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Origin Analysis of Overpressures and Quantitative Assessment in the Dongfang Area, Yinggehai Basin

Hangjun Xian[1], Caimin Zhang[2], Xuebing Du[1,] *, Xinong Xie[1], Cheng Zhang[1]

[1]Hubei Key Laboratory of Marine Geological Resources, China University of Geosciences, Wuhan 430074, China
[2]Wuxi Research Institute of Petroleum Geology, SINOPEC, Wuxi 214151, China

*Correspondence: xbdu@cug.edu.cn

Abstract: Analysis of overpressure origins serves as the foundation for pressure prediction and hydrocarbon accumulation studies. Overpressure is widely distributed in the Dongfang area of the Yinggehai Basin, demonstrating a close yet complex relationship with hydrocarbon accumulation. It is imperative to conduct in-depth research on the origins of overpressure and perform quantitative evaluation. Analysis utilizing well log combinations, loading-unloading curves, and acoustic velocity-density crossplots was conducted to investigate the origins of overpressure in the Dongfang area, Yinggehai Basin. Research results indicate that two-stage overpressure is widely developed in the Dongfang area of the Yinggehai Basin. The first overpressure zone occurs in strata above the mid-lower Yinggehai Formation at 1000-1500m depth, with a pressure coefficient over 1.3; the second segment is located in the Huangliu Formation below 2400m, with a pressure coefficient exceeding 1.5. Acoustic time difference, density, and resistivity logging curves exhibit significant responses to overpressure, manifesting as reversals to varying degrees. Integrated analysis with multiple methods indicates that the overpressure in the Dongfang area of the Yinggehai Basin is primarily caused by a combination of hydrocarbon-generation pressurization and undercompaction. The magnitude of hydrocarbon-generated overpressure primarily ranges from 5 to 20 MPa, contributing 40% to 70% of the total overpressure.

Keywords: Yinggehai Basin; Overpressure genesis; Hydrocarbon-generating pressurization; Quantitative evaluation

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1. Introduction

The recognition of overpressure began in the late 18th century with the observed deviation of formation fluid pressure from hydrostatic conditions. Further studies have since confirmed that this phenomenon is widespread and intrinsically associated with the development of sedimentary basins. However, the origins of overpressure are multifaceted, usually resulting from a confluence of various mechanisms. The prevailing explanation throughout the 1990s attributed the generation of overpressure, and notably elevated overpressure levels, to undercompaction in sedimentary basins. [1-3]. The same era saw the proposal of several other hypothesized mechanisms, encompassing overpressure generation from hydrocarbon maturation, diagenetic reactions like the montmorillonite-to-illite transformation, fluid pressure transfer, and tectonic stresses. However, overpressure genesis is not singular; it frequently arises from a confluence of factors acting in concert within a basin [4-7]. Previous research has classified overpressure systems into two primary categories: self-sourcing and allochthonous overpressure [8,9]. Self-sourced overpressure is generated by internal processes within a geological system, without the involvement of external fluids. Key mechanisms include undercompaction [10,11], hydrocarbon generation [12,13], clay mineral transformation [14,15], and aquifer thermal expansion [16,17]. Allochthonous overpressure is caused by externally derived forces, such as changes in tectonic stress or hydrodynamic conditions. Typical mechanisms include tectonic compression and fluid pressure transfer from adjacent formations, such as tectonic stress [18,19] and fluid conduction overpressure [8, 20,21]. In the early stage, the Yinggehai Basin was simply considered to be dominated by overpressure caused by undercompaction [22]. As operations targeted deeper reservoirs, a significant challenge emerged: pore pressure forecasts based solely on undercompaction frequently contained large errors when verified against downhole data. Currently, the primary methods to identify the mechanism behind overpressure in a single-genesis stratum include the well logging curve combination method [2,23,24], effective stress method [25,26], acoustic-density crossplots method [27,28].

Eaton's and Bowers' methods are the primary quantitative techniques for overpressure evaluation and have been extensively used in field applications. Eaton's method is restricted to loading-type overpressure, whereas the unloading equation in Bowers' method is specifically designed for unloading-type scenarios. Neither is fit for evaluating composite-genesis overpressure. The method by Zhang et al. for quantifying overpressure contributions relies on an invariant acoustic velocity, an assumption often broken by unloading and hydrocarbon generation, resulting in underestimation [29]. Grounded in the principles of rock stress-strain behavior and pore architecture, Liu et al. constructed an operational model to evaluate overpressure generated by undercompaction and fluid expansion, demonstrating its utility in field studies [30].

