RETRACTED ARTICLE: A research on seismic forward modeling of hydrothermal dolomite: An example from Maokou formation in Wolonghe structure, eastern Sichuan Basin, SW China

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ABSTRACT

To solve the problem of multi-resulted in seismic responses brought by dual impacts of the thickness and the lithologic association for further research of seismic response characteristics of hydrothermal dolomite, significant efforts have been made, which were based on the study of dolomite, the Maokou formation in the eastern Sichuan Basin, to conduct an analysis of mineral composition, strata distribution and dolomitization in its area, to develop layered medium models in accordance with different dolomitization degrees and thicknesses, and to build standardized wedge models for the full display of that in binary changes. Moreover, an essential application of the pre-stack and post-stack seismic forward modeling have been performed for analyzing how different dolomitization degrees and thicknesses had influences on the seismic response characteristics of hydrothermal dolomite. Given this, the sensitive seismic attributes of the target interval in the study area has been selected preferentially by analyzing the seismic response characteristics of hydrothermal dolomite, which plays a critical role in the entire process. The results show that: 1. The response characteristic of amplitude is greatly influenced by the dolomitization degree and bed thickness. 2. The dolomitization degree constitutes a transformation of AVO response characteristics from II to IV, while the variation of thickness leads to a transformation of AVO response characteristics from IV to II. 3. The actual results indicate that the relative fluid factor FF is one of the most sensitive AVO attributes, and the predicted results are in par with the actual results.

INTRODUCTION

The hydrocarbon exploration and production have taken a giant leap for the investigation of marine carbonates over the past few years. The role of the dolomite reservoir remains vital in oil and gas exploration as evidenced by hydrothermal dolomite reservoir ranked as one of the most common reservoir types among entire explored study areas in China, besides that, it increasingly becomes one of the hottest topics in the oil industry. The hydrothermal dolomites are widely rooted in sedimentary basin, for example, abundant oil and gas resources (Davies & Smith, 2011; Diehl et al., 2010; Dix et al., 2010; Smith, 2006) have been found in hydrothermal dolomite reservoirs in the United States and Canada, apart from that, in China, (Chen, X.et al., 2012; S. B. Zhu et al., 2016; Feng et al., 2016; Jiang et al., 2018; D. M. Zhang et al., 2013; D. Y. Zhu et al., 2007; Yao & Wang, 2009; S. Zhang et al., 2020) were also pregnant with abundant hydrocarbon resources showing a considerable prospect for exploration and production. According to previous studies, the hydrothermal dolomite reservoir was usually buried deep and constrained by multi-phase tectonic activities, meanwhile, the transverse distribution was controlled by sedimentary facies, leading to apparent heterogeneity, various types of hydrothermal dolomite reservoir, especially, multiplicity results of seismic response characteristics, these factors constituted to less prediction accuracy of hydrothermal dolomite reservoir.

The application of various main controlling factors of the reservoir is performed for seismic forward modeling, which is widely used by researchers to resolve the issue of multi-resulted seismic response characteristics and to define the change law of seismic response characteristics. As the most direct manifestation of a variety of reservoir parameters, the results of seismic forward modeling serve as the theoretical basis for seismic reservoir prediction in all respects.

The lower Permian Maokou formation in Sichuan basin enjoys its inbuilt advantage of being significant oil-bearing formation demonstrating a massive potential for exploitation by the momentous discovery of dolomite reservoir in this basin. However, for a long time, most attention was elicited on the research of the paleokarst and its regards, such as related reservoirs

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during the supergene period (Hu et al., 2015; Sima et al., 2015; Su et al., 2015). But only a few studies on the Maokou formation dolomite, and which are mostly in the western Sichuan region, have been conducted.

Previous studies indicate that the main causes of hydrothermal dolomite formation originated from a transformation that the limestone reshaped by Mg-rich hydrothermal fluid seepage, leading to a considerable difference between thickness and dolomite degree (Gao et al., 2020). The researchers’ focuses were always put on reservoir porosity and thickness characteristics when conducting a traditional investigation of seismic response characteristics of dolomite, the main factors of hydrothermal dolomite are mainly reflected in thickness and dolomitization development degree. However, there are relatively few studies on seismic response characteristics of this feature at present.

