Structural Evolution Model for the North Kuwait Carbonate Fields and its Implication for Fracture Characterisation and Modelling

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Abstract

This paper presents a new structural model for the North Kuwait Carbonate fields as well as its implications in term of fracture modelling and field development. It also describes a workflow which can be used as foundation for further fracture modelling study at production and exploration scales alike. This workflow consists of a four step approach: 1) elaboration of a regional structural model, 2) creation of 3D conceptual fracture diagrams, 3) elaboration of constraints capturing the key elements of the conceptual diagrams and 4) creation of fracture model properties for further dynamic simulation. The application of this workflow resulted in the creation of a series of fracture models for the North Kuwait Carbonates fields. During the first step of the study, a new structural model has been elaborated based on key kinematic observations from well and seismic data, as well as experimental and field analogues which have been linked to the known regional phases of deformation. These main phases of deformation are 1) post Triassic rifting, 2) Alpine 1 - late Cretaceous transtension and 3) Alpine 2 - Mid Tertiary compression related to the Zagros formation, which has the greatest impact on the formation of the pre-Gotnia structures and fracture development. The major difference between the new model and previous structural thinking is that the formation of the compressional folds in the Carbonate fields (an event that shaped the current outline of the fields) has happened during the Tertiary time instead of Jurassic time. The proposed structural evolution has been used to define characteristic structural domains. These structural domains have defined a foundation to elaborate conceptual fracture diagram to support fracture modelling study work. The fracture conceptual models have potential implications on fracture development and preferred direction of horizontal and deviated wells. Greater fracture connectivity is expected in compressional ridges developed in Tertiary time, while in the area between the compressional ridges, less dense fractures and probably more cemented fractures (likely to have developed before hydrocarbon emplacement) are expected. The new view on the timing of the structural development (i.e., late uplift of compressional ridges regionally) also has possible implications on maturation/charge history as well as reservoir properties development. The new proposed model for structural evolution is now being used as a foundation for appraisal and fracture modelling activities of the pre-Gotnia carbonate reservoirs. A fracture characterisation study integrating all available static and dynamic data is ongoing.

Introduction

Kuwait Oil Company (KOC) is currently engaged in aggressively developing the challenging tight carbonate reservoirs (Figure 1) of North Kuwait spread over an area of approximately 1700 sq.km. A paradigm shift in field development process was adopted for tackling these hitherto less developed plays. These North Kuwait reservoirs are characterized by low porosity (average < 5pu), low permeability (average <0.1mD) and occur in deep (> 13500ft depth), HP/HT (average 11000psi/280°F) sour conditions. Though dolomitization improves reservoir characteristics in parts of the area, natural fractures play a dominant role in aiding production from these reservoirs. Hydrocarbon fluids in these reservoirs range from near critical gas-condensate to volatile oil. A detailed interpretation and integration of log, core, and seismic data helped in refining the depositional model. Due to the early life cycle stage of these fields, concurrent appraisal and development of all the fields is ongoing, and a phased development plan has been adopted by KOC as the appropriate development strategy. This allowed KOC to focus on the initial objectives of early assessment of potential in Phase I and to integrate the learning’s from Phase I in
to the subsequent development phases. The plan generated a strong technical case supporting the business decision to implement Phase II of the development. Currently wells are producing to an early production facility but the desired production capacity (Phase II) requires a large number of new wells to be drilled including horizontal wells.

The appraisal and development of the North Kuwait Carbonate Reservoirs (NKCR) offer challenges such as lateral variations in reservoir quality, tight to very tight reservoirs and natural fracturing to a varying degree spatially. The presence of open, connected fractures (in part of the field area) is believed to be one of the key elements to achieve a successful development. As a result fracture characterisation and modelling study are ongoing. The static (e.g. excluding dynamic simulation) part of a fracture characterisation and modelling study can be summarized in a 4 step approach:

1) elaboration of a regional structural model,
2) creation of 3D conceptual fracture diagrams,
3) elaboration of constraints capturing the key elements of the conceptual diagrams and
4) creation of fracture model properties for further dynamic simulation.

