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Sources and Uses of Water in the Oil Industry - Deep Groundwater Aquifers (Achebyat and Hasawnah), SW Murzuq Basin, Libya

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ABSTRACT

Deep water sources are important in providing the amount of water required to be injected into the oil reservoirs to maintain reservoir pressures and to avoid a decrease in pressure below bubble point, which directly affect oil production and reserves. This objective of this study was to identify the deep aquifers water sources potential and quality of the Achebyat and Hasawnah formations within NC200 block, to be injected into the Erawin field Mamuniyat reservoir. The study provides a geological description of Achebyat and the Hasawnah formations, estimate the water volume, investigate the water productivity, determine water salinity, and propose optimum water source wells location. Seismic data, core and wireline logs information including image logs, well test results and outcrop information were used for this study. The Achebyat aquifer has a mean porosity of 12.4%, while Hasawnah has lower porosity than Achebyat with a mean value of 8.8%. The bulk rock volume is about 13.9 trillion cubic-feet, and the estimated water volume is 992 billion barrels. The required makeup water for water injection would be 16,5000 bbl/d, around 6 million barrels per year. E6-NC200 Achebyat-Hasawnah production test rate was 1,360 bbl/d. In this test, the determined PI was 2.0 bbl/d/psi. Water salinity was estimated during the well E6-NC200 production test to be 2000 ppm. The Achebyat and Hasawnah deep groundwater aquifers in the study area can be used, in addition to the oil industry, as a source for drinking and agricultural water after simple treatment.

Keywords: Deep Aquifers; Hasawnah Formation; Achebyat Formation; Erawin Field; Murzuq Basin.

1. Introduction

The study area of interest covers partially concession NC200 in the Murzuq Basin, SW Libya [1] , Fig.1. This report includes a geological description of the Achebyat and Hasawnah formations that form the main aquifers for Erawin E, G and H oil fields. Petrographic characteristics are also outlined for each of the aquifers with respect to aquifer quality.

A geophysical section describes the data used, horizons interpreted, well calibration and depth conversion methods. Well correlations have been performed for the aquifers in the upthrown and downthrown blocks of the main E-pool boundary fault. IP Petrophysics analysis was performed on E6-NC200 well (deep well which penetrates Achebyat and Hasawnah aquifers) to estimate porosity, volume of shale and predicted permeability index.

A geocellular model was constructed for NC200 concession with 250mx250m cell size to capture the geological character of these typically massive and generally uniform formations. The stratigraphic models were used as the basis for creating 3D corner point grids. The surfaces used for the structural model are top Achebyat, top Hasawnah and top Basement.

Core porosity and permeability data from NC115 wells were used to derive equations for permeability calculation to be propagated in the 3D model for Achebyat and Hasawnah aquifers. Fracturing evidenced by FMI logs is discussed in this report.

The primary objective of this study is to describe the geological characteristics of the Achebyat and Hasawnah aquifer formations using data from NC200 wells and the updated Erawin 3D seismic interpretations covering Erawin fields (E, G and H), as well as the information obtained from the adjacent fields in the area. The main objectives comprise, description of the geological characteristics and aquifer quality of the Achebyat and Hasawnah formations; calculation of thickness maps for the Achebyat and Hasawnah aquifers, and to understand the thickness variations of the Deep Aquifers within the study area; build a 3D geological model of the Deep Aquifers inside NC200 concession, and to calculate their respective water volumes; recommend locations for drilling future Deep Aquifers' Water Source Wells.

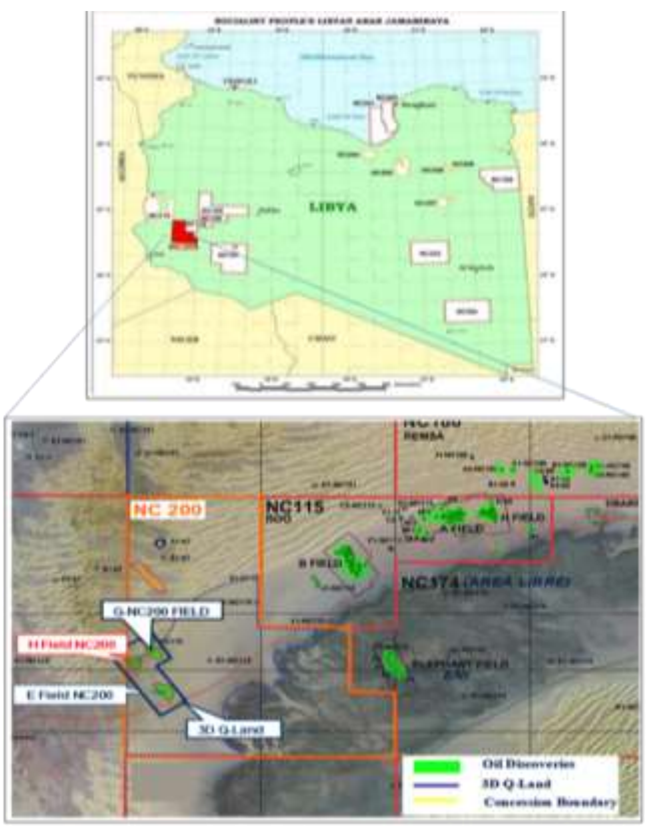

Fig. 1. Study area location map (NC200), From Repsol Exploration Murzuq, and Internal Report

2. Geological Setting

NC200 block is located within the Murzuq Basin, SW Libya, one of several intracratonic basins on the North African Platform. The basin extends over an area of more than 350,000km^2. A few events in the *Arenig* and then in the *Taconic* (glacial event) caused slight structuring, but the Devonian aged Caledonian orogeny represents the first major phase of movement. The sedimentation of the Cambro-Ordovician Achebyat/Hasawnah formations therefore took place in a relatively quiet basin where strata are believed to be mainly eustatically controlled [2]. The marine Achebyat formation is attributed to the Lower Ordovician period. It overlays the fluvio-deltaic, Cambrian-aged, Hasawnah formation [3-5], Fig.2. illustrates the general stratigraphy for Murzuq Basin that is dominated by clastic units [3]. Depositional environment is predominantly shallow marine settings for the Achebyat and the upper part of Hasawnah, and mainly fluvial for the lower part of Hasawnah.

The Achebyat is overlain by the fluvial to shallow marine Hawaz formation (Massa and Collomb 1960). The conformable Middle Ordovician Hawaz formation is represented by sandy, transgressive-regressive marine sequences with intense bioturbation. The Middle Ordovician is deeply incised due to erosion, intense lowstand, in the late Ashgillian (Hirnantian-glacial) unconformity, associated with the maximum advance of the Gondwana ice cap. The Upper Ordovician (Ashgillian), Melaz Shuqran and Mamuniyat formations, fill the incised valleys and rest unconformably on the Hawaz formation. The Melaz Shuqran formation is represented by diamictite and slumped delta front shales but is only locally present. It is overlaid/overstepped by incised cycles of coarsening upward marine and fluvio-deltaic sediments of the Mamuniyat formation (primary reservoir objective).

