Genesis of diagenetic zeolites and their impact on reservoir formation in the Middle Permian Lower-Wuerhe Formation of the Mahu Sag, Junggar Basin, Northwest China

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Abstract
Zeolites are important diagenetic minerals in petroleum reservoirs and have complex impacts on reservoir quality. To highlight this critical and challenging issue, we conduct a case study in the Middle Permian Lower-Wuerhe Formation in the Mahu Sag, Junggar Basin, China. Formation mechanism of zeolites and their impacts on the reservoir quality. Our results show that there are five types of zeolite minerals (i.e. laumontite, heulandite, analcime, stilbite, and clinoptilolite) in the Lower-Wuerhe Formation reservoir, with laumontite and heulandite being the main types. Petrographic and geochemical data suggested that laumontites developed in the Lower-Wuerhe Formation were mainly precipitated from pore water, whereas heulandites were formed associated with alteration of volcanic materials. In addition, the distribution of different type of zeolite minerals is generally controlled by sedimentary facies. The heulandite–laumontite zone developed mainly in the front of fan-delta plain, and the laumontite zone developed mainly in fan-delta front. The distal part of fan-delta front is dominated by albite. The zeolite mineral assemblages are generally controlled by geochemical composition of volcanic lithic fragments. The high content of

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intermediate-basic volcanic lithic fragments in the eastern Mahu Slope sediments is responsible for authigenic minerals such as heulandite, chlorite, and laumontite. However, the content of intermediate-basic volcanic lithic fragments in the western Mahu Slope sediments is low which results in the cement in this region is dominated by laumontite and mixed-layer illite/smectite. In general, conglomerates deposited in fan-delta front are favorable for the formation of early laumontite and late dissolution of laumontite due to resistance to compaction by coarse fraction and accumulation of acidic fluids in structural highs, which resulted in the formation of a high-quality reservoir. Our results have general implications for hydrocarbon exploration of the zeolite-bearing conglomerate reservoirs in non-marine petroliferous basins.

Keywords
Mahu Sag, Lower-Wuerhe Formation, conglomerate reservoir, zeolite, fluid–rock interaction

Introduction
Secondary pore development via the dissolution of zeolite minerals in reservoirs is an important new field for oil and gas exploration research. Previous studies have proposed that zeolite cementation leads to a significant reduction in intergranular pores, which degrades reservoir quality (Lian and Yang, 2017). However, other studies have suggested that zeolite cementation protects intergranular pores and can be dissolved during later diageneses (Fu et al., 2010; Yang et al., 2005). In general, the quality of zeolite-bearing reservoirs is affected by the zeolite type, content, and amount of dissolution of zeolites.

Zeolites are microporous framework silicate minerals that are sensitive to temperature and pressure, and can be formed in high heat flux, volcanically active, deep sea, soil, near-surface, and saline lake settings (Do Campo et al., 2007; Hay and Sheppard, 2001; Sun et al., 2014; Zhang et al., 2015). Since the 1950s, zeolite diagenesis has been a focus of research, particularly the origins of laumontite. Zhang (1992) and Zhang et al. (2011) have investigated zeolite types, origins, and thermodynamic stability. Various mechanisms for zeolite formation have been suggested: (1) heulandite, analcime, and other zeolite minerals transform from each other when the pH of formation water, ion species, and their concentrations in formation water changed; (2) laumontite forms by the alteration of intermediate volcanic rock and tuff fragments; (3) laumontite forms by low temperature metamorphism between 200°C and 260°C (Li et al., 2012; Zhang et al., 2011); and (4) laumontite formed from plagioclase by nitrification (Fu et al., 2010; Zhu, 1985).

Abundant zeolite minerals are found in the conglomerate reservoir of the Lower-Wuerhe Formation (P2w) in the Mahu Sag, Junggar Basin, China. The porosity of the conglomerate reservoir of the Lower-Wuerhe Formation (P2w) in the Mahu Sag varies from 6.0% to 12%, with an average of 8.82%. The permeability ranges from 0.014 to 1428.2 mD, with an average of 2.78 mD. In general, the reservoir shows low porosity and low permeability. Furthermore, previous studies also suggested that the variety of pores with thin throats are dominated by residual intergranular pores and dissolved pores in cements, and reservoir heterogeneity is strong (Fu et al., 2019). Therefore, the zeolite minerals found have significant influences on the quality and heterogeneity of the conglomerate reservoir of the Lower-Wuerhe Formation. However, the formation mechanism and distribution patterns of zeolite
minerals and their influences on the quality of conglomerate reservoir of the Lower-Wuerhe Formation have not been studied in detail. We used petrographic, scanning electron microscopy (SEM), electron microprobe, and reservoir analysis methods to systematically study zeolites in this reservoir. Our results will shed light on oil and gas exploration and exploitation in the Lower-Wuerhe Formation.

