Asian Journal of
Earth Sciences

ISSN 1819-1886

Academic
Journals Inc.

www.academicjournals.com

OPEN ACCESS Asian Journal of Earth Sciences

ISSN 1819-1886
DOI: 10.3923/ajes.2020.1.11

Research Article

Present-day *in situ* Pore Pressure Distribution in the Tertiary and Cretaceous Sediments of Zubair Oil Field, Iraq

[1]Hussein Saeed Almalikee and [2]Souvik Sen

[1]Fields Division, Basrah Oil Company, Ministry of Oil, Basrah, Iraq
[2]Geologix Limited, Dynasty Building, Wing A, Level 4, Andheri Kurla Road, Andheri East, 400059 Mumbai, Maharashtra, India

Abstract

Background and Objective: Supergiant Zubair oilfield is one of the major hydrocarbon producing assets in southern Iraq. This study presents the assessment of pore pressure distribution across the tertiary and cretaceous sedimentary sequences in five producing wells. **Materials and Methods:** Indirect pore pressure estimation employing compressional sonic slowness responses as well as direct pressure measurements have been combined to establish regional pore pressure profiles. **Results:** Study reveals hydrostatic pressure regime in tertiary sediments. Late cretaceous Tanuma shales are under-compacted and therefore reveals mild overpressure, while the primary reservoir middle Cretaceous Mishrif limestones are in sub-hydrostatic pore pressure due to production related depletion. **Conclusion:** This study will be directly beneficial for determining minimum mud weight for drilling, since too high or too low mud weight can result into mud losses and wellbore collapses respectively leading to expensive non-productive time (NPT) in terms of drilling and loss of put on production (POP) time.

Key words: Zubair oilfield, vertical stress, pore pressure, cretaceous sediments, tertiary sediments

Citation: Hussein Saeed Almalikee and Souvik Sen, 2020. Present-day *in situ* pore pressure distribution in the tertiary and cretaceous sediments of Zubair oil field, Iraq. Asian J. Earth Sci., 13: 1-11.

Corresponding Author: Souvik Sen, Geologix Limited, Dynasty Building, Wing A, Level 4, Andheri Kurla Road, Andheri East, 400059 Mumbai, Maharashtra, India

Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

A comprehensive understanding of present day *in situ* pore pressure distribution is critical for safe and sustainable execution of infill drilling in producing giant oil fields to enhance hydrocarbon production as well as optimization of steam injection for increased recovery[1-3]. Mud loss and wellbore collapsing are the two major concerns contributing to significant non-productive time (NPT) while drilling through the tertiary and cretaceous sediments of supergiant Zubair oil field, southern Iraq. A proper mud weight design via accurate pore pressure analyses is the prime requirement to address this challenge[3].

There has been no previous published literature on the present day pore pressure behavior across the tertiary stratigraphy in Zubair oil field. The only related study was performed by Almalikee and Al-Najim[4] from North Rumaila oil field, Iraq, situated in the northwest of the Zubair field. Almalikee and Al-Najim[4] established vertical stress and pore pressure gradient from well log dataset. We took this opportunity and investigated the high resolution geophysical logs and downhole direct pressure measurements available from the recently drilled wells.

The main purpose of this study was to determine vertical stress (i.e., overburden stress) and ascertain formation pore pressure. Regional pressure profiles have been proposed for the oilfield. The objective of this study was to model the regional vertical stress and characterize the present day *in situ* pore pressure distribution across stratigraphy in Zubair oil field to recommend necessary mud weight for safe and stable well bore drilling.

MATERIALS AND METHODS

Study area: The supergiant Zubair oil field is one of the largest oil fields in the world, discovered in 1949 by the Basrah Petroleum Company (BPC), it is located in the southern Iraq, about 20Km west of Basrah city, the field is a semi symmetrical NNW-SSE longitudinal anticline 60 km length and 15 km width as presented in Fig. 1. The duration of this study was from March, 2019 to November, 2019.

Stratigraphy column for Zubair oil field as presented in Fig. 2 is mainly comprised of carbonate rocks with few Shale and Sandstone formations, the main oil reservoir in the field is Mishrif (upper cretaceous carbonate). Four Technostratigraphic mega sequences (start with AP8 to AP11) had shaped the stratigraphic succession for South of Iraq, these mega sequences were controlled by tectonic evolution of the Arabian plate and separated by regional outstanding unconformity surfaces[5-6].

Data set: Five onshore vertical wells drilled till middle cretaceous Rumaila Formation were studied to model the vertical stress and pore pressure in the Zubair oil field. These wells had a primary reservoir target of Mishrif limestones and average true vertical depth (TVD) is around 2500 m. High resolution geophysical log suite consisting of gamma ray, resistivity, formation bulk density, compressional sonic slowness and caliper logs were the key inputs for the analyses. Here in this section, methods applied in this study have been elaborated.

This study was conducted from March-November, 2019.

Estimation of vertical stress: Vertical stress is the cumulative pressure by the overburden litho column. This is also known as Overburden stress. Plumb *et al.*[7] expressed the vertical stress (S_v) at a depth (Z) as:

$$S_v = \int_0^Z \rho(Z) g \, dZ \qquad (1)$$

where, ρ(Z) represents the depth vs. density profile of the entire overburden starting from surface to the depth of estimation (Z). In practical scenario, this is the density log recorded in the hydrocarbon wells[8]. In Eq. 1, g is the gravitational constant with a value of 9.8 m sec^{-2}. Since the wireline logs are not recorded from the surface level, synthetic density was determined by the following power law curve[2,8] against the interval not logged:

$$RHOB_{syn} = RHOB_{sur} + A \times (TVD - AG)^{\alpha} \qquad (2)$$

where, $RHOB_{syn}$ is the synthetic density for shallow section, $RHOB_{sur}$ is the surface sediment density, TVD is true vertical depth, AG is air gap (distance between drill floor and ground level), A and α are fitting parameters. The parameters of the power law curve were determined by adjusting the three reference points to match the power law curve to the density log over the depth interval for which density data was available.

