Petroleum Res. J. Vol. 14 (2002); P. 37–44, 10 Figs.

A Case History of Attic Oil Recovery of a Unique Multi-layered Bottom Water-drive Carbonate Reservoir

AM. Reda, C. Wong, M. Gharsalla and A. Majdoub*

إستخراج نفط لمكمن علوي جيري لحالة فريدة تتم بواسطة الدفع بالمياه عند القاع

رضا عبد المولى، و س. و نغ، و م. غرس الله و أ. المجدوب

تصف هذه الورقة دراسة محاكاة بعقد الإمتياز 103د في حقل الجيزة بليبيا، الذي يتكون المكمن فيه من صخور جيرية متعددة الطبقات غير إعتيادية ليكون ذا ميزة فريدة حيث يتم الدفع النفطي فيه بواسطة المياه عند قاعه بفعل تسرب كثيراً من المياه من نطاق تغليف بئر حقل المكمن أسفله وليس بواسطة اكتساح المياه الجوفية.

سلطت الظروف المحيطة بفقدان ماء المكمن، وما ترتب على ذلك تحديد لحالة الإنتاج العادية عند إيقاف الحقن، الضوء على وجود طبقة فريدة مجواة وسط التكوين ذات مسامية فريدة تصل إلى 4.5 دارسي. كما أدى مكان وتأكيد وجود طبقة ذات مسامية عالية إلى التعرف على تجمع هائل من الزيت.

هدفت هذه الدراسة إلى تحديد كمية وقوة الخزان الجوفي المائي ومعرفة الزيت المحصور والمتسرب وبحث إستراتيجية للإنتاج الأمثل. كل ذلك تم إنجازه بعد حل لغز تسرب المياه المبكر والذي يشمل الموقع والحجم والشكل وهل تأثير ذلك على نظام الدفع بالمياه طبيعياً.

Abstract: *This paper describes a simulation study of 103D El-Giza, an unusual multi-layered bottom water-drive carbonate reservoir in Libya that features a unique pre-mature water-out, caused not by aquifer invasion but by a massive casing leak of injection water from an underlying reservoir. The circumstances surrounding the reservoir's water-out and subsequent revival to normal production when injection was halted, sheds the light on the existence and extent of a unique 4.5-darcy high permeability vuggy layer in the middle of the formation. The location and confirmation of this dominating high permeability layer led to the identification of a significant attic oil accumulation.*

* Zueitina Oil Company, Tripoli, Libya

The objectives of the study were to quantify the strength of the aquifer, identify trapped and bypassed oil and investigate a strategy to optimize their recovery. These were accomplished after solving the puzzle of the early water-leakage, including its location, volume and profile and sorting out its impact on the natural water-drive system.

GEOLOGY

The reservoir is a symmetrical, dome-shaped structural trap with a shallow relief of 140 feet and a relatively uniform net pay of 50 feet (Fig. 1), overlying a massive bottom aquifer of thickness of 1300 feet. The oil zone is predominantly good quality, fossil-rich calcarenite carbonates. Contrastingly, the quiver is exclusively fine-grained tight calcilutite. Despite similar porosity (Fig. 2) showing across the oil zone, the reservoir is actually layered, as evidenced in the dramatic differences in its resistivity indicators. Based

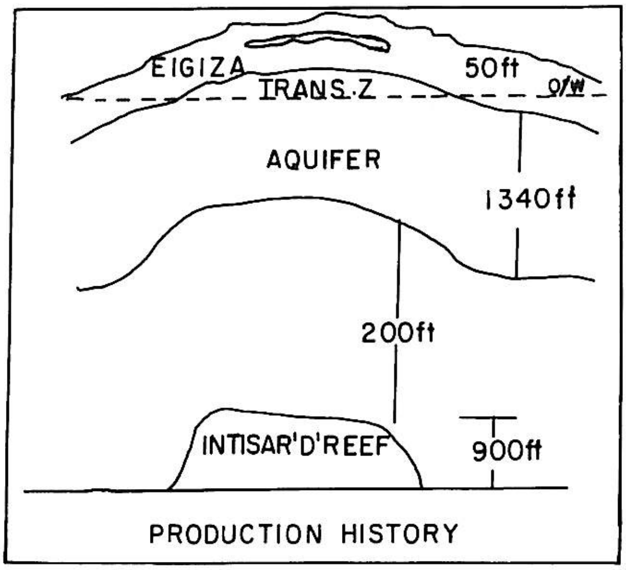

Fig. 1. Schematic structure of El-Giza.

