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Distribution Law and Main Controlling Factors of Illite/Smectite Mixed Layer in Upper Wuerhe Formation, Northwestern Mahu Sag, Junggar Basin, Northwest China

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Abstract

Exploring reservoir stratum sensitivity is an important basic work for oil and gas exploration and exploitation, in which the degree of water sensitivity damage is often affected by the clay mineral content and microscopic pore throat structure of illite/montmorillonite mixed clay minerals. To reveal the distribution law and the main controlling factors of illite/montmorillonite mixed layers, the diagenesis, regional distribution law, and main controlling factors of illite/montmorillonite mixed layers in the reservoir stratum of the Upper Wuerhe Formation in the study area were analyzed by high-resolution testing techniques such as scanning electron microscopy (SEM) and Advanced Mineral Identification and Characterization System. Diagenesis was the main cause of illite/montmorillonite mixed layers in the study area, and the occurrence state under SEM was mostly flaky, silky, and flocculent filling in intragranular dissolved pores or intergranular pores. The mass fraction of illite/montmorillonite mixed layers increased with the increase in depth in the longitudinal direction, which was closely related to the sedimentary microfacies and the hydrodynamic environment in the plane. Results show that potash feldspar is the material basis for the formation of illite/montmorillonite mixed layers, and the strength of the hydrodynamic environment is the main controlling factor for the quality distribution characteristics of such mixed layers. This study provides a new technical method and research idea for understanding the reservoir sensitivity characteristics, which has good guiding significance for the blocks with strong reservoir sensitivity. The original pore structure of the reservoir can also be protected against destruction by various sensitivity factors in the developmental stage caused by the unclear understanding of the spatial distribution characteristics of clay minerals affecting the yield in oil and gas field development.

Keywords: Junggar Basin, Mahu Sag, Upper Wuerhe Formation, illite/montmorillonite mixed layer, diagenesis

1. Introduction

Clay minerals, which are ubiquitous in strata, have various types. Of the damage in oil and gas reservoirs, 70% is caused by such minerals. The type and mass fraction of clay minerals determine the choice of oil and gas reservoir development methods. A large number of illite/montmorillonite mixed clay minerals occur in the reservoir of the Upper Wuerhe Formation in the Mahu Sag, which makes the reservoir vulnerable to water sensitivity damage. In predecessors' studies, diagenetic stages were usually divided in accordance with the mineral components and the occurrence state. Meanwhile, the reservoir-forming model has been further explored using the chemical formulas of various mineral components. However, the regional distribution characteristics of illite/montmorillonite mixed layers in the whole study area, the clay transformation mechanism, and the main controlling factors have been barely investigated.

On this basis, scholars have conducted considerable work on the quantitative identification technology for illite/montmorillonite mixed clay minerals [1-2]. The current conventional experimental means of acquiring the mass fraction of clay minerals are characterized by low resolution, making it difficult to obtain the accurate mass fraction of nanoscale clay particles. The experimental results obtained by different experimenters also differ greatly, failing to achieve unified standard results for evaluating the spatial distribution characteristics of clay minerals. Furthermore, conventional indoor experimental methods and technologies require considerable time to acquire the results of mineral components and thus cannot meet the needs for rapid on-site decision-making of oilfields. Hence, a problem to be urgently solved lies in accurately distinguishing the distribution characteristics of illite/montmorillonite mixed clay minerals and revealing the main controlling factors for the formation of clay minerals in these mixed layers.

For this reason, the Advanced Mineral Identification and Characterization System (AMICS), a quantitative mineral analysis system developed in Brook, Germany, and scanning electron microscopy (SEM) imaging technology were adopted in this study. These technologies could quantitatively identify the dependence relationship between the clay minerals and pore structure of illite/montmorillonite mixed layers at nano-submicron resolution. No human participation was involved in the whole quantitative mineral experimental process, and the experimental results were unified and reliable, allowing to determine the causes of minerals in illite/montmorillonite mixed layers, analyze the regional distribution characteristics of these mixed layers, and clarify the main controlling factors of illite/montmorillonite mixed clay minerals in the reservoir. The study results will provide data support for the protection

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and evaluation of water-sensitive reservoirs in the Upper Wuerhe Formation in the Mahu Sag, which is related to the adjustment of the overall development plan and thinking of the oilfield in the Mahu Sag.

