Petroleum System and Play Concept in the Area 113-3&4, Southern Margin of the Ghadames Basin, Libya

Takashi Sato* and Yoshihiro Watanabe*

Abstract: The Contract Area 113 Blocks 3 & 4 (Area 113-3 & 4) is located in the southern margin of the Ghadames Basin, where the glaciated Middle Ordovician Haouaz Formation and Silurian Basal Tanezzuft Hot Shale (BTHS) play important roles in the petroleum system. The newly acquired seismic data clearly indicate that the BTHS is distributed discriminatively in paleo-topographic lows surrounding Haouaz paleo-high structures. Maturation history is characterized by distinctive three heating phases and significant erosion of the post-Hercynian sediments, resulted in extremely high maturity of the BTHS in spite of its shallower present depths. In local depressions of the Area 113-3 & 4, the main hydrocarbon expulsion from the BTHS occurred in the Hercynian heating phase. The Haouaz Formation is divided into five (5) litho-stratigraphic units, Unit A to E in descending order. The Unit C sandstones have superior reservoir qualities, while those of sandstones in the other units are originally poor. Physical relationship/contacts between the Haouaz Unit C sandstones on the paleo-high structures and the surrounding BTHS are the most critical factor for formation of the Haouaz play from the viewpoint of hydrocarbon migration.

Keywords: Haouaz Formation, Silurian Basal Tanezzuft Hot Shale (BTHS), Maturity, Migration.

INTRODUCTION

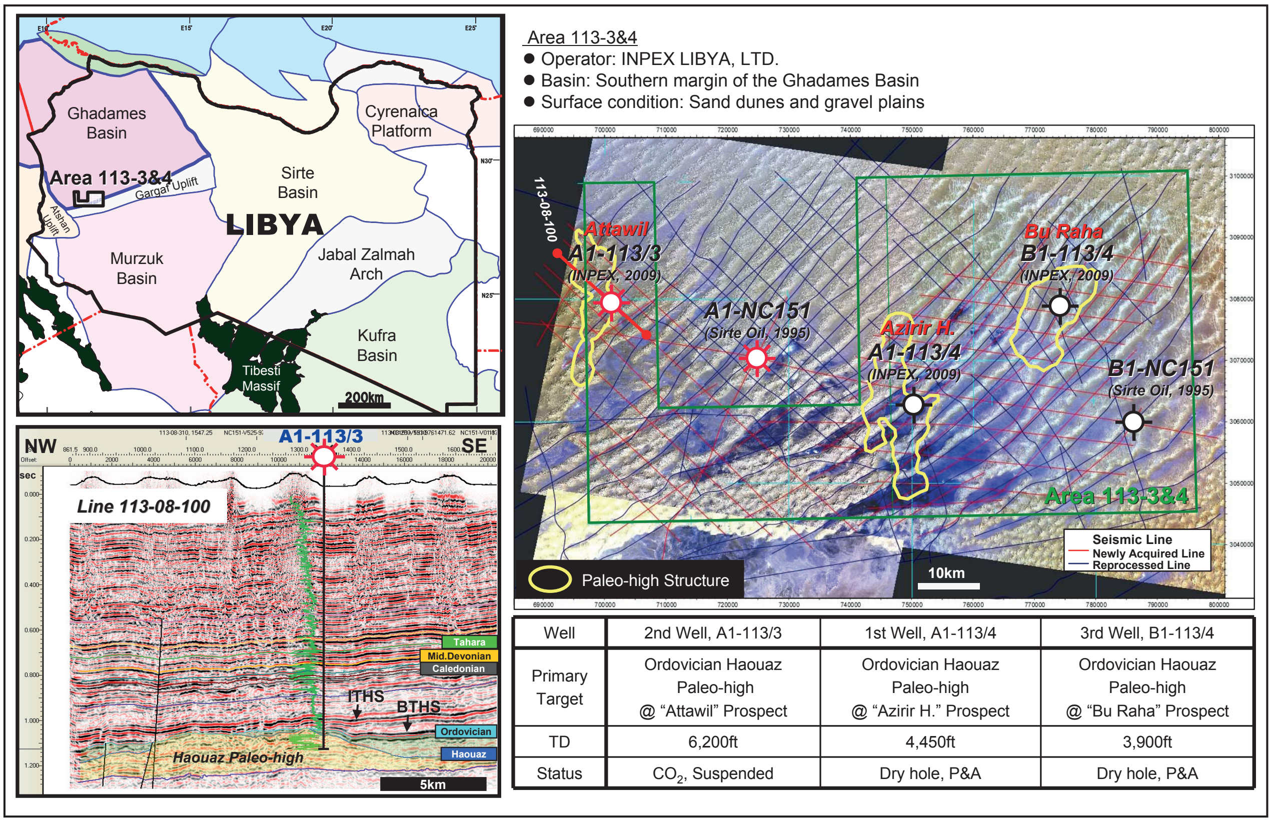
The Area 113-3 & 4 is geologically located in the southern margin of the Ghadames Basin and the southeastern corner of the Area belongs to the Gargaf Uplift that separates the Ghadames Basin from the Murzuk Basin to the south (Fig. 1).

INPEX had energetically conducted exploratory works such as reprocessing of the vintage 2D seismic data, a new 2D seismic survey, geological sample analyses, geological field excursions and integrated geological and geophysical studies since 2007. Based on these exploratory works and studies, three (3) prospects were tested through the 2009 drilling campaign (Fig. 1). The three (3) exploratory wells really validated INPEX's geological idea and/or concept, especially for the glaciated Middle Ordovician Haouaz Formation in the Area 113-3 & 4, however, they failed to demonstrate the presence of effective petroleum system aside production of unpredictable dry gas with extremely high concentration of CO_2 at the 2nd well, A1-113/3. Then an integrated post-drilling study including the reconstruction of stratigraphic framework, basin modeling study and petrographic study was carried out to bring some important speculations for the petroleum system and play concept in the southern margin of the Ghadames Basin.

*Exploration Department, INPEX LIBYA, LTD., Tripoli, Libya

GEOLOGICAL BACKGROUND

The southern margin of the Ghadames Basin is situated on the "Trans-Saharan Mega Belt", a mobile belt during Pan-African Orogeny (Lüning, *et al* 2007). The Paleozoic sediments are distributed on this Precambrian basement to dip generally northwestward in the Area 113-3 & 4. They are composed of the Cambro-Ordovician to the Carboniferous and estimated to have a total thickness of 5,000 to 7,000 ft in the Area 113-3 & 4 (Fig. 2). The Paleozoic of the Ghadames Basin is divided into some super-sequences bounded by major unconformities such as Taconic, Caledonian and Hercynian (Dardour, *et al* 2004). The post-Hercynian Mesozoic sediments, which are regionally distributed in the northern Ghadames and Murzuk basin, are believed to have been completely eroded out in the Area 113-3 & 4 at the later uplift event. The Carboniferous are widely exposed on the surface of the Area 113-3 & 4 at the present day.



Well	2nd Well, A1-113/3	1st Well, A1-113/4	3rd Well, B1-113/4
Primary Target	Ordovician Haouaz Paleo-high @ "Attawil" Prospect	Ordovician Haouaz Paleo-high @ "Azirir H." Prospect	Ordovician Haouaz Paleo-high @ "Bu Raha" Prospect
TD	6,200ft	4,450ft	3,900ft
Status	CO_2, Suspended	Dry hole, P&A	Dry hole, P&A

Fig. 1. Location map of the Area 113-3 & 4, summary of prospects tested through the 2009 drilling campaign and an interpreted seismic section showing the A1-113/3 gas structure.

