RESEARCH ARTICLE

Geological characteristics and abnormal pore pressure prediction in shale oil formations of the Dongying depression, China

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Abstract

Pore pressures in shale oil formations in the Dongying depression of the Bohai Bay Basin are highly overpressured. Understanding overpressure principles not only can reveal the mechanism of shale oil generation to provide prospects for shale oil exploration and production, but also can reduce potential drilling risks and provide insights for sweet spot identification. Overpressure generation mechanisms are analyzed based on petrophysical data, core analysis, sedimentation rate, oil saturation, and smectite and illite data. We find that undercompaction, oil generation, and smectite and illite transformation are primary causes of overpressures. Undercompaction is the major cause of overpressures in the Es3 formations because of their rapid deposition rate of 300-700 m/m.y. For the overpressures primarily generated by undercompaction, sonic transit time can be used to predict shale pore pressure with correctly selected depth-dependent normal compaction trend. In the Es3 and Es4 formations, overpressure data are consistent with the increase of vitrinite reflectance and oil saturation, indicators of oil generation. Additionally, in shallow formations, starting at about 2000 m, the smectite to illite transformation occurs, which makes rock property changes with depth. A composite normal compaction trendline is proposed to account for the smectite to illite transformation. Using well log data, the shale oil formations can be identified and there are two shale oil formations in the studied area, and a shale oil geo-marker is found. At this geo-marker, the pore pressure gradient reaches the highest value. This high pore pressure behavior is beneficial for shale oil production because of a higher pore pressure corresponds to a higher production.

KEYWORDS

oil generation, petroleum geology, pore pressure prediction, shale oil, sonic transit time, undercompaction
INTRODUCTION

Numerous theoretical research and cases studies have been reported for pore pressure predictions in conventional reservoirs (eg, [1-10]). However, as the exploration and production of hydrocarbons shift to shale gas and shale oil plays, studies of pore pressure predictions and overpressure mechanisms are needed for development of these unconventional resources. Most shale oil and gas plays in the United States have abnormal pore pressures, and high overpressures are very common (Table 1). For example, in the Haynesville and Bossier shale gas plays, the pore pressure gradient is extremely high, ranging from 0.75 to 0.94 psi/ft (1.73-2.17 g/cm³). This abnormally high pore pressure gradient has caused many drilling incidents (eg, kicks and blowouts). However, not many cases were reported on pore pressure prediction and overpressure mechanism studies in shale plays (eg, [11-19]).

It is estimated that shale oil reserves in eastern China might reach about 47 billion bbls (6.57 billion tons). Shale oil development is very important for eastern China because it is a densely populational and highly industrialized region. However, shale oil development is still in its initial stage in China. Data in several major shale formations show that pore pressures of shale plays in China are also overpressured (Table 2). The upside of the high-pressure gradient has been abnormally high well initial productions (9.5 MMscf/d (2.7 × 10⁵ m³), Sandrea and Sandrea21), almost five times those of the benchmark Barnett shale (with a normal pore pressure or slight overpressure). Shale oil production data in the Dongying depression of the Bohai Bay Basin shows a similar conclusion. That is, shale oil production increases as the pore pressure gradient of the shale oil formation increases.22 Therefore, pore pressure analysis is one of the most important steps for evaluating and developing shale plays. This study concentrates on overpressure generation mechanisms and pore pressure prediction near the basin (depression) center of the Dongying depression, because shale oil reserves are usually more abundant in the basin or depression center.

| Shale formation | Geological age | Depth (ft) | Pore pressure gradient (psi/ft) |
|----------------|---------------|-----------|-------------------------------|
| Antrim         | Devonian      | 500-2000  | 0.35-0.38                     |
| Bakken         | Late Devonian- Early Mississippian | 3100-11 000 | 0.5-0.82                  |
| Barnett        | Mississippian-Pennsylvanian  | 5000-8500 | 0.49-0.54                   |
| Eagle Ford     | Late Cretaceous | 2500-15 000 | 0.4-0.8     |
| Fayetteville   | Mississippian  | 1000-7000 | 0.44                         |
| Haynesville    | Late Jurassic  | 9600-13 500 | 0.75-0.94               |
| Mancos         | Late Cretaceous | 5000-8000  | 0.45-0.9                   |
| Marcellus      | Middle Devonian | 2000-8500  | 0.40-0.58                  |
| Monterey       | Middle and Upper Miocene | 4000-15 000 | 0.44-0.8                |
| New Albany     | Late Devonian  | 500-4500  | 0.43                         |
| Niobrara       | Cretaceous     | 5500-8500 | 0.41-0.67                   |
| Utica          | Middle Ordovician | 4000-14 000 | 0.56-0.8                |
| Wolfcamp       | Permian-Pennsylvanian | 5500-11 000 | 0.46-0.62               |
| Woodford       | Early Mississippian-Late Devonian | 6000-16 000 | 0.6-0.65                |