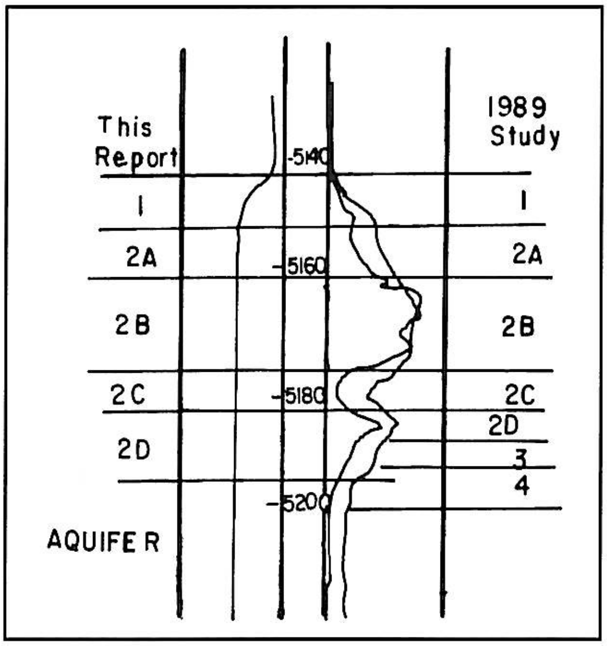

Fig. 2. Layer definitions.

on core permeability and resistivity logs, the thin oil zone can be broken down into five layers (1, 2A, 2B, 2C and 2D). All these layers, with the exception of 2B, and including the tight 2C, can be readily correlated across the field. From core analysis, the bulk of the productive intervals, *i.e.* 2A, 2B and 2D, have permeability in a range of 50 to 150 md, the tight layers, 1 and 2C, 5 md and 10 md, respectively, and the bottom aquifer, a mere two md.

However, this permeability only represents the rock quality of the matrix. Build-up tests show that five of the eight wells have overall permeability exceeding 700 md and as much as 150 md. This test-derived permeability indicates that a secondary porosity system exists. Since no open fractures have been identified in the core, the secondary porosity is most likely vuggy. Core study has, indeed, identified a large amount of mouldic vugs. Numulites and operculinoids are of size up to 20 mm in diameter. The location and area extent of these vugs become the first major puzzle of this study, which need to be resolved before simulation of the production history can proceed.

PRODUCTION HISTORY

The production history itself presents another major puzzle. The entire reservoir actually watered out in 1980, after a 7-year production and an oil recovery of only 8 MMSTB (nine per cent of original oil in place (OOIP) of 84 MMSTB) as shown in the water cut history in figure 3. It is interesting to note that this global water-out was not caused by natural aquifer invasion. Instead, it was caused by the leaking of injected fresh water, intended for another reservoir, the ‘D reef’, some 3300 ft below. This was confirmed by the low salinity water production and the unusual rise of the reservoir pressure (Fig. 4) prior to

