

Review of Mixed Sedimentation Studies

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Abstract: Since the 1950s, mixed sedimentation has come into people's attention, and has gradually become the research direction of sedimentology. On the basis of previous studies, the research progress of mixed deposition at home and abroad is summarized, and some problems and prospects of mixed deposition are put forward. Mixed sediment is widely developed in Marine and lake sedimentary environments. As a special sediment with complex sedimentary patterns, it is controlled by many factors such as terrigenous supply, climate change, sea level change, hydrodynamic conditions, tectonic action and so on. The genetic types of mixed sediments generally include intermittent mixing, facies mixing, insitu mixing and source mixing. Mixed sedimentary rocks include mixed sedimentary rocks and mixed sedimentary strata. The classification of mixed sedimentary rocks was first proposed by predecessors, and now it adopts more three-end element method. Mixed deposition has important oil and gas geological significance, and there are still some problems to be solved, including the establishment and improvement of sedimentary models in different sedimentary environments, the unified naming and lithology identification of mixed deposits, and the prediction of mixed deposits, etc. These studies are of great significance to the oil and gas exploration and development of mixed deposits.

Keywords: Mixed Deposition; Mixed Stone; Mixed Layer System; Sedimentary Model.

1. Introduction

Mixed deposition is a relatively special type of deposition, which is of great significance for understanding its deposition dynamics and related oil and gas exploration and development. The traditional sedimentological view is that one of the favorable conditions for the formation of carbonate sediments is clear water, and the injection of materials such as silicic and pyroclastic rocks will have a certain impact on carbonate sediments, so the two sediments will not mix together, however, starting from the 1950s, geologists have found a large number of mixed deposition events. Therefore, it is gradually realized that mixed sedimentation is a common sedimentary phenomenon in nature [1-5]. Subsequent studies by relevant scholars have shown that clastic rock and carbonate rock are not two completely independent sedimentary domains, but belong to a unified continuum, and mixed deposition is between them, but mixed deposition can only occur when terrigenous supply and carbonate production are in balance[6-7]. Mixed sediments not only developed in ancient sedimentary environments, but also widely developed in modern sediments[8-10].

Domestic and foreign scholars have put forward related concepts such as "mixed sediment" and "mixed rock"[11-13], laying a foundation for related studies on mixed sediment, and pointing out that mixed sediment can be widely developed in terrestrial lakes, Marine shelf, slope and platform and other environments[14-15]. At present, the relevant researches on mixed sediments and mixed deposits mainly include the sedimentary environment, lithology classification and naming, development characteristics, genetic mechanism, sedimentary controlling factors, as well as the discovery of mixed sedimentary oil and gas reservoirs and the exploration of oil and gas geological significance[16-28]. This paper summarizes the research results of mixed sedimentation at home and abroad, reviews the research status of mixed sedimentation, and puts forward some problems and prospects of the current research of mixed sedimentation.

2. Related Concepts of Mixed Deposition

Mixed sedimentation is a sedimentary phenomenon with special sedimentary mechanism and significant significance, and widely existed in nature. As early as the 1950s and 1960s, Maxwell[3], a foreign scholar, discovered the phenomenon of mixed sedimentation when studying the Great Barrier Reef of Australia. In 1977, Button[4] discovered and studied the lithology and mineral composition of mixed sedimentation in South Africa. It was not until 1984 that Mount[12] proposed the concept of "mixed sediment" for the first time, thus laying the theoretical foundation for the study of mixed sediment. Zhang Jinquan and Ye Hongzhan[14] were the first to study mixed sediments in China. They believed that mixed sediments could be composed of mixed sediments composed of carbonate and terrigenous clastic structures, and "pure" carbonate and clastic sediments in the form of interlayer, interlayer and transverse phase transition. Yang Chaoqing[13] first put forward the term "mixolite" in 1990, which was widely adopted by later scholars. Sha Qingan[21] believes that mixed sediments are typical products of mixed sediments, which are mixed sediments in a narrow sense. Corresponding to this, mixed sediments in a broad sense include mixed sediments, terrigenous clasts and carbonate layers, which constitute alternating interlayers or interlayers. Guo Fusheng[29] named the interlayers and interlayers in the stratigraphic section formed frequently alternately between terrigenous clastic rocks and carbonate rocks as "mixed strata". Mixed sedimentary rocks and mixed sedimentary series together constitute a broad sense of mixed sedimentary, which improves the previous division of mixed sedimentary in a narrow sense and a broad sense.