Note: Unit conversions: 1 ft = 0.3048 m, 1 psi/ft = 2.31 g/cm³.

| Shale formation | Field, Province | Geological age | Vertical depth (m) | Pore pressure gradient (g/cm³) |
|----------------|-----------------|----------------|-------------------|-------------------------------|
| Longmaxi shale gas | Weiyuan, Sichuan | Silurian | 1500-4000 | 1.0-1.96                     |
| Longmaxi shale gas | Fuling, Chongqing | Silurian | 2000-3000 | 1.0-2.1                      |
| Chang 7 shale oil | Erdos Basin, Shaanxi | Triassic | 2000-2500 | 1.2-2.2                      |
| Es3 & Es4 shale oila | Dongying, Shandong | Eocene | 3100-3900 | 1.4-1.91                     |
| P12 & P15 shale oil | Jimsar, Xinjiang | Permian | 2000-4000 | 1.0-1.2                      |

aEs represents the Eocene Shahejie formation.
2 | GEOLOGY SETTINGS

2.1 | Geological background of the Dongying depression

The Dongying depression is one of the most prolific depressions located in the south of the Bohai Bay Basin, east Shandong Province (Figure 1). It belongs to the Shengli oil field of Sinopec, one of the largest oil fields in China. The oil field was initially discovered in 1961, and oil production from conventional oil (mainly sandstone) reservoirs in 2018 is about 470,000 bbls/d (65,730 tons/d). In recent years, exploration and related study of shale oils from the source rocks in this area have been speeded up. Three systematic coring wells, Liye-1, Niuye-1, and Fanye-1 (Figure 1C), were drilled in 2014 in the Dongying depression for shale oil exploration and unconventional resource study. Production data show that there are more than 30 shale oil wells in the Dongying which achieved economic production. However, compared to the successful development of shale oil plays in the USA, there are still many challenges in shale oil exploration and production in the Dongying depression; for example, one challenge is how to solve the problem of the low hydraulic fracturing ability in geologically young Eocene source rocks, because they are soft, ductile (or with low brittleness). Therefore, it is very

FIGURE 1 Geographical location of the Bohai Bay Basin (A, B) and the studied area with three shale wells (Liye-1, Niuye-1, and Fanye-1) of the Dongying depression (C) (based on the data of Shengli oil field)
necessary to accurately predict in situ stresses and pore pressure to provide insights on how to effectively fracture the geologically young shale oil formations.

The Dongying depression is bounded by the Chenjiazhuhuang uplift in north, the Luxi uplift and the Guangrao uplift in south, the Qingcheng uplift and the Binxian uplift in west, and the Qingtuozu uplift in east (Figure 1). The Dongying depression is approximately 90 km long and 65 km wide with a total area of 5700 km², which contains the most abundant oil and gas resources and source rocks in eastern China. It is a northeast-southwest trending lacustrine basin, deposited with the Cenozoic sediments which are composed of, from old to new formations, the Paleogene Kongdian (Ek), Shahejie (Es), and Dongying (Ed) formations, the Neogene Guantao (Ng) and Minghuazhen (Nm) formations, and the Quaternary Pingyuan (Qp) formations.

Most conventional oil reservoirs and source rocks in the Dongying depression are located in the Shahejie formations, spanning from the early Eocene to early Oligocene and consist of interlayered sandstones, siltstones, oil shales, mudstones, and evaporates. The Shahejie formation can be further divided into four members: Namely, the first member (Es1), the second member (Es2), the third member (Es3), and the fourth member (Es4). The gray to black mudstones and calcareous mudstones in the Eocene Shahejie Formation (Es3 and Es4), mainly in lower Es3 (Es3L) and upper Es4 (Es4U), are the major source rocks dominated by Type I kerogens with the total organic content (TOC) of up to 18.6%. The shale thickness at the depression center is more than 200 m, which developed several shale oil formations (source rocks). Widespread overpressures are present in the Es3 and Es4 formations with a pressure gradient up to 1.99 g/cm³. The primarily depositional environments in the Es4U and Es3L were semi-deep and deep lacustrine, and some shallow lacustrine. Most conventional sandstone reservoirs were formed by a short distance oil migration from the source rocks in the Es4U and Es3L in the Dongying depression or formed by oil migration through faults (as shown in Figure 2).

Based on three coring shale oil wells (Liye-1, Niuye-1, and Fanye-1) drilled in the Dongying depression, a cross section for shale oil formations is plotted based on the coring data, as shown in Figure 3. The cross section shows the major formation members, formation tops, geologic ages, stratigraphic columns, and shale oil formations in the three wells. Well Liye-1 is the closest well to the depression center with thickest formations of the Es3 and Es4 members. The shale oil formations are mainly located in the Es3L and the Es4U formations.