2. State of the art

Scholars have done substantial work on the testing system and method for rock mineral components. El-Shater [3] studied the longitudinal distribution characteristics of clay minerals via an X-ray diffraction experiment. Zhou [4] mentioned that the current experimental methods of X-ray diffraction mainly include internal standard, incremental, matrix cleaning, external standard, adiabatic, and Rietveld full-map fitting methods. However, the evaluation criteria for various methods are not uniform at present, which leads to great differences in experimental results. Runcevski [5] believed that the Rietveld full-graph fitting method aims at phase quantification based on structural information. Ma [6] and Fu [7] et al. deemed that the Rietveld full-map fitting method is a high-precision quantitative method without standard samples. On the basis of the proposed method, Wang [8] performed quantification via TOPAS software so that the experimental results were accurate and the clay mineral content was independent. However, the results obtained by the Rietveld full-map fitting method were subjective, and the experiences of different experimenters differed, which led to the deviation in experimental results. Andrew [9] proposed the BigGAN method in 2018, which accurately controlled the diversity and fidelity of experimental samples but could not solve the differences in the experimental analysis link. Strandmann [10] used this method to explore geological samples, such as soil, shale, and sandstone. However, Guo [11] and Zhao [12] et al. found that different clay minerals had diverse abilities to adsorb cations because of their different negative charges. HrsTka [13] emphasized that the X-ray diffraction experimental method spent a long time in the identification of clay minerals. Xie [14] observed that the experimental method of X-ray diffraction was vulnerable to subjective interference in the identification of heavy minerals. Graham [15] found that a series of automatic quantitative analysis methods of minerals has shown wide application prospects in geology, petroleum, and environment in recent years. Chen [16] and MA [17] used such technologies as QEMSCAN, MAPS, TIMA, and AMICS in mineral identification but did not compare and verify these technologies. Scott [18] successfully established a digital rock model with SEM equipment. Wang [19] and Zhu [20] et al. indicated that AMICS is a widely used automatic mineral identification and characterization system with a database of more than 2,000 minerals. However, AMICS was not used in combination with SEM. Luo [21] introduced rock mineral analysis system and test from the perspective of application value for determining the distribution of minerals and the economic and use values of rocks and minerals. Sousa [22] deemed that technologies such as AMICS are applied to the identification of microscopic mineral components because of their high resolution. Zhang [23] and Li [24] et al. applied this system to obtain data on the mineral composition, distribution, dissociation degree, and recovery rate of ore dressing products and further optimized the technological process. Deng [25] quantitatively studied the uranium occurrence pattern of sandstone-type uranium ore samples, that is, the uranium distribution rate of the samples was calculated using the quantitative data on uranium-bearing materials, such as uranium minerals, organic matter, and zircon, of AMICS, combined with the average UO_2 content of uranium-bearing materials determined by electron probes. However, the occurrence form of uranium was not transformed from qualitative research to quantitative characterization. Wen [26] et al. carried out a seamless scanning measurement of samples based on AMICS. However, the automatic quantitative analysis of mineral composition, particle size, dissociation degree, and other characteristic parameters was not implemented. Davarpanah A [27] analyzed the controlling effect of clay minerals on reservoir sensitivity by SEM, but illite/montmorillonite mixed clay minerals could not be classified separately.

The above works were mainly aimed at the quantitative analysis of minerals by a single experimental method. The results obtained using the traditional X-ray diffraction experimental method were subjective, and the experiences of different experimenters varied, leading to the deviation in the experimental results and affecting the conclusions on mineral distribution laws. Meanwhile, the transformation law of various types of mineral components among different experimental means has been rarely investigated. In this study, AMICS and SEM were combined to reveal the spatial distribution characteristics of illite/montmorillonite mixed clay minerals. On the basis of the mineral composition and mineral particle morphology of rock samples, the longitudinal and vertical variation characteristics and main controlling factors of clay mineral content in illite/montmorillonite mixed layers under different provenances and hydrodynamic environments were discussed. This study could facilitate reservoir sensitivity evaluation and provided a basis for optimizing oil and gas field development schemes.

The remainder of this study is organized as follows: In Section III, the principle of the automatic mineral petrology detection method is described, and the process and method of clay mineral identification are proposed. In Section IV, the clay mineral types of the Upper Wuerhe Formation in the Mahu Sag in the northwestern margin of the Junggar Basin are analyzed based on experimental results, and the distribution characteristics and controlling factors of clay minerals in various sedimentary environments are obtained. In the final section, the whole study is summarized, and relevant conclusions are drawn.

3. Methodology

AMICS can scan the sample surface along the high-energy electron beam accelerated under the preset grating scanning mode and obtain the color map of the distribution characteristics of mineral aggregates. The instrument can emit X-ray energy spectra and provide information on element content at each measuring point. Through combining the gray level of the back-scattered electron (BSE) image with the intensity of the X-ray, the content of elements can be obtained and transformed into mineral phases. AMICS data include a complete set of mineralogical parameters and calculated chemical analysis results. The quantitative analysis results can generate any selected sample, independent particles, and particles with similar chemical compositions or structural characteristics (particle size, rock type, etc.). The greatest advantage of this technology is that it can identify nanoscale clay particles and micron-scale debris particles by using SEM technology. The resolution is higher than that of conventional experiments, so that the quantitative analysis results of minerals are more accurate and the identified mineral types are richer.