Therefore, the hydrothermal dolomite of Maokou formation in Eastern Sichuan basin is regarded as an example to develop the Pre-stack and Post-stack seismic forward modeling and to define seismic responses of hydrothermal dolomite, degrading the multiple results in seismic reservoir prediction and improving the precision of dolomite seismic prediction.

State of the art

With regard to the logging and well logging data, the seismic forward modeling, by keeping records of corresponding seismic model based on the modeling approach, namely, ray tracing and wave equation migration, was widely applied in the seismic hydrocarbon exploration and production. It can provide an empirical guidance for the seismic data processing and interpretation by analyzing different geological structures in those seismic response characteristics. With the aim to improve accuracy of seismic reservoir prediction, many crucial understandings and results have been achieved by using seismic forward modeling technology, especially in the field of the pre-stack seismic forward modeling of carbonate reservoir. (Klarner et al., 2005) adopted the AVO model, building the connections between various diagenetic histories and seismic response characteristics; by analyzing seismic forward modeling. (Malovichko et al., 2010) initially put forward the concept of the quantitative relationship between geometric shape and rock physics parameters after elimination of the varied response characteristics arising from the non-reservoir itself. (Min et al., 2011) drew the conclusion of response characteristics reflecting from the stack migration profile of cave reservoir bodies based on seismic forward modeling of inhomogeneous medium. The investigation of connections between the seismic response characteristics of vuggy reservoir and cave body itself, such as size, form and shape, and fluid factors, have been conducted by (Kumbalek, 2015); To present the main performance of how cave’s size, structures and its fluid exerted impacts on seismic response characteristics, (Xu et al., 2016) managed to obtain the seismic response characteristics of the carbonate reservoir in Tarim Basin according to the application of geophysical modeling; In the same year, (Corredor et al., 2016) proposed a different fault models for the generalization of how fault developments affected seismic response characteristics of the reservoir. Aside from the analysis of seismic response characteristics caused by lithology or thickness variations, some scholars, such as (Neff, 1993), have developed the seismic model by referring to thickness variations to analyze the influence by different thicknesses. In 2015, with regard to seismic models built by different lithologies, (Jing et al., 2015) looked into the variations of seismic attributes from the changes of mineral contents. Despite the geophysical modeling was built on a basis of the lithology and the thickness, these researches have been performed in the absence of the compound variation of lithology and thickness, constituting multiplicity results at the end of the modeling project.

These studies have shown that the analysis of seismic forward modeling of the carbonate reservoir would usually select the most sensitive element from a number of elements including the reservoir’s scale, structure, shape and fluid, thickness and lithology for modeling. This method is feasible and applicable to most geologic bodies except hydrothermal dolomite formation, mainly because of its heterogeneity which was caused by the discrepancy of lithologic association and thickness. Furthermore, if the utilization of single element modeling was conducted solely to analyze hydrothermal dolomite featured with varied changes of lithology and thickness, it would hard to eliminate multiplicity results of various lithologic association and thickness. If we analyze the internal complex formations in accordance with multiple models, it would maximize the accuracy of seismic response characteristics from complicated variations of lithology and thickness. Therefore, in this study, the geophysical model was built by referring to different lithologies and thicknesses of hydrothermal dolomite formation of the Maokou formation, eastern Sichuan, to address multiplicity results of seismic responses characteristics in hydrothermal dolomite.

The rest of this paper is organized as follows. Section 3 presents the investigation and survey on the size of study area, the analysis of geological conditions, the architecture design of model and the introduction of seismic modeling. Section 4 presents the analysis of how geological characteristics of hydrothermal dolomite in study area influence its...
geophysical response characteristics, the results of modeling in comparison with measurement data of study area, and the prediction of hydrothermal dolomite distribution in study area based on the results of seismic response characteristic by applying seismic forward modeling. Section 5 provides the conclusions.

