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RESEARCH PAPER

Influences of burial process on diagenesis and high-quality reservoir development of deep–ultra-deep clastic rocks: A case study of Lower Cretaceous Qingshuihe Formation in southern margin of Junggar Basin, NW China

CHEN Sirui[1, 2], XIAN Benzhong[1, 2, *], JI Youliang[1, 2], LI Jiaqi[3], TIAN Rongheng[2], WANG Pengyu[2], TANG Heyuan[2]

1. State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum (Beijing), Beijing 102249, China;
2. College of Geosciences, China University of Petroleum (Beijing), Beijing 102249, China;
3. School of Energy Resources, China University of Geosciences, Beijing 100083, China

Abstract: Taking the Lower Cretaceous Qingshuihe Formation in the southern margin of Junggar Basin as an example, the influences of the burial process in a foreland basin on the diagenesis and the development of high-quality reservoirs of deep and ultra-deep clastic rocks were investigated using thin section, scanning electron microscope, electron probe, stable isotopic composition and fluid inclusion data. The Qingshuihe Formation went through four burial stages of slow shallow burial, tectonic uplift, progressive deep burial and rapid deep burial successively. The stages of slow shallow burial and tectonic uplift not only can alleviate the mechanical compaction of grains, but also can maintain an open diagenetic system in the reservoirs for a long time, which promotes the dissolution of soluble components by meteoric freshwater and inhibits the precipitation of dissolution products in the reservoirs. The late rapid deep burial process contributed to the development of fluid overpressure, which effectively inhibits the destruction of primary pores by compaction and cementation. The fluid overpressure promotes the development of microfractures in the reservoir, which enhances the dissolution effect of organic acids. Based on the quantitative reconstruction of porosity evolution history, it is found that the long-term slow shallow burial and tectonic uplift processes make the greatest contribution to the development of deep–ultra-deep high-quality clastic rock reservoirs, followed by the late rapid deep burial process, and the progressive deep burial process has little contribution.

Key words: deep–ultra-deep layer; clastic rock reservoir; diagenesis; burial process Lower Cretaceous Qingshuihe Formation; southern margin of Junggar Basin

Introduction

In recent years, high-yield industrial oil and gas flows have been obtained from deep and ultra-deep clastic rocks in the Kuqa area on the south of the Tianshan Mountain and the southern margin of the Junggar Basin on the north Tianshan Mountain, which reveal a huge exploration potential of deep and ultra-deep reservoirs in the foreland basins of western China [1−2]. Previous studies have performed detailed research on the diagenesis of deep and ultra-deep clastic rocks in the Kuqa area. However, the oil and gas exploration of deep and ultra-deep layers in the southern margin of the Junggar Basin has just made a breakthrough. Restricted by unfavorable factors such as less exploration and limited geological data, the research on diagenesis and high-quality reservoir development of the deep and ultra-deep clastic rocks is more backward.

With the development of diagenetic theories and the

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* **Corresponding author.** E-mail: xianbzh@cup.edu.cn
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enrichment of experimental techniques, establishing geological models that match the burial process with diagenetic events is crucial for the explanation of reservoir development mechanisms [3]. Previous studies have shown that burial process can indirectly control diagenetic fluid properties and diagenetic intensity by impacting the openness of diagenetic systems, the maturity time of source rocks, and the formation time and intensity of overpressure, thus influencing the reservoir quality [3−6]. The southern margin of the Junggar Basin has similar burial process to the deep and ultra-deep layers in the Kuqa area, namely, the shallow burial time is longer and the deep burial time is shorter [2, 7]. For the Kuqa area, previous studies believe that the primitive alkaline fluids during the long-term shallow burial stage, the inherited alkaline fluids during the deep burial stage, the alkaline fluids from the overlying gypsum-salt layer and CO_2-rich acidic fluids played an essential role in the process of reservoir diagenetic evolution [7]. However, current research on the correlation between the above burial process and the diagenetic response of deep and ultra-deep clastic rocks in the south margin of the Junggar Basin is still weak. In particular, these studies only noted the influence of the above burial process on mechanical compaction, but research on the response mechanism of cementation and dissolution under the impact of this burial process is lacking. As a result, the relationship between this burial method and reservoir quality is still unclear, which makes it unfavorable for deeply understanding the mechanism and distribution of reservoir development. Simultaneously, although the southern margin of the Junggar Basin and the Kuqa area are adjacent to the Tianshan Mountains, the compositions of deep and ultra-deep clastic reservoirs are different. The Kuqa area is relatively rich in quartz-feldspathic components, and poor in volcanic materials, but develops thick gypsum salt layers [7]. In contrast, the southern margin of the Junggar Basin is relatively rich in volcanic materials, and poor in quartz-feldspathic components, and the development of the gypsum-salt layer is low [8]. Obviously, under the influence of similar burial processes, the explanation of the development mechanism of the deep and ultra-deep clastic reservoirs in the southern Tianshan Mountains is not suitable in the northern Tianshan Mountains. Consequently, it is urgent to research the development mechanism of clastic reservoirs suitable for guiding deep and ultra-deep oil and gas exploration in the southern margin of the Junggar Basin.

In this paper, we selected the clastic rocks of the Lower Cretaceous Qingshuihe Formation in the southern margin of Junggar Basin as the research object, which has made many breakthroughs in oil-gas exploration in recent years. Based on the burial history, drilling, logging, reservoir and lab data, researches on petrology, mineralogy, diagenetic fluid properties and geochemistry were conducted to establish the evolutionary history of diagenetic events and reservoir space, and then the influence of the "early long-term shallow burial and late rapid deep burial" process on the digenesis and high-quality reservoir development of deep and ultra-deep clastic rocks was discussed, with the intent to provide more theoretical supports for prediction and evaluation of deep and ultra-deep clastic reservoirs in petroliferous basins with similar burial processes to the southern margin of the Junggar Basin.

1. Geological setting

The southern margin of the Junggar Basin is located at the foreland thrust belt of the North Tianshan Mountains [8]. This area is bounded by the Zaire Mountains on the west, the Bogda Mountains on the east, the Yilinheibiergen Mountain on the south, and the central depression on the north (Fig. 1a). The Sikeshu Sag in the western section of the southern margin [2] (Fig. 1b) covers an area of approximately 6 300 km^2. It has been subjected to multiple phases of tectonic activity. The Gaoquan Fault and the Aika Fault were formed during the Hercynian-Indosinian period. Then the two fault zones were cut by the strike-slip faults and their associated faults formed during the Yanshanian period. Finally, the present tectonic framework was shaped after the shallow Himalayan thrust-nappe activity [8].

The study area is the Gaoquan area in the south of the Sikeshu Sag (Fig. 1b), where breakthrough was made to oil and gas exploration in 2019 [2]. The target interval is the Lower Cretaceous Qingshuihe Formation (Fig. 1c) which has abundant oil and gas resources [2, 8]. The clastic reservoirs in the underwater distributary channels of the fan delta widely developed at the bottom of the Qingshuihe Formation are 5 500–6 000 m deep and 20–180 m thick (Fig. 1c). The burial history data shows that the deep and ultra-deep clastic reservoirs of the Qingshuihe Formation have experienced slow shallow burial, tectonic uplift, progressive deep burial, and rapid deep burial (Fig. 2). From "slow shallow burial" to "progressive deep burial" (14–140 Ma), the fluid pressure in the Qingshuihe Formation reservoir was normal (Fig. 3). During the rapid deep burial stage, the fluid pressure gradually increased, indicating that fluid overpressure began to develop inside the reservoir (Fig. 3).

2. Samples and methods

The research data include drilling and logging data from 24 wells and lab data from 200 core samples collected from the Sikeshu Sag. The core samples were taken at 5 500–6 500 m. Experiments performed in this study include cast thin sections, SEM (scanning electron

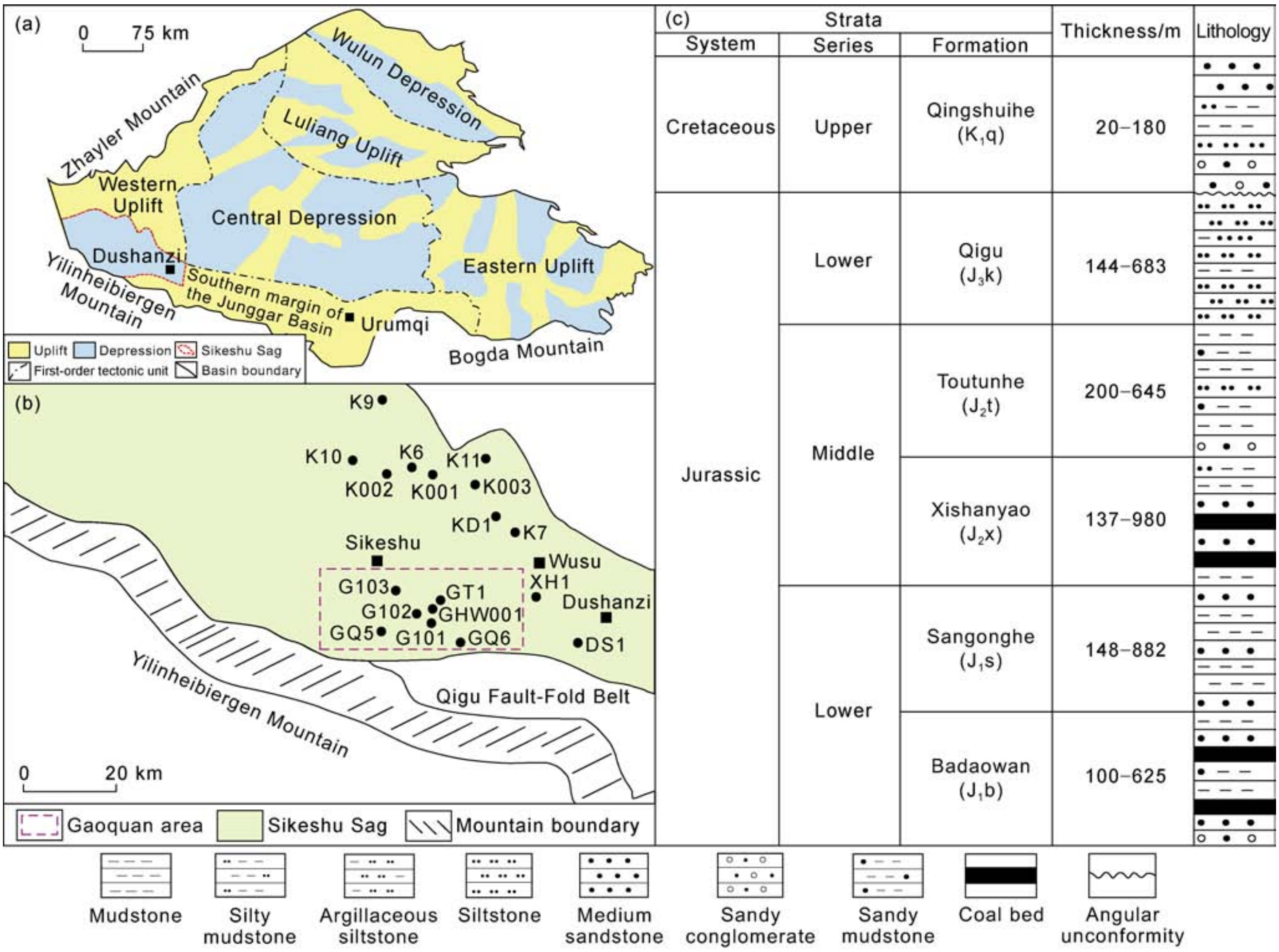

Fig. 1. Geographic location and stratigraphic column of Sikeshu Sag on the southern margin of the Junggar Basin. (a) geographic location of Sikeshu Sag; (b) Well locations in Gaoquan area; and (c) Stratigraphic column of Jurassic–Lower Cretaceous strata.

