

Article

Mixed Sedimentation in the Transition Zone Between a Shallow-Water Delta and Tidal Flat and Its Influence on Reservoir Quality: A Case Study of Member B of the Asmari Formation in C Oilfield, South Iraq

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Abstract: The transition zone between a shallow-water delta and tidal flat is characterized by a high degree of mixed siliciclastic–carbonate sedimentation. There are frequent lateral and vertical variations in sandstone, dolostone, limestone, and mixed siliciclastic–carbonate rock (MSR); however, their influence on reservoir quality remains uncertain. Member B of the Asmari Formation (Asmari B) in Iraq’s C Oilfield was deposited in a remnant ocean basin formed by the closure of the Neo-Tethys Ocean. During the Oligocene–Miocene, frequent exposure of the Arabian Shield provided intermittent sediment sources to the study area. Under shallow water and relatively arid conditions, widespread mixed sedimentation of siliciclastic sand and dolomitic components occurred. Taking Asmari B as a case study, this research employs core and thin-section observations, trace element analyses, and quantitative mineralogical interpretations of logging data to investigate the characteristics of mixed sedimentation and to evaluate its impact on reservoir quality. Four key aspects were identified: (1) Four main types of mixed lithofacies developed in Member B of the Asmari Formation, namely sandstone-bearing dolomite, dolomitic sandstone, dolostone-bearing sand, and sandy dolostone. These lithofacies were deposited in the transition zone between distributary channels and intertidal zone with different water depths. As the terrigenous input decreased, the water depth for sand-bearing facies increased. In particular, sandy dolostone was predominantly formed in subtidal settings under the influence of storm events. (2) MSRs are categorized based on the proportion of the minor component into high and low mixing degrees. Based on mineral compositions interpreted from well logging data, the mixing degree of MSRs was characterized by the thickness ratio, using the thickness of high- and low-mixing-degree MSRs relative to the total thickness of the formation. The MSRs mainly developed in the B1, B2, B3-1, B3-2, and B4 sublayers, where moderate provenance supply facilitated the high mixing of terrigenous clastic and carbonate components. (3) The pore and throat patterns of MSR reservoirs change with the mixing degree index. When the dolomite content in sandstone exceeds 25%, the pore–throat structure changes significantly. A small amount of sand in dolostone has little effect on the pore and throat. Sandy dolostone exhibits the poorest reservoir quality. (4) Mixed sandstone reservoirs are distributed on both sides of the distributary channels and mouth bar. The dolostone-bearing sand reservoirs are distributed in the transition zone between the sandy flat and dolomite flat. Sandy dolostone is mainly thin and isolated due to the influence of storm events. This study provides guidance for understanding the development patterns



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of MSR reservoirs under similar geological settings, facilitating the next step of oil and gas exploration in these special reservoirs.

Keywords: mixed siliciclastic–carbonate rocks; petrography; mixing degree index; distribution of mixing sedimentation

1. Introduction

The concept of mixed siliciclastic–carbonate sedimentation was first introduced by Mount [1], referring to rocks formed through the mixed sedimentation of terrigenous clastic and carbonate components. Subsequently, mixed siliciclastic–carbonate rocks (MSRs) were defined as rocks composed of a mixing of terrigenous clastic materials and carbonate components (including allochemical grains) within a single depositional unit [2]. A depositional assemblage alternating between terrigenous clastic rocks, carbonate rocks, and MSRs is termed a mixed siliciclastic–carbonate succession [3,4].

Mixed sediments have been reported in various stratigraphic units across multiple basins worldwide, such as the Late Miocene Anjou Formation of the Tortonian stage in western France; the Upper Cretaceous Khasib and Tanuma formations in the Mesopotamian Basin [5]; the Mississippian Visean Terrace in southwestern Spain [6]; and the Sendji Formation of the Lower Cretaceous in the Lower Congo Basin [7]. Over the past three decades, significant progress has been made in understanding the mixed depositional environments, classification schemes, and controlling factors of MSRs, which have attracted considerable attention [3,4,8,9]. Based on modern sedimentological studies, in shallow marine shelves without storm waves, modern mixed sediments are usually distributed at water depth ranging from 20 to 100 m [8]. MSRs are widely developed in transitional depositional environments, such as terrestrial lakes, shelves, slopes, semi-deep seas, and deep-sea settings, and are characterized by the lateral interweaving or vertical stacking of different depositional facies zones [10–12].

Because of the complicated components in MSRs, lithological classification lacks a unified standard. It is primarily based on refinements of Mount's classification scheme, which considers four end-member components: sand, allochemical grains, micrite, and muddy clay [1,13]. The formation and distribution of mixed rocks result from complex processes controlled by multiple factors. Previous studies have identified clastic material supply [14], climatic and aquatic conditions [15], paleogeographic settings [4], tectonic activity [16], sea (or lake) level fluctuations [9], hydrodynamic conditions [17], bioturbation [17], and diagenesis [16] as the main controlling factors of mixed rock deposition. However, the relationship between the mixing degree and reservoir quality remains underexplored.

High-quality MSR reservoirs have been discovered in the Asmari Formation of Iraq. Previous research has primarily focused on reservoir characteristics, controlling factors of reservoir quality, and heterogeneity [18–20]. However, the mixing degree, mixed sedimentary processes, and distribution patterns of MSRs have not been sufficiently addressed. The understanding of the depositional environments and reservoir characteristics of MSRs remains incomplete, and the distribution of MSR reservoirs needs further investigation to better guide oil exploration and development in this area.

This study aims to take the MSRs of Member B of the Asmari Formation in the C Oilfield, southern Iraq, as a case study to reveal the characteristics of mixed sedimentation in the transitional zone between a shallow-water delta and a tidal flat. Through core observations, thin-section identification, well-log data analysis, and geochemical characterization, this research classifies the lithofacies of MSRs in Member B of the Asmari Formation,

identifies depositional environmental differences in MSRs, reveals the pore and throat shapes and sizes in rocks with varying degrees of mixing, and then clarifies the distribution patterns of MSR reservoirs. This study provide theoretical guidance for future oil and gas exploration and development in MSRs and offers new perspectives and methodologies for the study of mixed siliciclastic–carbonate rocks (MSRs).

2. Geological Setting

The C Oilfield, part of the M oilfields group, is located in the southern Mesopotamian Zagros fold-thrust belt on the eastern Arabian Platform (Figure 1). The Zagros fold-thrust belt has undergone several geological stages. During NE-directed subduction, a NW-SE trending foreland basin formed, accompanied by the closure of the Neo-Tethys Ocean and the development of residual ocean basin deposits [21–23]. Member B of the Asmari Formation developed during the Chattian–Aquitanian stages, situated between the transgressive surfaces Ng10 and Ng30, with a geological age of approximately 23 to 15 million years [24,25].