Geological setting

The Mahu Sag is located in the western uplift of the Junggar Basin and is bounded by the Wuxia Fault Zone to the west, the Zhongguai Uplift to the south, the Dabasong and Xiayan Uplifts to the east, and the Shiyings Sands Uplift and Yingxi Sag to the north (Chen et al., 2002; He et al., 2004). The main study area is the Madong and Maxi slopes (Figure 1(a) and (c)). During the deposition of the Lower-Wuerhe Formation, the climate was humid, terrain was steep, and sediments were deposited in fan-delta facies (Cao et al., 2020). The sediment provenance was mainly from the north, east, and west (Bian et al., 2017; Kuang et al., 2005; Lei et al., 2017; Zhang et al., 2014). The Lower-Wuerhe Formation

Figure 1. (a) Map showing the location of the study area and the studied wells (Zhou et al., 2017). (b) Stratigraphic column of Lower-Wuerhe Formation in Da18 well from the Mahu Sag. (c) Seismic section of Wu35–Aike1–Ma2–Yanbei1–Yanbei4–Madong4.
comprises mainly a set of fan-delta deposits. The coarse fraction of the Lower-Wuerhe Formation was rapidly accumulated near the source rocks. Two major fans, the Xiazijie–Huangyangquan and the Madong–Xiayan fans, were formed on the Maxi Slope and the Madong Slope, respectively (Meng et al., 2015; Zou et al., 2017) (Figure 1(a)). The Lower-Wuerhe Formation can be subdivided into four members according to lithology (Figure 1(a) and (b)).

Samples and methods

In this study, we focused on conglomerates of the Lower-Wuerhe Formation from 30 wells in the Mahu Sag, and 436 thin sections were prepared for petrology study. Reservoir characteristics were studied under a Nikon ECLIPSE microscope with polarizing light.

Thirty-nine samples were selected for observations of pore morphology and structure using field emission SEM with a Carl Zeiss Supra 55 SEM instrument equipped with an Oxford Aztec X-Max 150 energy dispersive spectrometry system, with ×12 to ×1,000,000 magnification, and accelerating voltages of 15, 1, and 30 kV for resolutions of 0.8, 1.6, and 2.0 nm, respectively.

Thirty representative samples were selected for back-scattered electron imaging and in situ element analysis using an electron probe micro-analyzer (EPMA; JEOL JXA 8100), employing a 15-kV accelerating voltage, a 20-nA beam current, and a 2-μm-diameter electron beam. Analyses used 10 s and 5 s peak and background counting times, respectively.

Microthermometric analyses of petroleum-bearing fluid inclusions in laumontite were carried out to determine the stage of laumontite cementation. The section prepared for inclusion research was observed using a Zeiss microscope equipped with a UV-light source (Mercury lamp, λ = 365 nm) and a long-pass emission filter (400 nm) to recognize the fluorescent petroleum-bearing fluid inclusions. Microthermometric measurements of the fluid inclusions were carried out using a Linkam THMS600 heating–cooling stage with a temperature range of −195°C to +600°C. The stage was calibrated by measuring the melting temperatures of pure water (0°C) and pure CO₂ (−56.6°C) in synthetic fluid inclusions. Microthermometric data were collected using an objective lens with 50× magnification. The accuracy of measured phase changes in the fluid inclusions is about ±1°C.

Results

Conglomerate petrography and characteristics of reservoirs

The reservoirs of the Lower-Wuerhe Formation were mainly developed in the fan-delta front. The rocks consist mainly of gray-green lithic conglomerates with low componential and structural maturity (Figure 2). The conglomerate clasts consist of quartz (2.85 vol.%), feldspar (3.18 vol.%), and volcanic rock fragments (78.71 vol.%). The matrix (5%–10% of the rock mass) consists mainly of zeolites (31.84 vol.%), mixed-layer illite/smectite (31.84 vol.%), and chlorite (11.13 vol.%). The illite/smectite ratio is 48.48%. The porosity varies from 5.0% to 19.1%, with an average of 8.42%. The permeability ranges from 0.014 to 1428.2 mD, with an average of 2.78 mD. In general, the reservoir shows low porosity and low permeability.
Crystallography and geochemistry of zeolite groups

Five minerals of zeolite groups including laumontite, heulandite, analcime, stilbite, and clinoptilolite were identified in the reservoirs of the Lower-Wuerhe Formation based on the study of 436 thin sections from 30 wells. Laumontite and heulandite have the largest content among the five minerals. The zeolites occur mainly as cement and infilling fractures in the reservoirs of the Lower-Wuerhe Formation.