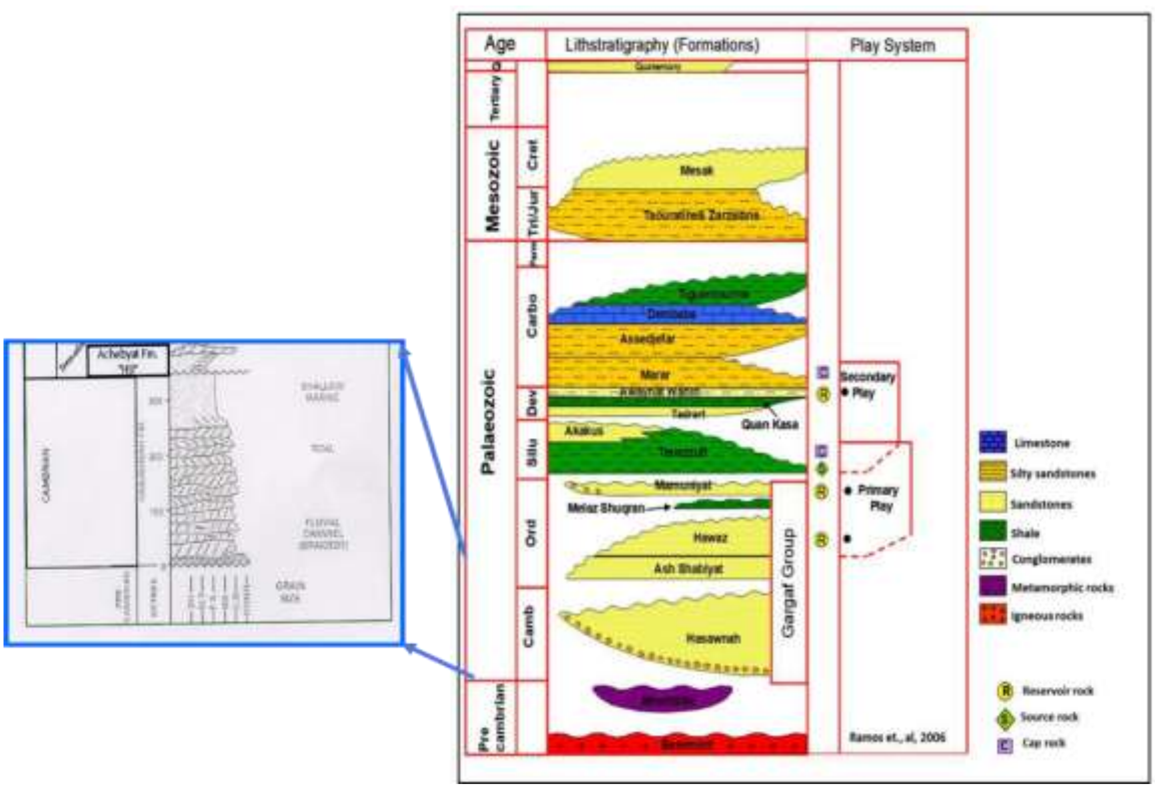

Fig.2. Stratigraphic Column with depositional setting interpretation for Deep Aquifers, modified from Davidson et al.

3. Geological Description of the Deep Aquifer Formations

The Lower Ordovician (*Arenig-aged*) Achebyat Formation was deposited in a quiet tectonic basin in a gentle shelf environment [6] Fig.3 where the strata are believed to be eustatically controlled [7]. Sediments comprise predominantly well-sorted fine to coarse-grained, bioturbated (usually *Skolithos*) marine sands. Other sediments include tidal channel and locally reworked facies.

The Achebyat is confidently broken into three formation members Fig .4. The lowermost member, the Lower Achebyat comprises mainly estuarine and tidal channel deposits. The Middle Achebyat member, has two distinctive high gamma ray peaks associated with it. This member comprises mainly fine-grained sandstones and siltstones [6]. These sediments may represent a period of relative sediment starvation, possibly related to sediment cut-off from the land. The Uppermost member, the Upper Achebyat comprises mainly shelfal, fine-grained sandstones together with coarser grained subtidal channel sandstones. This member is characterized by having a very low gamma ray response and very good permeability.

The principal diagenetic type is quartz overgrowths which developed early, thus providing a rigid framework preventing much porosity loss directly through compaction. These overgrowths fill 30-90% of the original pore spaces and generally have destroyed most porosity in the very clean fine-grained sediments. Minor secondary porosity was developed through the dissolution of feldspars and other grains. Illite and illitic clays are mostly recrystallisation/overgrowth products of detrital mud, and together have locally helped preserve porosity by inhibiting quartz overgrowth formation. Therefore, the slightly argillaceous bioturbated sediments generally have higher porosities. Than the cleaner less bioturbated sediments. The argillaceous sediments, however, are more prone to stylolite and associated small fracture development. The illite, mud and locally common kaolinite partially choke some pores reducing original macroporosity to microporosity and reduce overall permeability. Dolomite/siderite, quartz and anhydrite locally fill some fractures; however, most are open to partly open.

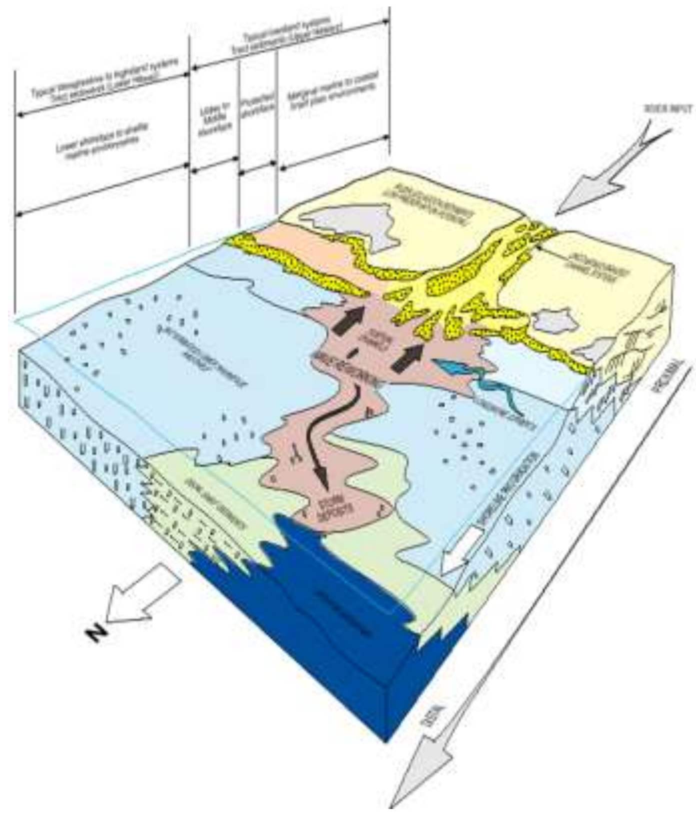

Fig.3. Depositional environment for the Achebyat Formation, From Repsol Oil Operation Internal Report

The Cambrian-aged Hasawnah Formation comprises mainly coastal braid plain to shallow marginal marine tidal and distributary channel sediments. It is predominantly sandstone; however local mudstones are common with serrated signature of gamma ray log response [8]. It is formally broken into Upper, Middle and Lower members. This breakdown is distinguished generally on sequence stratigraphic evaluation, which is largely based on the interpretation

of gamma ray character [6] Fig.4. Siltier deposits are more common in the upper layer, suggesting a restricted marine setting where tidal flat and distributary channels are common. The upper layer is the most radioactive of the layers. It contains abundant mica and kaolinite minerals. In contrast the middle layer is cleaner and sandier. This layer corresponds to an early transgressive systems tract where most of the parasequences show coarsening up profiles.