microscope), electron probe, stable isotopes and fluid inclusion. (1) Microscopic observation and quantitative statistics of surface porosity in cast thin sections were completed in the State Key Laboratory of Petroleum Resources and Prospecting in China University of Petroleum (Beijing) by using OLYMPUS-BX51 optical microscope and ZEISS Crossbeam 540 scanning electron microscope, respectively. (2) Experiments on analyzing carbon and oxygen isotopic compositions ($\delta^{13}C$ and $\delta^{18}O$ values) were finished at Beijing Research Institute of Uranium Geology. Each sample was milled into particle size 0.075 mm, then let the powders react with 100% phosphoric acid for 4–8 h in a vacuum chamber at 70 °C, and measured the CO_2 released by a Thermo-Finnigan MAT 253 isotope ratio mass spectrometer. The precision of the $\delta^{13}C$ values is ±0.08‰, and ±0.06‰ of $\delta^{18}O$. (3) Electron probe analysis was finished at the Institute of Geology and Geophysics in Chinese Academy of Sciences. Volcanic ash and authigenic minerals in core samples were tested for major elements using a JXA-8100 electron probe micro-analyser (EPMA) with spatial resolution up to 7 nm (measuring accuracy of ±1.0% for major elements, and ±3.0% for trace elements). The beam size for EPMA was 3–5 μm. (4) The experiment on fluid inclusion was completed at Beijing Research Institute of Uranium Geology. The micro-thermometry of these inclusions was analyzed using a petrographic microscope equipped with a LINKAM THMS600 heating-cooling stage. The measurement accuracy is ±0.1 °C for homogenization temperature and ±0.1 °C for final ice-melting temperature. Firstly, the aqueous inclusions were cooled to the lowest temperature and then the phase transition of the fluid inclusions was observed as temperature rose slowly. The final ice-melting temperature of the fluid inclusions was observed at a heating rate not exceeding 0.1 °C/min. Simultaneously, the homogenization temperature of the fluid inclusions was observed at a heating rate of 1 °C/min.

3. Deep and ultra-deep clastic reservoirs

3.1. Petrological characteristics

The sandstone in the Qingshuihe Formation of Sikeshu Sag is almost lithic sandstone with low maturity (Fig. 4a, 4b). In the sandstone, quartz is only 6.0%, with an average of 8.0%; feldspar is only 10.0%, with an average of 5.5%; and debris is 84.0%, with an average of 71.5% (Fig. 4a, 4b). The

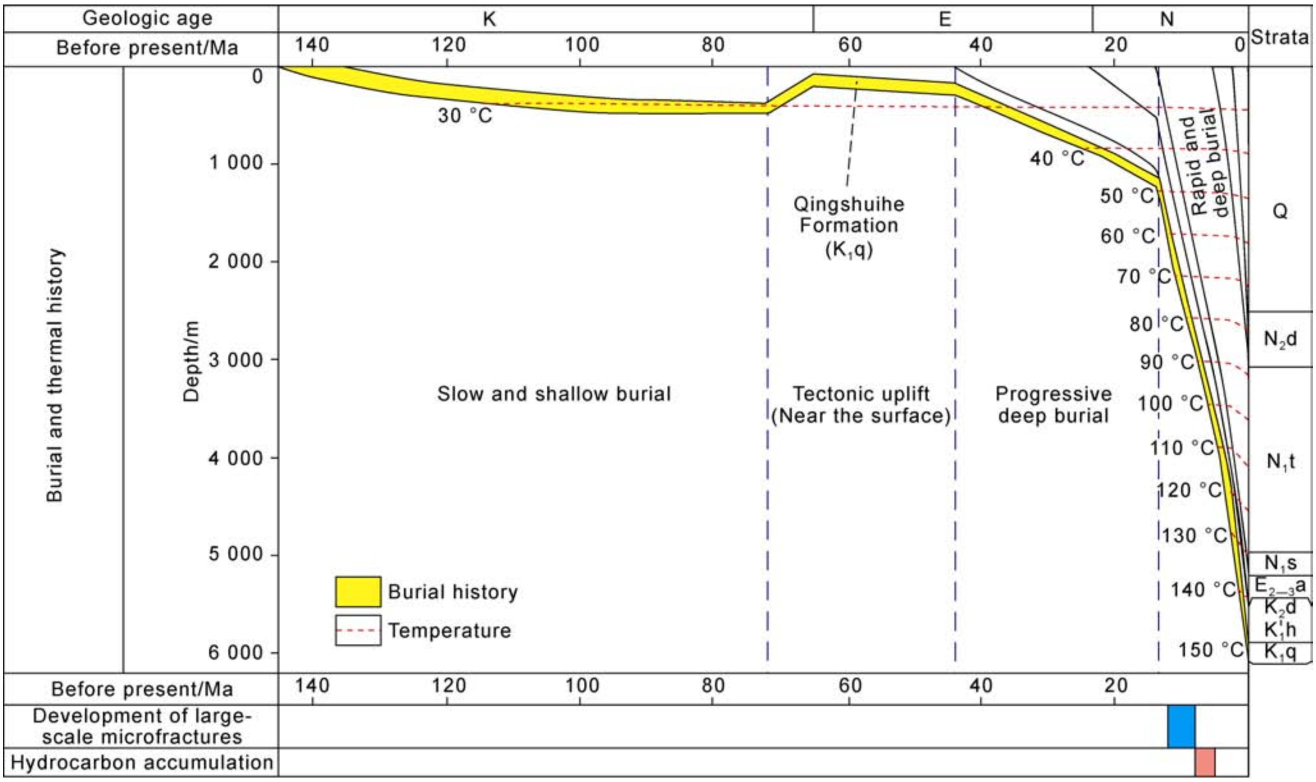

Fig. 2. Burial and thermal history of the Qingshuihe Formation in Gaoquan area, Sikeshu Sag, southern margin of the Junggar Basin (modified from the Reference [9]). Q–Quaternary; N_2d–Dushanzi Formation; N_1t–Taxihe Formation; N_1s–Shawan Formation; $E_{2-3}a$–Anjihaihe Formation; K_2d–Donggou Formation; K_1h–Hutubi Formation; K_1q–Qingshuihe Formation.

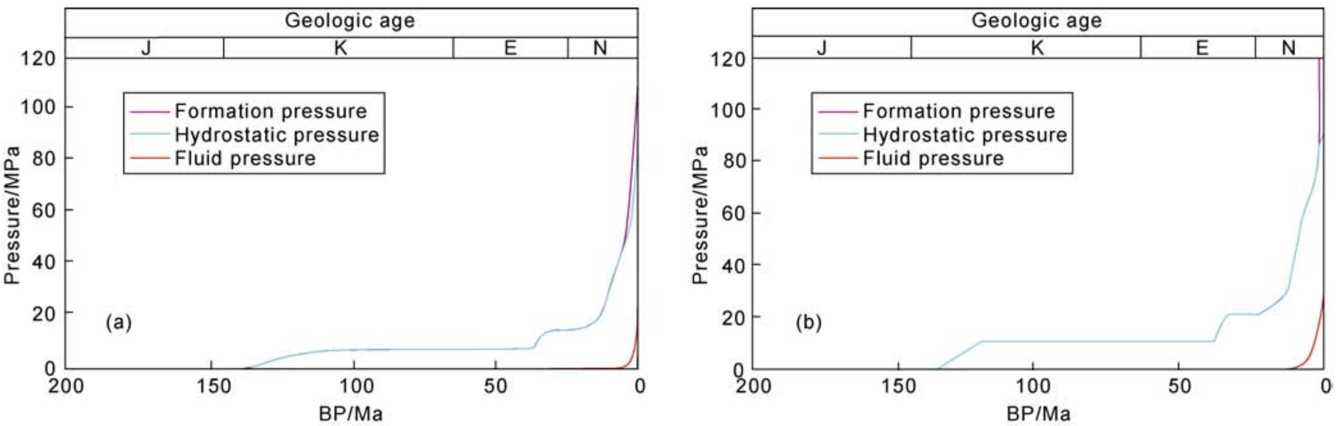

Fig. 3. Pressure evolutionary history of the Qingshuihe Formation in Gaoquan area, Sikeshu Sag, southern margin of the Junggar Basin (modified from the Reference [10]). (a) Pressure evolutionary history in Well GQ5; (b) Pressure evolutionary history in Well G101.

interstitial materials include authigenic cements (Fig. 4c) and volcanic ash (Fig. 5a). The authigenic cements consist of siliceous cements (only 4%), carbonate cements (21%), ferruginous cements (7%) and authigenic clay minerals (54%).

3.2. Diagenetic mineral characteristics

Exploring the influence of the process of "long-term shallow burial and late rapid deep burial" on mineral cementation and dissolution is one of the important subjects in this study. Based on the core samples in the Qingshuihe Formation of Sikeshu Sag, various cements and dissolution characteristics are analyzed.

3.2.1. Siliceous cements

Siliceous cements include microcrystalline quartz and secondary quartz overgrowth. Microcrystalline quartz is often associated with intergranular volcanic ash (Fig. 5b), indicating that the devitrification of intergranular volcanic ash is an important material source for microcrystalline quartz. Secondary quartz predominantly grows around the edges of detritus particles, and can be distinguished from quartz particles by identifying "dust lines" (Fig. 5c).

3.2.2. Carbonate cements

Two kinds of calcite cements are present in the clastic reservoirs of the Qingshuihe Formation. The first kind of calcite cements (Ca-I) occurs as irregular "dots" or

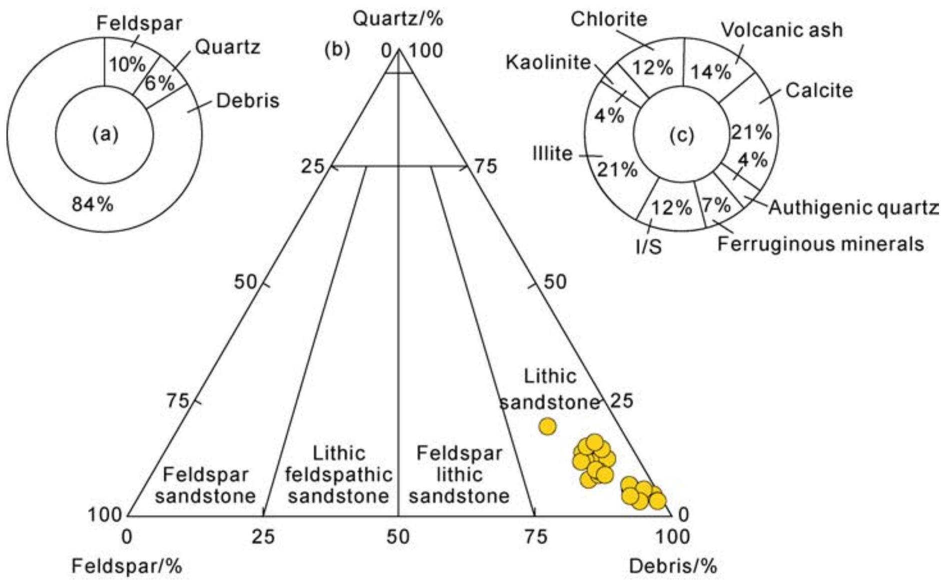

Fig. 4. Sandstone composition of the Qingshuihe Formation in Gaoquan area, Sikeshu Sag, southern margin of the Junggar Basin. (a) Detrital composition and proportion; (b) Ternary diagram of rock composition; (c) Interstitial matter component and proportion.

