Overpressure and its positive effect in deep sandstone reservoir quality of Bozhong Depression, offshore Bohai Bay Basin, China

Xiao Wang[a], Sheng He[a*], Stuart Jones[b], Rui Yang[a], Ajuan Wei[c], Changhai Liu[d], Qiang Liu[e], Chunyang Cheng[f], Weimin Liu[g]

[a] Key Laboratory of Tectonics and Petroleum Resources (Ministry of Education), China University of Geosciences, Wuhan, China, 430074

[b] Department of Earth Sciences, Durham University, Durham, UK, DH1 3LE

[c] CNOOC Tianjin Co, Institution of Petroleum Exploration & Development, Tianjin, China, 300452

[d] CNOOC EnerTech Drilling & Prod Co, Tianjin, China, 300452

[e] PetroChina Jidong Oilfield Company, Tangshan, China, 063004

[f] PetroChina Liaohe Oilfield Company, Panjin, China, 124005

[g] SINOPEC Shengli Oilfield Company, Dongying, 257000, China

*Corresponding author, email address: shenghe@cug.edu.cn

Abstract

Bohai Bay Basin is a Meso-Cenozoic terrestrial sedimentary basin in eastern China. Its offshore regions, including Bozhong and Liaodongwan Depressions, are favourable exploration targets which provide near a half of the petroleum reserves in the basin. Eocene Shahejie (Es) Formation and Oligocene Dongying (Ed) Formations are two important exploration targets in Bozhong Depression, and overpressure is commonly seen in Es and Ed Formations in this area. Our research examined the distribution characteristics of overpressure in the formations and suggest the main mechanism of overpressure is compaction disequilibrium due to the rapid sedimentation rates (~500m/Ma) of fine-grained sediments in this area. Also, oil and gas generation within the thick mudstones of the two formations has added the magnitude of overpressure. We investigated the reservoir quality especially primary porosity in Es and Ed formations, and their relationship with overpressure. The positive effect of overpressure on reservoir porosity preservation was validated through microscopic observations and vertical effective stress (VES) analysis. We established a quantitative model for evaluating the relationship of overpressure, pore structures, porosity, and VES. The result suggests the overpressure in the targeted formations were primarily originated from undercompaction. The overpressure kept VES from increasing and helped preserve the primary intergranular porosity. The porosity preserved by overpressure can be significantly higher than normally compacted porosity under the same condition of depth and temperature.

Keywords: overpressure; reservoir quality; Bohai Bay Basin; Shahejie Formation; Dongying Formation

1. Introduction

Reservoir quality evaluation is vital in the exploration and development of deeper targets. Pore geometry, porosity and permeability are the starting points of reservoir quality research (Pittman, 1979; Ehrenberg, 1989, 1990). Deeply buried sandstones with anomalous porosity and permeability are favourable reservoirs providing great probability for commercial production. Anomalous porosity or permeability is statistically higher than the values in typical sandstone reservoirs of a given lithology, age, and burial/temperature (Gluyas and Cade, 1997; Bloch et al., 2002; Taylor et al., 2010). The controlling factors and mechanism of porosity formation and preservation during diagenesis have long been investigated. Loucks et al. (1977) studied the reservoir qualities of Lower Tertiary Frio Formation in Texas Gulf Coast and proposed porosity in shallow reservoirs (<2500m) decrease due to compaction and cementation, however, deeper reservoirs (2500~3500m) gain greater porosities from late subsurface leaching. Bjørlykke (1992, 1998, and 2015) investigated clay mineral reactions in shales and sandstones and discussed their importance in mechanical and chemical compactions. The characteristics of clay coatings and their contribution to porosity preservation in deeply buried reservoirs have also been studied worldwide (Pittman, 1992; Ehrenberg, 1993; Hammer et al., 2010; Morad et al., 2010; Taylor et al., 2010; Maast et al., 2011; Dowey et al., 2012; Stricker et al., 2016a, 2018; Cui et al., 2017; Tang et al., 2018). Overpressure can make great impact on reservoir quality as well. Scherer (1987) looked into thirteen parameters for their influence on primary porosity in sandstones and suggested overpressure may resist the compaction process and preserve primary porosity at a rate of 2% porosity for every 6.9 MPa (1,000 psi) overpressure. Dixon et al. (1989) studied the preserved high primary porosity in deep Norphlet sandstones (20% at depths of more than 6000 m) in Alabama and proposed migration of hydrocarbons and geopressuring is one of the major factors of the preservation. Ramm et al. (1994) predicted the porosity in Norwegian Continental Shelf and summarised the positive correlation between fluid pressure and porosity. This positive correlation between porosity and overpressure has been proved in the researches of the central North Sea (Kugler et al., 1990; Haszeldene et al., 1999; Lander and Walderhaug, 1999; Osborne et al., 1999; Yardley et al., 2000; Lubanzadio et al., 2002; Wilkinson et al., 2006; Goulty et al., 2012; Nguyen et al., 2013; Grant et al., 2014; Sathar and Jones, 2016; Stricker et al., 2016b; Oye et al., 2018; O'neil et al., 2018).

Pleistocene Dongying Formation (Ed) and Eocene Shahejie Formation (Es) are two deep targets (>3000m) in the offshore regions of Bohai Bay Basin, in which overpressure is commonly seen (Wang et al., 2016; Liu et al., 2016, 2017, 2019). In this work, the characteristics of overpressure in Es and Ed are summarized, and the relationship between overpressure and anomalous porosity is investigated through the comprehensive analysis of wirelines, microscopic features, vertical effective stress, and test data including DST, core porosity and permeability.

2. Geological settings

2.1 The structural settings

Bohai Bay Basin, also known as ‘Bohai Basin’ (Allen et al., 1997, 1998), is a “young” sedimentary basin in eastern China. The recently published papers tend to reach an agreement that Bohai Bay Basin is a rift basin reformed by strike-slip faulting (Cai et al., 2001; Hu et al., 2001; Qi, 2004). The structural frame of the offshore regions, having the area of about 4.7×10^4 km^2 and currently covered by the Bohai Sea, is formed by Cenozoic tectonic deformation which is a part of Himalayan tectonic movements (Mi and Duan, 2001; Xu et al., 2002; Xu et al., 2006) and consists of two major depressions: Bozhong and Liaodongwan Depressions (Fig. 1). Bozhong Depression is located in the south and in its centre formed the thickest sedimentation (>11 km). Significant extension began in Bozhong Depression at approximately 43 ~ 45 Ma ago. This syn-rift stage formed the thick layers of Es and Ed Formations and ceased at the end of Oligocene. Then the post-rift thermal subsidence stage have been taking place since the Miocene (24.6 Ma to present) (Cai et al., 2001; Qi, 2004; Gong, 2004; Zhou et al., 2010).

