

Original Paper

Thermodynamic indicator of water sensitivity in deep geo-energy reservoirs

Shu-Heng Du^{a,b,*}, Zhuo-Shen Zong^{a,b}^a State Key Laboratory of Nonlinear Mechanics, Institute of Mechanics, Chinese Academy of Sciences, Beijing, 100190, China^b School of Engineering Science, University of Chinese Academy of Sciences, Beijing, 100049, China

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ABSTRACT

This study proposes a thermodynamic characterization method for reservoir water sensitivity based on macro-lens infrared thermal imaging, aiming to address the lack of an efficient and fully quantitative technique for evaluating the microscopic heterogeneity of the mixed layer ratio of illite/smectite (I/S). The I/S mixed layer is the dominant contributor to reservoir water sensitivity in extensively developed deep tight reservoirs in China and a core geological factor leading to generally low productivity of such reservoirs. A quantitative relationship between the I/S mixed layer ratio and apparent temperature is established in this study, which confirms that a lower apparent temperature corresponds to a higher content of smectite layers and stronger lattice expansion potential. Using this method, we reveal for the first time the ubiquitous thermal gradient characteristic of “hot edges and cold center” in I/S aggregates, and verify from a thermodynamic perspective that illitization is a centripetal metasomatic process controlled by fluid-mineral interfacial diffusion. On this basis, a three-level thermodynamic evaluation criterion for the water sensitivity potential of the I/S mixed layer is proposed, which enables rapid identification and quantitative classification of microscopic reservoir damage risks. The findings break through the technical bottleneck that traditional methods cannot efficiently and quantitatively characterize the planar heterogeneity of the I/S mixed layer ratio, and provide a fast, non-destructive and high-precision new method for reservoir water sensitivity evaluation. It will also provide a brand-new theoretical basis for sweet spot optimization and reservoir protection in tight oil and gas reservoirs.

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1. Introduction

With the continuous advancement of global oil and gas exploration and development, geo-energy represented by deep tight oil and gas has gradually become an irreplaceable component of global fossil energy (Liu, 2023; Tao, 2025; Li et al., 2026; Zhang et al., 2026). The Mahu area in Xinjiang, the largest tight conglomerate oil province discovered worldwide to date, has become an important replacement area for increasing reserves and production of unconventional oil and gas in China, with great strategic significance (Li et al., 2025). However, tight reservoirs represented by the Upper Wuerhe Formation in the Mahu Sag of the Junggar Basin have typical characteristics such as complex rock

and mineral features, diversified reservoir space, and strong heterogeneity (Sun et al., 2022; Zhu et al., 2023). Engineering practice shows that the productivity of such reservoirs drops significantly during water injection development. Previous studies have confirmed that water sensitivity caused by clay minerals represented by the I/S mixed layer is the key mechanism leading to large-scale damage to reservoir permeability and porosity, thereby inhibiting the enhancement of oil recovery (Wilson et al., 2014). Such issues have also attracted numerous scholars to conduct extensive theoretical and field studies in the development of other lithological reservoirs such as shale (Liu et al., 2025; Xie et al., 2026).

Aiming at the problem that reservoir water sensitivity greatly inhibits oil recovery, existing studies have confirmed the key controlling role of the I/S mixed layer from multiple perspectives. Anderson et al. (2010) reviewed clay swelling problems and pointed out that I/S mixed layer clay is the main mineral causing water sensitivity damage in oil reservoirs, and its swelling leads to wellbore instability and productivity decline. In terms of

* Corresponding author.

E-mail address: dushuheng@imech.ac.cn (S.-H. Du).

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quantitative characterization, [Carcione et al. \(2019\)](#) investigated the effect of clay on permeability through acoustic logging, and found that permeability decreases by 2.3 mD for every 1% increase in I/S mixed layer content. [Zhang et al. \(2019\)](#) and [Yu et al. \(2022\)](#) confirmed in studies on unconsolidated sandstone and the Bohai Oilfield, respectively, that high content of I/S mixed layer can lead to a water sensitivity damage rate of more than 60% and severe velocity sensitivity. Based on this, [Yu et al. \(2022\)](#) proposed a seepage damage model of “long-distance migration and near-wellbore blockage” of particles. [Tao et al. \(2019\)](#) also found in the study of coalbed methane reservoirs that water sensitivity swelling of the I/S mixed layer leads to a permeability reduction of 47.67%–76.82%.

In addition, scholars have explored the influence of the external environment on water sensitivity. For example, [Xiong et al. \(2020\)](#) and [Mohammed et al. \(2022\)](#) investigated the microscopic mechanism of low salinity and surface chemistry on the decline of permeability and oil recovery through molecular simulation and laboratory experiments, respectively. They pointed out that low salinity promotes surface charge neutralization, and surface charge modification of the I/S mixed layer affects its wettability. However, their studies lack sufficient consideration of the complexity of pore structure and the influence of temperature. [Li et al. \(2017, 2022a\)](#) further focused on the role of fluid media and stabilizers, and confirmed that the presence of oil phase or stabilizers with optimized formula can effectively inhibit mineral swelling, reduce water sensitivity damage rate, and improve pore connectivity. [Du et al. \(2024\)](#) combined FE-SEM, TIMA and other technologies to further clarify that clay mineral particles with high water sensitivity of 8.88–10.73 μm on the gravel surface are the main mineralogical barrier hindering the efficient development of tight sandy conglomerates. [Pang et al. \(2025\)](#) conducted a long-term study on the evolution of low-salinity water flooding in reservoirs, and pointed out that the permeability reduction of such reservoirs is not only related to physical processes such as hydration swelling and fine particle migration of clay minerals, but also affected by chemical processes such as ion exchange and mineral precipitation.

Although previous studies have fully recognized the core role of the I/S mixed layer in inhibiting reservoir productivity, there are still obvious deficiencies in the current microscopic geological mechanism research on the phenomenon of significant differences in production effects caused by the heterogeneous characteristics of the I/S mixed layer in different reservoirs.

First, traditional characterization techniques can hardly balance accuracy, field of view, and dynamic characteristics. [Li et al. \(2023\)](#) used AMICS technology to confirm that the proportion of I/S mixed layer in the Upper Wuerhe Formation of Mahu area generally exceeds 60%, and pointed out that traditional XRD technology is difficult to accurately quantify the content and heterogeneous distribution of nano-micron scale minerals due to insufficient resolution and poor sampling representativeness. [Tong et al. \(2025\)](#) combined nuclear magnetic resonance (NMR) and CT technology to find that clay-sand mixtures exhibit complex pore water reversal and hysteresis characteristics during wetting-drying cycles, leading to macroscopic asymmetric deformation. However, they also pointed out that existing low-field NMR and CT technologies have limitations in spatiotemporal resolution in microscopic dynamic monitoring, making it difficult to capture transient changes.

Second, most studies only focus on the total content while ignoring the distribution and structure. [Li et al. \(2020\)](#) showed that an extremely low clay content (0.24%–4.57%) in Mahu tight conglomerate can still induce strong water sensitivity, and pointed out that strong heterogeneity was the key constraint on

development, but did not provide detailed characterization at the microscale. Discrete element simulation by [Liu et al. \(2020\)](#) confirmed that non-uniform swelling of clay can significantly change the law of fracture generation and pore evolution, which directly indicates that microscopic heterogeneity is a key variable controlling the degree of reservoir damage. However, there is a lack of quantification of real crystal structure and microscopic flow. [Li et al. \(2022b\)](#) conducted a study on the tight conglomerate of the Baikouquan Formation in the Junggar Basin, and confirmed that the content of I/S mixed layer has a significant negative correlation with movable fluid saturation. However, their interpretation still stays at the level of the absolute content of the I/S mixed layer and its physical plugging effect after water absorption, ignoring the differential control effect of heterogeneous distribution.