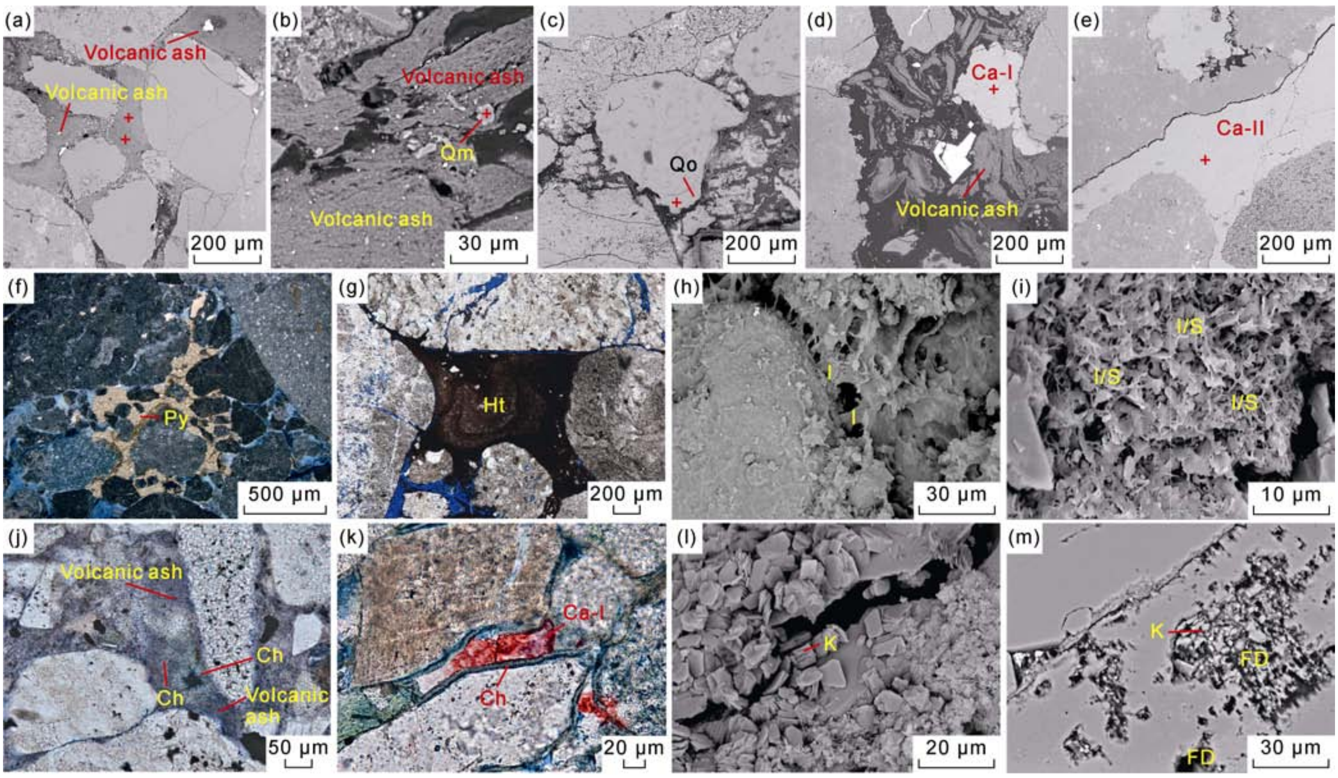

Fig. 5. Diagenetic minerals in clastic reservoirs of Qingshuihe Formation, Gaoquan area, Sikeshu Sag, southern margin of the Junggar Basin. (a) Intergranular volcanic ash, Well GHW001, 5 828.67 m, SEM; (b) Microcrystalline quartz in volcanic ash, Well GHW001, 5 833.96 m, plane-polarized light; (c) Quartz overgrowth, Well GHW001, 5 829.77 m, SEM; (d) First-phase calcite in volcanic ash, Well GHW001, 5 833.96 m, SEM; (e) Second-phase calcite in primary pores, Well GHW001, 5 825.00 m, cross-polarized light; (f) Pyrite with metallic lustre, Well GHW001, 5 829.77 m, cross-polarized light; (g) Hematite in brick red, Well G101, 6 081.96 m, plane-polarized light; (h) interparticle illite, Well GHW001, 5 824.19 m, SEM; (i) Honeycomb I/S, Well GHW001, 5 832.84 m; SEM; (j) Chloritized volcanic ash, Well GHW001, 5 825.19 m, plane-polarized light; (k) Chlorite on particle edges, Well GQ5, 6 051.96 m, plane-polarized light; (l) Worm-like kaolinite in microfractures, Well GQ5, 6 051.96 m, SEM; (m) Kaolinite in intragranular dissolution pores, Well GHW001, 5 832.84 m, SEM. Qo–authigenic quartz; Qm–microcrystalline quartz; Ca-I–first-phase calcite; Ca-II–Second-phase calcite; Py–pyrite; Ht–hematite; I/S–mixed-layer illite/smectite layer; I–illite; K–kaolinite; Ch–chlorite; FD–feldspar dissolution.

"porphyritic". They often fill in and are distinctly associated with volcanic ash (Fig. 5d). The second kind of calcite cements (Ca-II) is characterized by good crystallinity and high euhedral degree (Fig. 5e). They often fill in primary pores in a form of "continuous crystalline" (Fig. 5e).

3.2.3. Ferruginous cements

Ferruginous cements include pyrite and hematite. Pyrite exhibits a typical metallic lustre under the microscope (Fig. 5f). Hematite shows a distinct brick-red colour in plane-polarized light (Fig. 5g), suggesting that the diagenetic environment of the Qingshuihe Formation was once highly oxidized.

3.2.4. Autogenous clay cements

The primary clay minerals include illite, mixed-layer illite/smectite, chlorite, and kaolinite. Illite fills the primary pores as "fibrous matter" (Fig. 5h), mixed-layer illite/smectite occupies the primary pores as "honeycomb" (Fig. 5i), chlorite covers the particle as "coating" (Fig. 5j, 5k), and kaolinite fills the intragranular pores as "worms", and it was later than the chlorite coating (Fig. 5l, 5m).

3.2.5. Dissolution characteristics

Particles and cements in the clastic reservoirs of the Qingshuihe Formation were almost dissolved by acidic fluid in the process of "long-term shallow burial to late rapid deep burial". Feldspathic crystals in the tuffaceous fragments were selectively dissolved by acidic fluid to intragranular dissolution pores which are commonly associated with microfractures that cut through the particles (Fig. 6a, 6b). Volcanic ash and Phase I calcite dissolution promoted the development of intergranular dissolution pores (Fig. 6c–6f). In addition, primary pores are widely developed in the clastic reservoirs of the Qingshuihe Formation. These primary pores have regular shapes and straight edges (Fig. 6g), and part of the edges of the primary pores are evenly covered by chlorite coating (Fig. 6h). Statistical analysis indicates the primary intergranular pores are 55%, the secondary dissolution pores are 34%, and the microfractures are 11% (Fig. 7a). In the secondary dissolution pores, volcanic ash and irregular calcite (Ca-I) dissolution produced 17.3% and 5.4% of intergranular dissolution pores, respectively, and the intragranular dissolution pores produced by feldspathic crystal dissolution are 11.8% (Fig. 7b).

3.3. Reservoir physical properties

Tight clastic reservoir is defined as a reservoir with porosity less than 10%, in-situ permeability less than 0.1×10^{-3} μm^2 or air permeability less than 1.00×10^{-3} μm^2 in petroliferous basins in China [11]. The porosity of the deep and ultra-deep clastic reservoirs of the Qingshuihe Formation in Sikeshu Sag ranges from 2.6% to 17.4%, with an average of 8.3%, and the permeability ranges from $(0.01–38.60)\times10^{-3}$ μm^2, with an average of 4.7×10^{-3} μm^2 (Fig. 7c). In general, the physical properties of the deep and ultra-deep clastic reservoirs are close to the physical properties of tight clastic reservoirs. However, some reservoirs have porosity higher than 10% and permeability higher than 1.0×10^{-3} μm^2 (Fig. 7). They are typical high-quality clastic reservoirs in the Qingshuihe Formation.

3.4. Geochemical characteristics of diagenetic fluids in reservoirs

Successive changes in burial processes will inevitably influence the diagenetic fluid properties of the reservoir, thereby affecting cementation and dissolution. An analysis of the geochemical characteristics of formation water and fluid inclusions is required to determine the properties of reservoir diagenetic fluids.

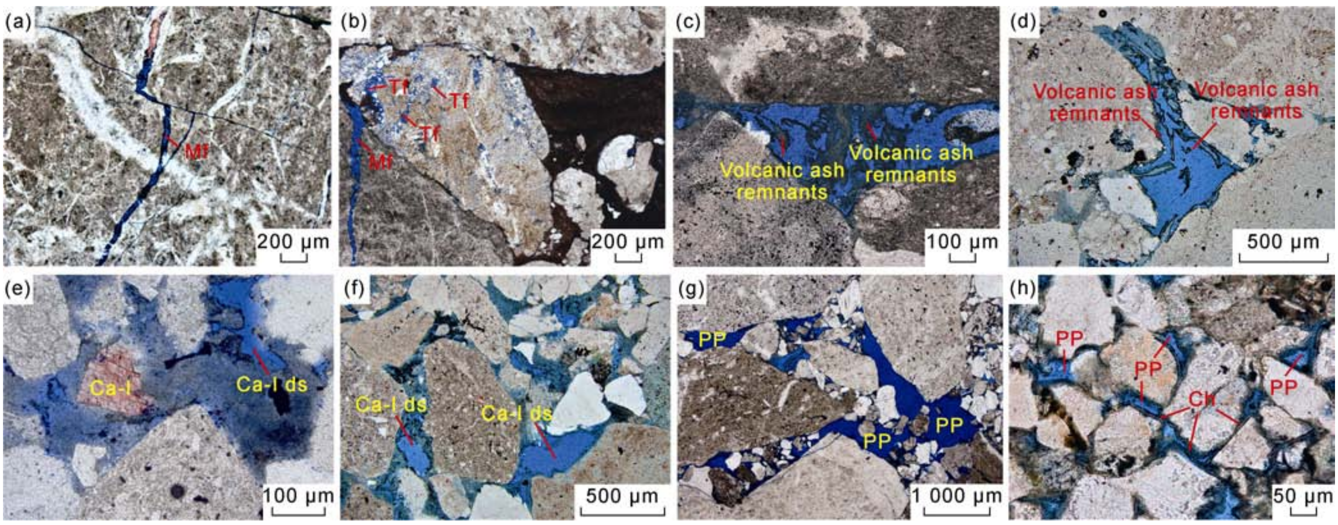

Fig. 6. Reservoir space of clastic reservoirs in Qingshuihe Formation, Gaoquan area, Sikeshu Sag, southern margin of the Junggar Basin. (a) Open microfractures, Well G101, 6 022.65 m, SEM; (b) Microfractures around intragranular dissolution pores, Well G101, 6 020.83 m, plane-polarized light; (c) Filamentous volcanic ash remnants, Well GHW001, 5 829.04 m, plane-polarized light; (d) Branched volcanic ash remnants, Well GHW001, 5 829.04 m, plane-polarized light; (e) Dissolved calcite in volcanic ash, Well GHW001, 5 828.67 m, plane-polarized light; (f) Dissolved calcite in volcanic ash, Well GHW001, 5 833.96 m, plane-polarized light; (g) Regular primary pores, Well GHW001, 5 828.67 m, plane-polarized light; (h) Chlorite on particle edges, Well GQ5, 6 051.96 m, plane-polarized light. Ch–chlorite; Ca-I ds–first-phase calcite dissolution. Mf–microfracture; PP–primary pore; Tf–tuffaceous fragments dissolution.