**Methodology**

**Study area**

Situated in the eastern Sichuan Basin, the Wolonghe structure (30°10'- 30°30’N, 106°50'- 106°70’E) is adjacent to the Bandong structure in the west, to the Goujiachang in the east, and besides the Shuanglong River in the south, the Tianchipu in the north (Figure 1). The Permian strata in this research area was subjected to strong tectonic movements characterized by strong fold and high fracture development, meanwhile, it features with large-extended fault displacement and high-angle thrust fault cutting the whole strata. The complex box structure was formed after the entire study area was cut by the “Nanchong-Peiling” basement fault from northwest to southeast in lateral direction and by numerous developed fractures from northeast in longitudinal direction (Wang, 2015).

The lithology of the first section of Maokou formation in eastern Sichuan basin was mainly dominated by gray-black/argillaceous bioclastic limestone, bioclastic silicolites, black shale and augen limestone reflecting relatively deeper water body and higher percentage of shale. The open platform facies with rich-argillaceous characteristic developed in most parts of that area while certain parts have depression (Wang et al., 2018); The second section of Maokou formation has dark gray to taupe thickness micrite, interbedded by strip mudstone which suggests that continuing transgressive cycles helped to develop vast area of open platform facies entering to the high tide of transgression; light grey Grayish white block sparly bioclastic limestone were developed in the upper second and third section of Maokou formation, shallow facies was formed with shallowing water body (Chen, 2007). The forth section of Maokou formation was nearly eroded and enlarged by uplift of the Soochow movement.

**Data source**

Due to the fact that comprehensive analysis of geological characteristics is a prerequisite for reasonable seismic forward modeling, the geologic information is based on core and log data of Maokou formation of Wolonghe structure in eastern part of Sichuan basin.

**Mineral composition**

In W83 well, Mao 2a submember of middle Permian Maokou formation of Wolonghe structure in eastern Sichuan basin (3339–3393 m) has been developed by strong dolomitization with regard to analysis of core data, indicating that aplite and dolomite siliceous dolomite bioclastic dolomite, breccia dolomite. Microscopic thin sections show that intercrystalline pore and intercrystalline solution hole are developed (Figure 2(a, b)). The pore was partially filled, and the crystal shape was shaped irregularly, mostly subhedral. Obvious residual grain can be seen in Figure 2(c). A large number of saddle dolomite was developed with and orthogonal polarization, wavy extinction (Figure 2(d, e)); In addition, euhedral crystal quartz formed by low-temperature hydrothermal environment can be seen in the core (Figure 2(f)) can be found regularly, certain parts developed Pore and cave that interbedded by coarse crystal, lattice plane bend, saddle dolomites. In the middle Permian Maokou formation of Wolonghe structure, these distinctive symbols give a full display of dolomite

![Figure 1. Structure diagram of eastern Sichuan Basin.](image-url)
in that area featuring with noticeable characteristics hydrothermal dolomite has (Davies & Smith, 2011).

(a) Wo 83 well, mesocrystalline dolomite, intercrystalline pore, intercrystalline solution hole, P1m2a, 3314 m, orthogonal polarization (+); (b) Wo 83 well, P1m2a, 3317 m, plainlight (-); (c) Wo 83 well, mesocrystalline dolomite, clastizoic, silicious, P1m2a, 3324.5 m, plainlight (-); (d) Wo 83 well, mesocrystalline dolomite and coarse-grained dolomite, P1m2a, 3318 m, orthogonal polarization (+); (e) Wo 83 well, mesocrystalline dolomite, solution cave, P1m2a, 3318.5 m, orthogonal polarization (+); (f) Wo 83 well, Columnar self-crystalline quartz, P1m2a, 3328.

**Stratigraphic distribution**

By constrained by basement faults activities, hydrothermal dolomites were mainly distributed as the form of “lenticular distribution” along deep fault and associated fracture system (Davies & Smith, 2011). The comparison of well tie in the eastern Sichuan region along the direction of “Nanchong Fuling” basement fault (Figure 3(a)) indicates that the dolomites of the Maokou formation in the eastern Sichuan region have a wide plane distribution with high frequency, which were characterized by good continuity, relatively large single layer thickness, ranging from 5 m to 30 m, and high concentration in the upper middle part of the
Maokou formation. The comparison of well tie perpendicular to the direction of the "Nanchong Fuling" basement fault shows that the dolomite was distributed along the "Nanchong-Fuling" basement faults developed as the form of "lenticular" distribution as a whole. Moreover, dolomite was fully developed with stable and thicker distribution in the two bases of the basement fault. The more distance from the basement faults, the more reduction of the thickness the dolomite gradually has. (Figure 3(b-d)).