Estimation of pore pressure: Fluids trapped in rock's pore spaces exert pore pressure (PP). Accurate understanding of formation pressure has critical implications in successful well delivery[3,8-10]. Formation pressure measurement data were available from repeated formation tester (RFT) tool against Mishrif Formation, the primary reservoir. These RFT points are the direct in-situ pore pressure measurements[11,12]. Since RFT measurements were not taken in other formations, indirect method involving geophysical logs have been employed to estimate PP across the stratigraphy encountered in the studied Zubair field.

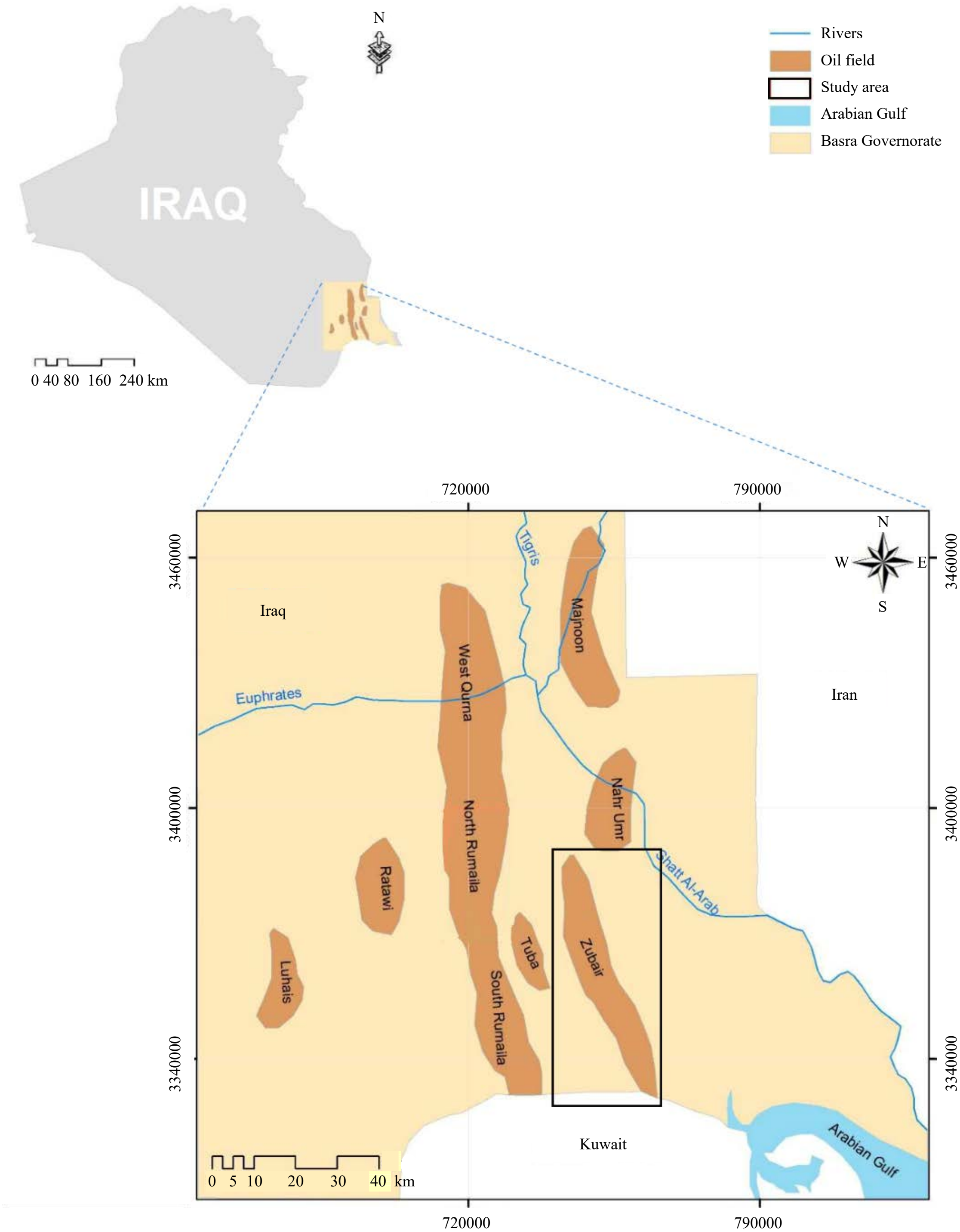

Fig. 1: Location of the study area

Eaton[13] had developed a method of predicting PP from resistivity and sonic logs and this is the most extensively used empirical relationship in hydrocarbon industry. As per this method, the magnitude of overpressure caused by disequilibrium compaction can be predicted from the response of resistivity and sonic slowness logs with respect to a normally compacted sediment section. Thus it employs a normal compaction trend line (NCTL) and identifies the pore pressure behavior with respect to the NCTL. High resolution compressional sonic slowness log (DT) was available from wireline suite in the studied wells and following equation had been utilized for pore pressure prediction[12]:

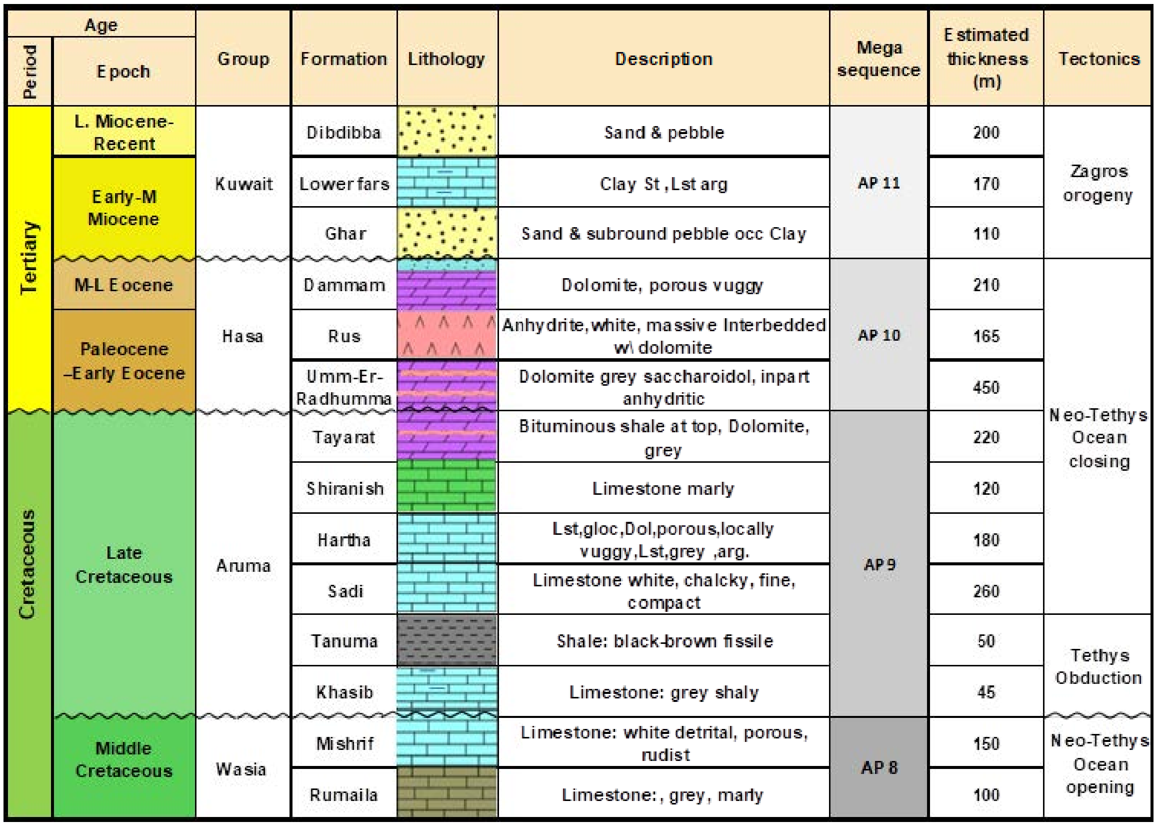

Fig. 2: Stratigraphic column for Zubair oil field

$$PP = S_v - \left(S_v - P_{hyd}\right) \times \left(\frac{DT_n}{DT}\right)^3 \qquad (3)$$

where, P_{hyd} is the hydrostatic pressure, DT_n is sonic travel time against normally compacted shale sections as characterized from NCTL[13]. Shale sections are identified from gamma ray log, based on interpreted gamma ray log responses against clean shale zones[14-17]. The DT is the observed acoustic travel time, available from wireline compressional sonic slowness logs. A ratio of (DT_n/DT) and its variation with depth with respect to the NCTL calculates the pore pressure profile[13, 18-20].

As a result of pressure exerted by overburden sediments, fluid in the pore spaces of rocks are expelled, thus rock density increases and it gets compacted. The NCTL represents this compaction equilibrium behavior and hence pore pressure gradient[19-21]. In a geological situation of rapid sedimentation rate, underlying rocks will not get enough time to expel its pore water following the normal trend of depth vs porosity reduction. As a result, these litho units will retain the pore fluid in the excess porosity and exert higher pore pressure[19-21]. From petrophysical perspective, with continued compaction along NCTL, compression sonic slowness value shall normally decrease in deeper rocks. But any abnormally porous litho unit will reveal a considerably higher sonic slowness value, deviating from the regional NCTL. The degree of separation of DT log response from NCTL will characterize the magnitude of pore pressure.

RESULTS

Vertical stress: Extrapolated density and wireline density logs have been used to model S_v in Zubair field. The outputs from the five wells have been presented in Fig. 3. Extrapolated density profile has been very effective since there were multiple intervals where well bore was affected by wash outs, as seen in Caliper logs. These are the zones with erroneous density values, since wireline density (RHOB) is measured by a padded tool which touches the borehole wall while logging up. Against the extensively washed out segments, pads cannot reach the enlarged well bore radius and hence produce unreliable data. In this study, a careful investigation of enlarged well bore portions and necessary density correction with the extrapolated values helped us minimized error in vertical stress estimation. Well wise estimated S_v has been plotted against depth to ascertain a depth vs. overburden trend across the stratigraphy as shown in Fig. 4. It provided the following correlation:

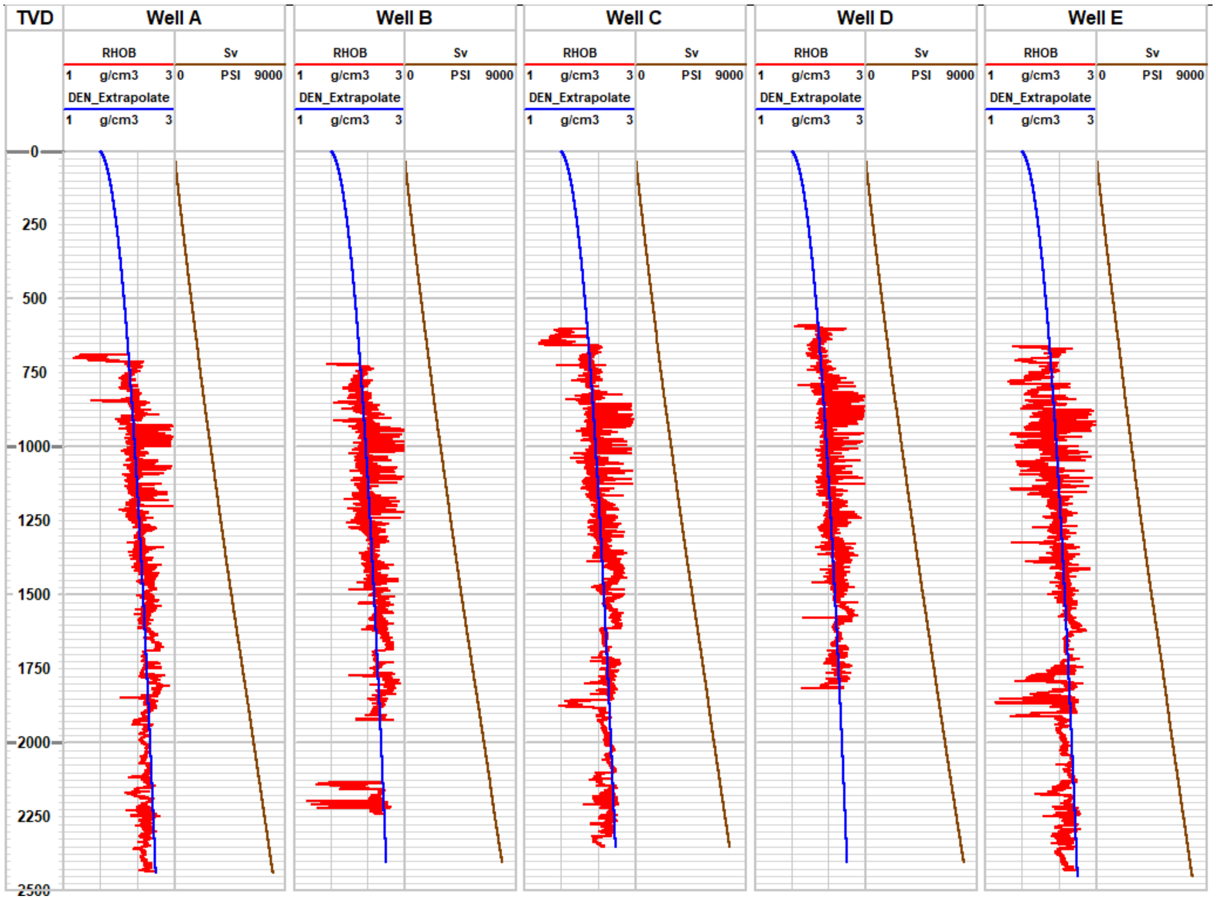

Fig. 3: Extrapolated density log (blue curve) to the surface, wireline density (red curve) and estimated vertical stress (brown curve) for the studied wells in Zubair field

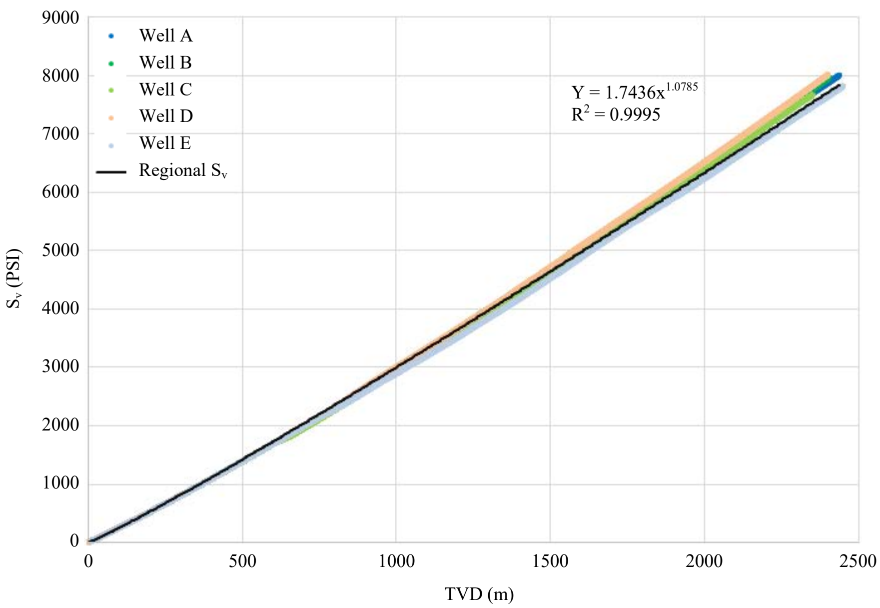

Fig. 4: Regional vertical stress (S_v) model in Zubair oil field

Table 1: Regional vertical stress (S_v) magnitude and gradient with depth in the studied formations of Zubair oil field

			S_v gradient	
Formation	TVD (m)	S_v (PSI)	PSI/ft	PSI/m
Dibdibba	100	251.51	0.77	2.52
	200	531.69	0.81	2.66
Lower Fars	300	823.83	0.84	2.75
	400	1124.02	0.86	2.81
Ghar	500	1430.33	0.87	2.86
Dammam	600	1741.62	0.88	2.90
	700	2057.10	0.90	2.94
Rus	800	2376.22	0.91	2.97
Umm Er Radhuma	900	2698.55	0.91	3.00
	1000	3023.77	0.92	3.02
	1100	3351.61	0.93	3.05
	1200	3681.84	0.94	3.07
	1300	4014.28	0.94	3.09
Tayarat	1400	4348.78	0.95	3.11
	1500	4685.20	0.95	3.12
Shiranish	1600	5023.41	0.96	3.14
Hartha	1700	5363.32	0.96	3.15
	1800	5704.84	0.97	3.17
Sadi	1900	6047.88	0.97	3.18
	2000	6392.37	0.97	3.20
Tanuma	2100	6738.23	0.98	3.21
Khasib	2150	6911.67	0.98	3.21
Mishrif	2200	7085.42	0.98	3.22
	2300	7433.88	0.99	3.23
Rumaila	2400	7783.54	0.99	3.24
	2450	7958.82	0.99	3.25

TVD: True vertical depth

$$S_v = 1.7436\times(TVD)^{1.0785} \quad (4)$$

where, S_v is the vertical stress magnitude in PSI and TVD is the true vertical depth in Meter.