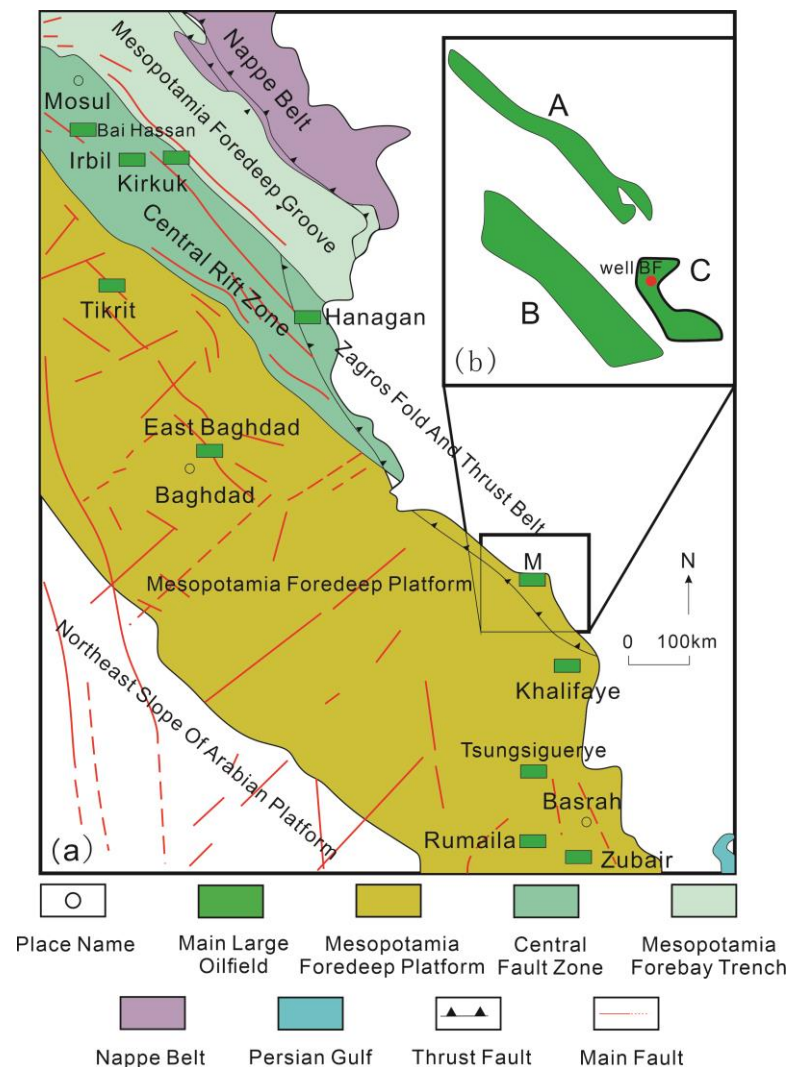


Figure 1. Location map of the study area [1]. (a) Regional tectonic location of the M oilfields group; (b) A, B, and C are three oilfields of the M oilfields group, among which C is the study area of this study. The C Oilfield is located in the northeastern part of the oilfields group. The main lithologies of Member B of the Asmari Formation in this area include sandstones, dolostones, and mixed siliciclastic–carbonate rocks.

During the early Oligocene, influenced by the Zagros orogeny, large-scale regression led to frequent exposure of the Arabian Peninsula. The depositional center gradually migrated toward the Zagros foreland belt, while the western region experienced significant uplift and became land, and the eastern marine basin became isolated from the open sea. This caused the Avaz Delta to gradually retreat from the C Oilfield region [23,26]. By the end of the Oligocene, the basin system had transformed into a restricted environment as the closure of the Neo-Tethys Ocean turned the Zagros foreland into a trough [23,27], limiting seawater circulation. From the late Oligocene to the Miocene, periodic changes in sea-level and sediment supply resulted in the development of alternating or mixed sedimentary strata of carbonate and clastic rocks within the Asmari Formation in the C Oilfield [28,29].

The study area, located in the transition zone between a shallow-water delta and a tidal flat, experienced enhanced paleo-weathering and erosion during sea-level falls. The current burial depth of the Asmari Formation is 2800–3200 m, with a total thickness of approximately 380 m. Stratigraphically, the formation is subdivided from top to bottom into four members: A, B, C, and D (Figure 2). Among them, Member B, with a thickness of 110–140 m, serve as the primary oil pay zone. As shown in Figure 2, two main subfacies are identified within Member B, mixed tidal flat and delta facies, with lithologies consisting of sandstone, dolostone, mixed MSR, and mudstone. Based on core and well-log data, Member B of the Asmari Formation can be further subdivided into five sixth-order stratigraphic sequences from top to bottom: B4, B3-2, B3-1, B2, and B1 (Figure 2). Sixth-order cycle represents the smallest-scale depositional units in high-frequency sequences stratigraphy, corresponding to short-term depositional rhythm driven by Milankovitch cycle, which usually corresponds to 4–20 kyr. Based on production variation, the C Oilfield can be divided into two regions: the northwest and the southern regions.

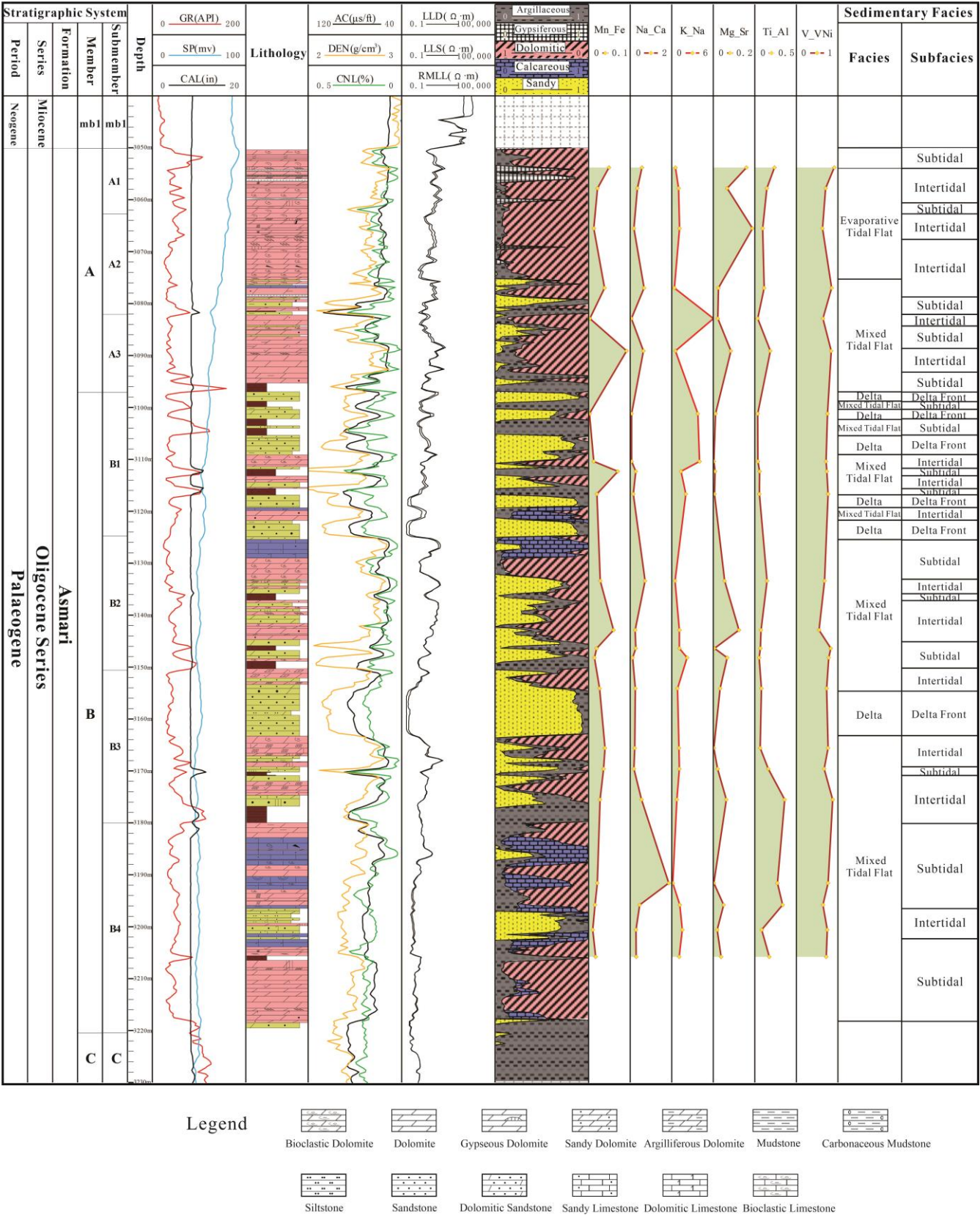


Figure 2. Comprehensive stratigraphic column for well BF. The colors in the mineral composition profile represent the content changes in different minerals. Pink represents dolomitic, yellow represents sandy, purple represents calcareous, white represents gypsiferous, and gray represents argillaceous.

3. Sampling and Testing Methods

In this study, rock samples were collected from the core data of 23 wells. A total of 351 cast thin sections were analyzed, including 123 drilling core samples, 81 wall core samples, and 147 broken samples. MSR samples covered the A3, B1, B2, B3, and B4 sub-layers. Five methods were used in this study, and the details of the samples are shown in Table 1.

Table 1. The sample information in the study.