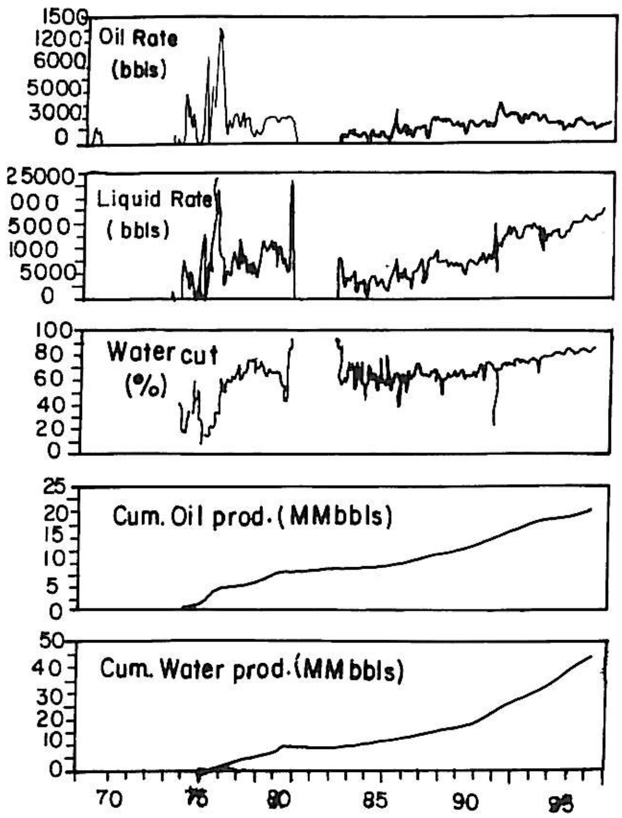

Fig. 3. Production history.

commencement of full-scale production in 1974. It was more amazing that when the 'D reef' water injection was terminated in 1982 and the El-Giza was returned to production, the reservoir has been able to produce normally ever since. It is important to note that during this second phase production period; (1) the produced-water salinity became gradually more saline and finally returned to the formation water salinity of 128,000 ppm by the later 1980s and (2) the reservoir pressure went on a major slide, losing more than 500 psi until stabilizing in 1994. The salinity development showed that a large amount of injected fresh water was stored when production was temporarily suspended in 1980 and was back-produced in the period of 1983-1990. This further confirms that the secondary porosity in El-Giza is of a vuggy nature rather than fracture, since fracture has little pore volume and would not serve as the capacitance required to retain the large amount of invaded fresh water. Two major conclusions can be drawn from the pressure and production history: (1) a thief zone of vugs in the reservoir was flooded by the invading fresh water during the early period of production (1974-1980) and this thief zone was resaturated with oil when fresh water invasion stopped and the flooded fresh water back-produced and (2) the bottom aquifer, despite its massive size, is not active, *i.e.* unable to maintain pressure for the given withdrawal rates of the 1980s.

THE ATTIC OIL RECOVERY PROJECT

Based on the understanding of the reservoir's geology and performances, a 2-phases, 3D simulation study was conducted using ECLIPSE. This simulation exercise had the objectives of: (1) confirming reservoir characterization, (2) history-matching the fresh water-leak period of 1974-1980 and the bottom water-drive period of 1982-1997, (3) identifying the remaining oil distribution in reservoir, (4) quantifying the strength of the bottom water-drive and (5) predicting the merits of increasing the reservoir withdrawal rate by switching from gas-lift to electrical submersible pump (ESP) production.

When the numerical model was satisfactorily history-matched, it was not surprising to find that most of the remaining oil was located as a blanket at the top two layers, i.e. 1 and 2A. In the prediction phase, the base case, *i.e.* the status-quo gas-lift operation, only achieved an overall oil recovery of 36.3%. At the end of the base case prediction (2025), it was astonishing to find that some 32.6% of the reservoir's OOIP of 84.3 MMSTB or 96.8% of the OOIP of the