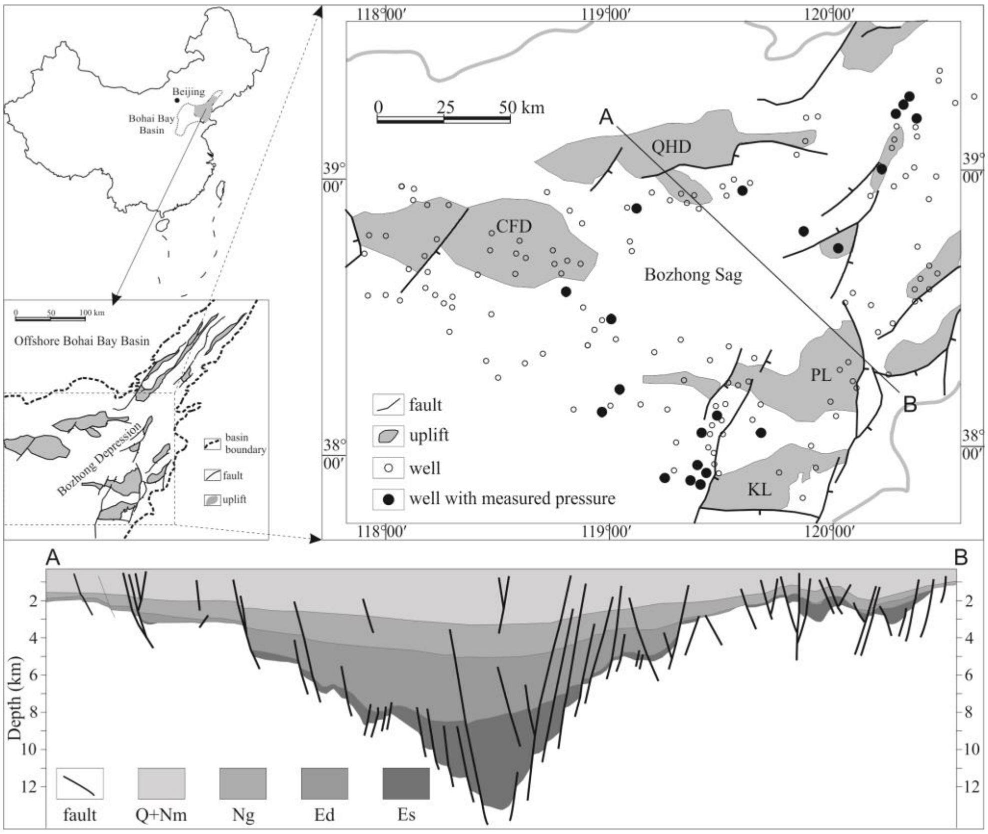

Figure 1. Location and structural distribution of Bozhong Depression.

2.2 The stratigraphic settings

The strata revealed by drilling in Bozhong Depression are (from bottom to top): Anz, Paleozoic (Pz), Mesozoic (Mz), Paleocene-Eocene Kongdian Formation (Ek), Eocene Shahejie Formation(Es), Oligocene Dongying Formation (generally accepted labelled as Ed), Lower-Neocene Guantao Formation (Ng), Upper-Neocene Minghuazhen Formation (Nm), and Quaternary (Qp) (Fig. 2). Their total thickness reached 12000m (39372 ft) in the Bozhong Sag which is the deepest sag of Bozhong Depression, among which Es and Ed Formations take up more than 70%. Es and Ed Formations are delta-lacustrine formations and form two main series of source rock and reservoirs.

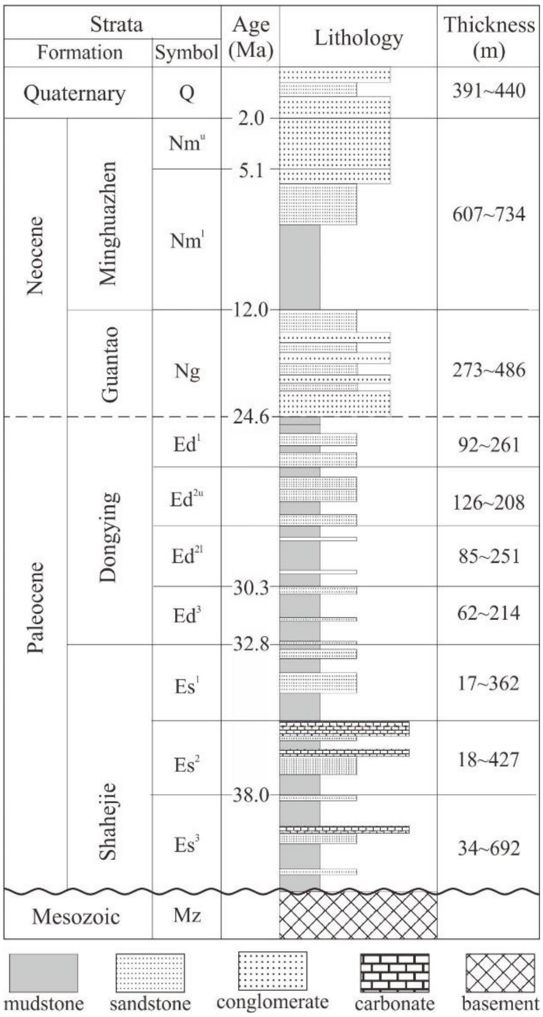

Figure 2. Summarized stratigraphic columns of offshore Bohai Bay Basin.

2.3 The burial and thermal maturity history

Es and Ed Formations are of great thickness in Bozhong Depression. Sedimentation rates of these two formations are relatively high, generally over 200m/Ma, highest reached 525m/Ma. The rapid sedimentation of Es and Ed made it difficult for pore pressure in and underneath Lower Ed to dissipate along the burial. This disequilibrium compaction directly caused the over pressures in Es and Ed Formations. The estimation of pore pressure evolution shows the overpressure (pore pressure extracts hydrostatic pressure) primarily emerged during the deposition of the second member of Ed Formation (Fig. 3).

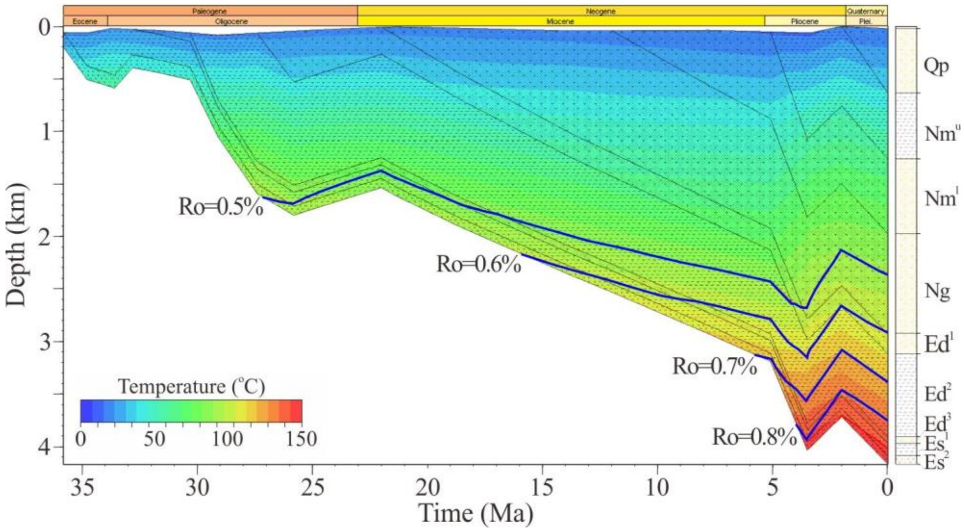

Figure 3. Burial and thermal history of Bozhong Depression.

3. Data and method

We used thin sections observations, core measurements, pore pressure data, and microscopic images to investigate the sandstone composition, reservoir property, pore pressure characteristics, and microscopic features corresponding to different pore pressure conditions. Basin modelling and VES analysis were used in analysing the origin and effect of overpressure.

194 sandstone thin sections of Ed and Es Formations were observed. Grain size and sorting data were obtained by measuring the long axis of framework grains that were selected using a point count grid. 2376 sets of core measurements included porosity and Klinkenberg permeability at in situ stress and 270 DST pore pressure measurements were used in this study. 89 Scanning electron microscopy (SEM) images were observed to examine the relationship between overpressure and microscopic textures.

4. Results

4.1 Sandstone composition and grain size

The Es Formation had been deposited through an environmental change of fluvial /delta – shallow/deep lacustrine – shallow lacustrine/ delta – lacustrine (Zhu et al., 2008). The changes formed four distinct members and sandstones are mainly encountered in the second and fourth members in Es Formation. Thin sections and casting thin section observations suggest the Es sandstones are mainly well sorted lithic arkose and Feldspar litharenite, and a small portion of arkose (Fig. 4a, red circles). The rock fragments are mainly from igneous and metamorphic rocks. The Ed Formation was dominantly formed in lacustrine environment with delta sediments in the slopes. The Ed sandstones comprise lithic arkose and feldspar litharenite, in which lithic arkose takes up slightly more portions (Fig. 4a, blue filled circles). Es and Ed sandstones are generally fine-medium grained. The sandstones are coarser in Es Formation than which in Ed Formation (Fig. 4b).

