


Article

Chemical Characteristics of Ordovician Formation Water and Its Relationship with Hydrocarbons in Halahatang Depression, Tarim Basin, NW China

Tong Xu ^{1,2}, Chuanqing Zhu ^{1,2,*} , Xiaoxue Jiang ^{1,2}, Boning Tang ^{1,2}, Xiang Wang ³, Haizu Zhang ³ and Baoshou Zhang ³

¹ State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum, Beijing 102249, China; tong_xu111@163.com (T.X.); jiangxiaoxue135@163.com (X.J.); tangboning@foxmail.com (B.T.)

² College of Geosciences, China University of Petroleum, Beijing 102249, China

³ Research Institute of Exploration and Development, PetroChina Tarim Oilfield Company, Korla 841000, China; wxiang-tlm@petrochina.com.cn (X.W.); zhanghz-tlm@petrochina.com.cn (H.Z.); zhangbaos-tlm@petrochina.com.cn (B.Z.)

* Correspondence: zhucq@cup.edu.cn

Abstract: The chemical characteristics of Ordovician formation water and its relationship with hydrocarbons in the Halahatang depression (Tabei Uplift, Tarim Basin, NW China) were analyzed on the basis of the detailed formation water test data. The formation water in the Halahatang depression can be characterized as CaCl₂ type with high total dissolved solids (TDS) generally. The TDS concentration has a weak negative relationship with the depth, and is above 200 g/L in the North Region (north of the pinch-out line), then gradually decreases to the south, but is still greater than 50 g/L. The ion-proportionality coefficients of formation water, including the sodium-chlorine coefficient, desulfurization coefficient and metamorphic coefficient, reflect that the present strata are well sealed and had once experienced strong water-rock interactions. Furthermore, the source and evolution of the formation water presents a closed relationship with the hydrocarbon accumulation. The meteoric source of the formation water indicates the denuding by the Ordovician formation and the damage from the previous oil and gas reservoirs. The reservoir quality was also improved due to the strong karstification during the denudation, which was beneficial for hydrocarbon accumulation. The distribution of the TDS concentration is controlled by the caprock (Sangtam Formation) and the high salinity fluids from overlying strata and adjacent regions. A geological model was established, the high salinity fluids penetrated the Ordovician strata resulting in the TDS increases in the northern part. Whereas, the South Region (south of the pinch-out line) was less affected due to the shielding layer of the O₃s. The favorable preservation conditions reflected by the high TDS and ion-proportionality coefficients correspond to the stable subsidence of strata since the Triassic era, the oil and gas reservoirs formed in the Himalayan can be preserved.

Keywords: Halahatang depression; formation water; salinity; petroleum entrapment; Tarim Basin



Citation: Xu, T.; Zhu, C.; Jiang, X.; Tang, B.; Wang, X.; Zhang, H.; Zhang, B. Chemical Characteristics of Ordovician Formation Water and Its Relationship with Hydrocarbons in Halahatang Depression, Tarim Basin, NW China. *Water* **2022**, *14*, 756. <https://doi.org/10.3390/w14050756>

Academic Editors: Tadeusz A. Przylibski and Dariusz Dobrzyński

Received: 14 January 2022

Accepted: 23 February 2022

Published: 27 February 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

As a result of the evaporation concentration, water-rock interactions and fluids flowing and mixing, the chemical characteristics of formation water can indicate the hydrogeochemical environment and the activities of the fluids of the basin [1,2]. In common practice, the TDS, water types, ion-proportionality coefficients and stable isotopes of formation water are used as indicators of the degree of water-rock interactions, the sealing condition of strata and the migration, accumulation and preservation of oil and gas [3–6].

Carbonate reservoir generated from paleo-karstification has a close relation with the hydrogeological process of the basin [7,8]. Meanwhile, the chemical and isotopic components of formation water is influenced by the water-rock interactions and the charging of hy-

drocarbons [9,10]. Thus, studying the chemical characteristics of formation water is of great significance to reveal the carbonate reservoirs' alteration and hydrocarbon accumulation.

Tarim Basin is the major marine sedimentary basin in China and the carbonate reservoir of Palaeozoic is the main petroleum production layer. In recent years, carbonate oil and gas pools have been discovered successively in the Tabei Uplift of the basin, such as Tahe Oilfield and Lunnan Oilfield. Studies have been completed, including the element and isotopic compositions, the spatial distribution characteristics and the source of formation water [11–17], the influence of formation water on the reservoir's physical properties and the relationship between the hydrochemical characteristics and hydrocarbon accumulation [11,18–21].

However, these investigations in the Halahatang depression are scarce. This paper analyzed the chemical characteristics and established the source and evolution model of Ordovician formation water in the Halahatang depression. The paper discusses the indicative significance of the hydrochemical characteristics to oil and gas accumulation. These results can provide references for the further study of oil and gas exploration and development in the study area.

2. Geological Setting

The Tarim Basin, in NW China (Figure 1a), is a large superimposed composite basin composed of the Paleozoic marine craton sedimentary and the Mesozoic-Cenozoic continental sedimentary. The basin has undergone a complex structural evolution process, formed the present tectonic framework, include the Kuqa Depression, Tabei Uplift, Northern Depression, Central Uplift, Southwest Depression, Southeast Uplift and Southeast Depression (Figure 1b) [22–24]. The Tabei Uplift, located in the north of Tarim Basin (Figure 1b, yellow area), is a long-term inherited paleo-uplift developed on the pre-Sinian metamorphic basement. The evolution of the Tabei Uplift can be summarized as the basement formation stage in pre-Sinian, the paleo-uplift formation stage between Sinian and Devonian, faults and fault-blocks mainly formed from Carboniferous to Triassic, followed by continuous subsidence ranging from the Jurassic to Paleogene periods and thereafter the rapid subsidence stage from the Neogene to Quaternary periods [25,26].

Halahatang depression is located in the central part of the Tabei Uplift, surrounded by the Yingmaili low uplift, the Manjiaer depression, the Lunnan low uplift and the Luntai uplift (Figure 1c). The whole exploration area is about 4369 km² [27]. As the target area for oil and gas migration, a large volume of petroleum has been found in the Halahatang depression.

Detailed geological characteristics of the Halahatang depression had been summarized in numerous publications [25,28,29]. In brief, the lower Paleozoic in the study area consists of the Silurian, Ordovician and Cambrian strata. The Silurian mainly consists of sandstone and mudstone. The Sangtamu formation (O_{3s}) of the Upper Ordovician is primarily composed of mudstone, lime mudstone and muddy limestone, which can be regarded as caprock for the carbonate reservoirs. Bioclastic limestone and arenaceous limestone are the main compositions of the Middle Ordovician Yijianfang formation (O_{2y}). The Yingshan formation (O_{1–2y}) mainly contains micritic limestone, arenaceous limestone, and partly dolomite. Both the Yijianfang and Yingshan formations are the major karst reservoirs. The petroleum produced in these layers includes condensate oils, light oils, normal oils, heavy oils and ultra-heavy oils.