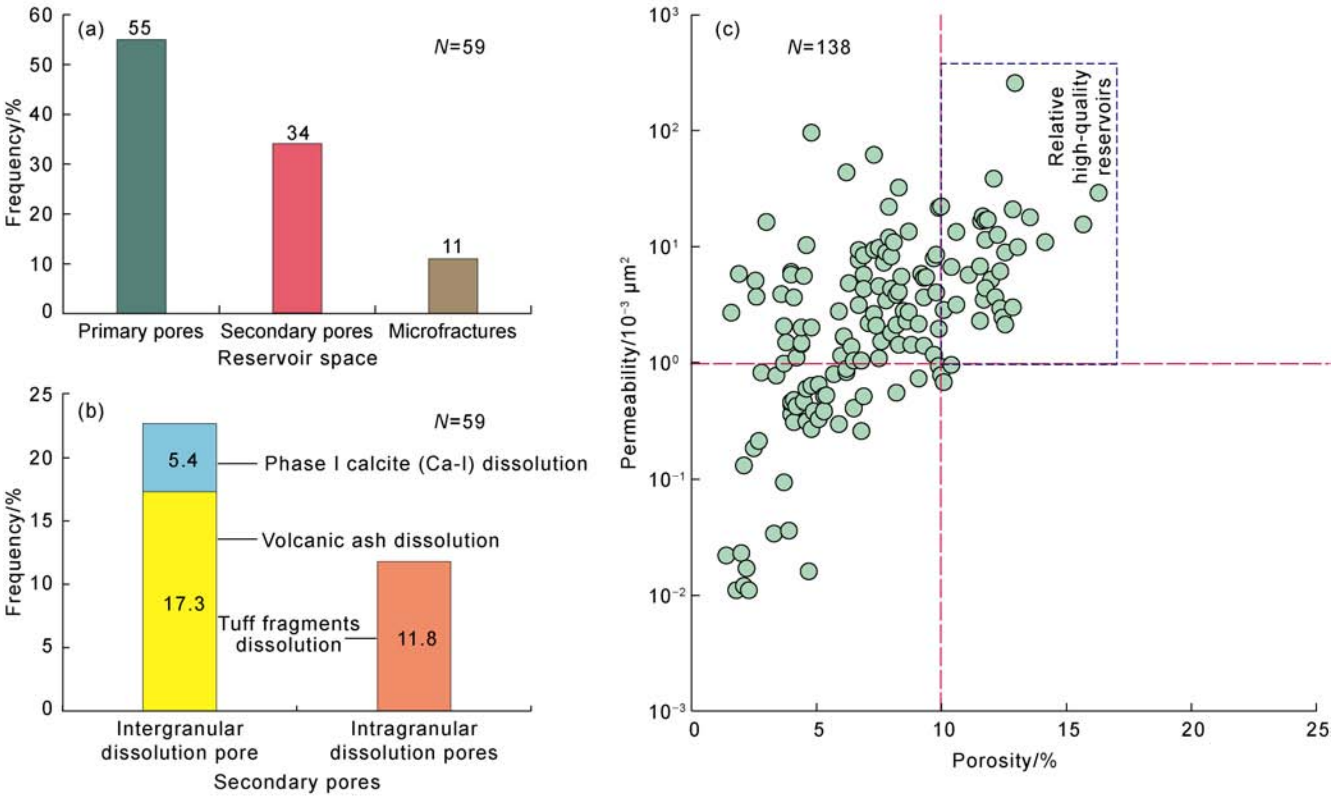

Fig. 7. Reservoir space of clastic reservoirs in Qingshuihe Formation, Gaoquan area, Sikeshu Sag, southern margin of the Junggar Basin (*N* represents sample number). (a) Distribution of primary pores, secondary pores and microfractures; (b) Distribution of intergranular and intragranular dissolution pores; (c) Distribution of porosity and permeability.

3.4.1. Geochemical characteristics of formation water

The formation water in the clastic rock reservoirs of the Qingshuihe Formation is of the $NaHCO_3$ type with typical low mineralization. Let's assume the original sedimentary water is the source of present-day formation water. In that case, the formation water should evolve towards highly mineralized $CaCl_2$ water after the formation experiences dramatic subsidence and intense dissolution [12]. However, the actual results didn't match the assumptions. Based on the above analysis, we believe that the formation water of the Qingshuihe Formation reservoir had been strongly mixed with low mineralized meteoric freshwater, resulting in the dilution of ionic concentration. Of course, the above situations usually require an open diagenetic system to support them. The calculation reveals that the metamorphic coefficient of formation water in the Qingshuihe Formation reservoir is generally close to 1, the desulphurization coefficient is generally greater than 10 (Fig. 8a, 8b). This evidence demonstrates that the hydrological activity of the formation water of the Qingshuihe Formation is relatively active [12], and the open diagenetic system lasts longer than the closed diagenetic system.

3.4.2. Fluid inclusions

Hydrocarbon and aqueous inclusions are mainly distributed in particle microfractures and quartz overgrowth.

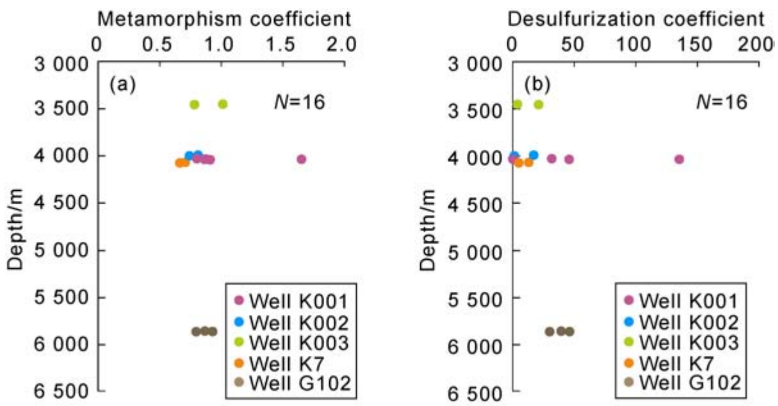

Fig. 8. Geochemical characteristics of formation water in Qingshuihe Formation, Gaoquan area, Sikeshu Sag, southern margin of the Junggar Basin. (a) Variation of metamorphic coefficient with burial depth; (b) Variation of desulphurization coefficient with burial depth.

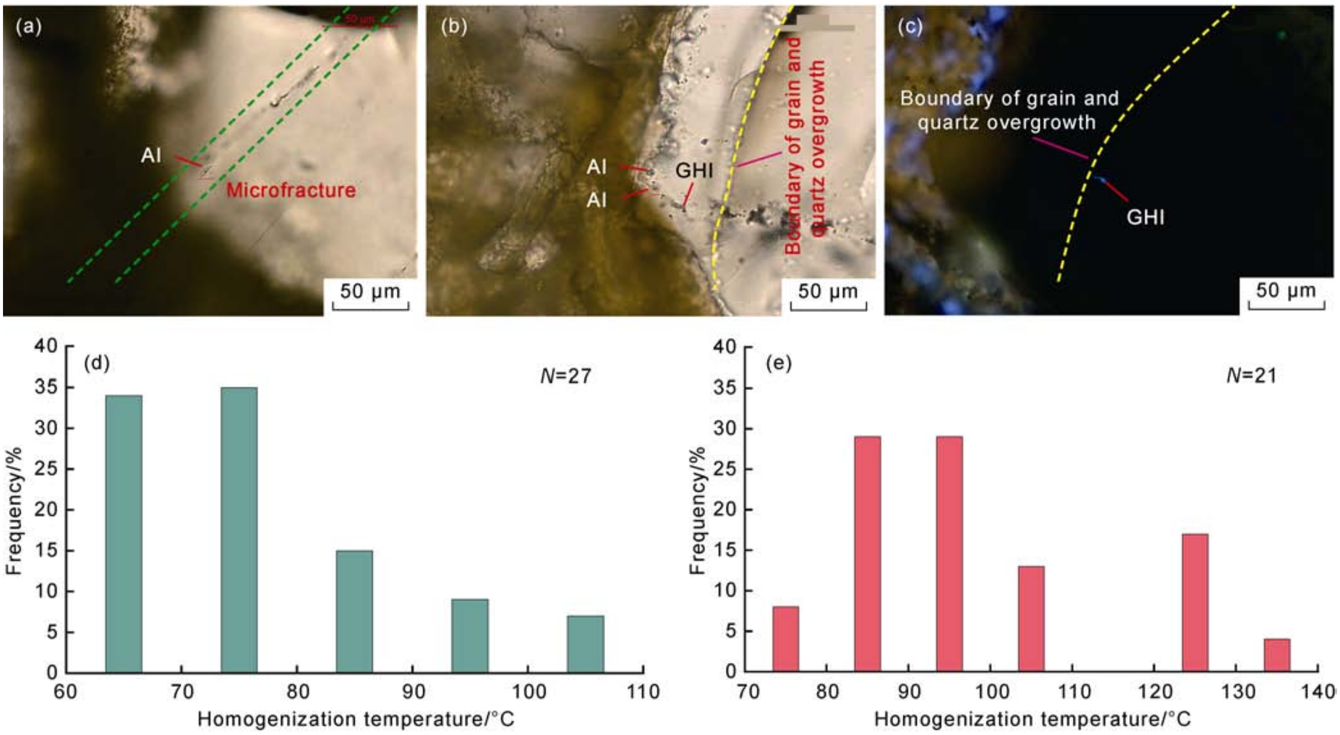

Fig. 9. Petrographic characteristics and homogenization temperature distribution of the fluid inclusions of clastic rock reservoirs of Qingshuihe Formation in the Gaoquan area of Sikeshu Sag, southern margin of Junggar Basin. (a) Well GHW001, 5 828.19 m, aqueous inclusions in the microfracture of detrital quartz, plane-polarized light; (b) Well GHW001, 5 828.67 m, aqueous inclusions associated with gas hydrocarbon inclusions in the quartz overgrowth, plane-polarized light; (c) Well GHW001, 5 828.60 m, gas hydrocarbon inclusions in the quartz overgrowth, fluorescence. AI–aqueous inclusion; GHI–gas hydrocarbon inclusion.