Taking the Dongfang area of the central diapiric belt in the Yinggehai Basin as the research object, this study integrates existing exploration results and previous research findings. Based on detailed analysis of measured formation pressure, mud density, and logging data, it applies comprehensive methods such as well logging curve combination, loading-unloading curves, and acoustic velocity-density crossplots to investigate origins of overpressure in the Yinggehai Formation and Huangliu Formation. The study aims to clarify the abnormal high-pressure genesis mechanism, evaluate the contribution rate of single overpressure genesis, and thus provide certain guidance for overpressure research in hydrocarbon-bearing basins and petroleum exploration.

2. Geological Background

The Yinggehai Basin, situated at the junction of the Indosinian plate and Eurasian plate, is a Cenozoic high-temperature and high-pressure basin [31,32], with multiple fluid diapiric structures developed in central part, and contains abundant natural gas resources, as **Figure 1a** [33]. The basin hosts thick sedimentary layers rich in natural gas resources, ranking among the key areas for China's offshore oil and gas exploration and development. From the bottom upward, the Dongfang area of the Yinggehai Basin is developed with strata from the Paleogene Yacheng Formation, Lingshui Formation to the Neogene Sanya Formation, Meishan Formation, Huangliu Formation, Yinggehai Formation and the Quaternary Ledong Formation as **Figure 1b**. The sediment in the basin is mainly composed of fine-grained deposits. The lithology is dominated by thick successions of mudstone, with sandstones mostly being siltstone and fine sandstone. The formations such as the Meishan Formation, Huangliu Formation, and Yinggehai Formation developed in the basin have formed a good source-reservoir-cap assemblage [34]. The maximum reservoir pressure coefficient encountered in most areas of the basin is close to 2.3 [35].