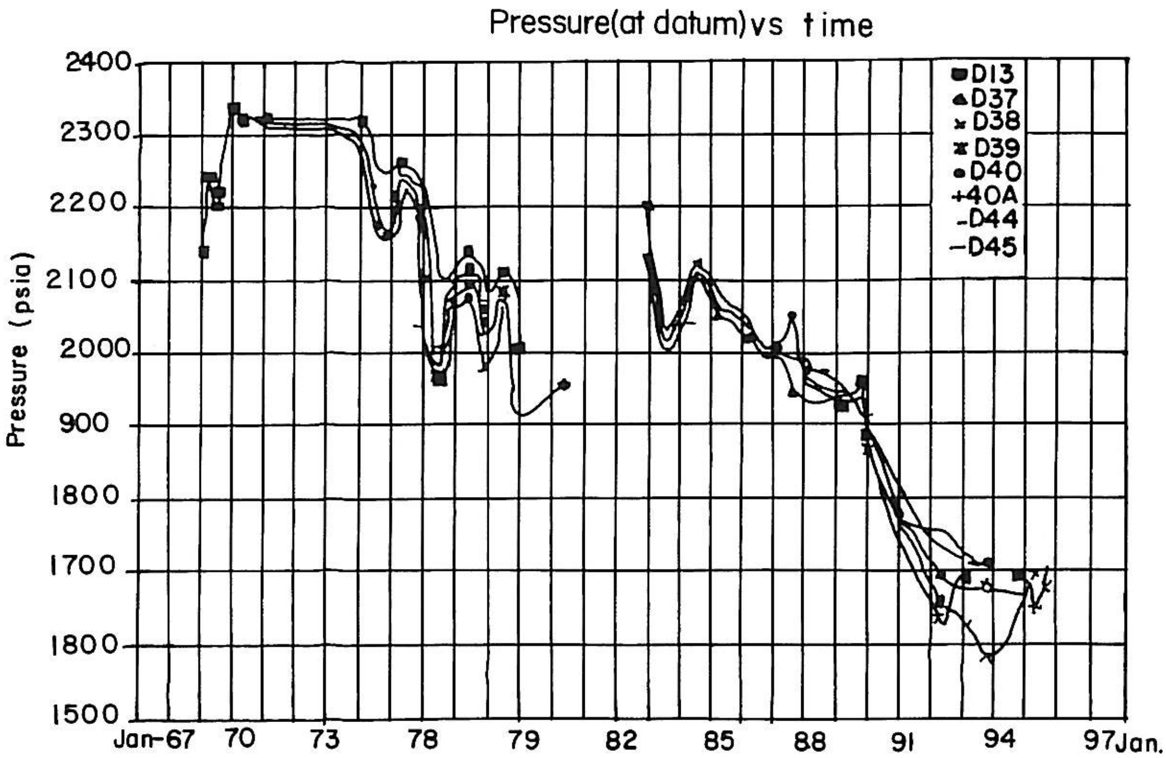

Fig. 4. El-Giza pressure history.

top two layers, 1 and 2 A remained at the reservoir's attic. It was more astonishing to find that the reservoir's overall recovery could be increased by 6.2% of the OOIP to 42.5% by switching to ESP operation.

The incremental recovery in the ESP case was found to be a result of the ESPs' ability in more than doubling the reservoir's withdrawal rate. This increased withdrawal caused the reservoir pressure to drop rapidly in the vuggy (high permeability) 2B layer, thereby pulling oil down from the thinner attic (layers 1 and 2A) across the field like a blanket (Fig. 5a,b).

It should be explained that the ability of ESPs in doubling the withdrawal rates in El-Giza is due to the production bottleneck caused by the gas-lift operation itself. Under gas-lift, small drawdowns (as little as 150 psi) and high wellhead pressures (as much as 650 psig) are the norm. These bottlenecks are caused by excessive pressure loss in the well bores due to the impulsive nature of the fluid stream and by the surface facility under-design in handling the third phase flow of such an emulsive fluid. ESPs eliminate the third phase flow and, therefore, most of these bottlenecks, thus following a much bigger drawdown to bring the bottom hole flowing pressure down to the productive 600 psig. The El-Giza oil is a 29 degrees API crude, having a low saturation pressure of 410 psia.

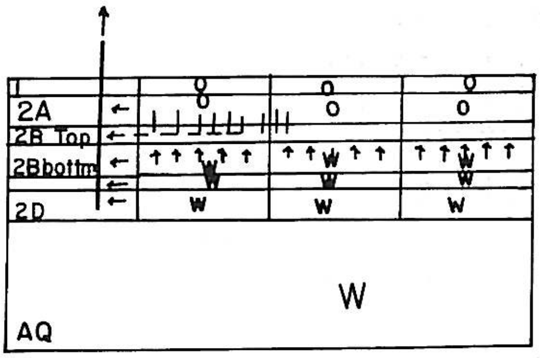

Fig. 5a. Fluid movement under gas-lift.

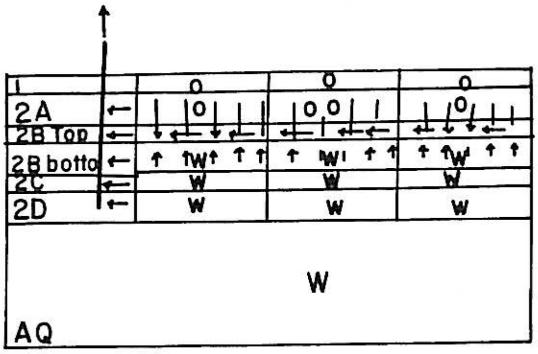

Fig. 5b. Fluid movement under ESPs.

