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Rock physics modeling and fluid–solid substitution for subsalt halite-cemented sandstones in West Africa

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Abstract

Drilling in the West African subsalt region has revealed the tight, low-porosity character of sandstones resulting from halite cementation. The extent of this cementation directly governs reservoir quality, hydrocarbon distribution, and exploration and development strategies. However, conventional fluid substitution methods based on Gassmann's theory are inadequate for performing the fluid–solid substitution required to analyze the seismic response of such halite-cemented sandstones. To address this limitation, we introduce a method for constructing a dedicated rock physics model for halite-cemented sandstones and demonstrate its use in fluid–solid substitution. The workflow comprises (i) determination of the volumetric fractions of rock constituents from well logs and core data, with total porosity defined as the sum of the halite volume fraction and the effective porosity after cementation; (ii) building an equivalent rock physics model through sequential integration of four established models: the Voigt–Reuss–Hill average model, the modified Xu–White model, the Wood equation, and Gassmann's relations; (iii) calibration and validation of the model using well-log and core measurements; and (iv) application of the calibrated model to conduct fluid–solid substitution and total-porosity variation, yielding elastic parameters for cases where halite is replaced by fluid, fluid is replaced by halite, or total porosity is altered. When applied to the L Gas Field in West Africa, the model predictions exhibit excellent agreement with measured data. Using this validated model, we systematically investigate the elastic properties, seismic amplitude response, and amplitude versus offset behavior of reservoir rocks at varying halite contents, total porosities, and pore-fluid types within the field.

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Citation: Han L, Tao W, Cheng T, Yang H, Chen Q. Rock physics modeling and fluid–solid substitution for subsalt halite-cemented sandstones in West Africa. *J Seismic Explor.*
doi: 10.36922/JSE026050020

Received: January 31, 2026**Revised:** August 16, 2026**Accepted:** August 19, 2026**Published online:** September 10, 2026

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Keywords: Halite cementation; Gabon; Rock physics modeling; Fluid–solid substitution; Equivalent model

1. Introduction

Cementation refers to the process by which minerals precipitate within the pores of clastic sediments, forming authigenic minerals and consolidating the sediments into rock. It is a key factor contributing to the reduction of reservoir porosity. Common types of cementation include argillaceous, calcareous, and siliceous cementation, each exhibiting distinct characteristics depending on the cementing material. In recent years,

localized halite cementation has emerged as a critical factor leading to the densification of sandstone reservoirs in various oil and gas fields, such as in Gabon, West Africa,¹ the Dutch North Sea,² and Eastern Siberia.³ Although these regions differ in stratigraphic configuration and in the formation mechanisms of halite cementation, they share a common characteristic: salt layers are connected to sandstone layers, allowing high-salinity brine to circulate within the pores of high-quality reservoirs. Subsequently, factors such as formation cooling or hydrocarbon charging cause salt crystals to precipitate and grow within the pores, ultimately forming halite cement. The extent and intensity of halite cementation directly affect reservoir quality and hydrocarbon distribution. Studies on halite cementation in evaporite-bearing basins have revealed that the distribution of halite cement is closely associated with tectonic fractures and fluid-migration pathways,⁴ and the spatial distribution of diagenetic cementation can be predicted using machine learning-based approaches.⁵ However, due to its unique formation mechanism and pore-filling pattern, existing research on the influence of cementation on rock elastic properties^{6–8} cannot be directly applied to the case of halite cementation.

The type and amount of pore-filling materials can induce complex seismic response characteristics, rendering it essential to quantitatively study their influence on the elastic properties of rocks. In hydrocarbon exploration, common pore fillings include gases (e.g., methane, carbon dioxide), liquids (e.g., brine, light oil, heavy oil), and solids (e.g., clay, bitumen, kerogen, gas hydrates, halite). For rocks saturated with fluids (gas, water, light oil), the classical Gassmann fluid substitution equations⁹ can accurately predict variations in seismic velocity or rock moduli with changing pore-filling properties without requiring information on pore geometry. However, these equations are not applicable to viscoelastic fluids (e.g., heavy oil) or solid fillings (e.g., halite). This limitation arises because Gassmann's theory assumes interconnected pores, pore-pressure equilibrium, and zero shear modulus of the pore-filling material, whereas both viscoelastic fluids and solid fillings possess a non-zero shear modulus, which impedes pressure transmission throughout the pore network. Truong *et al.*¹⁰ conducted ultrasonic velocity measurements on sandstone samples containing varying amounts of halite cement. Their results demonstrate that halite cementation significantly increases both P-wave and S-wave velocities, leading to substantial deviations from predictions of the classical biphasic theory.

Ciz and Shapiro¹¹ extended the anisotropic Gassmann equations^{12–13} by introducing a heuristic parameter related to the average deformation of the solid pore-filling

material. This generalization enabled the Gassmann framework to be applied to scenarios where pores are occupied by solids. The approach was first applied in heavy oil research¹⁴ and was later adopted in studies on halite cementation.³ However, Mavko *et al.*¹⁵ and Saxena and Mavko¹⁶ noted that this “solid Gassmann” equation still relies on the assumptions of connected pores and uniform pore pressure, which lead to substantial underestimation of the elastic moduli in rocks with solid pore fillings. Yuan *et al.*¹⁴ and Sun *et al.*¹⁷ conducted physical experiments and numerical simulations on sandstone samples saturated with heavy oil and octadecane, respectively. These pore fillings behave as fluids at high temperatures but exhibit viscoelastic or solid-like properties at lower temperatures. Their work demonstrated that although the solid Gassmann equation improves on the classical version by accounting for the shear modulus of pore-filling materials, it can still yield appreciable discrepancies. To address this, recent studies have proposed improved models that account for the transitional microstructure of solid pore fillings¹⁸ or, alternatively, have developed approaches combining geological genesis analysis and rock-physical characterization methods for locally halite-cemented reservoirs,¹⁹ aiming for a more accurate characterization of the impact of solid pore-filling materials. Moreover, when applying the solid Gassmann equation for fluid–solid substitution, the calculation of the pore modulus in cases of mixed solid–liquid filling must also be addressed. In their model, Shubin *et al.*³ treated halite as part of the pore fluid rather than the solid matrix, using the Voigt–Reuss–Hill (VRH) average to compute the pore modulus for a mixed halite–water filling, and constructed an equivalent model based on the solid Gassmann equation. Thin-section observations, however, reveal that in halite-cemented sandstones, halite almost entirely occupies the pore space and is firmly bonded to mineral grains—a configuration that inevitably provides mechanical support to the rock frame. Micro-computed tomography characterizations further confirm that halite can develop complex porous crystalline networks with diverse pore-occupying habits, which fundamentally alter pore-space architecture and rock mechanical responses.²⁰

In order to develop a fluid–solid substitution method better suited for halite-cemented zones, this study focuses on the L Gas Field in West Africa. Based on an integrated analysis of well log and sidewall core data, a rock physics modeling approach for halite-cemented sandstone is proposed, and fluid–solid substitution is implemented using this model. The elastic response, seismic amplitude response, and amplitude versus offset (AVO) response characteristics of the rocks are systematically analyzed under varying conditions of halite content, total porosity, and pore-filling type within the gas field.

2. Geological background and characteristics of halite cementation

2.1. Formation mechanism of subsalt halite cementation in Gabon

The study area is the L Gas Field in the deepwater zone offshore Gabon, West Africa. The reservoir consists of subsalt deltaic clastic sandstones. Drilling data show that some subsalt sandstone intervals have been rendered impermeable by halite cementation.¹ Structurally, the gas reservoir forms a three-way dip closure bounded by a fault on the fourth side. Fault activity has locally brought salt layers into direct contact with the subsalt sandstones, creating conduits for brine to migrate from the salt into the sandstone. This process constitutes the principal mechanism controlling the development of halite cementation in this area. The corresponding geological model is presented in Figure 1.