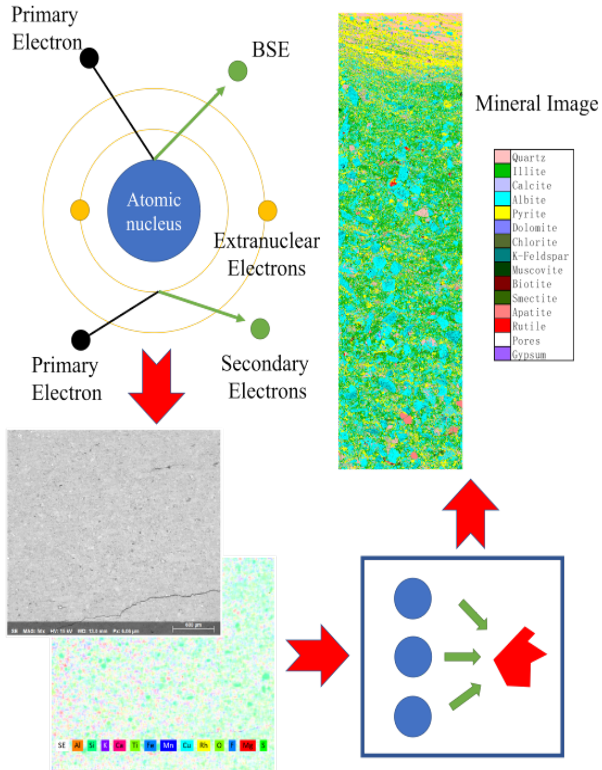


Fig. 1. Schematic of AMICS quantitative mineral analysis technology

4. Result Analysis and Discussion

4.1 Microscopic analysis of the genesis of illite/montmorillonite mixed layers

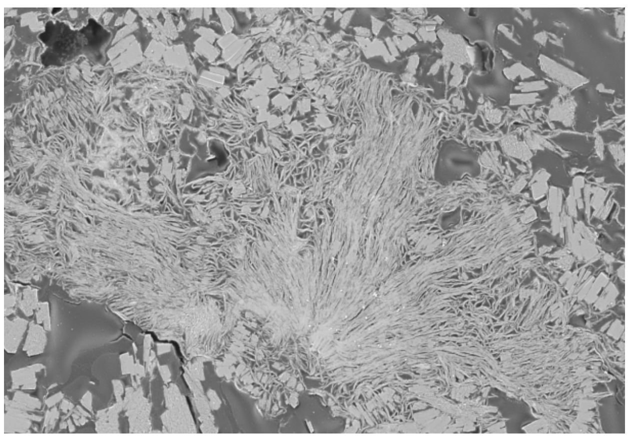
An illite/montmorillonite mixed layer is a kind of mineral in the process of transformation, which is almost flaky and layered, and silicate plays a dominant role in its composition. Usually, it is transformed from montmorillonite to illite, during which the relative content of the illite/montmorillonite mixed layer is directly proportional to the degree of order of occurrence. In this experiment, 280 samples of AMICS minerals in key wells in the study area were quantitatively analyzed. According to the analysis results of nano-submicron SEM images, the relative content of illite/montmorillonite mixed clay minerals in the study area was generally high, ranging from 60% to 80%. In clay minerals, the relative content of illite/montmorillonite mixed minerals exceeded 60%. On the basis of the characteristics of occurrence and composition, the genesis of illite/montmorillonite mixed layers in the reservoir could generally be classified into three types, namely, diagenetic, weathering, and volcanic hydrothermal types. Each type of illite/montmorillonite mixed clay minerals exhibited their own morphology under SEM.

In the early stage of diagenesis, illite/montmorillonite mixed clay minerals generally occurred at the edges of pores and rock particles in the form of thin film cementation, gradually forming liners. Most of the clay minerals formed by diagenesis occurred in pores in the form of scattered particles, and they were irregularly curved, flaky, silky, and honeycomb-shaped around the easily dissolved particles under SEM (Figure 2). This kind of illite/montmorillonite mixed clay minerals was common in the underwater sedimentary environment in the study area. They often appeared in intergranular dissolved pores, intragranular dissolved pores, and microcracks with easily soluble minerals, which were semifilled in the pores with a certain compaction effect and exerted a constructive effect on preserving primary pores in deeply buried reservoirs.

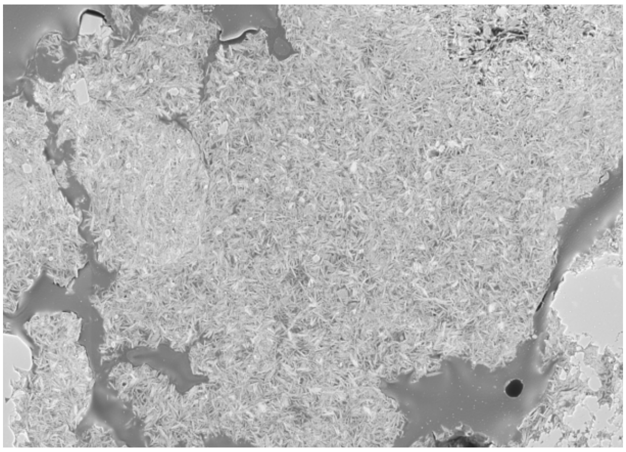
The clay minerals were transformed as numerous ions were brought in and out, which was a prerequisite. In the diagenetic process, the minerals vulnerable to dissolution were feldspar, mica, and pyroclastic. When encountering an acidic fluid, these minerals released substantial cations (potassium and aluminum ions accounted for a large proportion). With the introduction of cations, the iron and magnesium ions in clay minerals were replaced and gradually transformed into illite around montmorillonite clay mineral aggregates. Owing to the continuous ion exchange process during the transformation of clay minerals, the edge reflection effect of layered crystals of illite/montmorillonite mixed clay minerals was great. Under SEM, the brighter the edge of such clay minerals, the higher the ratio of mixed layers.