Laumontite (CaAl$_2$Si$_4$O$_{12}$·4H$_2$O). Laumontite is widely developed in the Lower-Wuerhe Formation. In hand specimen, laumontite is white and powder-like visually, and laumontite does not react with diluted hydrochloric acid. Under microscope, laumontite crystals are colorless or white automorphic columnar or continuous crystals, and have two cleavages with a large extinction angle (20°–30°). Laumontites occur mainly in intergranular pores (Figure 3(a) and (b)). In SEM images, laumontite crystals are typically plate-like or columnar in shape, with inter-crystal cracks occurring at contacts between different zeolite crystals (Figure 3(c)). Laumontite occurs frequently associated with heulandite, and dissolution of laumontite is common in fracture zones.

CaO contents of laumontite vary from 10.48 to 12.12 wt.%, with an average of 11.17 wt.%; SiO$_2$/Al$_2$O$_3$ ratios range from 2.45 to 2.70, with an average of 2.58; and Na$_2$O and K$_2$O contents are low (Table 1).

Heulandite (Ca, Na$_2$)Al$_2$Si$_7$O$_{18}$·6H$_2$O. Heulandites founded in the Lower-Wuerhe Formation are typically orange in color and anhedral fine-grained and idiomorphic fine- to medium-grained crystals. The anhedral fine-grained crystals (semi-) fill intergranular space in silty sandstones. Idiomorphic fine- to medium-grained crystals are developed mainly in medium- to coarse-grained sandstone or conglomerate (Figure 3(b)). In SEM images, the fine- to
Figure 3. Zeolite minerals in the reservoir of the Lower-Wuerhe Formation: (a) chlorite and laumontite (plane-polarized light; Yan 001 well; 4984.9 m); (b) heulandite coexisting with laumontite (plane-polarized light; Ma 217 well; 4005.8 m); (c) laumontite (SEM image; Ma 217 well; 4005.8 m); (d) heulandite (SEM image; Yanbei 7 well; 3881.98 m); (e) heulandite and volcanic detritus (plane-polarized light; Yanbei 2 well; 4468.7 m); (f) heulandite formed by metasomatism (plane-polarized light; Ma 218 well; 3929.5 m); (g) geopetal structure (plane-polarized light; Ma 607 well; 4102.7 m); (h) element map of iron element (Yan 001 well; 4983.5 m); (i) dissolution pore developed in laumontite (plane-polarized light; Ma 4 well; 3578.9 m). Hul: heulandite; Lmt: laumontite; Chl: chlorite.
Table 1. EPMA analyses of main zeolites in the Lower-Wuerhe Formation, Mahu Sag.