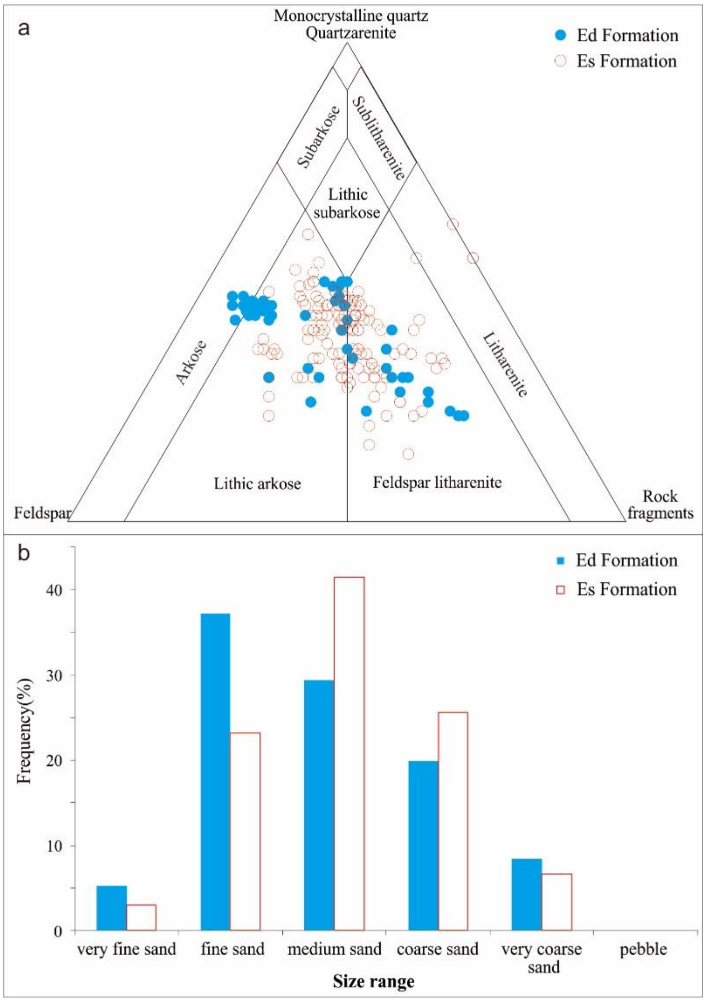

Figure 4. Composition and grain size of the Es and Ed sandstones in Bozhong Depression.

4.2 Porosity and permeability

Core measured sandstone porosities in Es Formation range 10 ~ 30 % from the depth of 2600 m; in Ed Formation they value 8~ 35% from the depth of 1700m (Fig. 5). The porosities in Es and Ed Formations generally demonstrate a decreasing trend versus depth, but off-trend high porosities are encountered in both formations. The porosity can reach 30% at the depth of ~4300 m (13124 ft.), which deviate from the regional porosity trend significantly. As the sandstone type and grain size don't vary substantially in the two formations, pore pressure is taken into account to explain the generation and maintaining of the off-trend high porosities in deep reservoir. Seen from the correlation of the porosities of the entire sandstone reservoir and porosities in the overpressured intervals, the off-trend high porosities predominantly fall in the overpressured intervals. Klinkenberg permeability in Bozhong Depression ranges 0.001 ~ 7000 mD and corelates well with porosities, suggesting the porosity can be relied solely to estimate the reservoir quality (Fig. 6).

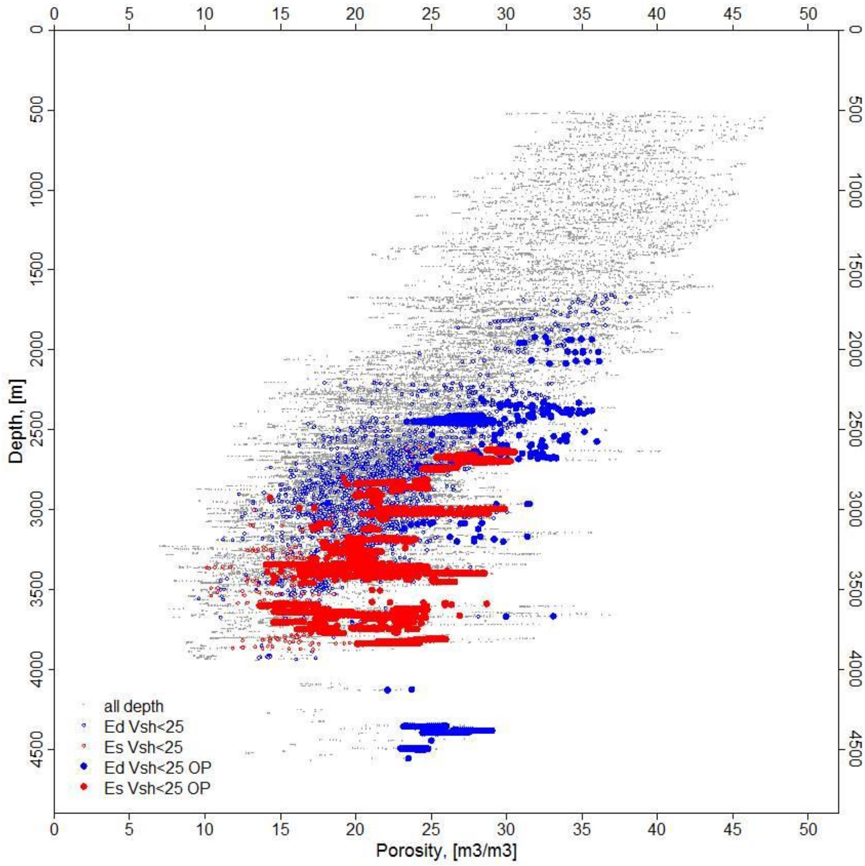

Figure 5. Porosity versus depth in Bozhong Depression.

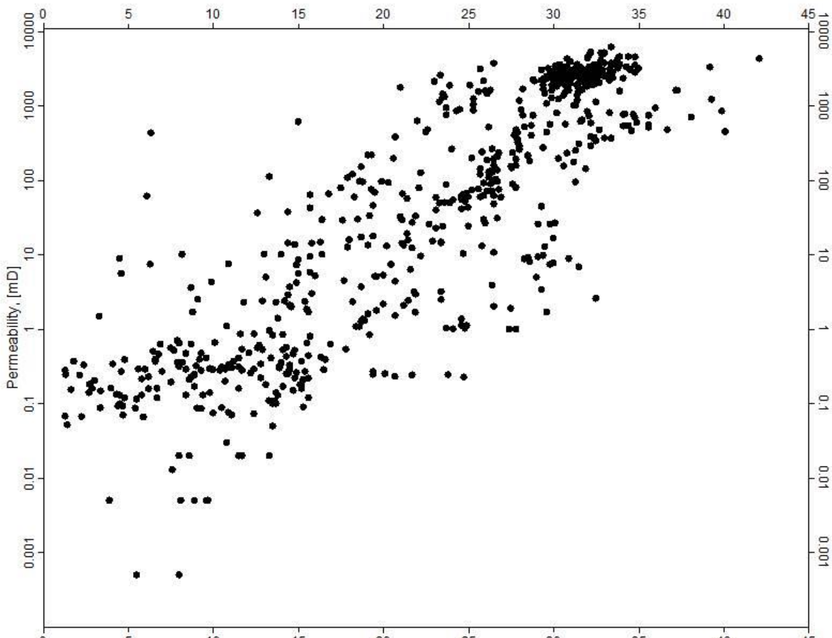

Figure 6. Porosity-permeability correlation in Bozhong Depression.

4.3 Pore pressure characteristics in Bozhong Depression

Vertically, DST data shows there are abnormally high pressures in Es and Ed Formations in this area (Fig. 7). Generally, the overpressure onset can be recognised from ~2500 m (8202 ft.) in depth and get the greatest magnitude between 3500m and 3800m (11483~12467 ft.). Pore pressure in Ed Formation reaches 59.63 MPa (8647 psi) at the depth of 3650 m (11977 ft.), with the overpressure coefficient (the ratio of pore pressure to hydrostatic pressure) of 1.65; in Es Formation, the maximum measured pore pressure, 61.46 MPa (8912 psi), occurs at the depth of 3768 m (12363 ft.). Wells revealed overpressure distribute around the Bozhong Depression (Fig. 8). There is no well drilled in the deep sag centre where current water depth of Bohai Sea reaches 85 m (279 ft.) or deeper, hence the regional distribution of overpressure was estimated from basin modelling.