3. Mixed Sedimentary Types

Mount[12] proposed for the first time four types of mixed

sediments: intermittent mixing, phase mixing, in-situ mixing, and parent mixing. Later, when scholars studied their respective regions, different mixed sedimentary models were proposed on this basis to complement and perfect the mixed sedimentary types.

(1) Intermittent mixing

Intermittent mixing is sedimentary mixing caused by high intensity intermittent events. Such as storms, debris flows, etc., transport sediment from the original sedimentary environment to another new sedimentary environment. Such sedimentary events are often characterized by abrupt sedimentation. Tucker[30] discovered fine-grained quartz sandstone in mixed sediments from the late Precambrian subtidal zone in southern Norway, which was analyzed to have been formed by storm springs brought in from the near shore. Yang Chaoqing[13] studied the sedimentary environment and composition of the Middle Devonian Qujing Formation in Qujing, Yunnan Province, and found that it was due to intermittent mixing caused by sudden strong currents (most likely storm currents). Ding Yi et al[31] found in their study on mixed lacustrine sediments in Da'anzhai Member of the Lower Jurassic Ziliujing Formation in Longgang area, central Sichuan that scattered storm shells and thin layers of storm sand can be seen in this area, in which storm shells are more commonly developed, and storm shells mainly come from shell beach sedimentary environment, while storm sand mainly comes from shallow lake sand bar sedimentary environment. This suggests that storms are one of the main causes of intermittent mixing.

(2) phase mixing

Phase mixing means that sediment mixing occurs in the boundary region between different phases. According to Walther's facies law, there is no strict dividing line between different sedimentary zones, and there are mixed sedimentary facies transition zones between carbonate sedimentary facies and clastic sedimentary facies. Zhang Xionghua[33] found in his study of the Upper Carboniferous sedimentary environment on the margin of Xuefeng ancient land in Yuanling, Hunan Province, that this area is a set of mixed sediments with alternating occurrence of carbonate rocks and terrigenous clastic rocks, which reflects frequent transgression and retrograde, and a gradual transition relationship between upper and lower strata, which is a typical mixed facies deposition. Phase mixing is one of the most commonly developed mixed sedimentary types, and its composition is mainly controlled by the dominant facies.

(3) In-situ Mixing

In situ mixing is formed by mixing in situ dead calcareous organisms accumulated above the basement with in situ or near in situ residual terrestrial source clasts, usually forming bioclast-dominated mélange, which is called in situ mixing deposition because the formation process contains locally in situ-formed sediments[34]. Li Xianghui et al[35], in their study of Devonian mixed sedimentation in the Longmenshan area, found that the mixing type I of the sedimentary type in this study area is typical of in situ mixing. When the storm passed, new communities rapidly entered this ecological region, and the benthic communities dominated by brachiopods and echinoderm communities flourished in large quantities, rapidly producing more calcium carbonate deposits and constituting in situ mixing with the background shelf mud.

(4) Parent-source mixing

Parent-source mixing is a mixed deposition formed by

mixing and redeposition with another component in situ controlled by tectonic action. Wang Huilai et al[36] found that the lithological characteristics and distribution of the Lower Cretaceous lake-phase dacites in the Erlan Basin were mainly controlled by the lithology of the parent source area, which is a typical type of parent-source mixing.