No.	Testing Method	Sample Quantity
1	cast thin sections	351
2	grading analysis	
3	element measurement	14
4	X-ray diffraction	31
5	porosity and permeability test	81

The petrological analysis was mainly performed using a microscope. The granularity of sandstone was measured under the microscope using dot notation. Combined with image analysis, the statistical error of granularity was found to be less than 8%. The crystal size of dolomite was also determined using the same method.

Fourteen samples were selected for element measurement, including two sandstones bearing dolomite, three dolomitic sandstones, four dolostones bearing sand, and five sandy dolostones. The samples were crushed into 80–100 mesh. After resolution, 9 major elements (e.g., Al, Fe, Mn) were measured using the PE 5300 V inductively coupled plasma atomic emission spectrometer (ICP-OES). Forty-five trace elements (e.g., V, Ni, Rb) were measured using the Agilent 7700 series ICP-MS at the State Key Laboratory of Oil and Gas Reservoir Geological Development in China. The standard for the experimental test followed the GB/T14506-2010 [30], part 29 (Chinese national standard). Fourteen bulk sample powders were dried in equal parts (100 mg each) at 100 °C for 2 hours and dissolved in a mixed solution consisting of 4 mL hydrofluoric acid, 2 mL hydrochloric acid, 3 mL nitric acid, 1 mL perchloric acid, and three drops of sulfuric acid. The sample dissolved in the solution was then heated to approximately 200 °C for 4 hours until white smoke was produced. Next, 5 mL of chlorazic acid was added to the solution to extract the elements. The solution was then transferred to a 50 mL volumetric flask and diluted to volume with deionized water. The main elements were determined by ICP-AES, and the trace element was determined by ICP-MS.

Thirty-one samples of MSRs and dolostones were analyzed by X-ray diffraction (Rigaku XRD/Rigaku Ultima IV), with only four samples containing clay minerals, with content distribution between 1.5 and 10%. The clay mineral type was mainly illite, with a small amount of Aemon mixed-layer minerals.

The porosity and permeability tests for 81 wall cores were conducted in the same laboratory using the gas method. The relative deviation of porosity was 0.5–1.5%, and for permeability, it was $\leq 10\%$ for low permeability samples.

To evaluate the mixing degree in both the vertical and lateral directions, a quantitative mineral interpretation of logging data well using the Elan model was performed after calibration with the XRD result. After interpretation, the types of mixing rocks were determined based on the relative content of sandy and cloudy materials, and the mixing degree was further calculated.

4. Results

4.1. Petrography of Mixed Siliciclastic–Carbonate Rock

4.1.1. Classification of MSR

The classification scheme for MSR follows a three-endmember classification combined with the tertiary nomenclature of sedimentary rocks [31]. Six lithofacies of MSRs were identified: dolostone-bearing sand, sandy dolostone, sandstone-bearing dolomite, dolomitic sandstone, sandy limestone, and argillaceous dolomite-bearing sand. The siliciclastic components are predominantly quartz, with minor feldspar. The first four are the main types of MSRs in the Member B of the Asmari Formation.

In this study, the classification of MSRs is based on the mineral composition identified by X-ray diffraction data. Dolostone-bearing sand contains approximately 10–25% sand. The sand is fine-grained, sub-angular to sub-rounded, with low sphericity and a long ellipsoidal shape. Dolomite content is about 75–90%, predominantly microcrystalline (accounting for 80% of all samples) with fine crystals (accounting for 10% of all samples) that are subhedral to euhedral (Figure 3a).

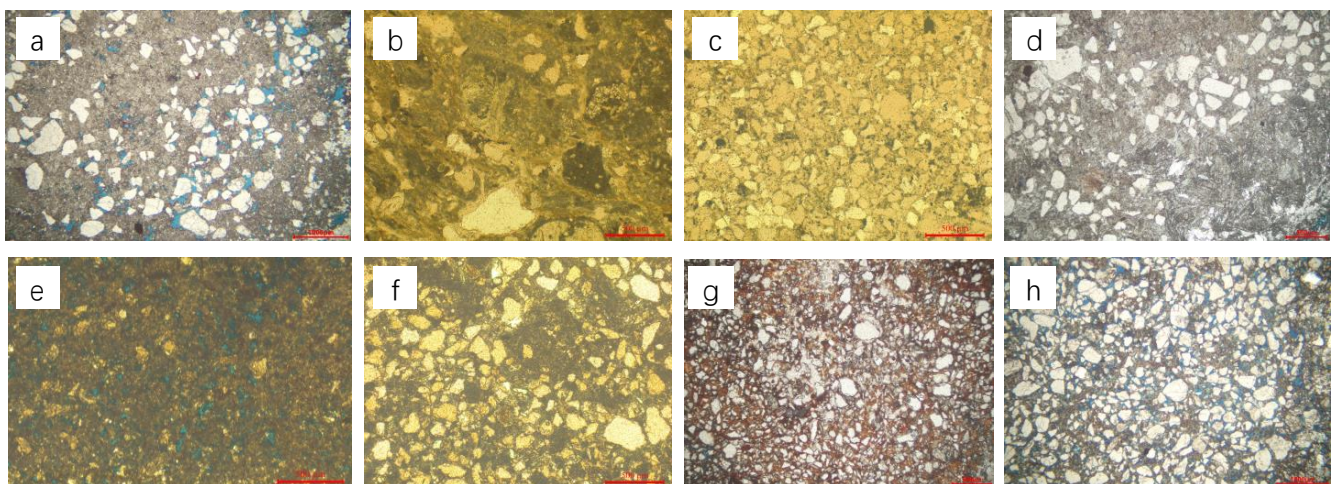


Figure 3. Thin section images of the lithofacies of MSRs. (a) Well BF, 3152.8 m, fine-crystalline dolostone-bearing sand. (b) Well BF, 3110.4 m, granular dolostone-bearing sand with some bioclastic debris. (c) Well BF, 3202.5 m, dolomitic sandstone. (d) Well BF, 3170.5 m, dolomitic sandstone with some gypsum cement. (e) Well BF, 3135.7 m, very fine-crystalline dolostone-bearing sand. (f) Well BF, 3138.4 m, sandy dolostone. (g) Well BF, 3151 m, sandy limestone. Note that calcite is stained red by alizarin red; (h) Well BF, 3154.95 m, dolomitic sandstone.

Sandy dolostone contains on average approximately 30% sand. The sand is medium- to fine-grained, sub-rounded to rounded, with high sphericity and a long ellipsoidal shape. Dolomite content is about 70%, predominantly fine-crystalline (Figure 3f).

Sandstone-bearing dolomite contains on average approximately 85% sand. The sand is fine-grained, with traces of medium-grained sand, sub-rounded to rounded, with high sphericity and a spherical shape. Dolomite content is about 15%, predominantly microcrystalline (Figure 3d).

Dolomitic sandstone contains on average approximately 65% sand. The sand is medium-grained, with traces of coarse-grained sand, sub-rounded, with low sphericity and an ellipsoidal shape. Dolomite content is about 10%, mainly fine-crystalline. In some cases, gypsum cements account for approximately 10–25% in these sandstones (Figure 3e,g).

Sandy limestone contains approximately 15% sand. The sand grains are coarse, angular to sub-angular, and the calcite content is approximately 80% (Figure 3c,h).

Argillaceous dolomite-bearing sand contains on average approximately 12% sand. The sand is fine-grained, sub-angular to sub-rounded, with high sphericity and a long ellipsoidal shape. Dolomite content is about 60%, predominantly microcrystalline, with an argillaceous content of 25~50% (Figure 3b).

