New insights into the Pore Pressure Estimation from Sonic Velocity Data—Application of the equivalent depth method in Chinese Basins

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Abstract. Pore pressure prediction is of fundamental importance in petroleum exploration and production operations. Because there is no direct method to measure pore pressure in shale, the indirect method (the equivalent depth method) for estimating pore pressure from sonic velocity data is widely used. It has been found in the application of the equivalent depth method in several Chinese sedimentary basins that the calculated pressures from sonic logging data are very consistent with the DST or RFT pressures measurements in some basins and are very divergent in others. The consistence of calculated and measured excess pressures in the basin with different excess pressure generation mechanisms such as in the cases in Tarim basin, Bohai Bay basin and Jiuquan basin showed that the pressure calculated by the equivalent depth method accounts for all excess pressure generation mechanisms such as disequilibrium compaction, tectonic compression, aquathermal pressuring, hydrocarbon generation and clay diagenesis. The divergence of calculated and measured excess pressures was found in the organic-rich source rocks in Triassic in Ordos basin and in Cretaceous in Songliao basin. Compared with common shales, organic-rich shales are composed of more solid organic matter, which can influence the sonic velocity values. Our study shows that the sonic velocity decreases dramatically when the TOC is higher than 2%. So the pore pressures calculated by the equivalent depth method from sonic velocity data may much higher than the actual pressures in organic-rich shale. The use of the equivalent depth method may mislead in predicting pore pressure of organic-rich shale without considering the influence of total organic carbon content.

Keywords: Pore pressure, sonic velocity, the equivalent depth method, Chinese basin.

1. Introduction
Pore pressure prediction is of fundamental importance in petroleum exploration and production operations (Magara, 1978; Vladimir et al., 1995; Master, 2011). Because there is no direct method to
measure pore pressure in shale, the indirect method (the equivalent depth method) for estimating pore pressure from sonic velocity data is widely used.

To quantify the magnitude of pore pressure from sonic velocity, a commonly used approach is the equivalent depth method (Magara, 1978). The equivalent depth method assumes that porosity relates directly to vertical effective stress. Using this method, for any value of velocity that does not plot on the normal compaction trend, the pressure can be estimated by projecting the value vertically onto the normal compaction trend on a sonic velocity versus depth plot (Figure 1).

![Figure 1. Profiles showing normal and anomalous compaction curves diverging below top of overpressure zone.](image)

From the application of this method in several Chinese sedimentary basins, it has been found that the predicted pressures from sonic logging data are very consistent with the drillstem test (DST) or repeat formation test (RFT) pressures in some basins and are very divergent in others. In this paper, new insights into pressure prediction from well logging data have been discussed through the studies of Bohai Bay basin, Jiuquan basin, Tarim basin, Ordos basin and Songliao basin (Figure 2).

![Figure 2. Distribution of Chinese sedimentary basins and location of studied areas.](image)
2. Results and discussion

2.1. Consistence of predicted and measured pressures in basins with different overpressure generation mechanisms

2.1.1. Bohai Bay Basin. Bohai Bay basin is a Cenozoic lacustrine basin that developed on the Paleozoic carbonate and Mesozoic volcanic rock basement. It is one of the most petrolierous basins in China, accounting for nearly one third of the total oil production of the country.

Sonic velocity data were used in prediction of formation pressure by the principle of the balanced depth (Hottman et al., 1965; Magara, 1978). The predicted pressure of shales and RFT pressure of the adjacent sands are almost identical (Figure 3).

![Figure 3](image-url)

**Figure 3.** Comparison of the predicted pressure with the measured pressure of Bohai Bay basin (Round points are the predicted pressures, red triangles are RFT pressures).

Bohai Bay basin contains two dynamic systems, the shallow system exhibits normal hydrostatic pressures, while the deep system which is a fluid compartment is abnormally overpressured (Figure 4, Figure 5). Overpressure in shales is mainly caused by hydrocarbon generation and disequilibrium compaction within this fluid compartment from the study of litho-sequence and multi-log curves (Figure 4, Figure 5).