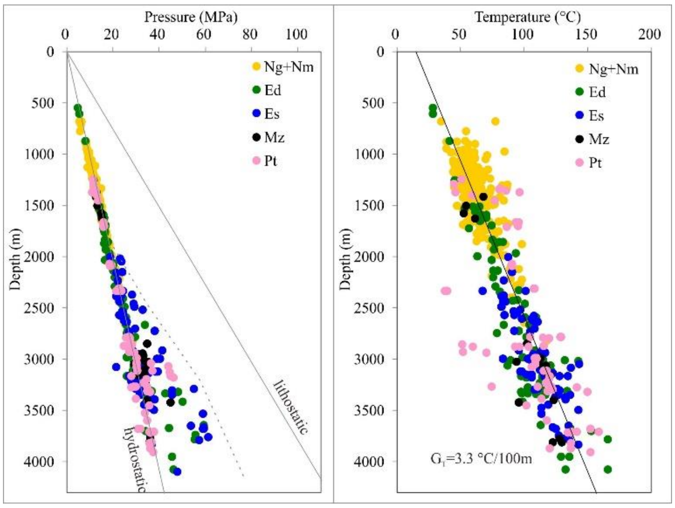

Figure 7. Measured data of pressure and temperature versus depth.

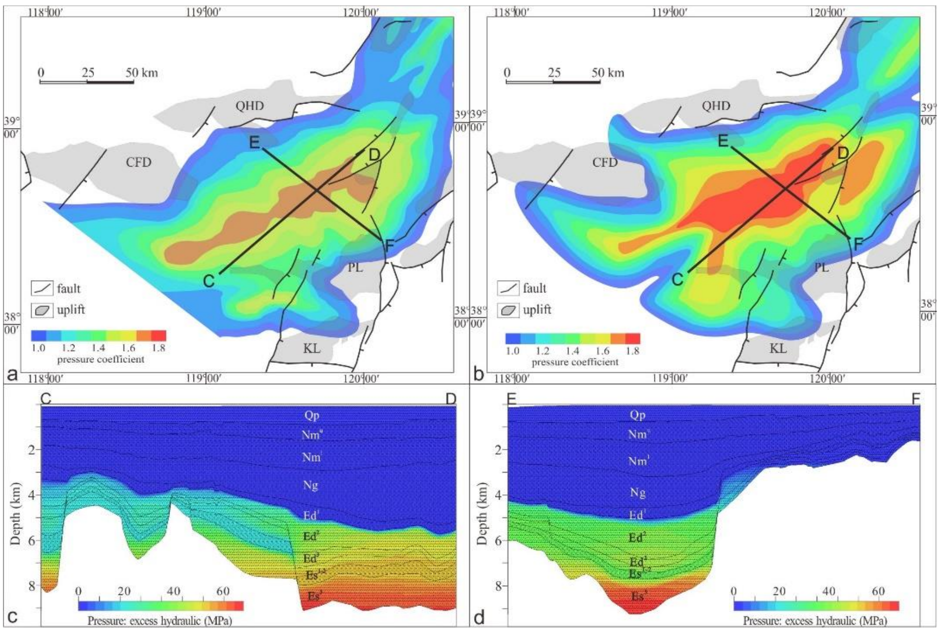

Figure 8. Distribution maps and profiles of overpressure in Bozhong Depression.

4.4 Microscopic characteristics

Micro analysis of porosity has been carried out to analysis the porosity preservation situations in normally compacted sandstones and overpressured ones. SEM photos of the sandstone samples are differentiated by their stratum and sedimentary facies. When compared, the micro porosities of sandstones in same stratum and same facies show significant difference as the pore pressure conditions are different

In Ed Formation, sample ① is taken from the depth of 2888 m (9475 ft.), the excess hydrostatic pressure is 8MPa (1160 psi); Neutron porosity at this depth is ~27% (Fig. 9a). In the SEM image, primary pores can be seen and the cementation is not severe. Cements are quartz, illite, and some kaolinite (Fig. 9b, ①).

Sample ② is taken from the depth of 2702 m (8866 ft.), the excess hydrostatic pressure is 2 MPa (290 psi); Neutron porosity at this depth is ~17% (Fig. 9a). In the SEM image, primary pores are filled by illite, kaolinite and some carbonate (Fig. 9b, ②).

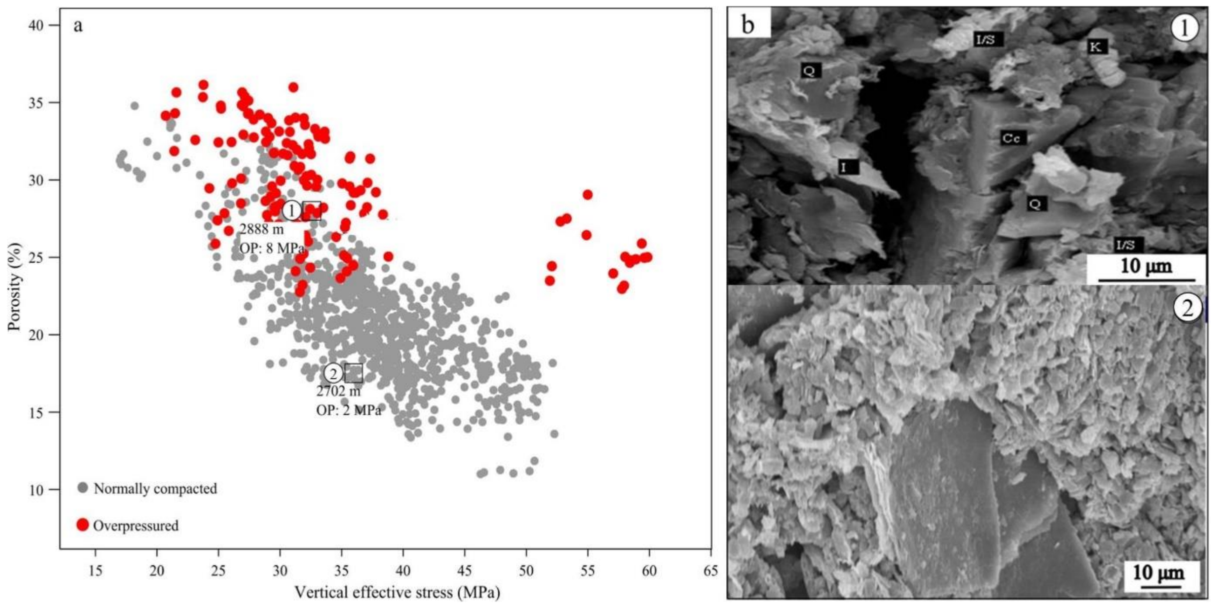

Figure 9. The SEM images of Ed sandstones within different pore pressure horizons.

Unlike Ed Formation which is overpressured in deeper part, Es Formation is generally overpressured. In Es Formation, sample ① is taken from the depth of 3002 m (9850 ft.), the excess hydrostatic pressure is 10 MPa (1450 psi); Neutron porosity at this depth is ~23% (Fig. 10a). In the SEM image, primary pores can be seen and the cements are quartz, illite, and some kaolinite (Fig. 10b, ①).

Sample ② is taken from the depth of 3704 m (12153 ft.), the excess hydrostatic pressure is 23 MPa (3335 psi); Neutron porosity at this depth is ~24% (Fig. 10a). In the SEM image, chlorite grain coats may help preserve the primary pores (Fig. 10b, ②). Though it is deeper, the porosity maintains high compare to other samples.