| Well   | Depth (m) | MgO | SiO$_2$ | MnO | K$_2$O | CaO | FeO | Al$_2$O$_3$ | Na$_2$O | TiO$_2$ | Cr$_2$O$_3$ | H$_2$O | Total | SiO$_2$/Al$_2$O$_3$ | Zeolite minerals |
|--------|-----------|-----|---------|-----|--------|-----|-----|-------------|---------|--------|-------------|-------|-------|-------------------|-----------------|
| Ma 4   | 3554.15   | 0.00| 52.44   | 0.11| 10.48  | 0   | 19.91| 0.43        | 0       | 0      | 0.01        | 16.63 | 83.37 | 2.63              | Laumontite       |
| Ma 009 | 3730.2    | 0.00| 52.38   | 0.11| 10.6   | 0   | 20.14| 0.19        | 0       | 0.06   | 0.02        | 16.52 | 83.48 | 2.60              | Laumontite       |
| Ma 607 | 4104.6    | 0.02| 50.82   | 0.04| 11.84  | 0   | 20.95| 0.05        | 0.05    | 0.05   | 0.01        | 14.25 | 85.75 | 2.52              | Laumontite       |
| Ma 217 | 4005.35   | 0.00| 52.69   | 0.08| 11.67  | 0   | 20.2  | 0.22        | 0       | 0      | 0.02        | 15.14 | 84.86 | 2.61              | Laumontite       |
| Ma 217 | 4128.50   | 0.00| 53.48   | 0.08| 11.13  | 0.12| 20.43| 0.24        | 0.06    | 0.06   | 0.01        | 14.46 | 85.54 | 2.62              | Laumontite       |
| Xiayan 2| 4718      | 0.00| 52.36   | 0.06| 10.38  | 0   | 19.41| 0.63        | 0       | 0      | 0.03        | 17    | 83    | 2.70              | Laumontite       |
| Ma 217 | 4003.20   | 0.00| 51.32   | 0.05| 0.1    | 11.3 | 20.09| 0.25        | 0       | 0      | 0.03        | 16.89 | 83.11 | 2.55              | Laumontite       |
| Ma 009 | 3782.3    | 0.00| 52.09   | 0.14| 11.17  | 0.11| 20.92| 0.32        | 0       | 0      | 0.03        | 16.25 | 83.75 | 2.61              | Laumontite       |
| Yanbei 4| 3915      | 0.00| 52    | 0.09  | 11.54 | 0   | 20.07| 0.35        | 0       | 0.04   | 0.03        | 15.91 | 84.09 | 2.59              | Laumontite       |
| Yanbei 4| 4468.7    | 0.00| 52.47  | 0.08| 11.57  | 0   | 20.29| 0.32        | 0.1     | 0.03   | 0.03        | 15.14 | 84.86 | 2.59              | Laumontite       |
| Ma 217 | 4003.20   | 0.00| 51.88  | 0.02| 12.12  | 0   | 20.81| 0.13        | 0.06    | 0.06   | 0.01        | 14.98 | 85.02 | 2.49              | Laumontite       |
| Ma 009 | 3782.3    | 0.00| 52.44  | 0.05| 0.1    | 11.2 | 20.05| 0.38        | 0       | 0      | 0.03        | 15.76 | 84.24 | 2.62              | Laumontite       |
| Yan 001| 4983.7    | 0.00| 52.52  | 0.05| 0.1    | 11.13| 20.16| 0.56        | 0       | 0      | 0.03        | 15.43 | 84.57 | 2.61              | Laumontite       |
| Yanbei 2| 4468.7    | 0.00| 51.66  | 0.05| 0.19   | 11.3 | 20.3  | 0.08        | 0       | 0      | 0.03        | 16.32 | 83.68 | 2.54              | Laumontite       |
| Yan 001| 4983.7    | 0.00| 53.5   | 0.11  | 11.08  | 0.31| 20.88| 0.05        | 0       | 0      | 0.03        | 14.07 | 85.93 | 2.56              | Laumontite       |
| Ma 009 | 3782.3    | 0.58| 58.98  | 0.02| 0.04   | 7.84| 0    | 14.86       | 0       | 0.04   | 0.05        | 17.56 | 82.44 | 3.97              | Stilbite         |
| Ma 217 | 4003.20   | 0.7  | 53.86  | 0.13| 0.63   | 5.23| 1.38| 14.36       | 0.09    | 0.05   | 0.05        | 24.25 | 75.75 | 3.75              | Clinoptilolite   |
| Ma 217 | 3929.5    | 0.2  | 43.49  | 0.16| 0.05   | 4.93| 0.13| 10.67       | 0.09    | 0       | 0.03        | 39.38 | 60.62 | 4.08              | Heulandite       |
| Ma 218 | 3929.5    | 0.15 | 54.33  | 0.13| 0.69   | 5.69| 0.17| 14.25       | 0.25    | 0       | 0.05        | 25.03 | 74.97 | 3.81              | Heulandite       |
| Ma 218 | 3929.5    | 0.31 | 54    | 0.14 | 0.59   | 5.91| 0.54| 13.5        | 0.17    | 0       | 0.05        | 25.43 | 74.57 | 4.00              | Heulandite       |
| Ma 218 | 3929.5    | 0.25 | 51.77  | 0.1  | 0.57   | 5.37| 1.28| 13.24       | 0.24    | 0       | 0.05        | 27.75 | 72.25 | 3.91              | Heulandite       |
| Ma 218 | 3929.5    | 0.35 | 39.57  | 0.1 | 0.47   | 4.78| 1.23| 10.33       | 0.14    | 0       | 0.03        | 43.46 | 56.54 | 3.83              | Heulandite       |
| Ma 218 | 3929.5    | 0.17 | 37.51  | 0.1 | 0.51   | 5.1 | 1.03| 8.65        | 0.15    | 0       | 0.03        | 47.29 | 52.71 | 4.34              | Heulandite       |
medium-grained crystals are lamellar aggregates. During diagenesis, zeolites precipitated in the early stage are perpendicular to the edges of detrital particles (Figure 3(d)).

CaO contents of heulandite vary from 5.23 to 5.91 wt.%, with an average of 5.55 wt.%; Na₂O contents range from 0.15 to 0.7 wt.%, with an average of 0.35 wt.%; FeO contents vary from 0.17 to 1.38 wt.%, with an average of 0.84 wt.%; SiO₂/Al₂O₃ ratios vary from 3.81 to 4.34, with an average of 4.0 (Table 1). The studied heulandites are Si- and Fe-rich.

**Other zeolite types.** The Lower-Wuerhe Formation also contains analcite, stilbite, and clinoptilolite. The analcites are colorless and transparent under plane-polarized light and are isopachous around detritus grains in inter-grain pores of the conglomerate. Stilbite occurs as plate-like sheets, and crystal twinning can be observed under microscope. Stilbites occur frequently associating with calcite. Clinoptilolite is light yellow, acicular, and typically associated with heulandite. The clinoptilolite contains trace amounts of Fe (Table 1).