The above relationship has a very high correlation coefficient of 99%. Therefore, we propose this empirical relationship to model regional S_v trend with great confidence. Regional vertical stress magnitude and gradient have been presented in Table 1, it reveals a maximum of 0.99 PSI/ft (equivalent to 3.25 PSI/m) S_v gradient at deeper depths.

Pore pressure: In any oil and gas field, it is mostly the reservoir section in a well where direct formation pressure measurements (i.e., RFT etc.) are conducted. Operator had taken RFT readings in Mishrif Formation, the primary hydrocarbon producer in Zubair field. Data reveals a sub-hydrostatic pore pressure condition in Mishrif limestones resulting from prolonged production induced depletion. Indirect method by using Eaton's sonic equation yielded pore pressure magnitudes in other formations. The established NCTL on the sonic slowness log data to ascertain the variation of porosity with depth, as presented in Fig. 5.

Table 2: Regional vertical stress, hydrostatic pressure and pore pressure distribution in various formations of Zubair oil field

Formation	TVD (m)	S_v (PSI)	Hydrostatic (PSI)	Pore pressure (PSI)
Dibdibba	0	0.00	0.00	0.00
	100	251.51	142.25	140.00
	200	531.69	284.49	280.00
Lower Fars	300	823.83	426.74	421.00
	400	1124.02	568.99	562.00
Ghar	500	1430.33	711.24	703.00
Dammam	600	1741.62	853.48	848.00
	700	2057.10	995.73	989.00
Rus	800	2376.22	1137.98	1127.00
Umm Er Radhuma	900	2698.55	1280.22	1275.00
	1000	3023.77	1422.47	1412.00
	1100	3351.61	1564.72	1545.00
	1200	3681.84	1706.96	1695.00
	1300	4014.28	1849.21	1835.00
Tayarat	1400	4348.78	1991.46	1975.00
	1500	4685.20	2133.71	2120.00
Shiranish	1600	5023.41	2275.95	2258.00
Hartha	1700	5363.32	2418.20	2400.00
	1800	5704.84	2560.45	2540.00
Sadi	1900	6047.88	2702.69	2685.00
	2000	6392.37	2844.94	2830.00
	2050	6565.13	2916.06	2920.00
Tanuma	2100	6738.23	2987.19	3000.00
	2120	6807.57	3015.64	3060.00
	2140	6876.95	3044.09	3250.34
Khasib	2150	6911.67	3058.31	3315.00
Mishrif	2200	7085.42	3129.43	2858.19
	2250	7259.49	3200.56	2759.26
	2300	7433.88	3271.68	3130.00
Rumaila	2400	7783.54	3413.93	3270.00
	2450	7958.82	3485.05	3400.00

TVD: True vertical depth, S_v: Regional vertical stress

The NCTL reveals higher porosity in Tanuma shale. This may be the result of compaction disequilibrium and this behavior can be persistently correlated in all the studied wells in Zubair field. A mild over pressure (200 PSI more than hydrostatic pressure) has been interpreted in Tanuma shale. Figure 6 represents the interpreted vertical stress and pore pressure profiles in the five wells.

The daily drilling reports (DDR) have been studied to look for influx events. Formation fluid influx indicates that the drilling mud weight is not sufficiently overbalanced, thus relates to *in situ* pore pressure calibration. However, such influx events were not reported and the mud weight was higher than the formation pore pressure. Regional vertical stress, hydrostatic pressure and pore pressure distribution in various formations of Zubair oil field have been graphically presented in Fig. 7 and the interpreted magnitudes have been documented in Table 2.