Sample ③ is taken from the depth of 3430 m (11254 ft.), the excess hydrostatic pressure is 9 MPa (1306 psi); Neutron porosity at this depth is ~17% (Fig. 10a). In the SEM image, primary pores are filled by illite and kaolinite (Fig. 10b, ③). The overpressure magnitude is relatively small considering its depth when compare to sample ①, and the porosity is smaller. Sample ④ is taken from the depth of 3091 m (10141 ft.), the excess hydrostatic pressure is 5 MPa (725 psi); Neutron porosity at this depth is ~20% (Fig. 10a). In the SEM image, grains are cemented by calcite and some kaolinite (Fig. 10b, ④).

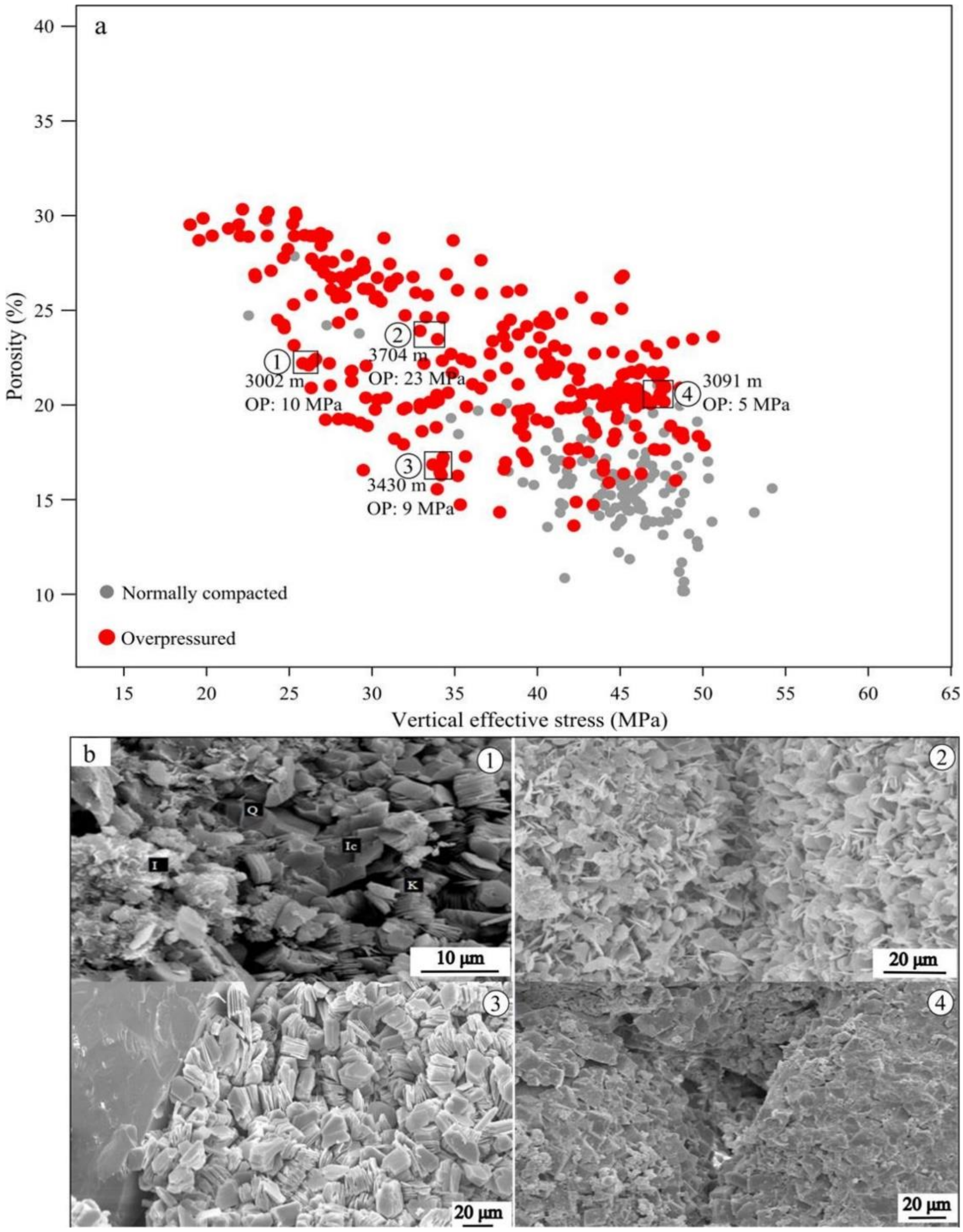

Figure 10. The SEM images of Es sandstones within different pore pressure horizons.

5. Discussion

5.1 The origin of overpressure

As stated in the geological settings, Es and Ed Formations are of great thickness in Bozhong Depression. Sedimentation rates of these two formations are relatively high, averaged over 200 m/Ma, with the highest reached 525m/Ma (see section 2.3). In normal compaction basin with similar age and lithology, the sedimentation rate is usually less than 100 m/Ma (Ibach, 1982; Katz, 2005). The rapid sedimentation of Es and Ed prevented pore pressure in and underneath Lower Ed to dissipate during the burial processes. This disequilibrium compaction gradually accumulated overpressures in Es and Ed Formations. The estimation of pore pressure evolution shows the overpressure (pore pressure extracts hydrostatic pressure) primarily emerged during the deposition of the middle member of Ed Formation (E_3d^2) (see Fig. 8).

Hydrocarbon generation is considered to be the second cause of overpressure. The source rocks in Es and Ed Formations were buried deep during the rapid burial which may have accelerated their maturation and generation behaviour. Source rocks in Es and Ed Formations have a vitrinite reflectance (Ro) values of 0.6% or higher under the depth of 2500 m (8203 ft.).

5.2 Vertical effective stress – porosity relationships

Since the overpressure in Bozhong Depression is mainly caused by disequilibrium compaction, mechanical compaction may have controlled the primary porosity preservation in sandstones. We used equation derived from Terzaghi's effective stress principle to investigate the VES (Nur and Byerlee, 1971; Tuncay and Corapcioglu, 1995). The relationship of porosity and vertical effective stress (VES) is employed in this research to investigate the process of mechanical compaction and its effect on the porosities. Sandstone porosities in Es and Ed Formations generally show a decreasing trend while the VES increases (Fig. 11, first column). The porosities in overpressured horizons are on the trend but a bit higher at same VES compared to which in normal pressured horizons, which may indicate overpressured sandstones have better porosity than normally compacted ones at the same depth.

The compaction rate of sandstones varies significantly from facies to facies. The finer grained sediments can be compacted relatively faster and easier than coarse grains. To eliminate the facies variation effect in compaction process, shale content (Vsh) is introduced to investigate the VES – porosity relationship in similar sandstones. Considering the facies evolution in Bozhong Depression, sandstones have Vsh less than 25% formed in shallow lacustrine or slope, Vsh less than 15% mostly occur in delta front. As in Fig. 11 (middle and right columns), sandstones with Vsh less than 15% show the most distinct and uniform decreasing trend. The high pore pressure horizons, which are the low in VES, correlate to high porosities. This indicates overpressure helped preserving the primary porosity.

Some anomalously high porosity occurs in Ed Formation in a deep well (stays 25~30 % below 4300 m / Fig. 11, upper row). This porosity may be added by the secondary dissolution porosity.