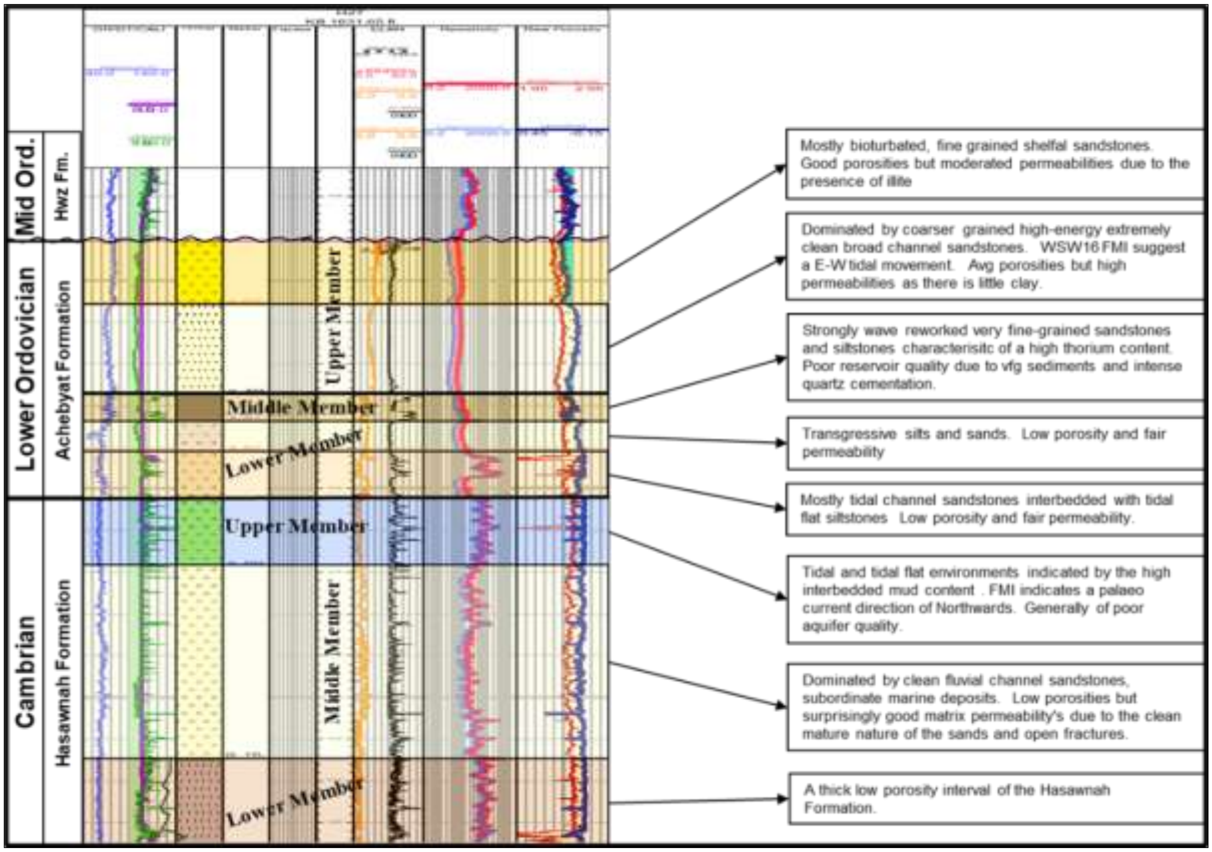

Fig .4. Achebyat and Hasawnah breakdown largely based on the interpretation of gamma ray character (1st track: blue DT, green GR and purple caliber; 2n; 6th track: orang por. And black volume of shale; 7th track resistivity; 8th track: red density and blue neutron), modified after Repsol Oil Operation Internal Report

These sandstones are dominated by fluvial channels. The lowermost layer was penetrated by only a few, very deep basement penetrating, wells. Due to greater accommodation space caused by regional tilting, the Hasawnah Formation gradually thickens to the northeast. Palaeocurrent analysis from image logs suggests sediment deposition from the South to North, a similar model to the deposition of the Hawaz and Mamuniyat Formations. The top of the Hasawnah is defined by an unconformity and the base lies mostly on Pan African basement, sometimes the volcanic derived sediments of the Mourizide Formation.

3.1. Well E6-NC200 result

The well E6-NC200 was drilled within NC200 with the objective to penetrate the deep aquifers and characterize the Achebyat and Hasawnah formations. Log response (GR and Sonic) for the deep aquifers Achebyat, Hasawnah and Basement for the well E6-NC200 is presented in Fig .4. Top of Achebyat was encountered at 4,864ftKB (-2,824ftSS), Hasawnah at 5,032ftKB (-2,992 ftSS) and top Basement at 5,854ftKB (-3,818ftSS).

Petrographically, the sandstones of the studied Achebyat and Hasawnah aquifers are mostly texturally and mineralogically extremely mature. They consist of mainly quartz arenites and sub-lithic arenites. The Upper Achebyat shows very good quality, where very good intergranular porosity is visible. The Hasawnah formation shows moderate to low aquifer quality where a mixture of grain sizes is shown in the middle part of the Hasawnah. Nonetheless, this formation comprises quite reasonable inter-granular porosity

