Petroleum Res. J. Vol. 18 (2005); P. 35–42, 13 Figs.

Hydraulic Frac Stimulation of the Sarir Sandstone in Nakhla Oilfield

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التنشيط بطريقة التكسير الهيدروليكي لحجر السرير الرملي بحقل النخلة

برند ليونهاردت

يقع حقل النخلة النفطي بعقد الامتياز رقم97 داخل حوض سرت حوالي 60 كيلومتر جنوبي عقد الامتياز 96 . تم اكتشاف الحقل بحفر البئر G1-97 سنة 1970. تم إلى اليوم حفر 13 بئرا تسعة منها تنتج بالدفق الطبيعي – ثلاثة وصلت صخورا بركانية أو ترسبات بركانية حلت كليا أو على الأقل الجزء العلوي من المكمن المحتوي على الزيت، وبئرا واحدا خفق فنيا بتكوين زلطن.

تنتج جميع الآبار من حجر السرير الرملي التابع للكريتاسي السفلي، وسمحت المسامية المتدنية (10 – 14%) والنفاذية الفقيرة ذات المدى من 0.1 – 20 مللي دارس بإنتاج متوسط (معتدل). تم التنشيط بطريقة التكسير الهيدروليكي لسبعة آبار عمودية ما بين 1995 – 2002. كما تم إجراء تقنيات حديثة تعتمد على التحليل الفعلي للوقت في تنشيط التكسير الهيدروليكي لتقييم أنسب عملية التكسير خلال الطبقات.

النتائج المتحصل عليها من طريقة التنشيط بالتكسير الهيدروليكي تم مقارنتها بنتائج إختبار البئر بعد التكسير والمتحصل عليها من تحليل تزايد الضغط . تعد مقادير التكسير داخل حدود الدقة (نصف طول الكسر) على سبيل المثال والمتحصل عليها بكلتا الطريقتين متطابقة وبشكل حسن .

تلخص هذه الورقة الدروس المستفادة في العلاج المنفذ وتأثيره على العمليات المستقبلية وتطوير الحقل.

سلوك الإنتاج للآبار المتكسرة وغير المتكسرة والنتيجة الإضافية لسعة الإنتاج تم عرضها ومناقشتها: إلى حد اليوم حوالي 45% من الإنتاج الكلي للزيت في حقل النخلة يمكن تخصيصه (تحديده) كعلاج بطريقة التكسير الهيدروليكي ، وفي السنتين الأخيرتين تم بذل مجهودات كبيرة تم تسخيرها لفهم ووصف المكمن ومتغيرات ميكانيكية الصخر أفضل من قبل. المحصلة تم تطبيقها لتحسين الطريق لتخطيط وإيجاد الأفضل من عمليات التنشيط الهيدروليكي مستقبلا.

في النهاية الخبرات الجيدة بطريقة المعالجة بالتكسير الهيدروليكي بحقل النخلة النفطي كان لها القرار الدافع لتطبيق هذه التقنية في آبار أخرى والتي تنتج من الحجر الرملي للسرير في المستقبل اعتمادا على ميكانيكية الدفع.

Abstract: *The Nakhla Oilfield is located in concession 97 within the Sirt Basin about 60 km south of concession 96. The field was discovered by drilling well G1-97 in 1970. 13 wells were drilled to date: nine of them are producing on natural flow, three found volcanics or volcanoclastic sediments replacing the entire or at least the oil-bearing, upper part of the reservoir, one technically failed in the Zelten Formation.*

All wells are producing from the Lower Cretaceous Sarir Sandstone. Low porosities of 10 to 14% and poor permeability ranging from 0.1 to 20 md only allow a moderate production. Therefore, hydraulic frac stimulation of seven vertical wells was performed between 1995 and 2002.

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State-of-the-art real-time analysis was performed in all hydraulic frac stimulations to evaluate and optimize the frac operation on-the-fly. Hydraulic frac simulation findings were compared to post-frac well test results obtained from pressure buildup analysis. Within their limits of accuracy the frac parameters (e.g. frac half-length) obtained by both methods match reasonably well.

This paper also summarizes the lessons learned from the treatment executed and their impact on future operations and field development.

The production behavior of fractured and unfractured wells and the resulting additional production capacity is presented and discussed. To date, about 45% of the cumulative oil produced from Nakhla oilfield can be assigned to the hydraulic frac treatments.

Especially during the last two years, a lot of effort was made to understand and describe the reservoir and its rock mechanical parameters better than before. The outcome was also implemented to improve the approach to plan and optimize future hydraulic frac stimulations.