The different mixing of carbonate and siliciclastic materials was deposited in different sedimentary environments. Based on thin section observations, in the vertical section, the MSRs lithofacies sequence is sandstone-bearing dolomite, dolomitic sandstone, and dolostone-bearing sand, from bottom to top. This sequence indicates a transformation from sedimentary environments dominated by sandstone to those dominated by carbonate rocks. Element indices were used to explain the differences in sedimentary environments. Al and Rb are mainly derived from terrigenous clasts and can indicate provenance effects. $V/(V+Ni)$ is widely used to infer redox conditions, while Mn/Fe can be used to indicate ancient water depth [31]. As shown in Figure 4a,b, as the terrigenous element content (Al and Rb) decreased, the Mn/Fe ratio increased [32]. Meanwhile, according to the element indicators, the MSRs were deposited in transitional sedimentary environments. As shown in Figure 4a, the depositional environments of sandy dolostone differs from that of other MRSs. Although they exhibit similar reducibility (with similar $V/(V+Ni)$ values), the sandy dolostone shows relatively higher Mn/Fe ratio, implying that the water depth during its deposition was greater than that of the other three lithofacies, corresponding to a subtidal zone less influenced by terrigenous materials. In contrast, the sandstone-bearing dolomite, dolomitic sandstone, and dolostone-bearing sand were deposited in the transition zone between distributary channels and the intertidal zone, with varying water depths.

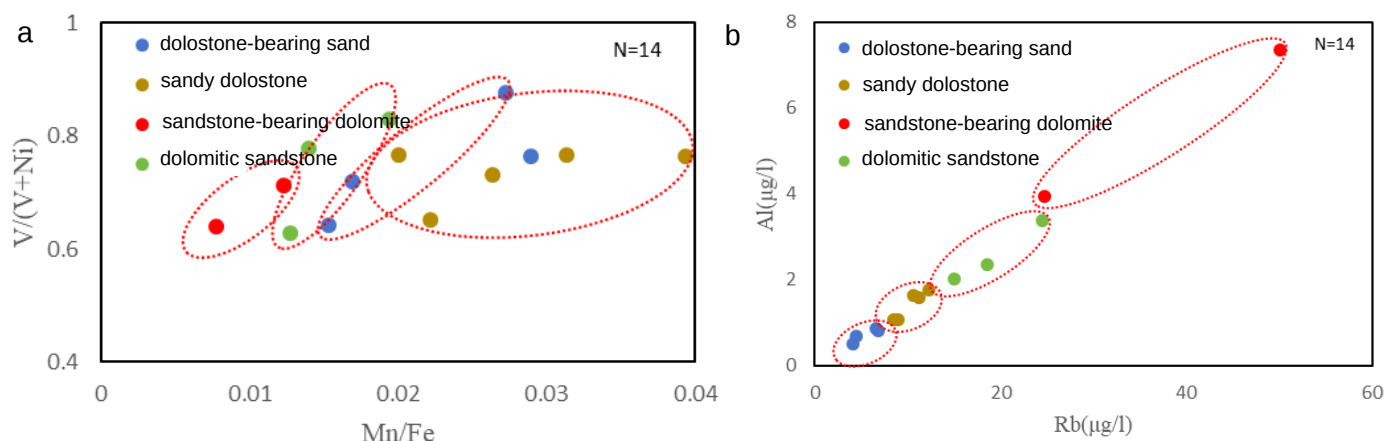


Figure 4. Element indices of the lithofacies of MSRs. (a) Cross-plot of $V/(V+Ni)$ and Mn/Fe in four types of MSRs; (b) cross-plot of Al and Rb in four types of MSRs with different mixing degrees.

4.1.2. Mixed Siliciclastic–Carbonate Successions

Mixed siliciclastic–carbonate successions are the products of discontinuous and repetitive changes in depositional environments. As depositional environments evolve, sediments (sedimentary rocks) and mixed successions undergo systematic evolution [32–34]. In the study area, the change in mixed siliciclastic–carbonate successions was not controlled by sea-level change, because the distribution of microfacies varies greatly within each transgressive–regressive cycle. Since the sea-level change in each cycle was not significant, the development of mixed siliciclastic–carbonate successions was mainly controlled by provenance. In Member B of the Asmari Formation in the C Oilfield, as shown in Figure 5, four main types of mixed successions are developed: MSR–carbonate rock–siliciclastic rock succession, MSR–siliciclastic rock succession, MSR–carbonate rock succession, and MSR–MSR succession. The MSR–carbonate rock–siliciclastic rock succession tends to be

distributed on both sides of the distributary channel and tidal flat influenced by provenance. In this depositional environment, mixed sedimentation is relatively weak, and pure carbonate and pure sandstone can deposit. MSR-carbonate rock succession occurs in the tidal flat with dolomite precipitation, where sand can be mixed by tidal currents. MSR-MSR succession is relatively uncommon and represents a turbulent transitional environment. MSR-siliciclastic rock succession deposited in a mixed tidal flat with dolomite precipitation during the early stage, which later transformed into a distributary channel. The different types of mixed siliciclastic-carbonate successions suggest that changes in provenance and sea-level can lead to the development of specific sedimentary facies assemblages in a paleo-landform with a gentle slope.

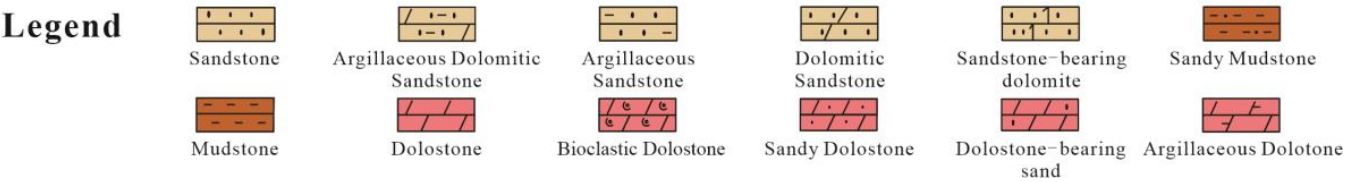
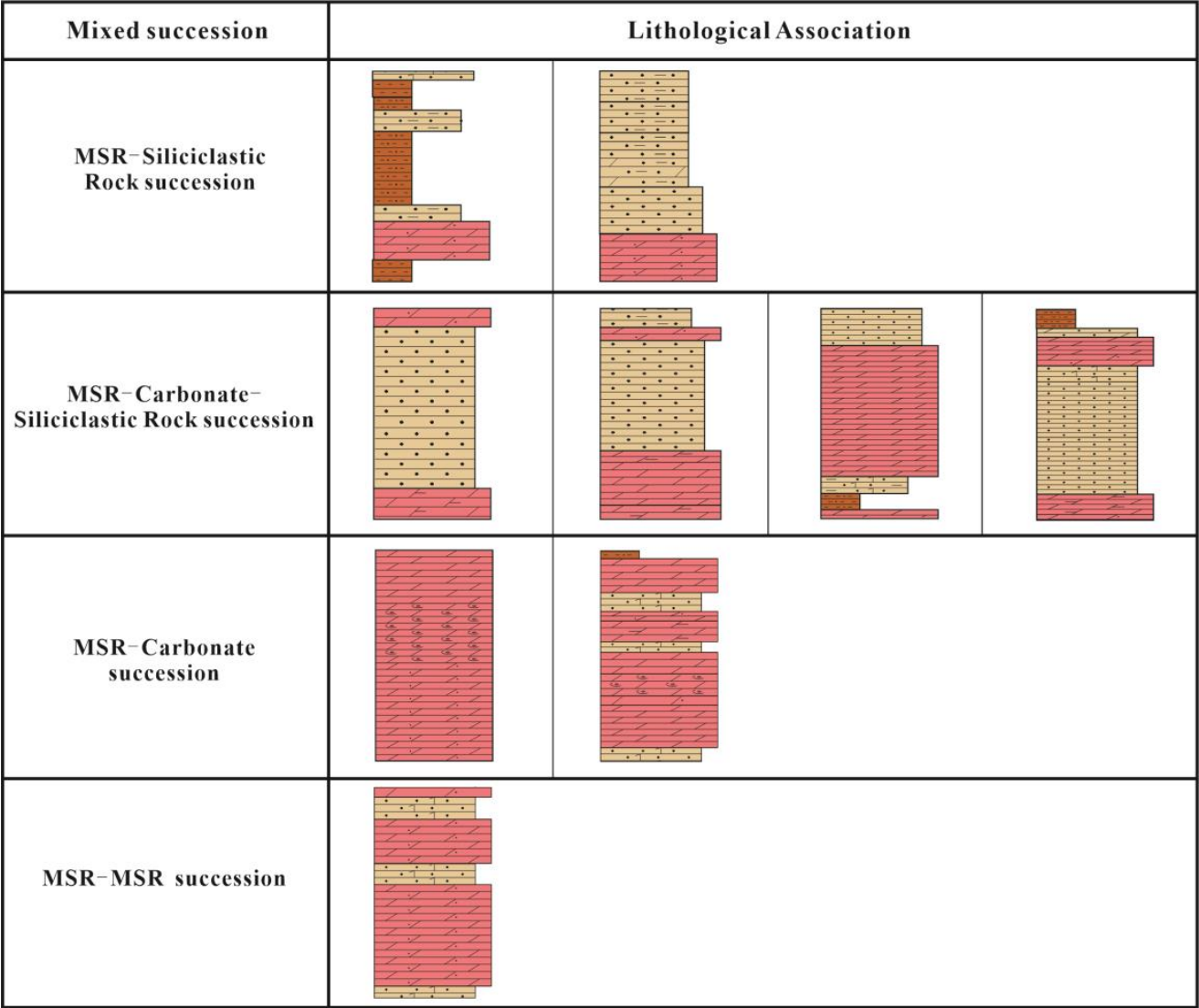


Figure 5. Types of MSR successions in Member B of the Asmari Formation in the C Oilfield.