**Spatial distribution of zeolites**

The spatial distribution of the different minerals of zeolite group was studied in detailed. In general, laumontite is mainly developed in fan-delta fronts that have a low matrix content and high initial permeability and porosity. There are four main zones according to laumontite contents: (1) laumontite contents of 0.5–6.0 vol.% in the Xiayan 2 and Yan 001 wells (Madong Slope); (2) laumontite contents of 1–7 vol.% in the Yanbei 4, Ma 217, and Ma 218 wells (Madong Slope); (3) laumontite contents of 0.5–4.0 vol.% in the Ma 4 and Ma 003 wells (Mabei Slope); and (4) laumontite contents of 0.5–5.0 vol.% in the Ma 607 well (Mabei Slope) (Figure 4(a)).

However, heulandite occurred mainly in fan-delta plain. There are three main zones based on heulandite contents: (1) heulandite contents of 0.6–3.0 vol.% in the Madong 2 well (Madong Slope); (2) heulandite contents of 1–7 vol.% in the Ma 217 and Ma 218 wells (Madong Slope); and (3) heulandite contents of 0.6–2.0 vol.% in the Ma 3 and Ma 005 wells (Mabei Slope) (Figure 4(b)).

![Figure 4](image_url) - Spatial distribution of zeolite minerals in the Lower-Wuerhe Formation: (a) distribution of laumontite and (b) distribution of heulandite.
**Discussion**

**Formation mechanisms for zeolite minerals**

Previous studies have suggested that the zeolites in the Lower-Wuerhe Formation were formed mainly by alteration of volcanic materials (Zhu et al., 2014). Our results suggest that the zeolites in the Lower-Wuerhe Formation could be formed by both alteration of volcanic materials and precipitation from pore water. Different minerals have different formation mechanisms. Laumontite was formed mainly by precipitation from pore water, whereas heulandite was formed mainly by alteration of volcanic materials.

*Heulandite formed by alteration of volcanic materials.* Heulandites formed by alteration of volcanic materials are developed mainly in the front of fan–delta plain. Previous studies showed that there is a positive correlation between the contents of volcanic materials and zeolites in the Lower-Wuerhe Formation (Broxton et al., 1987; Lian et al., 2017). Petrography observation under microscope shows that heulandite also occurred associating with altered tuff, and the heulandites are anhedral crystals dispersed in volcanic matrix material or blade crystals along grain edges (Figure 3(b), (d), and (e)). Petrographic observation indicated that there are a large number of primary inter-grain pores in the reservoirs in the front of fan-delta plain. These primary inter-grains provide facilitation for the exchange of pore fluids and are favor for precipitation of heulandites. With the increase of burial temperature and pressure, alkali fluids caused the hydrolysis of volcanic materials and transformed volcanic materials into clay minerals (mixed-layer illite/smectite) and zeolites (Shan et al., 2018) (Figure 3(f)). The heulandites that formed from volcanic material typically contain Fe and are orange in color (Figure 3(b), (e), and (f)).

*Laumontites precipitate from pore water.* The conclusion that laumontites found in the Lower-Wuerhe Formation were mainly precipitated from pore water is inferred from: (1) geopetal structure with laumontite (Figure 3(g)). Volcanic materials are denser than laumontites and thus deposited on the surface of detrital grains in early stage, and laumontite precipitated as late-stage cement showing an obvious geopetal structure; (2) inclusion temperatures of laumontites record at least three stages of laumontite formation (Figure 5(a) and (b)). Late-stage laumontites are separated from volcanic materials by early-stage laumontites, and therefore these late-stage laumontites cannot be formed by the alteration of volcanic detritus; and (3) laumontite cements have similar geochemical characteristics to the laumontites filled in rock fractures, which indicated that both laumontite cements and laumontites filled in rock fractures are precipitated from pore water (Figure 5(b)).

The conglomerates with a high primary porosity and permeability in the fan-delta front, and the pore water in the conglomerates exchanged extensively with formation waters. At the certain temperature and pressure in burial environment, laumontites had sufficient time to precipitate from pore fluids and consequently are euhehedral. The laumontite cements developed in the Lower-Wuerhe Formation were always formed relatively later, and the hydrolysis of volcanic detritus during diagenesis provides necessary material for laumontite precipitation in the late-stage diagenesis.

**Zeolite mineral assemblages and controls.** Our results indicate two different zeolite mineral assemblages in the Madong and Maxi regions. The zeolite mineral assemblage in Madong
Slope area is heulandite–chlorite–laumontite–calcite (Figure 5(c)), whereas in the Maxi Slope area is laumontite–silica–calcite (Figure 5(d)). The main difference between the two areas is the early diagenetic formation of heulandite and chlorite cements in the Madong Slope area, which might be related with diagenetic sequence and geochemical composition of parent rocks. Results of studies on diagenetic sequences in the Madong and Maxi Slopes indicated that conglomerates in the two areas have similar diagenetic sequence (Figure 5(c) and (d)). Thus, the differences of zeolite mineral assemblages in Madong and Maxi Slopes should be caused by geochemical composition of parent rocks.