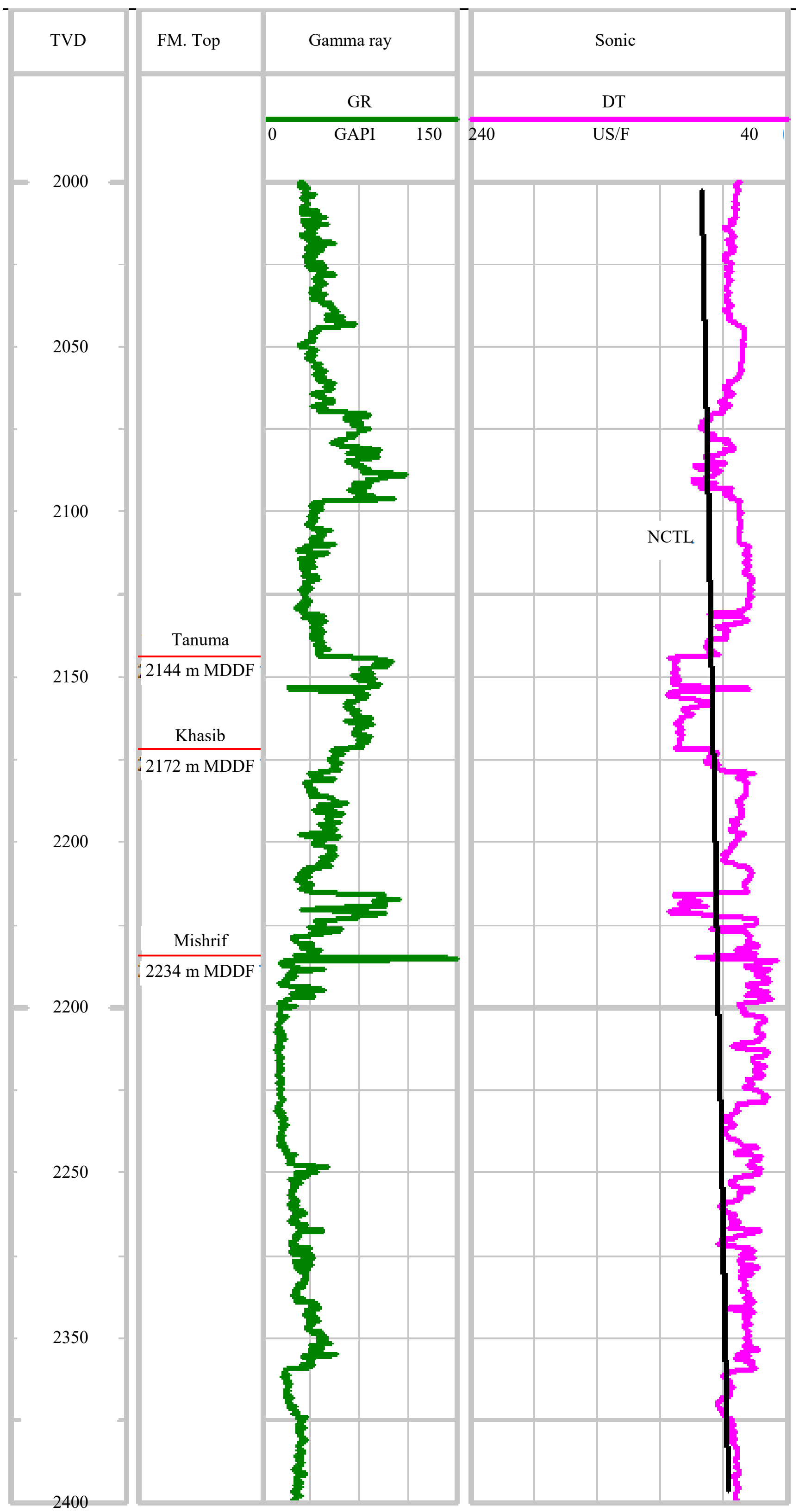

Fig. 5: NCTL on compressional sonic log in one of the studied wells form Zubair field, indicating Tanuma shale formation (2144-2172 m TVD) has higher porosity with respect to NCTL

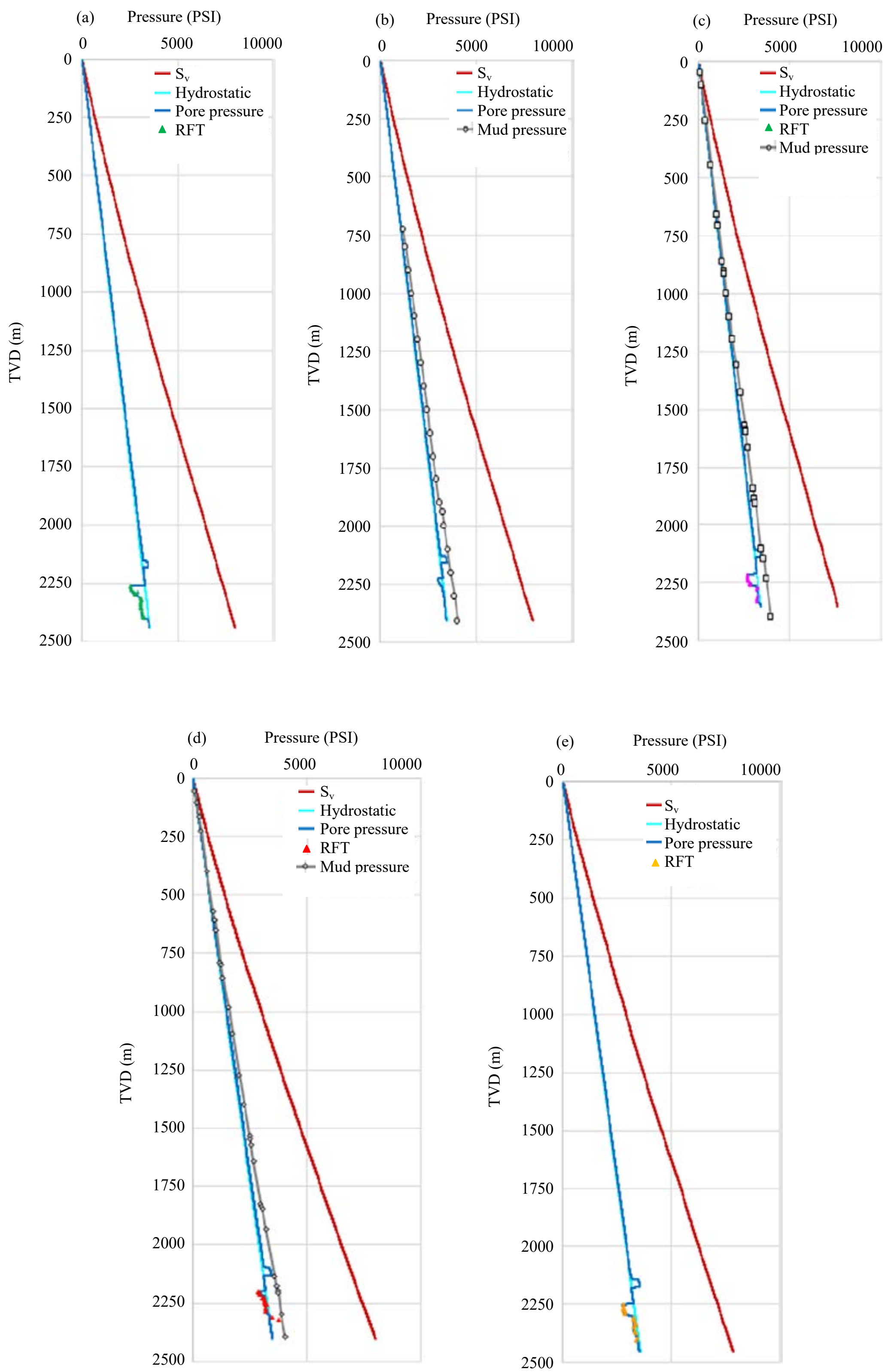

Fig. 6(a-e): Vertical stress, hydrostatic pressure and estimated pore pressure in (a) Well A, (b) Well B and (c) Well C (d) Well D and (e) Well E along with available mud weight and RFT data set