![Figure 4](image-url)

**Figure 4.** Comparison of compaction curves from multi-log curves

![Figure 5](image-url)

**Figure 5.** Relationship between litho-sequence and compaction curve in Bohai Bay basin
2.1.2. Jiuquan Basin. Jiuquan basin is a small continental basin that developed on Lower Paleozoic metamorphic rock basement. It’s one of the typical overpressured basins of China (Bian et al., 2009). Pressures of shales estimated from sonic velocity data are consistent with DST or RFT pressures of the adjacent sands (Figure 6).

The overpressure generation mechanism is different from Bohai Bay Basin. The sedimentation rate in Jiuquan basin was varied in geological time. When sedimentation rate increases after Eogene, there is not enough time for water to be expelled out of the shales, and part of the overburden is loaded on the pore fluids. As a result, overpressure is mostly generated by disequilibrium compaction (Figure 7). As the sedimentation rate increases, the excess pressure is increasing (Figure 8).

2.1.3. Kuqa depression, Tarim Basin. The Kuqa depression is located in the northern part of the Tarim basin and south of the Tianshan Mountains, northwest China. The structures in the Kuqa depression are dominated by thrust faults and related folds developed during Cenozoic.

Pressures of shales calculated from the equivalent depth method using sonic velocity data are almost identical with the measured pressures of the adjacent sands (Figure 9).

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**Figure 6.** Comparison of the predicted pressure with the measured pressure of Jiuquan basin

**Figure 7.** Burial history of Jiuquan basin

**Figure 8.** Sedimentation rate versus excess pressure
Figure 9. Comparison of the predicted pressure with the measured pressure of Kuqa depression

Depending on the point view of Guangdi Liu and Yaxing Wang (2004, 2006), the dominate mechanisms for overpressure in Kuqa depression are tectonic compression and fluid charging. As the strength of tectonic compression and intensity of hydrocarbon expulsion increase, the excess pressure is increasing (Figure 10-Figure 12).

Figure 10. Sketch map of structure compression degree

Figure 11. Relationship between excess pressure and the structure compression degree
2.2. Divergence of predicted and measured pressures in basins with organic-rich source rocks

Compared with common shales, organic-rich shales are composed of more solid organic matter, which can influence the logging response. It was showed that the sonic velocity decreases dramatically when the total organic carbon content is higher than 2% through the statistical study of TOC data versus sonic velocity of source rocks (Figure 13). Without considering this effect, application of sonic velocity in prediction of pore pressures may be misleading.

2.2.1. Ordos Basin. Ordos basin located in central China is a large intracontinental sedimentary basin. This basin is a smooth monocline with an east-to-west dip of less than 1°, where faults and folds are not developed (Liu et al, 2008; Ying et al., 2011).

Abundant oil resources are present in the Upper Triassic Yanchang Formation which can be divided into ten members (Chang-1 to Chang-10) from top to bottom. Specifically, Chang-7 member is the main source rock that is deposited in deep lacustrine environment with the average total organic carbon content of 7% (Figure 14).
Figure 14. Average total organic carbon content of different members of Yanchang Formation

Sonic velocity of organic-rich shales decreases dramatically because of the high total organic carbon content. So pressures calculated in shales by the equivalent depth method from sonic velocity data are much higher than the measured pressures of adjacent sands (Figure 15).

Figure 15. Comparison of the predicted pressure with the measured pressure of Ordos basin

Figure 16. Comparison of the predicted pressure with the measured pressure of Songliao basin
2.2.2. Songliao Basin. Songliao basin is an important oil-productive basin of China, and it was formed in extensional settings related to rifting processes. The main stratigraphic sequence is Cretaceous fluvial and lacustrine strata (Pan et al., 2009).

The first member of Qingshankou Formation is the main source rock of Songliao basin with the total organic carbon content is 1.5%~5%. The pore pressures estimated from sonic velocity data in organic-rich intervals are very divergent from the measured pressures of the adjacent sands (Figure 16).

3. Conclusions
The equivalent depth method using sonic velocity data can be used to estimate pressures of overpressured basins generated by different mechanisms. They can be disequilibrium compaction, hydrocarbon generation, tectonic compression and fluid charging, etc.

Application of the equivalent depth method may mislead pressures prediction of organic-rich shales without considering the influence of total organic carbon content.

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