In the Mahu Sag, volcanic fragments accounts for 90%. Among these volcanic fragments, the content of tuffaceous is approximately 74%. However, the geochemistry of volcanic fragments is different between the Madong and Maxi regions. In general, the Madong region is dominated by intermediate-basic volcanic rock detritus, whereas the Maxi region is dominated by intermediate-acidic volcanic rock detritus. Differences in volcanic fragments between the Madong and Maxi regions might provide different materials for zeolite minerals formation during diagenesis. The impacts of geochemical composition of parent rocks on zeolite mineral assemblages will be discussed in detailed in the next section.

Controls of zeolite minerals distribution

The development of zeolites requires the availability of Na⁺, K⁺, Ca²⁺, SiO₂, and Al₂O₃ (Wu et al., 2017; Yang et al., 2005). These elements can come from weathering of provenance and from hydrolysis of volcanic material during diagenesis. Therefore, sedimentary,
geochemical composition of lithic fragment, and diagenesis all have impacts on the distribution of zeolite group.

Observations on present sediments in a fan-delta front indicate that there are large- to medium-scale cross-beddings, parallel beddings, and other typical sedimentary structures developed in tractive current. Due to hydraulic sorting by tractive occurrences, the conglomerate clasts are sub- to well-rounded. Zeolite contents in the distributary channel and estuary dam sediments deposited in tractive occurrences are significantly higher than those in debris channel sediments deposited in gravity occurrences. The grain size also affected the content of zeolite. In general, the content of laumontite decreases from coarse gravelly sandstone to fine-grained conglomerate, and to medium- and fine-grained sandstone. The high content of laumontite in conglomerate might be caused by limits compaction and preservation of primary pores which are beneficial to the development of laumontite.

In study area, there are clear spatial changes in the minerals of zeolite group in the Lower-Wuerhe Formation in the Mahu Sag. Conglomerates in the fan-delta plains have a large amount of muddy matrix but a limited amount of zeolite. In the front of fan-delta plains, there is a small amount of muddy matrix, and laumontite and heulandite are the dominant minerals of zeolite group. In the fan-delta fronts, laumontite is the dominant minerals of zeolite group. In the distal parts of fan-delta front, Na-feldspar is the main autogenic mineral (Figure 6).

The clear spatial changes in the minerals of zeolite group in the Lower-Wuerhe Formation in the Mahu Sag may be also affected by geochemical composition of pore water, especially the pH value and contents of Na\(^+\), K\(^+\), and Ca\(^{2+}\) in pore water. In fact, it is believed that zeolites are typically formed in neutral–alkaline waters with a pH of 7 to 10 (Broxton et al., 1987; Mariner and Surdam, 1970). The formation waters in the fan-delta plain region of the study area were mainly neutral, with low contents of Na\(^+\), K\(^+\) (both <2100 ppm), and Ca\(^{2+}\) (<95 ppm) and, as a result, no zeolites formed. In the front of fan-delta plain region, the formation waters were mainly alkaline and contained high contents of Na\(^+\) and K\(^+\) (2100–2900 ppm) and Ca\(^{2+}\) (100–170 ppm), and the zeolite is mainly heulandite, with minor laumontite. The formation of heulandite is controlled by the specific activity ratio of ions (Sheppard and Hay, 2001). The formation waters in the fan-delta front region were mainly alkaline and had high concentrations of Na\(^+\), K\(^+\) (>3500 ppm) and Ca\(^{2+}\) (>260 ppm), so the zeolite is mainly laumontite (Figure 6).
The pH and contents of Na\(^+\), K\(^+\), and Ca\(^{2+}\) in pore water are finally depended on dissolution and hydration of volcanic material. It is predictable that dissolution and hydration of volcanic fragment with different geochemical composition release various contents of Na\(^+\), K\(^+\), and Ca\(^{2+}\) to pore water. During deposition of the Lower-Wuerhe Formation, thrust faults at the northwestern margin of the Junggar Basin resulted in a large amount of near-source coarse lithic fragments being deposited in the Mahu Sag. After sedimentation, these lithic fragments react with pore waters with increasing burial depth, temperature, and pressure (Yang et al., 2005). The early dissolution and hydration of volcanic material released large amounts of alkali metal ions such as K\(^+\), Na\(^+\), Ca\(^{2+}\), Mg\(^{2+}\), and SiO\(_2\) to the pore waters, which increases the salinity and alkalinity of the formation waters and further promotes the hydrolysis of volcanic material (Guo et al., 2016; Mariner and Surdam, 1970; Wu et al., 2017; Zhu et al., 2011).