The classical mixed sedimentary type of Mount[12] has been recognized by many scholars since it was proposed, and its correctness has also been verified by a large number of examples. Later scholars divided different mixed sedimentary types based on these four mixed sedimentary types according to the sedimentary characteristics of the study area. When studying the mixing of biocarbonate clasts and terrigenous clasts in modern reef areas, Wang Guozhong[37] divided them into three categories: random mixed sediments, phase mixed sediments and random-phase mixed sediments. On the basis of summarizing previous studies, Zhang Xionghua[33] classified the mixed sedimentation of terrigenous clastic and carbonate into five types: event-abrupt sedimentary mixing, facies marginal gradual sedimentary mixing, in-situ sedimentary mixing, erosion resedimentary mixing, and karst interspersed sedimentary mixing. Dong Guiyu[38-39], based on the actual data of Jiyang Depression in Bohai Bay Basin and Shimen Yangjiaping in Hunan Province, divided mixed sedimentation into three types according to the principle of "sedimentary events + profile structure", namely gradual mixed sedimentation, abrupt mixed sedimentation and compound mixed sedimentation. Compound mixed deposit is subdivided into compound mixed deposit I and compound mixed deposit II. The division of this type takes into account the mixed deposition of composition and structure, emphasizing the influence of the event on the profile structure while changing the composition [52]. Xu Wei et al[26] put forward the classification of mechanogenic facies and biogenic algal mix-stones according to the characteristics of mix-stones in saline lake basins. Mark et al [40] proposed a classification scheme of mixed sedimentary types applicable to continental saline lake basins in the study of mixed sedimentary sediments of Permian Lucaogou Formation in the Jigmsar Depression, combining the factors such as the composition of mixed sediments, provenance changes and sedimentary environment, and divided the mixed sedimentary types into three types: "facies margin mixing", "parent source mixing" and "abrupt mixing". Table 1 summarizes the previous research progress on the development of different mixed sedimentary types in different sedimentary environments.

4. Mixed Deposition Nomenclature and Classification

4.1. Classification and Nomenclature of Mixed Deposits

Mixed deposit is the product of mixed deposition in a narrow sense [21]. From the perspective of composition structure, mixed deposit is usually a set of rock assemblage, which is composed of a variety of rocks in accordance with certain laws, rather than a single rock type. Therefore, it is necessary to distinguish and name the rocks according to the content of each component, but there is no uniform rule for the classification and naming of mixed deposits.