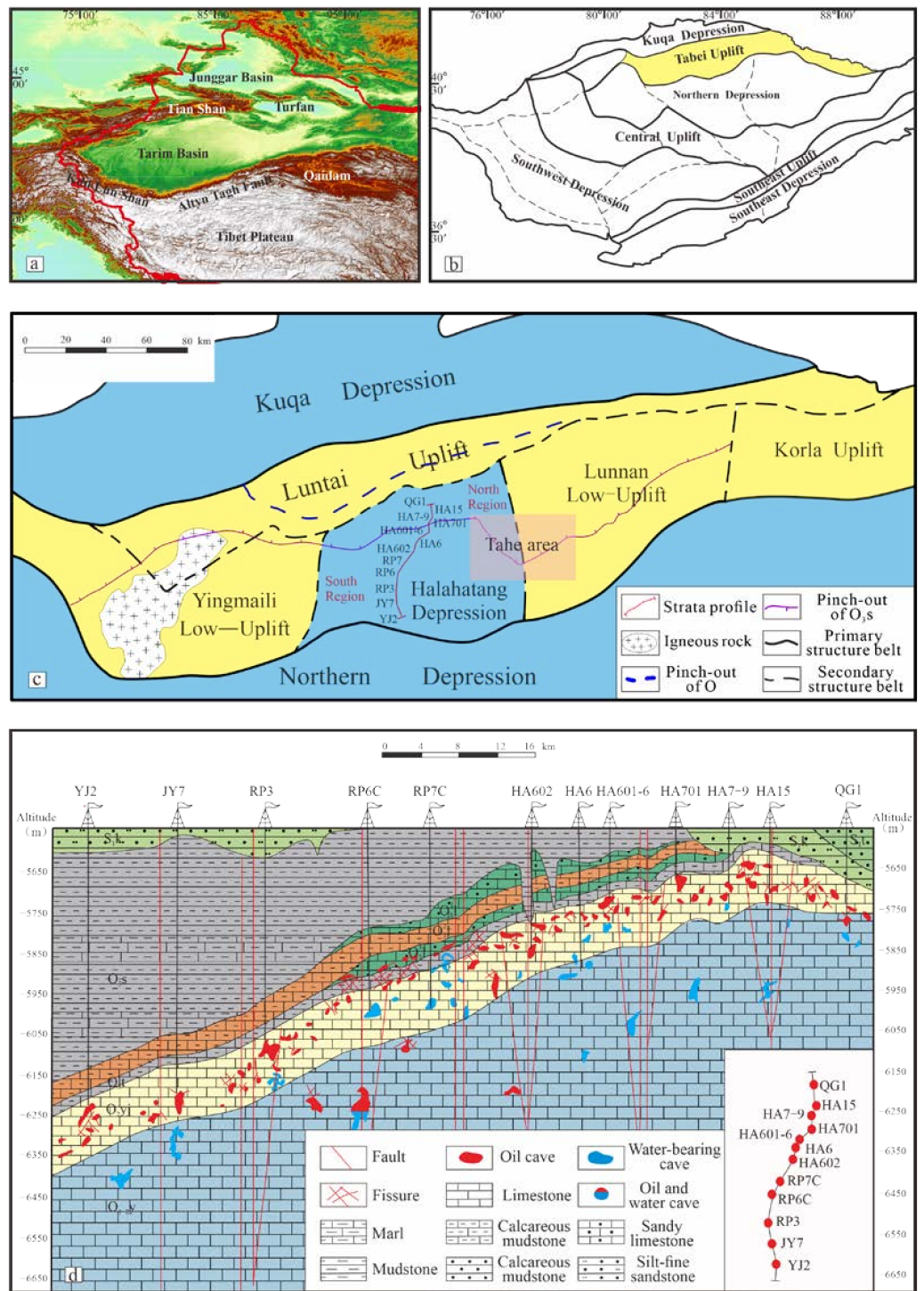


Figure 1. Structure schematic map of the study area; (a) the location of Tarim Basin in NW China; (b) tectonic units of Tarim Basin, including the Kuqa Depression, Tabei Uplift, Northern Depression, Central Uplift, Southwest Depression, Southeast Uplift and Southeast Depression, yellow area means Tabei Uplift; (c) tectonic units of Tabei Uplift and location of Halahatang depression, two regions are divided by the pinch-out line of O_3s in Halahatang depression, “North Region” and “South Region” means “north of the pinch-out line of O_3s ” and “south of the pinch-out line of O_3s ”, respectively. The same as below. Pink area means Tahe area which is mentioned in chapter 4.1; (d) cross-well section

from Well YJ2 to Well QG3 (section line see (c)). S₁t: Tataaiertage formation of Silurian; S₁k: Kepingtage formation of Silurian; O₃s: Sangtamu formation of Ordovician; O₃l: Lianglitage formation of Ordovician; O₃t: Tumuxiuke formation of Ordovician; O₂yj: Yijianfang formation of Ordovician; O_{1–2}y: Yingshan formation of Ordovician. Detailed geological background and formation development characteristics of study area can be learnt from [25,28,29].

Under the complicated tectonic events from the Caledonian to the Himalayas' orogeny, the upper Ordovician eroded and pinched out successively from the north to south, generating the angular unconformities and parallel unconformities among the Silurian and Ordovician strata (Figure 1d). The most intense uplift and denudation occurred after the deposition of the Sangtamu formation. In addition, the early-middle Caledonian tectonic movements formed a series of large strike-slip faults, showing an "X" type combination in the plane [30], and continued to be active until the Triassic period. These unconformities and strike-slip faults play an important role in the evolution of formation water and the accumulation of hydrocarbon, for providing conditions for the geofluids activities.

The Cambrian–Ordovician in the Tabei Uplift experienced three stages of oil and gas charging: Oil charging in the Late Caledonian–Early Hercynian; Oil charging in the Late Hercynian–Indosinian; Oil and gas charging in the Himalayan [29,31–34]. Oil reservoirs formed in the Late Caledonian–Early Hercynian were destroyed by multi-stage tectonic movements, part of the paleo-oil reservoir was preserved, but the oil was degraded into heavy oil. Late Hercynian–Indosinian was the major stage of the oil reservoirs' generation. A large quantity of hydrocarbons generated in the Cambrian source rocks then migrated through the faults into the Ordovician fractured-vuggy reservoirs, forming large-scale accumulations. Due to the varying degree of the tectonic movements, oil reservoirs in north of the Tabei uplift were degraded into heavy oil while they remained well preserved in the south and mainly contained medium oil. Light oil and dry gas generated in the Himalayan, mainly charging from south to north and well preserved.

3. Materials and Methods

A total of 200 items of formation water analysis data from 92 wells were selected after data screening. The chemical characteristics of formation water might be influenced by the acidizing fluids and fracturing fluids during the development and production process of oil and gas. This type of formation water cannot truly reflect the hydrological environment of the strata. A series of feasible test data screening schemes for formation water have been established in different regions [35]. In this paper, the test data of formation water of Ordovician in the Halahatang depression are screened in combination with the previous screening schemes and the development and production process of oil and gas. The criteria for screening data include: (1) The imbalance between cations and anions; (2) Too low or too high TDS concentration; (3) Too high or too low pH; (4) The content of K⁺ is higher than that of Na⁺.

The chemical characteristics of formation water can be described by water type, pH, the TDS concentration, chemical compositions and ion-proportionality coefficients. The water type and the TDS can indicate the hydrogeological environment and sealing condition of the strata to a certain extent [1,3]. The major chemical compositions consist of (Na⁺ + K⁺), Ca²⁺, Mg²⁺, HCO₃⁻, SO₄²⁻ and Cl⁻. The ion-proportionality coefficients include sodium-chlorine coefficient ($\gamma \text{Na}^+ / \gamma \text{Cl}^-$), desulfurization coefficient ($\gamma \text{SO}_4^{2-} \times 100 / \gamma \text{Cl}^-$) and metamorphic coefficient [$(\gamma \text{Cl}^- - \gamma \text{Na}^+) / \gamma \text{Mg}^{2+}$] [6,36,37]. These types' parameters can further reflect the hydrogeological environment, water-rock interactions and the preservation conditions of hydrocarbon.

4. Results and Discussion

4.1. Chemical Characteristics of Formation Water

4.1.1. Chemical Compositions

The TDS of Ordovician formation water in the Halahatang depression ranges from 59.7 g/L to 270.6 g/L, with an average of 178.5 g/L, which can be defined as brine

(TDS > 35 g/L) according to the salinity classification [10]. The ($\text{Na}^+ + \text{K}^+$), Ca^{2+} , Mg^{2+} , HCO_3^- , SO_4^{2-} and Cl^- are the major ions in the formation water. The ($\text{Na}^+ + \text{K}^+$) is dominated by cations, but in some samples, Ca^{2+} can account for more than 50% of the cations, the Mg^{2+} content being the lowest. Cl^- is the major anion (accounting for 98%) of the anion components, controlling the TDS of the formation water, followed by SO_4^{2-} and HCO_3^- . The pH of the formation water ranges from 4.2 to 7.9 (Avg: 6.2). The formation water is of a CaCl_2 type on the whole.