The aqueous inclusions often develop in the quartz microfractures and overgrowths, exhibiting grey or light brown under plane-polarized light (Fig. 9a). Hydrocarbon inclusions commonly occur in quartz overgrowths (associated with aqueous inclusions), exhibiting gray to dark gray under plane-polarized light, and blue under UV light (Fig. 9b, 9c). The peak value interval of homogenization temperature of aqueous inclusions in the microfractures and quartz overgrowths range from 60 °C to 80 °C and 80 °C to 100 °C, respectively (Fig. 9d, 9e). Projecting the peak value interval of the homogeneous temperature of aqueous inclusions in the microfracture on the burial–thermal evolutionary history (Fig. 2), we calculated the formation time of the microfracture was 12 Ma to 8 Ma. Simultaneously, projecting the peak value interval of the homogeneous temperature of aqueous inclusions associated with hydrocarbon inclusions in the quartz overgrowth on the burial–thermal evolutionary history (Fig. 2), we calculated the time of hydrocarbon and organic acid charging of the Qingshuihe Formation occurred during 5 Ma to 8 Ma.

4. Discussion

4.1. Impact of the process of “long-term shallow burial and late rapid deep burial” on the diagenesis of deep and ultra-deep clastic rocks

4.1.1. Impact of burial process on compaction

Based on mathematical model calculations, previous researchers have concluded that burial processes can influence the formation porosity [13]. The larger the area enclosed by the curve of burial history and the time axis, the greater the destruction caused by compaction to the primary pores [14]. The formation burial history of petroliferous basins in China can be classified into constant-velocity burial, decelerated burial, accelerated burial, and interrupted burial types. Compaction is strongest in the interrupted burial type, followed by the decelerated and constant-velocity burial types, and weakest in the accelerated burial type [13].

From the changing trend of burial rate, the Qingshuihe Formation has experienced three burial stages with different subsidence rates, namely, slow shallow burial (7 m/Ma), tectonic uplift, progressive deep burial (46 m/Ma) and rapid deep burial (346 m/Ma). From the duration of each burial stage, the slow shallow burial stage is 70 Ma, the tectonic uplift stage is 30 Ma, the progressive deep burial stage is 26 Ma, and the rapid deep burial stage is only 14 Ma (Fig. 2). Therefore, the Qingshuihe Formation has a typical accelerated burial process of “long-term slow-short-term rapid”. Based on the above analyses, the mechanical compaction in the background of the subsidence process of this type of formation has damaged the reservoir space to a relatively small extent, which is conducive to protecting primary pores. Comprehensive Fig. 7 further confirms that the high-quality reservoir formation in the deep–ultra-deep layer of the Qingshuihe Formation

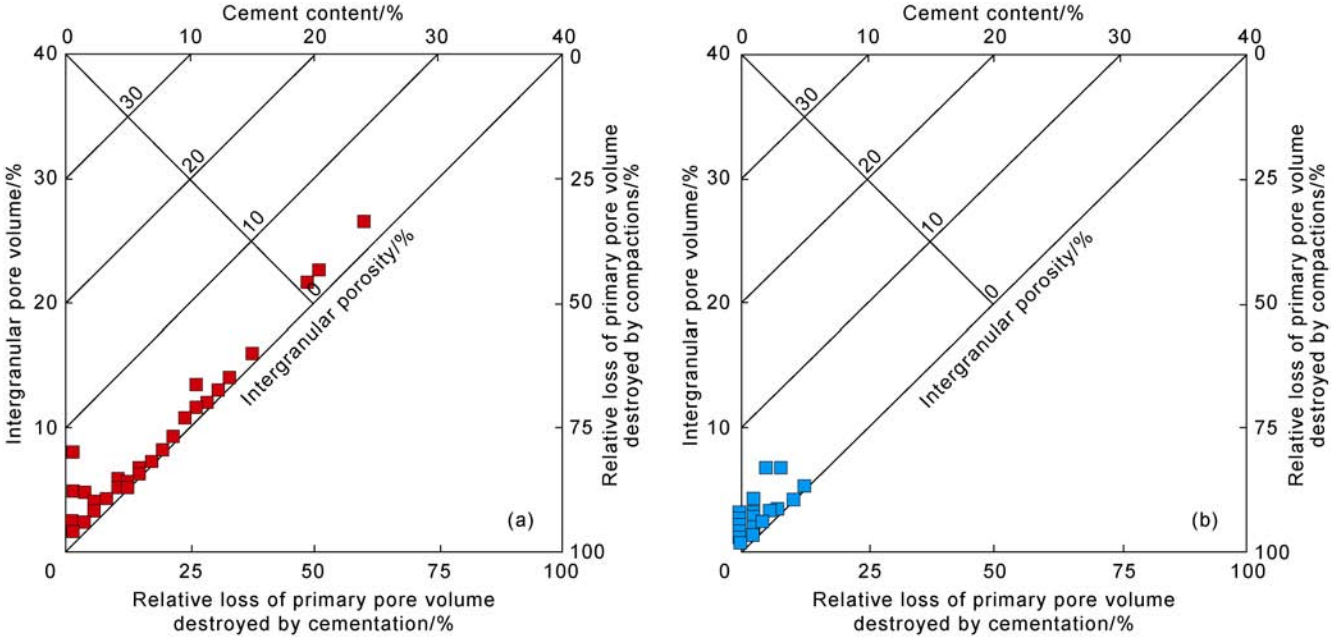

Fig. 10. Comparison of the mechanical compaction intensities of clastic reservoirs of Qingshuihe Formation in different areas in southern margin of the Junggar Basin. (a) Western Gaoquan area; (b) middle area.

depends on the preservation of primary porosity, which reveals the importance of the advantageous burial method in this area compared with acidic fluid charging for the development of high-quality reservoirs in the deep–ultra-deep layer.

The clastic rock reservoirs of the Qingshuihe Formation in the middle section of the southern margin of Junggar Basin, which is adjacent to the study area, were selected for the compaction intensity comparisons. This area has similar sedimentary environments, burial depths and rock compositions to the study area, but the burial history is a classic constant-velocity type [15]. Comparison results show that the loss of intergranular pore volume caused by mechanical compaction in clastic rocks under the influence of the accelerated burial mode of "long-term slow shallow burial-late rapid deep burial" is 50%–90% (Fig. 10a), while that in clastic rocks under the influence of the constant-velocity burial process is 75%–90% (Fig. 10b). The former inhibits compaction more significantly than the latter.

4.1.2. Impact of burial process on cementation and dissolution

According to the burial history (Fig. 2), diagenetic minerals (Fig. 5b–5m), elemental geochemistry (Fig. 11), and stable isotope compositions (Fig. 12), we discuss the impact of the "long-term shallow burial and late rapid deep burial" process on the cementation and dissolution of the reservoir.

4.1.2.1. Siliceous cementation

There are different silica sources in clastic reservoirs. For example, feldspar dissolution, tuff fragments alteration, and volcanic ash devitrification can provide silica for siliceous cements [16–17]. Formation temperature is a critical factor influencing dissolution and devitrification. For instance, volcanic material is unstable at low temperature (less than 50 °C) and easily transformed into microcrystalline quartz by devitrification [17]. The suitable formation temperature for organic acid preservation is 80–120 °C. It is worth noting that the changing trend of formation temperature depends on the burial process to some extent, indicating that the relationship between siliceous cementation and burial process is close. Based on the previous analyses, the duration of the "slow shallow burial" process in the Qingshuihe Formation was 70–140 Ma. The formation temperature during the period was less than 30 °C (Fig. 2), which was suitable for devitrification in volcanic materials and the formation of microcrystalline quartz. The SEM photomicrograph shows microcrystalline quartz formed by devitrification is scattered in volcanic ash (Fig. 5b). Titanium dioxide (TiO_2) was detected from microcrystalline quartz by electron probe analysis (Figs. 5b and 11a). This evidence confirms that amorphous silica formed by the devitrification of volcanic materials was subjected to the leaching of meteoric freshwater during recrystallisation, resulting in a small amount of titanium dioxide in the microcrystalline quartz [18]. Of course, volcanic ash dissolution also could inhibit devitrification. Therefore, the forming time of microcrystalline quartz was concentrated on the early stage of the "slow shallow burial" process. Quartz overgrowth hardly contains titanium dioxide, confirming small impact of meteoric freshwater on them (Figs. 5c and 11a). It is worth noting that brine inclusions in quartz overgrowth have peak homogenization temperature at 80–100 °C (Fig. 9e), which corresponds to the late

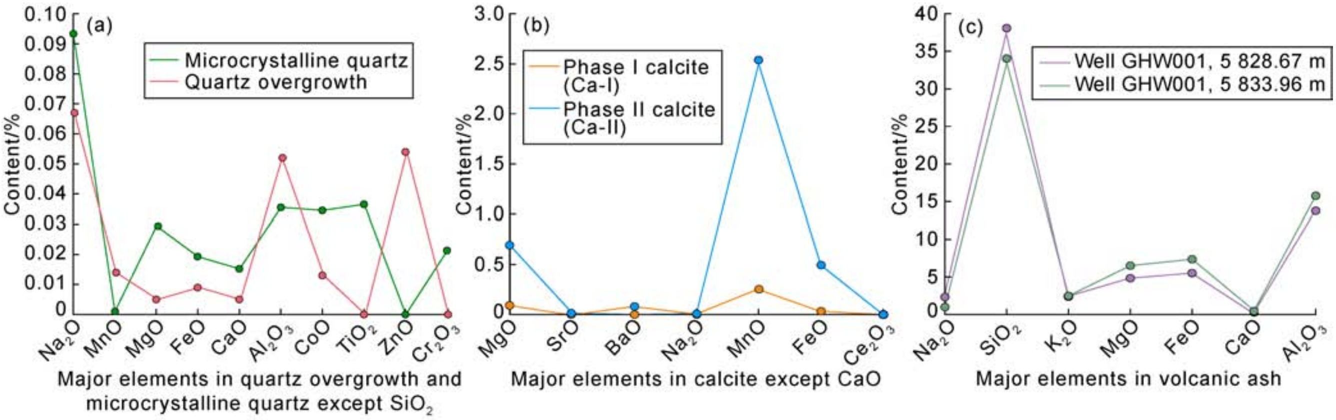

Fig. 11. Geochemical elements of the diagenetic minerals and volcanic ash in clastic reservoirs of Qingshuihe Formation, Sikeshu Sag, southern margin of the Junggar Basin.

"rapid deep burial" process (Fig. 2). The rapid increase in burial rate and formation temperature caused the source rock to rapidly become mature and release organic acids into the reservoir to dissolve feldspar and tuffaceous fragments. Therefore, SiO_2 in quartz overgrowth mostly came from the dissolution of feldspar and rock fragments.

4.1.2.2. Carbonate cementation

The Mn and Fe contents can reflect the diagenetic environment during calcite precipitation [19]. Mn and Fe under oxidizing conditions are in the form of Mn^{4+} and Fe^{3+}, which are not easy to enter the mineral lattice. Fe under semi-oxidizing environment is mostly Fe^{3+}, which is not easy to enter the mineral lattice, whereas Mn is mostly Mn^{2+}, which can enter the mineral lattice. Mn and Fe under reducing conditions are in the form of Mn^{2+} and Fe^{2+}, both of which are able to enter the mineral lattice. The clastic reservoirs of the Qingshuihe Formation have two kinds of calcite. Ca-I has a low Mn and Fe content (Figs. 5d and 11b), suggesting they formed in an oxidation or semi-oxidation environment. Ca-II has a high Mn and Fe content (Figs. 5d and 11b), suggesting they formed in a reducing environment.

