SE oriented fold axis. The Gara, Ranya, Shaikhan and Swara Tika anticlines are all located within the Highly Folded Zone, whereas the Ora Anticline is positioned within the Imbricated Zone of the Zagros-Taurus fold and thrust belt. These anticlines display a range of geometrical similarities and differences, in terms of structural styles and fractured reservoir characteristics.

### 2.2. Stratigraphy

The studied stratigraphic units are the Upper Triassic Kurra Chine and Lower Jurassic Sehkaniyan formations (Figs. 1b and 2). Both units are considered as good reservoirs in recent discoveries within Kurdistan, and contain hydrocarbons within the Shaikhan, Atrush and Swara Tika fields (Fig. 1a, b). The subsurface equivalents to the Sehkaniyan Formation in Iraq are the Alan, Mus and Adaiyah formations (van Bellen et al., 1959) (Fig. 2).

The Kurra Chine Formation was deposited during the Late Triassic within the Kand and Qara Chauq sub-basins of northern Iraq (Sadooni, 1995). The Kurra Chine Formation is assigned to the Kand Basin (Carnian-Norian) which covers an area of 10,000 $km^2$ in northern Kurdistan (Sadooni, 1995). Well data indicates a maximum sediment thickness of up to 1000 m in the basin. The thickness is varied in outcrops and this variation is possibly due to dissolution of evaporite beds (Aqrawi et al., 2010). Sedimentation