4.2. Mixing Degree Index of MSRs

The mixing intensity refers to the degree of mixing between terrigenous siliciclastic and carbonate components within a given depositional environment. In our previous study, based on the relative ratio of terrigenous siliciclastic and carbonate minerals in the same layer, three types of MSRs were identified: mixed terrigenous siliciclastic rocks, mixed carbonate rocks, and highly mixed siliciclastic–carbonate rocks [35]. Currently, the comprehensive characterization system of “component ratio + structural characteristics + sequence position” is mostly used, but there is no unified standard for grading the mixing degree [36,37]. Based on our study, there are two methods to represent the mixing intensity. For mixed successions composed of sandstone, carbonate rocks, and MSRs, the mixing degree can be quantified by calculating the ratio of MSR thickness to the total thickness of the corresponding formation. This ratio represents the mixing degree at different stratigraphic levels. The mixing degree index (MDI) can be calculated using the following formula:

$$\text{MDI} = \frac{\text{Thickness of mixed siliciclastic – carbonate rocks}}{\text{Total thickness of the sublayer}} \times 100\%; \quad (1)$$

Taking the B2 sublayer in well BF as an example, the MDI can be calculated using the thickness of MSRs (2.8 m) and the total thickness of the B2 layer (7.9 m). The MSRs were distinguished by quantitative mineral interpretation from the well logs. Therefore, the MDI is 0.35%.

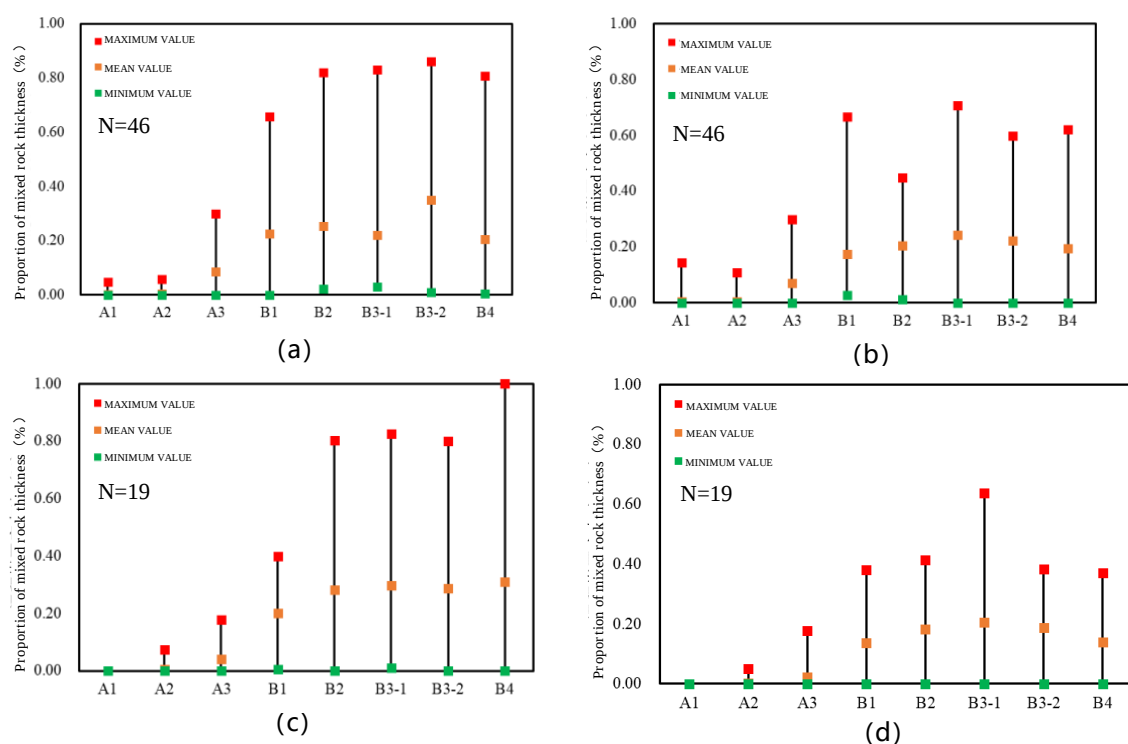
In the second method, for rock containing terrigenous siliciclastic and carbonate components, MSRs are further categorized based on the proportion of the minor component (the relatively low content of carbonate or terrigenous clastic materials): high mixing degree (minor component proportion of 25–50%), low mixing degree (minor component proportion of 10–25%). The MDI for MSRs with high and low mixing degrees can be calculated accordingly.

The contents of Rb and Al elements are closely related to the input of terrigenous clastic materials and serve as effective indicators of the mixing degree in mixed siliciclastic–carbonate rocks. These elements also reflect paleoenvironmental changes in the depositional environment [38]. Higher Rb and Al contents indicate a greater degree of mixing between terrigenous clastic and carbonate components (Figure 3b).

The mixing degree index for the vertical and lateral distribution of MSRs varies by region and sublayer. In the C Oilfield, the mixing degree of MSRs was calculated for 46 wells in the southern region and 19 wells in the northern region (Table 2), distinguishing MSRs with high or low mixing degrees. The MDI for MSRs with high and low mixing degrees in each sublayer was calculated. Since the data were obtained from 46 wells in the southern zone and 19 wells in the northern zone, the maximum, minimum, and average MDI values were calculated for each subzone and each well. As shown in Figure 6, the B2, B3-1, B3-2, and B4 sublayers have the highest proportions of MSRs with a higher mixing degree compared to other sublayers. Meanwhile, the proportion of MSRs with a high mixing degree is relatively greater in the southern region than in the northern region. In the southern region, carbonate and terrigenous siliciclastics are mixed to the greatest extent. The B2, B3-1, B3-2, and B4 sublayers all exhibit higher proportions of MSRs with low mixing degrees as well, with average percentages between 10% and 20%.

Table 2. Thickness ratio of high mixed and low mixed rocks in the northern and southern regions of the C Oilfield.

Well Area	Sublayer	MDI of MSR with High Mixing Degree			MDI of MSR with Low Mixing Degree			Number of Wells
		Maximum	Mean	Minimum	Maximum	Mean	Minimum	
South	A1	0.04	0.00	0.00	0.14	0.00	0	46
	A2	0.06	0.01	0.00	0.10	0.00	0	
	A3	0.30	0.08	0.00	0.29	0.07	0	
	B1	0.65	0.22	0.00	0.66	0.17	0.02	
	B2	0.81	0.25	0.02	0.44	0.20	0.01	
	B3-1	0.82	0.22	0.02	0.70	0.24	0	
	B3-2	0.86	0.34	0.01	0.59	0.21	0	
	B4	0.80	0.20	0.00	0.62	0.19	0	
North	A1	0.00	0.00	0.00	0.00	0.00	0	19
	A2	0.07	0.01	0.00	0.05	0.01	0	
	A3	0.18	0.04	0.00	0.17	0.02	0	
	B1	0.40	0.19	0.01	0.38	0.13	0	
	B2	0.80	0.28	0.00	0.41	0.18	0	
	B3-1	0.82	0.29	0.01	0.63	0.20	0	
	B3-2	0.79	0.28	0.00	0.38	0.18	0	
	B4	1.00	0.31	0.00	0.36	0.13	0	

**Figure 6.** Thickness ratio correlation chart of high-mixing and low-mixing rocks in the northern and southern regions of the C Oilfield. (a) Proportion of thickness of MSRs with a high mixing degree in eight sublayers of the southern region of the C Oilfield. (b) Proportion of the thickness of MSRs with a low mixing degree in eight sublayers of the southern region of the C Oilfield. (c) Proportion of the thickness of MSRs with a high mixing degree in eight sublayers of the northern region of the C Oilfield. (d) Proportion of the thickness of MSRs with a low mixing degree in eight sublayers of the northern region of the C Oilfield.

