Cantarell Giant Oilfield Fault-Thrust Kinematic Evolution and Synchronous Thermo-Fluid Dynamics

Introduction and Objectives

The Cantarell complex, located in the continental shelf of the Southern Gulf of Mexico, is a naturally fractured carbonate field discovered in the late 70’s by PEMEX. The complex is composed of five separated fields being the namely Akal Field the largest with 32 Bboe OOIP, considered the sixth largest world-class oilfield. Underlying the Akal filed, the namely Sihil field (1.2 Bboe OOIP) constitutes the thrusted footwall block of a complex fault propagation fold and thrust belt structure (Figure 1a).

Even if the Cantarell complex has been studied for several decades and its exploitation has reached a mature declination stage, several questions remain related to the physical and geochemical processes occurring during the trap fold thrust evolution and the synchronous thermo-fluid dynamics. Therefore, the objective of this study is to answer the following questions: How was the thermal-pressure evolution between the overlying Akal and the Sihil footwall during fold thrust formation? What was the timing of HC expulsion and the fluid migration interactions between both blocks? How was the evolution of the fluid composition and PVT phase behavior during HC charge? What are the implications for near field exploration (NFE) and field development?

Methodology

The applied methodology is a 2D structural kinematic restoration meshing tool (KronosFlow), coupled with a fault-related petroleum system modelling (TemisFlow). This workflow combines implicit dynamic fault geometry for heat transfer, effective stress and Darcy fluid flow modelling in sediments and across-along fault planes during simulated geological time. 1D PVT modelling was also applied in order to calibrate and predict fluid phase behaviour and composition. This integrated workflow allows to assess fault-related petroleum systems in complex structural domains, at field level or basin scale, for a dynamic fault seal analysis fluid interactions and PVT fluid phase behaviour evaluation.

Figure 1: a) Cross-section and stratigraphic record of the of the Cantarell/Sihil complex (modified after Aquino et al. (2003) and Ricoy-Paramo (2005); b) Kinematic restoration.
Geological context
The thrusting block of Cantarell, known as Akal and the thrustered footwall known as Sihil, form part of a complex fold and thrust belt with the repetition of the Mesozoic and Paleogene series, formed during the Miocene with a main detaching level within the Callovian salt (Figure 1a). Both structures have a regional NW-SE orientation with a northeast vergency, with a cut off in the west by a right-lateral strike-slip fault with a N-NW orientation (Mitra et al., 2005, Aquino et al., 2003 and Ricoy-Paramo, 2005). Their formation is believed to be related to a regional compressive stage triggered by the movement of the Chortis Block in the Pacific, causing a transpressive deformation and thrusting toward the northeast Campeche Sound.

The main reservoir is the K-T boundary natural fractured vuggy dolomitized breccia (Aquino et al., 2003) with excellent reservoir properties (Phi 5 - 35 %, k = 3,000 – 5,000 mD), sealed by Paleocene calcareous shale deposits. Secondary reservoirs and/or carrier beds include Lower Cretaceous dolomitized and fractured limestones, Kimmeridgian coarse-grained oolite shoals deposited in structural highs rift remnants, and Oxfordian siliciclastic shoreface ramp system. The source rock corresponds to the Tithonian organic-rich calcareous shales deposited under anoxic conditions as Type II organic matter kerogen with good to excellent source rock potential index of SPI > 10 TonHC/m² (Romero et al., 2000).

Kinematic restoration
The kinematic restoration was performed with a cross-balancing section and meshing tool (KronosFlow) considering a fault-propagation and detachment folding as main deformation mechanisms rooted within a pre-existing faulted terrain (Figure 1b). Initial present-day cross-section length is of 24 km with a maximum section length of 33 km during the Upper Jurassic. Restoration was based on the structural interpretations of Mitra et al. (2005), Aquino et al. (2003) and Ricoy-Paramo (2003). Four main episodes of deformation are identified:

1) A first episode of extension during the Late Jurassic to Early Cretaceous creating normal listric half-graben faulting related to the development of salt rollers, detaching in Callovian-Oxfordian units. A 2 km extension length is observed during this stage followed by a passive margin infill from Lower Cretaceous to Late Cretaceous.
2) A first main compressive deformation stage involving major folding and minor thrusting occurred during the Lower Miocene, however it is possible that early folding initiated since Late Cretaceous (internal interpretation). A 2.5 km section shortening is interpreted at this stage.
3) A second compressive stage occurred during the Middle and Upper Miocene involving major thrusting and minor folding, reactivating the pre-existing faulted terrain of the early extension phase. A 6.5 km section shortening is interpreted at this stage for a total amount of 9 km section shortening (27%). The resulting thrust fault ramp separates the allochthonous and autochthonous blocks (Akal and Sihil fields), with the juxtaposition of Oxfordian sand deposits above Paleocene-Cretaceous series.
4) Finally, a late extensional-transtensional stage occurred during the Plio-Pleistocene, creating a lateral-right strike-slip faulting affecting the overthrusted Mesozoic strata in the western area.