Table 1. Developmental types and characteristics of mixed sediments

Number	research area	stratum	Mixed sedimentary type	Sedimentary characteristics	Document source
1	Southern Norway	Late Precambrian	Intermittent mixing	Fine grained quartz sand, storm surge transport from nearshore to subtidal environment	Tucker[30]
2	Qujing in Yunnan Province	Qujing Formation of Middle Devonian Series	Intermittent mixing	Sudden events lead to intermingling of sediments and frequent alternations of sandstone, carbonate and mudstone	Yang Zhaoqing [13]
3	Pingchang, Sichuan Province	Da 'anzhai member of Ziliujing Formation, Lower Jurassic	Intermittent mixing	Thin layers of storm shell and storm sand, interlayer of shell limestone and mudstone, interlayer of sand-mudstone in shell limestone, interlayer of shell limestone, mudstone and mixed stone are developed	Ding Yi et al [31]
4	Gulf of Mexico	modern	Intermittent mixing	The tidal flow transforms and mixes the living organisms and sand bodies to form clastic sandstone in and around the tidal channel	Davis et al[48]
5	Central Hunan	Upper Carboniferous Series	phase mixing	Carbonate rocks and terrigenous clastic rocks appear alternately, and the upper and lower strata are in gradual transition	Zhang Xionghua [33]
6	Albemarle Basin, North Carolina, USA	Holocene series	phase mixing	A mixture of terrigenous clastic and Marine biogenic carbonates (algae and coral aragonites, algal benthic foraminifera mollusks, and high magnesium calcite of gastropods)	Coffey et al[41]
7	Jiangshan in Zhejiang Province	Outangdi Formation of upper Carboniferous series	phase mixing	In shallow coastal environment, sandstone and carbonate interlayer, fluvial clastic rock and Marine carbonate interlayer	Guo Fusheng et al [42]
8	Montana, USA	Lower Ellis Formation of Middle Jurassic	phase mixing	The granulolimestone and the clastic rocks of the tidal flat during the regressive period constitute the mixed sedimentary series	Parcell et al[46]
9	North of Dongying, Shandong Province	Paleogene Sha Member	phase mixing	Intermittent flooding and unstable lake wave action lead to mixed spiral bank deposits between near-shore underwater fan bodies	Meng Zhaohong et al [47]
10	Longmen Mountain, west Yangtze	Devonian period	In-situ Mixing	The background deposit is mud, mainly shale and calcareous shale, which may contain sand, gray matter and exogenous gravel.	Li Xianghui et al [35]
11	Cibao Basin, Dominican Republic	Late Miocene - Pliocene	In-situ Mixing	It consists of a mixture of bone fragments (mainly coral) in varying proportions and pelitic (silt) siliceous sediments	McNeill D F.et.al[43]
12	Southern Italy	Fourth period	In-situ Mixing	Shallow water mixed biosilica deposition; Repeated transition from offshore to shoreline environment	Chiarella D[44]
13	Erlian basin	Lower Cretaceous	parent-source mixing	Mixed deposits occur when carbonate rocks and pyroclastic rocks or carbonate rocks and granite are injected together into lake basins	Wang Huilai [36]
14	Bohai Sea	Paleogene system	parent-source mixing	The typical conglomerate is formed under the influence of carbonate parent rock, and the rock generally contains carbonate debris	Xu Wei et al [32]
15	Loreto Basin, Mexico	Pliocene epoch	parent-source mixing	Composed of sand-gravel grade carbonate clasts mixed with pyroclastic sand and gravel, the facies domain from proximal to distal includes shell conglomerate with rich and poor matrix, calcarenite, and bioturbated calcarenite sandstone	Dorsey R J[45]
16	Northern Jiangsu basin	The Fu 2 member of Jinhu Sag	parent-source mixing	Under the action of lake wave, storm wave or fault activity, the early coastal terrigenous debris continued to move to the remote carbonate sedimentary area, and finally deposited simultaneously with the carbonate sedimentary area	Huang Jianling et al [49]

In 1985, Mount [15] proposed a preliminary classification scheme of structural components for the first time. The mixed sediments were classified by stereograms of four-terminal siliceous clastic sand, siliceous clastic mud, carbonate clastic (allogenic particles) and plaster (micrite). The four groups are divided into four end elements to form a "tetrahedron", which is marked proportionally on the triangle composed of each three components and divided into several polygonal three-dimensional blocks, each of which represents a mixed component (sediment), and is named respectively. Such as allochemic sandstone (allochemic sandstone), stucco sandstone (micritic sandstone), sandy allochem limestone, muddy micrite (FIG. 1).

In 1990, Yang Chaoqing et al. [13] first proposed the term "mixolite". They classified the mixed sediments with carbonate composition > 25% and terrigenous clastic composition > 10% as mixolite by using three end elements:

terrigenous clastic composition > 10%. According to the content and structure of components in the rocks, a prefix was added before the mixolite to further describe it. Such as quartz-fine sand-stucco mixed stone (Figure 2). On the basis of the three-end-element division proposed by Yang Chaoqing et al., Zhang Xionghua[23] expanded the division scope by calling the mixed sediments with carbonate content of 5%-95% and terrigenous clastic content of 5%-95% in addition to the part of clay > 50% as claystone. Dong Guiyu[39] believes that clay rocks should be classified into terrigenous clastic rocks, so that the classification and naming of mixed aggregates can be carried out on the two elements of terrigenous clastic and carbonate, and the word mixed aggregates need not be used as the central word in the naming of rocks, so mixed aggregates can be divided into four categories: Containing terrigenous clastic - carbonate rocks, terrigenous clastic - carbonate rocks, carbonate-terrigenous