In the proposed workflow (Figure 2) the elaboration of the constraints has been primarily calibrated with horizon curvature calculation at various scales in close in order to match structural concept. The objective of this paper is however to share the work done primarily in the first 2 steps of the study, based on a new structural evolution model which has been recently developed. This new structural model has been used as a foundation for the elaboration of conceptual fracture models.

Figure 1. Field overview and stratigraphic column.
Top Middle Marrat depth structure map with fields (NWRA: North West Raudhatain; RA: Raudhatain; DA: Dhiba; UN: Umm Niqqa; SA: Sabriyah; BH: Bahra).

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Regional structural evolution

The North Kuwait Carbonate reservoirs are immediately overlain by the Gotnia formation (salt and anhydrite). The major known regional phases of deformation which occurred since their deposition (Sharland et al, 2001, Filbrandt et al, 2006) are the Jurassic rifting, the Cretaceous transtensional deformation (known as Alpine 1) and the mid to late Tertiary inversion (known as Alpine 2).

Figure 3 and Figure 4 illustrate how these phases are expressed within the regional structural context and how they can be recognised at field scale. The Alpine 1 phase of deformation is characterized by a regional transtensional stress regime with a NW-SE maximum horizontal stress (SHmax) (Figure 3a). The Alpine 2 phase of deformation (Figure 4a) is characterized by a compressional stress regime with a NE-SW SHmax (for more detailed information see Filbrandt et al 2006). Figure 3b and Figure 4b show some field-scale expressions of these two main phases of deformations on seismic illumination displays of the Top Natih E level (modified from Filbrandt et al, 2006).

In Figure 3b, the right-stepping and left-stepping en-echelon faults (yellow lines) indicate that under a NW-SE SHmax (Alpine1), NW-SE and N-S deep seated basement faults are activated with a right-lateral and left lateral sense of displacement respectively. While, in Figure 4b, the right-stepping en-echelon faults (blue lines) indicate that under a NE-SW SHmax (Alpine 2), the WNW-ESE deep seated basement faults are activated as left-lateral fault zones. The subtle undulation of the surface along the N-S fault zone might be tentatively interpreted as en-echelon compressional folds indicating a subtle inversion of lateral movement along the deep seated basement fault.

During these important tectonic events, the structural development of the fields is strongly controlled by the reactivation of pre-existing basement lineaments (Filbrandt et al 2006, Al Kindi and Richard, in press).
Figure 3. Regional phase of NW-SE compression (Alpine 1, -92 to -63 MY).
(a) Regional map. (b) Seismic horizon (Top Natih formation, Yibal-Al Huwaisah area) showing structural lineaments activated at Alpine 1 stage (modified from Filbrandt et al, 2006).

Figure 4. Regional phase of NW-SE compression (Alpine 2, -92 to -63 MY).
(a) Regional map. (b) Seismic horizon (Top Natih formation, Yibal-Al Huwaisah area) showing structural lineaments activated at Alpine 2 stage (modified from Filbrandt et al, 2006).
Elaboration of the structural evolution model

For the elaboration of the structural model, a series of detailed observations have been made at field scale in terms of overall fault geometries and structural styles. Then kinematic and stress orientation interpretations have been drawn and linked to the known regional phases of deformation. These interpretations have been compared with structural sandbox analogues extracted from Shell’s Sandbox Archive to explain the concepts as well as to attempt to link them to the regional analogues. Finally, these observations have been combined to build a regional picture at the scale of Kuwait. It is beyond the scope of this extended abstract to share all the detailed observations and analogues (this will be the topic of a future dedicated paper). We focus on a few key ones only. We first show one regional cross section where sediment thickness variations have been studied in detail (Figure 5). Then we illustrate how the distribution of faults above and below the Gotnia salt can demonstrate the presence of Jurassic normal faults below the Gotnia (Figure 6 and Figure 7). These observations and other key are then summarized in a 3D block diagram (Figure 8). Finally a structural evolution in cross section (Figure 109 and Figure 110) and map view (Figure 11) are proposed.

