Chemical compaction of deep buried mudstone and its influence on pressure prediction

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Abstract: The chemical compaction of mudstones which is dominated by the transformation of clay minerals leads to significant changes in the mineral composition and microstructure of mudstone during process of deep burial. In particular, the transformation of smectite to illite in mudstones results in noticeable impact on the pore pressure formation and the overpressure logging responses. At present, the study about the pressurization mechanism of chemical compaction and the impact on overpressure logging responses is really weak, which made it hard to pore pressure identification and pressure prediction for deep buried formations. Taking the Paleogene Shahejie Formation in the Dongying depression of the Bohai Bay Basin in eastern China as typical case, this paper analyses the characteristics of clay mineral transformation of the Shahejie Formation in the Dongying depression, the logging responses of overpressures, and the influence of chemical compaction on the prediction of pore pressure. The results showed that the chemical compaction of mudstones changes the relationship between the petrophysical properties of mudstone and vertical effective stress and the logging responses of overpressure. The typical characteristic of chemical compaction manifested as density increase continuous with the depth. The normal compaction trends of the different compaction stages are the basis for overpressure mechanisms identification and pore pressure prediction. The depth of the rapid transformation of clay minerals has a good consistency with the top of overpressure zone (2000–2800 m) in Dongying depression, which indicates that the overpressure and its logging responses may be related to the chemical compaction of mudstones. The measured pressure in intervals deeper than 3000 m is closer to the predicted pressure based on the normal compaction trend of chemical compaction.

1. Introduction

According to the burial depth and formation temperature, take the transformation of clay minerals in mudstone as a mark, the compaction of mudstones may go through three stages, i.e. the mechanical compaction stage (<70°C), transitional stage (70–100°C), and chemical compaction stage (>100°C). The transformation of clay minerals controls the behaviour of chemical compaction, especially the transformation from smectite to illite (Lahann and Swarbrick, 2011). The mechanical compaction process of mudstone is controlled by vertical effective stress, while the chemical compaction is mainly
controlled by temperature, which involves the formation of thermodynamically stable minerals in mudstone. The relationship between effective stress and porosity in the mechanical compaction stage has become the basis of basin numerical models, identification of overpressure mechanisms, and pore pressure prediction. It has good applicability to shallow buried, young, and low-temperature formations.

As the buried depth and formation temperature increase, the diagenesis process of mudstone is not only the mechanical compaction, but also chemical diagenetic reactions such as the transformation of clay minerals become more important, which control the mudstone porosity, pore structure changes, and overpressure formation evolution (Fig.1). The combined effect that is related to the transformation of clay minerals dominates the mechanism and process of mudstone compaction of deep buried formations, is called chemical compaction. By changing the microstructure and mineral composition of mudstone, chemical compaction not only enhances the effectiveness of closed systems of mudstone, promotes the development of overpressure, but also significantly affects the physical and mechanical properties of mudstone rock. The microstructure changes are significantly affected by temperature, the relationship between effective stress and porosity corresponding to chemical compaction is quite different from the traditional understanding of mechanical compaction. Therefore, the effective stress theory of the mechanical compaction stage is no longer applicable in deep basins, and the existing analysis methods are also difficult to determine the origin and distribution of overpressure, which brings great difficulties to deep oil and gas exploration (Li et al., 2020).

Taking the Shahejie Formation in Dongying depression as an object, this paper analyses the relationship between mudstone chemical compaction and overpressure logging responses and its influence on pore pressure prediction, in order to provide useful information and significant reference for the analysis of the formation mechanism of overpressure in the basin and the prediction of deep pore pressure.

**Fig. 1** Schematic of the evolution process of microstructure and pore pressure controlled by mudstone compaction. (a) the evolution of mudstones microstructure; (b) the evolution of porosity and minerals; (c) the distribution of pressure and effective stress

2. The characteristics of mudstone chemical compaction

The origin and distribution of overpressure in the Paleogene Shahejie Formation in Dongying depression has attracted wide attention of researchers. It is generally believed that the overpressure of the Shahejie Formation is mainly caused by the disequilibrium compaction related to the rapid burial of the third and fourth member of Shahejie Formation (the deposition rate is more than 500 m/Ma, the burial rate is greater than 200 m/Ma), and the hydrocarbon generation (TOC>2%, Ro>1.0%). However, the characteristics of mudstone compaction curves and the plots of effective stress-sonic difference/density showed that there is no typical density/porosity abnormality in the overpressure zone in the Dongying
depression. This is contrary to the characteristics of overpressure caused by disequilibrium compaction and hydrocarbon generation.