2.2. Impact of halite cementation on reservoir petrophysical and elastic properties

Halite cementation significantly influences the petrophysical and elastic characteristics of the reservoir. Analysis of core sample data demonstrates an inverse correlation between halite cement content and reservoir porosity: as halite content rises, porosity and permeability decrease markedly (Figure 2). In halite-cemented intervals (halite content > 2%), average porosity ranges from 9.0% to 11.3%, with corresponding permeability of 0.41–0.93 mD. By contrast, intervals containing less than 2% halite exhibit substantially better reservoir quality, with average porosity reaching 18.5% and permeability averaging 7.3 mD. These

findings underscore that halite cementation is a key driver of reservoir densification, with important consequences for subsalt reservoir prediction and gas resource evaluation.

Halite-cemented sandstones differ notably from their uncemented counterparts in terms of elastic behavior. As illustrated in Figure 3 using well-log and core-analysis data from a halite-cemented interval, the first two columns present fluid and porosity interpretations, indicating that dry zones are largely associated with porosity reduction due to salt cementation. The third column displays core-derived halite content and total porosity (halite content plus remaining porosity), where blue and red dots represent halite content and total porosity, respectively. The following four columns show, in order, compressional-wave velocity, shear-wave velocity, density, and compressional-impedance curves. The results demonstrate that halite-cemented sandstones exhibit relatively higher compressional-wave velocity, shear-wave velocity, and acoustic impedance compared to uncemented intervals.

To elucidate these variations from a microstructural standpoint, Figure 4 displays photomicrographs of thin sections from core sandstone samples: Figure 4A displays sandstone without halite cementation, showing well-developed intergranular pores filled with fluid, good pore connectivity, equilibrated pore pressure, and zero shear modulus of the pore fill; Figure 4B shows typical halite-cemented sandstone, in which intergranular pores are filled with solid halite, pore connectivity is reduced, and the shear modulus of the pore-filling material is correspondingly elevated.

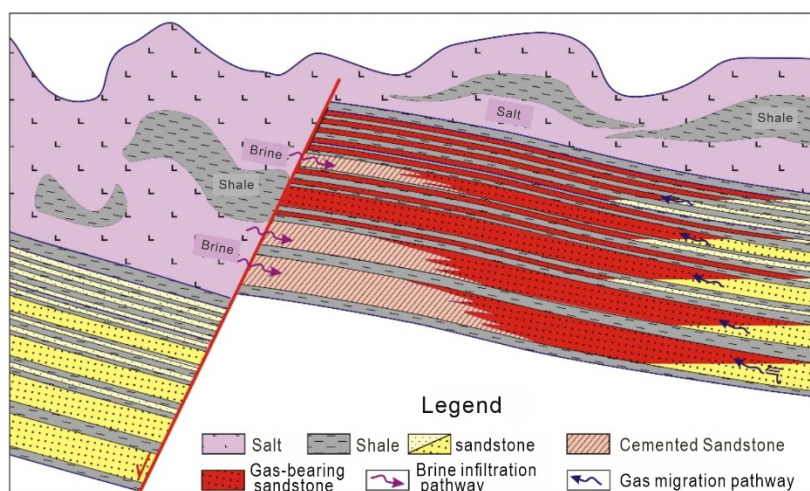


Figure 1. Halite cementation pattern of subsalt sandstone reservoir in the study area

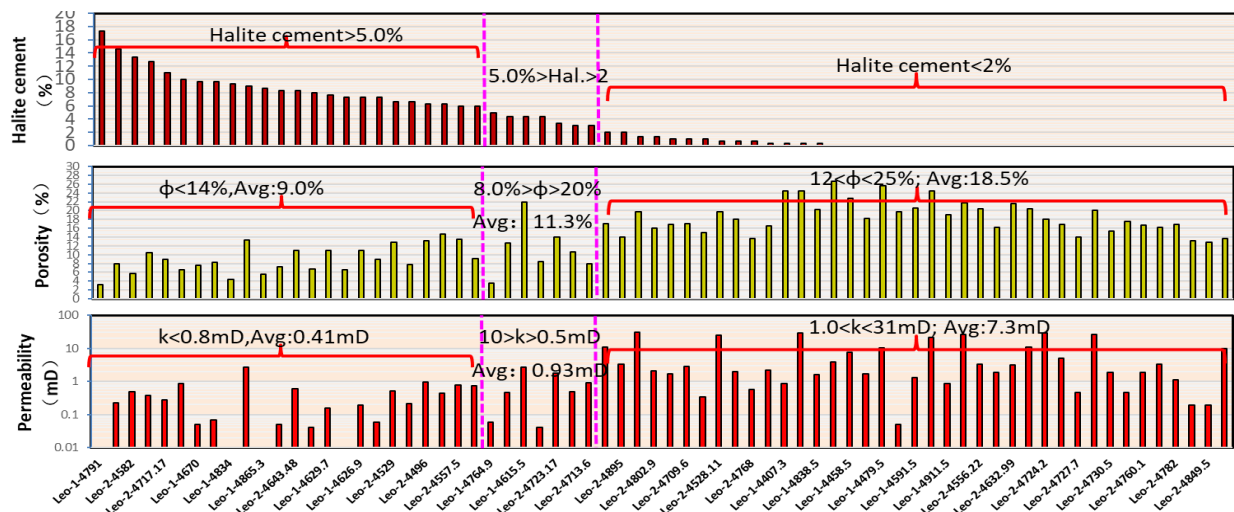


Figure 2. Histogram of porosity and permeability for intervals with different halite cement contents in the L Gas Field

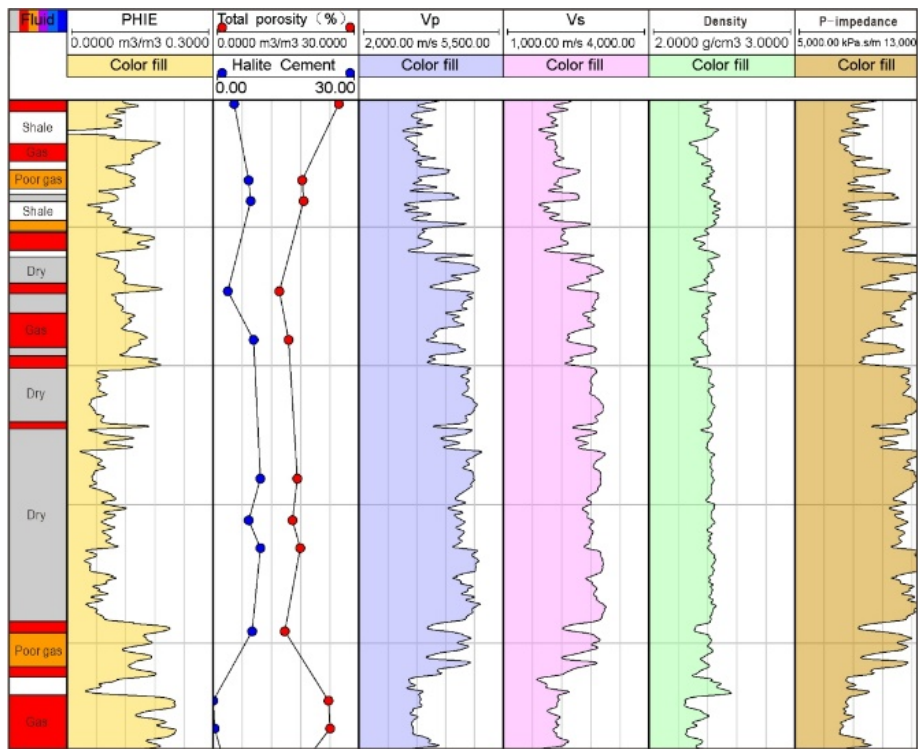


Figure 3. Well-log curves for halite-cemented sandstone and core-derived halite content