More importantly, interdisciplinary physical laws prompt us to focus on the crystal structure itself. Studies in soil physics have indicated that relying solely on total clay content while ignoring differences in crystal structure (e.g., reactive smectite vs. inert kaolinite) can lead to serious deviations in the prediction of hydraulic parameters (e.g., permeability, water retention) ([Lehmann et al., 2021](#)). At the microscopic theoretical level, molecular dynamics simulations have confirmed that the mixed layer ratio (i.e., the proportion of smectite layers in mixed layer minerals) is the decisive parameter controlling the expansion of interlayer spacing and hydration energy ([Rahromostaqim and Sahimi, 2018](#)). However, such theoretical studies based on ideal crystal models are often difficult to directly map to real geological reservoirs with complex components and strong heterogeneity. At present, there is still a lack of effective means to continuously and quantitatively characterize this key microscopic crystallographic parameter at the macroscopic scale of the reservoir, resulting in a disconnection between theoretical mechanisms and engineering applications.

To break through the limitations of traditional methods and capture the dynamic evolution process of water sensitivity damage, some scholars have started new explorations. In terms of monitoring methods, [Jin et al. \(2021\)](#) quantitatively evaluated the water sensitivity of conglomerate reservoirs using logging data, and established a mathematical model of clay content-damage rate with a prediction accuracy of 85%, but the model did not consider the influence of formation heterogeneity. [Zhao and Du \(2024\)](#) introduced solution conductivity monitoring technology to realize real-time characterization of hydration damage of Mahu tight conglomerate. They found that in addition to smectite content, microscopic pore structure parameters (e.g., surface porosity, tortuosity) significantly control the degree of damage, and illite and iron elements have a potential inhibitory effect on hydration damage. In addition, for the microscopic mechanism of hydration damage of tight conglomerate, they used field emission scanning electron microscopy, EDS, X-ray diffraction and other technologies to analyze the relationship between pores, elements, mineral composition and damage, and found that samples with high surface porosity, tortuosity and smectite content are more vulnerable to damage, providing new insights for the efficient development of conglomerate oilfields. The biomineralization study by [Cui et al. \(2022\)](#) further corroborated this phenomenon from the lattice mechanism. They confirmed that the reduction reaction of Fe(III) in the smectite lattice structure is the key driving force for the transformation of smectite to illite, and this transformation can significantly compress the interlayer spacing and inhibit water sensitivity swelling. [Liu et al. \(2026\)](#) introduced nanoindentation technology to realize the microscopic mechanical quantitative characterization of hydration damage of tight sandstone. Different from the previous single perspective focusing only on clay swelling, this study particularly emphasized the synergistic

mechanism of carbonate cement dissolution and clay mineral hydration swelling, and finely characterized the strong heterogeneous evolution characteristics of rock microscopic mechanical properties (e.g., Young's modulus and hardness) caused by this complex water-rock interaction through high-precision lattice indentation tests, providing new experimental evidence for understanding the reservoir damage mechanism under complex mineral components.

More critically, the thermodynamic perspective provides a new idea to solve the above problems. Zhao et al. (2025) further innovatively used infrared thermal imaging technology combined with conductivity monitoring to intuitively visualize the difference in thermal radiation on the surface of reservoir rocks during hydration, and confirmed that smectite-rich regions produce significant temperature response and microscopic fragmentation phenomena, indicating that the change in surface thermodynamic characteristics caused by mineral water absorption and swelling can be used as an effective indicator to identify water sensitivity damage. This inherent correlation between “water sensitivity and thermodynamics” has been strongly confirmed in recent macroscopic experiments and microscopic simulations. At the macroscopic scale, Yesmukhambet and Pourafshary (2025) explicitly introduced temperature as a key variable and confirmed that temperature changes can significantly aggravate the swelling behavior and permeability damage of sandstone containing I/S mixed layer. At the microscopic mechanism level, Yang et al. (2025) further quantified the regulatory effect of temperature on clay-water interface properties using molecular dynamics simulations, and found that increasing temperature can significantly change the ordered structure of interlayer water molecules and the mechanical strength of the interface. These studies jointly provide a solid physical basis for characterizing water sensitivity damage using thermodynamic parameters from a cross-scale perspective.

However, the above thermodynamic-related studies mainly focus on qualitative differentiation, and have not yet deeply quantified the mathematical relationship between the core parameter of mixed layer ratio and thermodynamic indicators at the lattice level. The I/S mixed layer is composed of alternating illite and smectite interlayers. The smectite layer has unique physical properties, including high interlayer water content (the smectite layer can accommodate 2–3 layers of water molecules, while the illite layer contains almost no water) (Ferrage, 2016), high surface roughness (water molecule expansion leads to lattice distortion and increases microscopic roughness), and high hydroxyl density (with a strong absorption peak in the 8–12 μm infrared band). These properties significantly affect the thermal radiation behavior, which is ultimately reflected in the apparent temperature of the rock (Bosire, 2025; Jozanikohan and Abarghoeei, 2022). A higher mixed layer ratio corresponds to stronger water absorption of the I/S mixed layer and higher degree of water sensitivity. Furthermore, spatial variations in I/S mixed-layer ratios across the reservoir inevitably result in heterogeneous water sensitivity, with magnitudes ranging from mild to severe. Compared with uniform distribution, when minerals with high mixed layer ratio show strong heterogeneous distribution in the reservoir, they have a higher contact probability with water, which often leads to more serious water sensitivity damage. Unfortunately, most conventional studies determine the average level of the mixed layer ratio of a sample through X-ray diffraction experiments (Bastida and Pardo-Ibañez, 2024), which cannot characterize its planar heterogeneity. The study by Zhao et al. (2025) also mainly focuses on qualitative differentiation. At present, there is no effective method to efficiently and quantitatively characterize the mixed layer ratio and its spatial heterogeneous distribution

using thermodynamic differences, which urgently needs in-depth research.

In summary, finding an efficient method that can simultaneously quantitatively evaluate the content, morphology and heterogeneous characteristics of the horizontal distribution of the mixed layer ratio of the I/S mixed layer, and draw a large-field and high-precision heterogeneous distribution map of the I/S mixed layer is of great significance for uncovering the key mineralogical mechanism of water sensitivity inhibiting crude oil recovery. Different from traditional XRD technology which can only obtain the average mixed layer ratio of samples, and SEM/NMR/CT technologies which have limitations in resolution, field of view or dynamic monitoring, this study introduces macro-lens infrared thermal imaging technology for the first time to establish a quantitative relationship between the I/S mixed layer ratio and thermal radiation characteristics. It can realize large-field, high-resolution and non-destructive characterization of the planar heterogeneity of water sensitivity, aiming to solve the above key scientific problems and provide a new theoretical basis for the efficient development and protection of tight reservoirs.

2. Thermodynamic response of heterogeneity of illite/smectite mixed layer

The author's team introduced macro-lens infrared thermal imaging technology into the fine characterization of geo-energy reservoirs for the first time, proposed 8 specific potential application scenarios, and pioneered a new research direction of reservoir characterization using thermodynamic indicators (Du et al., 2025; Zhou et al., 2025). It should be noted that some of the samples used in this study are identical to those employed in our previous works (Du et al., 2024; Du and Zong, 2026). However, those studies focused primarily on evaluating rock brittleness and mineral content, a topic completely distinct from the theme of the present work. The two studies address fundamentally different scientific questions. This study will use macro-lens infrared thermal imaging technology, give full play to its advantages of simplicity, high efficiency and high sensitivity, aiming to find the “thermodynamic indicator” reflecting the water sensitivity of the reservoir, provide a brand-new perspective for the evaluation of reservoir water sensitivity, and thus provide an important theoretical basis for development sweet spot identification, reservoir protection, and enhanced oil recovery. The main technical route is shown in Fig. 1.

Combined with backscattered imaging, secondary electron imaging, EDS, TIMA and other technologies, macro-lens infrared

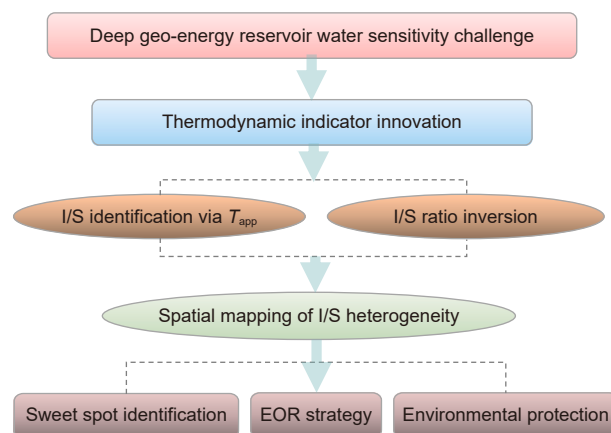


Fig. 1. Research roadmap of the “thermodynamic indicator” for reservoir water sensitivity.

thermal imaging technology is introduced to establish the corresponding relationship between the apparent temperature signal value and key mineral types, so as to realize the accurate identification of the I/S mixed layer.