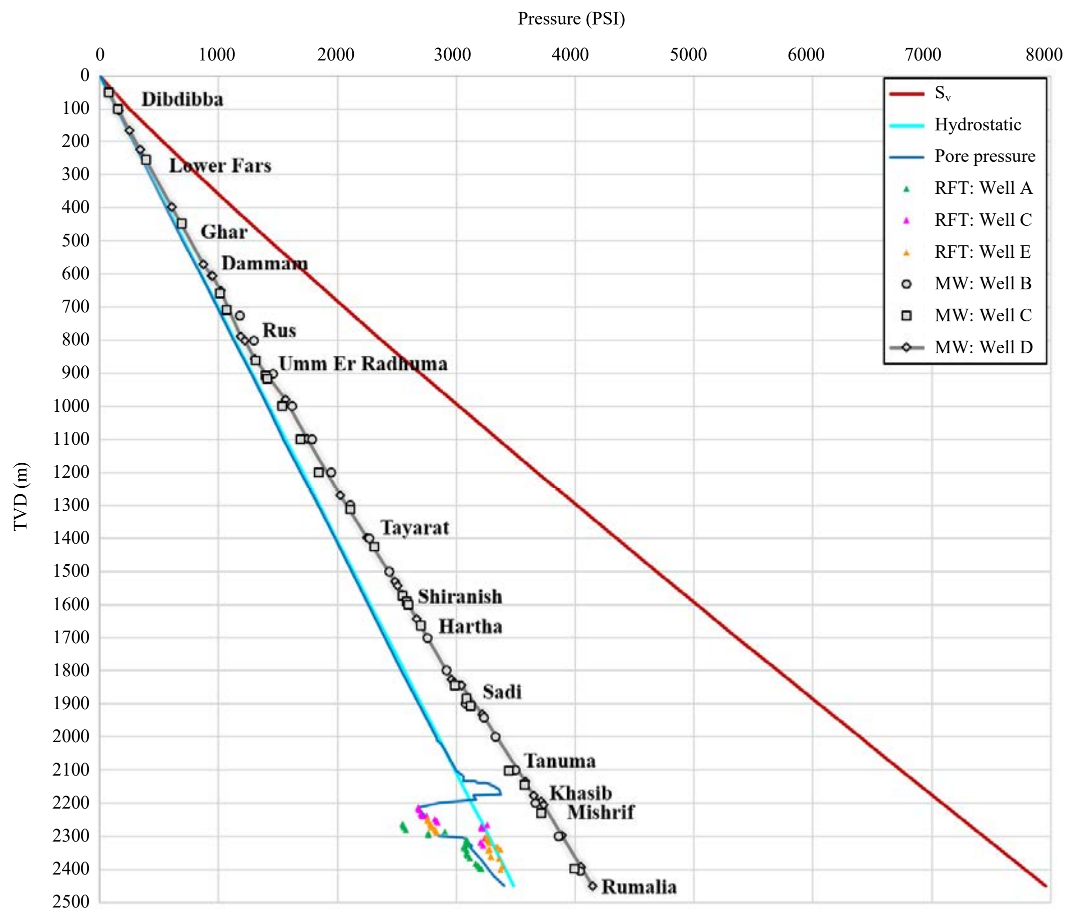

Fig. 7: Regional vertical stress, hydrostatic pressure and pore pressure profile for Zubair field along with formation tops, drilling mud weight and RFT measurements from five studied wells

DISCUSSION

This study integrated the wireline geophysical logs and downhole measurements to establish the vertical stress (S_v), hydrostatic pressure and regional pore pressure profile in the tertiary and upper cretaceous sediments of Zubair oil field, southern Iraq. Major findings are as below.

The vertical stress has a gradient of 0.99 PSI/ft. A regional empirical relationship of vertical stress with TVD has been proposed, which will be very effective in case of poor density data or unavailability of the density logs. Pore pressure estimated from sonic slowness log by Eaton's method reveals hydrostatic pore pressure conditions from Dibdibba to Sadi Formation. Mild overpressure of approximately 200 PSI has been interpreted in Tanuma shale from the sonic log response with respect to the NCTL. Disequilibrium compaction due to rapid sedimentation is responsible for excess porosity in Tanuma shale, which resulted in deviation of DT log from NCTL. Extensively available RFT measurements have been used to interpret present day pore pressure condition in Mishrif formation, which indicates dissimilar depletion in pore pressure in the upper and lower member of Mishrif Formation. This might be a result of permeability variation within the formation. The mud weight has been suggested to be slightly overbalanced with respect to the *in situ* formation pressure of Tanuma shale. However mud pressure should not be high enough against depleted Mishrif limestones, otherwise it may result in mud losses.

The observations and results of this study were compared with the finding of Almalikee and Al-Najim[4] from North Rumaila oil field, Iraq, which encompasses the similar stratigraphic succession as in Zubair oil field. Almalikee and Al-Najim[4] established an average 1.02 PSI/ft vertical stress gradient, which is a very close estimate when compared to the studied Zubair field (0.99 PSI/ft). Tanuma shale in Rumaila field has been deciphered as mildly over pressured

(150 PSI higher than hydrostatic)[4], which indicates a similar pressure distribution pattern and hence geological condition prevailing in the late Cretaceous across the region. Middle Cretaceous Mishrif formation serves as the primary reservoir unit in both the oilfields (Rumaila and this study) and the depletion induced pore pressure reduction has been seen to be consistent in both the cases.

CONCLUSION

This study captures the overburden pressure and present-day pore pressure distribution formation wise. This research establishes that the primary reservoir Mishrif formation is presently in sub-hydrostatic pressure regime due to depletion. The presented interpretation will guide the geoscientists and engineers to better plan and design drilling weight for any new infill well in Zubair oil field.