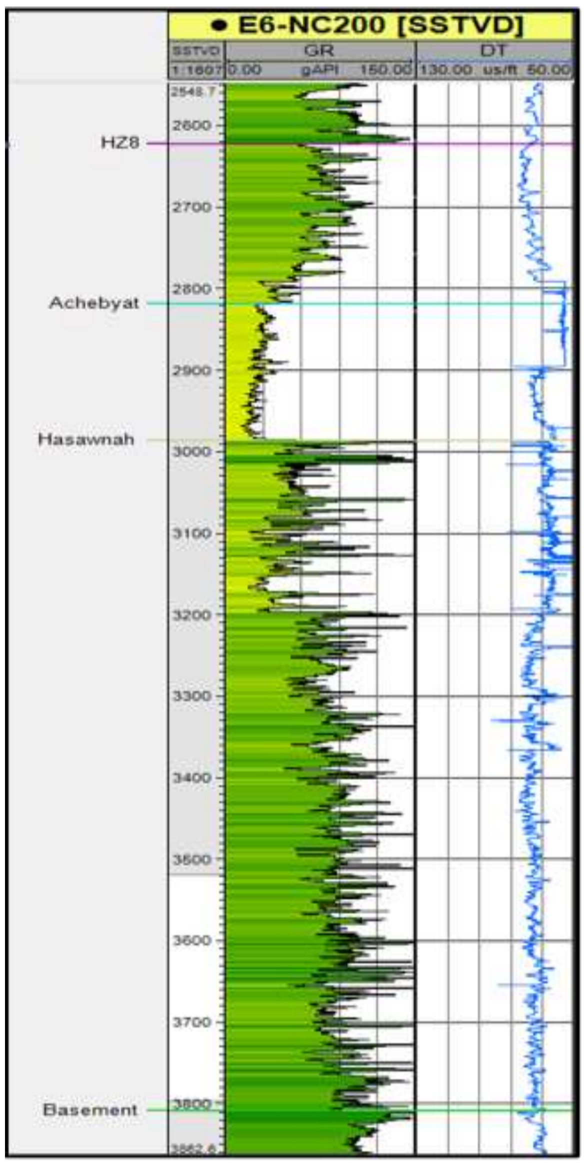

Fig.4. E6-NC200 log response for the Deep Aquifers (Achebyat and Hasawnah

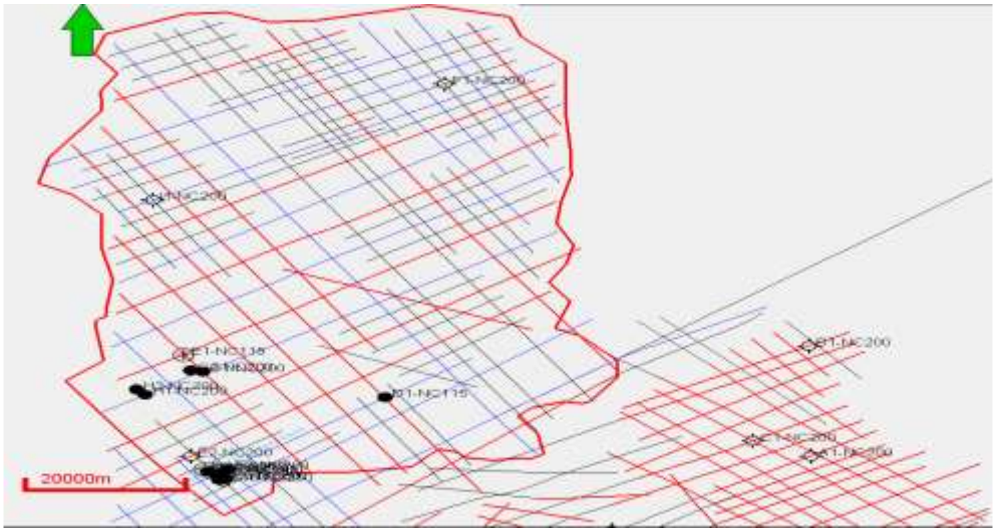

Fig.4. NC200 base map showing seismic lines.

3.2. Seismic interpretation

2D and 3D seismic data within NC200 concession is used for this study Fig.4. The interpreted horizons used for the deep aquifer model include top Achebyat, top Hasawnah and top Basement Fig.5. .The horizons were gridded and converted to depth using Petrel software.

Faults and fractures play a significant role in fluid movement and trapping/compartmentalization. Faults in some places create hydraulic seal insulating the formations, and in other places increase the permeability improving fluid displacement under differential pressure. Therefore, it is very important to understand the fault framework in the study area. Many faults are observed, most of which were rejuvenated during later tectonic events. In this study two main faults, which are associated with big throws, are incorporated in the 3D static aquifer model.

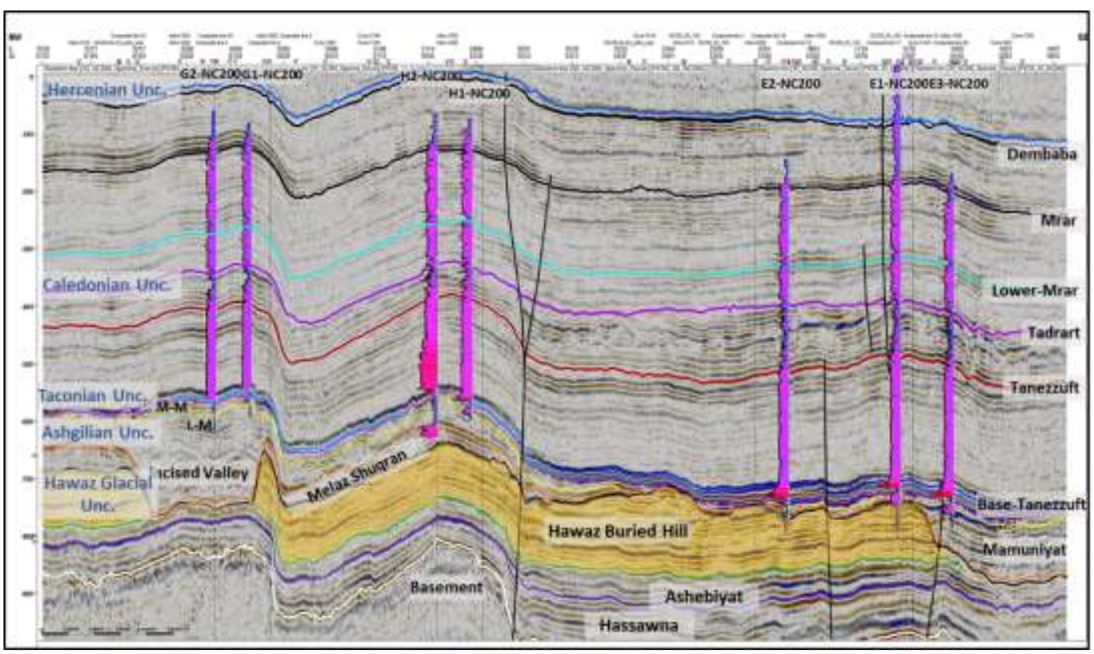

Fig.5. Seismic Section (with the horizons posted)

4. Results

The Deep Aquifers are sandstone dominated lithology characterized by fine to medium, locally coarse grained and cross bedded sandstones. Petrophysical analysis of Achebyat and Hasawnah aquifers for the well E6-NC200 using IP software indicate that the porosity and permeability of Achebyat is much better than Hasawnah with mean porosity values of 13% and 10% respectively. The net pay thickness of Achebyat is 157ft, and for Hasawnah formation is 443ft. Fig.6 shows the petrophysical analysis results for the Deep Aquifers in well E6-NC200, cut-off parameters used are presented in Table0.1. The Deep Aquifers' properties of future Water Source Wells are expected to be similar or better than the ones encountered by the well E6-NC200. Interpreted image log is presented in Fig.7 and SEM image for Achebyat and Hasawnah aquifers [6] are presented in Fig.8.

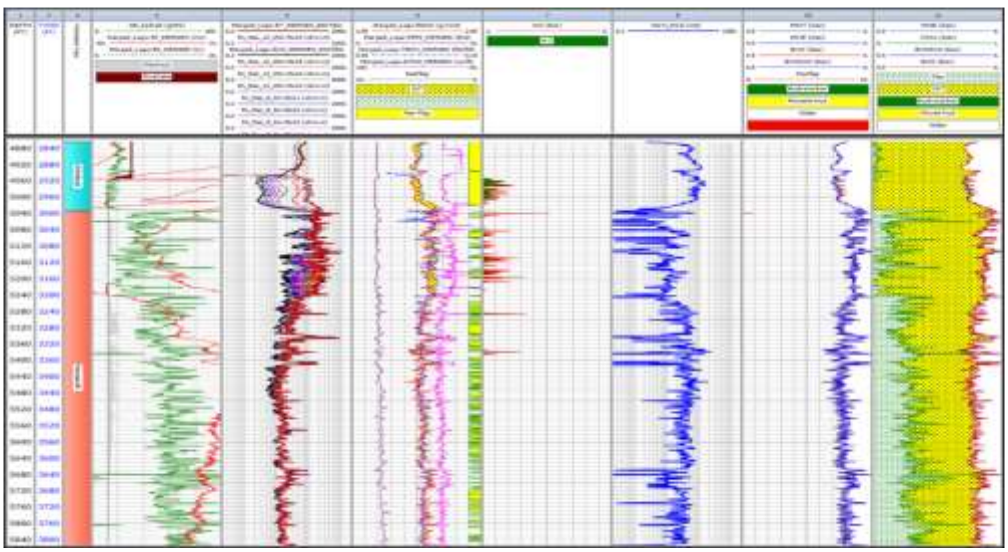

Fig .6. E6-NC200 Deep Aquifers Petrophysical Analysis

Table.1. Cutoffs used: Vcl ≤ 30%, Phi ≥ 8% for Achebyat & 6% for Hasawnah

Zone Depths | Reservoir Cutoffs | Pay Cutoffs | Reservoir Results | Pay Results

Zone # Name	Gross Interval	Net Res	Net/Gross Res	Av Phi Res
9: Achebyat	168.00	157.25	0.936	0.129
10: Hasawnah	822.00	443.00	0.539	0.097