The TDS of the formation water in the Halahatang depression has a weak negative correlation with depth (Depth above 6500 m: $\text{depth} = -5.16 \text{ TDS} + 6999.30$ $R^2 = 0.49$; Depth below 6500 m: $\text{depth} = -2.08 \text{ TDS} + 7234.50$ $R^2 = 0.34$) (Figure 2). Besides, the TDS of Ordovician formation water in Halahatang depression is higher in the North Region but lower in the South Region (Figure 3). North of the pinch-out line of O_3s in the study area, the TDS is mostly higher than 200 g/L and gradually decreases to the south, but is still greater than 50 g/L.

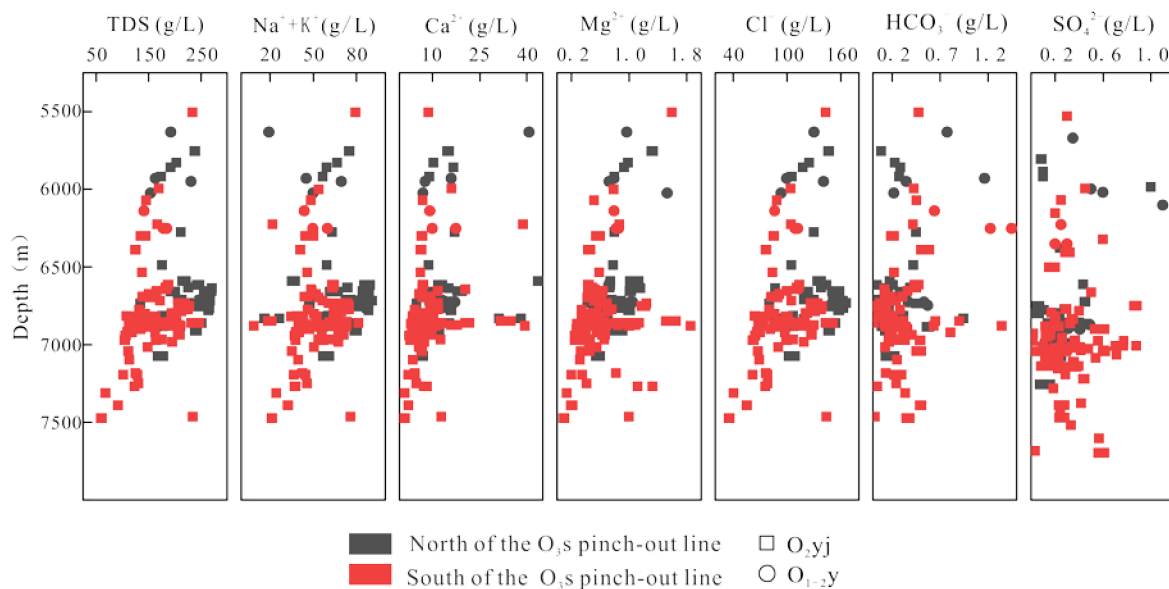


Figure 2. The ion concentration distribution of Ordovician formation water in the Halahatang depression with depth (The raw data sourced from Tarim Oil Field Company). A weak negative correlation between the depth and TDS. (Depth above 6500 m: $\text{depth} = -5.16 \text{ TDS} + 6999.30$ $R^2 = 0.49$; Depth below 6500 m: $\text{depth} = -2.08 \text{ TDS} + 7234.50$ $R^2 = 0.34$).

4.1.2. Ion-Proportionality Coefficients

The ion-proportionality coefficients, including sodium-chlorine coefficient ($\gamma \text{Na}^+ / \gamma \text{Cl}^-$), desulfurization coefficient ($\gamma \text{SO}_4^{2-} \times 100 / \gamma \text{Cl}^-$) and metamorphic coefficient [$(\gamma \text{Cl}^- - \gamma \text{Na}^+) / \gamma \text{Mg}^{2+}$], are mainly used to reveal the underground hydrological environment and the intensity of water-rock interactions [6,36,37]. The sodium-chlorine coefficient can reflect the sealing property of the formation and the degree of water-rock interactions (bounded by 0.85) [38]. The value less than 0.85 indicates that the strata have good sealing performance and experienced strong water-rock interactions. The desulfurization coefficient can indicate the degree of desulfurization, which in turn reflects the formation environment [11]. It is generally very low in the sealed environment, and greater than three while the formation has a certain degree of open or totally open condition. The metamorphic coefficient can also demonstrate the intensity of water-rock interactions [36]. The higher the metamorphism coefficient is, the stronger the water-rock interactions are.

In the Halahatang depression, the O_2yj and O_{1-2}y samples in both the North and South Regions have a sodium-chlorine coefficient between 0.144–0.873 and 0.211–0.782, respectively. The desulfurization coefficient ranges from 0.011 to 1.248 and 0.135 to 0.866, respec-

tively. The metamorphism coefficient distributes between 5.655–60.329 and 5.143–36.404, respectively. The average sodium-chloride coefficient, desulfurization coefficient and metamorphism coefficient are all less than 0.85, 1 and greater than 10, respectively (Table 1). These results reveal that the Ordovician strata have good preservation conditions. Despite being influenced by the meteoric water in early stage, the formation water still experienced strong water-rock interactions in the process of deep burying.

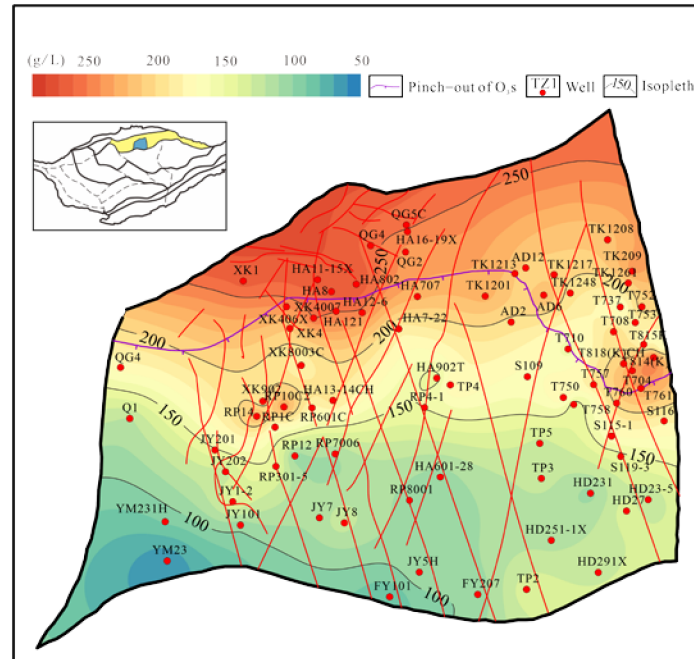


Figure 3. The distribution of TDS of Ordovician formation water in the Halahatang depression. The TDS is higher (basically above 200 g/L) in the North Region and gradually decreases to the south, but still greater than 50 g/L.

Table 1. Ion-proportionality coefficients of Ordovician formation water in the Halahatang depression. The ion-proportionality coefficients of Ordovician formation water in the Halahatang depression show similar characteristics in both the North region and South Region.