Hydrocarbon expulsion, migration and charge
Hydrocarbon expulsion, migration and charge evolution within the Akal and Sihil fields can be described as follows (Figure 2):

1) Upper Miocene (5.3 Ma): Hydrocarbon expulsion from Tithonian source rock occurred firstly within the underlying Sihil block kitchen due to the Akal thrusting overburden. This was followed by a hydrocarbon migration and charge of the K-T breccia reservoir retained below the Paleocene top capillary seal.
2) Early Pliocene (3.6 Ma): A lateral hydrocarbon fault seal leakage occurred from the Sihil block once the oil leg in the reservoir increased and was in contact with the overlying Oxfordian sandstone units of the Akal block (permeable fault thrust facies juxtaposition). This leakage triggered a vertical migration and the first hydrocarbon charge within the K-T breccia reservoir of the Akal field.
3) Late Pliocene (2.3 Ma): A second hydrocarbon charge occurred in the Akal field, fed by the hydrocarbons expelled from its western and eastern flanks, with a lateral up-dip migration through the highly permeable K-T breccia. At this time, the oil leg in the reservoir reached its maximum length close to the spill point of the Akal structure (> 3500 m).

4) Pleistocene–recent (0 Ma): Finally, a vertical dis-migration towards the seabed occurred due to top capillary pressure rupture in balance with the reservoir hydrocarbon pressure.

Figure 2: Hydrocarbon migration and charge history and fault seal juxtaposition leakage from underlying Sihil block

Reservoir fluids PVT phase behaviour
Several 1D PVT models were performed in different positions along the K-T breccia reservoir of the Akal and Sihil fields. Simulated compositional molar fractions of migrated hydrocarbons and the simulated reservoir temperatures and pressures were used as input data. Based on the initial reservoir fluids conditions, as described by Leon et al. (1995) and Aquino et al. (2003), and as simulated in this study (Figure 3), the first oil production in the Akal field was initially undersaturated oil from a hydraulically continuous pay zone of 1200. Initial petroleum fluid conditions remained above bubble-point pressure (reservoir pressure very close to pressure saturation) with oil densities of 20-24 °API and a GOR of 380-440 scf/bbl. The underlying Sihil field was discovered 20 years later (Cantarell-418D well) indicating initial petroleum fluid conditions also above bubble-point pressure with oil densities of 22-30 °API and a GOR of 400-680 scf/bbl.

As observed by Leon et al. (1995), and as reproduced in this study, uniform PVT properties vs. depth occur in the crest of the Akal structure. This means that reservoir fluids have similar phase envelope, pressure saturations and fluid composition along the crest, and showing slight variations towards the backlimb of the structure. It was also proposed by Leon et al. (1995) that thermal convection buoyancy-driven flow and gravity segregation are the main mechanisms responsible for these constant PVT properties. Thermal convection occurs due to the nature of the natural fractured K-T breccia reservoir with outstanding reservoir permeabilities (3,000 to 5,000 mD) and the high relief geometry of the Akal structure. Simulated temperature along the cross-section, reproduces the thermal anomaly at the crest of the structure, resulting in a lower thermal gradient in the crest of Akal field and higher normal thermal gradient within the flanks (less convective flow occurs).
K-T breccia reservoir temperature and pressure simulation indicates that before thrusting occurred, temperature and pressures were around 60 °C and 15 MPa. Temperature and pressure tend to increase significantly within the Sihil field during the thrusting stage (Middle–Upper Miocene), due to the Akal thrusting overburden. It is possible that during this stage hydrothermal fluid dissolution occurred resulting in the dolomitization and karstification of the reservoir as mentioned by Ricoy-Palermo (2005). Present-day reservoir temperature and pressure is around 100 °C and 26 MPa at the crest of the Akal field, and 145 °C and 48 MPa for the underlying Sihil field, herein, early secondary cracking of oil could occur, which could explain the slight increase of initial GOR and API in the Sihil field.

**Conclusion**

HC charge occurred mainly after, or at the latest stages of fold thrust trap formation. The Akal and Sihil fields are hydraulically connected with independent WOC. The Akal field was mainly fed by Sihil leakage through Oxfordian sandstones by lateral fault seal juxtaposition. A second charge occurred by structure flanks lateral up-dip drainage. Initial reservoir conditions were undersaturated oils close to pressure saturation in Akal field. Uniform PVT properties vs. depth occurs due to thermal fluid convection within the highly permeable K-T breccia. The proposed integrated workflow allows to assess the thermo-fluid dynamics in fault-related petroleum systems in complex structural domains for a dynamic fault seal analysis fluid interactions and PVT fluid phase behaviour evaluation. This has a direct application to mitigate exploration risk and evaluate field development strategy.

**References**