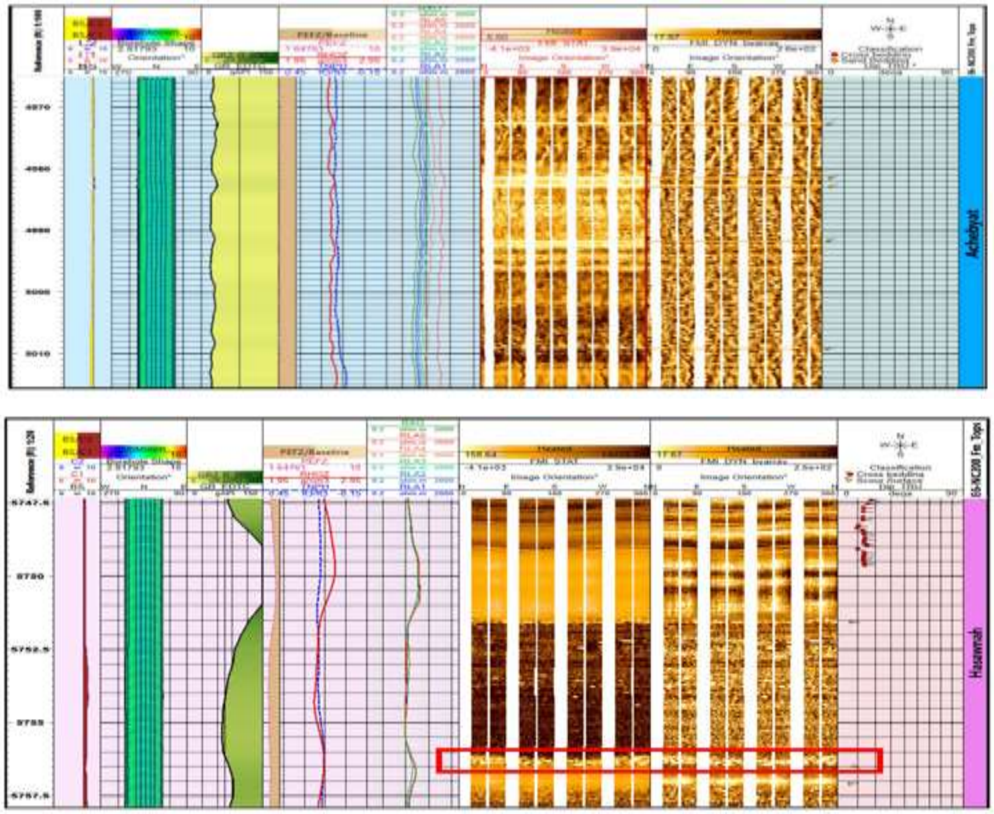

Fig.7.Achebyat biturbated sandstone units (upper FMI image) and Hasawnah conglomeratic sandstone (lower FMI image)

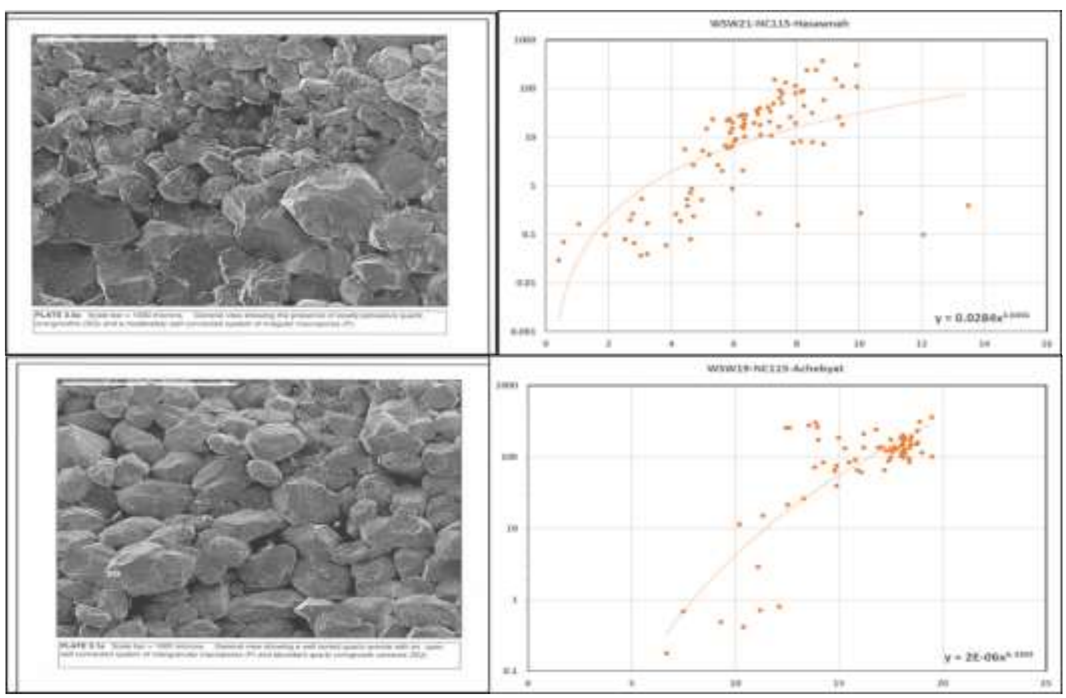

Fig.8. SEM from Achebyat sandstone (upper image) with good intergranular porosity and very good permeabilities (see porosity-permeability cross plot); and Hasawnah aquifer (lower image) shows low porosity and generally moderate permeabilities (see porosity-permeability cross plot), NC115 core data.

4.1. Deep Aquifers Productivity

In E6-NC200, Deep Aquifers Achebyat and Hasawnah 8 ½” open hole (OH) 4,944–6,212 ftKB interval was tested with an ESP inside 9 5/8” casing (pump intake at 4,657 ftKB). Main Flow number 3 water rate was 1,360 bbl/d for a flowing BHP of 1,165 psig. Phoenix sensor recorded maximum buildup pressure was 1,857 psig and determined test PI was 2 bbl/d/psi. The productivity test results are summarized in Table .2.