**Dolomitization degree**
The dolomitization degree of the Maokou formation in the study area was constrained by the hydrothermal influence range with regard to the diagenetic background that limestone stratum was transformed by the thermal fluid migration along the basement fault. The results as shown in Figure 4, the dolomitization degree of the target layer decreases with the increase of the vertical distance from the basement fault. It is due to the gradual weakening of the dynamic force of the Mg rich hydrothermal fluid flowing upward along the basement fault towards the far end of the basement fault, which leads to the gradual decrease of dolomitization ability. On the whole, effected by hydrothermal reformation, the distance from dolomitization degree, limestone transformation zone to perpendicular offset of basement faults should be necessary before building a geological model.

**Model design**

**Design ideas**

*Theoretical basis.* Feng Zengzhao in 1993 proposed that according to the relative content of calcite and dolomite in carbonate rock, carbonate rock can be respectively divided into two main types, limestone and dolomite. Afterwards, a series of over-types was developed on a basis of that results, specific classification methods were obtained as Table 1. The carbonate rock types in Table 1 were standardized by dolomite content, 90%, 75%, 50%, 25%, 10%, that is, limestone(Lim), dolomitic limestone(DL), dolo-limestone(DLL), lime-dolostone(LD), calciferous dolomite(CD) and dolomite(Dol).

**Technical ideas.** With reference to that generalized analysis, the main external manifestation of hydrothermal dolomite is characterized by the variation between dolomite degree and stratum thickness. Thus, taking the binary change of dolomite degree and thickness is an essential part of the research. By establishing the “Dolomite degree-thickness binary geology model”, the pre-stack gathers model and post-stack seismic profile are applied to analyze the seismic response characteristics of hydrothermal dolomite in accordance with pre-stack and post-stack seismic model. To design a binary seismic model with approximately actual stratigraphic distribution, it not only was developed in actual seismic modeling process which was conducted by the field outcrop samples and the petrophysical parameters of actual logging (P-wave velocity, S-wave velocity, density, etc.), but accorded with the variation of the lithologic association and the model stratum thickness.

**Design scheme**
The actual multi-well drilling data of the Maokou formation in the study area has provided the parameters of P-wave, S-wave velocity and density etc. for reliable statistics (Table 2), the sufficient and adequate considerations of different petrographic combinations and thickness distributions are required to develop the layered medium model of "overlay-target interval-sublayer" for dolomite(D), lime-dolostone(LD), calciferous dolomite(CD), dolomitic limestone(DLL), dolomitic limestone(DL) and limestone(L), and which are set to

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**Table 1.** Rock types about series of calcite and dolomite.

| Rock Type               | Calcite, % | Dolomite, % | CaO; MgO |
|-------------------------|------------|-------------|----------|
| Limestone (Lim)         | 100 ~ 90   | 0 ~ 10      | >50.1    |
| Dolomitic limestone (DL)| 9 ~ 76     | 10 ~ 25     | 50.1 ~ 9.1 |
| Dolo-limestone (DLL)    | 75 ~ 50    | 25 ~ 50     | 9.1 ~ 4.0 |
| Lime-dolostone (LD)     | 50 ~ 25    | 50 ~ 75     | 4.0 ~ 2.2 |
| Calciferous dolomite (CD)| 25 ~ 10   | 75 ~ 90     | 2.2 ~ 1.5 |
| Dolomite (Dol)          | 10 ~ 0     | 90 ~ 100    | 1.5 ~ 1.4 |

**Figure 4.** Cross-plots of vertical distance between the basement faults and dolomitization degree and the limestone transforming region.
the thickness of 40 m, 34 m, 28 m, 22 m, 16 m, 10 m respectively (Figure 5), while the lithology of overlay and substrata is limestone with both 20 m thickness. Considering the influence of fault on dolomitization degree and dolomite thickness, the abscissa 0 m starting point is taken as the fault location in the model design (dolomite thickness and dolomitization degree are the largest), and with the increase of the distance from the fault, the dolomitization degree and dolomite thickness gradually decrease. The parameter values of the carbonate model was built in turn as shown in Table 2.