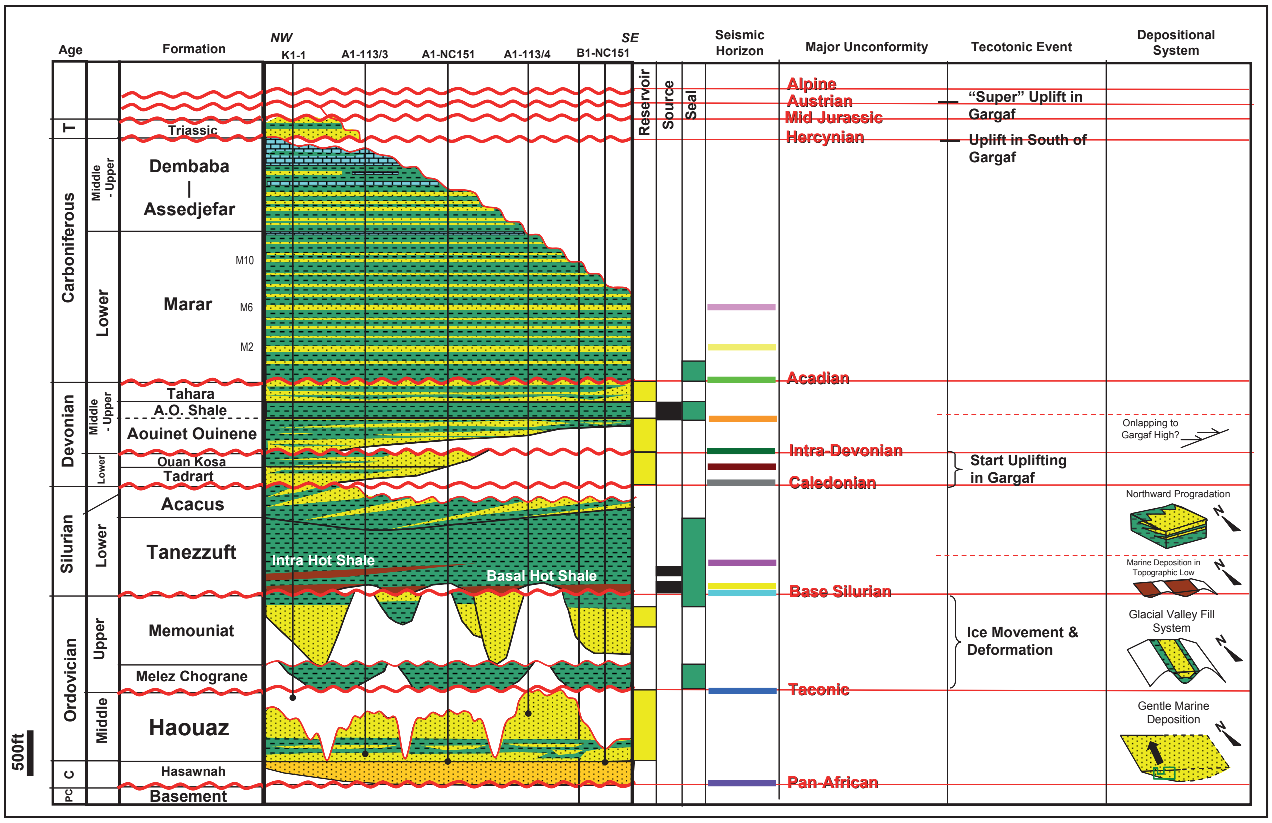


Fig. 2. Generalized stratigraphy in and around the Area 113-3 & 4

Among the Ordovician, the Haouaz paleo-high (buried-hill) structures and incised valleys resulted from glaciations in Late Ordovician are well recognized on seismic sections (Fig. 3). The shaly Melez Chograne and Memouniat Formations of the Upper Ordovician are interpreted to have been deposited with repetitious erosions to bury up paleo-topographic lows, and therefore, mal-distribution of the Ordovician sediments is resulted in a complicated well stratigraphy. The Silurian is composed of the shaly Tanezzuft and overlying sandy Acacus Formations. There are two "Hot Shale" horizons within the Tanezzuft Formation such as the Basal Tanezzuft Hot Shale (BTHS) and Intra Tanezzuft Hot Shale (ITHS). The former is distributed to surround the paleo-high formed by the Middle Ordovician Haouaz quartzitic sandstones as indicated by the amplitude anomaly of the BTHS horizon (Fig. 3). The Lower Devonian is composed of sandy Tadrart and Ouan Kosa Formations. These formations are distributed only in the west of the Area 113-3 & 4 due to the effect of the Caledonian and Middle Devonian Unconformities. The Middle to Upper Devonian consists of the Aouinet Ouinene Formation, the Aouinet Ouinene Shale (A. O. Shale) and the Tahara Formation in ascending order. The existing Carboniferous sediments thicken northwestward from approximately 800ft in the east to 3,300ft at the A1-113/3. The Lower Carboniferous Marar Formation consists mainly of shales with interbedded sandstone-rich intervals, and the overlying Assedjefar and Dembaba Formations have intercalations of carbonates.

The petroleum system of the Silurian source rock and Ordovician sandstone reservoir is proven in the Murzuk Basin. Especially El Sharara Oil Fields located in 100 km southeast of the Area 113-3 & 4 are worthy to note in that they have a particular petroleum system with the complicated stratigraphy, which is related to the paleo-high structure resulted from glacial actions in Late Ordovician (Sarkawi, 2007 and Franco, *et al* 2008). In addition, there are A1-NC151 gas discovery located in the adjacent block of the Area 113-3 & 4 and A1-113/3 CO_2 rich gas accumulation in the Area 113-3 & 4 as described above. They are also interpreted to be paleo-high structures with the Middle Ordovician Haouaz sandstone reservoir.

Geological and geophysical studies reveal that the Ordovician play, which is a paleo-high related structural-stratigraphic play like El Sharara Oil Fields, is most promising in the Area 113-3 & 4.