To verify the effectiveness of thermodynamic characterization, we performed fine spatial registration and comparative analysis between the mineralogical identification results and the infrared thermal image in the same field of view. Fig. 2(a) is the high-precision mineral distribution map obtained based on TIMA technology, in which the purple area clearly indicates the occurrence position of the I/S mixed layer; Fig. 2(b) is the thermal radiation distribution map of the I/S mixed layer extracted based on apparent temperature in the same field of view; Fig. 2(c) is the backscattered electron (BSE) image, showing the framework and pore structure characteristics of the rock.

By comparing Fig. 2(a) and (b), it can be seen that the thermal phase distribution extracted based on a specific temperature threshold has a high consistency with the I/S mixed layer mineral phase identified by TIMA in terms of spatial distribution. This indicates that the I/S mixed layer, the main clay mineral of the tight conglomerate reservoir in the Mahu area, has unique thermal radiation characteristics under thermal equilibrium conditions, which can be efficiently distinguished by macro-lens infrared thermal imaging technology. Combined with BSE image analysis, the I/S mixed layer in this reservoir mainly presents two typical occurrence states: one is as pore-filling material filled between framework minerals such as feldspar and quartz, mostly distributed in intergranular pores and intergranular dissolved pores, with a relatively full morphology; the other is widely attached to the surface of feldspar framework in scattered and banded forms, which is mainly secondary clay formed by the dissolution and weathering of feldspar during diagenesis.

More critically, the detailed comparison of local magnification in Fig. 2(d) reveals microscopic heterogeneous information that is difficult to capture by traditional mineralogical methods. It is observed that even mineral aggregates identified by TIMA as I/S mixed layers exhibit distinct thermal signatures (i.e., temperature differences) in infrared thermal images. The apparent temperature of the I/S mixed layer at different positions has obvious fluctuations, and the difference is significantly higher than the temperature measurement accuracy of the instrument (0.03 °C). As the instrument was used after calibration through standard procedures, the phenomenon of “same mineral but different temperature” exhibited in the same reservoir and even within the same mineral aggregate undoubtedly represents the significant microscopic heterogeneity of the I/S mixed layer in crystal structure or composition. Considering that the thermal radiation properties of the I/S mixed layer are affected by its lattice water content and surface roughness, this subtle change in the temperature field is most likely closely related to the microscopic distribution difference of the mixed layer ratio (I/S ratio), which provides a solid experimental basis for the subsequent establishment of a quantitative thermodynamic evaluation model.

3. Relationship between mixed layer ratio of illite/smectite mixed layer and its apparent temperature

Based on the mineralogical component analysis in Fig. 2, the main clay mineral of the tight conglomerate reservoir in the Mahu area is the I/S mixed layer, with a small amount of pure illite developed locally. Defined from the perspective of crystal structure, pure illite can be regarded as the end-member mineral with a mixed layer ratio of 0, while the mixed layer ratio of the I/S mixed layer is between 0 and 1. Therefore, determining the

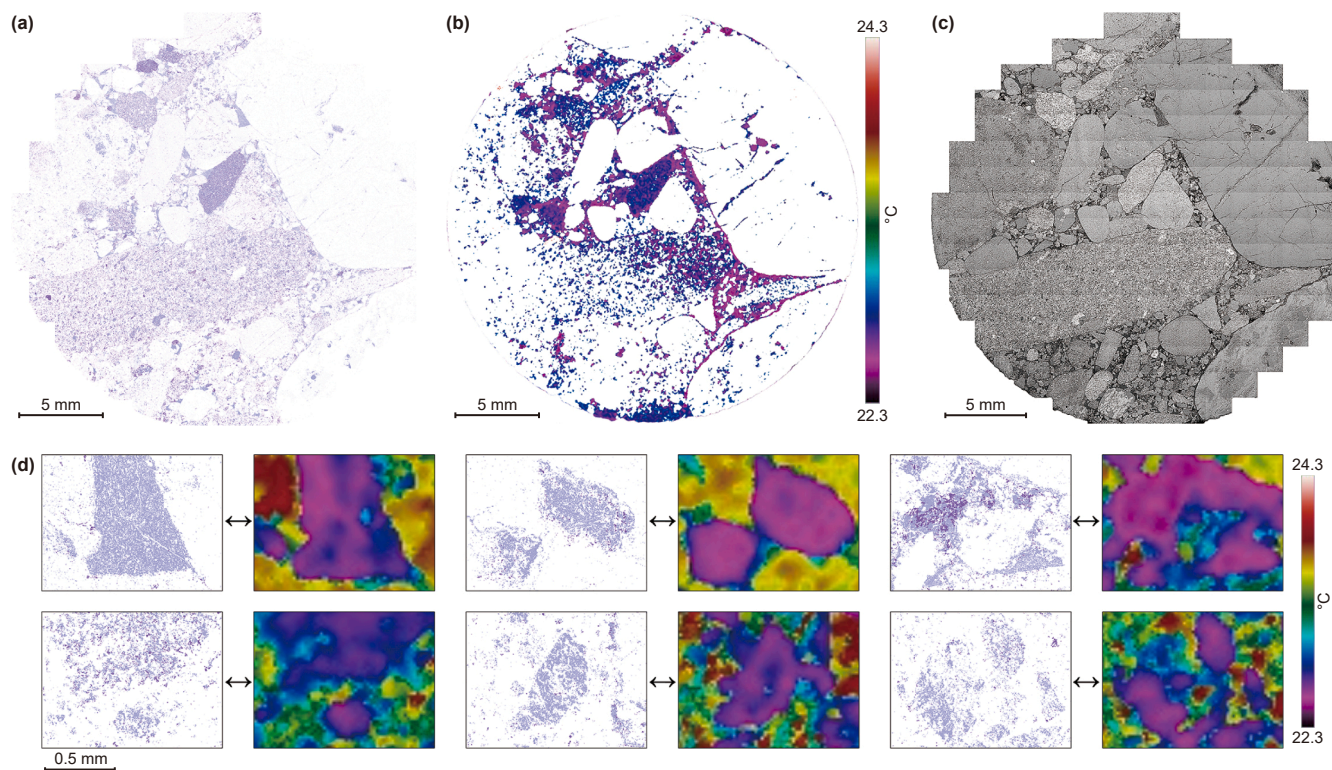


Fig. 2. Apparent temperature distribution characteristics of illite/smectite mixed layer in deep tight conglomerate. (a) Identification result of illite/smectite mixed layer distribution based on TIMA. (b) Distribution of illite/smectite mixed layer extracted based on apparent temperature. (c) BSE scanning result of the representative sample. (d) Detailed comparison of different illite/smectite mixed layer aggregates.

thermodynamic characteristics of pure illite is the basis and premise for establishing the quantitative relationship between the mixed layer ratio and apparent temperature. To deeply explore the inherent mathematical correlation between the two, this study selected pure illite development areas (Fig. 3) and I/S mixed layer development areas with different thermal phase characteristics (Figs. 4–6) for fine sampling constrained by the TIMA mineral map. Through multi-point apparent temperature extraction and statistical analysis of different mineral phases (Tables 1–4), this study aims to construct a set of evaluation methods for quantitative characterization of the mixed layer ratio based on thermodynamic indicators.

3.1. Pure illite (mixed layer ratio = 0)

Pure illite, with no adsorbed water between its crystal layers and a relatively complete lattice structure, is used as the standard reference sample with zero mixed layer ratio in this study. Fig. 3(a) shows the spatial distribution of pure illite mineral aggregates identified by TIMA technology in the field of view, and Fig. 3(b) correspondingly shows the specific sampling positions of 18 discrete temperature measurement points in this area, aiming to eliminate local measurement errors through multi-point statistics. The apparent temperatures measured at 18 points are shown in Table 1. The maximum apparent temperature value collected at the position of the pure illite is 23.59 °C, the minimum is 23.18 °C, and the average is 23.40 °C.