Structural growth illustrated by sediment thickness variation

Observations.

On the figure below (Figure 5), thickness variations (in TWT ms) are highlighted. Clear thickness variations are visible in the intervals Top Najmah to Top Gotnia, Top Ahmadi to Mishrif unconformity and Top Rus to present. In contrast, the interval Top Gotnia to Top Ahmadi and Mishrif unconformity to Top Rus are relatively uniform.

Interpretation.

The thickness variations observed in the 3 intervals mentioned are interpreted to be an indication of the structural pulse associated with the regional Jurassic rifting, Late Cretaceous (Alpine 1) and Mid Tertiary (Alpine 2) phases of deformation.

Evidence for a Jurassic normal fault below Gotnia salt

Observations.

On the figure below (Figure 6), the seismic coherence attribute is displayed. Potential fault/deformation zone can be recognised by the darker colours representing zone of poor seismic coherence. On the left and on the right, the coherence is displayed on the deeper Top Najmah and shallower Top Ahmadi horizons respectively (see figure 5 for the precise position of these horizons). At the top Ahmadi, a series of en-échelon faults aligned in an overall NNE-SSW fault zone can be observed.
These en-échelon faults can be described as right stepping. They are relatively short and straight, with relatively long overlaps between the segments. At the deeper Top Najmah level, a broad and rectilinear disturbance zone can be observed. The middle picture is a combined display where the Top Ahmadi coherence is displayed with some transparency to only show the potential faults, while the entire coherence range is displayed at the Najmah level. On this display, a clear lateral offset between the Ahmadi deformation zone and the deformation zone at the Najmah level can be observed.

**Interpretation.**

The right stepping en-échelon distribution of the faults is characteristic of left-lateral displacement. The relatively linear geometry of the faults with relatively long overlap is indicative of transtension (normal displacement associated with strike-slip). This is confirmed in cross section too (see summary block diagram, Figure 8). These en-échelon faults are consistent with a maximum horizontal stress SHmax oriented in a NW-SE direction. They are interpreted to have developed at the time of the Alpine 1 phase of deformation under a transtensional stress regime. The lateral offset between the en-échelon fault zone at Ahmadi level and the axis of the fault zone at Najmah level is interpreted as the result of the impact of a detachment level (Gotnia salt) during the reactivation in transtension of a pre-existing normal fault, below the Gotnia salt. This deeper normal fault is interpreted as related to the Jurassic phase of rifting. The impact of the presence of a detachment level in transtension is illustrated on Figure 7) with sandbox analogues.

**Figure 6. Lateral offset between Cretaceous and Jurassic fault zones (Sabriyah field).**

Figure 7 shows the results of two experiments in which a basement fault (red dashed line) has been activated in extension and faults developed in the overburden above. After the deformation, cross sections are made in the model to observe the fault geometries.

In (A) the overburden was made of sand only (representing a competent overburden made of brittle rocks) and the faults developed in the overburden are rooted into the basement faults.

In (B), a viscous layer (representing an analogue for salt) has been deposited between the brittle overburden and the basement fault. As a result, the faults in the overburden are offset on the up-thrown block and do not connect into the basement fault. The faults are detached from the basement fault due to the presence of the viscous layer (see Vendeville et al, 1987; Richard and Krantz, 1991 and Naylor et al, 1994 for more experimental details and discussion about detached faulting).
Summary of some key structural observations
Some key structural observations are summarised in the 3D block diagram below (Figure 8). These are:
1. Normal fault at Jurassic level
2. Tight compressional fold against normal fault
3. Indentation of Top Gotnia by Top Najmah
4. En-échelon transtensional faults in the Cretaceous overburden pre Mishrif unconformity
5. Sedimentary growth pre-Mishrif unconformity
6. Large wavelength folding at Tertiary level.