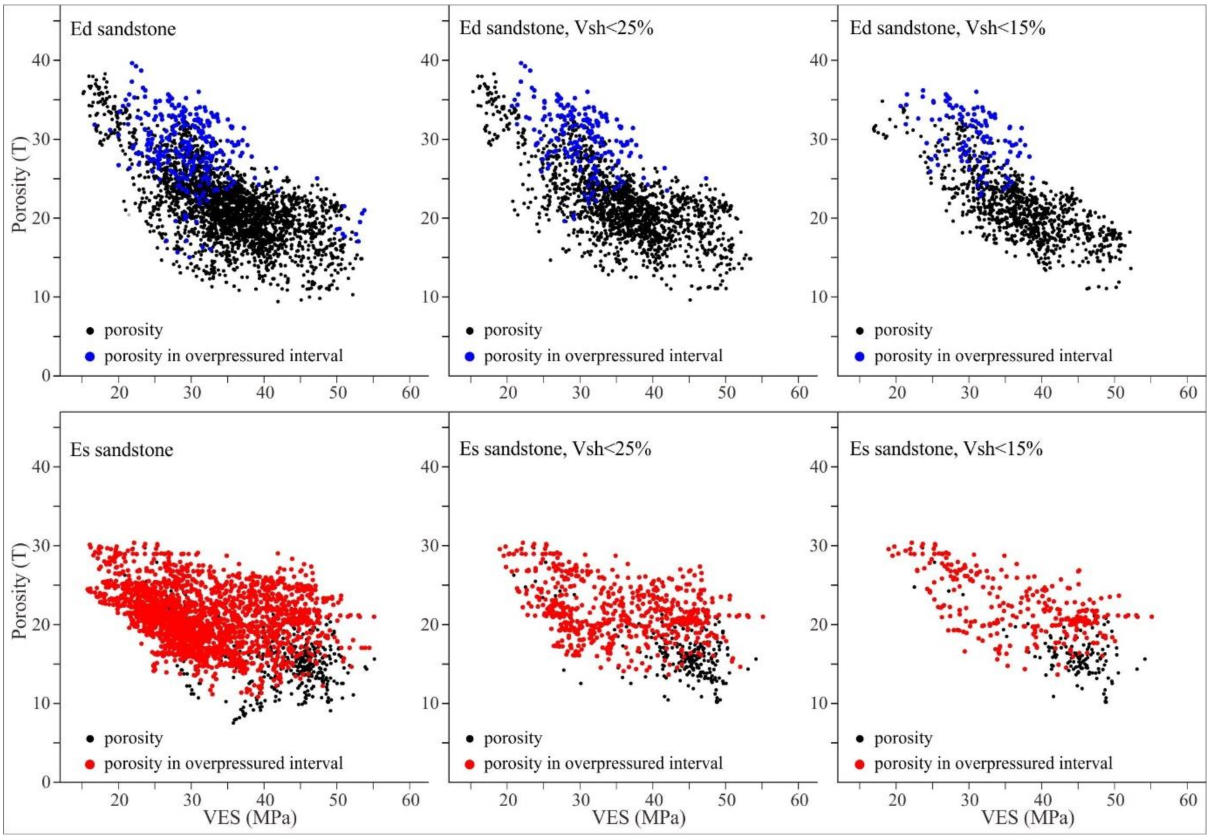

Figure 11. The relationship of porosity and vertical effective stress in Bozhong Depression.

5.3 Schematic model of the preservation effect of overpressure on sandstone porosity

Based on the above analysis, we have established a schematic model which illustrate the vertical effective stress and sandstone porosity evolution (Fig. 12). The intention of this model is to provide a quantitative reference for the relationship of overpressure, pore structures, porosity, and VES. For normally compacted sandstone reservoirs which consists mainly of quartz and feldspars and have initial primary intergranular porosity of ~30%, the initial VES would be ~20 MPa. The contact of grains were point contact, and cementation was weak. With the burial depth increasing, the VES increased. With increasing VES, the contact of matrix grains in sandstones became tighter, from point contact to line contact. The primary intergranular pores became smaller or even vanished. When VES reached ~40 MPa, the primary intergranular porosity would decline to less than 15%. However, the primary intergranular porosity in undercompacted reservoir (having an overpressure magnitude of ~20

MPa) can retain 25% at the similar depth. Undercompaction induced overpressures would be preserved in the matrix unless deformed afterwards, hence they can resist the stress act upon sandstone grains, keeping the VES from increasing. Therefore, the compaction between matrix grains and reservoir porosity were protected by overpressure. The primary intergranular porosity preserved by overpressure can be more than 10% higher than normally compacted porosity under the same condition of depth and temperature.

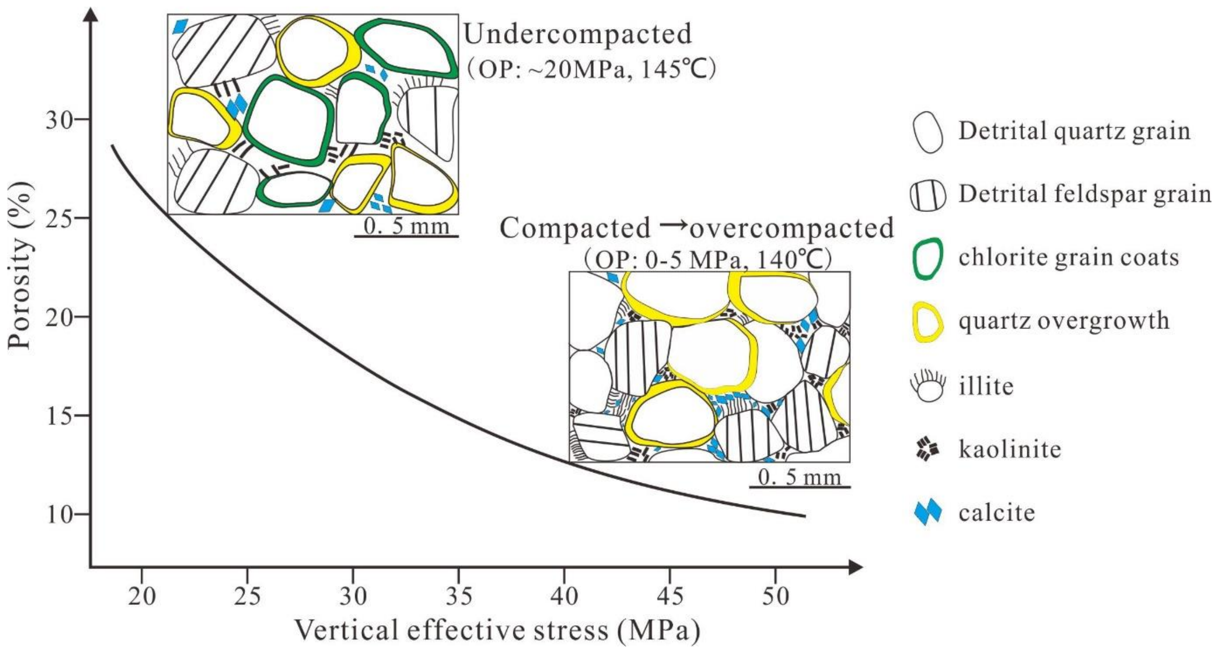

Figure 12. The schematic diagram of the relationship between VES and porosity.

6. Conclusion

Extensive overpressure has been encountered in Bozhong Depression of offshore Bohai Bay Basin. The overpressure is mainly confined in the Es and Ed Formations, and the pore pressure can reach ~60 MPa (8700 psi) at the depth of ~3700 m (12140 ft.) according to the measured data. Disequilibrium compaction is identified as the main mechanism of overpressure generation in this area. Hydrocarbon generation has added to the amount of overpressure at the present day.

Reservoir quality of sandstone in the Es and Ed Formations is variable but there are off-trend high porosities which can be up to 30% at the depth of ~4000 m (13124 ft.). Almost all of these off-trend high porosities are recorded in the intervals with overpressure. Porosity-vertical effective stress analysis and the micro pore structures validate the positive effect of overpressure on high porosity preservation. The primary intergranular porosity preserved by overpressure can be more than 10% higher than normally compacted porosity under the same condition of depth and temperature.

Acknowledgments

This work was supported by the Fundamental Research Funds for the Central Universities, China University of Geosciences (Wuhan), and China National Science and Technology Major Project (No. 2016ZX05006-003-001). Xiao Wang's visiting study in Durham University was supported by China Scholarship Council (No. 201406410047).

References

Allen, M., Macdonald, D., Xun, Z., Vincent, S., and Brouet-Menzies, C., 1997. Early Cenozoic two-phase extension and late Cenozoic thermal subsidence and inversion of the Bohai Basin, northern China. Marine and Petroleum Geology, 14: 951-972. http://dx.doi.org/10.1016/S0264-8172(97)00027-5

Allen, M. B., Macdonald, D. I., Xun, Z., Vincent, S. J., and Brouet-Menzies, C., 1998. Transtensional deformation in the evolution of the Bohai Basin, northern China. Geological Society, London, Special Publications, 135: 215-229. http://dx.doi.org/10.1144/GSL.SP.1998.135.01.14

Bjørlykke, K., and Aagaard, P., 1992. Clay minerals in North Sea sandstones, in Houseknecht, D. W. and Pittman, E. D. eds., Origin, diagenesis, and petrophysics of clay minerals in sandstones. Tulsa, Oklahoma, SEPM: 65-80.