4.2 Distribution law of authigenic illite/montmorillonite mixed layers

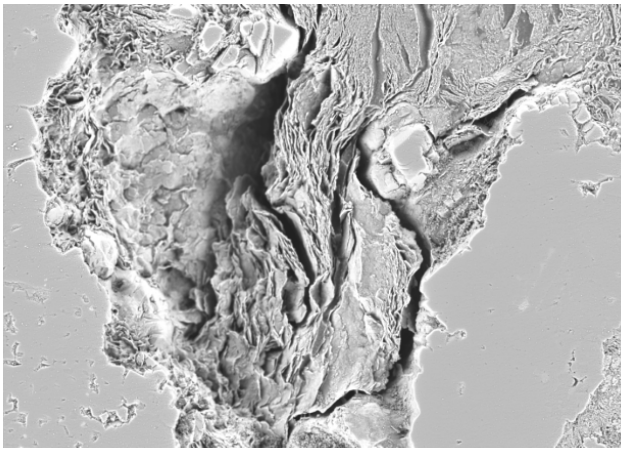
The scanning test in the AMICS quantitative mineral analysis system indicated that the relative proportion of illite/montmorillonite mixed layers in the Mahu Sag was relatively high, with an average content of >60%; however, the relative content of montmorillonite was less, generally less than 1%. When discussing the evaluation of water sensitivity damage of reservoirs in this area, the swelling characteristics of illite/montmorillonite mixed clay minerals when encountering external fluids should be mainly considered. In accordance with the quantitative analysis results of minerals in illite/montmorillonite mixed layers, the regional distribution law of illite/montmorillonite mixed layers in the study area was clarified, which provided data support for selecting the oilfield water injection development scheme and fracturing fluid. The planar distribution map of illite/montmorillonite mixed clay minerals in the first and second members of the Upper Wuerhe Formation was drawn on the basis of the quantitative analysis results of AMICS minerals.



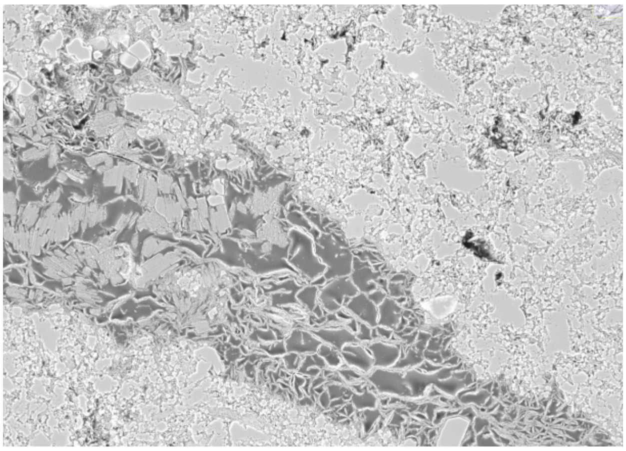
(a) Flocculent and filamentary illite/montmorillonite mixed clay minerals dispersed in intergranular pores



(b)Honeycomb-shaped illite/montmorillonite mixed clay minerals filled in pores in the form of dispersed particles



(c) Pore-lined illite/montmorillonite mixed clay minerals filled in pores in aggregate form



(d) Growth of bridging-type illite/montmorillonite mixed clay mineral crystals from pore walls to pore space

Fig. 2. Occurrence state and characteristics of illite/montmorillonite mixed layers in the study area under SEM

(1)Longitudinal distribution characteristics of illite/montmorillonite mixed layers

With the X001 Well in the southwest of the Mahu Sag as an example, the main clay minerals in the Upper Wuerhe Formation reservoir of the X001 Well were mainly divided into four categories (illite/montmorillonite mixed layer, illite, chlorite, and kaolinite). The relative mass fraction of illite/montmorillonite mixed layers was quite large, with the average relative content exceeding 60%. The proportion of other clay mineral types (mainly illite, chlorite, and kaolinite) in the total mass fraction of clay minerals decreased one by one, with average relative contents of 14.1%, 12.5%, and 3.6%, respectively. In the same interval, the vertical mineral characteristic distribution law in the X001 Well showed a cyclical change, and the relative content of illite/montmorillonite mixed clay minerals increased with the increase in depth. The sampling points covered the reservoir and mudstone interlayer of the first and second members of the Upper Wuerhe Formation in the X001 Well. The histograms of vertical mineral quantitative distribution characteristics of a single well were fitted in accordance with the experimental test results (Figure 3). From the vertical distribution curve of minerals, the content of illite/montmorillonite mixed clay minerals was affected by the hydrodynamic changes near the scouring surface, and the relative content was greatly increased. Owing to the enhancement of hydrodynamic force, ion exchange was frequent, which promoted the transformation and formation of illite/montmorillonite mixed clay minerals. The closer to the bottom of the reservoir, the greater the change near the scouring surface, and the maximum increase in the relative content of illite/montmorillonite mixed clay minerals exceeded 10%.