(A) In the figure, different lithologies are reflected by different color blocks; (B) Gray represents carbonate strata with dolomitic content change, dark gray indicates overlying strata and underlying strata, red circle suggests seismic reflection point, black dotted line reflects seismic wave channel, and angle of incidence.

### Calculation of the forward models

The intuitive manifestation of seismic wave in changing geologic settings can be made by the usage of post-stack section model and pre-stack gathers model for overall reflection pattern of geologic body and reflection characteristics of different incidence angles. The respective application of ray tracing forward modeling and AVO forward modeling can bring about corresponding post-stack geologic section model and pre-stack angle gathers model, meanwhile, the modeling results can be mutually verified due to different calculation principles.

#### Ray-tracing theory

The WFRT, as modern ray tracing algorithm, is widely known for twice media cutting based on Huygens principle and media heterogeneity (Huang et al., 1992). For the first time, the medium is divided into uniform rectangular grids of equal size, then into smaller ones for the second time, according to the requirements of calculation accuracy. The ray tracing calculation was adequately performed by full consideration of WFRT method for possible combinations of velocity interfaces in the calculation block, besides that, possessing them according to Snell’s law greatly improves the calculation speed.

#### AVO forward modeling

The CMP gather and AVO forward model were formed by the application of AVO forward modeling to calculate the reflection coefficient of geological model through Aki-Richards equation.

(Aki, 1980) suggested that the values were far less than 1. This assumption made Aki-Richards approximation discard high order terms and separate P-wave velocity, S-wave velocity and density terms. The reflection coefficient of P-wave velocity and S-wave velocity can be drawn:

$$ R_{pp}(\theta) \approx f \frac{\Delta \alpha}{\alpha} + g \frac{\Delta \beta}{\beta} + h \frac{\Delta \rho}{\rho} $$  (1)

### Table 2. Parameter values of six carbonate models.

| Type                  | Lithological Association | Vp m/s | Vs m/s  | \( \rho \) g/cm\(^3\) |
|-----------------------|--------------------------|--------|---------|------------------------|
| Limestone             | Limestone                | 6095.24| 3572.86 | 2.828                  |
| Limestone             | Limestone                | 6095.24| 3572.86 | 2.828                  |
| Limestone             | Limestone                | 6095.24| 3572.86 | 2.828                  |
| Dolomitic limestone   | Limestone                | 6095.24| 3572.86 | 2.828                  |
| Dolomitic limestone   | Dolomitic limestone      | 6022.26| 3554.05 | 2.817                  |
| Lime-dolostone        | Lime-dolostone           | 5928.78| 3321.03 | 2.731                  |
| Calciferous dolomite  | Lime-dolostone           | 6095.24| 3572.86 | 2.828                  |
| Calciferous dolomite  | Calciferous dolomite     | 5855.78| 3288.48 | 2.725                  |
| Dolomite              | Lime-dolostone           | 6095.24| 3572.86 | 2.828                  |
| Dolomite              | Dolomite                 | 5801.34| 3247.57 | 2.699                  |
| Lime-dolostone        | Dolomite                 | 6095.24| 3572.86 | 2.828                  |
| Lime-dolostone        | Lime-dolostone           | 5928.78| 3321.03 | 2.731                  |