The preceding analysis demonstrates that halite cementation substantially alters reservoir petrophysical and elastic properties by modifying both rock composition and pore structure. However, due to limited core availability, there is currently no systematic understanding of how rock elastic parameters vary with different degrees

of halite cementation. While the classical Gassmann fluid substitution equations—which assume connected pores, pressure equilibrium, and zero shear modulus of the pore fill—are effective for fluid substitution studies, they cannot be directly applied to describe pore spaces filled with solid halite cement. Therefore, to systematically elucidate

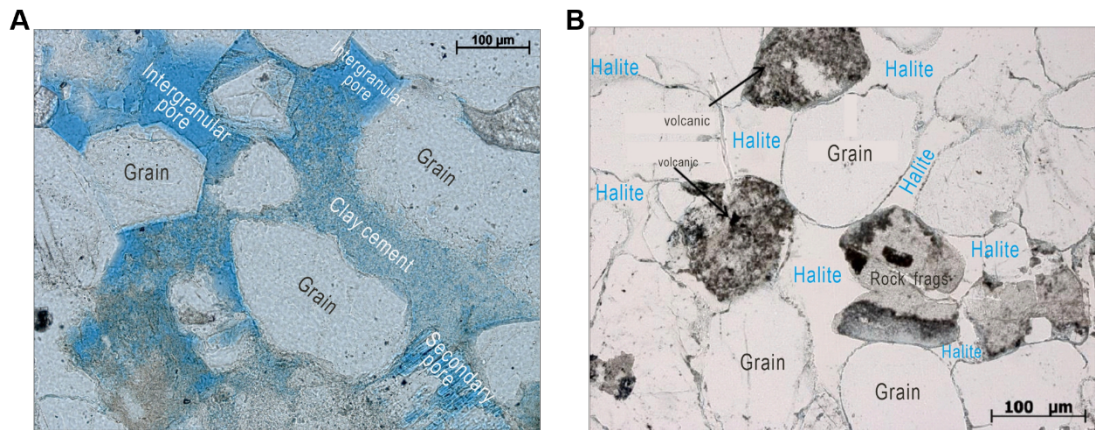


Figure 4. Thin sections of sidewall sandstones. (A) Sandstone without halite cementation. (B) Halite-cemented sandstone. Scale bars: 100 μm.

the influence of halite cementation on reservoir elastic behavior, it is essential to develop a rock physics model that accommodates solid halite pore fill. Such a model would enable equivalent fluid–solid substitution and provide a theoretical foundation for the accurate prediction of subsalt tight reservoirs and the reliable evaluation of gas resources.

3. Rock physics modeling for halite-cemented sandstones

The uniqueness of halite-cemented sandstone stems from the fact that its pores originally contain fluid but subsequently become filled with solid halite. Halite plays a dual role: it precipitates within and fills the pore space during cementation and subsequently becomes part of the solid rock matrix. Core analysis reveals that before halite cementation, the sandstone composition consists mainly of quartz, feldspar, lithic fragments, various cements (such as quartz, carbonate, and clay cements), and pore fluid. After halite cementation, halite occupies most of the pore space, resulting in a marked decrease in effective porosity (Figure 5). As a solid cement, halite bonds firmly with mineral grains and integrates into the rock matrix.

This not only influences the bulk modulus of the rock but also significantly enhances its shear modulus, thereby modifying the overall elastic properties of the reservoir.

The unique characteristics of halite cementation imply that conventional fluid–fluid substitution equations cannot be directly applied to describe the replacement between fluid and solid in halite-cemented rocks. Accordingly, in this study, the total porosity of the rock is defined as the sum of the halite volume fraction and the current porosity, with halite considered part of the present solid matrix (see Figure 5). Building upon this definition and in light of the formation mechanism of halite-cemented sandstone, a corresponding rock physics modeling workflow is established, as illustrated in Figure 6.

The halite-cemented sandstone rock physics model and subsequent fluid substitution based on this model refer to the replacement of pore-filling material between fluid (brine/gas) and solid halite, while keeping the total porosity constant. The physical essence is that halite acts as a load-bearing solid, not as a fluid, and therefore the shear modulus of the pore fill must be accounted for. This differs from the solid Gassmann approach, which represents the

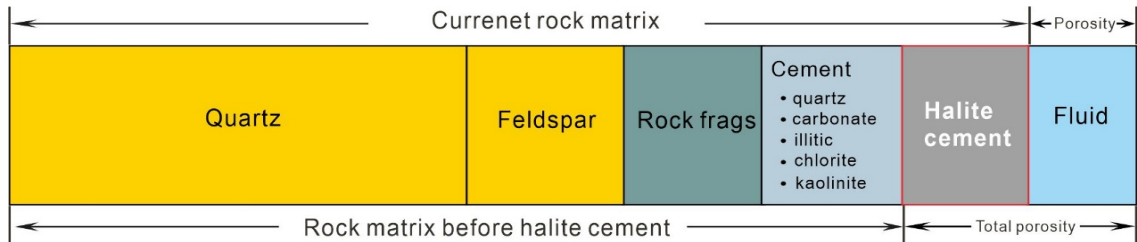


Figure 5. A schematic diagram of the composition of the halite-cemented sandstone rock

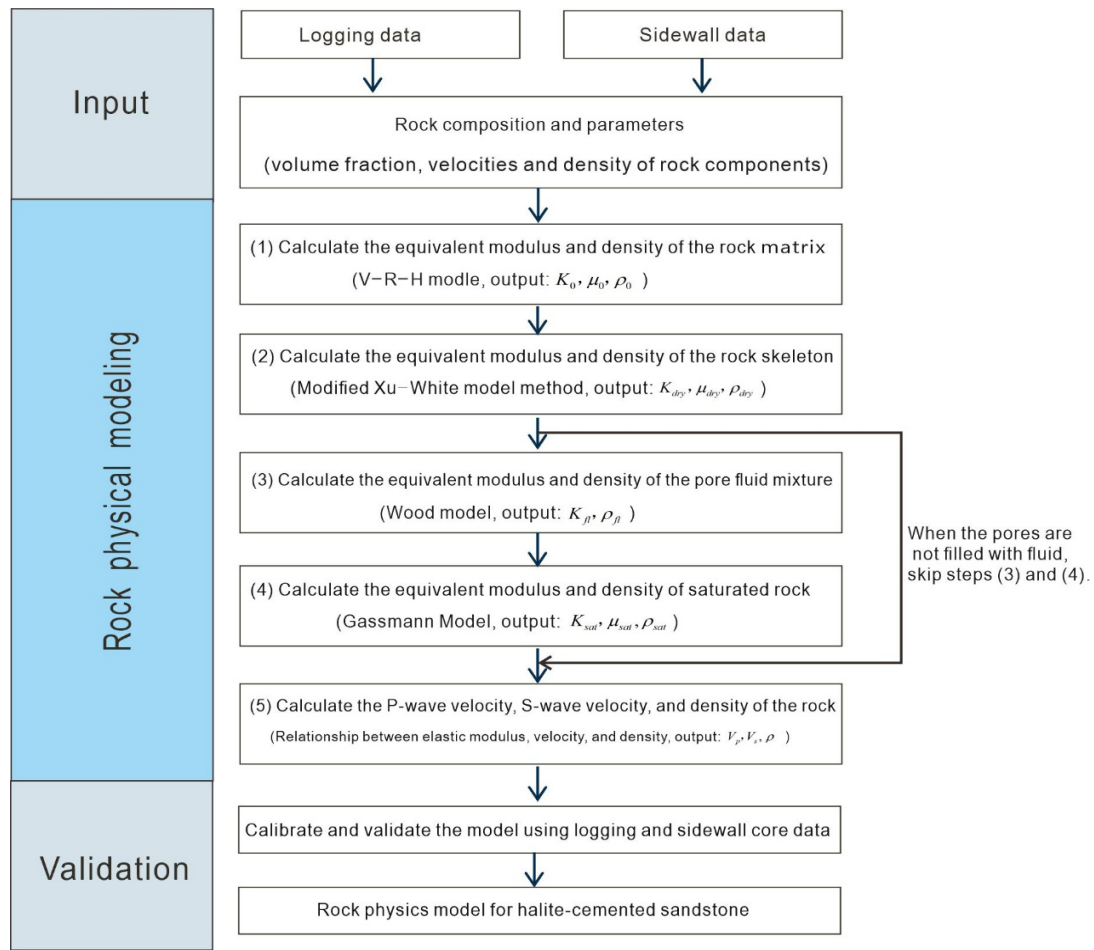


Figure 6. A general workflow for the rock physics modeling of the halite-cemented sandstone
Abbreviations: V-R-H: Voigt-Reuss-Hill.

solid material as a pore-filling phase within a Gassmann-type framework, whereas the present model incorporates cemented halite into the load-bearing solid matrix.