	Formation	$\gamma_{Na^+}/\gamma_{Cl^-}$	$\gamma_{SO_4^{2-}} \times 100/\gamma_{Cl^-}$	$(\gamma_{Cl^-} - \gamma_{Na^+})/\gamma_{Mg^{2+}}$
North of the O _{3s} pinch-out line	O _{2y}	$\frac{0.255-0.881}{0.734}$	$\frac{0.024-0.699}{0.140}$	$\frac{8.125-60.329}{17.724}$
	O _{1-2y}	$\frac{0.211-0.772}{0.672}$	$\frac{0.155-0.866}{0.304}$	$\frac{5.134-36.404}{16.381}$
South of the O _{3s} pinch-out line	O _{2y}	$\frac{0.144-0.873}{0.759}$	$\frac{0.011-1.248}{0.285}$	$\frac{5.388-29.407}{14.400}$
	O _{1-2y}	$\frac{0.645-0.782}{0.743}$	$\frac{0.135-0.214}{0.165}$	$\frac{10.497-15.666}{13.019}$

Note: $\frac{Min-Max}{Avg}$.

4.2. Source and Evolution of the Ordovician Formation Water

Formation water in sedimentary basins generally originates from meteoric water, river water or seawater, and would be influenced by the evaporation concentration, mixing of different water and water-rock interactions in the evolution of the strata [1,17].

4.2.1. The Source of Formation Water

The evolution process of the Halahatang depression is similar to those of the Lunnan buried hill anticline: both had experienced multiple periods of tectonic movements. In the Early Hercynian, Halahatang was part of the western slope of the Lunnan large anticline. The lower structural layer of Cambrian-Ordovician has similar tectonic features to the

Lunnan low-uplift. In the Late Paleozoic-Mesozoic, the Halahatang area gradually evolved into a structural depression [25]. The previous works from the Tahe area, which is located on the slope from the Halahatang depression to the Lunnan uplift (see Figure 1c) can provide references to this study.

By collecting 258 calcite samples from the karst fracture-cavity in the Ordovician carbonate rocks in the Tahe area [16,18,39,40] and 107 calcite samples from the karst fracture-cavity in the Ordovician carbonate rocks in the Halahatang area [41–43], the distribution of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ are similar. The $\delta^{13}\text{C}$ and the $\delta^{18}\text{O}$ mainly range from -13.74‰ to 9.06‰ (Avg: -10.17‰) and from -17.54‰ to -3.05‰ (Avg: -10.34‰), respectively (Figure 4). The positive correlation between the $\delta^{13}\text{C}$ and the $\delta^{18}\text{O}$ and the value of the stable isotopes that are widely distributed reflect the complicated diagenesis in the Halahatang depression. Compared with the carbonate background values of $\delta^{13}\text{C}$ (-1.58 – 0.12‰) and $\delta^{18}\text{O}$ (-6.01 – -6.52‰) in the Halahatang area [42], there is an obvious negative shift in most of the data. The value of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ in a meteoric water environment generally show a strong negative and a shift to positive when it was related to seawater [44,45]. When these two fluids were mixed, the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ distribute between the value of meteoric water and seawater. In the buried diagenetic environment, the value of $\delta^{13}\text{C}$ is stable or shifts to positive and the $\delta^{18}\text{O}$ shifts to strong negative [46]. Furthermore, influenced by the hydrothermal fluids show a more substantial negative of $\delta^{18}\text{O}$ [43]. Therefore, it can be concluded that the genesis of calcite in the Halahatang depression was mainly related to the influence of paleo-meteoric water, partly due to the influence of seawater, mixed fluids and the burial environment, and the hydrothermal fluid also had a certain degree of effect on the diagenesis process (Figure 4).

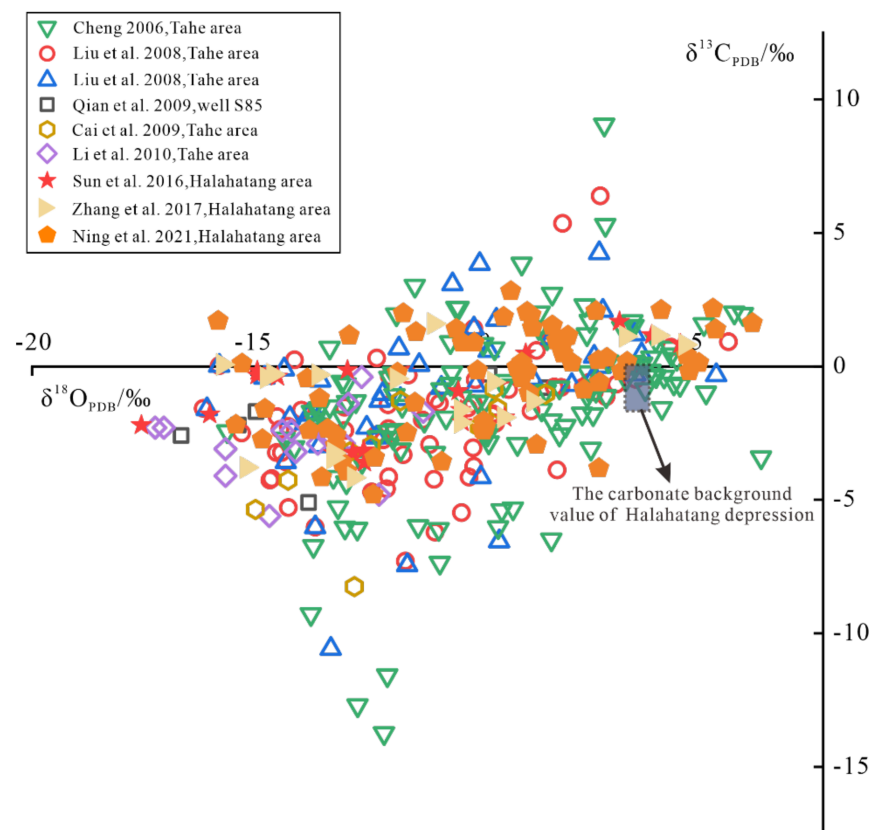


Figure 4. Distribution of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ of calcite in the Tahe and Halahatang areas. The genesis of calcite in the Halahatang depression was mainly influenced by paleo-meteoric water referred to in the previous studies [14,15,18,38,39,41–45].

In addition, the strontium isotopes in the Tahe area have the characteristic of a crust source [39]. Moreover, the fit line of hydrogen and oxygen isotopes of formation water in the Tahe and Lunnan areas intersect with the global precipitation line, after extension [13,14,21]. These results further proved that the primary source of formation water is paleo-meteoric water.

4.2.2. Water–Rock Interactions

The Piper diagram mainly uses the relative equivalent concentration percentage of the major cations and anions to represent the properties of formation water [47], which can reveal the sources of the dissolved constituents in waters without artificial influence.

The Ordovician formation water in the Halahatang depression can be divided into two types (Figure 5). The type I includes Cl-Na type and Cl-Na-Ca type, which are dominant in water samples. Type II contains Cl-Ca-Na type and Cl-Ca type. These two types of water are typical of brines from deep reservoirs in sedimentary basins [10], distributed in both the North and South Regions (Figure 5). This indicates that the present formation water experienced strong water-rock interactions in the Halahatang depression, which corresponds to the ion-proportionality coefficients.