Bjørlykke, K., 1998. Clay mineral diagenesis in sedimentary basins-a key to the prediction of rock properties. Examples from the North Sea Basin. Clay Minerals, 33: 15-34. http://dx.doi.org/10.1180/claymin.1998.033.1.03

Bjørlykke, K., and Jahren, J., 2015. Sandstones and sandstone reservoirs, Petroleum Geoscience. Springer.

Bloch, S., Lander, R. H., and Bonnell, L. M., 2002. Anomalously high porosity and permeability in deeply buried sandstone reservoirs: Origin and predictability. AAPG Bulletin, 86: 301-328. http://dx.doi.org/10.1306/61eedabc-173e-11d7-8645000102c1865d

Cai, D., Yuhui, L., Wenlai, W., and Changhua, Y., 2001. Shallow tectonic deformation and its relationship to hydrocarbon enrichment in Bozhong Depression and adjacent areas, Bohai Bay Basin. China Offshore Oil and Gas, 1: 006-010.

Cui, Y., Jones, S. J., Saville, C., Stricker, S., Wang, G., Tang, L. and Chen, J., 2017. The role played by carbonate cementation in controlling reservoir quality of the Triassic Skagerrak Formation, Norway. Marine and Petroleum Geology, 85: 316-331. http://dx.doi.org/10.1016/j.marpetgeo.2017.05.020

Dixon, S. A., Summers, D. M., and Surdam, R. C., 1989. Diagenesis and preservation of porosity in Norphlet Formation (Upper Jurassic), southern Alabama. AAPG Bulletin, 73: 707-728.

Dowey, P. J., Hodgson D. M., and Worden, R. H., 2012. Prerequisites, processes, and prediction of chlorite grain coatings in petroleum reservoirs: A review of subsurface examples. Marine and Petroleum Geology, 32: 63-75. http://dx.doi.org/10.1016/j.marpetgeo.2011.11.007

Ehrenberg, S., 1989. Assessing the relative importance of compaction processes and cementation to reduction of porosity in sandstones: Discussion. AAPG Bulletin, 73: 1274-1276. http://dx.doi.org/10.1306/44B4AA1E-170A-11D7-8645000102C1865D

Ehrenberg, S., 1990. Relationship between diagenesis and reservoir quality in sandstones of the Garn formation, Haltenbanken, mid-Norwegian Continental shelf. AAPG Bulletin, 74: 1538-1558.

Ehrenberg, S., 1993. Preservation of anomalously high porosity in deeply buried sandstones by grain-coating chlorite: examples from the Norwegian continental shelf. AAPG Bulletin, 77: 1260-1286. http://dx.doi.org/10.1306/BDFF8E5C-1718-11D7-8645000102C1865D

Gluyas, J. G., and Cade, C. A., 1997. Prediction of porosity in compacted sands, in J. A. Kupecz, J. G. Gluyas, and C. A. Cade, eds., Reservoir quality prediction in sandstones and carbonates. AAPG Memoir, 69: 19-28.

Gong, Z., 2004. Neotectonic movement and hydrocarbon accumulation in petroliferous basins, offshore China. Oil & Gas Geology, 2:562-570. (in Chinese)

Goulty, N., Ramdhan, A., and Jones, S., 2012. Chemical compaction of mudrocks in the presence of overpressure. Petroleum Geoscience, 18: 471-479. http://dx.doi.org/10.1144/petgeo2012-018

Grant, N. T., Middleton, A. J., and Archer, S., 2014. Porosity trends in the Skagerrak Formation, Central Graben, United Kingdom Continental Shelf: The role of compaction and pore pressure history. AAPG Bulletin, 98: 1111-1143. http://dx.doi.org/10.1306/10211313002

Hammer, E., Mork, M. B. E., and Naess, A., 2010. Facies controls on the distribution of diagenesis and compaction in fluvial-deltaic deposits. Marine and Petroleum Geology, 27: 1737-1751. http://dx.doi.org/10.1016/j.marpetgeo.2009.11.002

Haszeldene, R. S.,Wilkinson, M., Darby, D., Macaulay, C. I., Couples, G. D., Fallick, A. E., Fleming, C. G., Stewart, R. N. T., and McAulay, G., 1999. Diagenetic porosity creation in an overpressured graben, in Fleet, A. J. and Boldy, S. A. eds., Petroleum geology of northwest Europe. Proceedings of the 5th Conference: London, United Kingdom, Geological Society.

Hu, S., O'Sullivan, P. B., Raza, A., and Kohn, B. P., 2001. Thermal history and tectonic subsidence of the Bohai Basin, northern China: a Cenozoic rifted and local pull-apart basin. Physics of the Earth and Planetary Interiors, 126: 221-235. http://dx.doi.org/10.1016/S0031-9201(01)00257-6

Ibach, L. E. J., 1982. Relationship between sedimentation rate and total organic carbon content in ancient marine sediments. AAPG Bulletin, 66(2): 170-188.

Katz, B. J., 2005. Controlling factors on source rock development-a review of productivity, preservation, and sedimentation rate. SEPM Special Publication, 82:7-16. http://dx.doi.org/10.2110/pec.05.82.0007

Kugler, R. L., and McHugh, A., 1990. Regional diagenetic variation in Norphlet Sandstone: Implications for reservoir quality and the origin of porosity. Gulf Coast Association of Geological Societies Transactions, 40: 411-423.

Lander, R.H., and Walderhaug, O., 1999. Predicting porosity through simulating sandstone compaction and quartz cementation. AAPG Bulletin, 83: 433-449.

Liu, H., Jiang, Y., Song, G., Gu, G., Hao, L., and Feng, Y., 2017. Overpressure characteristics and effects on hydrocarbon distribution in the Bonan Sag, Bohai Bay Basin, China. Journal of Petroleum Science and Engineering, 149: 811-821. http://dx.doi.org/10.1016/j.petrol.2016.11.029

Liu, H., Jing, C., Jiang, Y., Song, G., Yu, Q., and Feng, Y., 2016. Characteristics and genetic mechanisms of overpressure in the depressions of Bohai Bay Basin, China. Acta Geologica Sinica - English Edition, 906: 2216-2228. http://dx.doi.org/10.1111/1755-6724.13032

Liu, H., Yuan, F., Jiang, Y., Zhao, M., Chen, K., Guo, Z., and Wang, Y., 2019. Mechanisms for overpressure generated by the undercompaction of paleogene strata in the Baxian Depression of Bohai Bay Basin, China. Marine and Petroleum Geology, 99: 337-346. http://dx.doi.org/10.1016/j.marpetgeo.2018.10.001

Loucks, R., Bebout, D., and Galloway, W. E., 1977. Relationship of Porosity Formation and Preservation to Sandstone Consolidation History--Gulf Coast Lower Tertiary Frio Formation. Gulf Coast Association of Geological Societies Transactions, 27:109-120.