clastic rocks and carbonate-terrigenous clastic rocks. Yan Jihua[50] takes carbonate minerals, clay minerals and felsic minerals as the three end-elements, and takes "fine-grained mixed sedimentary rocks" as the main name. According to the relative content of felsic minerals, carbonate minerals and clay minerals, The fine grained mixed sedimentary rocks are divided into three categories: cloud (ash) fine grained mixed sedimentary rocks, clay fine grained mixed sedimentary rocks and felsic fine grained mixed sedimentary rocks. Yuan Jianying et al. [51] took the total amount of mud, terrigenous clastic particles and carbonate as the three end elements in the classification and naming of the mixed stones. The end element with the highest relative content was designated as the main name, and the other two end elements were

determined as prefixes according to the "three-level nomenclature" of the rocks, and those with content in the range of 25%-50% were designated as "quality" and those with content in the range of 10%-25% were designated as "containing". If the main name is carbonate rock, it is further divided into limestone or dolomite according to the relative content of calcite and dolomite. Ye Maosong et al. [17] established a new lithologic classification system of mixolite with terrigenous detrital material, biogenic carbonate particles and chemically-precipitated carbonates as three component end elements in combination with the composition characteristics of thin sections of the mixolite in the Bohai Sea, and divided the mixolite into 4 categories and 16 subcategories.

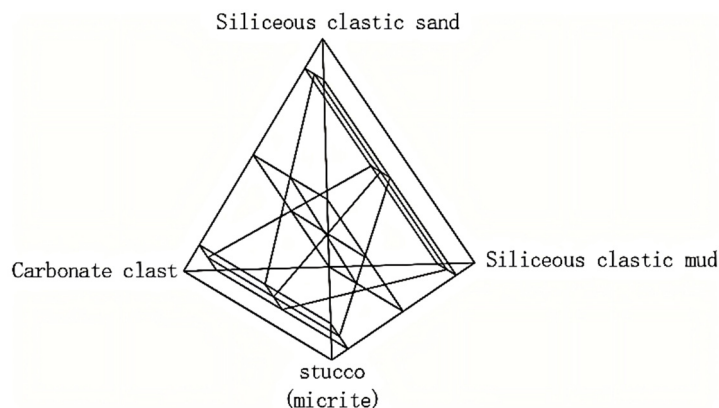


Figure 1. Four-terminal stereogram classification of mixed sediments [15]

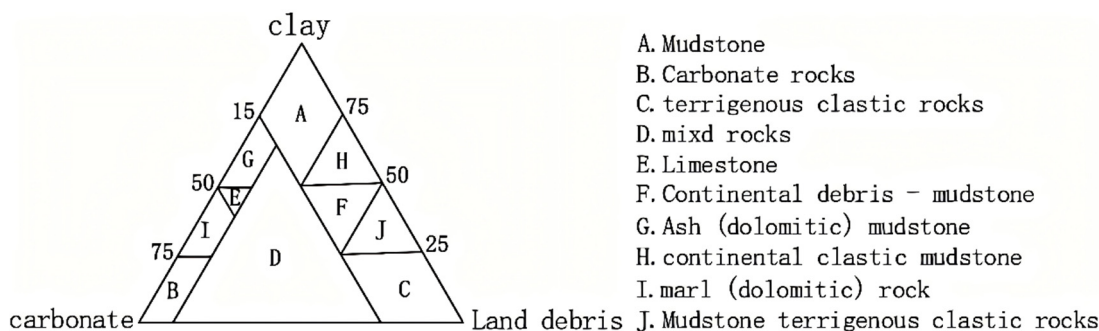


Figure 2. Three terminal classifications of mixed deposits [13]

4.2. Classification and Nomenclature of Mixed Layers

Sha Qingan [21] first proposed in 2001 that the phenomenon of interbedding and interbedding in strata profiles formed frequently alternately between terrigenous clastic rocks and carbonate rocks is also a broad category of mixed sediments. Guo Fusheng[29] later named this interbedded and interbedded combination "mixed stratigraphy", which represents the broad meaning of mixed sedimentation.