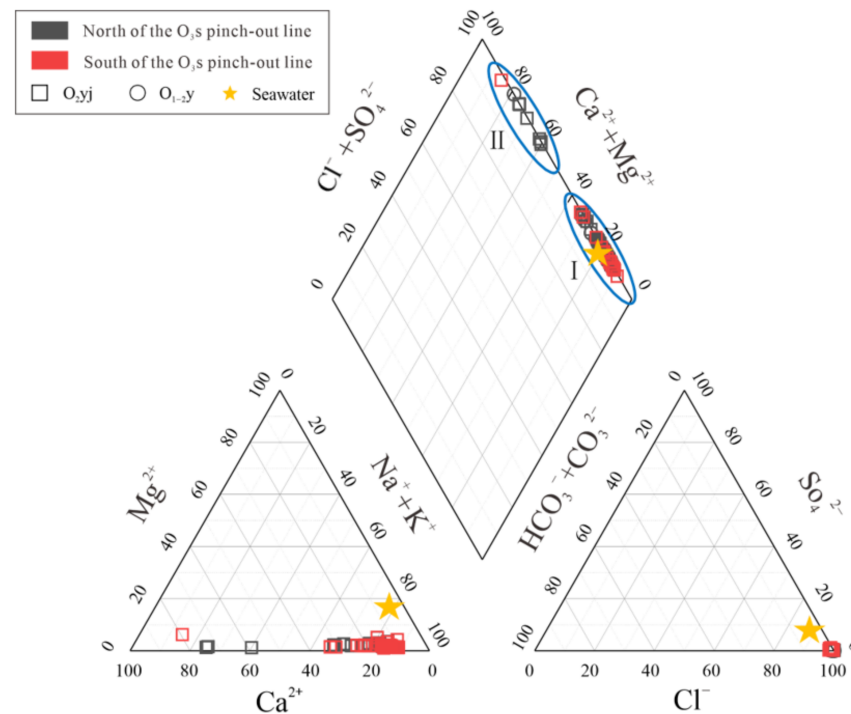


Figure 5. Piper diagram of Ordovician formation water in the Halahatang depression. I: Cl-Na type and Cl-Na-Ca type; II: Cl-Ca-Na type; and Cl-Ca type. These two types of water are distributed in both North Region and South Region, indicating that the formation water experienced strong water-rock interactions in the Halahatang depression.

4.3. Relation between Formation Water and Oil and Gas

Formation water has both modified and destructive effects on oil and gas reservoirs. The solution pores formed under the dissolution of carbonate rock by formation water, which was conducive to generate oil and gas reservoirs [48,49]. However, meteoric water entering the formation will damage the oil and gas reservoir [50]. In addition, the hydrochemical parameters, such as the TDS and ion-proportionality coefficients, can reflect the hydrogeological environment to a certain extent [51]. Thus, we can further determine whether it is conducive to the accumulation and preservation of hydrocarbons.

4.3.1. Effect of Formation Water on Oil and Gas Accumulation

The orogenic movements in the Caledonian and Hercynian periods played an essential role in the generation and improvement of reservoirs. Because of the denudation of strata and the dissolution of carbonate reservoirs by meteoric water, the Ordovician strata in the Halahatang depression mainly developed quasi-syngenetic karst, weathering crust karst and buried karstification [28,52]. These karstification processes made the Ordovician carbonate strata become favorable reservoirs. The strike-slip faults major formed in the Middle Caledonian period provided the migration channel of fluids, which further promotes the karstification. Besides, the acid water migrated with petroleum and hydrothermal fluid were also suggested as a source of improved reservoir quality.

However, the tectonic uplift also has a significantly destructive effect on oil and gas reservoirs. Because of the Caledonian and Hercynian tectonic uplift, a mass of microorganisms and sufficient oxygen carried by meteoric water entered the oil and gas reservoirs. This denudation promoted biodegradation together with water washing of crude oil, causing further damage in the pools. The widespread presence of heavy oil and asphalt in the North Region demonstrated this destructive effect. Although the biodegradation usually masks the development of water washing [53], the tectonic evolution and the source of formation water in Halahatang depression were sufficient to prove the effect of water washing on crude oil.

Due to the different intensities of tectonic evolution in the North and South Regions, the degree of destruction of oil and gas reservoirs is also different (Figure 6). The strata in the North Region were subjected to more intense uplift and denudation. Oil and gas reservoirs formed in the early stage were basically destroyed in the process of tectonic evolution and the crude oil degraded into heavy oil and asphalt. However, the strata in the South Region were less affected and the paleo-reservoirs partly preserved. Since the Triassic period, the strata subsided stably and were less influenced by destructive structures. Oil and gas generated in the later stage entered the reservoir and mixed with the pre-existing oils, forming the present oil and gas reservoir [29,32,33].

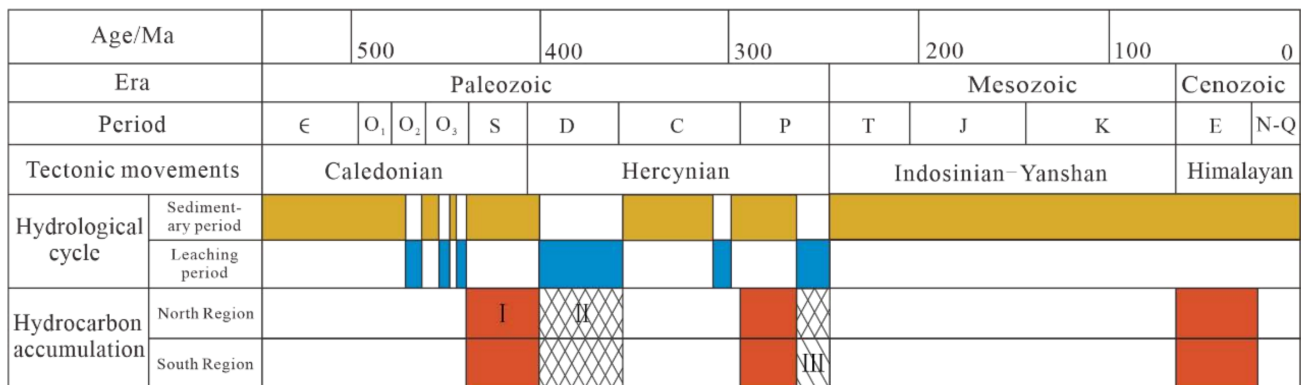


Figure 6. A sketch showing the hydrocarbon accumulation events and factors in the Halahatang depression. I: oil and gas accumulation; II: oil and gas reservoirs destroyed extensively; III: oil and gas reservoirs destroyed slightly. The leaching period mainly developed in the Caledonian and Hercynian periods. Reservoirs formed in the Late Caledonian-Early Hercynian periods were basically destroyed in both North Region and South Region. Reservoirs formed in the Late Hercynian period experienced weaker destruction in South Region than those in North Region.

4.3.2. Indication of Hydrochemistry Characteristics to Oil and Gas

The TDS has a certain indication to the migration of oil and gas. In many basins, the increasing TDS corresponded to the direction of hydrocarbon migration [54–57]. However, this is not applicable in all regions. In addition, the ion-proportionality coefficients of formation water can reflect the hydrological environment of underground strata, which can determine whether the strata are conducive to oil and gas accumulation and preservation.

The geochemical characteristics of crude oil in the Halahatang depression show that oil and gas migrated from south to north and northeast [25,32,58,59], which is consistent with the increasing direction of the TDS. However, the distribution of the TDS of formation water in Halahatang depression is mainly controlled by the caprock (Sangtam Formation) and the high salinity fluids from overlying strata and adjacent regions.

The influence of halite dissolution on brine salinity of formation water in sedimentary basin has been discussed [60,61]. Previous works on the Tarim basin also have concluded that the formation water in the Lunnan low uplift and the Tahe area was influenced by the dissolution of halite in the overlying strata [11,17,20,21,62,63]. Gypsum-salt is distributed widely in the Carboniferous strata in the Halahatang depression (Figure 7), which is an effective source of halite. It can be seen that the Carboniferous (gypsum-salt layer) formation water has high TDS (area III) but the TDS of the Ordovician formation water in the South Region is relatively low (area I) (Figure 8). However, the TDS data of the North Region Ordovician formation water (area II) are close to those of Carboniferous, indicating a certain correlation (Figure 8).

The fluids that had leached the halite from the overlying strata entered the Ordovician strata along the unconformities and strike-slip faults. When mixed with connate water it resulted in the salinity increase of formation water in the Ordovician (Figure 9). However, due to the existence of the mudstone shielding layer of O₃s, the high salinity fluids cannot enter the Ordovician strata directly. The diffusion of the solute from the high salinity fluids gradually weakens to the south, causing the TDS to be lower than that in the North Region (Figure 9).