4.3. The Porosity and Permeability of MSRs

Based on the measured porosity and permeability data, the physical properties of the MSRs were selected and compared with some sandstones and dolomites. As shown in Figure 7a, the porosity of sandstone is the highest (>22%), while the porosity of sandstone-bearing dolomite is lower (15–22%), although the difference in permeability compared to sandstone is not significant. The porosity and permeability of dolomitic sandstone are significantly reduced (porosity of 10–20%, permeability of 0.1–2 mD). In Figure 7b, the porosity and permeability of sandy dolostone are the lowest (<8% and 0.01–1 mD, respectively), and the porosity and permeability of dolostone and sandy dolostone are similar, making them difficult to distinguish completely.

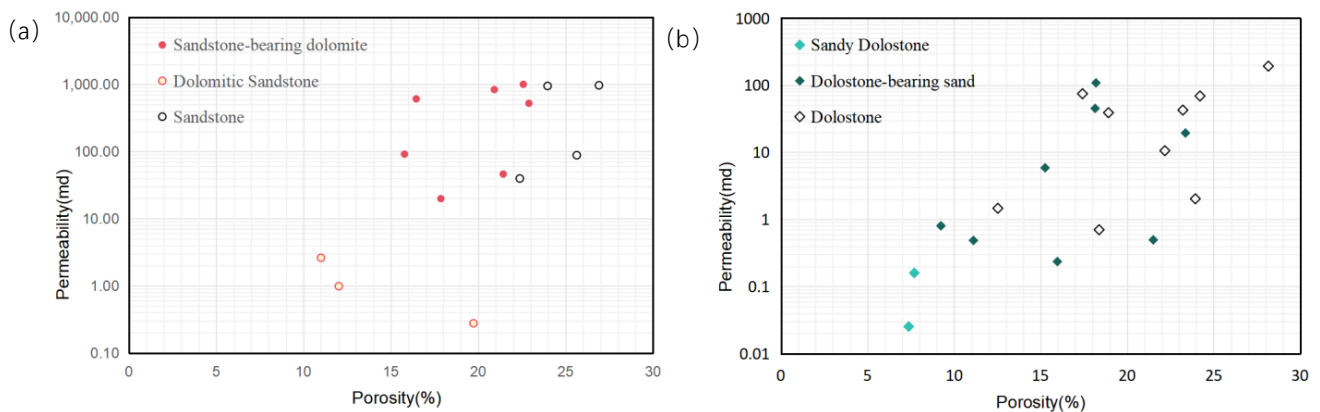


Figure 7. The cross-plot of porosity and permeability of sandstone, MSRs, and dolostone reservoirs. (a) The cross-plot of porosity and permeability of sandstone, dolomitic sandstone, and sandstone-bearing dolomite. (b) The cross-plot of porosity and permeability of dolostone, sandy dolostone, and dolostone-bearing sand. Note that these samples were collected from wall cores of drilling wells.

5. Discussion

5.1. The Influence of MSR Mixing Degree on Pore Structure

The reservoir quality of sandstone can be influenced by grain size, pore types, sedimentary structures, and facies types [39]. The carbonate rock reservoirs are heavily impacted by lithofacies classification [40]. However, under mixed sedimentation, the degree of mixing has a significant effect on the pore structure of the MSRs, thus affecting the reservoir quality. When large particle-sized terrigenous sand (20–200 μm) and small particle-sized dolomite (1–20 μm for mud and microcrystals) are mixed together during sedimentation, the stacking pattern of particles with different sizes changes with the sand content, and its impact on physical properties also varies (Figure 8).

When sandstone undergoes mixed deposition with dolomite, that is, when a small amount of dolomite is mixed into terrigenous sands, the original intergranular pores among the sands (with close packing generally about 25%) cannot be completely “filled” by dolomite at a low mixing degree. As a result, many residual intergranular pores remain. The permeability of sandstone-bearing dolomite decreases as the dolomite content increases (Figure 7). A double-pore–throat mode can appear when the crystalline gap increases (a double-peak structure will appear on the pore throat radius distribution diagram). When the degree of mixing becomes high, the pore structure of MSRs changes significantly: the intergranular pores basically disappear and are replaced by intercrystalline pores (dissolved intercrystalline pores) and intercrystalline gap assemblies. With fewer sandy particles and more fine-crystalline dolomites per unit volume, the number of intercrystalline pores (dissolved intercrystalline pores) increases. Theoretically, both porosity and permeability are significantly reduced (Figure 7).

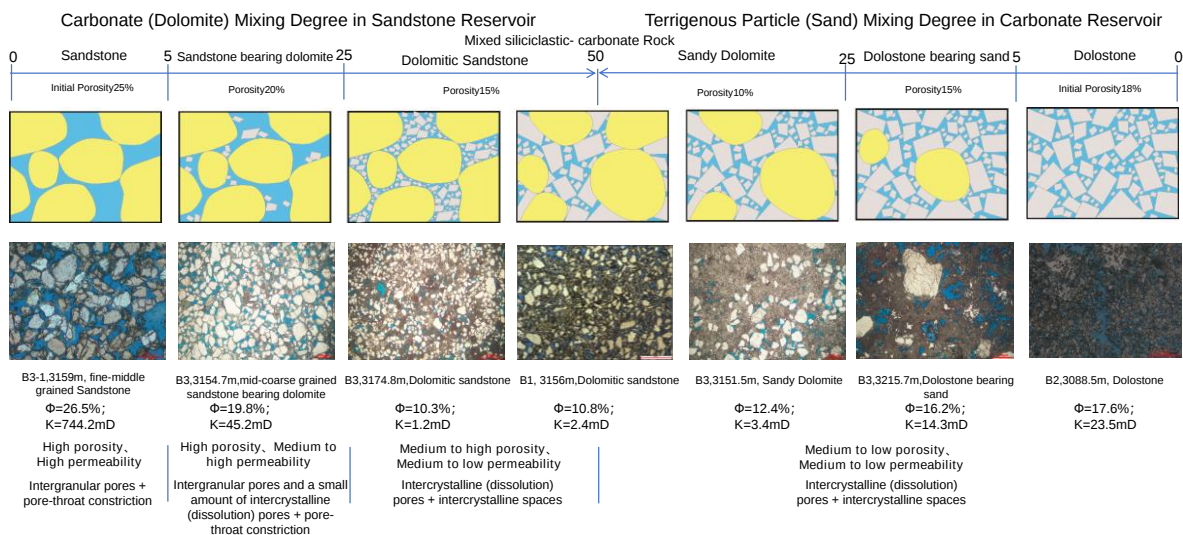


Figure 8. The pore and throat of sandstone, MSRs, and dolostone with mixing degree.

When mixed sedimentation occurs in dolostones with a crystalline structure, that is, when a small amount of sand is mixed into fine-crystalline dolomites, the addition of large sand particles can reduce the porosity of the rock (Figure 7). Because the sand particles are “suspended”, the pore structure of dolostone-bearing sand is not significantly affected by sand mixing, and the pore structure type remains primarily intercrystalline (dissolved) pores and crystalline gap assemblies.