Dong Guiyu[39] found that in addition to the interdeposits of terrigenous clasts and carbonates, there are also a large number of interdeposits of terrigenous clasts and mixed sediments, carbonate and mixed sediments, and different types of mixed sediments themselves. Therefore, the mixed sediments can be divided into four categories: the interdeposits of terrigenous clasts and carbonates; Interdeposition of terrigenous debris and mixed sediments; The interaction between carbonate and mixed deposits and the interaction between different types of mixed deposits

themselves. At the same time, it is pointed out that the four types of mixed sedimentary series are more common in the geological profiles of mixed sedimentary development, and they represent different sedimentary environments.

5. The Main Influencing Factors of Mixed Deposition

Although mixed sedimentation is a relatively special sedimentary phenomenon, as a kind of sedimentary event in the historical period, its main influencing factors are similar to other sedimentary events, mainly including terrigenous source supply, climate change, sea level change, hydrodynamic conditions, tectonic action, etc. In most cases, various factors contain each other. Influence each other [14,21,28,32,53].

(1) Terrigenous supply

The supply of terrigenous clastic material directly affects the composition characteristics and development scale of mixed sediments[59]. Terrigenous clastic supply can inhibit the development of carbonate rocks, so different terrigenous

clastic supply quantity and direction directly affect the development of intercalated rocks under the same depositional environment. Huang Jianling et al.[49] found in their study on the sedimentary characteristics of mixolite in the saline faulted lake basin environment that the development of carbonate rocks was inhibited due to the large supply of terrigenous debris, resulting in the overall undevelopment of mixolite. On the contrary, the mixed deposits are more developed. Yan Jihua et al.[50] found in their study on the characteristics of fine-grained mixed sedimentary rocks in the second member of Kongdong Sag, Bohai Bay Basin, that during flood, terrigenous clastic material supply capacity is strong, and a large number of fine silt and clay with suspended loads are transported to deep water area, and fine-grained mixed sediments with high felsic minerals are deposited. The clastic material supply capacity of terrigenous source was weakened, the felsic minerals transported to the deep-water area by suspension load decreased, the sedimentation rate slowed down, and clayey fine-grained mixed sedimentary rocks were formed.

(2) Climatic factor

Climatic factors affect the production of carbonate rocks, the supply of siliceous clastic sediments and the distribution of sediments[54-57]. Climate change mainly affects the development distribution and yield changes of carbonate rocks by influencing precipitation and dry and wet processes, thus playing an important role in controlling the formation and distribution of mixed-stone[58]. When the climate is humid, atmospheric precipitation and surface runoff increase, terrigenous input increases, carbonate deposition is inhibited, and terrigenous debris dominates mixed deposition. When the climate is dry, atmospheric precipitation and surface runoff decrease, terrigenous input decreases, and carbonate dominates mixed deposition[60]. In short, carbonate components, as the main sediments of mixed sediments, are closely related to climatic factors. Carbonate rocks are more developed in arid climates, and siliceous clastic sediments are more abundant in humid climates. About 50% of the tropical shallow sea shelf is related to mixed sediments[61]. Therefore, in the tropical and temperate regions, the intermittent drought-moist climate conditions are more conducive to the formation of mixed sediments.