Note that the block diagram has been inspired by the seismic cross section illustrated on Figure 9. It is also important to note that the presence of the normal fault at the Jurassic level is interpreted from the detached deformation observed at the Ahmadi level.
Overall structural evolution of the North Kuwait Carbonate fields
The elaboration of the overall structural evolution diagrams of the North Kuwait Carbonate fields has been based on a section through the Sabriyah structure (Figure 9).
The sequential structural evolution is displayed on Figure 10 and can be summarised as follows:

1. Jurassic deposition. Tectonically quiet period during the Lower and Middle Jurassic, time of deposition of the Marrat, Sargelu and Najmah Formations.

2. Gotnia deposition. Extensional faulting event during the Upper Jurassic (Figure 11), time of deposition of the Gotnia Salt. This tectonic event is known regionally as the Jurassic rifting event with NE-SW SHmax. This has led to the formation of normal faults in the Jurassic section recognised by local Gotnia Salt thickening (Figure 5).

3. Cretaceous till Turonian. Tectonically quiet period during the Lower Cretaceous till Upper Cretaceous Turonian - time of deposition of the Makhul to Mishrif Formations.

4. Middle Turonian. Transtensional faulting event during the Middle Turonian time. This tectonic event is known regionally as the Cretaceous, Alpine 1 phase of deformation with NW-SE SHmax (see Figure 3 and Figure 11) and expressed as the regional Middle Turonian Unconformity (Sharland et al., 2001). This has led to the reactivation of normal faults in the Jurassic level, the formation of dominantly transtensional faults in the Cretaceous section. This transtensional fault system is decoupled from the underlying fault present in the Jurassic units by the Gotnia Salt.

5. Turonian to Mid Tertiary. Tectonically quiet period during the Lower and Middle Tertiary, time of deposition of the Sadi to Rus Formations.

6. Mid Tertiary till present. Compressional event during the Miocene to present day time. This tectonic event is known regionally as the Tertiary Alpine 2 phase of deformation with NE-SW SHmax (see Figure 4 and Figure 11) and directly related to the formation of the Zagros mountain range. Ultimately, this has led to the inversion of the normal faults at Jurassic level, the formation of the compressional anticlines at Jurassic level and the formation of long wavelength anticlines in the shallower sequence and particularly visible at Tertiary level.

The fact that the pre-Gotnia structures are still visible on flattened seismic sections at Top Gotnia can lead to the interpretation that these structures are of pre-Gotnia origin. This is however not supported by the regional structural phase of deformation.

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**Figure 10. Simplified structural evolution of the North Kuwait Carbonate fields.**
Based on this regional structural evolution, several typical structural compartments with variable strain intensities have been defined. These compartments are (Figure 12) NW Raudhatain, Dhabi, Sabriyah ridge, Umm Niqqa and the central area (or terrace area). A notional conceptual diagram has been defined for each area (Figure 12). Fracture intensities vary from very low to high. For example, in the low strain compartment (central area), fractures may be limited to fault damage zones and isolated fracture corridors. In more deformed compartments (e.g. Sabriyah and Dhabi ridges (Figure 12), the fracture intensity is likely to increase strongly due to the successive transtensional and transpressional reactivations of pre-existing grabens.

In all compartments, 3 main sets of fractures related to the 3 successive main phases of deformation are expected to be found with various intensities. These are:

1 – an overall N-S fracture set developed during the Jurassic phase of extension. These fractures have a tendency to be concentrated in fault damage zones, and their intensity is expected to increase with increasing fault dimensions and in specific structural compartments like fault relays (see Filbrandt et al, 2006 for reference).
2 – an overall NW-SE fracture set developed during the Cretaceous phase of transtension (Alpine 1). These fractures have a tendency to be located within the earlier Jurassic graben reactivated in transtension, as well as along newly formed faults especially in the central area between Raudhatain and Sabriyah and in the extensional horsetail of Sabriyah.
3 – a dominant NE-SW fracture set developed during the Tertiary transpressional phase of deformation (Alpine 2). These fractures are expected to have the highest intensity in the tighter compressional ridge of Sabriyah, NWRA, Dhabi and North Raudhatain (N-S ridge). They are also expected to be highly permeable because they are parallel to the present day maximum horizontal stress.