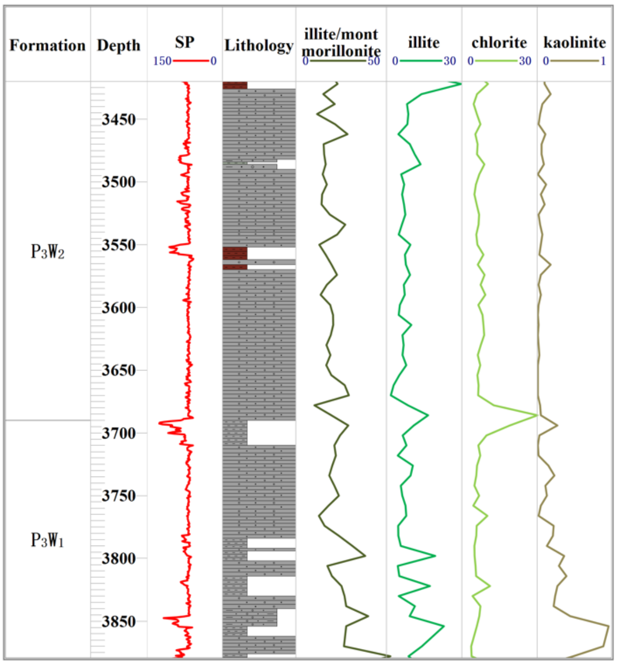
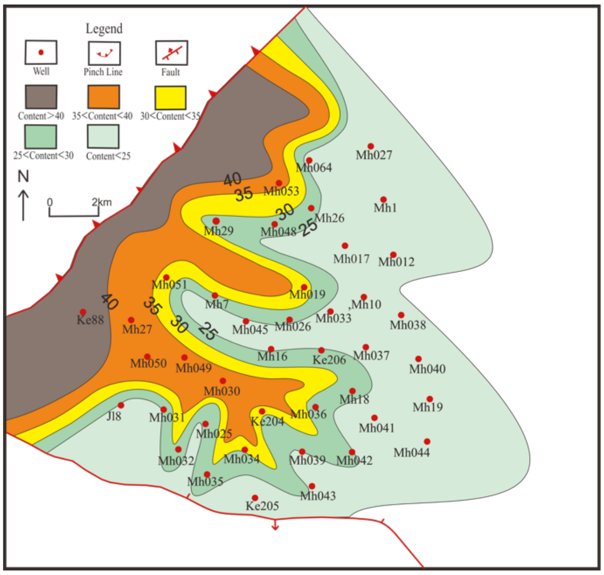


Fig.3. Vertical variation diagram of relative mass fraction of clay minerals in the first and second members of the Upper Wuerhe Formation in the Mahu X001 Well

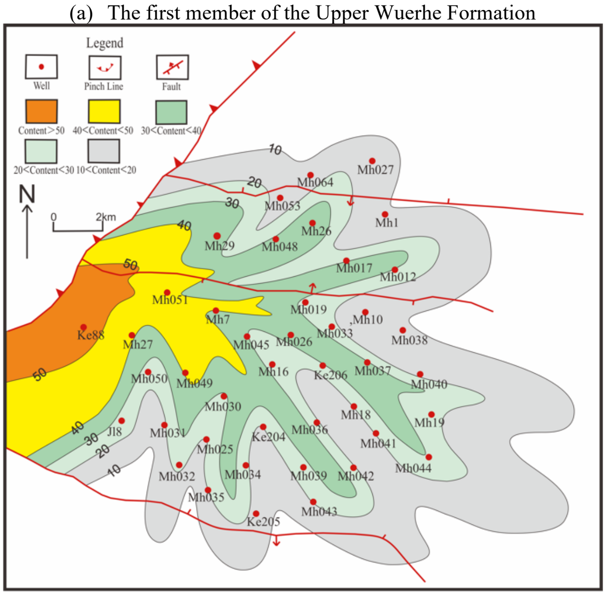
(2) Planar distribution characteristics of illite/montmorillonite mixed layers

The first member of the Upper Wuerhe Formation in the Mahu Sag was mainly composed of fan prodelta deposits, and alluvial fan sedimentary microfacies developed near the erosion line in the northwest. Fan prodelta deposits also developed in the second member of the Upper Wuerhe Formation, but compared with that in the first member of the Upper Wuerhe Formation, the provenance supply was reduced, the lake level rose, and lake deposits developed in the east. In this study, the quantitative analysis results of illite/montmorillonite mixed clay minerals in the Upper Wuerhe Formation of 30 main production wells in the Mahu Dag were plotted as a plane distribution map. This map could not only reveal the planar distribution characteristics of illite/montmorillonite mixed clay minerals but also facilitate the subsequent judgment and analysis of the main controlling factors of illite/montmorillonite mixed clay minerals.

The planar distribution characteristics of illite/montmorillonite mixed clay minerals in the Upper Wuerhe Formation were described as follows: Near the erosion line in the northwest of the Mahu Sag, the content of illite/montmorillonite mixed clay minerals was relatively high, with the relative mass fraction exceeding 80%. The content of illite/montmorillonite mixed clay minerals was 10%-20% at the position where the sedimentary microfacies of a fan-shaped channel developed. From the planar distribution map of sedimentary microfacies of the Upper Wuerhe Formation in the Mahu Sag, the relative content of illite/montmorillonite mixed clay minerals decreased along the direction of the far end of the river. According to the occurrence state analysis of clay minerals in the micropore structure, diagenesis was one of the main reasons for the large-scale development of illite/montmorillonite mixed clay minerals in the study area (Figure 4).



(a) The first member of the Upper Wuerhe Formation



(b) The second member of the Upper Wuerhe Formation

Fig.4. Planar distribution map of the relative content of illite/montmorillonite mixed clay minerals in the study area

4.3 Main controlling factors of authigenic illite/montmorillonite layer distribution

In this study, consistent with the previous results on the sedimentary characteristics in the study area, the ion exchange frequency, the degree of material supply, and the change in the sedimentary environment exerted a combined action on the spatial distribution of clay minerals in authigenic illite/montmorillonite mixed layers. Specifically, the change laws of authigenic illite/montmorillonite layer distribution were investigated mainly from two aspects: the provenance supply degree of clay minerals in illite/montmorillonite mixed layers and the changes in the sedimentary environment.