Table .2. E6-NC200 PI Test Results-Phoenix Sensor @ 4,685 ftKB

ESP Production Test-SN3600-Deep Aquifer-8 1/2" OH Interval: 4,944-6,212 ftKB												
Flow Period	Day	Startup time	Δt hour	Frequency Hz	Choke /64"	Water Rate bwpd	BHFP psig	BHT ºF	PI bwpd/psi	Salinity ppm	WHT ºF	WHP psig
Cleanup	22-Sep-21	06h42	2.7	45	64		1,219	174		26,000	131	43
		09h25	4.0	45	48	1,451	1,192	175		8,000	140	45
		13h27	Diverted well to Test Separator									
		13h30	3.6	50	48	544	1,014	176		4,000	155	55
		15h31	Diverted well to Gauge Tank							2,000		
Main Flow no. 1	22-Sep-21	17h05	6.3	45	32	1,308	1,146	176	1.84	2,000	146	23
Main Flow no. 2	22-Sep-21	23h23	3.7	45	48	1,341	1,131	177	1.85	2,000	147	8
Main Buildup	23-Sep-21	03h05	31.1				1,857	172				
Main Flow no. 3	24-Sep-21	10h08	8.6	45	32	1,360	1,165	177	1.96	2,000	145	40
	24-Sep-21	18h43	End of Test									

4.2. Thickness of Achebyat and Hasawnah Aquifers

E6-NC200 Deep Aquifers well was drilled down to basement and reached TD inside the Basement at 6,212 ftKB. Achebyat and Hasawnah formations were encountered and used to calibrate the interpretation of the Deep Aquifers' horizons. Thickness maps were calculated for Achebyat and Hasawnah aquifers using Deep Aquifers static model Fig.9. At the down thrown side of the E pool main boundary, fault the deep aquifers at the proposed water source WSW1-NC200 location, the estimated thickness of Hasawnah Formation is about 822ft and reaches more than 1,350ft in the area around E pool Fig.9. The thickness of Achebyat in the study area ranges from 0 to more than 350ft, whereas at the well E6-NC200 Achebyat thickness is 168ft. In general, Achebyat thickness is higher in the downthrown block of the main E-pool boundary fault where it can be more than 250ft. Hasawnah thickness can be superior to 2,500ft withi the study area Fig.9 and is more uniform the Achebyat.

4.3. Deep Aquifers Static Model

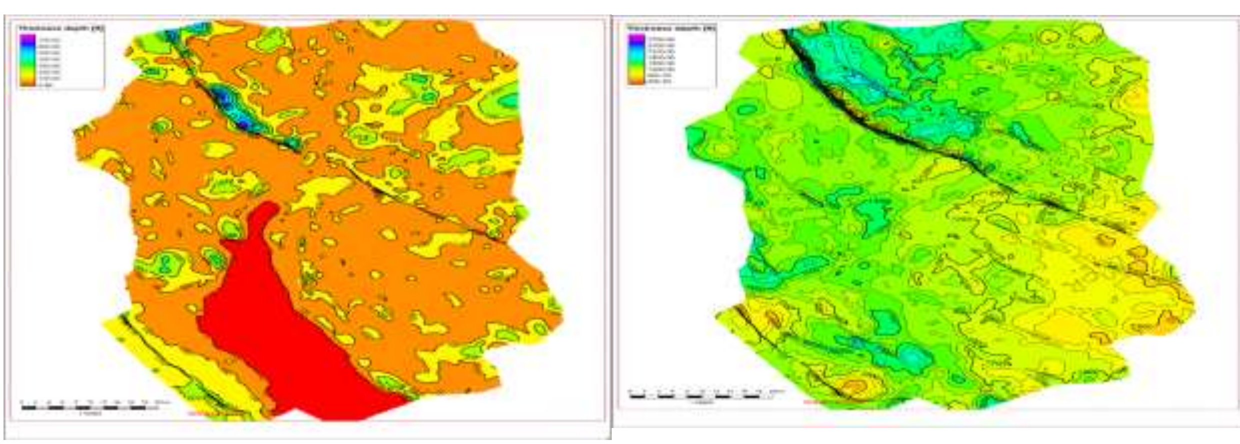

Fig.9. Thickness map for Achebyat–left (CI 50ft) and Hasawnah-right (CI 100ft)

The static reservoir model is based on seismic interpretation (2D & 3D), well logs (including E6-NC200) and core data from adjacent areas (NC115). Top Achebyat, top Hasawnah and top Basement surfaces are used for the structural modeling. Grid dimension of 250m x 250m was selected, which is suitable for such formations and to represent the lateral heterogeneities.

Two faults with considerable vertical throw are incorporated to the model, the west E-pool main boundary fault and the northern area main fault Fig.10.

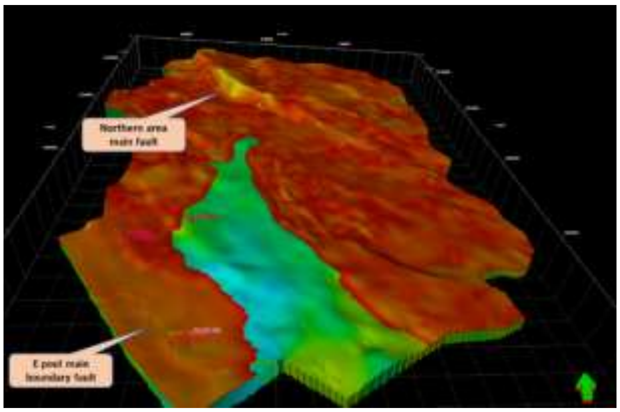

Fig.10. Achebyat and Hasawnah Zones (bulk volume properties)-E pool main boundary and northern area faults

4.4. Facies Modeling

Two facies were interpreted and selected for both aquifers (Achebyat and Hasawnah) and are incorporated in the 3D facies modeling, which include sandstone facies (Code 1) and shale facies (Code 2). The sandstone facies is more dominant than the shale facies and forms about 90% for Achebyat and about 80% for Hasawnah Fig.11.

4.5. Porosity Modeling

Porosity log was calculated for the well E6-NC200 using IP software for the Deep Aquifers (Achebyat and Hasawnah) is upscaled using arithmetic algorithm and biased by facies Fig.12. 3D porosity model results for the Deep Aquifers (Achebyat and Hasawnah) are presented in Fig.13 with a mean porosity value of 12.4 for Achebyat and 8.8% for Hasawnah Fig.13.