Finally, the good experiences with hydraulic frac treatments in the Nakhla oilfield, were driving the decision to apply this technology also in other wells producing from the Sarir Sandstone in the future, dependent on their drive mechanism.

OVERVIEW

Geology. Located in the Hameimat trough in the south-east of the Sirt Basin in Concession 97 (Fig. 1), the Nakhla Oilfield was found by drilling well G1-97 in 1970. The development of the field started in 1993.

The main productive formation is the so-called Upper Sarir Sandstone, which is forming the uppermost layer of the Sarir Group. The Sarir Group consists of two sandstones (Upper and Lower Sarir Sandstone), which are separated by the Sarir Shale Member. The Upper Sarir Sandstone is a well consolidated sandstone, which can be described as deposits of an ephemeral fluvial system, with channels, sheet flood and inter-channel sand flats (Fig. 2). Thus, clean sandstone layers alternate with shale streaks. It was deposited in the Early Cretaceous (eventually Late Jurassic) age.

The Nakhla structure is a WNW – ESE trending Sarir arm (Fig. 3). Its northwestern end is in contact with the Amal/Nafoora-Augila Basement High via a broad saddle. In the Southeast the field is bordered by the so-called "B-High" where the basement has been reached by well B1-97.

Reservoir Parameters. The Upper Sarir Sandstone in the Nakhla oilfield is at a depth of 11,700 to 12,500 ft. The net pay is in the range of 130 to 400 ft. and the porosity is 10% to 14%. Reservoir

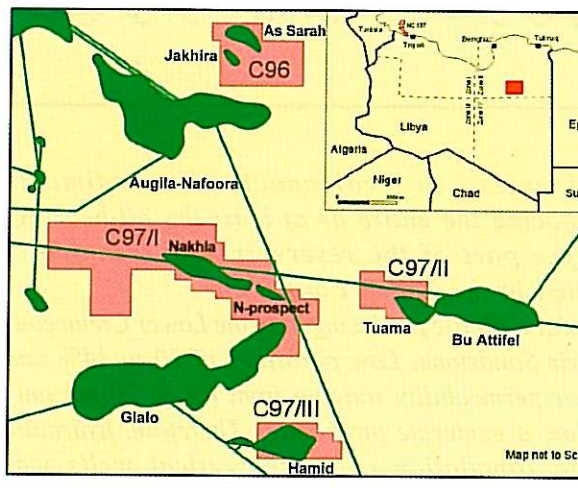


Fig 1. Location map of Nakhla Oilfield.

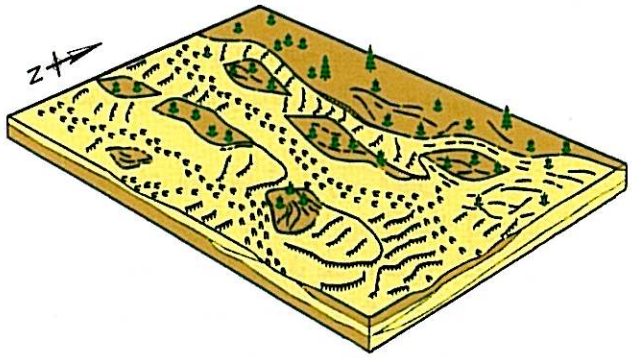


Fig. 2. Fluvial facies model, sheetflood dominated sand bed river (changed after Miall 1996).

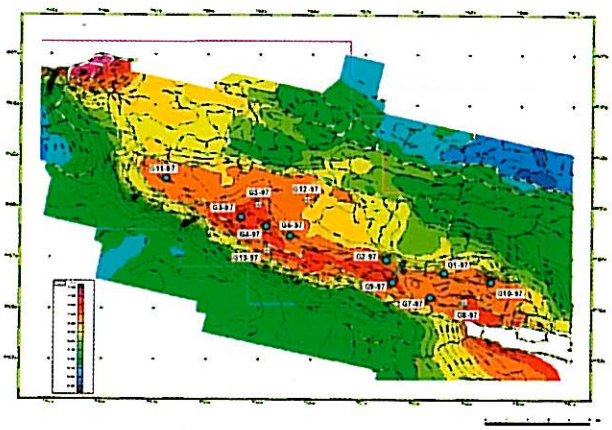


Fig. 3. Structure map Nakhla Oilfield – top upper Sarir Sandstone.

parameters and especially average permeability are improving from NW to SE, while higher pay heights have been drilled in the Northwest compared to Southeast. The permeability range is from tight (0.1 md) to fair (20 md). The main reservoir parameters are summarized in Table 1.