3.2. Illite/smectite mixed layer (mixed layer ratio > 0)

The maximum apparent temperature value collected at the position of the I/S mixed layer is 23.09 °C, the minimum is 22.78 °C, and the average is 22.95 °C (Tables 2, 3 and 4). Combined with Fig. 3, the apparent temperature values of pure illite are generally higher than those of the I/S mixed layer, which strongly proves that under the experimental conditions set in this study, a

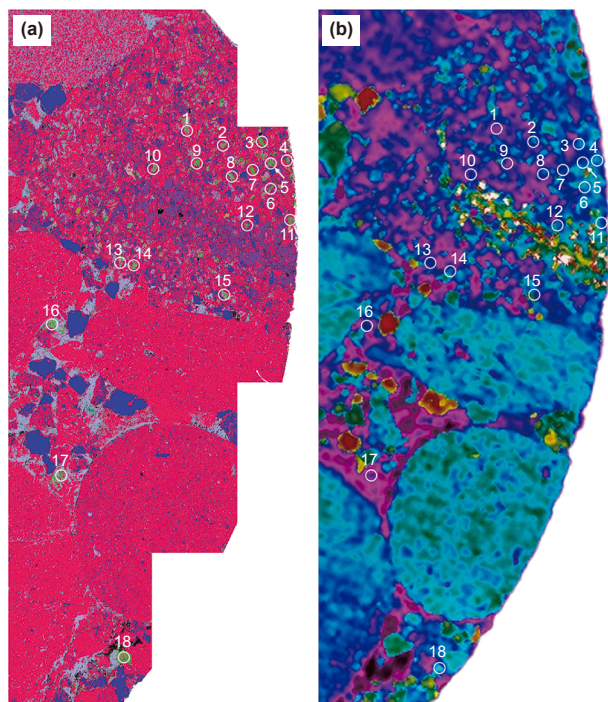


Fig. 3. Apparent temperature extraction of pure illite. The samples are identical to those used in Du and Zong (2026).

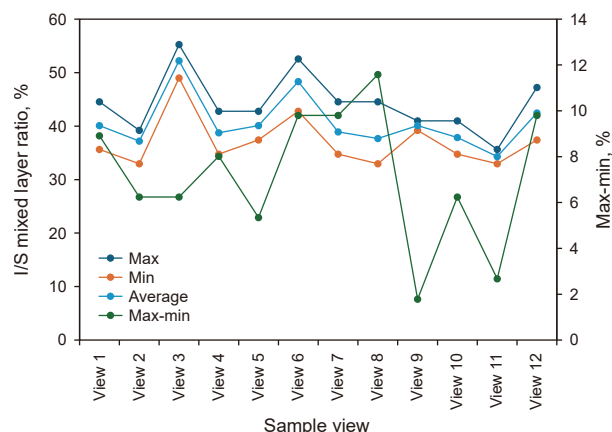


Fig. 4. Statistical characteristics of heterogeneity of illite/smectite mixed layer ratio inverted based on infrared thermodynamic indicators.

lower apparent temperature corresponds to a higher mixed layer ratio, that is, the mixed layer ratio is negatively correlated with the apparent temperature.

The average mixed layer ratio of the series of samples measured by X-ray diffraction is 40.1%. Linear fitting shows that for every 0.1 °C decrease in the apparent temperature, the mixed layer ratio increases by 8.91%. To further quantify this microscopic heterogeneity, this study selected 12 typical microscopic fields of view containing multiple independent sampling points of the I/S mixed layer, and inverted the distribution range of the I/S mixed layer ratio in each field of view using the established quantitative “apparent temperature-mixed layer ratio” conversion model. The statistical results are shown in Fig. 4. The average mixed layer ratio of each field of view fluctuates between 37% and 52%, while the maximum value of single-point measurement even exceeds 55%, and the minimum value is as low as about 33%. The difference in the mixed layer ratio of different fields of view demonstrates the macroscopic heterogeneity of the I/S mixed layer in the samples. The range line further reveals the intensity of microscopic heterogeneity. Within the same tiny field of view (hundreds of microns), the range of the I/S mixed layer ratio is mainly distributed between 1.8% and 11.6%, with an average range as high as 7.2%. This means that the properties of the I/S mixed layer at different positions may be completely different in a very small field of view under the thermal imager.

The statistical law in Fig. 4 strongly corroborates the aforementioned viewpoint: the mixed layer ratio of the I/S mixed layer is not uniformly distributed. Traditional XRD experiments usually can only provide an average mixed layer ratio, and this single value completely masks the real heterogeneous characteristics of the reservoir. Representing a spatially heterogeneous property by a single bulk-average value is prone to causing systematic misjudgment of the local water sensitivity risk of the reservoir, which is bound to cause large deviations and is extremely unfavorable for development.

Based on the significant heterogeneous characteristics found above, to realize rapid identification and quantitative classification of the local water sensitivity damage risk of the reservoir, this study established a set of thermodynamic water sensitivity evaluation criteria according to the distribution statistical law of the apparent temperature value of the I/S mixed layer. We divided the water sensitivity potential of the I/S mixed layer into three grades (Grade I, Grade II, Grade III), with the apparent temperature intervals of 22.78–22.88 °C, 22.88–22.99 °C and 22.99–23.09 °C, respectively.

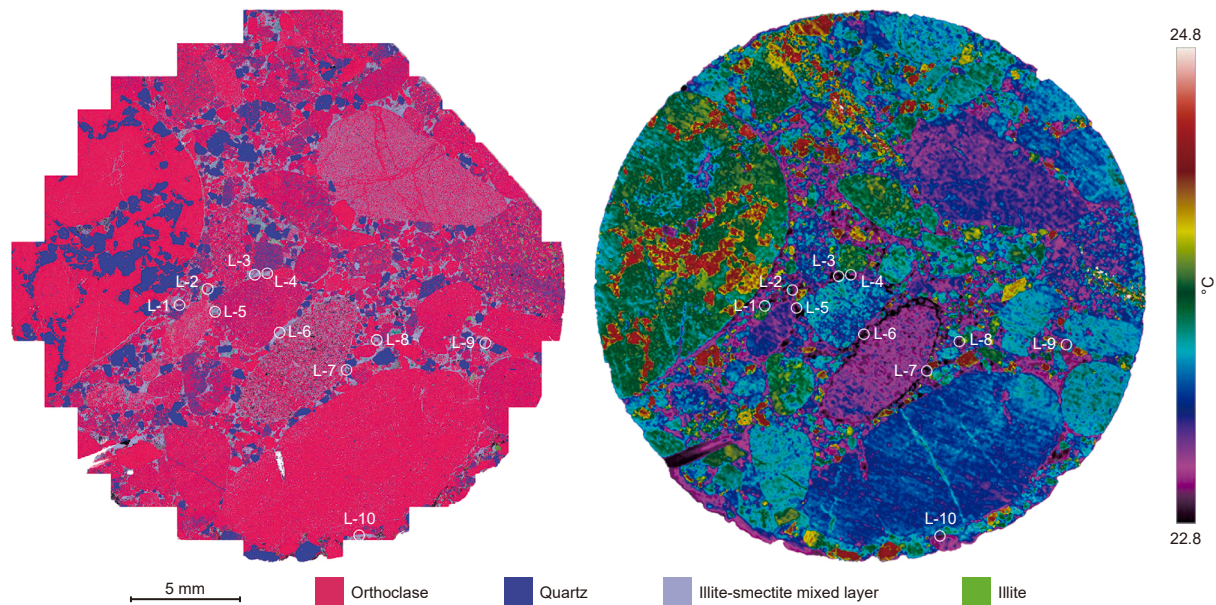


Fig. 5. Apparent temperature extraction of illite/smectite mixed layer with low apparent temperature (high mixed layer ratio) (10 sampling points). The samples are identical to those used in Du and Zong (2026).