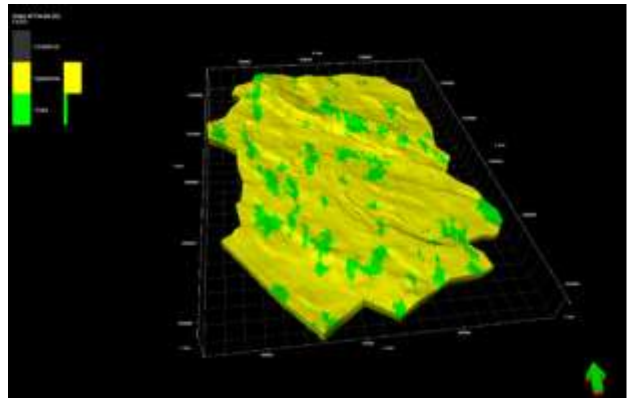

Fig.11. Achebyat and Hasawnah-3D Facies Modeling

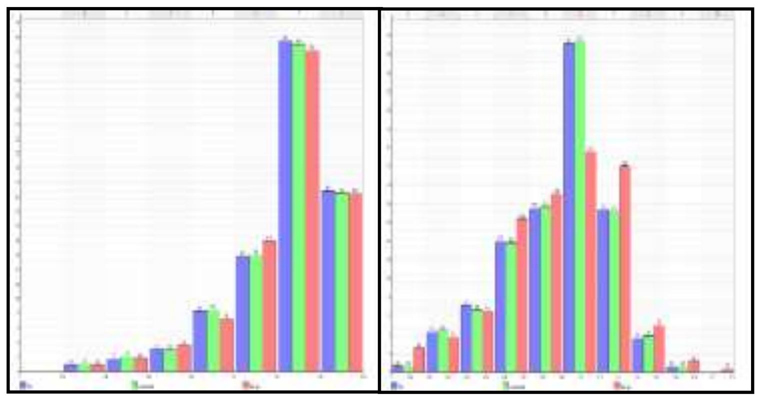

Fig.12. Porosity histogram indicates consistency between well, upscaled and 3D property results *(Achebyat on the left and Hasawnah to the right)*. Note: original well data (purple); upscaled well data (green); 3D model result (red)

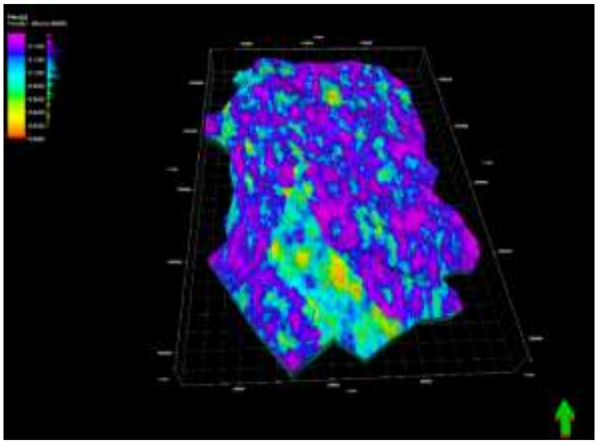

Fig.13. Achebyat and Hasawnah-3D porosity Model

4.6. Permeability Modeling

3D permeability distribution (Amaefule and Altunbay, 1993) is caluculated using equations obtained from core porosity and permeabilty for the Deep Aquifers (cored well data from NC115 Concession, see Fig.10). The model results are presented in Fig .14. Achebyat permeabilty ranges from less than 0.1mD to about 130mD, and in Hasawnah permeability can reach 127mD.

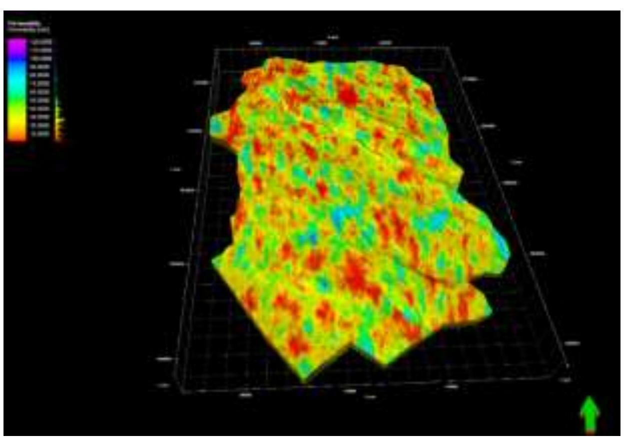

Fig. 14. Achebyat and Hasawnah-3D permeability Model

4.7. NTG 3D Property

NTG 3D proporty Fig.15 was estimated using facies and permebility cutoff. Shale facies (facies 2) and sandstone units with less 1.0mD are non reservoir with NTG=0.

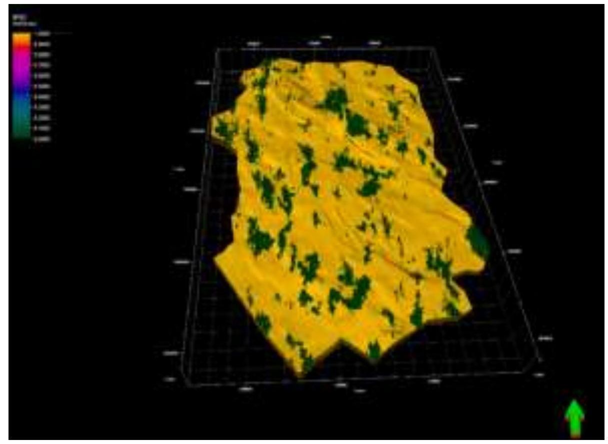

Fig.15. Achebyat and Hasawnah-3D NTG Property Modeling

4.8. Aquifers (Achebyat and Hasawnah) Water Volume Estimation.

Water volume for the Deep Aquifers was estimated for the area under investigation, which covers part of NC-200 Fig. 16. The top surface used for the volumetric calculation is top Achebyat and the base is the top Basement surface (see Deep Aquifers static model section). The estimated bulk rock volume is about 13.9 trillion cubic-feet (13.9 x 1012 ft3) and the estimated water volume is 992 billion barrels (992 x 109 bbl).
For E-pool 16,000 bbl/d oil plateau period without any produced water from E, G and H pools and total absence of aquifer support, 16,500 bbl/d makeup water are needed for pressure maintenance (1.0 Voidage Replacement Ratio). Although future WSWs should have a better PI than E6-NC200, even a 2.0 bbl/d/psi WSW can produce more than 3,500 bbl/d for a flowing BHP of 100 psig and setting ESP pump intake at the 9 5/8” casing shoe. Hence, 4-5 WSWs should be enough to produce the required 16,500 bbl/d makeup water.

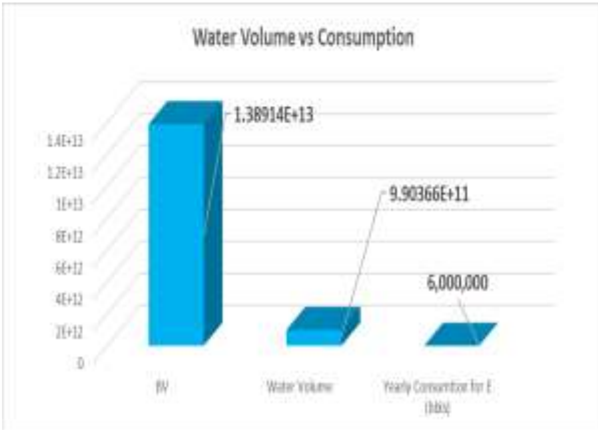

Fig. 16. Achebyat and Hasawnah Aquifers-Water Volume and E-pool yearly water Consumption (note: bulk volume in ft3, water volume and yearly water consumption are bbls)

5. Discussion

From well and seismic data, the Achebyat thickness ranges from zero in the E-pool eastern area in the upthrown side of the E-pool main boundary fault and becomes more than 250ft in the downthrown side of the E-pool boundary fault. Generally, the Achebyat aquifer properties are good with porosity values up to 15% and permeability up to 130mD. This aquifer properties indicate good to very good productivity. The Hasawnah Formation has moderate aquifer properties with mean porosity values of 8.8% and permeability averaging 27mD. Hasawnah thickness is quite high when compared to Achebyat and reaches more than 1,300ft in the downthrown side of the E-pool main boundary fault. Productivity of Hasawnah aquifer expected to range from moderate to good. Vertical communication may exist in the upthrown area of the E-pool main boundary fault in the areas where Melaz Shuqran, Hawaz and Achebyat are progressively eroded because of post Melaz Shuqran/Hawaz erosional events Fig.17. When Achebyat is partially to totally eroded and the Mamuniyat reservoir aquifer is setting on top of Achebyat or Hasawnah, vertical and lateral communication with the Deep Aquifers is possible. In the E-pool main boundary fault downthrown block, Mamuniyat aquifer does not overlay Deep Aquifers (presence of Melaz Shuqran and Hawaz unit H7), and Deep Aquifers are isolated from upthrown block Mamuniyat by Tanezzuft. In line with foregoing points, from the perspective of communication with Mamuniyat aquifer, the downthrown block is a more suitable area to place Water Source Wells. In addition, Achebyat thickness in the downthrown block exceeds 250ft and Hasawnah has a thickness of more than 1,300ft.