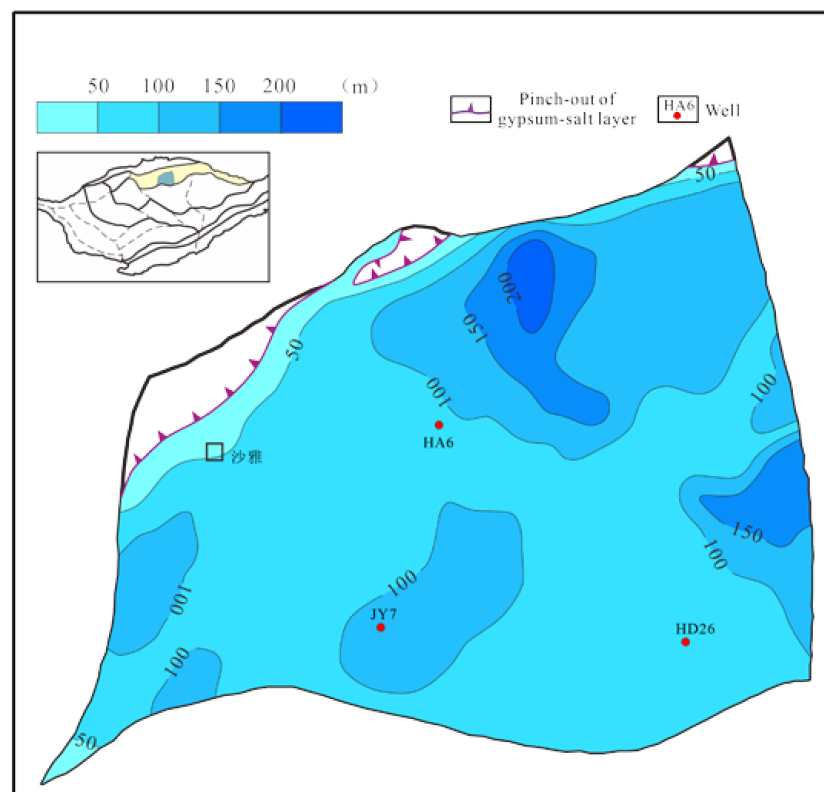


Figure 7. The thickness distribution of the gypsum-salt layer of the Carboniferous strata in Halahatang depression. The gypsum-salt layer distributes in Carboniferous strata.

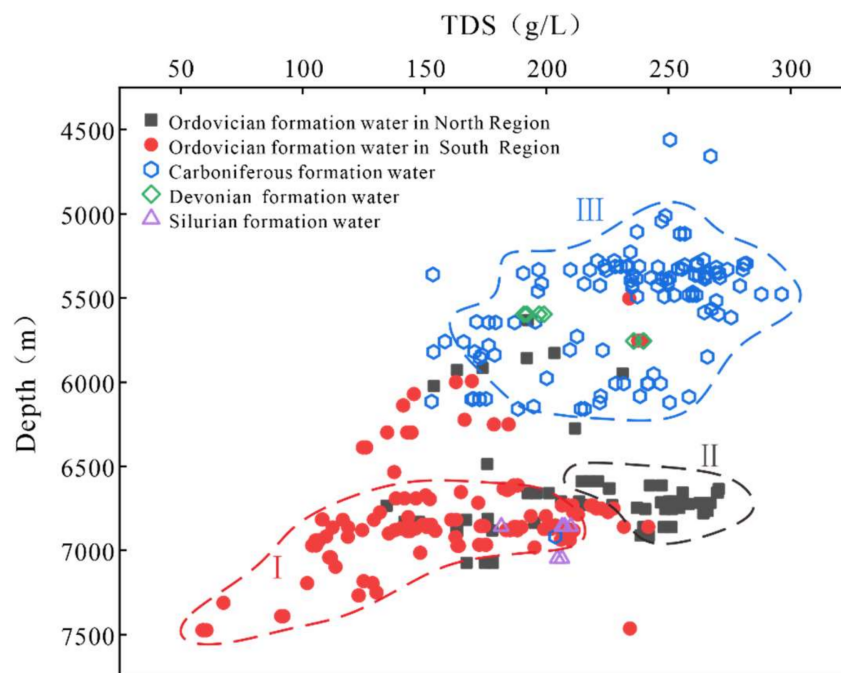


Figure 8. TDS of formation waters in different strata in Halahatang depression. Area I: The major part of the TDS data of Ordovician formation water in South Region; Area II: The major part of the TDS data of Ordovician formation water in North Region; Area III: The major part of the TDS data of Carboniferous formation water. The Carboniferous formation water has high TDS than Ordovician formation water in South Region.

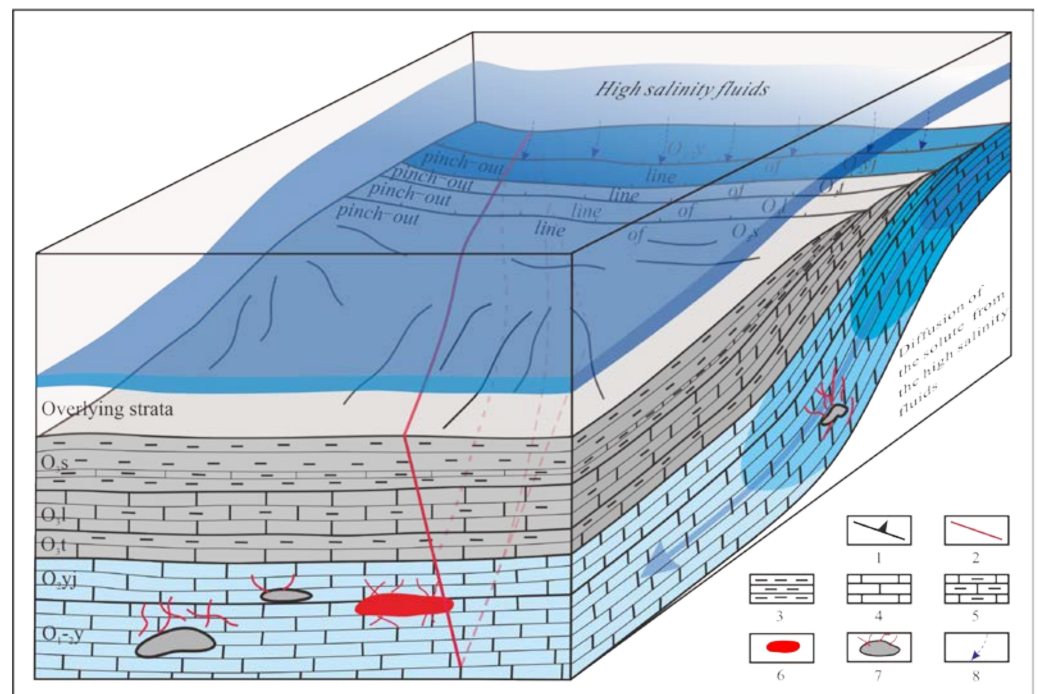


Figure 9. Migration direction pattern of high salinity fluids and hydrocarbon in the Halahatang depression 1: pinch-out line; 2: faults; 3: mudstone; 4: limestone; 5: muddy limestone; 6: hydrocarbon reservoir; 7: karst fracture-cavity; 8: high salinity fluids entered the Ordovician strata. The TDS in the Ordovician is controlled by the caprock and the high salinity fluids from overlying strata and adjacent regions.

Nonetheless, the CaCl_2 type formation water with high TDS and reductive ion-proportionality coefficients on the whole reflect the good preservation conditions of the Ordovician strata. After the Caledonian-Hercynian tectonic uplift, the overlying strata settled steadily onto the Ordovician strata, leading to the gradual improvement of preservation conditions. The Ordovician strata altered by karstification can be regarded as favorable reservoirs and the strike-slip faults provided the migration pathway for hydrocarbon. Oil formed in the Himalayan entered the reservoir and mixing with heavy oils that had been destroyed earlier, forming the present oil and gas reservoirs.