A brief comparison with the fracture interpretation from re-oriented cores (ongoing detailed and comprehensive core fracture interpretation work currently ongoing) has shown a good fit between the proposed fracture sets based on the structural evolution and the open (partially cemented to non cemented) natural fractures observed on the cores. For example, the comparison of the orientations of the “open” fractures observed on core from the well SA-A with the fracture orientations predicted from the kinematic model is illustrated on Figure 13. Similar matches have been observed between fracture orientation from cores and the conceptual diagram from several other wells, but more detailed characterisation work is still required. Overall a good match has been found as well between the proposed structural compartments and the dynamic response from pressure transient analysis (PTA) of pressure build up tests. This is however extremely early days and requires a more in-depth analysis.
Figure 12. Definition of conceptual structural diagram for 5 structural compartments.

Figure 13. Kinematic evolution and expected fracture patterns for the Sabriyah ridge.
Further work
Although it is based on a limited dataset of vertical wells without detailed fracture characterisation yet, the first pass conceptual fracture models show an encouraging match with the currently available dynamic data, especially in the Sabriyah, Dhabi and NW Raudhatain compressional ridges. A detailed fracture characterisation (for all the individual fields) integrating all static (especially core and borehole image) and dynamic data (especially permeability from PTA) is required. This characterisation work is aiming amongst other objectives at creating single well conceptual fracture diagrams. Such diagrams need to capture the range of uncertainty. These diagrams need to be extended to field scale combining the learning’s of the individual wells. Particular emphasis is brought to the characterisation of mechanical stratigraphy and the relation between lithology and fracture intensity. The detailed fracture characterisation work allows as well to characterise the input that each type of data really provides in term of fracture identification. For example, Figure 14 and Figure 15 illustrate the difference between the appearance of partially cemented (partially open) and fully cemented fractures on acoustic images and cores. These two figures illustrate how critical the calibration of core to BHI is essential to avoid mis-interpreting the real nature of the fractures encountered in the sub-surface and their potential impact on production.

Figure 14. Comparison of appearance of partially cemented fractures on core and acoustic image. The black and red arrows point to fractures and bedding plane respectively. In this example, relatively small partially cemented fractures visible on core could easily be misinterpreted as a large open fracture on the acoustic image.
The sinusoids corresponding to the cemented fractures visible on core are displayed on the acoustic image. This illustrates that due to the absence of density contrast the cluster of cemented fractures observed in the core is not visible on the acoustic image.

5 Conclusions
A new structural model for the North Kuwait Carbonate fields has been developed. The model is based on key kinematic observations which have been linked to the known regional phases of deformation. These main phases of deformation are:

- the Jurassic rifting,
- the late Cretaceous transtension (known as Alpine 1),
- the Mid Tertiary compression (known as Alpine 2).

The major difference between the new model and previous structural thinking is that the formation of the compressional folds at Jurassic level has happened during the Tertiary time related to Zagros event (regional Alpine 2 phase of deformation). The model has some potential implications on fracture development and preferred direction of horizontal wells. The major implications in term of fracture distribution and orientation are:

- In the compressional ridges, the dominant direction of open fracture is expected to be oriented NE-SW parallel to the direction of present day maximum horizontal stress.
- In the area between the compressional ridges, less dense (Alpine 1) fractures and probably more cemented fractures are expected.
- Greater fracture connectivity is expected in compressional ridges than in the area between them.

The new view on timing of structural development (i.e., late uplift of Jurassic compressional ridges regionally) has some potential implications on maturation/charge history as well as on reservoir development. The timing of charge is critical to better understand fracture cementation and aperture.

- Fractures developed before hydrocarbon emplacement are more likely to be cemented.

A more detailed investigation using detailed observations from cores as well as dynamic data is however still required. This will be achieved thanks to an ongoing detailed fracture characterisation integrating all static (especially core and bore hole image) and dynamic data (especially permeability from PTA).
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References