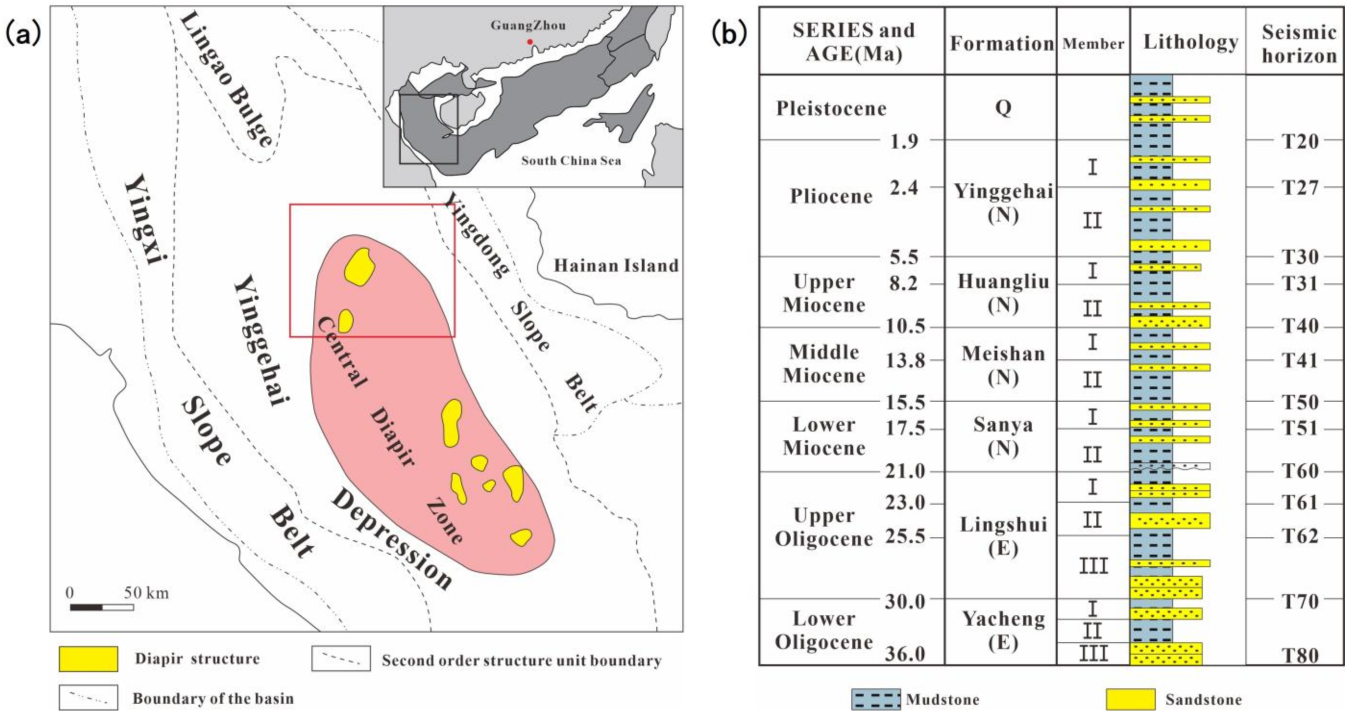

Figure 1.(**a**) Location of the Dongfang Area in the Central Diapiric Belt of the Yinggehai Basin; (**b**) Comprehensive Stratigraphic Column.

3. Results

3.1. Overpressure Structural Characteristics

An integrated analysis of data from the Dongfang area, comprising formation pressure while drilling, mud density, and measured pressures from exploration wells, confirms the widespread presence of overpressure in the Yinggehai Basin. Vertically, the overpressure top interface in the study area is located within the Yinggehai Formation and Huangliu Formation, corresponding to depths of around 1100m and below 2500m, with pressure coefficients ranging from 1.0 to 2.1. The Dongfang area of the Yinggehai Basin exhibits two set of overpressure systems in the **Figure 2**. The first stage is mainly distributed in the strata above the middle-lower part of the Yinggehai Formation at a burial depth of 1000-1500 m. With increasing depth, the acoustic transit time and resistivity of mudstone remain basically constant or stable, while density increases linearly. The formation pressure reaches 10-20 MPa, pressure coefficient over 1.3. The second stage is primarily distributed in the Huangliu Formation at a burial depth of below 2.4 km. As depth increases, the acoustic transit time, density, and resistivity of mudstone deviate from the normal trend. The formation pressure reaches 40-70 MPa, pressure coefficient exceeding 1.5 (**Figure 2a**).

The overpressure top interface in the study area shallows with decreasing distance from the diapir. In the diapiric zone, the overpressure top interface of the Yinggehai Formation, as shown in wells D1 and D3 (**Figure 2b**), corresponds to depths of 900 m and 1050 m, respectively. In the non-diapiric zone, the overpressure top interface of the Yinggehai Formation, as indicated by well D4, is at a depth of 1.1 km. However, the overpressure in the Huangliu Formation is primarily developed in the diapiric zone, with corresponding depths generally below 2.2 km.