5. Conclusions

- (1) The formation water in the Halahatang depression is CaCl_2 type with high salinity and the TDS decreases with the depth. High salinity fluids entered the Ordovician strata and the distribution of mudstone barrier layer of O_3s accounted for the TDS distribution. The ion-proportionality coefficients show that the present Ordovician strata are well sealed and had experienced strong water-rock interactions;
- (2) The formation water mainly originated from paleo-meteoric water, mixed or re-placed with seawater and was affected by hydrothermal activities to a certain extent. With the stable sedimentation of overlaying strata, the sealing conditions and the water-rock interactions became stronger. Reflected in the Piper diagram, the formation water of the Ordovician strata in the Halahatang depression is typical of brine from deep reservoirs in sedimentary basins that experienced strong water-rock interactions;
- (3) Formation water has both positive and destructive effects on oil and gas reservoirs. The increasing direction of the TDS is consistent with the direction of hydrocarbon migration, but the caprock and high salinity fluids from overlying strata and adjacent regions controlled the TDS distribution. The high TDS and reductive ion-proportionality coefficients reveal that the sealing condition of the Ordovician strata in the Halahatang depression is beneficial to the accumulation and preservation of oil and gas reservoirs.

Author Contributions: Conceptualization, T.X. and C.Z.; methodology, T.X., C.Z. and X.J.; data curation, X.W., H.Z. and T.X.; writing—original draft preparation, T.X. and C.Z.; writing—review and editing, C.Z. and X.W.; visualization, B.T. and T.X.; supervision, H.Z. and B.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by the “National Science and Technology Major Project of China” (Grant No. 2017ZX05008004) and the PetroChina Tarim Oilfield Company.

Data Availability Statement: The data used to support the findings of this study are available from the first author upon request (first author: T.X. tong_xu111@163.com).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Zeng, J.; Yong, M.; Lamei, L. *Petroleum Hydrogeology*; China University of Petroleum Press: Beijing, China, 2021.
2. Land, L.S.; MacPherson, G.L. Origin of Saline Formation Waters, Cenozoic Section, Gulf of Mexico Sedimentary Basin. *AAPG Bull.* **1992**, *76*, 1344–1362.
3. Sun, X.; Xie, X. Relationship Between the Chemical Characteristics of Formation Water and Hydrocarbon Accumulation in the Dongying Sag. *Exp. Pet. Geol.* **2001**, *3*, 291–296.
4. Panno, S.V.; Hackley, K.C.; Locke, R.A.; Krapac, I.G.; Kelly, W.R. Formation Waters from Cambrian-Age Strata, Illinois Basin, USA: Constraints On their Origin and Evolution. *Geochim. Cosmochim. Acta* **2013**, *122*, 184–197. [[CrossRef](#)]
5. Birkle, P.; García, B.M.; Padrón, C.M.M. Origin and Evolution of Formation Water at the Jujo–Tecominoacán Oil Reservoir, Gulf of Mexico. Part 1: Chemical Evolution and Water–Rock Interaction. *Appl. Geochem.* **2009**, *24*, 543–55412. [[CrossRef](#)]
6. Zhang, S.; Zhang, L.; Bao, Y. Formation Fluid Characteristics and Hydrocarbon Accumulation in the Dongying Sag, Shengli Oilfield. *Pet. Explor. Dev.* **2011**, *38*, 394–405. [[CrossRef](#)]
7. Zhao, W.Z.; Shen, A.J.; Hu, S.Y.; Zhang, B.M.; Pan, W.Q. Geological Conditions and Distributional Features of Large-Scale Carbonate Reservoirs Onshore China. *Pet. Explor. Dev.* **2012**, *39*, 1–12. [[CrossRef](#)]

8. Zhu, G.; Milkov, A.V.; Zhang, Z.; Sun, C.; Zhu, Y. Formation and Preservation of a Giant Petroleum Accumulation in Superdeep Carbonate Reservoirs in the Southern Halahatang Oil Field Area, Tarim Basin, China. *AAPG Bull.* **2019**, *103*, 1703–1743. [[CrossRef](#)]
9. Chen, J.; Liu, D.; Hou, X.; Fan, Y.; Jia, W.; Peng, A.; Zhang, B.; Xiao, Z. Origin and Evolution of Oilfield Waters in the Tazhong Oilfield, Tarim Basin, China, their Relationship to Multiple Hydrocarbon Charging Events—Sciencedirect. *Mar. Pet. Geol.* **2018**, *98*, 554–568. [[CrossRef](#)]
10. Kharaka, Y.K.; Hanor, J.S. Deep Fluids in the Continents: I. Sedimentary Basins. *Treatise Geochem.* **2003**, *5*, 1–48.
11. Qian, Y.; Cai, L.; Yi, G. Ion Related Parameters of Formation Water Distribution in the Tahee Oilfield and its Relationship to Petroleum Migration. *Pet. Geol. Exp.* **2005**, *27*, 82–87.
12. Qian, Y.; Cai, L.; Yi, G.U. The Oilfield Water in Tahe Area, Tarim Basin—Constraints From its Element Composition. *Pet. Geol. Experiment* **2005**, *25*, 751–757.
13. Jia, C.S.; Ma, X.J.; Rao, D.; Gao, R.X. Isotopic Characteristics of Oil Filled Waters from Ordovician Oil Accumulations in Tahe Oilfield and its Geological Significances. *Pet. Geol. Exp.* **2007**, *29*, 292–297.
14. Cai, C.F.; Kaikai, L.I.; Bin, L.I.; Cai, L.L.; Lei, A.J. Geochemical Characteristics and Origins of Fracture- And Vug-Fillings of the Ordovician in Tahe Oilfield, Tarim Basin. *Acta Petrol. Sin.* **2009**, *25*, 2399–2404.
15. Li, K.; Lei, J. Fluid Origin of Cave-Filling Giant Crystalline Calcites in the Early Paleozoic in Tahe Oilfield, Tarim Basin and the Model of the Fluid Action. *Chin. J. Geol.* **2010**, *45*, 595–605.
16. Li, K.; Cai, C.F. Origin of Palaeo-Waters in the Ordovician Carbonates in Tahe Oilfield, Tarim Basin: Constraints from Fluid Inclusions and Sr, C and O Isotopes. *Geofluids* **2011**, *11*, 71–86. [[CrossRef](#)]
17. Chen, J.; Liu, D.; Peng, P.; Yu, C.; Zhang, B. The Sources and Formation Processes of Brines from the Lunnan Ordovician Paleokarst Reservoir, Tarim Basin, Northwest China. *Geofluids* **2013**, *13*, 381–394. [[CrossRef](#)]
18. Cheng, J. *Study on the Characteristics of Ordovician Subsurface Fluid and Reservoir Formation in Tahe Oilfield*; Zhejiang University: Hangzhou, China, 2006.
19. Zhu, R.; Lou, Z.; Lu, X.; Jin, A.; Su, D. Chemical Characteristics of Underground Water and Development Performance of Fracture-Cave Units in Tahe Oilfield. *Acta Pet. Sin.* **2008**, *29*, 567–572.
20. Liu, D.; Chen, J.; Peng, P.; Xiao, Z.; Yu, C. The Control of Reservoir Types in Lunnan Oilfield on Characters of Formation Water. *Shiyou Xuebao/Acta Pet. Sin.* **2012**, *33*, 367–371.
21. Liu, D.; Chen, J.; Peng, P.; Li, H.; Xiao, Z.; Zhang, B.; Lu, Y. Geology of Deeply Buried Weathering Reservoir in the Lunnan Oilfield and its Controls on the Mixing of Formation Waters. *Bull. Mineral. Petrol. Geochem.* **2016**, *35*, 890–896.
22. Jia, C.Z.; Wei, G.Q. Structural Characteristics and Petroliferous Features of Tarim Basin. *Chin. Sci. Bull.* **2002**, *47*, 1–11. [[CrossRef](#)]
23. He, D.F.; Jia, C.Z.; Li, D.S. Formation and Evolution of Polycyclic Superimposed Tarim Basin. *Oil Gas Geol.* **2005**, *26*, 64–77.
24. Zhang, G.; Zhao, W.; Wang, H.; Li, H.; Lei, L. Multicycle Tectonic Evolution and Composite Petroleum Systems in the Tarim Basin. *Oil Gas Geol.* **2007**, *28*, 653–663.
25. Zhu, G.; Yang, H.; Zhu, Y.; Gu, L.; Lu, Y.; Su, J.; Zhang, B.; Fan, Q. Study on Petroleum Geological Characteristics and Accumulation of Carbonate Reservoirs in Hanilcatam Area, Tarim Basin. *Acta Petrol. Sin.* **2011**, *27*, 827–844.
26. Zhu, G.Y.; Zhang, S.C.; Wang, H.H.; Yang, H.J.; Su, J. The Formation and Distribution of Deep Weathering Crust in North Tarim Basin. *Acta Petrol. Sin.* **2009**, *25*, 2384–2398.
27. Chang, X.; Wang, T.G.; Li, Q.; Cheng, B.; Tao, X. Geochemistry and Possible Origin of Petroleum in Palaeozoic Reservoirs from Halahatang Depression. *J. Asian Earth Sci.* **2013**, *74*, 129–141. [[CrossRef](#)]
28. Zhang, X.F.; Li, M.; Chen, Z.Y.; Jiang, H.; He, Y.L. Characteristics and Karstification of the Ordovician Carbonate Reservoir, Halahatang Area, Northern Tarim Basin. *Acta Petrol. Sin.* **2012**, *28*, 815–826.
29. Cui, H.F.; Zheng, D.M.; Teng, T.Y. Petroleum Geologic Characteristics and Exploration Orientation in Halahatang Depression of Tabei Uplift. *Lithol. Reserv.* **2009**, *21*, 54–58.
30. Sun, D.; Yang, L.; Wang, H.; Zheng, D.; Sun, Q.; Li, G.; Dai, D.; Fang, Q. Strike-Slip Fault System in Halahatang Area of Tarim Basin and its Control on Reservoirs of Ordovician Marine Carbonate Rock. *Nat. Gas Geosci.* **2015**, *26*, 80–87.
31. Li, J.; Tao, X.; Bai, B.; Huang, S.; Song, W. Geological Conditions, Reservoir Evolution and Favorable Exploration Directions of Marine Ultra-Deep Oil and Gas in China. *Pet. Explor. Dev.* **2021**, *48*, 60–79. [[CrossRef](#)]
32. Tao, X.; Zhang, Y.; Duan, S.; Zhang, L.; Zhu, W. Crude Oil Accumulation Processes and Causes of Highly Variable Oil Density in Halahatang Oilfield, Tarim Basin. *Shiyou Xuebao/Acta Pet. Sin.* **2015**, *36*, 405–415.
33. Lu, Y.H.; Xiao, Z.Y.; Gu, Q.Y.; Zhang, Q.C. Geochemical Characteristics and Accumulation of Marine Oil and Gas Around Halahatang Depression, Tarim Basin, China. *Sci. China* **2008**, *51*, 195–206. [[CrossRef](#)]
34. Zhao, J.; Li, Q. Timing and History of Marine Hydrocarbon Accumulation in Tarim Craton. *Chin. Sci. Bull.* **2002**, *47*, 120–127. [[CrossRef](#)]
35. Guan, Y.; Wang, L.; Zhang, J. Characteristics of Mixed Liquid of Formation Water with Residual Acid and Drilling Fluid. *Nat. Gas Explor. Dev.* **2011**, *34*, 62–64.
36. Li, P.; Liu, C. Geochemical Behaviors of the Ordovician Formation Water in the Tazhong Area and its Origin and Evolution. *Oil Gas Geol.* **2007**, *6*, 802–808.
37. Zeng, J.; Wu, Q.; Yang, H. Chemical Characteristics of Formation Water in Tazhong Area of the Tarim Basin and their Petroleum Geological Significance. *Oil Gas Geol.* **2008**, *29*, 223–229.