(1) Material basis

The formation of illite/ montmorillonite mixed layers was associated with the decomposition of potassium-rich minerals. The formation process of illite/montmorillonite mixed layers was presented as follows: K^+ and Al^{3+} entered montmorillonite, and the substitution of Fe^{3+}, Mg^{2+}, and Si^{4+} resulted in the formation of clay minerals in illite/montmorillonite mixed layers. Under the background of increasing buried depth and temperature, montmorillonite dehydrates and octahedral Al^{3+} replaced tetrahedral Si^{4+}, which increased the negative charge between layers; thus, K^+ entered the crystal layer and began to form clay minerals in illite/montmorillonite mixed layers. The introduction of K^+ and Al^{3+} was mainly related to the decomposition of feldspar, mica, and other minerals. The Al^{3+} in the study area might have resulted from the decomposition of kaolinite minerals and K^+ derived from many sources, including the corrosion of igneous rock debris and the leaching of clastic mica or alkali feldspar.

According to the high-resolution SEM imaging and AMICS mineral quantitative results, the reservoir in the study area was mainly composed of silicate minerals, including quartz with silica as the main component and feldspar rich in sodium and potassium elements. The mineral content of feldspar was 8%–35%, with an average of 20.4%, of which the average mineral content of potash feldspar was 5.2% and that of albite was 17.1%. The relatively large mineral component particles and feldspar particles in the Upper Wuerhe Formation reservoir were not stable and easily eroded into clay minerals, such as illite/montmorillonite mixed layers, because of the hydrodynamic changes of the sedimentary environment during the reservoir formation. Rock thin section identification results indicated that the content of tuff cuttings in the reservoir of the Mahu Sag was high, and the phenomenon of clayey was widespread. The main reason for this phenomenon was that in the early diagenetic stage, owing to frequent volcanic activities, a large amount of tuff debris was deposited and stored in the reservoir. With the passage of time, the reservoir with tuff debris was buried deeper and deeper, and the formation temperature was positively correlated with the buried depth. In the high-temperature and high-pressure environment, the illite/montmorillonite mixed clay minerals, which were transformed from the alteration of a large amount of tuff debris, were wrapped, in quantity, at the margin of rock particles or filled in intergranular pores, finally forming illite/montmorillonite mixed clay mineral shells in the reservoir. The above findings implied that the main material bases for the formation of illite/montmorillonite mixed clay minerals were the feldspar skeleton and tuff debris rich in potassium ions.

(2) Hydrodynamic conditions

The necessary condition for the transformation between minerals lied in a relatively open diagenetic system and fluid field characteristics in the reservoir. Illite/montmorillonite mixed clay minerals were a kind of occurrence state of clay minerals in the transformation process under diagenesis. In addition, clay minerals could be smoothly transformed only in an open fluid environment. The Upper Wuerhe Formation of the Mahu Sag belonged to conventional pressure, and a relatively low-pressure field would reduce the stability of bound water in strata and thus accelerate the transformation of all kinds of clay minerals. K+ ion exchange was required in the transformation of montmorillonite into illite, so the content of illite/montmorillonite mixed clay minerals increased gradually with the increase in depth. In particular, near the scouring surface was usually a release zone of fluid pressure, which increased the exchange frequency between ions and gradually elevated the content of illite/montmorillonite mixed clay minerals.

Given 280 samples of the Upper Wuerhe Formation from 30 wells in the study area, the particle radius of the samples was counted. With the increase in the radius of rock particles (Table 1), the relative content of illite/montmorillonite mixed clay minerals gradually increased. That is, the average particle size of sandy conglomerate was 1000-2000 μm, and the relative content of illite/montmorillonite mixed clay minerals was 82%. The average particle size of coarse sandstone was 500–1000 μm, and the relative content of illite/montmorillonite mixed clay minerals was 61%. The average particle size of coarse pebbled sandstone was 800-1200 μm, and the relative content of illite/montmorillonite mixed clay minerals was 77%. The average particle size of medium sandstone was 250–500 μm, and the relative content of illite/montmorillonite mixed clay minerals was 56%. The average particle size of medium pebbled sandstone was 400–800 μm, and the relative content of illite/montmorillonite mixed clay minerals was 72%. The average particle size of fine sandstone was 125-250 μm, and the relative content of illite/montmorillonite mixed clay minerals was 53%. The average particle size of fine pebbled sandstone was 200–400 μm, and the relative content of illite/montmorillonite mixed clay minerals was 64%. This result revealed that the larger the rock particle sizes in the reservoir, the poorer the separation, and the better it was for the formation of illite/montmorillonite mixed layers. On the contrary, the smaller the particle size, the better the separation, and the worse it was for the formation of illite/montmorillonite mixed layers.