Under ESP operation, simulation showed that the benefit was not limited to recovering more oil from the attic. Production was also projected to more than double immediately from the current 2100 STB/D to 4700 STB/D.

These production and recovery (Fig. 6) projections yield a highly, economically prolific project, with incremental NPVs (at 10%) of 52 MM$ at $29/Bbl, or 27 MM$ at $10/Bbl, with a payout time of less than 6 months.

Since the completion of the study, an ESP has been implemented on a pilot well, D13 and the simulation model's prediction of ESPs ability of doubling the oil production rate has been confirmed. Test results have shown this well's production increased from 300 STB/D to 790 STB/D at water cuts even lower than those under gas-lift. The production engineer's fear of the higher withdrawal rate drawing in more water and accelerating the water-out of these already high water cuts wells is now overcome. The project is now waiting for the extension of the power highline and the field-wide installation of ESPs.

CONVENTIONAL ANALYSIS AND SIMULATION

The benefits of this project, in terms of production, recovery and economics, are small in Libyan standards and are by no means unique. The uniqueness of this project, in fact, lies in the puzzles and the approaches in solving these puzzles. In the modeling exercise, it was equivalent to simulating a water flood history without the knowledge of the injector locations, the amount of injection as well as the injection profile. Although the location of the

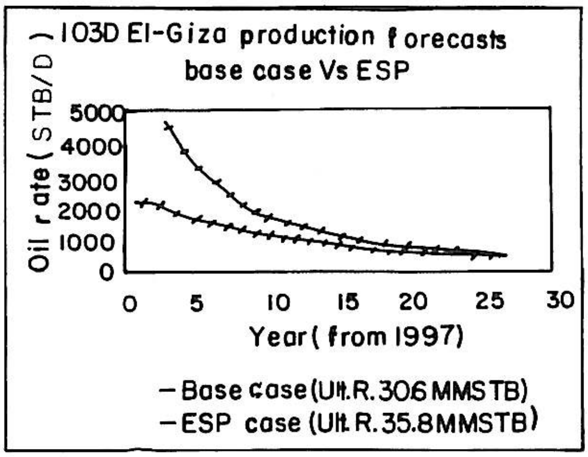

Fig. 6. 103D El-Giza production forecasts.

vuggy thief zone at the top of layer 2B is rather obvious as demonstrated in the resistivity logs, the areal extent and its connectivity are not known. In addition, the total pore volume of the thief zone, which dictates the pace of the water-out in the fresh water invasion period as well as the water cuts development in the fresh water back-produced period, has to be estimated correctly, bearing in mind that the major objective of the simulation is to quantify the strength of the aquifer's natural water drive. This requires first filtering out the influence of the fresh water invasion, more importantly in the later period (1982-1990), when aquifer water gradually replaced fresh water that was left behind in the reservoir. The analysis that led to the proper initialization of the numerical model are summarized as follows:

(1) Fresh Water Leak Volume. The history shows that the reservoir pressure was in equilibrium (at 2200 psia) when production was reactivated in 1982. The total amount of fresh water invasion was easily estimated from material balance at 18.5 MMRB or approximately 20% of the total hydrocarbon pore volume.

(2) Fresh Water Leak Location. There were 16 water injectors in the 'D reef' project. Temperature logs were run on some suspected injectors but failed to identify the culprit. Intuition suggests that the leaking of such a large amount of water will require a direct passage to the vuggy zone. This intuition limited the search only to the high structure area where the vuggy zone existed. This reduced the suspected injectors to seven. The analysis of the historical pressure trends and early salinity patterns had further reduced the suspect to two injectors in the east, D38 and D24. The pressure history has clearly demonstrated that the producer in the east, D13, has a consistently higher-pressure trend than all other wells throughout the entire water leak period. The lowest salinity of D13 confirms that the D38 well was the nearest well to the source of the water leak. A visit to the injection record of these two injectors finally identified D24 as the source of the water leak. The other injector, D38 has a small injection volume and cannot account for the leak. Using D24's injection profile and the historical pressure trends of the producers, a hypothetical injection profile was created to serve as initial injection input for the pseudo injector at the D24 location.