### 2.2 Petrophysical characteristics of shale oil formations

Three shale wells were drilled with full coring of shale oil formations. Various well logging tools were also applied to evaluate shale oil reserves and production potentials in the Es3 and Es4 formations. Well logging data in two of the studied wells are analyzed to determine the relationship of shale oil formations, gamma ray (GR), resistivity ($R_t$), and sonic compressional transit time (DT) (published data can be found in some references; for example, 24,26-28). Figures 4 and 5 present the well log analyses in two wells of Liye-1 and Niuye-1.

![Figure 2](image-url)
Liye-1 is located in the depression center, and the formation tops are deeper than those in Niuye-1, which is not so close to the depression center. Based on the coring sample observations, we use resistivity data of $R_t \geq 5$ ohm.m combining with gamma ray value of GR $\geq 75$ API to identify shale oil formations in Liye-1 and Niuye-1. Two relatively large groups of shale oil formations (shale oil group 1 and shale oil group 2) are recognized, which are consistent to the observations of the coring samples.

The shale oil group 1 located in the Es3L (Figures 4 and 5) mainly consists of laminated calcareous mudstones, having a lower gamma ray (GR). It has low clay mineral content (<31%) and contains high contents of brittle minerals such as quartz and calcite. However, the shale oil group 2 in the Es4U mainly consists of clay-rich calcareous mudstones, having a higher gamma ray (GR) and higher clay content than those in the shale oil group 1.

Figure 4 shows the shale oil group 1 located from 3560 to 3662 m with a gross thickness of about 100 m and a net thickness about 50 m. There is an obvious geo-marker in sonic log for this shale oil formation, where the transit time has a highest value ($\Delta t > 120$ μs/ft, up to 140 μs/ft) compared to other formations in the Es3 and Es4. This could be caused by high porosity or high TOC. In other wells (such as Niuye-1 and Fanye-1), the same behavior can be found (Figure 5). This petrophysical geo-marker can be used to identify the shale oil group 1, but it should be noted that only the lower section of the shale oil group 1 has this behavior. The shale oil group 1 in well Niuye-1 is thinner (about 40 m in net thickness) than that in well Liye-1 because the Es3L is thinner in Niuye-1 due to it is not so close to the depression center (Figures 4 and 5).

Compared to the shale oil group 1, the shale oil group 2 is thinner and contains more clay minerals. This implies that its fracturing ability may be lower than that in the group 1. It should be noted that only relatively thick shale oil layers are identified here, and there are many thin layers of shale oil (eg, <1 m) which are not marked in Figures 4 and 5.

Near the bottom of the Es4U, a silt-bearing clay-rich and mudstone-dominated formation (clay content of 12-54 wt%, Ma et al27) is a formation marker with very high gamma ray value (GR $> 100$ API) and very low resistivity ($R_t < 1$ ohm.m). This formation is a good marker because the formations below this marker are very close to the top of the Es4L. This formation marker can be identified from well log data in Liye-1 (at depth of ~3880 m) and Niuye-1 (at ~3470 m). It is an important lithofacies, which also are found in other wells in the Dongying depression, and can be used as a formation marker to identify the Es4L.

### Table: Lithologic and geophysical properties of the shale oil formations in Liye-1, Niuye-1, and Fanye-1

| Series | Formation | Member | Fanye-1 | Niuye-1 | Liye-1 |
|--------|-----------|--------|---------|---------|--------|
| Miocene | Guantao | Ng | | | |
| Oligocene | Dongying | Ed | 1457 | 1501 | 1430 |
| Shahejie | No coring | 2275 | 2215 | 2100 |
| Eocene | No coring | 2591 | 2771 | 2340 |
| | No coring | 2414 | 2611 | |
| | 3053 | 3019 | |
| | 3349 | 3491 | |
| | 3604 | |

Yellow = Sandstone, Gray = Shale, Red = Oil-bearing formation

**FIGURE 3** Simplified stratigraphy and shale oil formations of three shale studied wells in the Dongying depression.
OVERPRESSURE GENERATION MECHANISMS IN THE DONGYING DEPRESSION

Overpressure generation mechanisms in the Dongying depression have been studied from different disciplines (eg., 4, 25, 29-32). Undercompaction or compaction disequilibrium and oil generation were previously considered as the major causes of abnormal pore pressure generation. We further analyze overpressure generation mechanisms and find the overpressure generations have different mechanisms in different formations.