(3) Sea level change

The rise and fall of sea level affects the progress and intensity of mixed sedimentation from the aspects of controlling the supply of terrigenous materials and the development degree of carbonate rocks[62]. The change of sea level directly controls the migration track of the shoreline, and the change of sea level has obvious control over the supply of terrigenous debris. When the sea level drops, the carbonate yield decreases obviously. In addition, the supply of terrigenous siliceous debris has a certain inhibitory effect on the carbonate production, so when the sea level drops and it is located in the low system domain, siliceous clastic sediments dominate. The change of sea (lake) level also has a direct impact on carbonate productivity. When the depth of sea water is less than 50-100m, it is conducive to the formation of carbonate deposits in large quantities. In addition, when the sea water rise rate is similar to or slightly greater than the growth rate of organisms such as reefs, it is more suitable for the mass reproduction of photosynthetic organisms[28]. In the high water stage, the carbonate platform was submerged by water, which greatly increased the production area of shallow water carbonate and the

probability of mixed deposition[63]. On the contrary, in the low water stage, the shallow water carbonate production area in the Taiwan area was reduced, the carbonate deposition was limited, and the probability of mixed deposition was small[64].

(4) Hydrodynamic condition

Hydrodynamic conditions are the direct driving force for transporting terrigenous debris and carbonate particles, and are crucial factors for controlling mixed deposition[32]. Tidal currents, waves and coastal currents are the main hydrodynamic conditions. Tidal currents and coastal currents can carry beach sand from estuaries or coastal areas to carbonate sedimentary areas, forming a mixture of terrigenous debris, bioclastic particles and biological reefs[21,37,48,60]. Strong hydrodynamic forces promote the transport sediments to mix fully to form mixolite, but too strong hydrodynamic forces may inhibit the formation and deposition of biocarbonate, which is not conducive to mixed deposition.

(5) Tectonism

The influence of tectonic activities on mixed sediments is more obvious in the active continental margin. Tectonic uplift controls the distribution and state of provenance and sedimentary areas, and has a great influence on the supply and supply direction of provenance[65]. Tectonic activities also control mixed sediments by controlling the type and morphology of basins. Fault activity in the slope area affects the mixed sediments of the slope and even the basin. The rise and fall of structures and the overlaying of deposition rates also significantly affect mixed deposition[62]. When the tectonic sedimentation rate is high, the clastic material and the bioclastic material developed in the short intermittent period of the source form a thick mixed deposit, and otherwise the thickness is small[38].

6. Research Status of Mixed Deposition

Although mixed deposition is a relatively special kind of deposition, as a kind of sedimentary event in the sedimentary history period, it has the same potential for oil and gas exploration as pure clastic rock and pure carbonate rock, and its rich oil and gas resources have gradually attracted people's attention[27,31,66-69]. Due to its unique formation process, mixed sedimentary reservoirs are often dense. As one of the types of unconventional oil and gas, mixed sedimentary oil and gas resources are of great significance for the exploration and development of unconventional oil and gas[70]. In recent years, examples of mixed deposits containing oil and gas have been reported at home and abroad. Like the northeast Netherlands Triassic in DeWijk and Wanneperveen gas fields[71], Lower Keuper Formation, Germany Basin[72], Triassic Kum Formation, Kashan Area, Central Iran Basin[73], Permian Lucaogou Formation, Junggar Basin[74], Da Ansai Member, Lower Jurassic Ziliujing Formation, Sichuan Basin[75], Sha-12 Member, Bohai Sea[76] Mixed type oil and gas reservoirs were found in the Paleozoic of Danniudi gas field, northeast Ordos, etc[77].

Ding Yi et al.[31] found in their study on lacustrine mixed deposition in Da 'Anzhai Member of Ziliujing Formation, Longgang area, central Sichuan that mixed deposition was consistent with tight oil formation. The reservoir in this area was characterized by low porosity and low permeability, strong longitudinal heterogeneity, extensive development of source rocks, large area of oil bearing but dispersed oil and gas, etc. Feng In et al.[27] put forward a schematic diagram