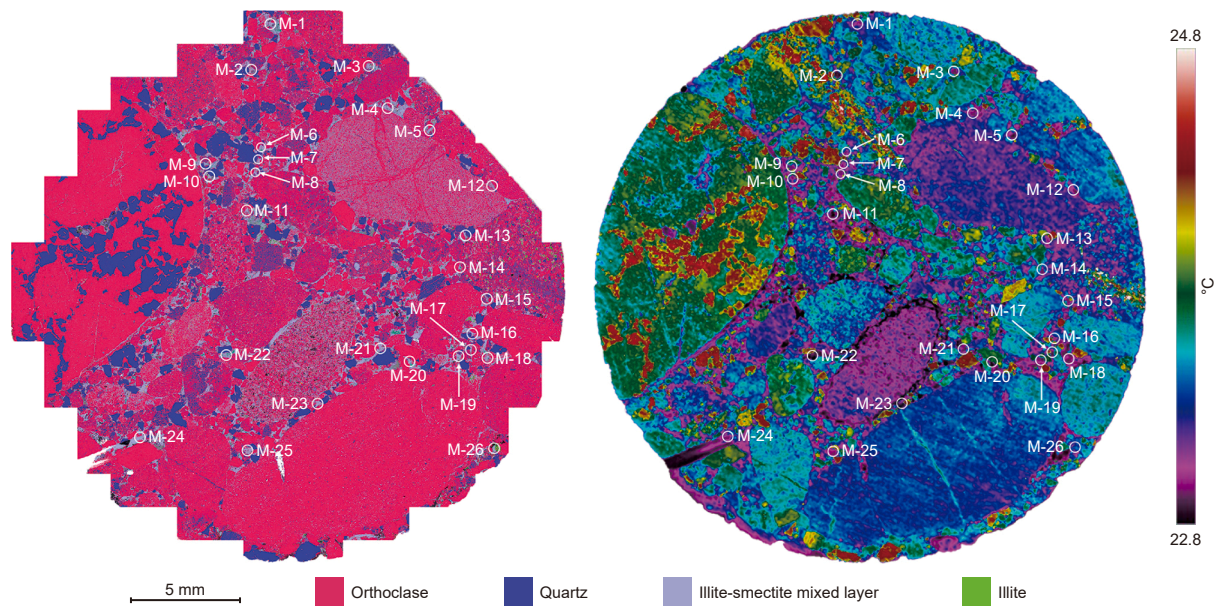


Fig. 6. Apparent temperature extraction of illite/smectite mixed layer with medium apparent temperature (medium mixed layer ratio) (26 sampling points). The samples are identical to those used in Du and Zong (2026).

Table 1
Statistics of apparent temperature values of pure illite.

No.	Apparent temperature, °C	No.	Apparent temperature, °C	No.	Apparent temperature, °C
1	23.21	7	23.45	13	23.39
2	23.27	8	23.34	14	23.47
3	23.45	9	23.18	15	23.41
4	23.39	10	23.36	16	23.59
5	23.47	11	23.39	17	23.30
6	23.54	12	23.54	18	23.38

According to the aforementioned negative correlation physical mechanism between apparent temperature and mixed layer ratio, a lower apparent temperature indicates a higher mixed layer ratio of the I/S mixed layer, stronger lattice water absorption and

expansion capacity, and higher water sensitivity damage risk. Therefore, from Grade I to Grade III, with the increase of apparent temperature, the risk of hydration expansion and dispersion migration of the reservoir when encountering water (degree of

Table 2

Statistics of apparent temperature values of illite/smectite mixed layer with low apparent temperature (high mixed layer ratio).

No.	Apparent temperature, °C	No.	Apparent temperature, °C
L-1	22.83	L-6	22.83
L-2	22.85	L-7	22.81
L-3	22.80	L-8	22.87
L-4	22.78	L-9	22.87
L-5	22.81	L-10	22.87

water sensitivity) decreases sequentially. To further verify the effectiveness of this classification standard and reveal the microscopic occurrence characteristics of the I/S mixed layer of different grades, the following sections carry out detailed microscopic thermodynamic and mineralogical dissection of typical I/S mixed layer aggregates falling into these three temperature intervals, namely high mixed layer ratio (Grade I), medium mixed layer ratio (Grade II) and low mixed layer ratio (Grade III).

3.2.1. Grade I water sensitivity potential: high mixed layer ratio illite/smectite mixed layer (low apparent temperature)

The Grade I water sensitivity potential area corresponds to the area with the highest content of smectite layers (maximum mixed layer ratio) in the I/S mixed layer, which is the key target for water damage prevention and control of the reservoir. Fig. 5 shows the mineral distribution and thermodynamic characteristics of this type of typical field of view, which appears as a significant cool tone (dark blue/purple area) in the infrared thermal image. To quantitatively characterize its thermal radiation characteristics, we selected 10 representative sampling points (L-1 to L-10) in this field of view, and their spatial distribution and temperature measurement results are shown in Fig. 5 and Table 2, respectively.

The statistical data show (Table 2) that the apparent temperature of the I/S mixed layer in this area is concentrated between 22.78 °C and 22.87 °C, with an average temperature of only 22.83 °C. Compared with pure illite (mean value 23.40 °C), its temperature is significantly reduced by about 0.57 °C. This temperature difference reveals that the minerals in this area have an extremely high mixed layer ratio: the presence of a large number of smectite layers leads to an increase in the content of adsorbed

water between lattices and an increase in surface microscopic roughness, thereby significantly increasing the emissivity (reducing the apparent temperature under the same environment). Such areas are very prone to strong water absorption, expansion, dispersion and migration after encountering water, and are “high-risk areas” leading to a sharp decline in permeability.

3.2.2. Grade II water sensitivity potential: medium mixed layer ratio illite/smectite mixed layer (medium apparent temperature)

The Grade II water sensitivity potential area represents the most widely distributed type of I/S mixed layer in the reservoir, with a medium mixed layer ratio. Fig. 6 shows the thermal image characteristics of this type of field of view, with a tone between dark blue and cyan, reflecting the transition of thermal radiation intensity. To obtain statistically significant data, we intensively selected 26 sampling points (M-1 to M-26) in this field of view, covering different particle edges and pore-filling positions.

As shown in Table 3, the apparent temperature values of the I/S mixed layer in this area show a high degree of uniformity, strictly distributed in the range of 22.90 °C to 22.98 °C, with an average value of 22.94 °C. Compared with the Grade I area, its apparent temperature is increased by about 0.11 °C as a whole, indicating that the proportion of smectite layers is decreased and the crystal structure tends to be ordered. Although its water sensitivity is weaker than that of the Grade I area, considering its wide distribution in the reservoir, the cumulative damage effect caused by this type of I/S mixed layer (e.g., pore throat narrowing caused by water sensitivity swelling) cannot be ignored, and it belongs to the “medium-risk area” that requires continuous monitoring.

3.2.3. Grade III water sensitivity potential: low mixed layer ratio illite/smectite mixed layer (high apparent temperature)

The Grade III water sensitivity potential area corresponds to the I/S mixed layer with a high degree of illitization, whose properties are close to pure illite. Fig. 7 shows that this area presents a warmer cyan-green tone in the thermal image, indicating low emissivity and high apparent temperature. We selected 18 sampling points (H-1 to H-18) in this field of view for precise measurement.

The statistical results (Table 4) show that the apparent temperature of this type of I/S mixed layer further rises, with a

Table 3

Statistics of apparent temperature values of illite/smectite mixed layer with medium apparent temperature (medium mixed layer ratio).

No.	Apparent temperature, °C	No.	Apparent temperature, °C	No.	Apparent temperature, °C
M-1	22.98	M-10	22.96	M-19	22.92
M-2	22.90	M-11	22.98	M-20	22.90
M-3	22.94	M-12	22.98	M-21	22.92
M-4	22.96	M-13	22.90	M-22	22.92
M-5	22.94	M-14	22.94	M-23	22.92
M-6	22.96	M-15	22.98	M-24	22.90
M-7	22.98	M-16	22.98	M-25	22.98
M-8	22.96	M-17	22.94	M-26	22.90
M-9	22.96	M-18	22.98		

Table 4

Statistics of apparent temperature values of illite/smectite mixed layer with high apparent temperature (low mixed layer ratio).