3.1. Obtaining volumetric fractions and elastic parameters of rock components

Step 1 involves determining the volumetric fractions of rock constituents—such as quartz, feldspar, dolomite, illite, chlorite, kaolinite, halite, and pore fluid—using sidewall core data. The dataset included 76 sandstone sidewall-core samples from two wells, L-1 and L-2. Laboratory analyses provided the volume fractions of the above components as well as rock porosity. Because of data-authorization restrictions, only data from Well L-1 are presented in this paper. Assign compressional-wave velocity, shear-wave velocity, and density values for each constituent based on The Rock Physics Handbook,²¹ as listed in Table 1. Specifically, quartz and quartz cement are assigned the

elastic moduli of quartz; feldspar and lithic fragments are assigned those of feldspar; dolomite cement is assigned the elastic properties of dolomite; illite, chlorite, and kaolinite are assigned those of clay; and halite is assigned its own elastic moduli. Define the total porosity of the rock as the sum of the halite volume fraction and the effective porosity remaining after salt cementation, as follows:

$$\varphi_{total} = f_{halite} + \varphi_{effective} \quad (1)$$

where φ_{total} is the total rock porosity before halite cementation, f_{halite} is the halite volumetric fraction, and $\varphi_{effective}$ is the effective porosity of the rock after halite cementation.

3.2. Establishing the equivalent rock physics model for halite-cemented sandstone

As shown in Figure 7, based on the parameters obtained in

Table 1. Rock component mineral moduli and elastic parameters

Rock constituents	Minerals	Bulk modulus (GPa)	Shear modulus (GPa)	Density (g/cm ³)
Quartz, quartz cement	Quartz	36.60	45.00	2.650
Feldspar, rock fragments	Feldspar	75.60	25.60	2.630
Illite, chlorite, kaolinite	Clay	25.00	9.00	2.550
Dolomite cement	Dolomite	94.90	45.00	2.870
Salt cement	Halite	24.80	14.90	2.160
Pore fluid	Gas	0.34	0.00	0.100
	Water	2.20	0.00	1.090

Section 3.1, an equivalent rock physics model for halite-cemented sandstone is established by jointly applying the VRH model, the modified Xu–White model, the Wood model, and the Gassmann equations. The specific steps are as follows:

3.2.1. Calculating the equivalent moduli and density of the rock matrix based on the Voigt–Reuss–Hill model

The VRH average is used to compute the effective elastic moduli of the mineral mixture. We acknowledge that the Hill average lacks rigorous theoretical justification²² and that the Voigt and Reuss bounds assume isotropic minerals and interconnected pores, respectively. In our study, the minerals (quartz, feldspar) are anisotropic, and occluded porosity may exist. The VRH average is adopted as a pragmatic approximation. Halite is included in the VRH mixture along with other minerals, as it is considered part of the solid matrix.

In the VRH model,²³ the Voigt strain average M_V represents the upper bound of the equivalent elastic modulus for a mixture of N minerals, the Reuss stress average M_R represents its lower bound, and the Hill average M_{VRH} is the arithmetic mean of the Voigt upper bound and Reuss lower bound, i.e.:

$$M_V = \sum_{i=1}^N f_i M_i \quad (2)$$

$$M_R = \left(\sum_{i=1}^N \frac{f_i}{M_i} \right)^{-1} \quad (3)$$

$$M_{VRH} = (M_V + M_R) / 2 \quad (4)$$

where f_i and M_i are the volumetric fraction and elastic modulus of the i -th component, respectively; N is the number of solid-matrix components. When M

in **Equations 2–4** is the rock bulk modulus K or shear modulus μ , the equivalent bulk modulus K_0 and equivalent shear modulus μ_0 of the rock matrix are:

$$K_0 = \left(\sum_{i=1}^N f_i K_i + \left(\sum_{i=1}^N \frac{f_i}{K_i} \right)^{-1} \right) / 2 \quad (5)$$

$$\mu_0 = \left(\sum_{i=1}^N f_i \mu_i + \left(\sum_{i=1}^N \frac{f_i}{\mu_i} \right)^{-1} \right) / 2 \quad (6)$$

where f_i , K_i , and μ_i are the volumetric fraction, bulk modulus, and shear modulus of the i -th component of the rock matrix, respectively. The rock matrix includes solid components such as quartz, feldspar, lithic fragments, conventional cements, and halite.

The average density of the rock matrix ρ_0 is:

$$\rho_0 = \sum_{i=1}^N f_i \rho_i \quad (7)$$

where f_i and ρ_i are the volumetric fraction and density of the i -th component, respectively.

3.2.2. Calculating the equivalent moduli and density of the dry rock frame based on the modified Xu–White model

Keys and Xu²⁴ modified the Xu–White model^{25–26} by solving linear ordinary differential equations to calculate the equivalent bulk modulus K_{dry} and shear modulus μ_{dry} of the dry rock frame at porosity φ , thereby avoiding the computationally intensive iterative calculation in the original model:

$$K_{dry} = K_0 (1 - \varphi)^p \quad (8)$$

$$\mu_{dry} = \mu_0 (1 - \varphi)^q \quad (9)$$

where K_0 and μ_0 are the bulk and shear moduli of the solid minerals composing the rock; the coefficients p and q are defined as:

$$p = \frac{1}{3} (v_s T_{ijj}(\alpha_s) + v_c T_{ijj}(\alpha_c)) \quad (10)$$

$$q = \frac{1}{5} (v_s F(\alpha_s) + v_c F(\alpha_c)) \quad (11)$$

where v_s and v_c are the volumetric fractions of the sandstone (other rock matrix excluding clay) and shale (clay) in the rock frame, satisfying $v_s = 1 - v_c$; the modified Xu–White model assumes spherical pores and ellipsoidal cracks, which are idealizations. The effective pore aspect ratio (α) is a fitting parameter that represents the average pore geometry; α_s and α_c are the pore aspect ratios for sandstone and shale, respectively. In this study, for sandstone, we set $\alpha_s = 0.12$; for mudstone, $\alpha_c = 0.035$. $T_{ijj}(\alpha)$ and $F(\alpha)$ are functions related to the pore aspect ratio.²⁴

The average density of the dry rock frame ρ_{dry} is:

$$\rho_{dry} = (1 - \varphi) \times \rho_0 \quad (12)$$

where ρ_0 is the rock matrix density.

3.2.3. Calculating the equivalent modulus of the pore fluid based on the Wood model

According to the Wood model,²⁷ the equivalent bulk modulus (Reuss average) K_{fl} and average density ρ_{fl} of a mixed fluid are defined as:

$$K_{fl} = \left(\sum_{i=1}^N \frac{f_i}{K_i} \right)^{-1} \quad (13)$$

$$\rho_{fl} = \sum_{i=1}^N f_i \rho_i \quad (14)$$

where f_i , K_i and ρ_i are the saturation, bulk modulus, and density of each component, respectively. The shear

modulus of the mixed fluid is zero. Wood's equation is included for forward modeling generality and to enable future applications involving mixed pore fluids under different charge scenarios.