3.1 Overpressure generation from undercompaction

Two evidences demonstrate that undercompaction is the most likely reason for pore pressure generation in the Dongying depression, particularly in the Es3 formations. One evidence is the porosity reversal with depth, and the other is the fast sedimentation of the sediments. When sediments compact normally, formation porosity is reduced at the same time as pore fluid is expelled. During burial, formation overburden stress increase is the prime...
cause of fluid expulsion. If the sedimentation rate is low, normal compaction occurs, that is, the equilibrium between increasing overburden and ability to expel fluids is maintained. The normal compaction generates hydrostatic or normal pore pressure in the formation, as shown in the shallow section of Figure 6. If the sediments subside
rapidly and the formation has extremely low permeability (such as in shales), fluids can only be partially expelled, and the remained fluid in the pores of the formation must support all or part of the weight of overburden sediments. Consequently, the pores are less compacted which results in a higher porosity than the normally compacted formation. This generates abnormally high pore pressure, causing porosity to decrease less rapidly than it should be with depth. Formations in this situation are undercompacted, and this status is undercompaction. Therefore, if a shale has a higher porosity at a given depth and the porosity deviates from the normal porosity trend, undercompaction occurs and overpressure is generated (e.g., the deep section in Figure 6). Figure 6 shows how to identify undercompaction and overpressure from porosity profile.34 In the normally compacted formation, porosity decreases as the depth increases. However, in the formation with undercompaction, porosity (ϕ) increases at a certain depth, or porosity is larger than that in the normal compaction trend (ϕn). When this porosity reversal occurs, it corresponds to overpressure, and the starting point of the porosity reversal is the top of overpressure (Figure 6).

We analyze the porosity data from several wells in the Dongying depression. Figure 7 presents the porosity profiles obtained from well logging data. Both porosities obtained from sonic log and bulk density log show porosity reversals with depth after 2800 m. Therefore, the formation is undercompacted from depth of 2800 to 3800 m (mainly in the Es3 formations). This indicates that undercompaction should be one of the mechanisms for overpressure generation in the Dongying depression.

In this study, the porosity from sonic log is estimated using the modified empirical time-average equation35 with a factor of Csh for calculating porosities in shales (see Equation 1), because the original time-average equation was proposed based on the properties of sandstones.

\[ \phi = C_{sh} \frac{\Delta t - \Delta t_m}{\Delta t_{ml} - \Delta t_m} \]  

(1)

where \( \Delta t, \Delta t_m, \) and \( \Delta t_{ml} \) are the sonic compressional transit time of the formation, rock matrix, and the mudline (the surface), respectively; \( C_{sh} \) is a calibration factor for shales, and \( C_{sh} = 0.42 \) in this study for the Dongying depression with \( \Delta t_m = 60 \, \mu s/ft \) and \( \Delta t_{ml} = 200 \, \mu s/ft \).

The porosity calculated from the density log in Figure 7 uses the following equation:

\[ \phi = \frac{\rho_m - \rho_b}{\rho_m - \rho_f} \]  

(2)

where \( \rho_m, \rho_m, \) and \( \rho_f \) are the bulk density of the formation, density of the rock matrix, and density of the pore fluid, respectively.

Applying it to the Dongying depression the following parameters are used: \( \rho_m = 2.68 \, g/cm^3, \rho_f = 1.06 \, g/cm^3. \) The bulk density (\( \rho_b \)) data we used are obtained from the density log.

To analyze whether the formation experience undercompaction or not, the normal compaction trend of the porosity is needed. Field tests and laboratory experiments have shown that formation porosity in the normal compaction condition decreases as the burial depth increases. The following equation, first proposed by Athy,3 can be used to determine the normal compaction trend of porosity:

\[ \phi_n = \phi_0 e^{-cZ} \]  

(3)

where \( \phi_n \) is the porosity in the normal compaction condition or the normal compaction trend of porosity; \( \phi_0 \) is the porosity when \( Z \) is zero; \( Z \) is the depth; and \( c \) is the compaction constant.

In the Dongying depression, the following parameters are used to determine the normal compaction trend: \( \phi_0 = 0.48, c = 0.00058. \) Therefore, the normal compaction trendline can be obtained in the following form, as shown in Figure 7:

\[ \phi_n = 0.48e^{-0.00058Z} \]  

(4)

where \( Z \) is in meters.

Figure 7 plots the porosity variations with depth compared to the measured porosities from the nuclear magnetic resonance
(NMR) measurements and the normal compaction trend. It shows that the formations are in normal compaction condition when the depth is less than 2800 m. From 2800 to 3200 m the formations are slightly undercompacted with a higher porosity than the normal compaction trend. This implies that the pore pressure gradient starts to increase, because a higher porosity than the normal compaction trend means an overpressure presence. The porosity at depth of 3600-3700 m is significantly higher than the normal compaction trend; therefore, the pore pressure is highly overpressured. Figure 7 illustrates that the formations from 2800 to 3750 m (mainly in the Es3 formations) are undercompacted, and this undercompaction probably is the primary reason for overpressure generation in the Es3. When the depth is >3750 m (roughly at the top of the Es4 formations), porosity decreases with depth, then the formation is gradually back to the normal compaction condition.