Lubanzadio, M., Goulty, N. R., and Swarbrick, R. E., 2002. Variation of velocity with effective stress in chalk: Null result from North Sea well data. Marine and Petroleum Geology, 19: 921-927. http://dx.doi.org/10.1016/S0264-8172(02)00135-6

Maast, T. E., Jahren, J., and Bjørlykke, K., 2011. Diagenetic controls on reservoir quality in Middle to Upper Jurassic sandstones in the South Viking Graben, North Sea. AAPG Bulletin, 95:1937-1958. http://dx.doi.org/10.1306/03071110122

Mi, L., and Duan, J., 2001. Characteristics of middle and shallow strata oil-gas reservoirs and oil-gas accumulation rule in the middle area of Bohai. Acta Petrolei Sinica, 2: 006-010. (in Chinese)

Morad, S., Al-Ramadan, K., Ketzer, J. M., and De Ros, L. F., 2010. The impact of diagenesis on the heterogeneity of sandstone reservoirs: A review of the role of depositional facies and sequence stratigraphy. AAPG Bulletin, 94: 1267-1309. http://dx.doi.org/10.1306/04211009178

Nguyen, B. T., Jones, S. J., Goulty, N. R., Middleton, A. J., Grant, N., Ferguson, A., and Bowen, L., 2013. The role of fluid pressure and diagenetic cements for porosity preservation in Triassic fluvial reservoirs of the Central Graben, North Sea. AAPG Bulletin, 97: 1273-1302. http://dx.doi.org/10.1306/01151311163

Nur, A., and Byerlee, J., 1971. An exact effective stress law for elastic deformation of rock with fluids. Journal of Geophysical Research, 76(26): 6414-6419. http://dx.doi.org/10.1029/JB076i026p06414

O'Neill, S. R., Jones, S. J., Kamp, P. J., Swarbrick, R. E., and Gluyas, J. G., 2018. Pore pressure and reservoir quality evolution in the deep Taranaki Basin, New Zealand. Marine and Petroleum Geology, 98: 815-835. http://dx.doi.org/10.1016/j.marpetgeo.2018.08.038

Osborne, M. J., and Swarbrick, R. E., 1999. Diagenesis in North Sea HPHT clastic reservoirs: Consequences for porosity and overpressure prediction. Marine and Petroleum Geology, 16: 337-353. http://dx.doi.org/10.1016/s0264-8172(98)00043-9

Oye, O. J., Aplin, A. C., Jones, S. J., Gluyas, J. G., Bowen, L., Orland, I. J., and Valley, J. W., 2018. Vertical effective stress as a control on quartz cementation in sandstones. Marine and Petroleum Geology, 98: 640-652. http://dx.doi.org/10.1016/j.marpetgeo.2018.09.017

Pittman, E. D., 1979. Porosity diagenesis and productive capability of sandstone reservoirs. SEPM Special Publication, 26: 157-173. http://dx.doi.org/10.1306/C1EA4545-16C9-11D7-8645000102C1865D

Pittman, E. D., Larese R. E., and Heald, M. T., 1992. Clay coats: Occurrence and relevance to preservation of porosity in sandstones. SEPM Special Publication, 47: 241-255. http://dx.doi.org/10.2110/pec.92.47.0241

Qi, J., 2004. Two tectonic systems in the Cenozoic Bohai Bay basin and their genetic interpretation. Chinese Geology, 1: 001-005. (in Chinese)

Ramm, M., and Bjørlykke, K., 1994. Porosity/depth trends in reservoir sandstones: Assessing the quantitative effects of varying pore-pressure, temperature history and mineralogy, Norwegian Shelf data. Clay Minerals, 29: 475-490. http://dx.doi.org/10.1180/claymin.1994.029.4.07

Sathar, S., and Jones, S., 2016. Fluid overpressure as a control on sandstone reservoir quality in a mechanical compaction dominated setting: Magnolia Field, Gulf of Mexico. Terra Nova, 283: 155-162. http://dx.doi.org/10.1111/ter.12203

Scherer, M., 1987. Parameters influencing porosity in sandstones: a model for sandstone porosity prediction. AAPG Bulletin, 71: 485-491. http://dx.doi.org/10.1306/703C80FB-1707-11D7-8645000102C1865D

Stricker, S., Jones, S. J., and Grant, N. T. 2016b. Importance of vertical effective stress for reservoir quality in the Skagerrak Formation, Central Graben, North Sea. Marine and Petroleum Geology, 78: 895-909. http://dx.doi.org/10.1016/j.marpetgeo.2016.03.001

Stricker, S., Jones, S. J., Meadows, N., and Bowen, L., 2018. Reservoir quality of fluvial sandstone reservoirs in salt-walled mini-basins: an example from the Seagull field, Central Graben, North Sea, UK. Petroleum Science, 151: 1-27. http://dx.doi.org/10.1007/s12182-017-0206-x

Stricker, S., Jones, S. J., Sathar, S., Bowen, L., and Oxtoby, N., 2016a. Exceptional reservoir quality in HPHT reservoir settings: examples from the Skagerrak Formation of the Heron Cluster, North Sea, UK. Marine and Petroleum Geology, 77: 198-215. http://dx.doi.org/10.1016/j.marpetgeo.2016.02.003

Tang, L. X., Gluyas, J., Jones, S., and Bowen, L., 2018. Diagenetic and geochemical studies of the Buchan Formation Upper Devonian in the Central North Sea. Petroleum Science, 152: 211-229. http://dx.doi.org/10.1007/s12182-018-0232-3

Taylor, T. R., Giles, M. R., Hathon, L. A., Diggs, T. N., Braunsdorf, N. R., Birbiglia, G. V., Kittridge, M. G., Macaulay, C. I., and Espejo, I. S., 2010. Sandstone diagenesis and reservoir quality prediction: Models, myths, and reality. AAPG Bulletin, 94: 1093-1132. http://dx.doi.org/10.1306/04211009123

Tuncay, K., and Corapcioglu, M. Y., 1995. Effective stress principle for saturated fractured porous media. Water Resources Research, 31(12): 3103-3106. http://dx.doi.org/10.1029/95WR02764

Wang, X., He, S., Wei, A., Liu, Q., and Liu, C., 2016. Typical disequilibrium compaction caused overpressure of Paleocene Dongying Formation in northwest Liaodongwan Depression, Bohai Bay Basin, China. Journal of Petroleum Science and Engineering, 147: 726-734. http://dx.doi.org/10.1016/j.petrol.2016.09.014

Wilkinson, M., Haszeldene, Haszeldene, R. S., and Fallick, A. E., 2006. Hydrocarbon filling and leakage history of a deep geopressured sandstone, Fulmar Formation, United Kingdom North Sea. AAPG Bulletin, 90: 1945-1961. http://dx.doi.org/10.1306/06270605178

Xu, C., Jiang, P., Wu, F., Yang, B., and Li, D., 2002. Discovery and sedimentary characteristics of the Neogene delta in Bozhong depression and its significance for oil and gas exploration. Acta Sedimentologica Sinica, 20: 588-594. (in Chinese)

Xu, Z., Chen, S., and Wang, Y., 2006. Mesozoic tectonic activities and sedimentation in the Bohai Gulf area. Chinese Geology, 33: 201-211. (in Chinese)

Yardley, G. S., and Swarbrick, R. E., 2000. Lateral transfer: A source of additional overpressure. Marine and Petroleum Geology, 17: 523-538. http://dx.doi.org/10.1016/S0264-8172(00)00007-6

Zhou, X., Yu, Y., Tang, L., Lv, D., and Wang, Y., 2010.Cenozoic offshore basin architecture and division of structural elements in Bohai sea. China Offshore Oil and Gas (Geology), 22: 285-289.(in Chinese)

Zhu, W., Li, J., Zhou, X., and Guo, Y., 2008. Neogene shallow water deltaic system and large hydrocarbon accumulations in Bohai Bay, China. Acta Sedimentologica Sinica, 26: 575-582. (in Chinese)

Figure captions

Figure 1. Location and structural distribution of Bozhong Depression.

Figure 2. Summarized stratigraphic columns of offshore Bohai Bay Basin.

Figure 3. Burial and thermal history of Bozhong Depression.

Figure 4. Composition and grain size of the Es and Ed sandstones in Bozhong Depression.

Figure 5. Porosity versus depth in Bozhong Depression.

Figure 6. Porosity-permeability correlation in Bozhong Depression.

Figure 7. Measured data of pressure and temperature versus depth.

*The hydrostatic pressure gradient in this area is 10 MPa/km (0.442 psi/ft).

*Overlapped depth of different stratum is due to the difference of structural location.

Figure 8. Distribution maps and profiles of overpressure in Bozhong Depression.

Figure 9. The SEM images of Ed sandstones within different pore pressure horizons.

Figure 10. The SEM images of Es sandstones within different pore pressure horizons.

Figure 11. The relationship of porosity and vertical effective stress in Bozhong Depression.

Figure 12. The schematic diagram of the relationship between VES and porosity.