No.	Apparent temperature, °C	No.	Apparent temperature, °C	No.	Apparent temperature, °C
H-1	23.01	H-7	23.05	H-13	23.00
H-2	23.01	H-8	23.09	H-14	23.03
H-3	23.05	H-9	23.00	H-15	23.01
H-4	23.03	H-10	23.01	H-16	23.01
H-5	23.00	H-11	23.00	H-17	23.01
H-6	23.01	H-12	23.03	H-18	23.00

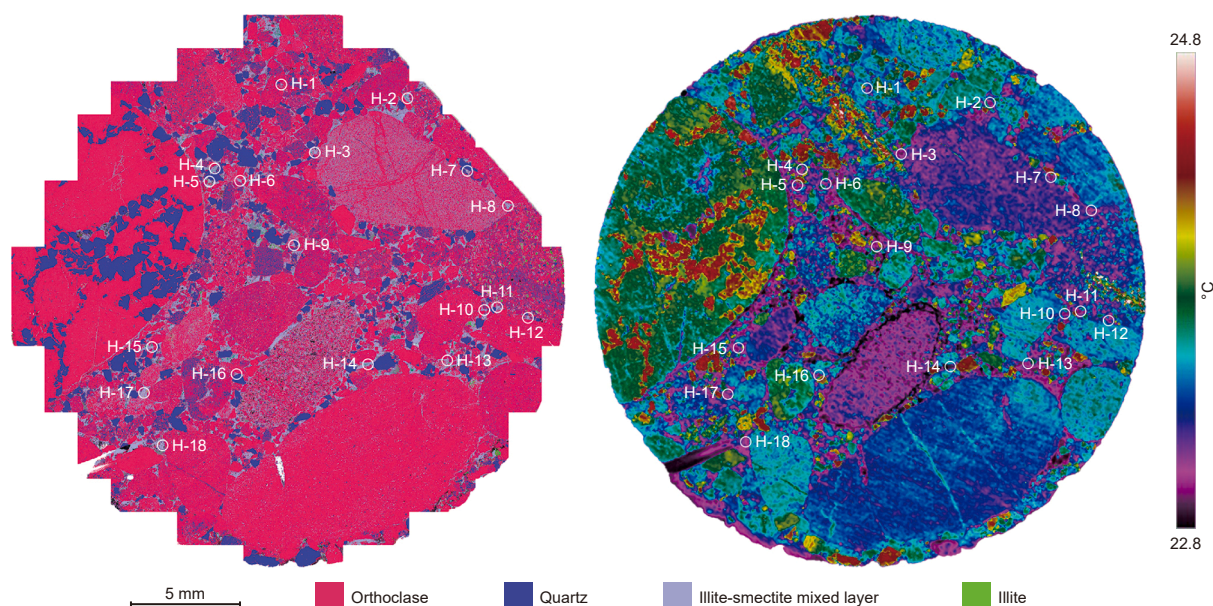


Fig. 7. Apparent temperature extraction of illite/smectite mixed layer with high apparent temperature (low mixed layer ratio) (18 sampling points). The samples are identical to those used in Du and Zong (2026).

distribution range of 23.00 °C to 23.09 °C, and an average temperature of 23.02 °C. This value is very close to the lower temperature limit of pure illite (23.18 °C), suggesting that its smectite layer content has dropped to a low level. In such areas, the lattice expansion potential is greatly inhibited, and the water sensitivity damage is mainly manifested as weak surface hydration rather than violent volume expansion. Therefore, this area belongs to the “relatively safe area” in reservoir development, and the restriction standard for fluid compatibility can be appropriately relaxed when formulating water injection or stimulation measures.

3.3. Microscopic heterogeneity and genetic mechanism of illite/smectite mixed layer aggregates

Based on the fine characterization by macro-lens infrared thermal imaging, we selected 9 typical tight conglomerate samples for thermodynamic response characteristic analysis in Fig. 8. A universal thermal gradient phenomenon can be clearly observed from the thermal images: the edge of the I/S mixed layer aggregate usually presents a high apparent temperature, while the temperature gradually decreases towards the center. Combined with the aforementioned quantitative model, this thermodynamic characteristic reveals the microscopic heterogeneous law that the mixed layer ratio gradually increases from the particle edge to the center (i.e., the content of smectite layers increases and the degree of illitization decreases). This phenomenon offers robust microscopic evidence that the transformation of smectite to illite (i.e., illitization of the I/S mixed layer) is not uniform, but occurs as a centripetal metasomatic process advancing gradually from particle edges toward the center. The particle edge, as the front of water-rock interaction, exhibits a low mixed layer ratio (high illite content), indicating that the transformation reaction is the most thorough here. The potential mechanisms leading to this heterogeneous structure mainly include three aspects.

1) Fluid-rock surface reaction mechanism: Pore fluid is the main supply source of potassium ions (K^+). Potassium-rich fluid preferentially contacts the particle edge, so that the smectite inter-layer domain at the edge can capture K^+ first and undergo immobilization reaction, thus transforming into illite layers first.

- 2) Diffusion limitation: The illitization reaction requires K^+ to enter the lattice interior and discharge Na^+/Ca^{2+} and water molecules. Compared with the edge, the solid-phase diffusion rate of K^+ into the particle center is much lower than the ion exchange rate on the surface, and the huge mass transfer resistance leads to a significant lag in the transformation process of the center.
- 3) Energy gradient: The particle edge is usually rich in lattice defects, dangling bonds or microcracks. These high-energy sites significantly reduce the activation energy barrier for illite nucleation, while the lattice at the particle center is relatively complete, and nucleation requires higher activation energy.

The preferential reaction at the fluid-mineral interface and the hysteresis effect of internal mass transfer jointly shape this zoned structure of “low mixed layer ratio at the edge and high mixed layer ratio at the center”. In addition, by comparing different occurrence states, it is found that the overall apparent temperature of the pore-filling type I/S mixed layer is lower than that of the feldspar particle surface type, indicating a higher mixed layer ratio (more smectite components). This may be because the pore-filling materials are mostly formed by authigenic precipitation, and limited by the fluid renewal capacity of the confined pore space, their illitization degree is often lower than that of the feldspar surface transformation products subjected to strong weathering and leaching in open space.

Overall, the thermodynamic characterization method for water sensitivity proposed in this study breaks through the core limitation that the averaging evaluation by traditional XRD masks microscopic heterogeneity, and can accurately locate water sensitivity damage hotspots in reservoirs. This method directly supports the fine screening of sweet spots, differentiated design of reservoir protection fluids and optimization of layered water injection schemes, providing practical technical support for the efficient development of tight conglomerate reservoirs in the Mahu area.

3.4. Limitations of the method

This method is mainly applicable to clastic reservoirs where the I/S mixed layer is the dominant clay mineral causing water sensitivity. For reservoirs where the dominant clay mineral is not