The undercompaction has been determined to be the major cause of overpressure, particularly in geologically young formations (such as formations in the Neogene and Paleogene) and fast-subsided basins in many worldwide petroleum provinces.36 When the sedimentation rate is greater than 152 m/m.y., it is usually considered as a fast-subsided basin, where undercompaction occurs and overpressure generates. Shale oil and shale gas plays are normally in geologically old formations in the USA; therefore, undercompaction may not be the primary generation mechanism of overpressures in the US shale plays. However, the source rocks in the Dongying region are located in geologically young formations in the Eocene Epoch. Sedimentation rate in a shale oil exploration well (Niuye-1) was analyzed by Zhao et al,28 as shown in Figure 8. It demonstrates that the sedimentation rate in the Es3 formations is significantly high, ranging from 300 to 700 m/m.y. Compared to the threshold value of 152 m/m.y., which was cited as the criterion of undercompaction formation in worldwide petroleum basins, undercompaction could be the primary cause of overpressure, particularly in the Es3 formations in the Dongying depression.

The deposition rate in the Es4 of Figure 8 is clearly slower, and only in some sections, the sedimentation rate is faster than 152 m/m.y.; therefore, undercompaction may be a partial cause of overpressure generation in the Es4. Because different formations of the Es3 and Es4 have different sedimentation rates, pore pressure generation mechanisms in different formations might be different. It needs to examine other overpressure mechanisms for a better prediction of pore pressures in the Es3 and Es4, because for different overpressure generation mechanisms it needs to use different methods to predict pore pressure.

3.2 Overpressure generation from oil generation

Undercompaction is proposed as the cause of overpressures in the Dongying depression in previous section because of rapid deposition of fine-grained sediments. However, the following evidences seem to contradict the overpressure generation mechanism from undercompaction. The measured 193 reservoir pressure data from the Es4 formations demonstrate that the hydrocarbon-bearing sandstones have high overpressures; however, some water-bearing sandstones have normal pressures.37 Therefore, some overpressures in the Es4 formations could be caused by oil generation.

Generation of liquid and gaseous hydrocarbons from kerogen maturation is kinetically controlled and dependent on a combination of time and temperature. The oil generation is the creation of mobile oil from an original solid immobile kerogen, causing fluid volume to increase if the fluids cannot be expelled. The coincidence of overpressure and hydrocarbon generation was given early prominence by the study of the Bakken shale in the Williston Basin, Montana and North Dakota, USA (Meissner,38). The distribution of hydrocarbon generation with depth indicates that considerable hydrocarbon expulsion and migration occurred in the US Gulf Coast wells at below 3048 m, where vitrinite reflectance values ranged from Ro = 0.65% to 0.9% through the hydrocarbon generation interval (Hunt,
Whelan, Eglinton, & Cathles III, 39). The source rocks in the Dongying depression are dominated by Type I kerogens. The vitrinite reflectance value Ro reaches 0.6%, which is usually used as the threshold of overpressure generation caused by oil generation, at the depth of >2500 m. At this depth oil generation started, and then Ro increases exponentially with depth and reaches 1.5 at about 4800 m. Therefore, oil generation from the source rocks in the Es3 and Es4 intervals can be another reason for overpressure generation. Measured data also demonstrate that the overpressured Es3 and Es4 reservoirs are predominantly filled with oil or oil-bearing, and overpressures are not found in the formations with Ro < 0.5%. The oil saturation data in shales also show a good correlation between oil generation and overpressure.

Analyzing shale oil saturation data and measured reservoirs pressures, we find that there is a good correlation between reservoir overpressures and oil saturation of the Eocene shales in the Es3U and Es4U formations (Figure 9). A higher oil saturation in a source rock should correspond to larger oil generation in the rock. This implies that larger oil generation might create a higher pore pressure in the source rock. The generated high-pressure oil then migrated to sandstones and formed high-pressure reservoirs. Through analyzing shale formations, Sun22 found a similar conclusion in the Es3 and Es4 formations, that is, over-pressure is closely related to oil saturation of the shales. However, the Es1 and Es2 formations basically have normal pressures (refer to Figure 9) because of very low oil generation in those formations.

3.3 Overpressure generation from smectite and illite transformation

At a certain depth and temperature, smectite transforms to a new mineral, illite, which involves releasing water and causes to increase pore volume and pore pressure. It has been found that pore pressure only increases slightly from smectite to illite transformation. However, the smectite and illite transformation greatly changes rock properties, which will markedly affect pore pressure prediction if a single normal compaction trend is used for both smectite and illite shales.

By cross-plotting bulk density and sonic transit time from well logs, smectite and illite transition with depths...
can be identified. Not many density data, particularly in the shallow depth, are available for analysis in this study. Here we make a cross-plot of bulk densities in shales and the sonic transit time in shales ($\rho_b - \Delta t$) in well Fanye-1 (Figure 10) and compare it to the smectite and illite trends obtained based on the data of the Gulf of Mexico.\textsuperscript{2} It can be seen from Figure 10 that the shallow data and deep data follow different trends. When the depth >2700 m, most data points in Fanye-1 follow the illite trend; at a shallow depth (<2700 m), the data points follow a different trend – the smectite trend. And this smectite trend in Fanye-1 is a lower than the smectite trend (red dashed line) in the Gulf of Mexico.