(3) Thief Zone Location. A vuggy zone has little surface area to trap irreducible water. The abnormally low water saturation environment of a vuggy zone, therefore, can easily be identified from the resistivity logs. Using resistivity logs, the thief zone was identified to be at the top of the 2B zone and in only the high structure area, covering 6 of the 8 El-Giza producers (Fig.7). This area coverage is consistent with the wells' high build-up permeability distribution.

(4) Thief Zone Permeability. A flow meter survey was conducted at D40a. This survey (Fig. 8) showed 85% of the flow coming from a 10-ft. interval at the top of the 2B zone. Using the well's overall build-up permeability of 1250 md, the permeability of this 10 feet vuggy zone was estimated at approximately 4500 md.

(5) Reservoir Characterization. Using the vuggy zone permeability of 4500 md, the overall build-up permeability of the wells and the matrix core permeability as a guideline, the individual zones were characterized for all 45 wells that penetrated the reservoir. The resistivity logs were heavily used in correlating the reservoir properties for the 38 wells that did not have a build-up test. A log-core match and the reservoir characterization of the individual layers of the D1 well are shown in figure 9.

(6) Aquifer Influence. The bottom aquifer is situated in an exclusively fine-grained calcilutite

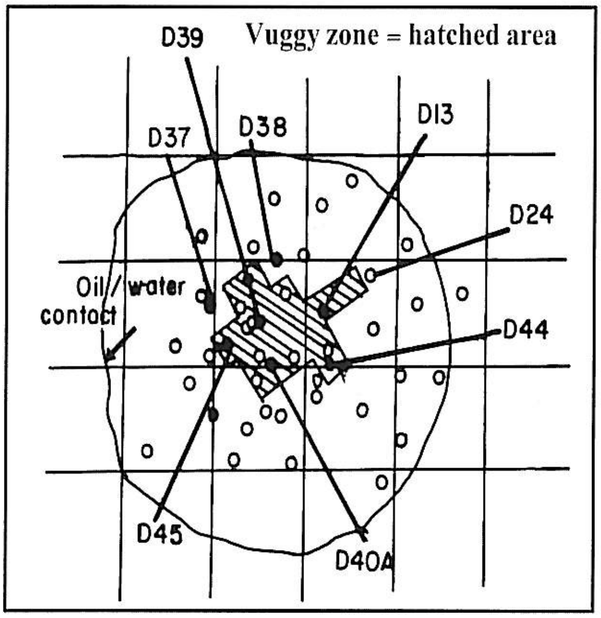

Fig. 7. El-Giza vuggy zone area extent.

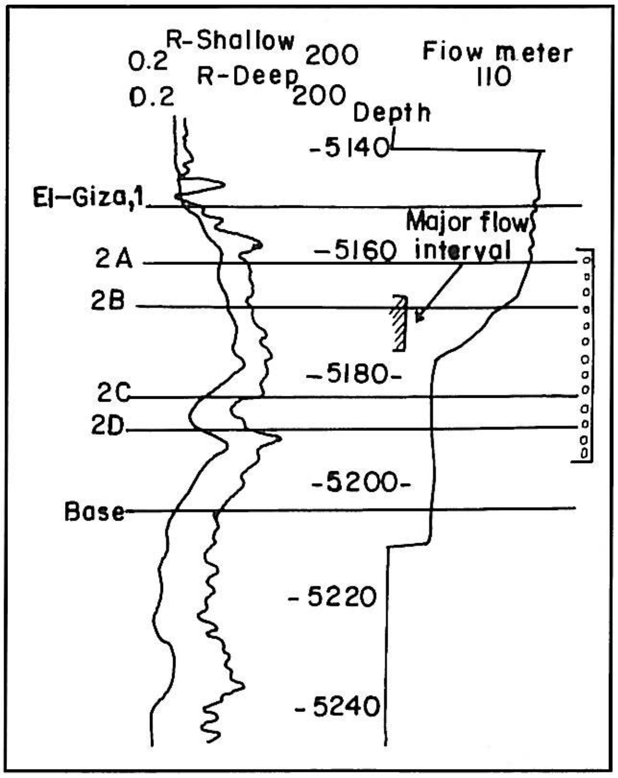

Fig. 8 D40A flow meter.