Table 1. Reservoir parameters of Upper Sarir Sandstone (Nakhla Oilfield).

Age	Lower Cretaceous (or Late Jurassic)	
Depth	3565 – 3760 m ss	11,700 to 12,330 ft ss
Area above OWC	60 km²	14,700 acres
Net pay	40 – 125 m	130 – 400 ft
Porosity	10 – 14 %	0.10 – 0.30
Permeability	0.1 – 12 md	0.1 – 12 md
Initial water saturation	30 – 55 %	0.30 – 0.55
Initial reservoir temperature	140 °C @ 3703 m ss	284 °F @ 12,150 ft ss
Initial reservoir pressure	414 bar @ 3703 m ss	6000 psi @ 12,150 ft ss
Initial oil in place[1]	148 MM m³	933 MMstb

[1] Status July 2002.

Oil Properties. The oil is a light oil API gravity of about 42°. Due to paraffins and waxes, pour point is high, about 100°F. Live oil viscosity is low, 0.35 cp at initial reservoir conditions. The oil properties are summarized in Table 2.

Table 2. Oil properties (Nakhla Oilfield).

Oil gravity	0.810 – 0.816 g/cm³	42 – 43 °API
Pour point	+40 °C	+104 °F
Viscosity @ *in situ* conditions	0.35 mPa · s	0.35 cp
Gas-oil-ratio	223 m³ (V_n)/m³	1250 scf/stb
Formation volume factor	1.65 m³/m³	1.65 rb/stb

FIELD HISTORY AND STATUS

Early Development Phase. The first two wells (G1-97 and G2-97) were drilled in 1970 and 1982, respectively. Initial production rates from the early wells drilled were found to be 1200 to about 2000 bopd. To improve production, Wintershall Libya decided to carry out hydraulic prop frac treatments in the existing and future wells.

The first development phase started 1993 and went through 1997. During this period six additional wells (G3- to G8-97) were drilled, of these wells G5-97 encountered volcanics, while G8-97 technically failed in the Zelten Limestone.

Since in the mid 1990's there was no provider for hydraulic frac stimulation services in the country, Wintershall Libya negotiated with three companies in order to make this service available in Libya. Finally, the jobs were awarded to Dowell Eastern (now Schlumberger Well Services).

Between 1995 and 1997, the six producing wells were successfully stimulated by hydraulic prop frac treatments. Comparison of the post-frac versus the pre-frac productivity index reveals an average productivity improvement (fold-of-increase) in excess of 3 (Fig. 4).

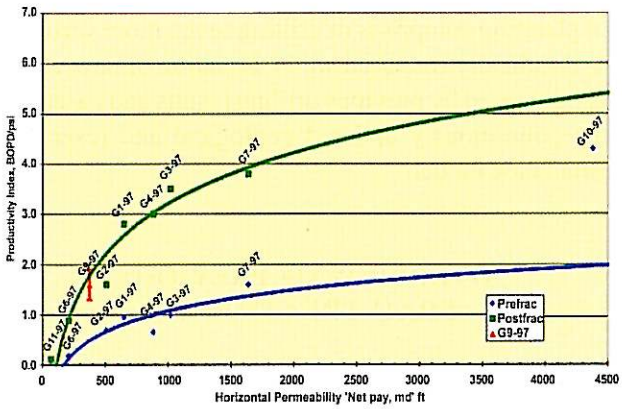


Fig. 4. Pre and post-frac productivity indices (pls) Nakhla Oilfield.

Recent Status of Field Development. After G8-97, five additional wells were drilled to date. While G9-97 is a barefoot completed horizontal well with a 3000 ft section in the Upper Sarir Sandstone, the subsequent wells were again planned vertical to delineate the extent of Nakhla oilfield to the East, West, North and South.

G10-97 in the East encountered as the first Nakhla well the initial oil water contact within the Upper Sarir Sandstone. Well G11-97 in the west, struck oil, but found extremely low permeability of 0.1 md. on average. G12-97 in the north and G13-97 in the south hit volcanoclastic sediments replacing the entire, or at least, the oil-bearing, upper part of the reservoir. Well G11-97 was hydraulically fractured in November 2002. (Fig. 5)

Future Field Development. The recent development concept foresees two more phases called Nakhla Phase II and Phase III. Phase II consists of a significant investment in surface facilities, such as upgrading of the existing Gas Oil Separation Plant (GOSP) and utilizing the gas via pipeline to the