It was found that the montmorillonite (a member of the smectite group) and illite have an obvious transition occurred at 2000-3000 m in the Es3 and Es4 shales.\textsuperscript{22} An obvious transition was also found between kaolinite and illite minerals in the Es3 and Es4 sandstones at a certain depth.\textsuperscript{43} Therefore, smectite to illite transition is present in the Dongying depression, which should be considered in pore pressure prediction, particularly at the shallow depth.

4 | PORE PRESSURE PREDICTION IN THE DONGYING SHALE PLAYS

4.1 | Overburden stress determination

Overburden stress (vertical stress) is a fundamental parameter used for pore pressure prediction. Pore pressure in the shale formation can be calculated from the effective stress and overburden stress using the following relationship:

$$p_p = \sigma_V - \sigma_e$$  \hspace{1cm} (5)

where $p_p$ is the pore pressure; $\sigma_V$ is the overburden stress; and $\sigma_e$ is the vertical effective stress and can be obtained from well logs.

Overburden stress is generated by the weight of the overlying formations; therefore, it can be obtained by integrating bulk density logs by the following equation:

$$\sigma_V = g \int_0^Z \rho_b(z) \, dz$$  \hspace{1cm} (6)

where $\rho_b(z)$ is the formation bulk density as a function of depth; $g$ is the acceleration of gravity, and $g = 9.81 \text{ m/s}^2$; and $Z$ is the depth of interest.

For the Dongying depression, the bulk densities from well logs for three shale oil exploration wells are available in deeper sections. We calculate the overburden stress by integrating the bulk densities, then compare the calculated overburden stress to the one obtained from the average density. It shows in Figure 11 that the average density of 2.32 g/cm\textsuperscript{3} is very good to be used for estimating overburden stress in this area. Compared to other shale oil basins, the formations in the Dongying depression is relatively young; therefore, it has a smaller bulk density and a lower overburden stress. The empirical equation for estimating the overburden stress in the Dongying depression can be expressed in the following form:

$$\sigma_V = 0.0228Z$$  \hspace{1cm} (7)

where $Z$ is the depth from the ground level in m; $\sigma_V$ is the overburden stress in MPa.

4.2 | Pore pressure prediction from sonic transit time in the Dongying depression

4.2.1 | Pore pressure prediction method

During the study of the pore pressure behavior of the conventional reservoirs in Shengli oil field, it has been found that sonic

![Figure 11](image_url)

Figure 11: (A) Bulk densities from well logs in three shale oil exploration wells. (B) Calculated overburden stress from the bulk densities compared to the one calculated from the average density of 2.32 g/cm\textsuperscript{3} (Equation 7)
transit time has a good correlation with overpressures. Zheng et al\textsuperscript{32} obtained the following empirical equation for estimating the excess pressure (or net overpressure, i.e., the extraction of pore pressure and hydrostatic pressure) in the Dongying depression:

\[ \Delta p = 0.131Z - 409.375 \ln \left( \frac{660}{\Delta t} \right) \]  

(8)

where \( \Delta t \) is the compressional transit time in \( \mu s/m \); \( Z \) is the depth in m; and \( \Delta p \) is the excess pressure in kg/cm\(^2\).

We test several methods for pore pressure prediction (e.g., the methods proposed by Eaton\textsuperscript{3} and Bowers\textsuperscript{4}) in the shale oil wells in the Dongying depression and find the sonic method proposed by Zhang\textsuperscript{34,44} is more suitable for pore pressure calculation in this area. Pore pressure can be obtained from compressional transit time of sonic log by the following equation\textsuperscript{34}:

\[ p_p = \sigma_v - (\sigma_v - p_n) \frac{\ln (\Delta t_m - \Delta t_m) - \ln (\Delta t - \Delta t_m)}{cZ} \]  

(9)

where \( p_p \) and \( p_n \) are the pore pressure and normal pore pressure, respectively; other parameters are the same to those defined in the previous equations. This method was verified that it can obtain a better result in pore pressure prediction in the Dongpu depression, southwest Bohai Bay Basin\textsuperscript{45}.

The following normal compaction trend is used to determine the compaction parameter \( c \) (the same parameter as used in Equations 3 and 4) in Equation (9):

\[ \Delta t_n = \Delta t_m + (\Delta t_m - \Delta t_m)e^{-cZ} \]  

(10)

Analyzing measured pore pressures data and comparing the normal pressures to the corresponding transit time, we find that the following parameters can be used to describe the normal compaction in the Dongying shale oil wells: \( \Delta t_m = 200 \mu s/ft; \Delta t_m = 60 \mu s/ft; c = 0.00058 \). Therefore, Equation (10) can be expressed in the following form:

\[ \Delta t_n = 60 + 140e^{-0.00058Z} \]  

(11)

where \( Z \) is in m; \( \Delta t_n \) is in \( \mu s/ft \).

The normal compaction trend, Equation (10), can also be used to determine the normal compaction parameter \( c \) for pore pressure prediction. It can be firstly estimated through plotting the transit time in shales vs depth. Usually, the shallow formation is normally compacted, and based on this principle, the parameter \( c \) can be estimated.