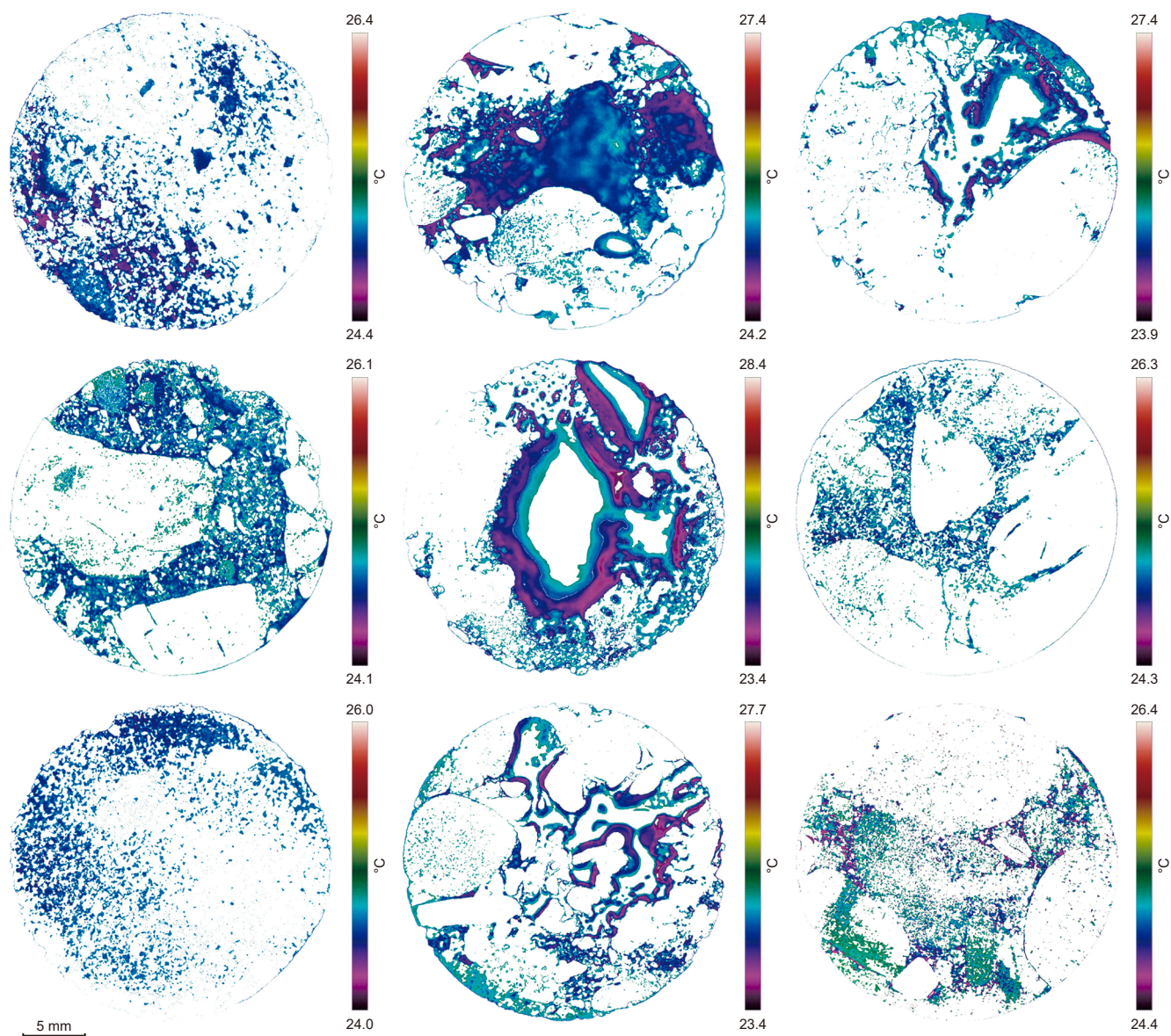


Fig. 8. Analysis of thermodynamic response characteristics of illite/smectite mixed layer in tight conglomerate reservoirs in the Mahu area, Xinjiang.

the illite/smectite (I/S) mixed layer, their thermal radiation characteristics are more complex, and the quantitative relationship established in this study needs to be further corrected. In addition, the current research is carried out at room temperature, and the influence of high temperature and high pressure conditions in deep reservoirs on the thermodynamic response needs to be further studied in the future.

4. Conclusions

- 1) Macro-lens infrared thermal imaging technology can not only accurately identify the spatial distribution of the I/S mixed layer, but also reveal the microscopic heterogeneity of the mixed layer ratio that cannot be captured by traditional XRD technology, confirming the significant difference in thermodynamic properties within the same mineral.
- 2) A quantitative model of linear negative correlation between the I/S mixed layer ratio and the fourth power of the apparent temperature is established. A lower apparent temperature indicates a higher content of smectite layers (mixed layer ratio),

greater lattice water absorption and expansion potential, and higher risk of water sensitivity damage.

- 3) The thermal gradient characteristic of “hot edges and cold center” in I/S mixed layer aggregates is discovered, which confirms that the transformation of smectite to illite is a centripetal metasomatic process controlled by fluid-mineral interfacial reaction and advancing from the particle edge to the center.
- 4) A three-level thermodynamic evaluation criterion for the water sensitivity potential of the I/S mixed layer based on apparent temperature is proposed, which realizes rapid identification and quantitative classification of microscopic reservoir damage risks and provides a new theoretical basis for sweet spot optimization and reservoir protection in tight oil and gas reservoirs. The temperature range can be fine-tuned according to the characteristics of reservoirs in different blocks.
- 5) In the future, this technology can be further extended to core-scale dynamic monitoring of water sensitivity, correction of logging interpretation models and real-time evaluation of on-site water injection effects, providing strong technical support

for the efficient development of deep tight oil and gas reservoirs.

CRediT authorship contribution statement

Shu-Heng Du: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Zhuo-Shen Zong:** Writing – original draft, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