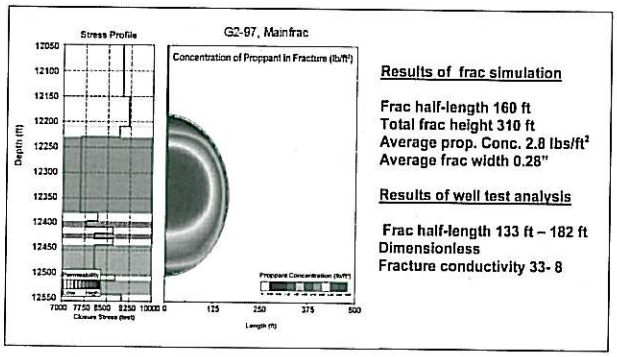


Fig. 5. Example of comparison of frac simulation and well test analysis results.

existing Jakhira GUP, furthermore drilling of six additional vertical wells including hydraulic frac treatments. The next Phase III at the current stage of planning comprises of drilling seven more vertical, hydraulically fractured wells. Location of new wells is influenced by previous drilling results and based on the continuously updated geological and reservoir simulation model.

OVERVIEW OF PREVIOUS FRAC TREATMENTS

Review of Previous Frac Jobs. To date seven wells have been hydraulically fractured in the Nakhla Oilfield: G1-, G2-, G3-, G4-, G6-, G7- and G11-97. All of these jobs have been pre-designed and optimized during execution by using a state-of-the-art, commercially available software package. This allows real-time analysis (RTA) and 3D frac simulation.

To allow RTA, job data like pressures, temperatures, pump rates and proppant concentrations were online transmitted to a laptop computer and fed into the program. Before performing the main frac, a data frac was carried out to provide specific data like the actual friction in the well and the leak-off coefficients for the different frac fluids used. In order to achieve this, bottomhole gauges were used during the frac.

Comparison of the actual data versus the expected data from designs allows changes in the pump program on-the-fly to permit an optimization of the treatment at any time during job execution. Post-job analysis and results obtained from the frac simulation, especially the frac half-length Xf and the dimensionless fracture conductivity FCD, can later be compared with information from other sources like pressure buildup (well test) analysis.

The frac-half length can directly be compared, while the frac conductivity can be crosschecked qualitatively. The following rule of thumb applies: in order to achieve a good conductivity (FCD>10-20), the proppant concentration in the frac should exceed 2 lbs/ft² in reservoirs having permeability like in the Nakhla Oilfield. An example is given in Figure 5 and the complete comparison can be obtained from Table 3. It can be seen that the data from both methods agree quite well within their limits of accuracy.

Table 3. Comparison of frac parameters from simulation and well test.

Well name	Frac half-length		Proppant concentrate	Dimensionless frac conduct.
	Frac simulation	Well test analysis	Frac simulation	Well test analysis
G1-97	240 ft	218-267 ft	1.4 lbs/ft²	>14
G2-97	160 ft	133-182 ft	2.8 lbs/ft²	>33
G3-97	260 ft	282 ft	1.5 lbs/ft²	16
G4-97	200 ft	190-212 ft	2.1 lbs/ft²	>23
G6-97	280 ft	283-302 ft	1.4 lbs/ft²	>15
G7-97	210 ft	217-224 ft	3.8 lbs/ft²	>50
G11-97	170 ft	N/A	3.6 lbs/ft²	"

Lessons Learned from Previous Frac Jobs. All job parameters like pad volume, total fluid and proppant pumped were reviewed and compared to the post job evaluation. This resulted in a significant reduction of pad volume compared to total fluid pumped (Fig. 6a), while the average proppant concentration pumped was increased (Fig. 6b).

Overall, the lessons learned so far can be summarized as follows:

- A pad volume of 20% to 25% of the total fluid volume pumped is sufficient to complete the frac job successfully.

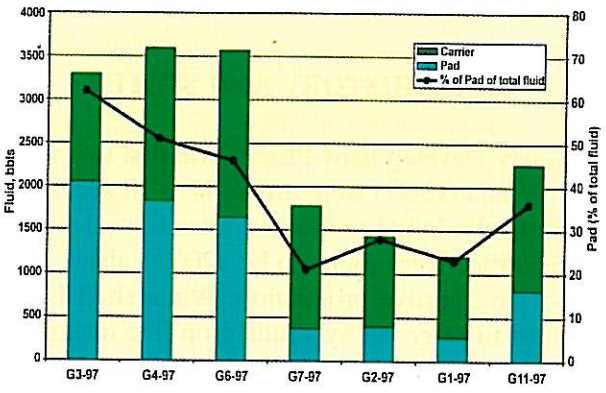


Fig. 6a. Fluid volumes pumped and percentage of pad of total fluid volume (Nakhla Oilfield).