4.2.2 | Pore pressure prediction in shale oil wells

Pore pressure controls oil production in the Dongying shale oil play and is also the most important parameter to predict in situ stresses and formation breakdown pressure for hydraulic fracturing design. In the following section, we use the method described above to predict pore pressure in the shale oil play in the Dongying depression. Here we present the pore pressure analysis using well log data (mainly gamma ray and transit time) from three shale oil wells.

Prior to applying the method described in the above section, we need to obtain the sonic transit time in shales. Therefore, for pore pressure calculation, the first step is to select the clean shales in well log data. Gamma ray data in well logs can be used to differentiate shale intervals from other lithologies. Drawing shale baselines in gamma ray data are used to identify and separate shale from other rocks, as shown in Figure 12A. In the following analysis, the high gamma ray values (e.g., GR > 80 API) are assumed to be shale lithology, whereas points where gamma ray values are greater than the shale baselines are used for analysis. Shale points defined on the gamma ray log are then transferred to the corresponding sonic log used for pore pressure analysis\textsuperscript{44}.

After obtaining the transit time in shales, the second step is to obtain the normal compaction trend in the shale transit time using Equation (10). By doing so, the compaction constant \( c \) can be obtained. To determine the normal compaction trend line, the sonic transit time in the shallow depth (or the section with known normal pore pressure) is fit to the normal compaction line by using Equation (10) with parameters of \( \Delta t_m = 200 \mu s/ft; \Delta t_m = 60 \mu s/ft; c = 0.00058 \) m\(^{-1}\), as shown in Figure 12B. The transit time of shales greater than the normal compaction trend corresponds to the overpressure.

The third step is to use the filtered transit time of shales for calculating pore pressure using Equation (9). Then, the pore pressure can be obtained with the parameters determined from the normal compaction trend and using overburden stress gradient of 2.32 g/cm\(^3\) (from Equation 7) and normal pore pressure gradient of \( p_n = 1 \) g/cm\(^3\). Figure 12C plots the calculated pore pressure in well Liye-1 compared to the measured pore pressure results in three shale wells. The measured pore pressures at three depths in Figure 12C are from different wells of Fanye-1 (in the Es\textsuperscript{3}\textsuperscript{L}, the shallowest point in the figure), Niuye-1 (in the Es\textsuperscript{4}\textsuperscript{U}, the second shallowest point), and Liye-1 (in the Es\textsuperscript{4}\textsuperscript{U}, the deepest point). Compared to the measured pore pressure data, the pore pressure calculated from Equation (9) gives a good result in pore pressure prediction, particularly in the Es\textsuperscript{3} formation. However, the pore pressure calculation mismatches the deepest pore pressure point measured in the Es\textsuperscript{4}\textsuperscript{U} formation. It may have a different pore pressure generation mechanism in the Es\textsuperscript{4} as described in the previous section, and oil generation may be the primary cause of the overpressure in this formation.

Figure 12 indicates that the overpressure corresponds to higher transit time compared to the normal compaction trend of transit time vs depth. Figure 12 also shows that the transit time does not decrease monotonically with depth as the normal compaction trend does. When the formation is
overpressured, the transit time reversal occurs (Figure 12B); that is, the transit time increases (so that overpressure increases) as the depth increases starting from the Es₃ᵛ. A slight overpressure occurs around the top of Es₁, and pore pressure calculation in the shallower section is affected by the smectite and illite transformation and will be addressed in the following section. The top of overpressure primarily starts at the Es₃ᵛ, thereafter the pore pressure is gradually overpressured, as shown in Figure 12. The transit time in the Es₃ᵛ reaches its maximum value at depth of 3660 m (the shale oil marker) or about 100 m above the top of Es₄ᵛ in Liye-1, where the highest overpressure occurs based on the

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FIGURE 12  Pore pressure calculated from sonic transit time using Equation(9) in well Liye-1. The gamma ray and shale baseline (red line) are shown in the left track; the normal compaction trend line of transit time (DT NCT, from Equation 10), the filtered shale points of sonic transit time (DT shale filtered), sonic transit time (DT original), and major formation tops are plotted in the middle track; and the calculated pore pressures from the filtered shale transit time from Equation(9) (Pp DT), hydrostatic pore pressure (normal pressure) and overburden stress are shown in the right track with comparison to the measured formation pressures.

FIGURE 13  Pore pressure calculated from sonic transit time using Equation(9) in well Niuye-1. Refer to Figure 12 for the instruction of each plot.
pore pressure prediction from sonic log. It should be noted that the transit time values in the Ed formations (between the top of the Ed to the top of the Es1) are abnormally high; those are probably caused by the smectite shales, but not caused by formation overpressures, which will be discussed in the following section.