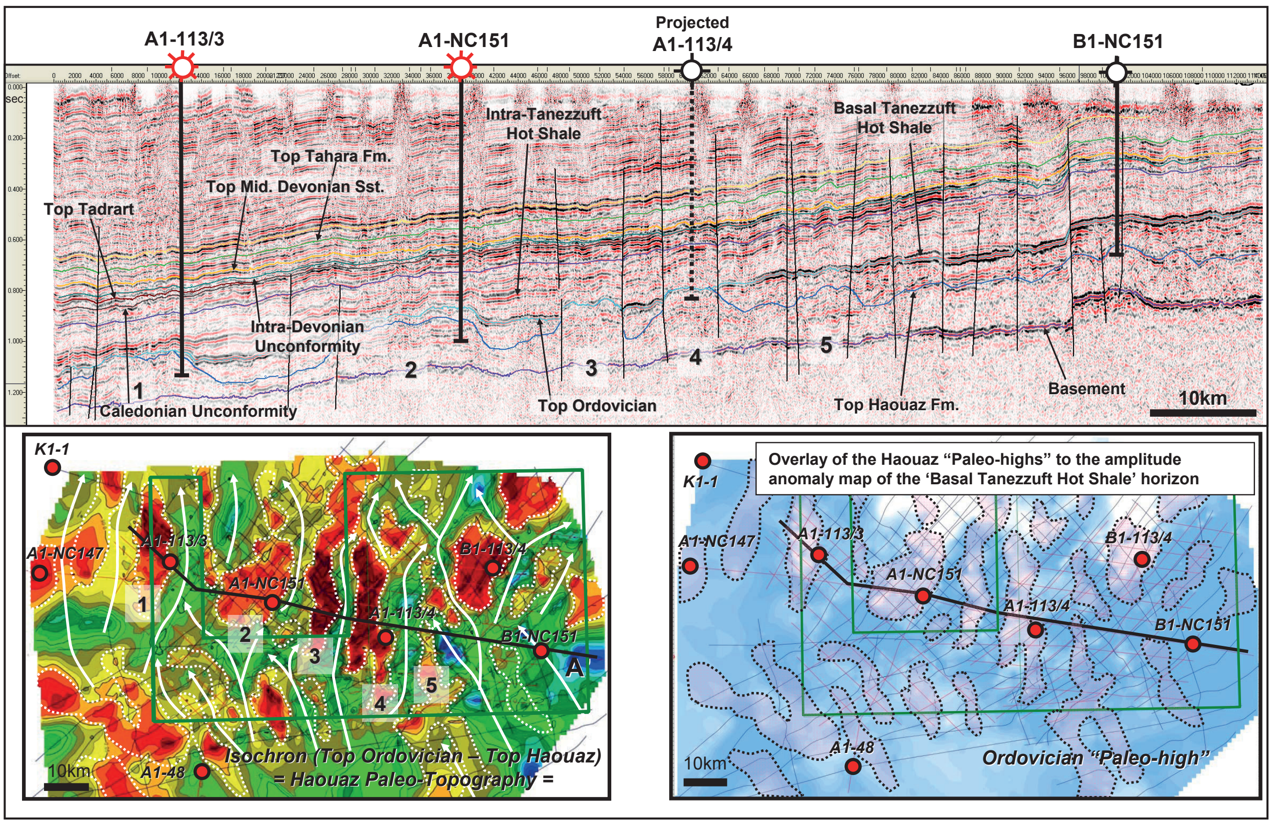


Fig. 3. A regional composite seismic line, the isochron map of Top Ordovician – Top Haouaz horizon and the amplitude anomaly map of the 'Basal Tanezzuft Hot Shale' horizon, showing the distribution of Haouaz Paleo-high and BTHS in the Area 113-3 & 4.

Isochron map between the 'Top Haouaz' and 'Top Ordovician' horizons, which is presumably assumed as the Haouaz paleo-structure map, shows the glaciated paleo-topography and presence of a lot of N-S trending paleo-high structures with 2km to 10km in width at the top of the Haouaz Formation (Fig. 3). The Melez Chograne and Memouniat shaly facies are interpreted to have been deposited to bury up the glaciated paleo-topographic lows in the Late Ordovician. They are expected to work as lateral seal, while the Silurian Tanezzuft shales as top seal for the Haouaz paleo-high structures. Matured primary source rock is the BTHS distributed to surround the Haouaz paleo-high structures (Fig. 3). Such physical relationships as onlapping of the BTHS onto the Haouaz paleo-high and direct contact of the Hot Shales with the Haouaz Formation through faults are desirable for hydrocarbon migration.

SOURCE ROCK AND BASIN MODELING

Newly acquired seismic data and geological data reveal that Tanezzuft Hot Shales are distributed within the Area 113-3 & 4. In addition, they are found to be oil-prone and are in late mature to main gas generation stage in spite of their shallower present depths. It indicates in-situ hydrocarbon generation and migration within the Area 113-3 & 4 and dispensable long lateral migration from the northwestern basin-ward, though there used to be some variations of interpretation on the kitchen area as indicated in published literatures (Echikh, K., 1998, Boote, *et al* 1998, and Seddiq and Bhaduri, 2006). Against this background, 1D basin modeling study was carried out in order to figure out the remaining unknown factors such as the timing of hydrocarbon generation and expulsion from the source rocks and expelled hydrocarbon volume. The basin modeling software, "Basin Mod 1D" by Platte River Associates was used for this study.

Source Rock Potential: The matured potential source rock within the Area 113-3 & 4 is primarily the BTHS. The geochemical data from the wells A1-113/3 and A1-113/4 indicate that the BTHS and ITHS are originally rich in Type I kerogen (Fig. 4), though very low Hydrogen Index (HI) values due to low S2 values resulted from high maturity level may suggest the possibility of admixture of Type II kerogen. The A. O. Shale is also recognized as a potential source rock containing Type II kerogen.

Heatflow History: The heat flow history is one of

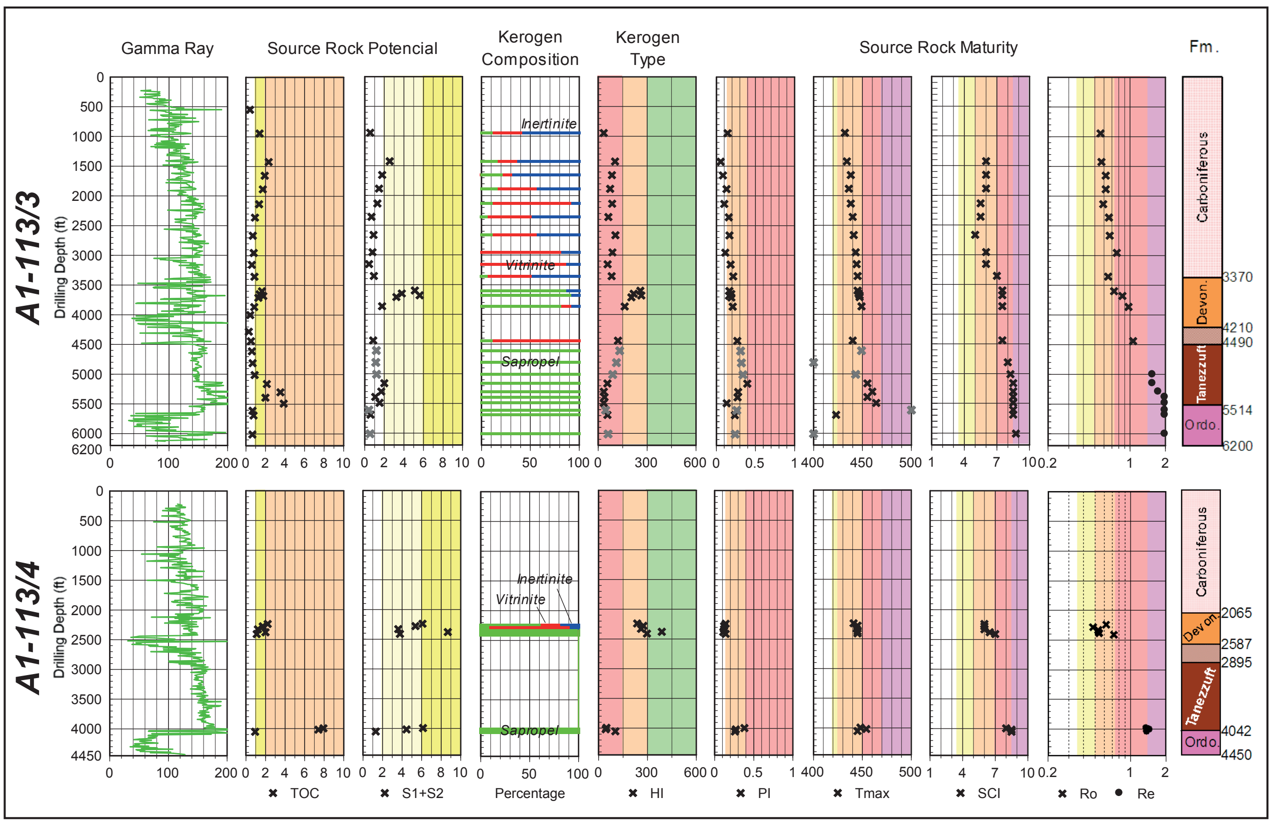


Fig. 4. Geochemical Logs of wells A1-113/3 and A1-113/4, showing source rock potential, kerogen type and maturity of the BTHS, ITHS and A. O. Shale..

key factors for the basin modeling as it is sensitive to source rock maturation. The heat flow history is interpreted to be characterized with the following three phases.

1) Post rift thermal sag after Pan-African Orogeny: The geological history of western Libya is believed to have started with the build-up of super continent Gondwana accompanied by the Pan-African Orogeny. Ghadames-Murzuk Basin was initiated on a mobile belt, called Trans Saharan Mega Belt, which appeared between the West African craton and the East Saharan craton (Lüning, *et al* 2007). At this beginning stage of the basin, it is supposed that rifting was active under high heat flow regime as indicated by volcanic rocks in the basement. Then the heat flow gradually decreased with basin evolution as sag basin until Permian.
2) Hercynian continental collision and Triassic rifting followed by thermal sag: The Hercynian Orogeny is well known as one of the largest geological events in sedimentary basins of North Africa, which was caused by the continental collision related to Pangea super continent construction in Permian (Craig, *et al* 2004). As this event was accompanied by Traissic rifting and volcanism as confirmed in northern Ghadames Basin, it is supposed that heat flow increased rapidly and then gradually decreased during the subsequent thermal sag phase.
3) Alpine volcanism to the present: The present-day geothermal gradient is reported to be very high in Gargaf region (Underdown, *et al* 2008) and is estimated to be 4.75degC/100m in the Area 113-3 & 4, based on the available well data. High geothermal gradient is probably related to the Alpine thermal activity starting in Tertiary, which is recorded as volcanic outflows in eastern Gargaf region.