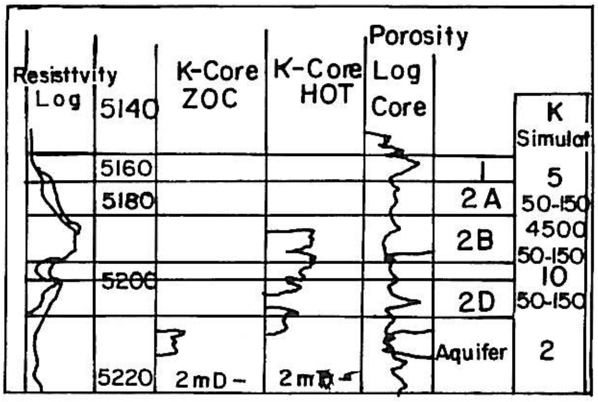

Fig. 9 DOI log core correlation.

carbonate. The core-measured permeability of 2 md was used to characterize the entire aquifer, with the exception of the southern area of D40.

Using the core-measured 2-md to represent the aquifer rock is consistent with the DST result of the aquifer at the D1 well. The reason the southern area was initially given a slightly higher permeability is due to the observation that this area is the only area that registered a water/oil contact movement. A TDT survey was conducted in the early 1980s on 10 wells, covering the entire reservoir.

The above analysis has provided a reasonably good understanding of the reservoir and enabled an adequate initial characterization of the reservoir for simulation. As it turned out, the only major effort spent in the history match was adjustment in the thickness and areal distribution of the vuggy zone as well as the injection profile. The results of the reservoir's history match is shown in figure 10 and the individual well history match in Table 1.

Table 1: Summary of history match results. (at April 1, 1996)

Well	Cum. oil (MMSTB)		Cum. water (MMBbl)		Water cut (%)	
	Model	Actual	Model	Actual	Model	Actual
D13	3.73	3.76	9.06	7.43	82.2	85.1
D37	2.23	2.23	4.04	3.44	83.1	75.3
D38	1.58	1.58	1.45	1.42	65.6	65.3
D39	4.36	4.40	11.28	8.02	82.7	66.2
D40	1.39	1.38	1.57	2.51	-	-
D40a	0.34	0.34	3.44	5.42	93.1	96.9
D44	2.94	2.94	7.09	6.47	90.2	89.7
D45	2.78	2.78	2.89	4.19	60.3	68.3
Field	19.36	19.41	40.83	38.90	84.4	83.9

CONCLUSION

This attic oil recovery project is a successful improved-oil-recovery project, but is not extraordinary in terms of scale, numbers or economics. However, it is a classical example of good reservoir engineering work. In conclusion, three major issues can be highlighted from this project as follows:

1- Secondary porosity frequently exists in a marine carbonate environment, particularly in Libya and the nature, location and areal extent of the secondary porosity have to be understood and expedited prior to a successful simulation.

2- The behaviour of water influx, which dictates the production and recovery of a water drive reservoir, is not only a function of the size of the aquifer, but more importantly, the nature of the aquifer rock itself.

3- This study utilized all available reservoir engineering tools, i.e. production history, pressure history, core, logs, build-up tests, DSTs, TDTs, salinity, material balance, core floods, PVT and inflow-outflow performances *etc.* A good analysis of the data is the key to this project's success. Simulation only serves to confirm concepts and quantify numbers.