Figures 13 and 14 present the pore pressure prediction applications in other two shale wells: Niuye-1 and Fanye-1. The two figures also demonstrate that the pore pressure calculations from the proposed method match the measured pore pressure results. The same behavior of the maximum transit time and maximum overpressure at the shale oil marker can be found in Niuye-1 and Fanye-1. For example, the transit time reaches its maximum value at depth of 3296 m (the shale oil marker) in the Es3L in Niuye-1 or about 20 m above the top of Es4U, where the highest overpressure occurs based on the pore pressure prediction from sonic log.

Comparisons of the transit time and the predicted pore pressure in the three wells show that below the Es3U, the shale formation in each well has a trend of increase in transit time and corresponding an increase in overpressure, as shown in Figures 15 and 16. At the shale oil markers, the pore pressure gradients

**FIGURE 14** Pore pressure calculated from sonic transit time using Equation(9) in well Fanye-1. The gamma ray and shale baseline are shown in the left track; the normal compaction trend line of transit time (DT NCT, from Equation10), the filtered shale points of sonic transit time (DT shale filtered), sonic transit time (DT original), and major formation tops are presented in the second track; and the calculated pore pressures from the filtered shale transit time from Equation(9) (Pp DT), hydrostatic pore pressure (normal pressure) and overburden stress are shown in the third track with comparison to the measured formation pressure; the pore pressure and overburden gradients are plotted in the right track (the Kelly Bushing height, KB = 8.25 m)
reach their highest values in Liye-1 and Niuye-1. This high pore pressure behavior in the shale oil formation may be beneficial for shale oil production because a higher pore pressure corresponds to a higher production, as previously shown in Figure 17.

4.2.3 | Pore pressure prediction accounting for smectite to illite transformation

Since rock properties change greatly from smectite to illite (as illustrated in Section 3.3), it should use two different normal compaction trendlines or a composite one for pore pressure prediction. Otherwise, if only the illite normal compaction trendline is used for pore pressure prediction, the shallow pore pressure will be overestimated, particularly if this normal compaction trend is calibrated by measured pore pressures in the deep formations.

Therefore, a multi-segmental (composite) normal compaction trend, which has different compaction parameters ($c_s$ and $c_i$) should be used for pore pressure prediction; that is:

For smectite shale: $\Delta t_{n,s} = \Delta t_{n} + (\Delta t_{ml} - \Delta t_{n})e^{-c_sZ}$ (12)
where $\Delta t_n_s$, $\Delta t_n_i$, and $\Delta t_n_t$ are the normal compaction trends of transit time in smectite, illite, and transition zone, respectively; $c_s$, $c_i$, and $c_t$ are the normal compaction parameters in smectite, illite, and transition zone, respectively.

If assuming a linear transition of the compaction parameter from $c_s$ (smectite shale) to $c_i$ (illite shale), then, the compaction parameter $c_t$ in the transition zone can be obtained from the following equation:

$$c_t = c_s + \frac{(c_i - c_s)(Z - Z_s)}{(Z_i - Z_s)} \quad (15)$$

where $Z_s$ is the depth of the smectite; $Z_i$ is the depth of the illite; and $Z_s$ and $Z_i$ can be determined from mineral test results in offset wells or estimated from the regional temperature profile which is associated with smectite to illite transformations.

Therefore, if the depths of $Z_s$ and $Z_i$ are known, the pore pressures in smectite shale, illite shale, and the smectite-illite transition zone can be obtained by submitting $c_s$, $c_i$, and $c_t$ to Equation (9), respectively. Figure 18 illustrates how to use this method to predict pore pressures in Liye-1. In this well, $Z_s = 2000$ m, $Z_i = 2500$ m. Figure 18 shows that the pore pressure result obtained from this method is better to predict pore pressures, particularly in the shallow section. Compared Figure 18 to Figure 12, the method without considering the smectite effect in Figure 12 overestimates the pore pressures in the smectite (shallow) formation.

5 | CONCLUSIONS

A good correlation between the shale oil formations and well log data is found in the Dongying depression. Resistivity log
of $R_t \geq 5 \text{ ohm m}$ combining with gamma ray log of GR $\geq 75$ API can be used to identify shale oil formations. Two relatively large groups of shale oil formations are recognized from well log data, which are consistent to the observation of the coring data. The overpressure generations in shale formations of the Dongying depression have three different mechanisms, that is undercompaction, oil generation, and smectite and illite transformation: (a) Undercompaction is the primary cause of overpressures in the Es3 formations because of their rapid deposition rate of 300-700 m/m.y.; (b) in the Es3 and Es4 formations, overpressure data are consistent with the increase of vitrinite reflectance and oil saturation, indicators of oil generation; (c) in shallow formations, starting at about 2000 m, the smectite to illite transformation occurs, which results in rock property changes with depth. A composite normal compaction trendline is proposed to account for the smectite to illite transformation for pore pressure prediction. Case study in three shale wells indicates that pore pressure in shale plays can be accurately obtained from the sonic well log using the proposed method with necessary calibrations.

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