Table 1. Samples of different particle sizes and lithologies in the study area and the relative content of illite/montmorillonite mixed clay minerals

S/N	Lithology	Average particle size (μm)	Relative content of illite/montmorillonite mixed clay minerals (%)
1	Sandy conglomerate	1000-2000	82
2	Coarse sandstone	500-1000	61
3	Coarse pebbled sandstone	800-1200	77
4	Medium sandstone	250-500	56
5	Medium pebbled sandstone	400-800	72
6	Fine sandstone	125-250	53
7	Fine pebbled sandstone	200-400	64

Based on the sedimentary facies characteristics of the Upper Wuerhe Formation, the content of montmorillonite was almost zero in the sedimentary microfacies of the fan channel, and nearly all montmorillonite was transformed into illite/montmorillonite mixed clay minerals. Clay minerals could be more easily transformed in the underwater sedimentary environment than in the terrestrial sedimentary environment. The pore water liquidity in the sand body in prodelta subfacies was also better than that in other sedimentary microfacies, increasing the frequency of the transformation of montmorillonite into illite.

5. Conclusions

To explore the distribution law and the main controlling factors of illite/montmorillonite mixed clay minerals, the illite/montmorillonite mixed clay minerals in the sandy conglomerate reservoir of the Upper Wuerhe Formation were identified and analyzed via AMICS from the perspectives of mineral composition and diagenesis. The following conclusions could be drawn:

(1) The clay minerals in the sandy conglomerate reservoir of the Upper Wuerhe Formation in the study area were mainly authigenic illite/montmorillonite mixed clay minerals, which occurred in the reservoir in quantity because of diagenesis. Substantial illite/montmorillonite mixed clay minerals were filled in intergranular dissolved pores, and most of them developed along quartz particles in flocculent and pore-lined shapes. A small quantity of illite/montmorillonite mixed clay minerals were semifilled in pores in filamented and thin-sheet forms, and the remaining pore space could serve as the oil and gas storage and seepage channel.

(2) The SEM and AMICS energy spectral analysis results indicated that the dissolution of acidic fluids in the reservoir in the study area played a constructive role in the transformation of illite/montmorillonite mixed clay minerals, increasing the transformation frequency of minerals. In the underwater sedimentary environment, the intensity of the fluid was an important factor deciding the transformation frequency of clay minerals. In a sedimentary environment with relatively weak fluids, the exchange frequency between cations in feldspar and clay minerals prevented the transformation of various clay minerals to some extent. Near the scouring surface of the sandstone–mudstone thin interbed, the ion exchange frequency was promoted because of the relatively large particle size of sandstone and the strong hydrodynamics, which facilitated the transformation and formation of all kinds of clay minerals.

In this study, laboratory experiments and theoretical research were combined, and a precise quantitative evaluation method for illite/montmorillonite mixed clay minerals in sandy conglomerate reservoirs based on AMICS mineral quantitative analysis technology was proposed. The revealed spatial distribution law of illite/montmorillonite mixed clay minerals and the main controlling factors can be referenced to formulate the follow-up development scheme for all kinds of sensitive reservoirs in oilfields, preventing reservoir damage in the developmental stage, which will affect the final yield. In consideration of the lack of actual data on field production, the means of production and the results of this study can be combined and modified to achieve more accurate evaluation of reservoir sensitivity.

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References

[1] Y.P. MA,*et al*, "Sedimentary characteristics and controlling factors of fandelta of the Upper Urho Formation of Permian in Mahu Sag," *Lithol. Reserv.*, vol. 33, no.1, pp. 57-70, Feb. 2021.

[2] J. W. Yu,*et al*, "Diagenesis and Diagenetic Facies of Upper Wuerhe Formation in the Shawan Sag," *Geosci.*,vol.36,no.4,pp.1095-1104,Aug.2022.

[3] A. El-Shater,A.M. Mansour, M.R. Osman, A.A.A.E. Ghany,A.A. El-Samee, "Evolution and significance of clay minerals in the Esna Shale Formation at Dababiya area," *Egypt. J. Petrol.*,vol.30,no.2,pp. 9-16,Jun.2021.

[4] X. Zhou,*et al*, "XRD-based quantitative analysis of clay minerals using reference intensity ratios,mineral intensity factors, and full pattern summation methods: A critical review," *Solid Earth SCI.*,vol.3,no.1,pp.16-29,Mar.2018.

[5] T. Runcevski, C. M. Brown, "The Rietveld refinement method: Half of a century anniversary,"*Cryst. Growth Des.*, vol.21,no.9, pp.821-4822, Sep.2021.

[6] L. J. Ma, *et al*, "Study on mechanism and theoretical model of tool wear in fluorophlogopite glassceramics turning,"*J. Mater. Process. Tech.*, vol.275, pp.1-10, Jan.2020.

[7] Fu, W., Peng, Z., Luo, P., et al, "Accuracy Testing of Soil Mineral Quantification by XRD-Rietveld Full-Spectrum Fitting Method: Simulation Experiments and Comparison with Traditional Method," *Spectrosc. Spect. Anal.*,vol.40,no.3,pp. 950-955, Mar. 2020.

[8] Q. Wang, L. Ma, K. J. Huang,Z.Y. Lei,S.Y. Xie, "Quantitative Analysis of Kaolinite, Illite and Montmorillonite by X-ray Diffraction," *GuiZhou Geol.*, vol.38,no.1, pp:71-78, Jan. 2021.

[9] B. Andrew, D. Jeff, S. Karen, "Large Scale GAN Training for High Fidelity Natural Image Synthesis," in *Proc. the Int. Conf. Learn. Represent.*, New Orleans, LA, USA, 2019, pp.20-26.