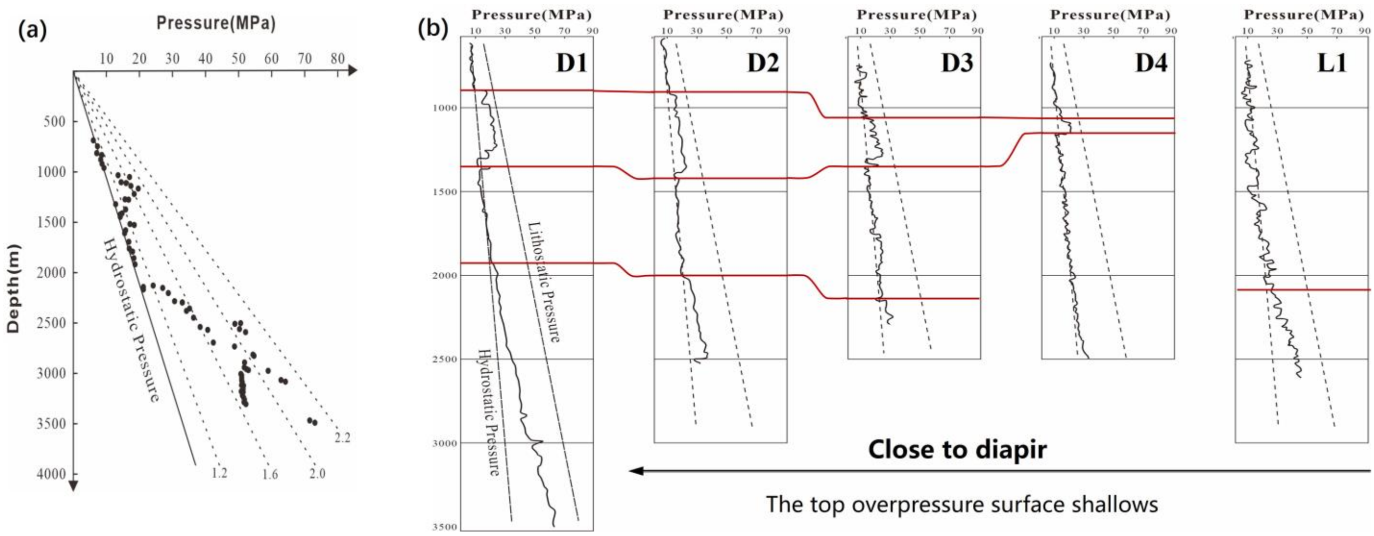

Figure 2. Pressure distribution with depth (**a**) and overpressure top interface distribution (**b**) in the Dongfang area of the Yinggehai Basin.

3.2. Origin of Overpressure

The process of abnormal pressure analysis involves two key steps: Identification, based on interpreting diagnostic well-log responses that reflect mechanism-specific changes in reservoir properties; and Discrimination, which utilizes methods from direct empirical techniques to indirect reasoning via integrated geological and experimental analysis [37-40]. Based on these methods, a comprehensive analysis is conducted using a synthesis of well-logging curves, loading-unloading diagnostics, and acoustic velocity-density crossplots to characterize the overpressure in the Dongfang area.

3.2.1. Combination analysis of logging curves

The intrinsic complexity of overpressure genesis, combined with the diverse factors influencing logging results, presents a significant challenge for accurate characterization. [36,39,41]. Given the complexity of overpressure genesis, its identification from logging data must rely on a comprehensive analysis combining multiple parameters. Therefore, a robust application of this method necessitates a dual consideration of logging responses: those sensitive to conductive properties (e.g., resistivity) and those sensitive to volumetric properties (e.g., acoustic, density) [42]. The combined interpretation of acoustic, resistivity, and density log data represents a minimum prerequisite for applying this method [2,23,36,43]: (1) disequilibrium compaction, if acoustic, resistivity, and density logs exhibit synchronous anomalies; (2) fluid expansion or pressure transfer, if anomalies are unsynchronized or density remains stable; (3) tectonic compression, if none of the curves show significant anomalies.

A characteristic feature of the overpressure in the Dongfang area is the asynchronous reversal observed in the well-logging curves. Specifically, the reversal depth of the density curve lags behind that of the acoustic transit time and resistivity curves. In well D1 (**Figure 3a**), the acoustic transit time reversal occurs at approximately 1.4 km, while the resistivity reversal is at 1.9 km. In well D3 (**Figure 3b**), within the depth range of 1.1-1.3 km, the acoustic transit time and resistivity reversals are at 1.1 km, but the density reversal is not obvious and shows a normal pressure trend. Based on this, it can be determined that the overpressure in the middle-lower part of the Yinggehai Formation and the Huangliu Formation in the Dongfang area of the Yinggehai Basin is not dominated by undercompaction, but should be attributed to fluid expansion or pressure transmission.