In the sedimentary environment of a tidal shoal with a large number of dolomitic allochems, granular dolostone-bearing sand occur. In this type of MSR, the stacking pattern of a small amount of sand and a large amount of dolomite is similar to that of fine-crystalline dolomite mixed with sand. However, the difference lies in the pore types: granular dolostone-bearing sand exhibit large-scale intergranular pores, dissolved intragranular pores, and moldic pores. Small sand particles can fill these pores, resulting in a slight reduction in porosity and permeability (Figure 7). Because the tidal shoals are deposited in the subtidal zone, which is generally less influenced by the delta and contains fewer sands, the granular dolostone-bearing sand is mainly deposited in mixed tidal shoals with limited sand input. The pore–throat pattern of granular dolostone-bearing sand is basically the same as that of fine-crystalline dolostone-bearing sand deposited in normal tidal shoals.

Therefore, the pore and throat patterns of MSRs reservoirs can change with the mixing degree index, which is very different from those of pure sandstone and dolostone. When the content of dolomite in sandstone exceeds 25%, the pore–throat characteristics change significantly. However, a small amount of sand in dolostone has little effect on the pore–throat structure. This theory will help improve reservoir evaluation for the oil and gas industry in mixed sedimentary rocks.

5.2. The Influence of MSR Mixing Degree on Reservoir Quality

Mount proposed four mechanisms for mixed sedimentation in shallow marine environments, including punctuated mixing, facies mixing, in situ mixing, and source mixing [12]. Member B of the Asmari Formation in the C Oilfield is characterized by a delta–mixed tidal flat depositional environment [33]. Terrigenous clastics from the west of the Arabian Shield were transported to the shelf margin of the New Tethys Ocean. On the relatively gentle slope, the distributary channels of shallow deltas could extend far and gradually transition into the tidal flat. In the transition zone between the delta and tidal flat, mixed sedimentation of terrigenous siliciclastic and carbonates was common. As shown in Figure 9, in the

vertical source direction, the mixed sedimentary microfacies show some variations. Based on Mount's classification and further studies, the mixed sedimentation in Member B of the Asmari Formation in the C Oilfield is attributed to two genetic types: proximal reworked mixing and distal transported mixing.

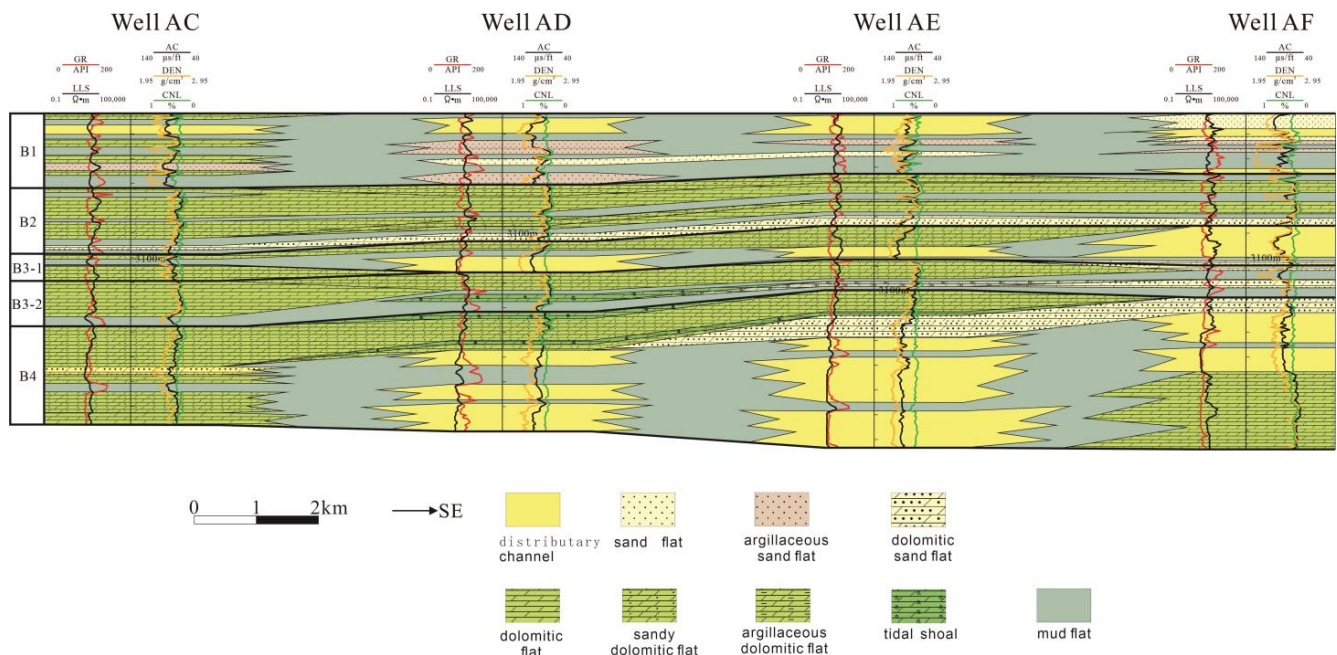


Figure 9. Cross-well profile of mixed microfacies of Member B (vertical source direction).

5.2.1. Distal Transported Mixing Under Tidal Current

Under tidal current, terrigenous clastic particles undergo a more complex process of distal transport and mixed sedimentation. During normal tidal conditions on the tidal flat, these particles are transported to the intertidal zone and mixed with carbonates and other sediments present there. During storm surges, stronger tidal energy transports these particles further into the subtidal zone, where they mix with seafloor sediments, forming sedimentary records of distal transported mixing. The main MSR types deposited in this model include limestone- or dolomite-bearing sand, and sandy dolomite.

5.2.2. Proximal Reworked Mixing of Distributary Channel Sands

Proximal reworked mixing of distributary channel sands and distal transported mixing occur under tidal currents. Member B is predominantly influenced by proximal reworked mixing, which takes place in the transitional zone between the distributary channels of the delta and the mixed tidal flat, while tidal-influenced terrigenous clastics develop in the intertidal and subtidal zones of the mixed tidal flat.

In the vicinity of distributary channels, sands carried by the river are redistributed by tidal current, resulting in a specific type of mixed sedimentation. During rising tides, tidal waters bring carbonate-rich seawater into the tidal flat environment, where the carbonates interact with terrigenous sands delivered by the delta. During falling tides, the tidal waters facilitate the mixing and precipitation of carbonates and terrigenous sands, forming distinctly stratified mixed sedimentary strata. From a compositional perspective, the main MSR types in this model include dolomitic sandstone and sandstone-bearing dolomite. In the proximal reworked mixing, the mixing degree between sandy and dolomitic components is higher than that in tidal flat sequences, whereas tidal shoal sequences exhibit the weakest mixing.

5.3. Distribution of Mixed Sedimentation and the MSR Reservoirs

5.3.1. Mixed Sedimentation Controlled by Provenance Supply and Tidal Current

Previous studies have identified sea-level fluctuations, paleogeographic conditions, and provenance supply as the primary factors influencing the distribution of mixing sedimentation [41–46]. In the transition zone between the shallow-water delta and tidal flat on a gentle slope, the distribution of mixed sedimentation in Member B of the Asmari Formation in the C Oilfield is mainly controlled by provenance supply and tidal currents. Over extended periods, persistent provenance supply and the repeated action of tidal currents transform the original pure sedimentary system into a mixed sedimentary system. Provenance supply profoundly affects the spatial variation, properties, and amounts of terrigenous material, thereby controlling the distribution of mixed sedimentation. River channel sands are repeatedly reworked by tidal processes, gradually transitioning into tidal flat deposits. Tidal currents are a critical force determining the final depositional site of terrigenous clastic particles, as well as the composition and spatial distribution of MSRs. Tidal energy influences transport distance, sediment distribution, mixed layer thickness, particle size, and compositional ratios. More MSRs occurred around the tidal flat than in other depositional environments.