Figure 5. Petrophysical model.
The Aki-Richards equation was reorganized in sequence by referring to the angles of incidence and the distance from offset vector, apart from that, Wiggens separated the equation into three reflection terms, each of which was smaller than the previous one. By applying the formula \( \sec^2 \theta = 1 + \tan^2 \theta \), a more intuitive form was generalized as follows:

\[
R_{pp}(\theta) \approx \frac{1}{2} \left( \frac{\Delta \alpha}{\alpha} + \frac{\Delta \rho}{\rho} \right) + \left( \frac{1}{2} \frac{\Delta \alpha}{\alpha} - 4 \frac{\beta^2}{\alpha^2} \frac{\Delta \beta}{\beta} - 2 \frac{\beta^2}{\rho^2} \frac{\Delta \rho}{\rho} \right) \sin^2 \theta + \frac{1}{2} \frac{\Delta \alpha}{\alpha} (\tan^2 \theta - \sin^2 \theta) \quad (2)
\]

**Resist analysis and discussion**

**Amplitude response characteristics and verification**

**Amplitude response of wedge model**

The Figure 6(a) indicates a simple geological section of “Dolomite degree-thickness binary geology model”. The post-stack forward model section (Figure 6(b)) obtained by ray tracing forward modeling shows that the amplitude intensity decreases gradually as dolomitization content increases. The analysis of amplitude trend was conducted by extracting the amplitude values (Figure 6(c)) from the top interface of stratum, which suggests that the amplitude intensity increases negatively as the stratum thickness decreases in a single lithology, given that the dolomite content decreases, the amplitude values increase. Constrained by the “lithology-thickness binary change” of wedge body, a stepped upward trend showing as the main feature in the amplitude curve is caused by the lithology change which has greater impacts on amplitude intensity than thickness change has. The amplitude characteristics are summarized in Table 3.

**Comparison of measured seismic profiles**

With roughly equal thickness of the dolomite stratigraphic profiles, the seismic event intensity does not change significantly as it is gradually away from the basement faults, the amplitude values of the top interface are consistent with the prediction results of seismic forward modeling and remains almost unchanged as a whole showing on the nearly 25 m thickness of the dolomite strip (Figure 7(a)). The amplitude of the two wings of the profile make changes in line with the middle-to-two wings decrease of dolomite stratum's thickness from 25 m to 0 m, while the overall amplitude of dolomite stratum changes as opposed to that of the two wings of the profile. Therefore, the corresponding connections between the amplitude variation characteristics and that of the forward model (Figure 7(b)) indicates that there is a negative correlation between the thickness variation of dolomite formation and the amplitude variation.

(A) Hydrothermal dolomite seismic profile were measured by SEE-trending; (B) NNE-trending indicates hydrothermal dolomite seismic profile, the yellow line in the seismic profile is the well path, the green line represents the top interface of Mao 2A subsection, the red line in the legend suggests the location of the seismic profile, the lower dark blue curve represents the top interface amplitude of the hydrothermal dolomite formation, and the red curve represents the trend line of the top interface amplitude of the hydrothermal dolomite formation.

**AVO response characteristics and verification**

**AVO Characteristics and comparison**

**Dolomite.** The lithology characteristics of “dolomitic limestone” and “limestone” is basically consistent with the overlying and underlying strata, it is unable to effectively characterize the variation law of seismic response characteristics. Therefore, the target layers are mainly dolomite(D), lime-dolostone(LD), calciferous dolomite(CD) and dolomitic limestone(DL).

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*Figure 6. Geological model profile of binary change between thickness and dolomitization degree.*
The angle gathers model and amplitude curve of dolomite (D) as shown in Figure 8(a). When the thickness of dolomite stratum decreases (40 M-10 m), the seismic event gradually moves upward; The top amplitude of the stratum decreases first (+30 m) then increases with the thickness decreasing. But when they are at the same thickness, the top amplitude of the stratum increases gradually with the increase of incident angle. Apart from that, the measured formation angular gathers (W93, 25 m, Dol) have the same characteristics of seismic event and amplitude variations as the model shows.

Calciferous dolomite. Figure 8(b) indicates the presence of the angle gathers model and amplitude curve of lime-dolostone (LD). When the thickness of dolomite stratum decreases (40 M-10 m), the seismic event gradually moves upward; the amplitude at the top of stratum decreases first (+30 m) and then increases with the thickness decreasing and the incident angle increasing. The variation characteristics of amplitude and event measured by the actual angle gathers (W67, 25 m, CD) is consistent with what the model shows.