Burial History: The A1-NC151, B1-NC151 and A1-113/3 well locations are control/calibration points of 1D basin modeling. Geological section penetrated by the well A1-113/3 is 6,182ft in thickness, which consists of Paleozoic succession from the Middle Ordovician Haouaz Formation to the Carboniferous Assedjefar/Dembaba Formation. There are such four (4) unconformities as Taconic, Caledonian, Intra-Devonian and Acadian in the Paleozoic succession. Eroded amounts at each unconformity are estimated based on regional well correlations with some geological assumptions, however, it is revealed through the basin modeling that these four unconformities have very minor impacts on the results, compared with the post-Carboniferous unconformities.

Huge amount of Mesozoic sediments are highly likely to have been deposited in the past and completely eroded out by the post-Carboniferous unconformities. At least four (4) unconformities, such as Hercynian, Jurassic, Austrian and Alpine, can be recognized in the southern Ghadames to Murzuk Basins, among which, the Austrian event probably shows the largest impact on uplift and erosion in the Area 113-3 & 4 as indicated by clear angular unconformity on the published geological maps of Libya (Industrial Research Centre, 1984-1985). The amount of Austrian erosion is uncertain and estimation of its eroded thickness is one of the key/sensitive issues in the basin modeling.

It is highly important that Ro profile of the well A1-113/3 show a remarkable change in trend at Devonian level. Based on this noticeable phenomenon which is likely caused by rapid and massive amounts of sedimentation in Mesozoic, several stratigraphic models with different amount of erosion by the Austrian unconformity were simulated in order to examine sensitivity of eroded thickness on maturity records and to find out the best model to fit the actual maturity and temperature profiles (Fig. 5). Consequently the eroded thickness by the Austrian unconformity was determined to be of the scale of 1,900m at the A1-113/3 well location.

Maturation: The geohistory diagram shows at the A1-113/3 well location that both ITHS and BTHS had reached into the oil window (early-mature-stage) in Devonian to Carboniferous and the main gas generation stage during the Hercynian heating phase (Fig. 6), while the A. O. Shale is suggested to have been in the mid-mature-stage since the Hercynian heating event.

Setting of Peudo-well: Overlay of the Haouaz paleo-highs to the amplitude anomaly map of the 'BTHS' horizon clearly shows that the BTHS are distributed to surround the paleo-highs. In such geological setting, hydrocarbons are expected to have been migrated from these local BTHS kitchens to nearby structures. In order to simulate the timing of hydrocarbon generation and expulsion and expelled volume in the kitchens, a pseudo-well is created. The pseudo-well PSW-1 is located in the north-south elongated BTHS kitchen between the "East Bu Raswan" and "Azirir H." structures (Fig. 7). Stratigraphic and paleo-historical model at the pseudo-well location is constructed based on

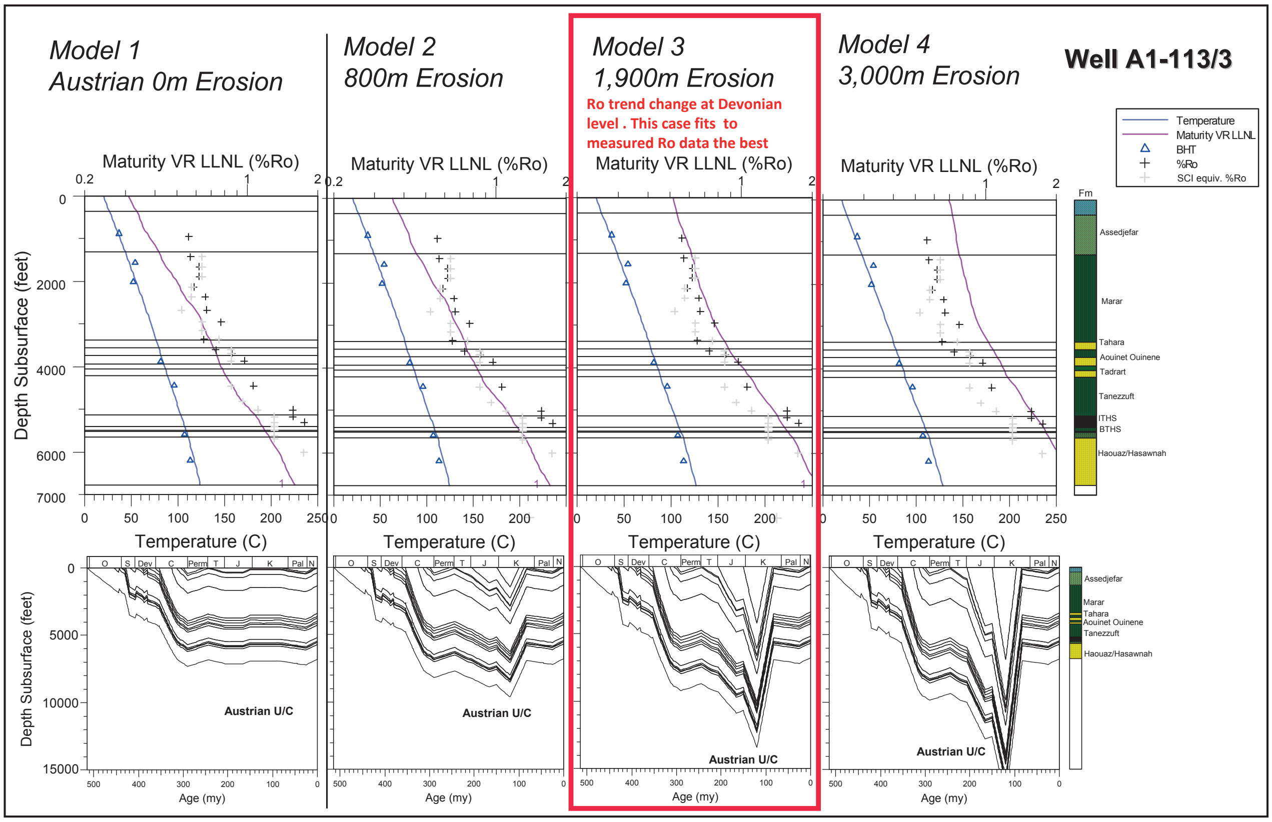


Fig. 5. Comparison of four different stratigraphic models to estimate the amount of Austrian erosion at the A1-113/3 well location, indicating eroded thickness up to 1,900m at the Austrian unconformity.