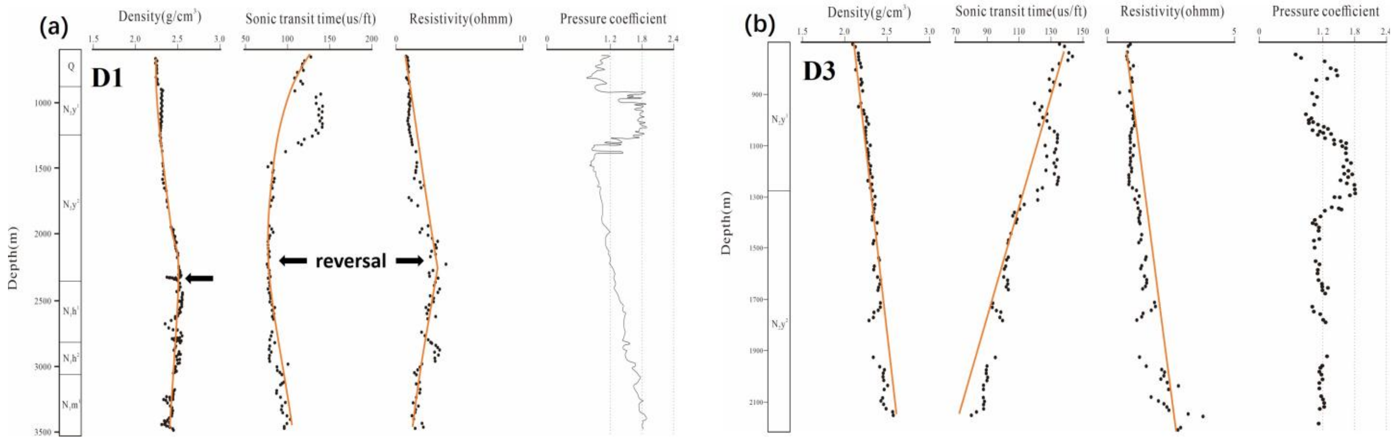

Figure 3. Pressure and electrical characteristics of (**a**) well D1 and (**b**) well D3.

3.2.2. Loading-unloading curve

Bowers defined the relationship between porosity and vertical effective stress--known as the Bowers chart or loading-unloading curve--as a diagnostic method for identifying overpressure origins [44]. Following its proposal, and especially since 2000, this technique has become a cornerstone in the field, with its successful application leading to widespread recognition [45]. Using the loading-unloading curve to further identify the overpressure genesis in the Dongfang area of the Yinggehai Basin, it is found that the overpressure points on the density-vertical effective stress and acoustic velocity-vertical effective stress (**Figure 4**) all deviate from the loading curve and fall on the unloading curve, indicating that there is unloading-induced overpressure in the Dongfang area.

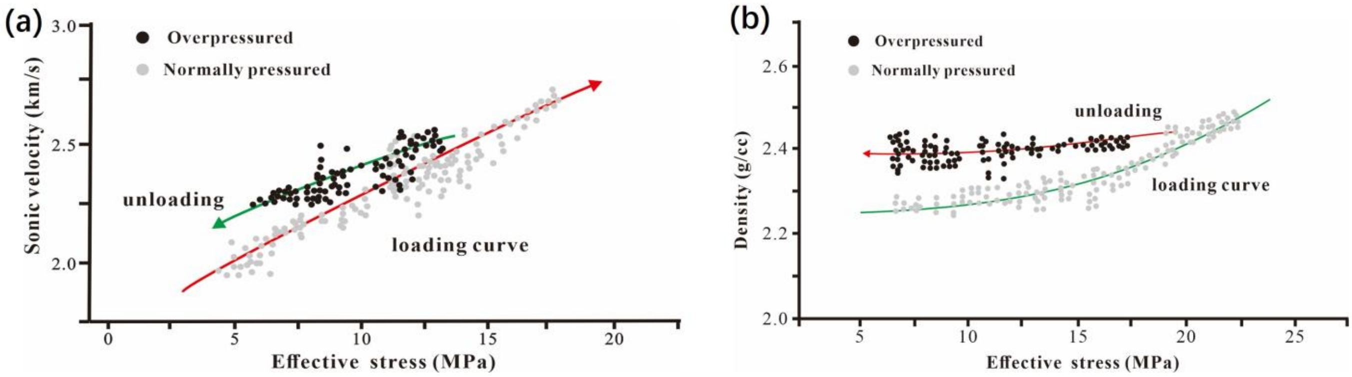

Figure 4. Loading-unloading curve of the Dongfang area (**a**) crossplots of vertical effective stress vs. acoustic velocity (**b**) crossplots of vertical effective stress vs. density.

3.2.3. Acoustic velocity-density crossplots

Since the early 21st century, the acoustic velocity-density crossplots method for identifying overpressure genesis has seen growing adoption. On acoustic velocity-density crossplots, any overpressure not caused by disequilibrium compaction will deviate from the loading curve. The specific pattern and location of this deviation vary with the underlying genetic mechanism.: (1) Overpressure from fluid expansion or pressure transmission is identified by a slight acoustic velocity decrease and a stable or slightly decreasing density [46]; (2) Overpressure resulting from clay mineral transformation manifests as a stable or slightly decreasing acoustic velocity but an increasing density [47,48]; (3) Overpressure caused by load transfer or combined origins exhibits a clear acoustic velocity decrease accompanied by a density increase [37].

All overpressure points plotted on the acoustic velocity-density crossplots deviate downward from the loading curve, with the degree of deviation increasing with depth, and all fall within the overpressure zone of fluid expansion/pressure transmission and other non-disequilibrium compaction causes (**Figure 5**). Therefore, it is comprehensively determined that the overpressure in the Dongfang area of the Yinggehai Basin is dominated by fluid expansion/pressure transmission causes.