SIGNIFICANCE STATEMENT

This study establishes the regional vertical stress in the Tertiary formations and deciphers the present day *in situ* pore pressure regime across the stratigraphy from a normal compaction trend. This study will help the engineers and geoscientists to confidently design drilling mud weight to avoid wellbore influxes and fluid loss related near wellbore damages in the producing horizons.

ACKNOWLEDGMENTS

Authors are sincerely grateful to Basrah Oil Company for the dataset. The SS thanks Geologix Limited for giving the access to Pore Pressure and Geomechanics module of GEO suite of software, which has been instrumental for various analyses presented here. Interpretations and conclusions drawn in this study are solely of authors and do not necessarily represent those of their employers.

REFERENCES

1. Rajabi, M., M. Tingay and O. Heidbach, 2016. The present-day state of tectonic stress in the Darling Basin, Australia: implications for exploration and production. Mar. Petrol. Geol., 77: 776-790.
2. Sen, S., A. Kundan, V. Kalpande and M. Kumar, 2019. The present-day state of tectonic stress in the offshore Kutch-Saurashtra Basin, India. Mar. Petroleum Geol., 102: 751-758.
3. Tingay, M., 2015. Initial pore pressures under the Lusi mud volcano, Indonesia. Interpretation, 3: SE33-SE49.
4. Almalikee, H.S.A. and F.M.S. Al-Najim, 2018. Overburden stress and pore pressure prediction for the North Rumaila oilfield, Iraq. Model. Earth Syst. Environ., 4: 1181-1188.
5. Sharland, P.R., R. Archer, D.M. Casey, R.B. Davies and S.H. Hall *et al*., 2001. Arabian Plate Sequence Stratigraphy. Gulf PetroLink, Manama, Bahrain, pp: 371-384.
6. Aqrawi, A.A.M., D.H. Andrew, C.G. Jeremy and N.S. Fadhil, 2010. The Petroleum Geology of Iraq. Scientific Press, Beaconsfield, UK., ISBN: 978-0-901360-36-8, Pages: 424.
7. Plumb, R.A., K.F. Evans and T. Engelder, 1991. Geophysical log responses and their correlation with bed to bed stress contrasts in Paleozoic rocks, Appalachian Plateau, New York. J. Geophys. Res., 96: 14509-14528.
8. Sen, S., J. Corless, S. Dasgupta, C. Maxwell and M. Kumar, 2017. Issues faced while calculating overburden gradient and picking shale zones to predict pore pressure. Proceedings of the 1st EAGE Workshop on Pore Pressure Prediction, March 19-21, 2017, Pau, France.
9. Sen, S. and S.S. Ganguli, 2019. Estimation of pore pressure and fracture gradient in volve field, Norwegian North sea. Proceedings of the SPE Oil and Gas India Conference and Exhibition, April 9-11, 2019, Mumbai, India.
10. Kundan, A., A.K. Vinod, P.N.S. Bose, S. Sen and M. Kumar, 2015. Analysis of wellbore breakouts and determination of horizontal stress direction from four arm calipers-A study from Gulf of Kutch, Western Offshore Basin. Proceedings of the 11th Biennial International Conference & Exposition, SPG., Secember 4-6, 2015, Jaipur, India, pp: 1-7.
11. Mouchet, J.P. and A. Mitchell, 1989. Abnormal Pressures while Drilling: Origins, Prediction, Detection, Evaluation. Editions Technip, Paris, France, ISBN: 978-2-7108-0907-4.
12. Sen, S., C. Maxwell and M. Kumar, 2018. Real time pore pressure interpretation from drilling events-A case study from high pressure offshore exploratory well. Proceedings of the Operations Geoscience Adding Value Conference, November 7-8, 2018, The Geological Society, London.
13. Eaton, B.A., 1975. The equation for geopressure prediction from well logs. Proceedings of the Fall Meeting of the Society of Petroleum Engineers of AIME, Dallas, Texas, September 28-October 1, 1975, Society of Petroleum Engineers.
14. Ganguli, S.S., S. Sen and V.P. Dimri, 2018. A comprehensive geomechanical assessment of an Indian mature oil field for CO2-Enhanced oil recovery and its sequestration. Proceedings of the American Geophysical Union (AGU) Fall Meeting, December 10-14, 2014, Washington, D.C.

15. Ganguli, S.S., S. Sen and M. Kumar, 2017. Geomechanical analysis for feasible CO2 storage in an Indian mature oil field. Proceedings of the 12th Biennial International Conference & Exposition, November 17-19, 2017, SPG Jaipur, India.
16. Sen, S., A. Kundan and M. Kumar, 2018. Post-drill analysis of pore pressure and fracture gradient from well logs and drilling events-an integrated case study of a high pressure exploratory well from Panna East, Mumbai Offshore basin, India. Proceedings of the Pore Pressure and Geomechanics from Exploration to Abandonment, AAPG Geosciences Technology Workshop, June 6-7, 2018, Perth, Australia.
17. Zhang, J. and S. Yin, 2017. Real-time pore pressure detection: Indicators and improved methods. Geofluids, Vol. 2017. 10.1155/2017/3179617.
18. Sen, S., I. Ghosh and M. Kumar, 2015. Uncertainty in well log analyses and petrophysical interpretations. Proceedings of the 11th Biennial International Conference & Exposition, December 4-6, 2015, SPG, India.
19. Barnett, A.J., V.P. Wright and M. Khanna, 2010. Porosity evolution in the Bassein Limestone of Panna and Mukta fields, Offshore Western India: Burial corrosion and microporosity development. Proceedings of the AAPG Annual Convention and Exhibition, April 11-19, 2010, New Orleans.
20. Narciso, J., 2014. Pore pressure prediction using seismic velocities. Instituto Superior Técnico, Lisboa.
21. Hantschel, T. and A.I. Kauerauf, 2009. Fundamentals of Basin and Petroleum Systems Modeling. Springer-Verlag, Berlin, Germany, ISBN-13: 9783540723189, Pages: 492.