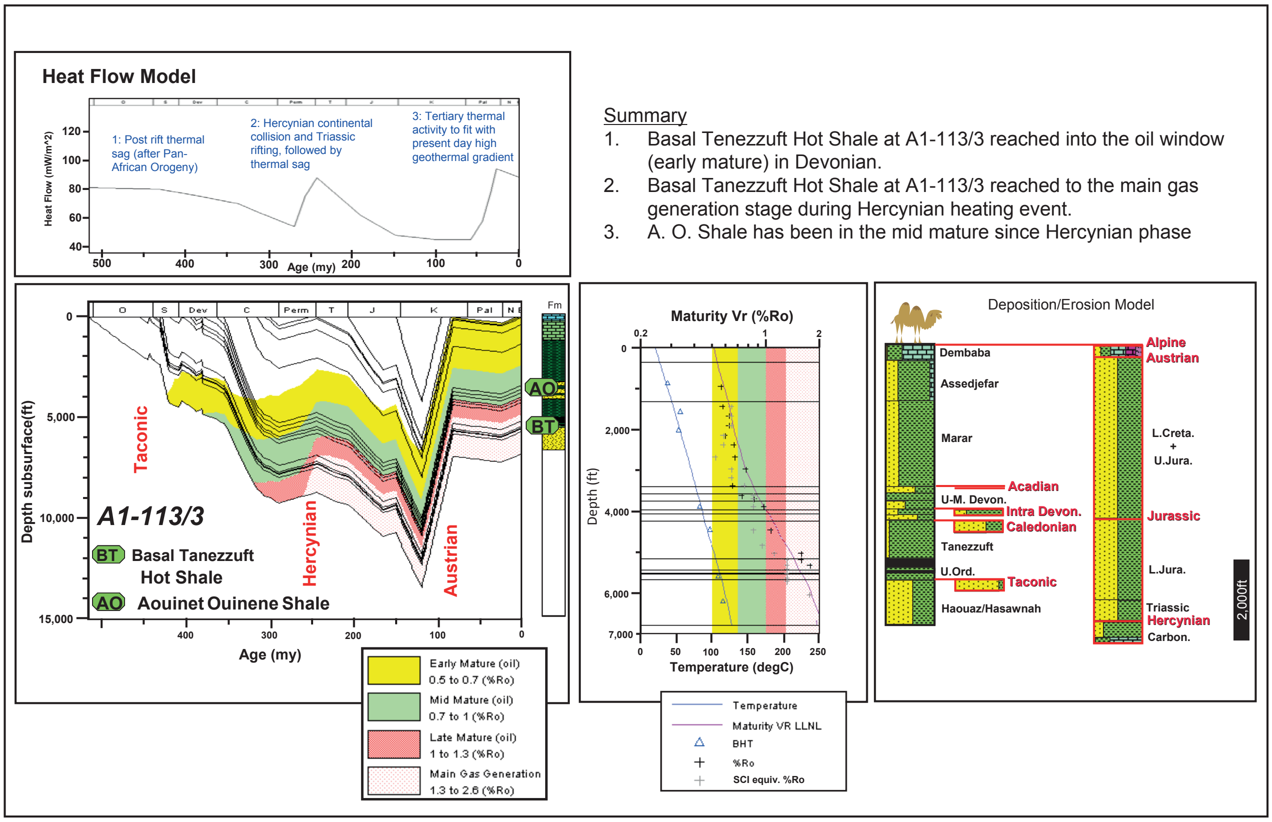


Fig. 6. The reconstructed paleohistory with maturation history at the A1-113/3 well location.

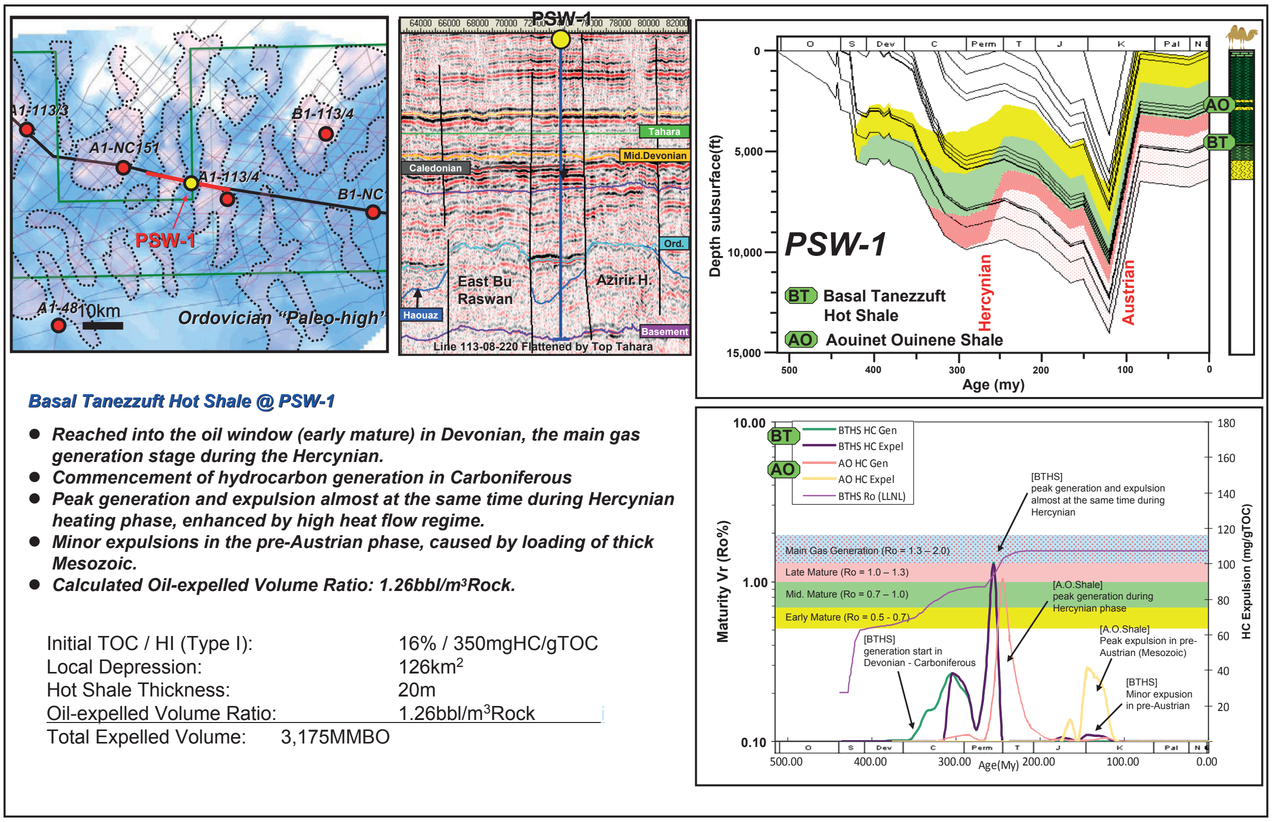


Fig. 7. Summary of 1D basin modeling at the pseudo-well PSW-1, including the maturation history, timing of hydrocarbon generation and expulsion and expelled hydrocarbon volume..

the following assumptions: 1) Present formation thickness based on post-drilling seismic/structural interpretations, 2) Almost same burial history as the well A1-113/3 but greater erosions at the Austrian event than the well A1-113/3 to be consistent with the existing geologic column and 3) Same heat flow model as the well A1-113/3.

The modeled geohistorical diagram shows that the BTHS at the pseudo-well PSW-1 reached into the oil window (early-mature-stage) in Devonian and the main gas generation phase during the Hercynian heating phase. On the other hand, the A. O. Shale is suggested to have been in the middle-mature-stage since the Hercynian heating phase.

Hydrocarbon Generation and Expulsion: The simulated hydrocarbon generation and expulsion history of the BTHS at the pseudo-well PSW-1 is summarized (Fig. 7):

- Commencement of hydrocarbon generation in Carboniferous
- Peak generation and expulsion almost at the same time during Hercynian heating phase, enhanced by high heat flow regime.
- Minor expulsions in the pre-Austrian phase, caused by loading of thick Mesozoic.
- Calculated oil-expelled volume ratio: 1.26bbl/ m3 rock at PSW-1.
- Estimated total expelled oil volume: 3,175MMBO from a local depression between “Azirir H.” and “East Bu Raswan” structures with assumed kitchen area of 126km2 and hot shale thickness of 20m.