[10] P.A.E.P.V. Strandmann, S.A. Kasemann,J.B. Wimpenny, "Lithium and Lithium Isotopes in Earth's Surface Cycles," *Elements*, vol.16,no.4, pp.253-258, Feb. 2020.

[11] B. Guo, X. Zhu, A. Dong, B. Yan, G. Shi, Z. Zhao, "Mg isotopic systematics and geochemical applications: A critical review," *J. Asian Earth Sci.*, vol.176, pp.368-385, Jun. 2019.

[12] W. Zhao, W.F. Tan, "Quantitative and structural analysis of minerals in soil clay fractions developed under different climate zones in China by XRD with Rietveld method, and its implications for pedogenesis,". *Appl. Clay Sci.*, vol.162, pp.351-361,Sep. 2018.

[13] T. Hrstka, P. Gottlieb, R. Skála, K. Breiter, D. Motl, "Automated mineralogy and petrology-applications of TESCAN Integrated Mineral Analyzer (TIMA),". *J. Geosci.*, vol.63,no.1, pp.47-63,Jan.2018.

[14] X. Xie, L. Li, Q. Yuan, F. Wu, R.A.M. Analysis, "Grain Size Distribution of Organic Matter and Pyrite in Alum Shales Characterized by TIMA and Its Paleo-environmental Significance," *Rock Miner. Anal.*, vol.40,no.1, pp.50- 60, Jan. 2021.

[15] S. Graham, N. Keulen, "Nanoscale automated quantitative mineralogy：A 200-nm quantitative mineralogy assessment of fault gouge using Mineralogic," *Minerals*, vol.9,no.11, pp.665,Nov.2019.

[16] Q. Chen, *et al*, "Principle of automated mineral quantitative analysis system and its application in petrology and mineralogy:An example from TESCAN TIMA," *Miner. Deposits*, vol.40,no.2, pp.345-368,Apr.2021.

[17] C.L. Ma, X.H. Jing, L.Q. Jia,H. Li,A.G. Wang, "Application of Mineral Automatic Quantitative Analysis System in the Petrology and Mineralogy Analysis of Aluminiferous Rock Series:Taking Taiyuan Formation in the Longdong area as an example," *Acta Sedimentolog. Sinica*, to be published. Accessed: Jun. 25, 2023. doi: 10.14027/j.issn.1000-0550.2023.034. [Online]. Available: https://doi.org/10.14027/j.issn.1000-0550.2023.034

[18] M.Y. Wang, Y.W. Xiao, X.J. Qi, "Process mineralogy and its influence on metallurgy technology of a copper-cobalt oxidized ore in Congo (DRC)," *Conserv. Util. Miner.Resour.*, vol.40,no.1, pp.118-123,Jan. 2020.

[19] G. Scott, K. Wu, Y. Zhou, "Multi-scale image-based pore space characterization and pore network generation: Case study of a North Sea sandstone reservoir," *Transport Porous Med.*,vol.129,no.3, pp. 855-884,Jun. 2019,

[20] D. Zhu, X.J. Sun, G.Z. Cheng, F. Yang, S.Y. Pan, S. Liu, "Analysis of the Occurrence of Cu-Co Elements in Smelting Slag by AMICS," *Nonferr. Metal.(Miner. Process)*,no.4, pp.10-16,Aug. 2023.

[21] W.S. Luo, "Ways to Improve the Ability of Rock and Mineral Analysis and Testing in the Geochemical Laboratory," *Chem. Eng. Des. Commun.*, vol.49,no.4, pp.90-98,Apr. 2023.

[22] R. Sousa, *et al*, "Use of mineral liberation quantitative data to assess separation efficiency in mineral processing:Some case studies," *Miner. Eng.*, vol.127, pp.134-142,Oct. 2018.

[23] Y.F. Zhang, Y. Fan, J. Chen, L.H. Liu, M.M. Li, "Establishment of a research workflow for occurrence state of critical metal in ore concentrate powder: A case study of the cobalt-rich sulfur ore concentrate powder from the Middle-Lower Yangtze River Valley Metallogenic Belt,China," *Acta Petrol. Sin.*, vo.37,no.9, pp.2791-2807, Sep. 2021.

[24] Z.X. Li, M.K. Qin, X.Y. Liu, W.Q. Wang, J. Wang, L.L. Li, "Characteristics, genesis and research significances of multielements enrichment layer of black rock series," *World Nucl. Geosci.*, vol.39,no.1, pp.14-26,Jan. 2022.

[25] L.M. Deng, *et al*, "The uranium occurrence and mineral composition characteristic of the DL uranium mineralized zone in southwestern Songliao basin," *Ur. Geol*,vol.37.no.2, pp.192-204,Apr. 2021.

[26] L.G. Wen, Q. Fu, M.X. Jia, Q. Wang, M.M. Cai, J.J. Zhao, "Quantitative investigation of fine-grained gold minerals by automated process mineralogy analyzing system," *Nonferr. Met. Eng.*, vol.12,no.11, pp.76-84, Nov. 2022.

[27] A. Davarpanah, B. Mirshekari, "Sensitivity analysis of reservoir androck properties during low salinity water injection," *Energy Rep.*, vol.5, pp.1001-1009, Nov. 2019.