3.2.4. Calculating the equivalent moduli and density of the saturated rock based on the Gassmann equations

Use the Gassmann equations⁹ to calculate the equivalent bulk modulus K_{sat} and equivalent shear modulus μ_{sat} of the rock frame filled with fluid:

$$K_{sat} = K_{dry} + \left(1 - \frac{K_{dry}}{K_0} \right)^2 \left/ \left(\frac{\varphi}{K_{fl}} + \frac{1 - \varphi}{K_0} - \frac{K_{dry}}{K_0^2} \right) \right. \quad (15)$$

$$\mu_{sat} = \mu_{dry} \quad (16)$$

where K_{dry} , K_0 , and K_{fl} are the equivalent bulk moduli of the dry rock frame, rock matrix, and pore fluid, respectively; μ_{dry} is the shear modulus of the dry rock frame.

The average density ρ_{sat} of the fluid-saturated rock is:

$$\rho_{sat} = (1 - \varphi) \times \rho_0 + \varphi \times \rho_{fl}, \quad (17)$$

where ρ_0 and ρ_{fl} are the average densities of the rock matrix and pore fluid, respectively.

3.2.5. Calculating rock compressional wave velocity, shear wave velocity, and density

For dry rock (pores containing no hydrocarbons or water), use the equivalent moduli and average density of the dry rock frame obtained in Step 2 to calculate the compressional wave velocity V_p , shear wave velocity V_s , and density ρ :

$$V_p = \sqrt{\frac{K_{dry} + 4\mu_{dry}/3}{\rho_{dry}}} \quad (18)$$

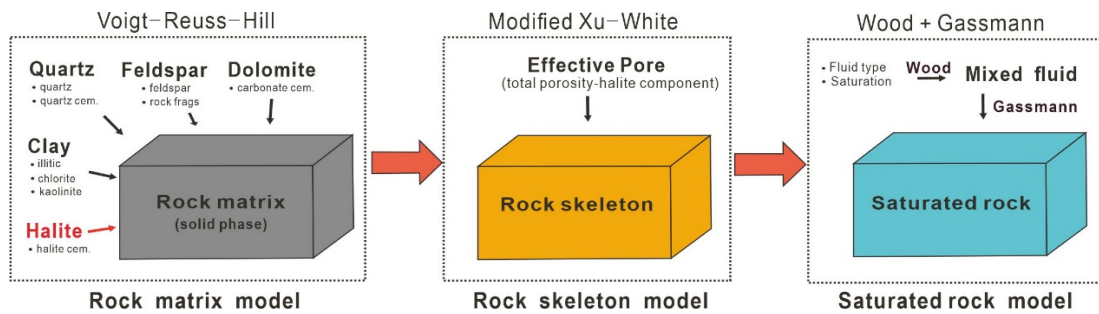


Figure 7. A workflow of the establishment of the equivalent rock physics model for the halite-cemented sandstone

$$V_s = \sqrt{\frac{\mu_{dry}}{\rho_{dry}}} \quad (19)$$

$$\rho = \rho_{dry} \quad (20)$$

If the rock pores contain fluid (gas or water), use the equivalent moduli and average density of the saturated rock obtained in Step 4 to calculate the compressional wave velocity V_p , shear wave velocity V_s , and density ρ :

$$V_p = \sqrt{\frac{K_{sat} + 4\mu_{sat}/3}{\rho_{sat}}} \quad (21)$$

$$V_s = \sqrt{\frac{\mu_{sat}}{\rho_{sat}}} \quad (22)$$

$$\rho = \rho_{sat} \quad (23)$$

If the rock is dry, skip Steps 3 and 4.

3.3. Calibration and validation of the rock physics model for halite-cemented sandstone

Utilize measured data from existing wells—including well log and sidewall core analysis data—to calibrate and validate the aforementioned equivalent rock physics model for halite-cemented sandstone. The pore aspect ratio, a key parameter reflecting the pore morphology of compacted halite-cemented sandstone, directly influences the calculation of the dry rock frame equivalent moduli and overall controls the range of elastic parameters predicted by the model. This parameter can be calibrated by using the volumetric fractions of components derived from sidewall core analysis as model inputs and comparing the model-output elastic parameters with actual measured data. Within the same target interval and geological setting, this parameter generally remains constant due to similar diagenetic conditions. Once determined, the correlation coefficient between the model predictions and the measured data for all samples should be calculated. A high correlation coefficient indicates that the model is effective and accurately simulates the elastic characteristics of the sandstones in the area.

Taking the L Gas Field as an example, the area contains localized halite-cemented sandstones. Following the modeling workflow outlined above, a rock physics model was established for the main target layers in the study area. Figure 8 presents the model validation results, in which the blue dots denote the well-log-measured compressional wave impedance, while the red dots represent the compressional wave impedance calculated by the model using mineralogical data from sidewall cores. Since one of the key aspects of the proposed method is the consideration

of the shear rigidity effect introduced by solid halite filling, the S-wave response provides an important basis for evaluating the physical validity of the model. Figure 8B presents the comparison between the modeled S-wave velocity and the well-log-measured S-wave velocity. The correlation coefficients for both the predicted P-wave impedance and the predicted S-wave velocity against the logging data are 0.95, demonstrating the effectiveness of the proposed modeling approach.

4. Elastic characteristics and seismic response characteristics of halite-cemented sandstones

Once the rock physics model for halite-cemented sandstone was established and validated, it was applied to perform fluid–solid (halite) substitution via repeated modeling. This enabled the derivation of elastic parameters for scenarios where halite is replaced by pore fluid or vice versa. The approach allows for the systematic investigation of how varying halite content, total porosity, and porefilling types affect the elastic response, seismic amplitude behavior, and AVO characteristics of the rock.

Following the halite-cemented rock physics modeling workflow, the halite-cemented fluid–solid substitution process is as follows: When a portion of the original pore volume undergoes halite cementation, the fluid in that volume is replaced by halite. First, the halite is combined with other rock minerals to build the rock matrix using the VRH model. Then, the remaining pore volume after halite filling is added, and the modified Xu–White model is applied to construct the rock frame. Finally, the Wood equation and Gassmann relations are used to compute the elastic moduli of the fluid-saturated rock, which serve as the post-cementation elastic parameters for subsequent seismic response analysis.

4.1. Fluid–solid substitution based on the rock physics model

Based on the established rock physics model for halite-cemented sandstone, fluid–solid (halite) substitution analysis was conducted, as illustrated in Figure 9. Figure 9A presents the constructed geological model, which consists of a 50-m-thick sandstone layer in its initial *in situ* state as halite-cemented sandstone. The total porosity (16%) and halite content (9.6%) used in the model are derived from sidewall core analysis. The corresponding elastic parameters of the model are shown in Table 2. A comparison of Figure 9B and 9C demonstrates that the seismic response simulated by the rock physics model closely matches the measured *in situ* response. This consistency not only validates the model but also