RESERVOIR GEOLOGY

Stratigraphic Subdivision of the Haouaz Formation: The presence of thin Upper Ordovician Melez Chograne Formation and extremely thin BTHS and lack of the Upper Ordovician Memouniat Formation on the glaciated Haouaz Formation at the wells A1-113/3, A1-113/4 and B1-113/4 indicate these well locations are very close to the crest of each paleo-high structure drilled. Flattened images of the seismic data and difference in thickness of the Melez Chograne Formation encountered at the wells A1-113/3, A1-113/4, A1-NC151 and B1-113/4 suggest the Haouaz remnants encountered at each well location are not stratigraphically same with each other as the degrees of glacial erosion are different among the Haouaz paleo-high structures (Fig. 8). The Haouaz Formation at the well B1-NC151 is overlain by thick Melez Chograne and

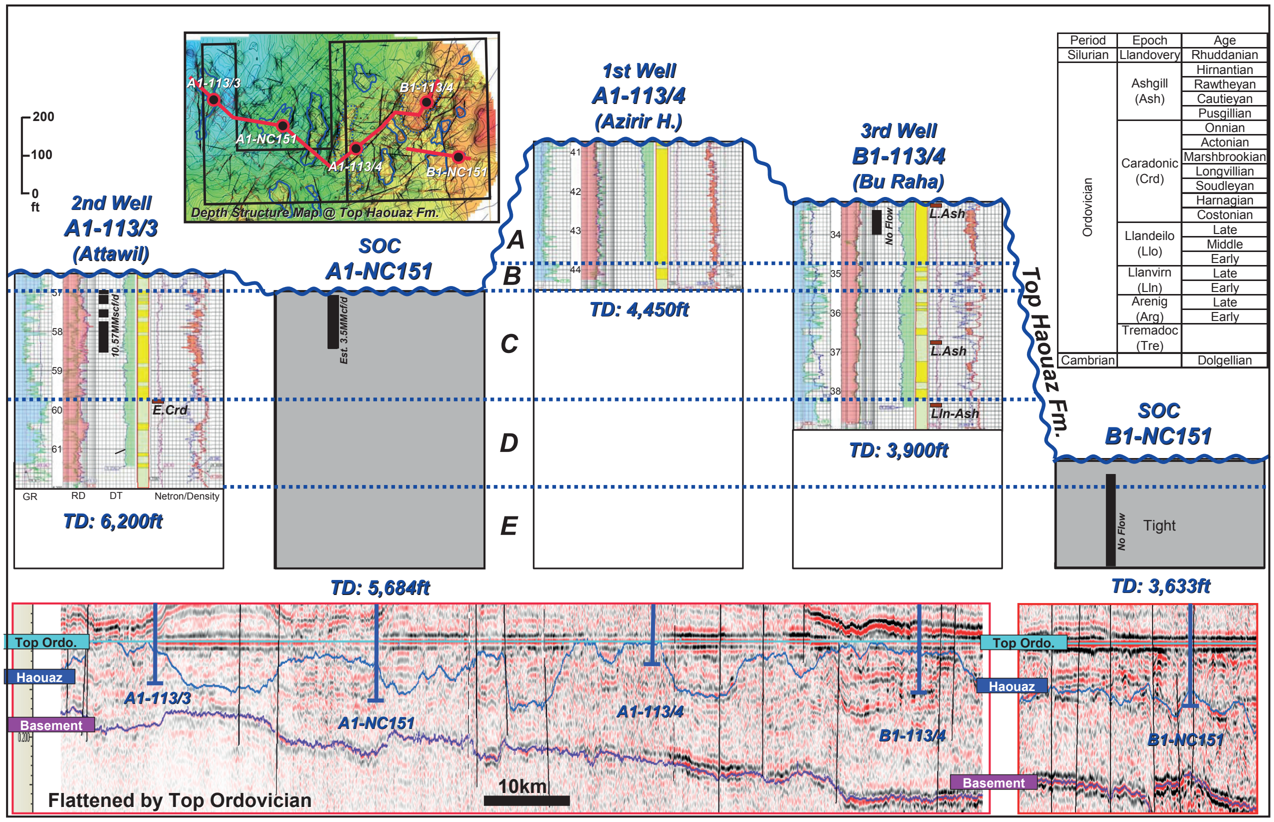


Fig. 8. Well correlations and flattened seismic sections, showing five (5) litho-stratigraphic units of the Haouaz Formation.

Memouniat Formations and relatively thick BTHS is present, indicating that the structural anomaly drilled by the well B1-NC151 is not a paleo-high structure.

The Haouaz Formation in and around the Area 113-3 & 4 is divided, based on the well correlation, seismic interpretation and biostratigraphic analysis, into five (5) litho-stratigraphic units, Unit A to Unit E in descending order, among which the Unit B and the Unit D are shaly. The uppermost parts of the Haouaz Formation are made up of the Unit A at the wells A1-113/4 and B1-113/4, the Unit B at the well A1-113/3, and the Unit C at the well A1-NC151. The Haouaz Formation penetrated at the well B1-NC151 is composed of the lower part of the Unit D and the Unit E. This litho-stratigraphic subdivision indicates that the wells A1-NC151 and A1-113/3 produced gas from the Unit C and that the Unit C may become shaly eastward though the unit was not penetrated at the well A1-113/4 and has been completely eroded out at the B1-NC151 well location.

Reservoir Property: Microscopic analysis (thin section examination) reveals that sandstones of the Unit C show the best reservoir quality. Conventional core samples taken from the Unit A at the well B1-113/4 are composed of poorly sorted sandstones which are characterized with high grain percentage up to 80% and high clay contents, indicating that reservoir properties of the Unit A sandstones have been originally very poor (Fig. 9). It is noted that point count porosities by thin section examination are much lower than CCAL porosities in the Unit A due to the dominance of micro pores between clay minerals. In contrast, SWC samples taken from the Unit C at the well A1-113/3 consist of fine-grained and well sorted quartzites which had the original porosity up to 35% without any clay content and are characterized significant quartz overgrowth (Fig. 10). SWC samples taken from the uppermost part of the Unit A at the well A1-113/4 and conventional core samples from the bottom part of the Unit C at the well A1-113/3 are silty/shaly and very fine-grained sandstones with very poor reservoir quality. The reservoir quality of the Haouaz sandstones is varied among litho-stratigraphic units and seems to be controlled by the original texture and composition rather than the latter diagenetic alteration.

It is interpreted that originally superior reservoir properties of the Unit C sandstones was deteriorated to some extent due mainly to quartz overgrowth,