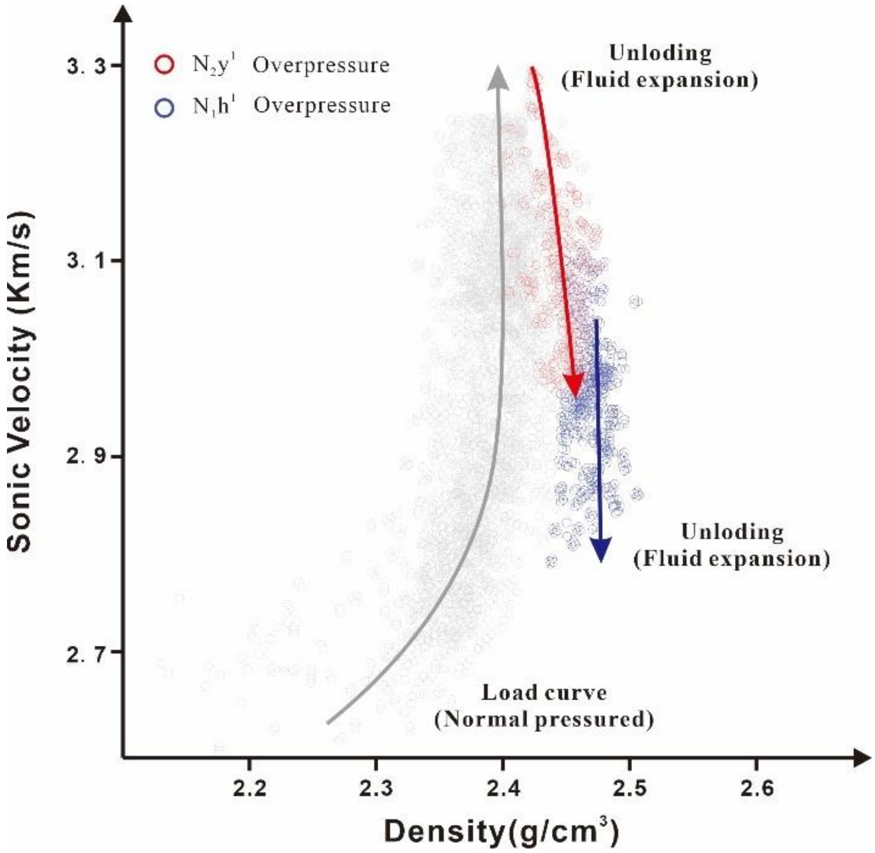

Figure 5. Acoustic velocity-density crossplots of the Dongfang area.

3.3. Quantitative Evaluation of Overpressure Genesis

Based on previous analysis, a method for evaluating overpressure contribution is proposed by fitting an exponential relationship between the acoustic velocity or density and vertical effective stress in normally pressured formations within the study area [49].

$$v = k * e^{c\rho} \quad (1)$$

$$\rho = k * e^{c\sigma} \quad (2)$$

in the above equation, v represents acoustic velocity, km/s; ρ denotes density, g/cm^3; k, c are constants; σ stands for effective stress, MPa.

Acoustic velocity, density, and resistivity typically increase with effective stress under normal pressure. Undercompaction delays this compaction trend, whereas fluid expansion overpressure causes a precipitous drop in effective stress, resulting in decreased velocity and resistivity but stable density.

The overpressure generated by any mechanism (e.g., fluid expansion, transmission, undercompaction) causes a decrease in effective stress, where the magnitude of the decrease is equal to the magnitude of the overpressure.

$$\Delta\sigma_1 = \ln(\rho/k) \& * \frac{1}{c} - \Delta\sigma \quad (3)$$

$$G = \frac{\Delta\sigma_1}{\Delta\sigma} * 100\% \quad (4)$$

in the above equation, $\Delta\sigma_1$ represents the overpressure increment, MPa; $\Delta\sigma$ denotes the corresponding total overpressure, MPa; G stands for the corresponding overpressure contribution rate, %.

Calculation results indicate that the overpressure from hydrocarbon generation primarily ranges between 5 MPa and 20 MPa, with its contribution accounting for 40%-70% (**Table 1**). The measured pressure points show a 45% contribution from hydrocarbon generation-induced overpressure, highlighting that overpressure from hydrocarbon generation is of critical importance for pressure prediction in hydrocarbon source rocks (**Figure 6)**.