Stable isotopic data ($\delta^{13}C$ and $\delta^{18}O$) contribute to judging the formation time of calcite cement [9]. Calcite precipitation temperatures show that Ca-I precipitation temperatures are generally less than 30 °C (Fig. 12), which corresponds to the "slow shallow burial" stage (Fig. 2). The precipitation temperature of Ca-II is close to 50°C (Fig. 12), which corresponds to the “progressively deeper burial” stage with increasing formation temperature (Fig. 2). Previous studies show that when the “carbon” of calcite comes mainly from CO_2 in meteoric freshwater, their $\delta^{13}C$ values are usually –5‰ to –1‰ [20]. When the "carbon" source of calcite comes from CO_2 derived from the thermal evolution of organic matter, their $\delta^{13}C$ values are usually around –25‰ [20]. The distribution of $\delta^{13}C$ values in Ca-I and Ca-II ranges from –5‰ to –1‰ and near –25‰ (Fig. 12), indicating the “carbon source” of the Qingshuihe Formation calcite is related to both meteoric freshwater leaching and thermal evolution of organic matter.

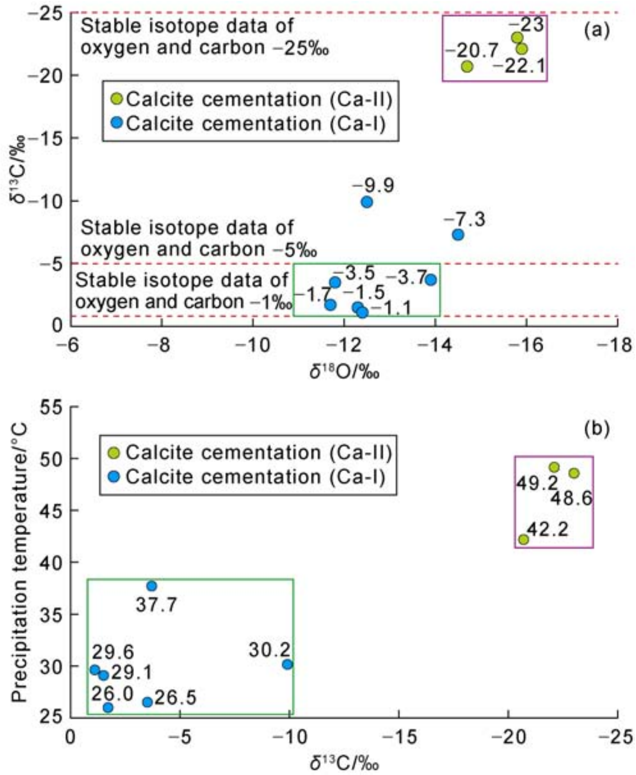

Fig. 12. Stable isotopic compositions and precipitation temperature characteristics of different kinds of calcite of clastic rock reservoirs of Qingshuihe Formation in the Sikeshu Sag, southern margin of Junggar Basin. (a) Stable isotope characteristics of calcite; (b) Precipitation temperature characteristics of calcite.

From 100 Ma to 140 Ma, the depth of the Qingshuihe Formation was less than 500 m in the "slow shallow burial" process (Fig. 2). The reservoir environment was an open diagenetic system with weak compaction and oxidization. At the same time, the humid climate [21] brought abundant freshwater which entered the reservoir through faults. Freshwater fully dissolved the intergranular volcanic ash and produced intergranular dissolution pores. Of course, Ca^{2+}, Mg^{2+}, CO_3^{2-}, and HCO_3^- were released after volcanic ash dissolution. Subsequently, the study area was subjected to a hot, arid climate during the late "slow and shallow burial" stage (70–100 Ma) [21]. The lack of meteoric freshwater supply caused the pore water to transition from weakly acidic to alkaline. During that period, Ca^{2+} in the pore water combined with CO_3^{2-} and HCO_3^- to form Ca-I and part of Ca-I precipitated in the dissolution pores in the volcanic ash (Figs. 5d and 6c). Ca-II started to precipitate at the end of the “progressive deep burial” stage (Fig. 5e). This stage was influenced by a gradual increase in burial rate and formation temperature (30–50 °C) (Fig. 12), and the thermal evolutionary degree of organic matter began to increase and release organic-originated CO_2. Due to the impact of organic carbon, the $\delta^{13}C$ values of Ca-II show a significantly “negative drift” (Fig. 12). Therefore, Ca-I belongs to the product caused by the joint influence of "slow shallow burial" and paleo-climate, while Ca-II is the product caused by the joint influence of "progressive deep burial" and thermal evolution of organic matter.

4.1.2.3. Autogenous clay cementation

Thin-section observation and electron probe analyses show that the volcanic ash of the Qingshuihe Formation is relatively rich in Fe and Mg elements (Figs. 5a and 11c), and the volcanic ash has undergone significant chloritization (Fig. 5j). Even the precipitation of chlorite crystals was observed near the edges of some volcanic ash dissolution pores (Fig. 5j), indicating that the formation of chlorite coating is closely related to the dissolution and alteration of volcanic ash. The formation of chlorite coating requires an open diagenetic system with high porosity, high permeability, and an alkaline environment [22]. The "slow shallow burial" process alleviated the destruction to the pores and throats caused by compaction and provided a relatively open geochemical system for chlorite coating development. In the humid climate (100–140 Ma), a large amount of meteoric freshwater was poured into the clastic reservoirs through faults and dissolved the volcanic ash and released Fe^{2+} and Mg^{2+} required for the development of chlorite coating. When the climate changed from humid to hot and arid (66–100 Ma) and the pore water changed from weakly acidic to alkaline, early Fe^{2+} and Mg^{2+} combined with smectite from volcanic ash alteration to form chlorite coating [22].

Feldspar and volcanic matter in rock react with acidic fluid to produce kaolinite [3, 16]. If the geochemical system maintains open and steady in the dissolution process, the product that’s favorable for unstable composition may be taken out of the dissolution zone and inhibits kaolinite precipitation [3]. The secondary pores in the clastic reservoirs of the Qingshuihe Formation account for 34% (Fig. 7a), but the kaolinite precipitation is only 4% (Fig. 4c), suggesting that the kaolinite precipitation during the dissolution process is extremely low. Such a diagenetic phenomenon is closely related to the unique burial process of the Qingshuihe Formation. The burial depth of the Qingshuihe Formation within 100 Ma was less than 500 m, and even close to the earth's surface during the tectonic uplift stage (Fig. 2). Such a burial history is not common in deep and ultra-deep fields worldwide. The long-term shallow depth not only provided an open and stable diagenetic system, but also ensured that abundant freshwater can carry the chemical components required for kaolinite precipitation out of the dissolution zone by their high mobility while dissolving the unstable components. As a result, kaolinite precipitation was rarely found near the dissolved volcanic ash in this study. In addition, the Qingshuihe Formation entered the deep burial stage late (Fig. 2), and the charging time of organic acids was short, resulting in a limited amount of kaolinite precipitation under the deep closed system.

Volcanic ash can be transformed into smectite through alteration during early diagenesis, and then into illite with K^+ in pore water [23]. Previous studies showed that smectite can be transformed into illite at any diagenetic stage [24]. Therefore, the supply of K^+ is most important for the transformation from smectite to illite. Because the average value of feldspar content in the Qingshuihe Formation is only 5.5%, volcanic ash becomes a key source of K^+. According to electron probe analyses, the K_2O content in volcanic ash of the Qingshuihe Formation is low (Figs. 5a and 11c). In addition, even if volcanic ash releases K_2O when leached by meteoric freshwater, it is easily removed from the reservoir in the open diagenetic system created by long-term "slow and shallow burial" and "tectonic uplift", so it is difficult to reach the K^+ concentration required for illite precipitation. Therefore, “slow and shallow burial” and “tectonic uplift” are not favorable for illite precipitation. After entering deep burial, organic acid dissolved feldspars and volcanic ash can also provide K^+. Simultaneously, K^+ loss decreased in the increasing closed geochemical system. All these factors were favorable for the transform from smectite to illite. The process of "progressive deep burial" and "rapidly deep burial" is suitable for the precipitation of illite and mixed-layer illite/smectite (Fig. 5h, 5i).

4.2. Impact of “long-term shallow burial and late rapidly deep burial” on the development of high-quality deep and ultra-deep clastic reservoirs

Previous studies showed that climate was a critical factor influencing the diagenetic environment during "shallow burial" or "tectonic uplift" [25]. Prevailing paleoclimate indirectly controls the property of diagenetic fluid by affecting the geochemical properties of the primary water in marine or lacustrine basins, and has an essential impact on diagenesis and high-quality reservoir development [25]. Under the influence of humid climate, the secondary pores caused by meteoric freshwater leaching reach 22.7% of total secondary pores (Fig. 7b). The intergranular dissolution pores provided by volcanic ash dissolution is 17.3%, and the intergranular dissolution pores formed by Ca-I dissolution is 5.4% (Fig. 7b). In addition, it's not easy for the dissolution products to precipitate and therefore secondary pores that increase reservoir space can be preserved for high-quality reservoir development in deep and ultra-deep formations. Moreover, the chlorite coating formed in hot and arid climates can inhibit the precipitation of SiO_2 in pore water, indirectly prevent the nucleation and growth of SiO_2 on particle surface and inhibit quartz overgrowth, thus protecting the primary pores [26]. The higher the relative content of chlorite, the better the reservoir's physical properties (Fig. 13).