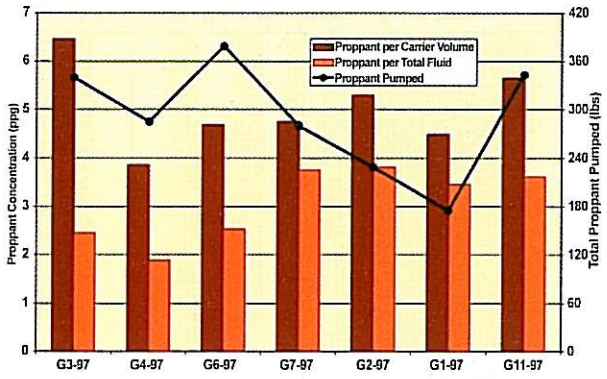


Fig. 6b. Proppant amounts pumped and average proppant concentration in frac fluids (Nakhla Oilfield).

- An average proppant concentration of 5.0 to 5.5 ppg in the carrier fluid over the whole job is anticipated to give optimal results.
- Technical procedures have been optimized to minimize risk of equipment failures during frac job execution.

Production Enhancement by Hydraulic Fracturing. To evaluate the production gain by the prop frac stimulations, decline curve analysis (DCA) was used on a well-by-well basis (Fig. 7a). Integration of the monthly production over time gave the two cumulative production figures, i.e. with and without hydraulic frac treatment (Fig. 7b).

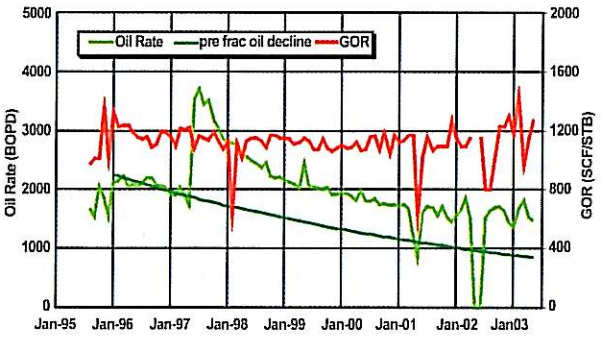


Fig. 7a. Oil rates G1-97 with and without hydraulic frac treatment, pre-frac oil decline obtained from decline curve analysis (DCA).

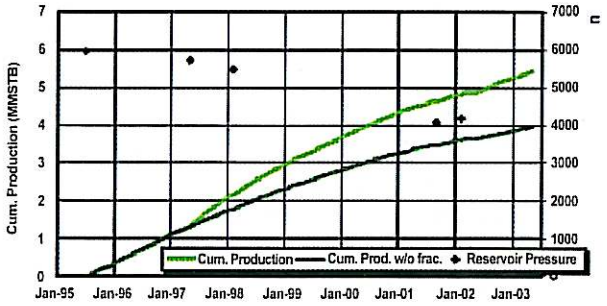


Fig. 7b. Cumulative oil production G1-97 with and without hydraulic frac treatment. Cumulative production without frac from DCA.

The same method was applied to each of the hydraulically fractured wells to obtain the cumulative production for both cases for total Nakhla Oilfield (Fig. 8). To date (status as of May 2003) 23.4 MMSTB of oil have been produced. The estimated cumulative production without frac treatments amounts to 12.8 MMSTB. Thus, the additional cumulative oil production gained to date by the fracturing project is about 45% of the actual total production.

It has to be stated clearly that part of the oil recovered is just production acceleration. However, part of it is also actually additional recovery, since the hydraulic frac treatments extend the time on how long the well can be economically produced and defers the point in time when the bottomhole flowing pressures will drop below bubble point.

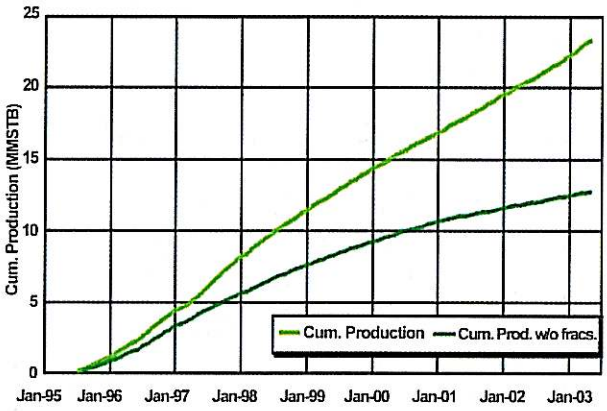


Fig. 8. Cumulative oil production Nakhla Oilfield with and without hydraulic fracs. Cumulative production without fracs obtained from well-by-well DCA.