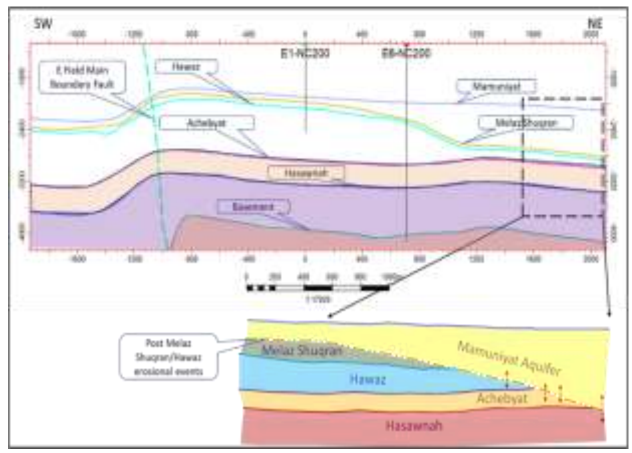

Fig.17. Cross section through the E-pool main boundary fault shows the progressive erosion of Melaz Shuqran, Hawaz and Achebyat towards the NE in the upthrown block, and the possible vertical communication between the Mamuniyat and Deep Aquifers (Achebyat and Hasawnah)

E6-NC200 Achebyat and Hasawnah water productivity is low when compared to NC115 and NC186 average WSW productivity. Tentative WSW locations selected for five wells in E-pool main boundary fault downthrown block, plotted in Fig.18, should have a PI better than E6- NC200. The water salinity is estimated to be 2000 ppm and therefore the deep aquifers Achebyat and Hasawnah can be used as water source for drinking (require simple treatment) and for agricultural utility.

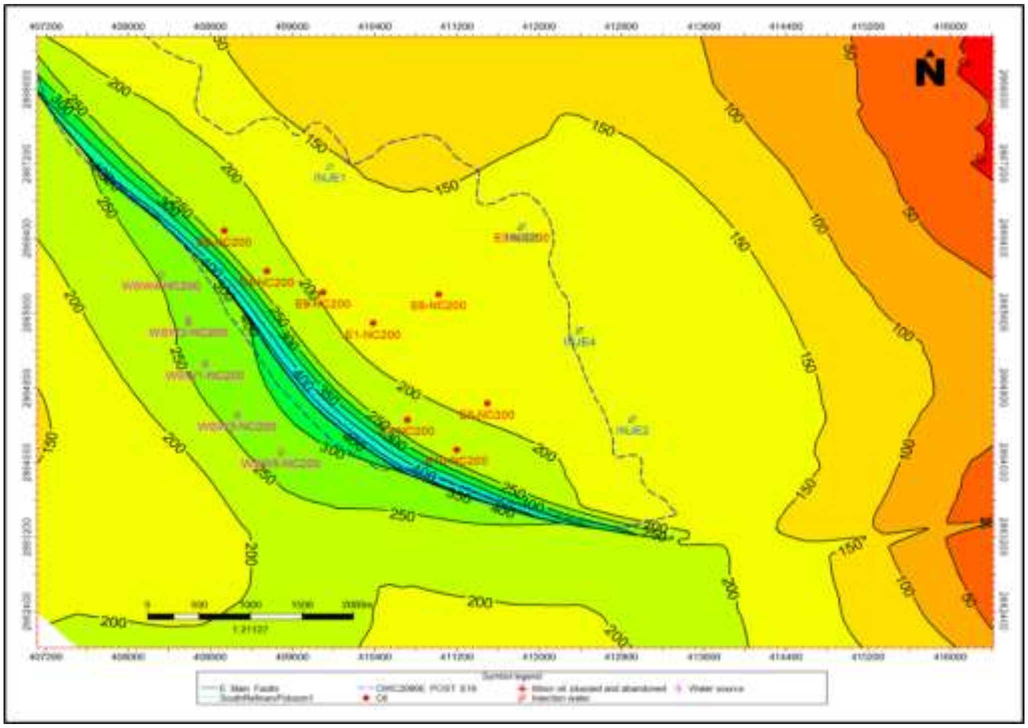

Fig.18. Achebyat Aquifer Thickness Ma- Tentative locations for WSWs

6. Conclusion

The Deep Aquifer formations are present within NC200 with variable thickness ranging from 0 to over 250ft for Achebyat and more than 1,300ft for Hasawnah. In the NE sector of E-field, Mamuniyat overlays Achebyat.

Therefore, WSWs shall not be placed in that area. Equally, WSWs should not be selected where Achebyat is thin or eroded. The Achebyat aquifer has a mean porosity value of 12.4% while Hasawnah has lower porosity than Achebyat with a mean value of 8.8%. Permeability value for both Achebyat and Hasawnah exceeds 25mD on average. Within the control area, the bulk rock volume is about 13.9 trillion cubic-feet (13.9 x 10^{12} ft^3) and the estimated water volume is 992 billion barrels (992 x 10^9 bbl). For E-pool 16,000 bbl/d oil plateau period without any produced water from E, G and H pools and total absence of aquifer support, the estimated makeup water rate required for water injection is 16,500 bbl/d, hence, around 6 million barrels in one year. At E6-NC200 location, the Deep Aquifers deliverability is below NC115 and NC186 average WSW deliverability of 10,000-12,000 bbl/d. The deliverability of well E6-NC200 during the PI test was 1,360 bbl/d for a drawdown pressure of 693 psig. Reducing the flowing BHP to 100 psig and setting the ESP intake at 9 5/8" casing shoe will make E6-NC200 to produce more than 3,500 bbl/d (PI of 2.0 bbl/d/psi). Then, 5 WSWs like E6-NC200 would be enough to deliver 16,500 bbl/d makeup water. Moreover, future WSWs should have a better PI. In the end, the required number of WSWs can be reduced to 4-5 by well location selection and optimizing well location selection and ESP design and setting the ESP intake at 9 5/8" casing shoe.

Aiming at avoiding vertical and lateral communication between Deep Aquifers and Mamuniyat, and increasing PI, which is related to Achebyat thickness, tentative WSW locations are proposed in the downthrow block of E-pool main boundary fault. Mamuniyat aquifer study indicates that partial aquifer support is likely in E-pool.

Therefore, the need for makeup water will be less than predicted above. However, production history is needed to determine the strength of the Mamuniyat aquifer.

7. References

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