In addition to long-term "slow shallow burial" and "tectonic uplift", late "rapid deep burial" is another essential factor for the development of high-quality clastic reservoirs in deep and ultra-deep formations. Rapid burial can inhibit the dissipation of fluid pressure and make it accumulate in pores to cause fluid overpressure [5]. This overpressure development mechanism is common worldwide. For example, the overpressure in the margin of the North Sea Basin in Norway and local zones in the Gulf of Mexico in the United States is the result of late rapid burial similar to the Qingshuihe Formation [5, 27]. Fluid overpressure can resist mechanical compaction and

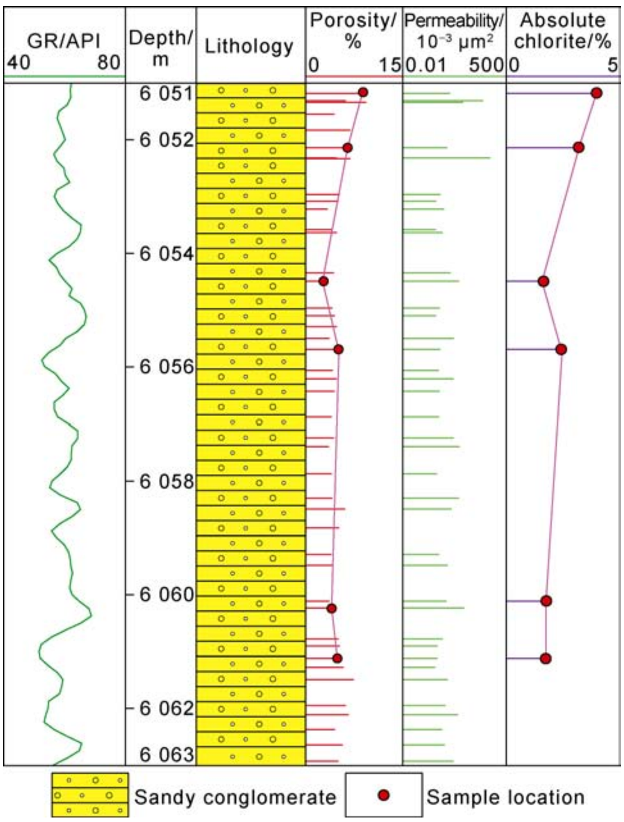

Fig. 13. Relationship between chlorite content and reservoir quality of clastic rock reservoirs of Qingshuihe Formation in the Sikeshu Sag, southern margin of Junggar Basin.

protect primary pores [5]. Based on theoretical modelling, previous studies have deduced that 1 MPa fluid overpressure corresponds to a reduction of actual burial depth by 80 m [28]. The pressure coefficient of the Qingshuihe Formation is 2.16, so the inhibiting effect of fluid overpressure on mechanical compaction is significant. In an overpressure environment, the carbonate solubility in an aqueous solution increases with fluid pressure [29]. Therefore, fluid overpressure can inhibit carbonate precipitation. In addition, fluid overpressure can enhance the stability of water between smectite layers and indirectly inhibit the transform from smectite to mixed-layer illite/smectite or illite [30]. This mechanism can protect primary intergranular pores and retard the destruction to reservoir quality by cementation. The content of carbonate and clay minerals increase with burial depth in the middle to shallow formations at normal pressure (Fig. 14a–14d), causing the porosity and permeability of the reservoir to decrease with burial depth (Fig. 14e, 14f). In contrast, the content of carbonate and clay minerals decreases with burial depth in the deep to ultra-deep formations at overpressure (Fig. 14a–14d), so the porosity and permeability increase with burial depth (Fig. 14e, 14f).

Besides primary porosity, fluid overpressure has an essential impact on the development of secondary pores. High fluid pressure broke through the lowest limit of rock's fracturing pressure, and caused very open microfractures in the Qingshuihe Formation, ultimately increasing the fluid seepage capacity [9]. From the normal-pressure zone to the overpressure zone, the reservoir permeability of the Qingshuihe Formation shows an increasing trend (Fig. 14f). It is worth noting that the formation of microfractures occurred in the same period as organic acid charging. Therefore, microfractures also acted as transport channels for organic acids, and increased the amount of organic acids into the reservoir and improved the dissolution of tuff fragments. The percent of intragranular pores caused by the dissolution of tuff fragment is 11.8% (Fig. 7).

Core samples whose present porosity is 15% were selected to recover the porosity evolution history of deep to ultra-deep clastic reservoirs in the process of "long-term shallow burial and late rapid deep burial" by using previous research methods[23, 31], and quantitatively determine how burial process contributes to high-quality reservoirs. In the process of "slow shallow burial" and "tectonic uplift", the loss of primary pores caused by mechanical compaction was only 5.9%, and meteoric freshwater leaching provided about 2.3% of secondary pores (Fig. 15). During late "rapid deep burial", microfractures interacted with organic acids to provide 1.2% of secondary pores (Fig. 15). Simultaneously, fluid overpressure induced by late "rapid deep burial" effectively reduced the

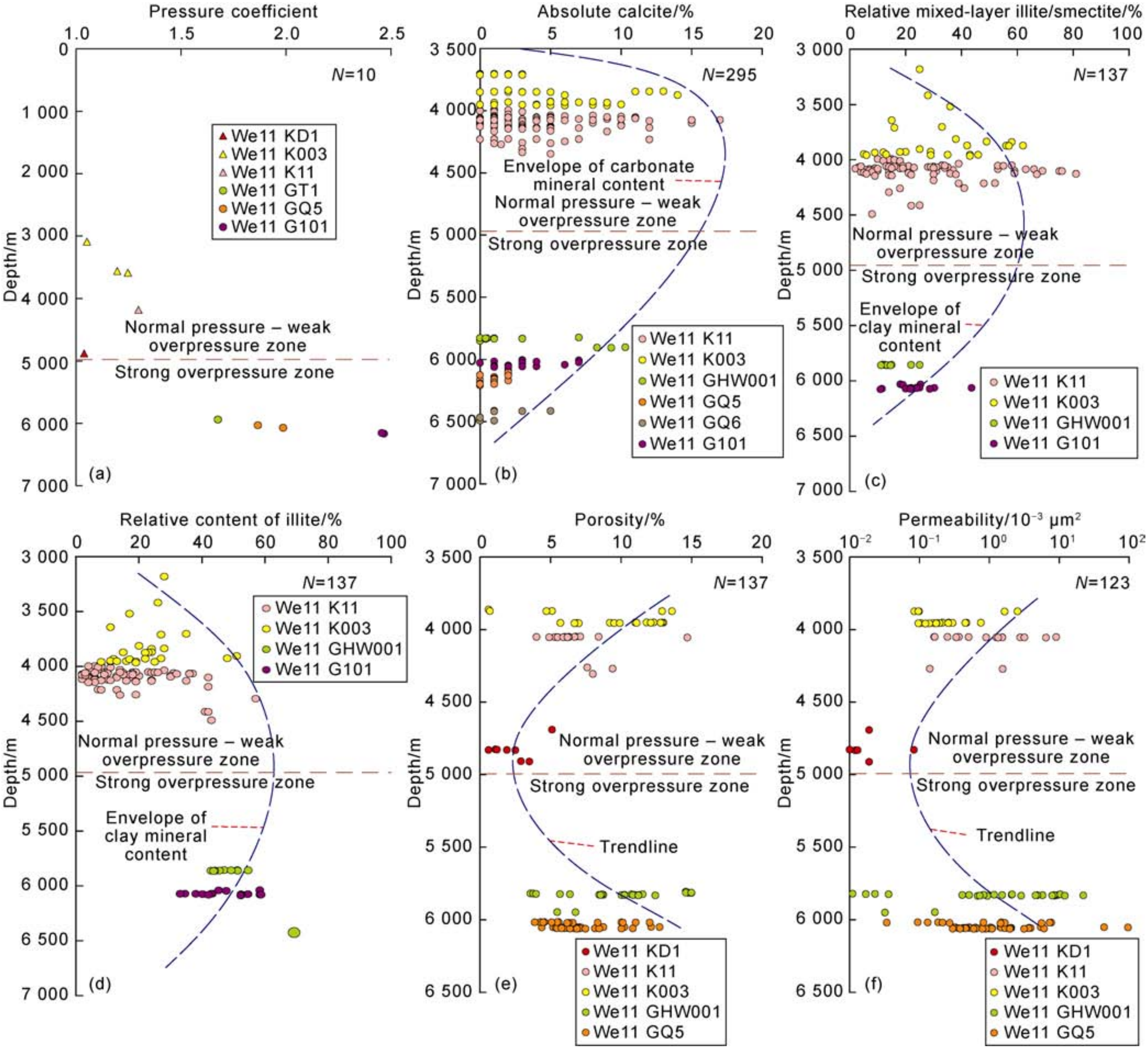

Fig. 14. Vertical distribution of pressure coefficient, calcite, porosity, permeability and clay minerals of clastic reservoirs in Qingshuihe Formation, Sikeshu Sag, southern margin of the Junggar Basin. (a) Pressure coefficient; (b) Calcite content; (c) Mixed-layer illite/smectite relative content; (d) Illite relative content; (e) Porosity; (f) Permeability.

loss of primary pores. From the porosity evolution history, it’s found that the loss of primary pores caused by mechanical compaction is not more than 10% from 1 200 m to 6 000 m (Fig. 15). In addition, the “progressive deep burial” process dominated by compaction and cementation is not conducive to protecting primary pores and increasing secondary pores (Fig. 15). Therefore, for deep and ultra-deep clastic reservoirs developed in the process of "long-term shallow burial and late rapid deep burial", "slow shallow burial" and "tectonic uplift" had the maximum contribution to the development of high-quality reservoirs, followed by the late "rapid deep burial" process (Fig. 15). "Progressive deep burial" is unfavorable for the development of high-quality reservoir.

5. Conclusions

The "slow shallow burial" and "tectonic uplift" processes alleviated the destruction caused by compaction to the primary pores of the clastic rock reservoirs of the Qingshuihe Formation during the long geological time. The chlorite coating adequately developed at the edge of the particles and enhanced their compaction resistance. As a result, the loss of primary pores was only 5.9%. Late "rapid deep burial" facilitated the development of fluid overpressure, making the loss of primary pores by less than 10% against the background of subsidence approaching 6 000 m. Fluid overpressure inhibited the precipitation of carbonate minerals and transform of clay minerals, alleviating the destruction caused by late

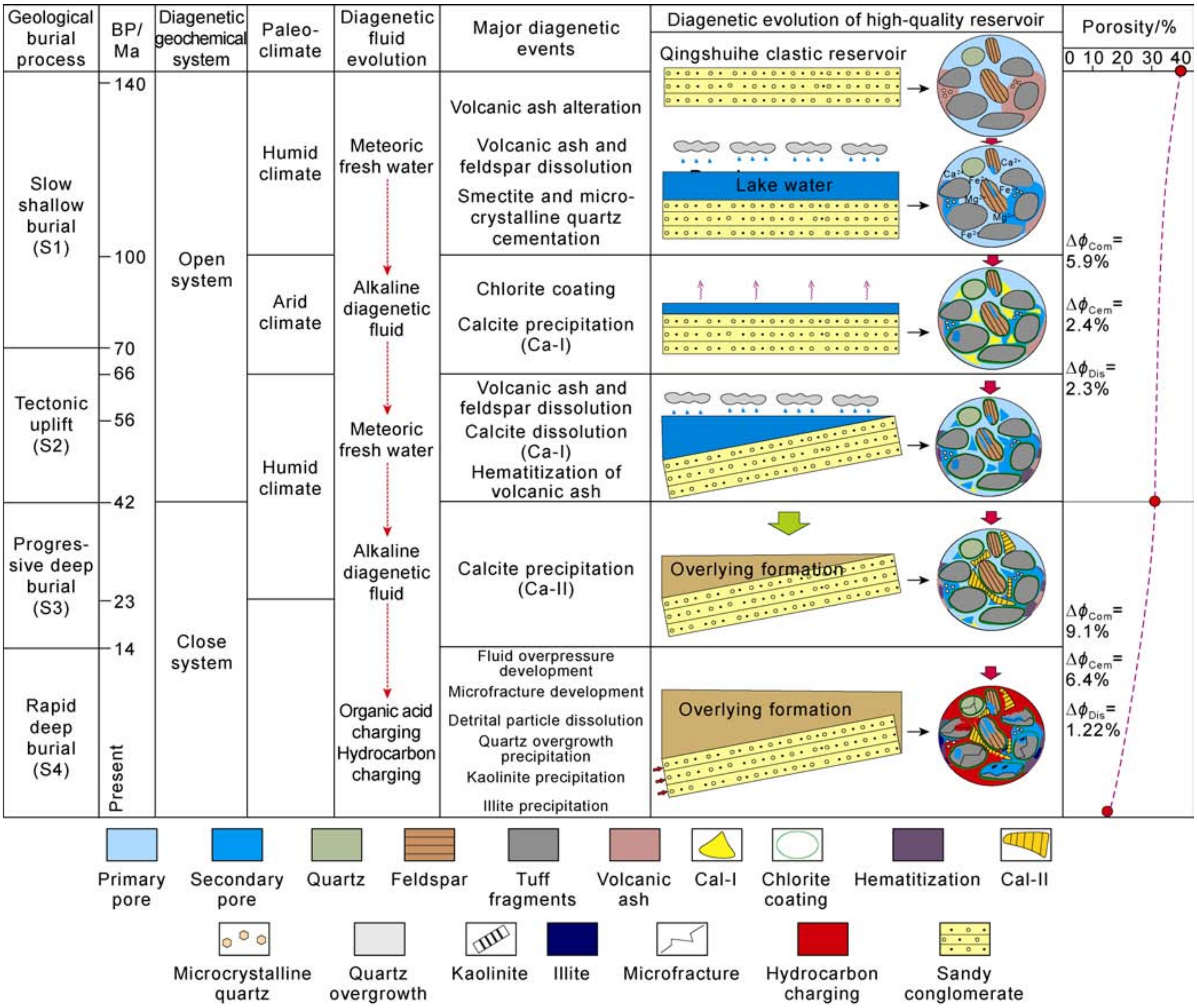

Fig. 15. The evolution history of high-quality deep and ultra-deep clastic reservoirs of Qingshuihe Formation, Sikeshu Sag, southern margin of the Junggar Basin. $\Delta\phi_{Com}$—porosity loss caused by mechanical compaction; $\Delta\phi_{Cem}$—porosity loss caused by cementation; $\Delta\phi_{dis}$—porosity increase caused by dissolution.

cementation on the primary pores.