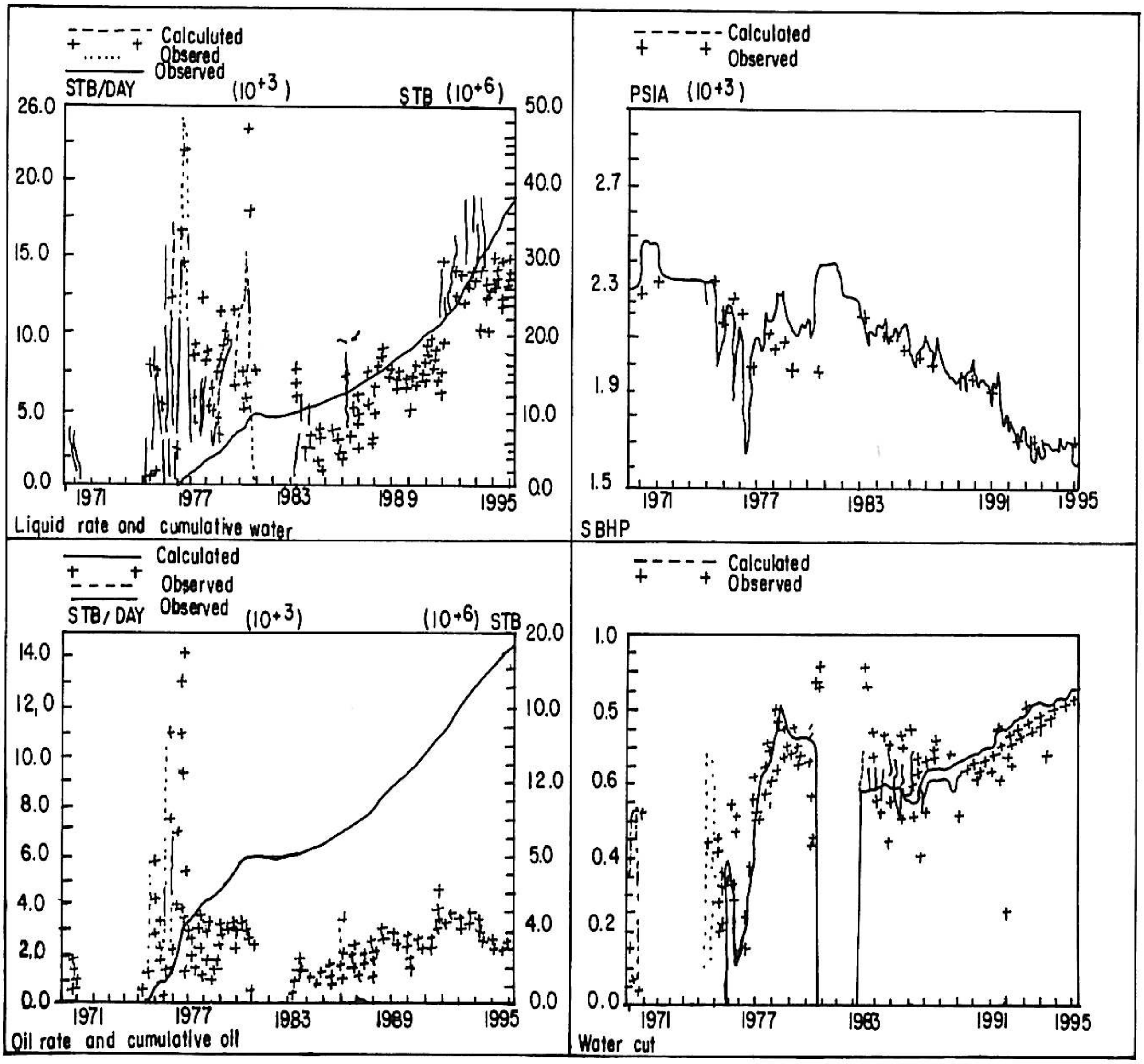

Fig. 10. Total field history match.

ACKNOWLEDGEMENT

The authors wish to express their appreciation to the management of the Zueitina Oil Company for the permission to publish this paper and to Mr. C. Struyk for his contribution in the petrophysical analysis of this project.

REFERENCES CONSULTED

[1] Engineering Dept., Occidental of Libya Inc.1969. *El-Giza Development 103D Structure.*

[2] Vadjama, U.N. 1977. *103D El-Giza Status report.*

[3] Vargas, T. and Sharafeddin, A., 1988. *Formation Evaluation of El-Giza Reservoir, NC 103D.*

[4] HOT Engineering, 1990. *103 D El-Giza Reservoir Study.*

[5] PHH, 1979. *103 D Reef Simulation Study.*