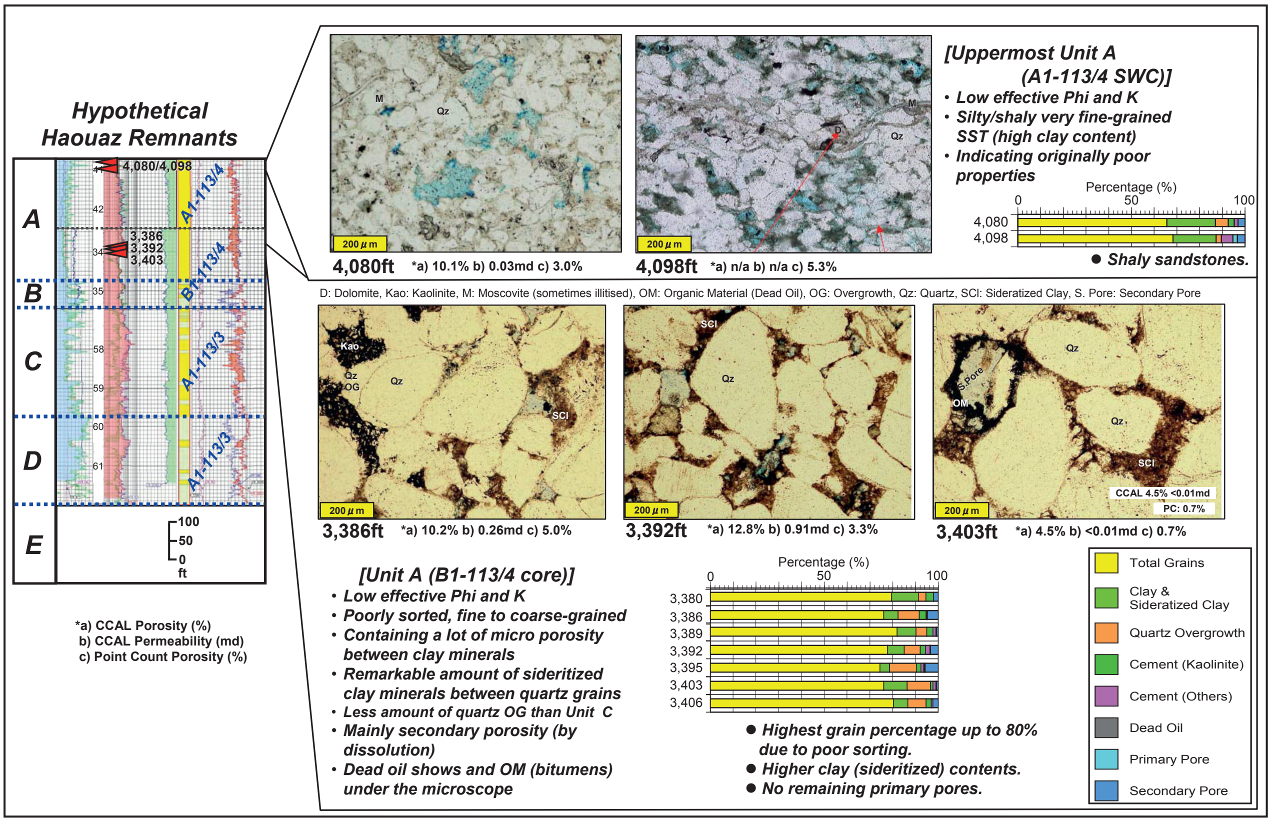


Fig. 9. Hypothetical type section of the Haouaz Formation with photomicrographs and petrographic descriptions of the Unit A.

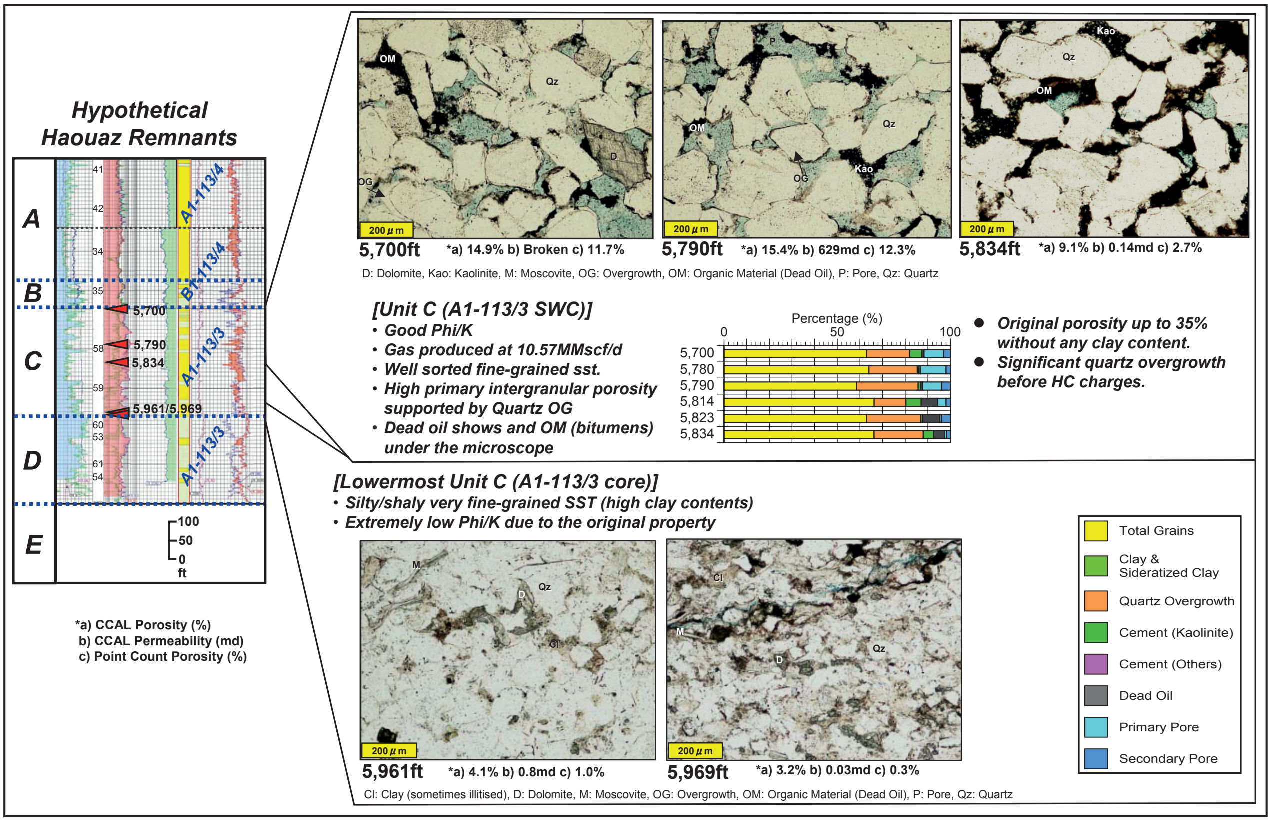


Fig. 10. Hypothetical type section of the Haouaz Formation with photomicrographs and petrographic descriptions of the Unit C.

however, have been retained by efficient hydrocarbon migration into the sandstones. On the other hand, originally poor reservoir properties of the Unit A sandstones had less chance to receive hydrocarbon charges and have become worse.

PETROLEUM SYSTEM

Diagenesis and Hydrocarbon Migration: The above-mentioned source rock and reservoir studies suggest the following diagenesis and hydrocarbon/non-hydrocarbon migration history/steps to form the A1-113/3 gas accumulation (Fig. 11).

- Deposition of well-sorted fine quartz grains of the Haouaz Unit C (original porosity up to 35%).
- Pre-Hercynian quartz overgrowth.
- Subsequent minor clay infiltration/cement.
- Oil charge into remaining intergranular pore spaces of the Haouaz Unit C during Hercynian phase from the juxtaposed BTHS.
- Replacement of oil with gas or thermal cracking (generation of dead oil stain).
- Generation of secondary pores by dissolution possibly in Austrian.
- Replacement of gas with CO_2.
- On the other hand, the following steps are interpreted for tight and no hydrocarbon-bearing Haouaz Unit A of the B1-113/4 structure.
- Deposition of poorly sorted fine to coarse quartz grains accompanied with clay (much lower original porosity).
- Pre-Hercynian quartz overgrowth.
- Sideritization of original clay.
- Subsequent clay infiltration/cement.
- Very minor oil charge in Hercynian due to negligible permeability.
- Minor dolomitic cementation and generation of secondary pores by dissolution possibly in Austrian.

Critical Factor for Haouaz Play: The main hydrocarbon generation and expulsion from the BTHS are simulated to have occurred in the Hercynian phase. Therefore direct contacts between the Haouaz Unit C sandstones on the paleo-high structures and the surrounding BTHS during Hercynian phase are most desirable to achieve an efficient hydrocarbon migration from source rock to reservoir (Fig. 12). Meanwhile, such efficient hydrocarbon migration is unlikely between the Unit A and the BTHS and under the condition of poor physical contacts due to the presence of thick and shaly Upper Ordovician. The most critical factor for formation of the Haouaz play is physical relationships between the Haouaz sandstones and the BTHS, though a certain level of trap deformation and secondary hydrocarbon migration might have occurred in and after the great Austrian uplift and tilting event.

SUMMARY AND CONCLUSION

The integrated post-drilling study including the reconstruction of stratigraphic framework, basin modeling study and petrographic study brought the following speculations for the petroleum system and play concept in the Area 113-3 & 4.