According to statistical data of volcanic fragments from the Mahu Sag, geochemical characteristics of volcanic fragments in the Madong Slope and Maxi Slope have marked differences (Figure 7(a)). Volcanic fragments in the Madong Slope area contains more intermediate-basic volcanic detritus than those in the Maxi Slope area, and this intermediate volcanic detritus, especially intermediate-basic volcanic detritus, has high concentration of Fe (Figures 3(h) and 7). During the hydrolysis of this intermediate-basic volcanic detritus, large amounts of Fe and Mg were released, which is favorable for precipitation of authigenic chlorite and heulandite (Figure 3(a) and (b)). Thus, minerals in the Madong Slope area are characterized by heulandite, chlorite, and laumontite. However, in the Maxi Slope area, the content of intermediate-basic volcanic detritus is low, and thus cementation was characterized by laumontite and mixed-layer illite/smectite. Previous studies have also suggested that intermediate-basic volcanic rocks are favorable for the formation of laumontite, while intermediate-acidic volcanic rocks are favorable for the formation of analcime, and heulandite forms in all volcanic rock types (Zhu et al., 2014).

**Relationship between zeolites and oil–gas reservoirs**

Recent exploration and exploitation indicate that the conglomerate reservoir of the Lower-Wuerhe Formation is now a field of exploration (Tao et al., 2019; Zhang et al., 2019). The main pore type in the conglomerate reservoir of the Lower-Wuerhe Formation in the Mahu Sag is primary intergranular pores, but dissolution pores such as inter-particle and intergranular dissolution pores are also developed. Laumontite dissolution is common in the

![Figure 7. Reservoir rock composition in the Lower-Wuerhe Formation: (a) geochemical types of volcanic fragments and (B) Fe contents of conglomerate rocks of different fan deltas.](image-url)
study area (Figures 3(i) and 8), whereas heulandite dissolution is rare. Organic acids produced during thermal evolution of organic matter may result in laumontite dissolution (Li et al., 2014; Wu et al., 2018, Xia et al., 2019). It is clear that laumontite contents and dissolution in the fan-delta front are related to the reservoir porosity, permeability, and well production according to database of reservoir property, test, and production in the Mahu Sag. There is a positive relationship between contents of laumontite and reservoir porosity and permeability and well production through 0 to 8 of the content of laumontite (Figure 9). However, the higher contents of laumontite (>8) seemly result the lower porosity, permeability, and well production (Figure 9). It may be caused by laumontite infilling and blocking pores and less dissolution of laumontite. The impacts of laumontite on the reservoir involve sedimentary facies and laumontite dissolution which is associated with diagenetic process.

The Ma 003 well is located in the fan-delta front and has high laumontite contents (>8%); however, the laumontites exhibit no obvious dissolution. Reservoir properties in

| Well    | Depth (m)       | Sedimentary facies type | Rang of porosity (%) (average value) | Rang of permeability (mD) (average value) | Content of laumontite (%) | Daily production (t) |
|---------|-----------------|-------------------------|--------------------------------------|------------------------------------------|--------------------------|----------------------|
| Ma 004  | 3600.0–3622.0   | Fan-delta plain         | 0.05–2.1 (1.2)                       | 0.025–0.32 (0.06)                       | 0                        | 2.43                 |
| Ma 005  | 3510.0–538.0    | Fan-delta plain         | 0.05–2.3 (1.1)                       | 0.025–0.35 (0.035)                      | 0                        | 0.97                 |
| Ma 001  | 3593.0–3652.0   | Fan-delta front         | 2.6–16.0 (8.6)                       | 0.012–3.5 (0.72)                       | 5.31                     | 12.9                 |
| Ma 003  | 3635.0–3697.0   | Fan-delta front         | 0.01–2.2 (0.85)                      | 0.020–0.34 (0.01)                      | 13                      | 0.007                |
| Ma 4    | 3514.5–3560.5   | Fan-delta front         | 3.50–16.0 (9.85)                     | 0.50–4.90 (2.26)                       | 7.5                      | 21.953               |
| Madong 2| 3732.0–3768.0   | Fan-delta front         | 2.6–15.0 (7.0)                       | 0.030–3.20 (0.75)                      | 0                        | 10.86                |
| Xiayan 2| 4743.0–4748.0   | Fan-delta front         | 2.2–8.5 (5.8)                        | 0.016–2.8 (1.2)                        | 3.65                     | 7.55                 |
| Ma 201  | 3648.5–3665.5   | Fan-delta front         | 0.03–2.35 (2.02)                     | 0.025–0.35 (0.05)                      | 0.5                      | 1.93                 |
| Ma 217  | 3980.0–4006.0   | Fan-delta front         | 4.6–7.5 (5.84)                       | 0.025–0.541 (0.258)                    | 8                        | 4.29                 |
| Ma 211  | 3760.0–3796.0   | Fan-delta front         | 2.6–8.9 (6.0)                        | 0.016–2.6 (1.0)                        | 0.5                      | 6.64                 |
| Yantan 1| 4805.0–4825.0   | Fan-delta front         | 2.3–15.2 (11.18)                     | 0.015–2.6 (0.35)                       | 0                        | 10.02                |
| Yanbei 4| 3904.0–3917.0   | Fan-delta front         | 6.3–14.0 (7.91)                      | 0.012–4.0 (0.81)                       | 4.95                     | 15.98                |
| Ma 218  | 3940.0–3972.0   | Fan-delta front         | 2.7–14.0 (7.15)                      | 0.036–3.21 (0.75)                      | 1.125                    | 12.91                |
| Ma 006  | 3525.0–3568.0   | Fan-delta front (structural high) | 5.3–19.5 (14.5)                  | 0.50–6.21 (4.75)                       | 0.5                      | 40.1                 |
| Ma 2    | 3516.5–3561.5   | Fan-delta front (structural high) | 4.50–15.2 (11.75)                  | 0.50–5.92 (3.0)                        | 0.5                      | 28.57                |
Ma 003 well are poor, and daily oil production is also low. With increasing laumontite contents, the reservoir properties and daily oil production decrease (Table 2; Figures 8(a) and 9). The poor reservoir properties and low daily oil production may be related to the high degree of laumontite infilling in early intergranular pores and lack of later dissolution.