PREPARING FOR THE FUTURE

Nakhla Stress Field. To improve our understanding of the field, a lot of effort was made especially during the last two years by carrying out a number of measurements and studies. To a large extent, these have been geological and sedimentological studies. Nevertheless, they contain extremely valuable rock mechanical information, which was used to optimize hydraulic frac planning. On the other hand, rock mechanical measurements carried out on Nakhla core material provide additional input to geological modeling.

Combining interpretations from FMI logs (Formation Micro Imager) with core measurement results provided a complete picture of the in situ stress directions of Nakhla Oilfield (Fig. 9). The maximum horizontal stresses run NE-SW, i.e. perpendicular to

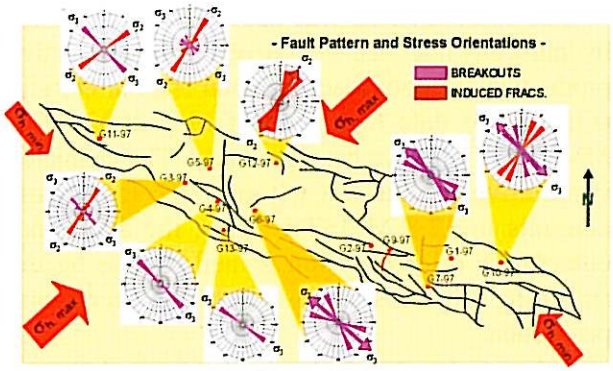


Fig. 9. Fault pattern of Nakhla Oilfield and directions of principal horizontal stresses.

the main faults of the field. The stress trend is similar to the regional trend in the Cyrenaica area (Fig. 10).

Rock Mechanics. One of the main input parameters for frac simulation programs are in-situ rock mechanical parameters such as Poisson's Ratio, Young's Modulus and formation closure stress lumped over certain intervals.

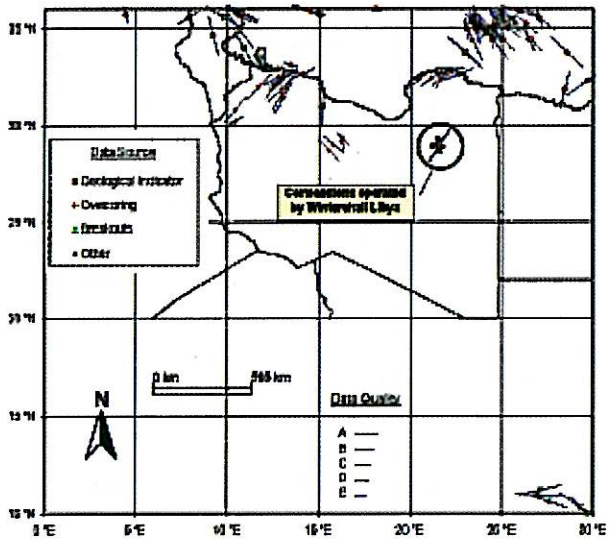


Fig. 10. Regional stresses (taken from World Stress Map, release 1997).

Usually, measurement of these in-situ values in the lab is cost intensive. Fortunately, reasonably good data can be obtained from open hole logs (Fig. 11). However, since some correlations are included in this process, laboratory measurements are required to verify or calibrate the calculations (Fig. 12).

Using these input data, the frac simulator predicts the vertical and lateral propagation of the frac and the resulting bottom hole net pressure for the whole frac operation. During job execution this pressure is compared to the actually observed net pressure (Fig. 13).

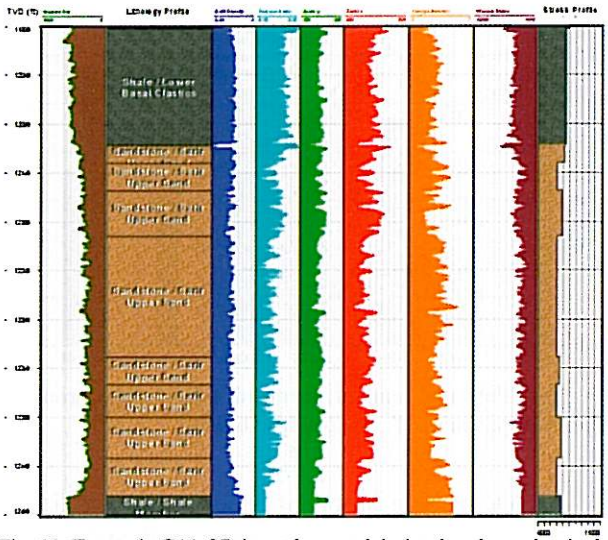


Fig. 11. Example G11-97: input logs and derived rock mechanical model for frac simulation.