- The potential matured source rock is primarily the BTHS, which is distributed discriminatively in paleo-topographic lows surrounding Haouaz paleo-high structures.
- Maturation history is characterized by distinctive three heating phases: 1) Post-rift thermal sag after the Pan-African Orogeny, 2) Hercynian continental collision and Triassic rifting followed by thermal sag, and 3) Alpine volcanism, and by significant erosion of the post-Hercynian sediments more than 6,000ft in thickness, resulted in extremely high maturity of the BTHS in spite of its shallower present depths.
- The pseudo-well PSW-1 in the central part of the Area 113-3 & 4 simulated that the THS reached the early oil generation window in Devonian Age and the main hydrocarbon expulsion occurred in the Hercynian heating phase.
- The Haouaz Formation is divided into five (5) litho-stratigraphic units, Unit A to E in descending order. The Haouaz remnants encountered at each well location are not stratigraphically same with each other as the degrees of glacial erosion are different among the Haouaz paleo-high structures.
- The Unit C sandstones have superior reservoir qualities, while those of sandstones in the other units are originally poor. The reservoir quality of the Haouaz sandstones seems to be controlled by the original texture and composition rather than the latter diagenetic alteration.
- Physical relationship/contacts between the Haouaz Unit C sandstones on the paleo-high structures and the surrounding BTHS are the most critical factor for formation of the Ordovician play from the viewpoint of hydrocarbon migration in the southern margin of the Ghadames Basin.

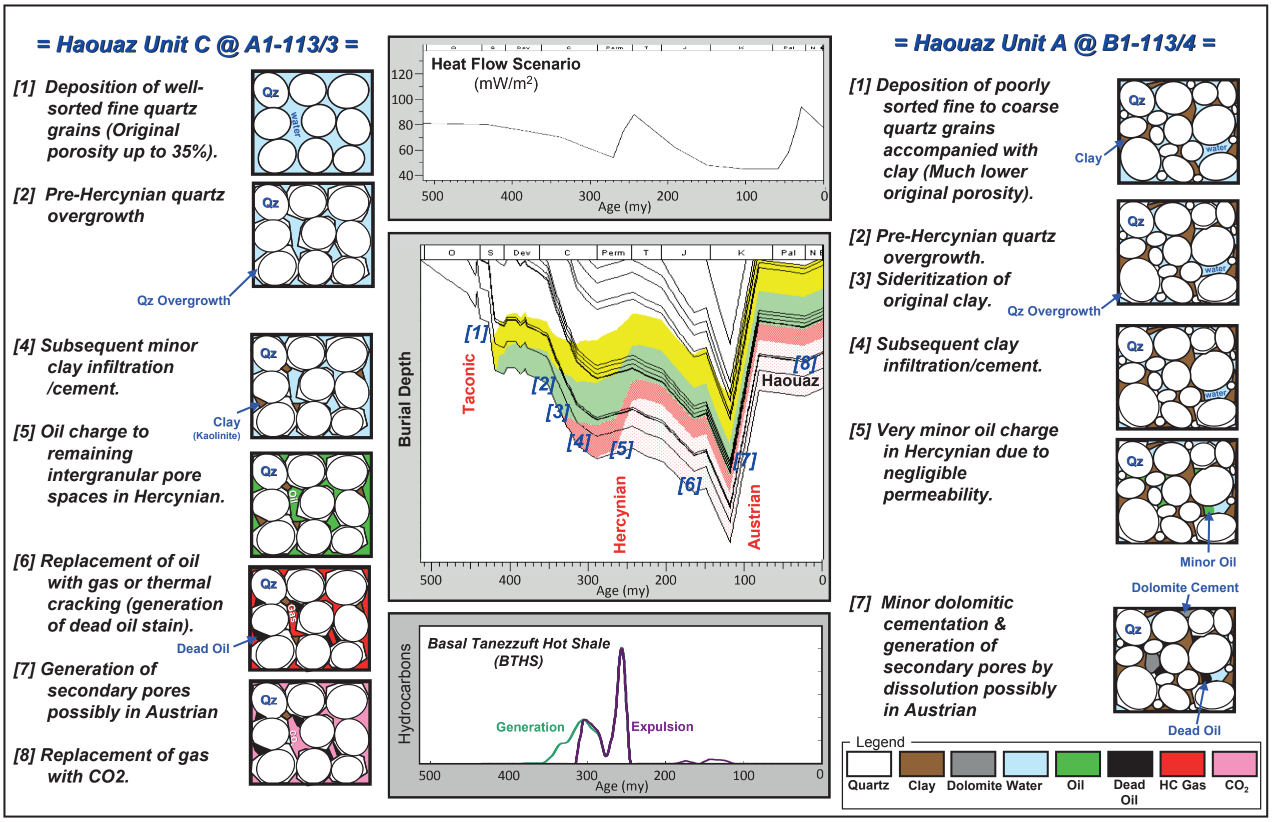


Fig. 11. Relationship of diagenesis and hydrocarbon migration for the tested Haouaz paleo-high structures.

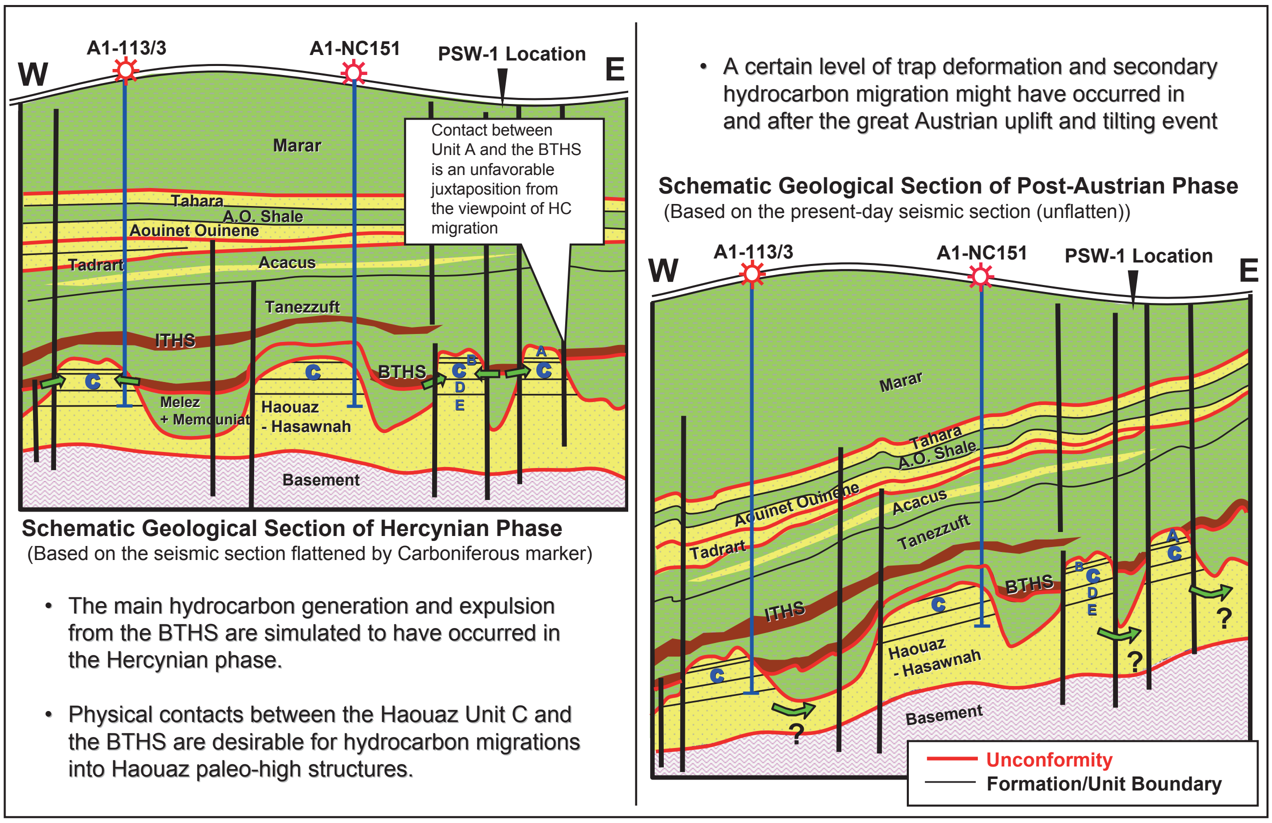


Fig. 12. Hydrocarbon migration model in the Area 113-3&4.

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