The Ma 001 well is also located in the fan-delta front but has moderate laumontite contents of 4–8 vol.%. With increasing laumontite contents, the reservoir properties and oil production improve (Table 2; Figures 8(b) and 9). This is related to the favorable combination of the sedimentary facies, early laumontite formation, and late laumontite dissolution in these wells.

The Ma 006 well is located in the fan-delta front and contains low laumontite (~0.5%). The low content of laumontite is caused by dissolution of laumontite. Physical properties of reservoir in the Ma 006 are relatively good with porosity of 11.8%–14.5%, permeability of 3.00–4.75 mD, and high oil test yields of 28.57–40.10 t/d (Table 2; Figures 8(c) and 9). It indicated that the early precipitation of laumontite in the conglomerate of the fan-delta front can retain some primary pores and provide a pathway for the migration of acidic fluids during the middle stage of diagenesis. These wells are located in a structural high (well depth = 3500–3600 m) that was the main region for acidic fluid migration. Therefore, laumontite experienced strong dissolution and a large volume of dissolution pores developed.

![Figure 8](image1.png)

Figure 8. Dissolution characteristics of laumontite in the Lower-Wuerhe Formation: (a) Weak dissolution of laumontite (plane-polarized light; Ma 003 well; 3610.5 m); (b) moderate dissolution of laumontite (plane-polarized light; Ma 001 well; 3650.0 m); (c) strong dissolution of laumontite (plane-polarized light; Ma 006 well; 3560.0 m).

![Figure 9](image2.png)

Figure 9. Relationships between laumontite contents, reservoir properties, and daily oil outputs in the Lower-Wuerhe Formation: (a) laumontite content vs. porosity; (b) laumontite content vs. permeability; (c) laumontite content vs. daily oil output.
The Ma 004 well is located in the fan-delta plain, contains no laumontite, and has poor reservoir physical properties due to strong compaction. The average porosity is 1.2%, average permeability is 0.06 mD, and oil test results are poor (Table 2; Figure 9).

Conclusions

1. There are five types of zeolite in the reservoir of the Lower-Wuerhe Formation, with laumontite and heulandite being dominant zeolite minerals. Heulandite formed by the alteration of volcanic material and laumontite precipitated from pore water.
2. Zeolite development was influenced by the sedimentary facies, diagenetic environment, and rock composition. The heulandite–laumontite zone developed in the front of fan–delta plain, the laumontite zone developed in the fan–delta front, and the Na-feldspar zone developed in the distal part of the fan–delta front.
3. Cementation in the Madong Slope area was characterized by heulandite, chlorite, and laumontite due to the high content of intermediate-basic volcanic detritus. In the Maxi Slope area, the content of intermediate-basic volcanic detritus is low, and cementation was characterized by laumontite and mixed-layer illite/smectite.
4. The distribution of favorable reservoirs in structural highs was controlled by grain size and resistance to compaction, which allowed early laumontite to form, and the subsequent dissolution of laumontite.

Acknowledgements

We thank engineers from PetroChina Xinjiang Oilfield Company for insightful discussion.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This study was supported by China’s National Science and Technology Major Project (Grant No. 2017ZX05008-004-008).

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