The provenance supply of terrigenous siliciclastics directly impacts the compositional characteristics and scale of mixed sedimentation. The distance to the provenance area and regional topographic features define the intensity and attributes of provenance supply. In the southeastern area of the M Oilfields Group, there was a large-scale Ahwaz Delta identified in previous studies [47]. The C Oilfield, located in the northeast of the M Oilfields Group, was therefore influenced by provenance supply from the southeast. There are obvious differences in mixed sedimentation between the provenance-affected zone and the northwestern and southeastern areas of this oilfield. As shown in Figure 10, the thickness ratios of MSRs vary among the provenance-affected zone and the northwestern and southeastern areas of the oilfield. In the B4 sublayer, which is strongly influenced by provenance supply, a relatively large scale of distributary channels developed, resulting in no MSRs being distributed in the provenance-affected zone. Relatively clean depositional water during the B3-2 to A3 sequences resulted in more carbonate precipitation in these sublayers. From the B3-2 to B1 layers, with reduced influence from provenance, there was more intensive mixed sedimentation in the provenance-affected zone, where some sands could still be supplied. During the A3 sequence, as provenance supply further weakened, very few MSRs deposited.

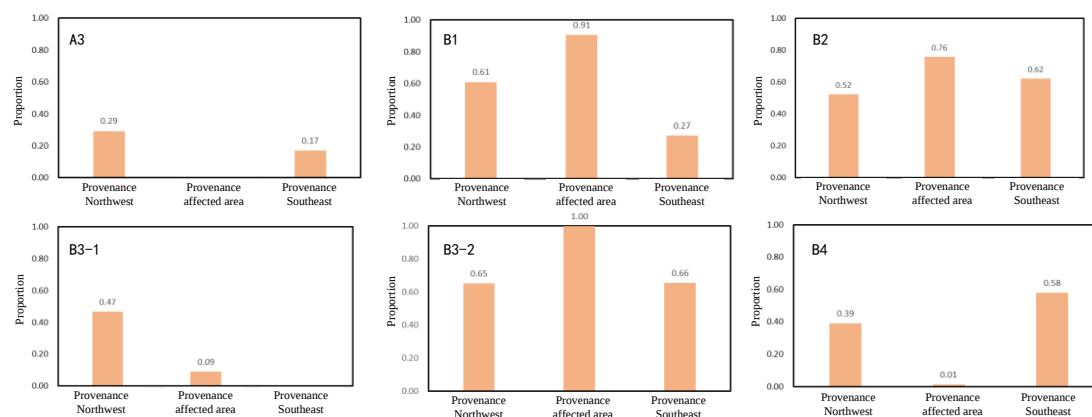


Figure 10. Thickness ratio of MSRs in six sublayers of the C Oilfield in different region. Note that the codes of different sub-members are shown in the upper left corner of each subfigure, including A3, B1, B2, B3-1, B3-2, and B4 layers.

5.3.2. Distribution of the MSR Reservoirs

Changes in provenance supply provide varying mineral compositions and particle sizes in sedimentary rocks, significantly influencing the distribution of MSR reservoirs. As shown in Figure 7, the four types of MSR reservoirs differ in quality. Sandstone and sandstone-bearing dolomites have the highest porosity and permeability among these MSRs, followed by dolostone, sandy dolostone, and dolomitic sandstone. In particular, sandy dolostone exhibits the poorest reservoir quality and often cannot serve as a conventional reservoir.

The distribution of sandstone reservoir is directly related to regions with abundant provenance supply, where distributary channels or mouth bar developed (Figure 11). On both sides of the channel beds, sand particles are reworked by tidal currents, resulting in sand particles mixing with dolomite crystals, thereby forming sandstone-bearing dolomite and dolomitic sandstone reservoirs (Figure 11). Dolostone-bearing sand reservoirs are distributed in the transitional zone between sandy flat and dolomite flat (Figure 11). In regions without direct provenance supply, thinner and isolated sandy dolostone deposits formed in the subtidal zone (Figure 11), controlled primarily by storm-induced tidal currents. The worst physical properties of sandy dolostone are mainly due to poor particle sorting and small pore throats, which are caused by density flow deposition under storm conditions.

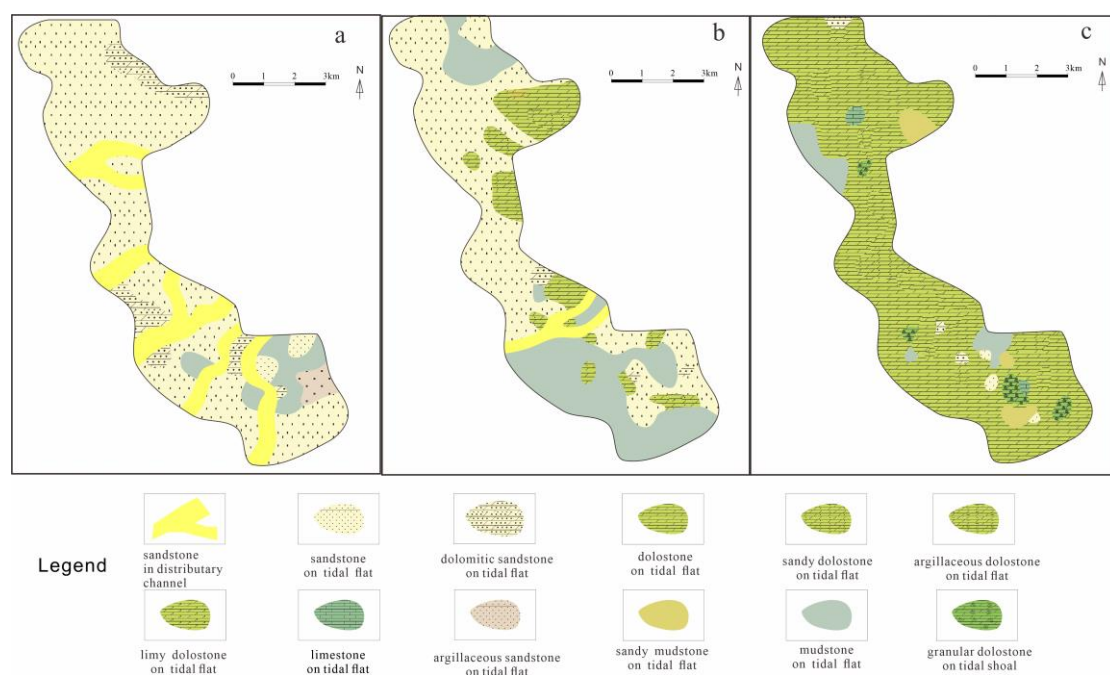


Figure 11. Distribution of MSR reservoirs across different mixed microfacies. (a) Distributary channel mixed with sandy flat; (b) sandy flat and dolomitic flat mixed with sandy dolomitic flat; (c) dolomitic flat and tidal shoal mixed with sandy dolomitic flat.

6. Conclusions

(1) There are mainly four lithofacies types of MSRs. As the terrigenous element content decreases, the water depth of deposition increases. Sandy dolostone develops in the subtidal zone under the influence of storms. The mixing degree index was calculated based on the minor component proportions derived from mineral compositions interpreted from well logging. The B2, B3-1, B3-2, and B4 sublayers show a higher proportion of MSRs with high mixing degrees compared to other sublayers in the southern region.

(2) The pore and throat patterns of MSR reservoirs change with the mixing degree index. Sandstone and sandstone-bearing dolomites have the highest porosity and perme-

ability among the MSRs, followed by dolostone, sandy dolostone, and dolomitic sandstone. Sandy dolostone exhibits the poorest reservoir quality. When the dolomite content in sandstone exceeds 25%, the pore–throat structure changes significantly. However, a small amount of sand in dolostone has little effect on the pore–throat structure.

(3) The mechanisms driving mixed sedimentation include proximal reworked mixing and distal transported mixing. Proximal reworked mixing of distributary channel sands under tidal influence occurs in the transitional zone between distributary channels of the delta and the mixed tidal flat. The distal transported mixing model develops in the intertidal and subtidal zones of the mixed tidal flat under tidal influence.

(4) The distribution of MSRs reservoirs is mainly controlled by provenance supply and tidal currents. The distance from the provenance area and paleo-topographic features determine the degree of mixing. Tidal currents directly rework terrigenous clastic particles and determine their final deposition locations. Mixed sandstone reservoirs are distributed on both sides of distributary channels and mouth bar. Dolostone-bearing sand reservoirs occur in the transition zone between sandy flat and dolomitic flat. Sandy dolostone deposits are typically thin and isolated, primarily due to storm activity.

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