"Slow shallow burial" and "tectonic uplift" created a steady and open diagenetic system for the development of secondary pores. Meteoric freshwater can fully dissolve the easy-to-dissolve minerals and inhibit kaolinite precipitation, thus providing 2.3% of secondary pores for the reservoir. The two burial processes contributed the most to secondary pores. Late "rapid deep burial" was the second contributor to the development of secondary pores. The process triggered fluid overpressure that caused particles to crack and produced microfractures. Organic acids flew into the reservoir through the microfractures and dissolved unstable particles, providing 1.2% of secondary pores for the deep and ultra-deep reservoirs.

Whether high-quality clastic reservoirs can develop in the deep to ultra-deep formations which underwent "early shallow burial and late deep burial" depends firstly on the preservation of primary pores, and secondly on the development of secondary pores. The longer the early "shallow burial" or "tectonic uplift", the shallower the formation, and the better the preservation of primary pores are. If the process falls in a humid climate environment, more effective secondary pores will be created through meteoric freshwater leaching. The shorter the late deep burial, the more favorable the formation of fluid overpressure. Fluid overpressure is conducive to protecting primary pores and maintaining good pore structures. If the overpressure exceeds the lowest limit of rock fracturing pressure, a large number of microfractures will be induced. These microfractures will facilitate the migration and accumulation of late hydrocarbon into reservoir.

References

[1] HE Dengfa, JIA Chengzao, ZHAO Wenzhi, et al. Research

progress and key issues of ultra-deep oil and gas exploration in China. Petroleum Exploration and Development, 2023, 50(6): 1162–1172.

[2] GUI Lili, ZHUO Qingong, LU Xuesong, et al. Restoration of reservoir diagenesis and hydrocarbon accumulation process by calcite in-situ U-Pb dating and fluid inclusion analysis: A case study on Cretaceous Qingshuihe Formation in Gaoquan, southern Junggar Basin, NW China. Petroleum Exploration and Development, 2023, 50(6): 1209–1220.

[3] CAO Yingchang, YUAN Guanghui, WANG Yanzhong, et al. Successive formation of secondary pores via feldspar dissolution in deeply buried feldspar-rich clastic reservoirs in typical petroliferous basins and its petroleum geological significance. SCIENCE CHINA Earth Sciences, 2022, 65(9): 1673–1703.

[4] HAKIMI M H, AL-MATARY A M, SALAD HERSI O. Burial and thermal history reconstruction of the Mukalla-Sayhut Basin in the Gulf of Aden, Yemen: Implications for hydrocarbon generation from Paleocene potential source rock. Journal of African Earth Sciences, 2018, 144: 59–75.

[5] SATHAR S, JONES S. Fluid overpressure as a control on sandstone reservoir quality in a mechanical compaction dominated setting: Magnolia Field, Gulf of Mexico. Terra Nova, 2016, 28(3): 155–162.

[6] SUN D Q, LIU X P, LI W H, et al. Quantitative evaluation the physical properties evolution of sandstone reservoirs constrained by burial and thermal evolution reconstruction: A case study from the Lower Cretaceous Baxigai Formation of the western Yingmaili area in the Tabei Uplift, Tarim Basin, NW China. Journal of Petroleum Science and Engineering, 2022, 208(Part B): 109460.

[7] LI Ling, TANG Hongming, WANG Xi, et al. Evolution of diagenetic fluid of ultra-deep Cretaceous Bashijiqike Formation in Kuqa Depression. Journal of Central South University, 2018, 25(10): 2472–2495.

[8] ZHANG Z Y, ZHU G Y, CHI L X, et al. Discovery of the high-yield well GT1 in the deep strata of the southern margin of the Junggar Basin, China: Implications for liquid petroleum potential in deep assemblage. Journal of Petroleum Science and Engineering, 2020, 191: 107178.

[9] JIN Jun, XIAN Benzhong, LIAN Lixia, et al. Reformation of deep clastic reservoirs with different diagenetic intensities by microfractures during late rapid deep burial: Implications from diagenetic physical simulation of Cretaceous Qingshuihe Formation in the southern margin of Junggar Basin, NW China. Petroleum Exploration and Development, 2023, 50(2): 309–321.

[10] LIU Wei. Formation mechanism and evolution characteristics of the lower anomalous high pressure in the southern margin of the Junggar Basin. Shanxi: Xi'an Shiyou University, 2019.

[11] ZOU C N, ZHU R K, LIU K Y, et al. Tight gas sandstone reservoirs in China: Characteristics and recognition criteria. Journal of Petroleum Science and Engineering, 2012, 88/89: 82–91.

[12] CHEN Zhonghong, WANG Shunan, WANG Li, et al. Characteristics of formation water chemical fields and its petroleum significance of the Neogene in Dongying Sag, Shandong Province. Journal of Palaeogeography, 2012, 14(5): 685–693.

[13] HE Xiaohu, LIU Zhen, LIANG Quansheng, et al. The influence of burial history on mudstone compaction. Earth Science Frontiers, 2010, 17(4): 167–173.

[14] XIA Lu, LIU Zhen, LI Weilian, et al. Ternary analytic porosity-reduction model of sandstone compaction trend and its significance in petroleum geology: A case study of tight sandstones in Permian Lower Shihezi Formation of Shilijiahan area, Ordos Basin, China. Petroleum Exploration and Development, 2018, 45(2): 275–286.

[15] GUO Huajun, SI Xueqiang, YUAN Bo, et al. The characteristics and main controlling factors of ultra-deep sandstone reservoir in the middle part of the southern margin of Junggar Basin. Marine Origin Petroleum Geology, 2022, 27(3): 313–324.

[16] XI K L, CAO Y C, JAHREN J, et al. Quartz cement and its origin in tight sandstone reservoirs of the Cretaceous Quantou Formation in the southern Songliao Basin, China. Marine and Petroleum Geology, 2015, 66(Part 4): 748–763.

[17] ZHANG Shunli, LYU Zhengxiang, XIONG Chenhao, et al. Characteristics and formation mechanism of Jurassic microcrystalline quartz coating in Qikou Sag. Xinjiang Petroleum Geology, 2018, 39(5): 537–541.

[18] XU Fanghao, XU Guosheng, LIU Yong, et al. Factors controlling the development of tight sandstone reservoirs in the Huagang Formation of the central inverted structural belt in Xihu Sag, East China Sea Basin. Petroleum Exploration and Development, 2020, 47(1): 98–109.

[19] YU Bingsong. The application and development of catho-doluminescence microscope in the study of carbonate rocks. Bulletin of Geological Science and Technology, 1992, 11(4): 92–96.

[20] WANG Z K, CAO Y C, SWENNEN R, et al. Meteoric freshwater leaching and its significance to reservoir quality in a buried hill of Lower-Middle Jurassic fluvial sandstones: A case study from the Huanghua Depression, Bohai Bay Basin, China. Journal of Petroleum Science and Engineering, 2022, 210: 109834.

[21] WANG Yizhe, WU Chaodong, MA Jian, et al. Strata color rhythm of the Cretaceous-Neogene and evolution of palaeoenvironment and palaeoclimate in Junggar Basin. Journal of Palaeogeography, 2019, 21(3): 451–468.

[22] GARCÍA-ROMERO E, VEGAS J, BALDONEDO J L, et al. Clay minerals as alteration products in basaltic volcaniclastic deposits of La Palma (Canary Islands, Spain). Sedimentary Geology, 2005, 174(3/4): 237–253.

[23] SUN N L, ZHONG J H, HAO B, et al. Sedimentological and

diagenetic control on the reservoir quality of deep-lacustrine sedimentary gravity flow sand reservoirs of the Upper Triassic Yanchang Formation in Southern Ordos Basin, China. Marine and Petroleum Geology, 2020, 112: 104050.

[24] STORVOLL V, BJØRLYKKE K, KARLSEN D, et al. Porosity preservation in reservoir sandstones due to grain-coating illite: A study of the Jurassic Garn Formation from the Kristin and Lavrans fields, offshore Mid-Norway. Marine and Petroleum Geology, 2002, 19(6): 767–781.

[25] WANG J, PANG Y H, CAO Y C, et al. Sedimentary environment constraints on the diagenetic evolution of clastic reservoirs: Examples from the Eocene “red-bed” and “gray-bed” in the Dongying Depression, China. Marine and Petroleum Geology, 2021, 131: 105153.

[26] EHRENBERG S N. Preservation of anomalously high porosity in deeply buried sandstones by grain-coating chlorite: Examples from the Norwegian continental shelf. AAPG Bulletin, 1993, 77(7): 1260–1286.

[27] BAIG I, FALEIDE J I, MONDOL N H, et al. Burial and exhumation history controls on shale compaction and thermal maturity along the Norwegian North Sea Basin margin areas. Marine and Petroleum Geology, 2019, 104: 61–85.

[28] KUPECZ J A, GLUYAS J, BLOCH S. Reservoir quality prediction in sandstones and carbonates. Tulsa: American Association of Petroleum Geologists, 1997: 19–27.

[29] DUAN W, LI C F, LUO C F, et al. Effect of formation overpressure on the reservoir diagenesis and its petroleum geological significance for the DF11 Block of the Yinggehai Basin, the South China Sea. Marine and Petroleum Geology, 2018, 97: 49–65.

[30] COLTEN-BRADLEY V A. Role of pressure in smectite dehydration—effects on geopressure and smectite-to-illite transformation. AAPG Bulletin, 1987, 71(11): 1414–1427.

[31] WANG W G, LIN C Y, ZHANG X G, et al. Effect of burial history on diagenetic and reservoir-forming process of the Oligocene sandstone in Xihu Sag, East China Sea Basin. Marine and Petroleum Geology, 2020, 112: 104034.