Lime-dolostone. Figure 8(c) is the presence of the angle gathers model and amplitude curve of calciferous dolomite (CD). When the thickness of dolomite stratum decreases (40 M-10 m), the seismic event moves upward gradually; the amplitude at the top of stratum increases first (+30 m) and then decreases with the thickness decreasing and the incident angle increasing. The variation characteristics of amplitude and event measured by the actual angle gathers (W67, 25 m, CD) is consistent with what the model shows.

| Lithology                  | Amplitude          | AVO Type | Other Observations                                                                 |
|----------------------------|--------------------|----------|------------------------------------------------------------------------------------|
| Dolomite (Dol)             | Lowest             | IV       | With the increase of dolomit content, the seismic event moves upward gradually.     |
| Calciferous dolomite (CD)  | Higher amplitude   | IV       | With the increase of dolomite content, the reflective interface moves from trough to half trough gradually |
| Lime-dolostone (LD)        | Higher amplitude   | IV       |                                                                                   |
| Dolo-limestone (DLL)       | Higher amplitude   | IV       |                                                                                   |

The Table above shows the seismic response characteristics of carbonate rocks.

Figure 7. Analysis of measured seismic profiles.

Figure 8. Forward modeling analysis.
increasing. The variation characteristics of amplitude and event measured by the actual angle gathers (W59, 5 m, LD) is consistent with what the model shows.

**Dolo-limestone.** Figure 8(d) shows the presence of the angle gathers model and amplitude curve of dolomitic limestone (DL). When the thickness of dolomite stratum decreases (40 M-10 m), the seismic event gradually moves upward; the amplitude at the top of stratum decreases first (+30 m) and then increases with the thickness decreasing and the incident angle increasing. The variation characteristics of amplitude and event measured by the actual angle gathers (W74, 5 m, DLL) is consistent with what the model shows.

The angle gather model of carbonate rocks represents its "thickness to lithology". The color squares in the picture represent different lithologies (grey means limestone, purple represents dolomite, blue indicates limestone dolomite, and green suggests dolomitic limestone). The grey transparent mask is dolomite stratum; the red trend line indicates the change of amplitude; the single model indicates the increasing direction of incidence angle from left to right; the left side of the red dashed line box is the corner gather model, and the right side is the actual seismic angle gather with the same geological conditions.

**The characteristics and comparation of P-G cross**

The analysis of cross plot has been conducted for the intercept P and slope G attributes of angle gathers. The results (Figure 9(a)) show that intercept P value decreases while slope G value increases as dolomite thickness becomes larger, when it gradually over 30 m, intercept P value slumps but slope G value moves upward. The P-G cross points move clockwise in the second quadrant; AVO response characteristics were transformed from category II to category IV; with dolomite content scaling up, intercept P value decreases gradually while slope G value gradually mounts up. In the second quadrant, the migration of P-G intersection runs counterclockwise, and the AVO response characteristics were changed from class II to class IV. AVO features are organized in Table 3.

The analysis of P-G cross plot based on measured wells' data suggests that the intercept P value increases first and then decreases as the thickness and content of dolomite picking up, but the slope G value are on the contrary to the intercept P value. The P-G sample points show a clockwise rotation change which is consistent with the change rule of forward model in the previous results. Therefore, the P-G cross-points of carbonate rocks, to a certain degree, are sensitive to the change of formation thickness and dolomite content. The reliability of the pre-stack gather model designed in the previous results is confirmed by the change rule of P-G intersection sample points on a basis of measured wells’ data; meanwhile, the summarized AVO change rule is feasible and applicable as well.

**Analysis of practical application effect**

**AVO sensitive attribute selection**

The selection of AVO sensitive attributes is conducted by two principles: to begin with, the response characteristics of forward modeling serves as the guidance for selecting the AVO attributes that have the same exception response when the thickness changes, and then to determine the optimal attributes with regard to the value of the sensitivity coefficient R attribute (Table 4).

The calculation formula of R value of AVO attribute sensitivity coefficient is as follows:

\[ R = \frac{X_2 - X_1}{X_2 + X_1} \]  

Where X1 and X2 represent AVO attribute parameters of dolomite and surrounding rock limestone respectively, and R value represents AVO attribute sensitivity coefficient.