- Anderson, R.L., Ratcliffe, I., Greenwell, H.C., et al., 2010. Clay swelling—A challenge in the oilfield. *Earth Sci. Rev.* 98 (3), 201–216. <https://doi.org/10.1016/j.earscirev.2009.11.003>.
- Bastida, J., Pardo-Ibañez, P., 2024. Applications of X-ray powder diffraction microstructural analysis in applied clay mineralogy. *Minerals* 14 (6), 584. <https://doi.org/10.3390/min14060584>.
- Bosire, V., 2025. Infrared spectroscopy for real-time detection of swelling clays in geothermal wells. A case of Olkaria, Kenya. In: 50th Workshop on Geothermal Reservoir Engineering. SGP-TR-229.
- Carcione, J.M., Gei, D., Yu, T., et al., 2019. Effect of clay and mineralogy on permeability. *Pure Appl. Geophys.* 176 (6), 2581–2594. <https://doi.org/10.1007/s00024-019-02117-3>.
- Cui, K., Wang, C., Li, L., et al., 2022. Controlling the hydro-swelling of smectite clay minerals by Fe(III) reducing bacteria for enhanced oil recovery from low-permeability reservoirs. *Energies* 15 (12), 4393. <https://doi.org/10.3390/en15124393>.
- Du, S., Bai, L., Zhao, A., et al., 2025. Infrared thermal imaging under a macro lens empowers geo-energy exploration and development: Application scenarios and scheme conceptions. *Adv. Geo-Energy Res.* 16 (1), 4–7. <https://doi.org/10.46690/ager.2025.04.02>.
- Du, S., Zhao, A., Wei, Y., et al., 2024. The dominant mineralogical triggers hindering the efficient development of the world's largest conglomerate oilfield. *Int. J. Hydrogen Energy* 60, 688–701. <https://doi.org/10.1016/j.ijhydene.2024.02.061>.
- Du, S., Zong, Z., 2026. World's first microscale infrared thermal image of 25-mm-diameter, ~3500-m-deep subsurface tight rocks: overestimated brittleness jeopardizes China's deep energy revolution. *Innov. Geosci.* 4, 100220. <https://doi.org/10.59717/j.xinn-geo.2026.100220>.
- Ferrage, E., 2016. Investigation of the interlayer organization of water and ions in smectite from the combined use of diffraction experiments and molecular simulations. A review of methodology, applications, and perspectives. *Clays Clay Miner.* 64 (4), 348–373. <https://doi.org/10.1346/CCMN.2016.0640401>.
- Jin, L., Liu, Y., Gao, J., et al., 2021. Quantitative interpretation of water sensitivity based on well log data: A case of a conglomerate reservoir in the Karamay Oil Field. *Lithosphere* 2021 (Special 1), 5992165. <https://doi.org/10.2113/2021/5992165>.
- Jozanikohan, G., Abarghoeei, M.N., 2022. The Fourier transform infrared spectroscopy (FTIR) analysis for the clay mineralogy studies in a clastic reservoir. *J. Pet. Explor. Prod. Technol.* 12 (8), 2093–2106. <https://doi.org/10.1007/s13202-021-01449-y>.
- Lehmann, P., Leshchinsky, B., Gupta, S., et al., 2021. Clays are not created equal: How clay mineral type affects soil parameterization. *Geophys. Res. Lett.* 48 (20), e2021GL095311. <https://doi.org/10.1029/2021GL095311>.
- Li, B.W., Sun, L.H., Liu, X.G., et al., 2022b. Effects of clay mineral content and types on pore-throat structure and interface properties of the conglomerate Reservoir: A case study of baikouquan formation in the Junggar Basin. *Minerals* 13 (1), 9. <https://doi.org/10.3390/min13010009>.
- Li, C., Li, J., Shi, H., et al., 2026. Modeling overpressure vertical transfer via faults in clastic sequences at the basin scale: Implications for overpressure generation and fluid flow. *Nat. Gas Ind. B* 13 (2), 129–146. <https://doi.org/10.1016/j.ngib.2026.03.001>.
- Li, G., Qin, J., Xian, C., et al., 2020. Theoretical understandings, key technologies and practices of tight conglomerate oilfield efficient development: A case study of the Mahu oilfield, Junggar Basin, NW China. *Petrol. Explor. Dev.* 47 (6), 1275–1290. [https://doi.org/10.1016/S1876-3804\(20\)60135-0](https://doi.org/10.1016/S1876-3804(20)60135-0).
- Li, J., Li, W., Li, L., 2017. Experimental study on water sensitivity difference based on oiliness of porous medium rock. *Geofluids* 2017 (1), 5758046. <https://doi.org/10.1155/2017/5758046>.
- Li, J.Y., Zhang, K., Cheng, N., et al., 2022a. Optimization and evaluation of stabilizers for tight water-sensitive conglomerate reservoirs. *ACS Omega* 7 (7), 5921–5928. <https://doi.org/10.1021/acsomega.1c06140>.
- Li, X., Zhang, J., Wang, H., et al., 2023. Distribution law and main controlling factors of illite/smectite mixed layer in Upper Wuerhe Formation, Northwestern Mahu Sag, Junggar basin, Northwest China. *Journal of Engineering Science and Technology Review* 16 (5), 52–58. <https://doi.org/10.25103/jestr.165.07>.
- Li, X., Li, F., Huang, Z., et al., 2025. Characterization and simulation of conglomerate reservoirs using core data of Triassic Baikouquan Formation, Mahu Depression. *Sci. Rep.* 15 (1), 29293. <https://doi.org/10.1038/s41598-025-09954-4>.
- Liu, K., Sheng, J.J., Zhang, Z., 2020. A simulation study of the effect of clay swelling on fracture generation and porosity change in shales under stress anisotropy. *Eng. Geol.* 278, 105829. <https://doi.org/10.1016/j.enggeo.2020.105829>.
- Liu, D., Wu, J., Zhao, S., et al., 2025. Experimental study on hydraulic fracture propagation in middle-deep shale gas reservoirs in the southern Sichuan Basin: The effects of vertical heterogeneity. *Nat. Gas Ind. B* 12 (6), 705–717. <https://doi.org/10.1016/j.ngib.2025.11.003>.
- Liu, L., Ma, X., Zou, Y., et al., 2026. Study on microscopic pore structure and mechanical characteristics of tight sandstone under hydration effect. *Processes* 14 (3), 453. <https://doi.org/10.3390/pr14030453>.
- Liu, S., 2023. Review of the development status and technology of tight oil: Advances and outlook. *Energy & Fuels* 37 (19), 14645–14665. <https://doi.org/10.1021/acs.energyfuels.3c02726>.
- Mohammed, I., Al Shehri, D., Mahmoud, M., et al., 2022. Effect of native reservoir state and oilfield operations on clay mineral surface chemistry. *Molecules* 27 (5), 1739. <https://doi.org/10.3390/molecules27051739>.
- Pang, J., Chen, H.T., Yang, Y., et al., 2025. Evolution of pore structure and permeability damage mechanisms in reservoirs with different permeabilities under long-term low-salinity water flooding. *Environ. Earth Sci.* 84 (21), 625. <https://doi.org/10.1007/s12665-025-12646-x>.
- Rahromostaqim, M., Sahimi, M., 2018. Molecular dynamics simulation of hydration and swelling of mixed-layer clays. *J. Phys. Chem. C* 122 (26), 14631–14639. <https://doi.org/10.1021/acs.jpcc.8b03693>.
- Sun, J., You, X., Zhang, Q., et al., 2022. Development characteristics and genesis of deep tight conglomerate reservoirs of Mahu area in Junggar Basin. *Nat. Gas Geosci.* 34 (2), 240–252. <https://doi.org/10.11764/j.issn.1672-1926.2022.10.004> (in Chinese).
- Tao, S., 2025. Exploration and development of unconventional oil and gas resources: Latest advances and prospects. *Energies* 18 (15), 3933. <https://doi.org/10.3390/en18153933>.
- Tao, S., Gao, L., Pan, Z., 2019. Swelling of clay minerals and its effect on coal permeability and gas production: A case study of southern Qinshui Basin, China. *Energy Sci. Eng.* 7 (2), 515–528. <https://doi.org/10.1002/ese3.301>.
- Tong, K.W., Pereira, J.M., Huang, K., et al., 2025. Experimental study on the microscopic swelling-shrinking mechanisms of clay-sand mixtures from wetting to drying. *Acta Geotech.* 20 (7), 3477–3500. <https://doi.org/10.1007/s11440-025-02580-4>.
- Wilson, M.J., Wilson, L., Patey, I., 2014. The influence of individual clay minerals on formation damage of reservoir sandstones: A critical review with some new insights. *Clay Miner.* 49 (2), 147–164. <https://doi.org/10.1180/claymin.2014.049.2.02>.
- Xie, B., Tan, J., Lyu, Q., et al., 2026. Nonlinear fluid flow regimes in fractured shale: Impact of confining stresses and water-supercritical CO₂ interactions. *Nat. Gas Ind. B* 13 (1), 44–59. <https://doi.org/10.1016/j.ngib.2026.01.007>.
- Xiong, H., Devegowda, D., Huang, L., 2020. EOR in clay-hosted pores: Effects of brine salinity, water saturation, pore surface chemistry and pore width. In: Proceedings of the 8th Unconventional Resources Technology Conference. Presented at the Unconventional Resources Technology Conference. <https://doi.org/10.15530/urtec-2020-2911>.
- Yang, T., Chu, C.M., Zhang, Y.G., et al., 2025. Molecular dynamics simulation of clay mineral-water interfaces: Temperature-dependent structural, dynamical, and mechanical properties. *Water* 17 (3), 347. <https://doi.org/10.3390/w17030347>.
- Yesmukhambet, M., Pourafshary, P., 2025. Investigating clay swelling and permeability impairment in sandstone formations during steam flooding. *Clays Clay Miner.* 73, e20. <https://doi.org/10.1017/cmn.2025.10008>.
- Yu, D., Long, M., Wang, Y., et al., 2022. Research on water sensitivity and velocity sensitivity of loose sandstone reservoir in China offshore oilfield. *World J. Eng. Technol.* 10 (2), 254–263. <https://doi.org/10.4236/wjet.2022.102016>.
- Zhang, L., Zhou, F., Zhang, S., et al., 2019. Investigation of water-sensitivity damage for tight low-permeability sandstone reservoirs. *ACS Omega* 4 (6), 11197–11204. <https://doi.org/10.1021/acsomega.9b01286>.
- Zhang, Y., Chen, S., Peng, Y., et al., 2026. Deflagration fracturing modification of nanoporous structure in the shale reservoirs of the Longmaxi Formation,

- Southern Sichuan, China. Nat. Gas Ind. B 13 (1), 30–43. <https://doi.org/10.1016/j.ngib.2026.01.002>.
- Zhao, A., Du, S., 2024. Hydration-induced damage of tight conglomerates. Chem. Eng. J. 495, 153426. <https://doi.org/10.1016/j.cej.2024.153426>.
- Zhao, A., Du, S., Zhang, Y., et al., 2025. Surface hydration-induced damage in tight oil-bearing sandy conglomerate reservoirs. Deep Underground Science and Engineering 2025, 1–20. <https://doi.org/10.1002/dug2.70060>.
- Zhou, B., Du, S.H., Wei, Y., et al., 2025. Heterogeneity and anisotropy of tight Conglomerates: mechanisms and implications. Adv. Geo-Energy Res. 18 (1), 7–20. <https://doi.org/10.46690/ager.2025.10.02>.
- Zhu, Y., Deng, Y., Qin, J., et al., 2023. Fracture propagation mechanism of tight conglomerate reservoirs in Mahu Sag. Processes 11 (7), 1958. <https://doi.org/10.3390/pr11071958>.