Thermal Decay Time (TDT) Logging. To examine the aquifer influx in Nakhla Oilfield, TDT logging was carried out in well G10-97 one year after the well had been put into production. No change in water saturation behind pipe and especially at the oil-water-contact was observed. Thus, it could be verified that the aquifer in Nakhla Oilfield is very weak or inactive.

OUTLOOK

Nakhla Oilfield. The next step in future field development is the so-called Nakhla Phase II, which has already been started: drilling of the first well and construction of a 12" pipeline to Jakhira GUP is already ongoing, upgrading of existing surface facilities will be completed by the end of 2004.

A major frac campaign will be executed as well in 2004. Due to the broad database gained from the previous frac jobs and all the work carried out, a general main frac design can already be done and has only to be slightly adjusted to the actual drilling results of the Nakhla Phase II wells.

Adjacent Oilfields. The Upper Sarir Sandstone is also target formation of other exploration and appraisal drilling in Concession 97, which is ongoing or planned for the coming years. In these wells generally, hydraulic frac treatments costs involved are integral part of the drilling and well completion budget.

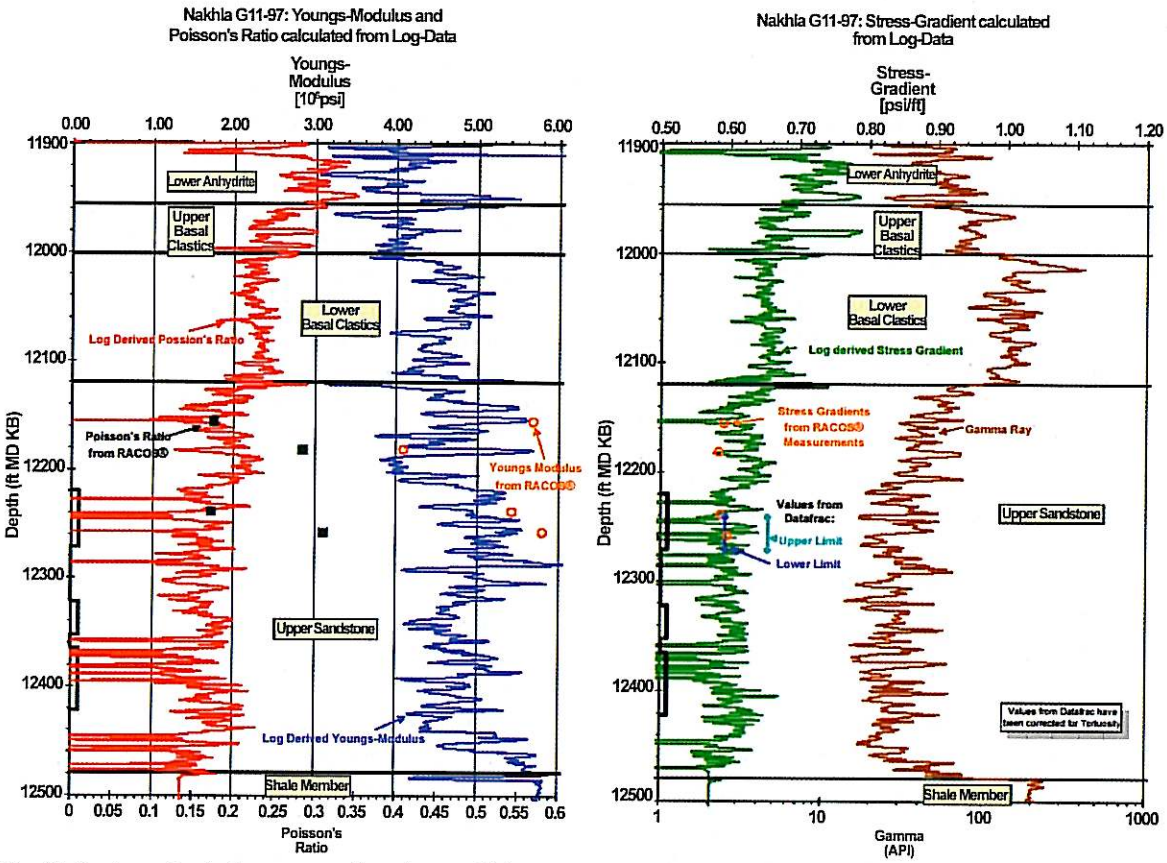


Fig. 12. Rock mechanical parameters from logs and lab measurements (RACOS®).