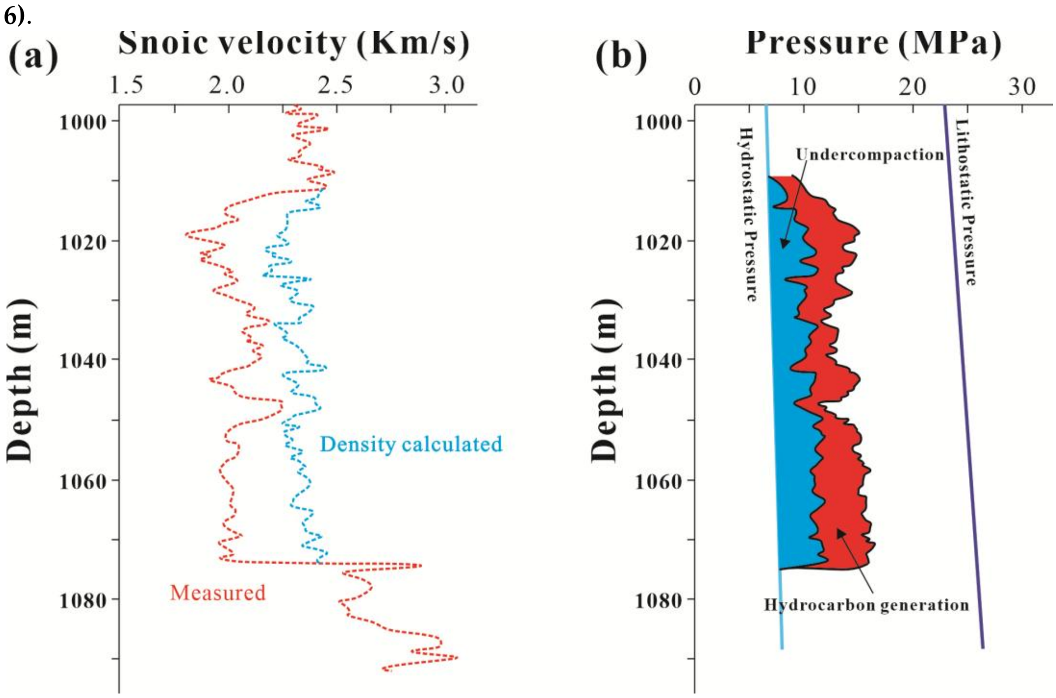

Figure 6. (**a**) Comparison of the measured snoic velocity and density calculated sound velocity. (**b**) Pressure prediction using snoic velocity and density calculated sound velocity in the Dongfang area.

Table 1. Contribution of hydrocarbon-generated to overpressure in Dongfang area.

Well	Depth(m)	Pressure (MPa)	Overpressure (MPa)	Hydrocarbon generation (MPa)	Contribution rate (%)
D1	920-1400	24.1	15.2	8.7	57.2
	>1950	48.4	33.5	19.7	58.8
D2	950-1400	18.5	9.7	4.7	48.5
	>2000	56.4	14.4	8.9	61.8
D3	1050-1350	21.4	11.2	5.8	51.2
L1	>2150	38.7	24.6	16.3	66.3

4. Conclusions

1) Two overpressure segments are widely developed in the Dongfang area. The first segment, with a pressure coefficient exceeding 1.3, lies above the mid-lower Yinggehai

Formation at 1-1.5 km depth. The second segment, with a pressure coefficient over 1.5, is located in the Huangliu Formation beneath 2.4 km. The overpressure distribution exhibits a characteristic of bulge-shaped uplift: the depth to the top of overpressure at the diapir core is relatively small, while that at the diapir margin increases.

2) Integrated geophysical analysis reveals the overpressure characteristics of the Dongfang area in the Yinggehai Basin: well-logging curves exhibit typical asynchronous reversals in acoustic interval time, resistivity, and density. Based on a comprehensive diagnosis using multiple methods such as composite well-log analysis, loading-unloading curves, and acoustic velocity–density crossplots, the overpressure in this area is determined to result from a combined origin of hydrocarbon generation and undercompaction. Quantitative evaluation indicates that hydrocarbon generation contributes an overpressure magnitude of approximately 5–20 MPa, accounting for 40% to 70% of the total overpressure.

Acknowledgments

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