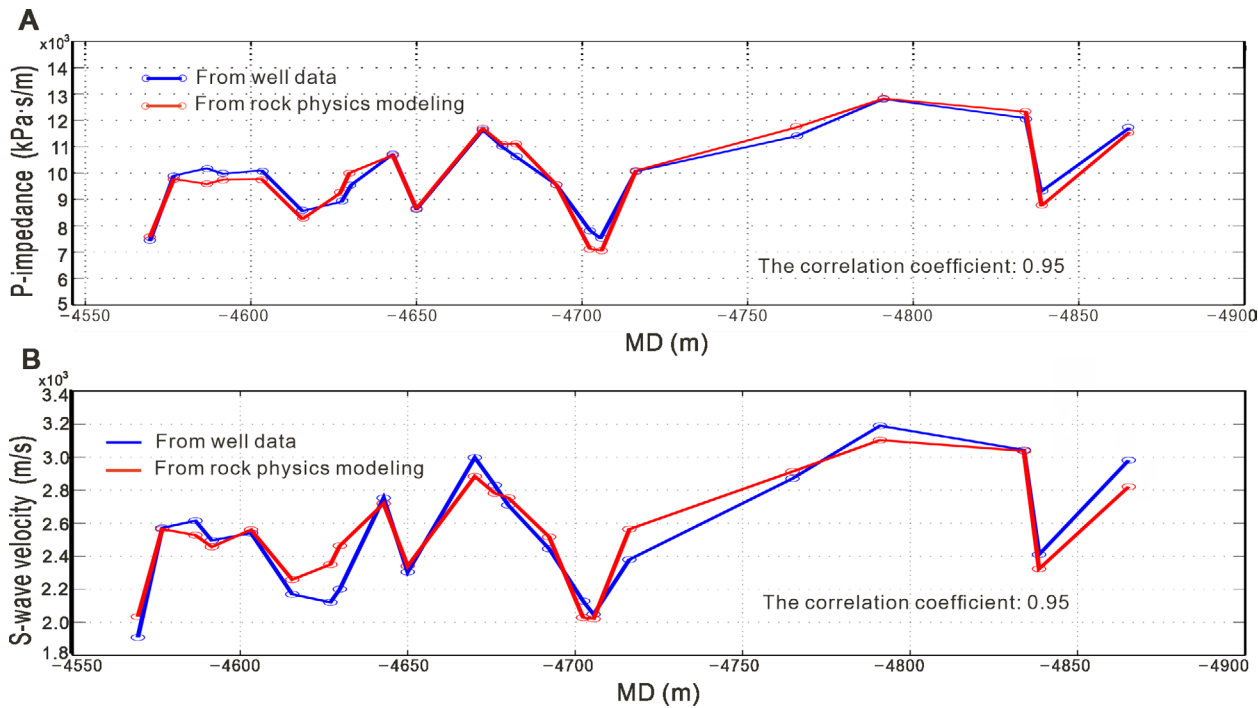


Figure 8. Verification of the rock physics model for halite-cemented sandstone. (A) Comparison of modeled P-wave impedance with well log data. (B) Comparison of modeled S-wave with well log data.

Table 2. Model elastic parameters used in Figure 9

Parameters	Dry	Dry	Gas	Water	Shale
	<i>In situ</i>	Modeled	Halite = 0	Halite = 0	
V_p (m/s)	4,772	4,825	3,887	3,969	3,368
V_s (m/s)	2,997	3,044	2,548	2,461	1,923
Rho (g/cm ³)	2.44	2.42	2.23	2.39	2.46
Acoustic impedance (kPa·s/m)	11,639	11,640	8,668	9,486	8,295

indicates that halite-cemented sandstones in this area are characterized by strong amplitude reflections. By contrast, Figure 9D and 9E show that water-saturated sandstone without halite cementation exhibits moderate to weak amplitudes, whereas gas-saturated sandstone without halite cementation displays weak amplitude characteristics. The simulation uses a 30-Hz Ricker wavelet at normal incidence.

Using the elastic parameters derived from fluid–solid substitution, the AVO responses and intercept–gradient crossplot for sandstone under varying pore-fill conditions can be calculated, as presented in Figure 10. In the main target zone of the study area, halite-cemented sandstone

displays Class I AVO behavior, whereas water-saturated sandstone without halite cementation exhibits weak Class I AVO characteristics. In contrast, gas-saturated sandstone without halite cementation shows Class IIp AVO behavior. These AVO calculations assume isotropy; anisotropic in actual formations may alter the response.

4.2. Seismic elastic and amplitude response characteristics of sandstones with different degrees of halite cementation

Based on the established rock physics model for halite-cemented sandstone, and with total porosity held constant, the compressional-wave velocity, shear-wave velocity,

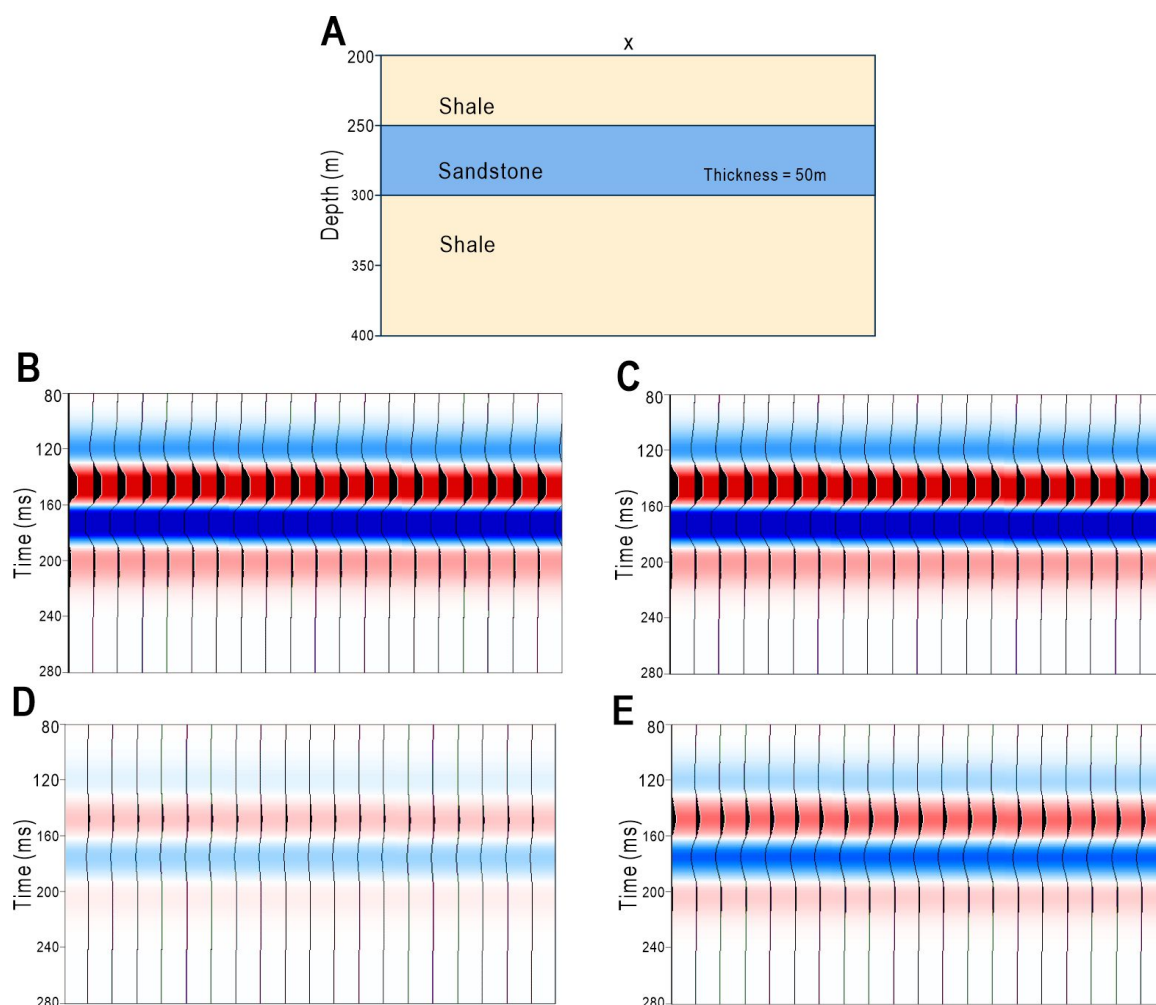


Figure 9. Fluid–solid (halite) substitution and corresponding synthetic seismic amplitude response. (A) The geological model. (B–E) Seismic records of *in situ* halite-cemented sandstone, modeled halite-cemented sandstone, substituted water-saturated sandstone, and substituted gas-saturated sandstone, respectively.

and density of the rock were calculated for varying halite contents. Using these elastic parameters, a sandstone–shale model with progressively increasing halite content was constructed, as shown in Figure 11A. The model assumes a total porosity of 16% and a layer thickness of 50 m, bounded above and below by shale. The halite content increases gradually from 0% to 16% from left to right.