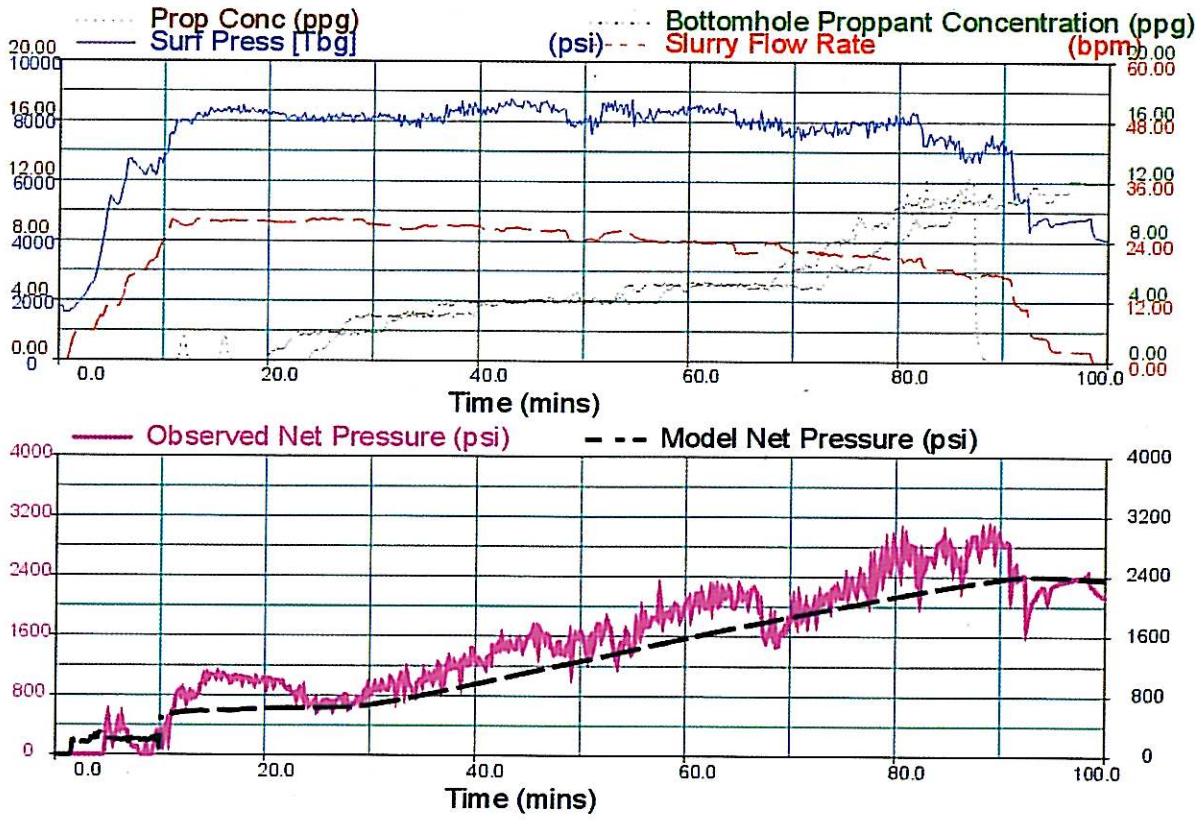


Fig. 13. Actual job data Mainfrac G7-97 and net pressure match.

CONCLUSIONS AND RECOMMENDATIONS

Five important lessons have been learned from the work carried out to date:

1. The Upper Sarir Sandstone is generally a good candidate for hydraulic frac treatments.

2. Productivity improvement achievable by prop fracs is significant. The frac treatment improves the economics of field development, and also enhances the recoverable oil reserves.

3. Best results can be expected from more aggressive frac designs.

4. Thorough frac planning is required in order to fulfill this target and get decent frac coverage over the entire pay.

5. Hydraulic fracturing should be applied early in the lifetime of a well.

However, hydraulic frac stimulation is not the solution to everything and not advisable for all applications. Oilfield wells with a strong underlying aquifer and/or existing gas cap are, in most cases, not optimal candidates for hydraulic frac treatments, since changing (oil-water or gas-oil) fluid levels will at a point in time cone into the frac. If this occurs, the unwanted phase might preferentially be produced instead of the oil.

ACKNOWLEDGEMENTS

The author wishes to thank NOC, PRC and Wintershall Libya for the opportunity to publish this material. Also, the author would like to thank his colleagues for their helpful comments and suggestions.

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