Mineralogy analysis reveals the obvious transformation of clay minerals in the Paleogene mudstone in Dongying depression. The quantitative interpretation results of XRD show that the clay minerals in the mudstone are mainly illite and mixed-layer illite/smectite, with a small amount of chlorite and kaolinite (contents <3% and 8%, respectively) (Fig. 2a). The content of mixed-layer illite/smectite is between 20% and 90%, and gradually decreases with the depth. The content of illite gradually increases from about 10% at 1000m to 80% at 4000m, and the ratio of smectite in mixed layer decreases from 80% to 15%. The clay minerals of mudstone within the range of 2000~2500m changed significantly. The content of mixed-layer illite/smectite was significantly reduced, the smectite in mixed-layer illite/smectite decreased rapidly from 60% to 15% (Fig. 2b), the total content of illite increased from 30% to about 75% (Fig. 2c), the ratio of smectite in mixed layer decreases from 80% to 30% (Fig. 2d). Although the transformation of clay minerals continues to occur at depths of 2500m, the content changes very slowly.

According to the clay mineral transformation in the Dongying depression, it can be determined that the mechanical compaction occur at depth below 2000m, the changes of petrophysical properties (porosity and density) during mechanical compaction is mainly controlled by the vertical effective stress that increases with the overlying load. The transition stage from mechanical compaction to chemical compaction corresponding to 2000~2500m. And the intervals buried deeper than 2500m mainly is at the chemical compaction stage, and the compaction process of mudstone is controlled by the diagenesis of clay minerals. Effective stress may also have a certain degree of influence on the mudstone compaction in the chemical compaction stage, but as the depth increases, the mechanical compaction effect becomes weaker.

![Fig. 2](image) A profile of clay mineral transformation of mudstone of a type well in Dongying Sag, Bohai Bay Basin. (a) the clay minerals of mudstones; (b) the content of smectite in the mix layer; (c) the total content of illite; (d) the ratio of smectite/illite.

3. The characteristics of overpressure logging responses

The depth of rapid transformation of clay minerals in mudstone is approximately corresponding to the top of the overpressure zone (2000-2800m) of the Shahejie Formation in the Dongying depression, suggesting that the development of overpressure may be related to the smectite-illite transformation. The transformation of clay minerals is not only the possible cause of overpressure in the Dongying depression, but also play a significant impact on the overpressure logging responses.

The mudstone comprehensive compaction curves show that the acoustic time represents obviously reversed from the normal pressure intervals to the overpressure intervals in Dongying depression, indicating the development of overpressure. While it is contrarian to the traditional understanding, the mudstone density logging has continued to increase (Fig. 3). This phenomenon is exactly the
overpressure logging responses caused by the chemical compaction of mudstone, and it also reflects that the formation of overpressure may be closely related to the smectite-illite transformation (Zhang et al., 2020).

4. Pore pressure prediction

During normal compaction conditions, as the overlying load increases, the effective stress borne by the mudstone increases, resulting in a continuous decrease in mudstone porosity. The normal compaction trend defines the response of porosity to effective stress under hydrostatic pressure, which is the basis for predicting pore pressure based on porosity. The basic assumption of pore pressure prediction methods based on the effective stress-porosity relationship (balanced depth method, Eaton method) is that the intervals of normal pressure and the overpressure section have the same lithology, clay mineral, and pore fluid properties.

![Figure 3](image-url)

**Fig. 3** Variation of log parameters and fluid pressure with depth for a well from the Dongying sag. (a) the pore pressure distribution; (b) the acoustic time versus depth; (c) the density versus depth.