As shown in Figure 11B–11D, with increasing halite content, the compressional-wave velocity, shear-wave velocity, density, and compressional impedance of the sandstone all increase. Furthermore, under a given total porosity, higher halite content leads to stronger reflection amplitudes, as illustrated in Figure 11E and 11F.

Figure 12 presents the AVO response characteristics of

sandstone with varying halite content. As halite content increases, the AVO response of the sandstone gradually shifts from Class IIp to Class I, and the distinction between gas-saturated and water-saturated sandstone AVO responses diminishes. The velocity and density parameters for each halite content shown in the figure were derived from the halite-cemented sandstone rock physics model, and the corresponding reflection-coefficient curves as a function of incidence angle were computed using the Shuey equation.²⁸

4.3. Template for the relationship between halite content, total porosity, and compressional impedance

As illustrated in Figure 13, using the rock physics model

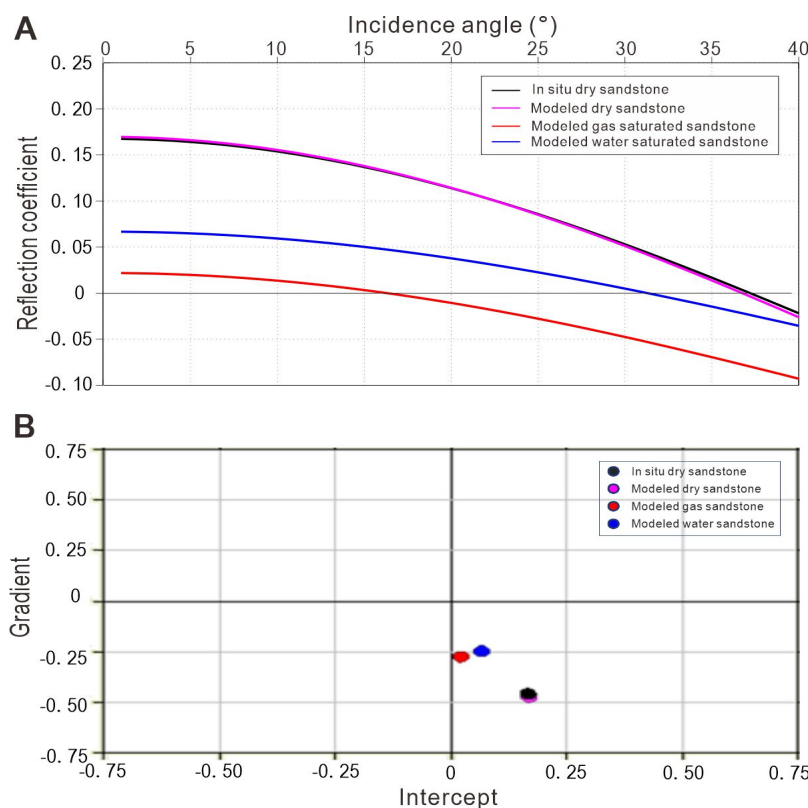


Figure 10. Impacts of halite cementation on amplitude-versus-offset types. (A) The amplitude versus offset response based on the fluid/solid (halite) substitution in the study area. (B) Corresponding intercept–gradient crossplot.

for halite-cemented sandstone, elastic parameters were simulated for various halite contents and total porosities, thereby establishing a template that relates total porosity to compressional impedance as a function of halite content. This template clearly quantifies the interplay among the three variables: for a fixed total porosity, compressional impedance rises with increasing halite content; for a given halite content, it declines as total porosity increases. Based on this template, once the halite content is known, the total porosity prior to halite cementation can be derived from compressional impedance inversion, which in turn enables the calculation of effective porosity.

5. Discussion

This study proposes a rock physics modeling approach for halite-cemented sandstones and applies it to perform fluid–solid substitution. Within the model, the halite component plays a dual role: it precipitates within and fills the pore space during cementation and subsequently becomes part of the solid rock matrix, contributing to the load-bearing

framework and increasing rock stiffness. Building on this framework, the model enables not only conventional fluid–fluid substitution but also effective fluid–solid substitution, thereby deriving the elastic parameters of sandstones under varying halite contents and total porosities.

Applied to the analysis of seismic response characteristics in the halite-cemented sandstones of the L Gas Field, Gabon, West Africa, the model demonstrates good agreement with the measured well data, supporting its applicability to this dataset. This work addresses a gap in traditional fluid substitution theory, which often inadequately handles pore-filling scenarios involving solids or solid-liquid mixtures. It thus offers a new rock-physics framework for the quantitative interpretation of seismic responses in analogous geological settings.

This study has several limitations and assumptions. The VRH averaging scheme is an approximation that may not fully capture the complexity of pore structures. The model assumes isotropic mineral properties, neglecting