The results of AVO forward modeling indicate the presence of conclusions, when the thickness is less than 10 m, the exception response of PR and DRHO is transformed from negative anomaly to positive anomaly (Figure 10(a, b)), while the S-wave velocity difference (DVs) is from positive anomaly to negative
anomaly (Figure 10(c)). The negative anomalous monotonic changes remain as the reflection of The intensity conversion attributes (PROD_SIGN), P-wave velocity difference (DVp) and fluid factor (FF) when thickness decreases (Figure 10(e,f,g)). The relatively low sensitivity of PROD_SIGN and DVp reflected by the value of attribute sensitivity coefficient R attribute can’t effectively distinguish the thickness change of dolomite.

The reversal of AVO sensitive attribute value was caused by the decrease of intercept P and slope G that it can not identify dolomite formation when the thickness is more than 30 m. Therefore, FF attributes are more conducive to our identification of dolomite strata below 30 m. Model AVO Sensitive Attribute Table

**AVO inversion prediction**

AVO inversion was conducted and FF attribute of fluid factors is calculated by referring to forward model analysis results. According to fluid factor attributes plane (Figure 11(a)), the south-east part of the study area contains a large area of positive anomaly values (yellow area) which gradually decrease along the south-east direction and reach the lowest in the east direction (blue-dark blue area), apart from that, the predicted results of geological well-to-well distribution are consistent with the distribution area of negative anomaly values. Prediction of dolomite thickness (Figure 11(b)) shows that the dolomite thickness of the target layer increases by degrees along the NE-trending subsidiary fracture to the SE-trending, reaching the highest and being stable to the east of well W83. Meanwhile, dolomite strip becomes thinner along the flanks of the basement faults.

**Conclusions**

To make a solution of seismic responses in multi-results for more accuracy of seismic reservoir prediction, The Maokou formation of Wolonghe area in the eastern Sichuan Basin is selected as an example for further research of seismic response characteristics of hydrothermal dolomite. A binary geological model designed for hydrothermal dolomite was proposed by adopting pre-stack and post-stack seismic forward
modeling technology that it helped to specify the seismic response law of hydrothermal dolomite of Maokou Formation and to realize the prediction of the distribution of hydrothermal dolomite reservoirs in the study area. The results were obtained as follows:

(1) The forward modeling results of the “Dolomite degree-thickness binary geology model” indicate that the amplitude values of the dolomite’s top interface minimize as dolomitization degree decreases while incidence angles increase, but it is on an upswing when dolomite thickness is in a deduction. The intercept value gradually decreases until the thickness is over 30 m while the slope value is on the contrary; meanwhile, the AVO response type changes from IV to II. Moreover, the AVO response type varies from category II to category IV as the dolomite content increases that the intercept value decrease by degrees and the slope value gradually increases.

(2) Fluid factor FF can effectively indicate hydrothermal dolomite with high accuracy. The dolomite thickness of Maokou Formation in Wolonghe area increases by degrees along the NE-trending subsidiary fracture to the SE-trending, reaching the highest and being stable to the east of well W83. Meanwhile, dolomite strip becomes thinner along the flanks of the basement faults.

This study has proposed a “Dolomite degree-thickness binary geology model”, and the forward modeling results are also verified in AVO attribute inversion. In addition, the results of this research can give a strong boost to the application of seismic reservoir prediction technology to predict lateral distribution of hydrothermal dolomite. The absence of gas-bearing capability of hydrothermal dolomite formation makes impossible for an accurate explanation of the implications that different gas saturations have for seismic response characteristics of hydrothermal dolomite. On this basis, the future research should focus on the analysis of gas-bearing capability for much more objective, accurate identification and evaluation of the gas-bearing hydrothermal dolomite. Moreover, the results of this research can provide valuable and practical guidance for analyzing the seismic response characteristics of the hydrothermal dolomite formation with different gas saturation.

Disclosure statement

The authors declare that they have no conflict of interest.

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Data and/or code availability

The data are included in this published article, and its supplementary information could be obtained from the author on reasonable request.

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