of mixed lacustrine and Marine sedimentary facies patterns related to oil and gas reservoirs, which intuitively shows the oil and gas geological significance of mixed sediments. Ye Ziqian et al.[19] analyzed the development characteristics and controlling factors of the Palaeogene mixed deposits in the Huanghe Kou Sag, Bohai Bay Basin, and summarized their sedimentary models. Taking the upper submember of Member 4 of Shahejie Formation in Chenguanzhuang area on the southern slope of Dongying Depression as an example, Peng Jun et al. [20] discussed the sedimentary characteristics, genetic mechanism, sedimentary controlling factors and reservoir property of fine-grained mixed-stone in continental lacustrine basin, and established a lithologic naming scheme suitable for fine-grained mixed-stone in continental lacustrine basin. The lithology identification chart is formed by the intersection of the mudstone index and the mudstone index, so as to identify the lithology effectively in the study area. Liu Xiaojian et al. [79] carried out multi-scale quantitative characterization of the reservoir space of lacustrine mixed deposits in Shahejie Formation, and combined with the fractal characteristics of pore throat, classified and evaluated the pore throat structure of the lacustrine mixed deposits in the study area. Xiao Yanshi et al.[80] took the mixed deposits of Lucaogou Formation in Jimsal Sag, Junggar Basin as an example to classify and distinguish the pore-throat system of the mixed deposits, identify the development characteristics and control factors of the pore-throat system of the mixed deposits, and analyze the influence of each component on the mixing process.

Previous studies on mixed sedimentation have been systematic and comprehensive, from the initial description of the phenomenon of mixed sedimentation to the improvement of basic theories, especially the sedimentary model, genetic mechanism, classification and naming of mixed sedimentary rocks and mixed layers, to the petroleum geological significance of mixed sedimentation, as well as the study on the characteristics, classification and evaluation of mixed sedimentary reservoirs by various research means. This is of great significance to the exploration and development of mixed sedimentary oil and gas reservoirs.

7. Prospects of Mixed Deposition Research

As a special deposit with complex sedimentary mode, mixed sediment is controlled by many factors such as structural setting, sedimentary environment, sea (lake) plane change, tectonic fluctuation, hydrodynamic and climate change, etc. Since it entered people's attention in the 1950s, it has been attracting scholars' attention. However, due to its characteristics such as complex composition, strong heterogeneity, variable sedimentary environment and diverse control factors, mixed sediment has attracted much attention from scholars. There are still some problems to be solved, which is of great significance for the theoretical and practical research of mixed deposition.

(1) The four existing basic mixed sedimentary models were put forward by Mount according to the sedimentary environment of the shallow sea shelf, and most of the sedimentary models proposed by later scholars were improved on this basis. For different sedimentary environments, it is necessary to establish their own sedimentary models, especially for complex sedimentary processes, which are often variable, to establish mixed

sedimentary models under different geological conditions. The clear distribution of mixed sedimentary system plays an important role in the differential accumulation and distribution of oil and gas in mixed sediments.

(2) The classification of mixed sedimentary rocks by predecessors has changed from the three-dimensional four-end element method first proposed to the more three-end element method adopted now. Due to the complexity of mixed deposition, scholars have different division of each end element component and the content boundary value of different components. Therefore, with the further development of mixed deposition research, component content is divided. A unified scheme for classification and naming of mixed sedimentary rocks is established.

(3) It is a common technical means to identify reservoir lithology by using logging data, but for the strong heterogeneity of mixed sediments, identification methods different from general reservoirs are required. The establishment of lithology identification methods suitable for mixed sediments by combining multiple means is conducive to the study of mixed sedimentary facies and provides guidance for oil and gas exploration in mixed sediments.

(4) There are many cases of reservoir prediction of clastic rock and carbonate rock based on geophysical response characteristics, but there are few reports on the prediction of mixed sedimentary reservoir. Because most of the mixed sedimentary rocks have the lithology characteristics of clastic rock and carbonate rock, the response characteristics of reservoir prediction are more complicated. It is the development trend of mixed reservoir prediction to identify the difference of response between mixed sedimentary reservoir and pure clastic rock and carbonate rock by single well analysis, seismic facies analysis, forward modeling analysis and attribute analysis.

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