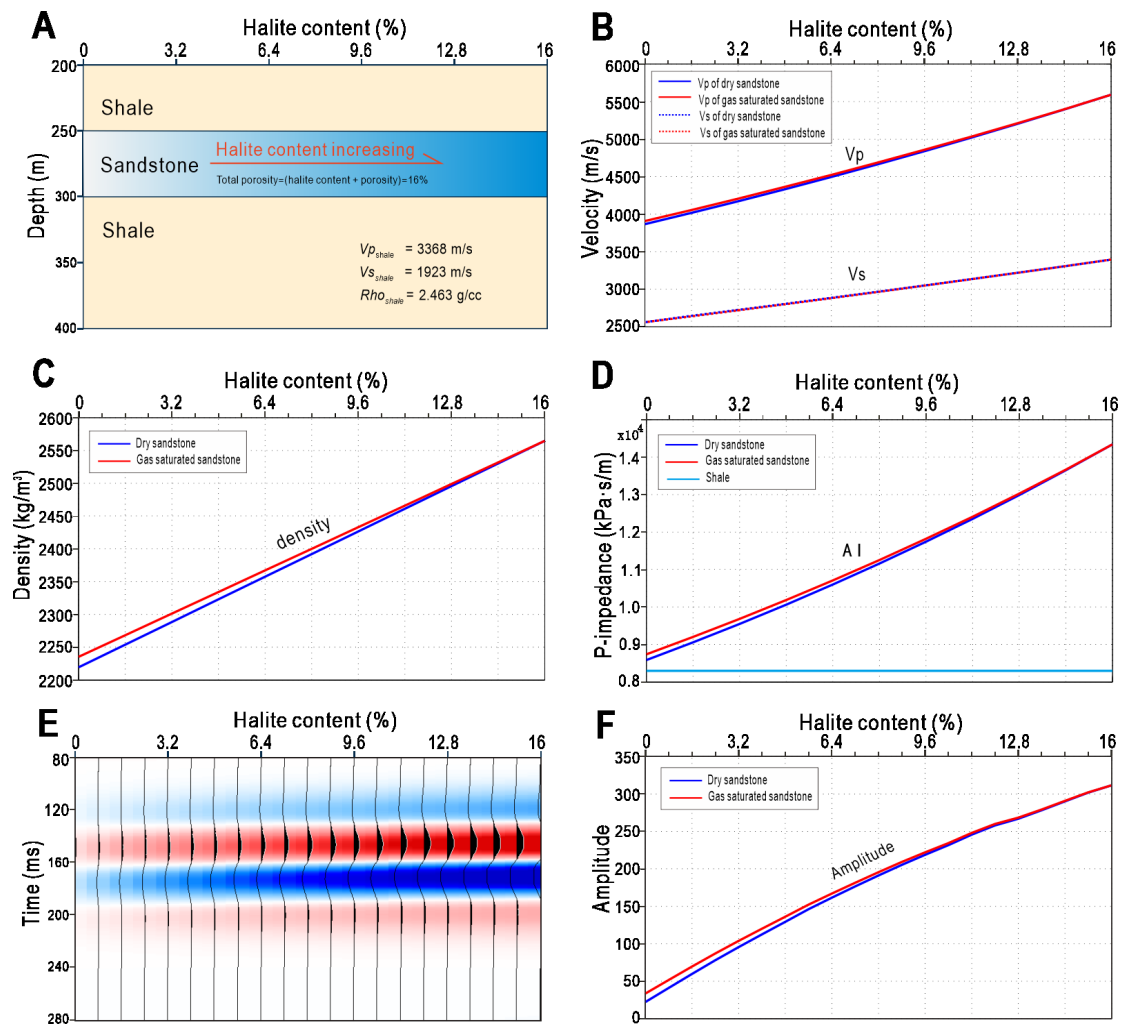


Figure 11. Seismic elastic and amplitude responses of sandstone models with different halite contents. (A) The geologic sandstone/shale model with different halite content of sandstone; (B–D) Velocity, density, and P-wave impedance curves, respectively; (E–F) Seismic records and corresponding maximum amplitude curves, respectively.

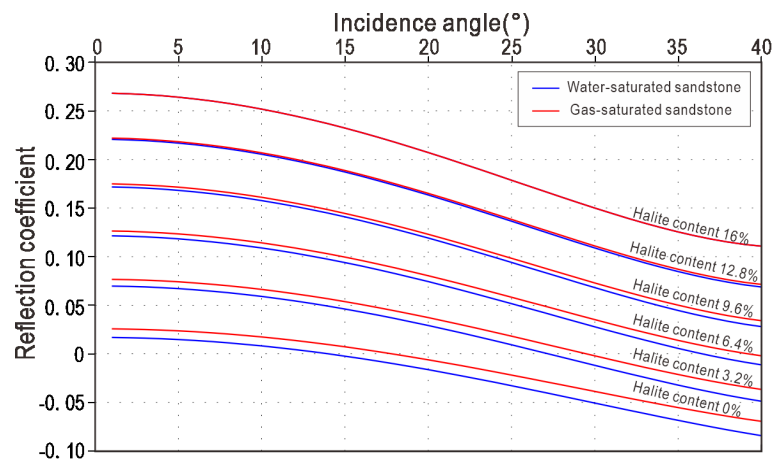


Figure 12. Amplitude versus offset responses of sandstone at different halite contents

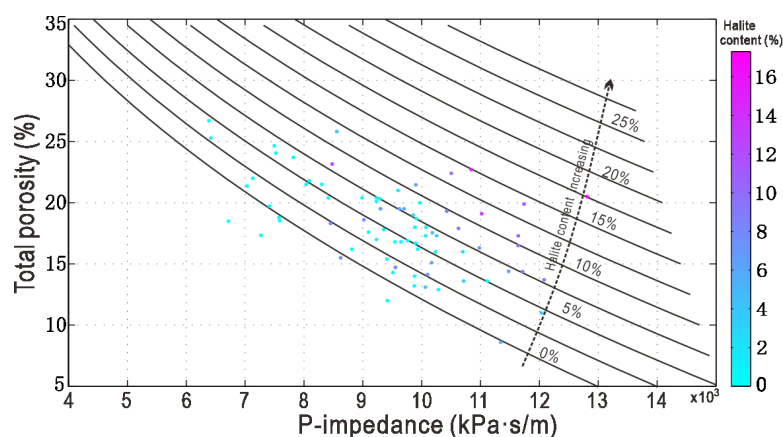


Figure 13. Template relating total porosity to P-wave impedance at different halite contents

potential anisotropy in real formations. In addition, several key assumptions inherent to the proposed workflow warrant explicit discussion. First, the model assumes a relatively uniform distribution of halite cement within the pore space. While this simplification is consistent with the definition of total porosity as the sum of halite volume and effective porosity, thin-section observations reveal that halite can exhibit pore-lining, pore-filling, or pore-bridging morphologies, and the uniform assumption may not hold in highly heterogeneous reservoirs. Second, the substitution process assumes that pore-structure parameters, particularly the pore aspect ratio used in the modified Xu–White model, remain unchanged. This is reasonable when halite cementation does not significantly alter the original pore geometry, but may introduce errors in intervals affected by intense cementation or dissolution. Third, the elastic properties of halite used in this study are taken from standard reference values; however, actual halite may exhibit variations due to impurities, crystal defects, or measurement uncertainties. Although a detailed sensitivity analysis is beyond the scope of this study, these uncertainties should be considered when applying the model to other fields.

The proposed salt cementation modeling workflow was not further compared with other fluid–solid implementation methods in this study. Such a comparison could be undertaken in future research. To further clarify the contribution and boundaries of this work, we briefly contrast our method with existing approaches. Unlike the solid Gassmann equation, which treats halite as a pore-filling material within a Gassmann-type framework, the proposed method incorporates halite as part of the solid matrix, consistent with the microscopic evidence that halite bonds firmly with mineral grains. Compared with the differential effective medium model,

the proposed workflow avoids iterative computation and is therefore more computationally efficient. Compared with the contact cement model, it does not require detailed grain-contact geometry, making it simpler in terms of parameter requirements. The main advantages of the proposed method include: (i) computational efficiency—the sequential integration of VRH, modified Xu–White, Wood’s equation, and Gassmann’s relations provides a fast and straightforward workflow suitable for large-scale reservoir modeling; (ii) minimal parameter requirements—only conventional well-log and core data (mineral composition, porosity, halite content) are needed; and (iii) exploration applicability—the method is specifically designed for halite-cemented subsalt sandstones in West Africa, enabling reliable fluid–solid substitution for seismic response and AVO analysis. Nevertheless, the model’s assumptions (isotropy, uniform cement distribution, constant pore aspect ratio) define its limits of applicability, and caution is advised when extending it to more complex reservoirs.

6. Conclusion

This study developed a rock physics modeling workflow for halite-cemented sandstones and demonstrated its application to fluid–solid substitution in the subsalt L Gas Field, West Africa. The proposed method defines total porosity as the sum of halite volume and effective porosity, treats halite as part of the load-bearing solid matrix, and sequentially integrates the Voigt–Reuss–Hill average, modified Xu–White model, Wood equation, and Gassmann’s relations to construct an equivalent rock physics model. Calibration against well-log and sidewall core data yielded correlation coefficients of 0.95 for both P-wave impedance and S-wave velocity, supporting the reliability of the model.

Using the validated model, fluid–solid substitution was performed to simulate scenarios in which halite is replaced by fluid and fluid is replaced by halite. The results show that halite cementation significantly increases P-wave velocity, S-wave velocity, density, and acoustic impedance. With increasing halite content, the sandstone AVO response shifts from Class IIp toward Class I, and the distinction between gas- and water-saturated responses diminishes. A template relating halite content, total porosity, and P-wave impedance was established, enabling the estimation of pre-cementation total porosity and effective porosity from seismic inversion.

The proposed method addresses the limitation of conventional Gassmann theory in handling solid pore-filling materials and provides a practical, computationally efficient tool for reservoir characterization and seismic interpretation in halite-cemented settings. While the model assumes uniform halite distribution, a constant pore aspect ratio, and isotropic mineral properties, it offers a practical framework for the quantitative evaluation of subsalt tight reservoirs and can be extended to analogous geological environments with appropriate calibration.

Acknowledgments

None.

Funding

None.

Conflict of interest

The authors declare they have no competing interests.

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Availability of data

Data are available from the corresponding author upon reasonable request.

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