It has been recognized that the compaction trends of smectite and illite are different significant. The compaction process of mudstone under low-temperature conditions approximately follows the smectite compaction trend line, and the mixed-layer smectite/illite transformation can be achieved under certain buried depth conditions, and then the compaction along the trend of illite compaction continues. These new insights make up for the shortcomings of establishing normal compaction trend lines in previous pore pressure predictions, that is, mudstone normal compaction trend lines should not be considered as a single effective stress/depth trend, but should be a function coupling of multiple factors in the diagenesis process. The normal compaction trend line obtained in shallow sediments is only applicable for intervals above the smectite-illite transformation window, and the prediction of pore pressure in deep buried formations should be based on the normal compaction trend line in the chemical compaction stage. In order to quantify the change of the normal compaction in the smectite-illite transformation process, Zhang and Yin (2017) established the normal compaction trend line equations of mudstones in different compaction stages. The normal compaction trend line of the smectite is:

\[ \Delta t_s = \Delta t_m + (\Delta t_0 - \Delta t_m) \cdot e^{-C_sZ} \]  

(1)

The normal compaction trend line of the transitional stage is:

\[ \Delta t_{s-1} = \frac{(Z-Z_1) \cdot \Delta t_s + (Z_2-Z) \cdot \Delta t_s}{(Z_2-Z_1)} \]  

(2)

The normal compaction trend line of the illite is:
\[
\Delta t_i = \Delta t_m + (\Delta t_0 - \Delta t_m) \cdot e^{-C_i Z}
\]

Where \(\Delta t_i\) is the acoustic time of the smectite, \(\mu s/ft\); \(\Delta t_s\) is the acoustic time of the illite, \(\mu s/ft\); \(\Delta t_c\) is the acoustic time of transitional stage, \(\mu s/ft\); \(\Delta t_m\) is the acoustic time of the matrix, \(\mu s/ft\); \(\Delta t_0\) is the acoustic time at the surface, 200 \(\mu s/ft\); \(C_s\) and \(C_i\) are the compaction coefficients of smectite and illite, respectively; \(Z\) is the depth, m; \(Z_1\) and \(Z_2\) is the top depth and bottom depth of the smectite-illite transformation window, m; \(Z_1\) and \(Z_2\) can be determined by XRD results or regional temperature changes related to the smectite-illite transformation. The segmented normal compaction trend is used to other areas or wells; an accurate pore pressure prediction can be achieved.

Chemical compaction causes the mineral composition of mudstone to change from rich in smectite to rich in illite, which in turn causes obvious differences in the normal compaction trend of mudstone. Therefore, two different normal compaction trend or a comprehensive normal compaction trend should be used for pore pressure prediction. Here, the above method is used to predict the pressure of Shahejie Formation in Dongying depression. According to the mineralogical analysis of mudstone, the \(Z_1\) and \(Z_2\) in formulas (1) ~ (3) are 2000m and 2500m respectively. Through the data fitting, the normal compaction trend line of mechanical stage, transitional stage and chemical compaction stage can be obtained (Figure 14a). Furthermore, the equivalent depth method was used to calculate the pore pressure (Figure 14b). The results show that the pore pressure obtained by using the segmented normal compaction trend accurately reflect the actual pore pressure, especially for the chemical compaction stage, the measured pressure is closer to the predicted pressure based on the chemical compaction trend line. However, the pore pressure calculated using only the normal compaction trend line of the mechanical compaction trend will significantly underestimate the deep pore pressure (Figure 14b). This research further confirms that chemical compaction of mudstone is an important factor that cannot be ignored in the formation pressure analysis and pressure prediction.

\[\text{Fig. 4 Pore pressure prediction results of typical wells in Dongying Sag, Bohai Bay Basin. (a) the compaction curves of mudstones and normal compaction trends; (b) the pore pressure prediction}\]

5. Conclusions

The chemical compaction of mudstones is dominated by combined effect of the mechanism and process of mudstone compaction related to transformation of clay minerals under deep buried formations. The transformation of smectite to illite is considered to be the most important and most common chemical
compaction process in mudstone. Chemical compaction changes the petrophysical properties of mudstone, and the mudstone's porosity trend to decrease, while the density continues to increase with the transformation of clay minerals.

The mechanical compaction of mudstones is limited at depth below 2000m in Dongying depression, and when the depth deeper than 2500m, the chemical compaction of mudstone happened. The rapid transformation depth of clay minerals in the mudstone (2000 ~ 2500m) is consistent with the overpressure top of the Shahejie Formation (2000 ~ 2800m). The responses of overpressure are characterized by the reversal of the acoustic time and the increase in density, indicating the influence of chemical compaction on overpressure. The pore pressure predicted by the segmented normal compaction curve is closer to the real formation pressure, especially for the deep chemical compaction stage, the predicted pressure based on the chemical compaction trend line is more reliable.

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