38. Qian, S.Y.; Zeng, J.H. Chemical Characteristics of Shahejie Formation Formation Water and their Petroleum Geological Significance, Dongying Sag. *Nat. Gas Geosci.* **2009**, *20*, 603–609.
39. Liu, C.G.; Guo-Rong, L.I.; Zhu, C.L.; Liu, G.Y.; Lu, Y.F. Geochemistry Characteristics of Carbon, Oxygen and Strontium Isotopes of Calcites Filled in Karstic Fissure-Cave in Lower-Middle Ordovician of Tahe Oilfield, Tarim Basin. *Earth Sci. J. China Univ. Geosci.* **2008**, *33*, 377–386.
40. Qian, Y.X.; Chen, Y.; Luo, M. Mineralogical and Geochemical Identification for Diagenetic Settings of Paleo-Caves and Fractures-Filling & Vugs Calcites in Carbonate: Taking Wells S79 and S85 for Example. *Acta Sedimentol. Sin.* **2009**, *27*, 1027–1032.
41. Ning, C.; Sun, L.; Hu, S.; Xu, H.; Pan, W.; Li, Y.; Zhao, K. Karst Types and Characteristics of the Ordovician Fracture-Cavity Type Carbonate Reservoirs in Halahatang Oilfield, Tarim Basin. *Acta Pet. Sin.* **2021**, *42*, 15–32.
42. Sun, C.H.; Zhu, G.Y.; Zheng, D.M.; Zhao, K.Z.; Hu, F.I. Characteristics and Controlling Factors of Fracture-Cavity Carbonate Reservoirs in the Halahatang Area, Tarim Basin. *Bull. Mineral. Petrol. Geochem.* **2016**, *35*, 1028–1036.
43. Zhang, Q.; Qin, F.; Liang, B.; Yong, D.; Li, J.; Chen, L. Paleogeomorphology and Karst Reservoir Development of Ordovician Carbonate in Halahatang Area, Northern Tarim Basin. *Geol. Sci. Technol. Inf.* **2017**, *36*, 168–175.
44. Liu, X.; Cai, Z. Element Geochemistry Characteristics of Karstic Cave Deposition in Tahe Oilfield and its Environmental Significance. *Geol. Sci. Technol. Inf.* **2009**, *28*, 53–57.
45. Knoerich, A.C.; Mutti, M. Missing Aragonitic Biota and the Diagenetic Evolution of Heterozoan Carbonates: A Case Study from the Oligo-Miocene of the Central Mediterranean. *J. Sediment. Res.* **2006**, *76*, 871–888. [[CrossRef](#)]
46. Chen, R. Application of Stable Oxygen and Carbon Isotope in the Research of Carbonate Disgenetic Environment. *Acta Sedimentol. Sin.* **1994**, 11–21.
47. Piper, A. A Graphic Procedure in the Geochemical Interpretation of Water-Analyses. *Eos Trans. Am. Geophys. Union* **1944**, *25*, 914–923. [[CrossRef](#)]
48. Chen, J.; Li, Z.; Wang, Z. Paleokarstification and Reservoir Distribution of Ordovician Carbonates in Tarim Basin. *Acta Sedimentol. Sin.* **2007**, *25*, 858–868.
49. Hu, M.Y.; Fu, X.S.; Cai, Q.S.; Yang, W.; Zhu, W.P. Characteristics and Genetic Model of Karst Reservoirs of Ordovician Yingshan-Yijianfang Formation in Halahatang Area, Northern Tarim Basin. *Geol. China* **2014**, *41*, 1476–1486.
50. Zhang, S.C.; Zhu, G.Y.; Yang, H.J.; Su, J.; Cui, J. The Phases of Ordovician Hydrocarbon and their Origin in the Tabei Uplift, Tarim Basin. *Acta Petrol. Sin.* **2011**, *27*, 2447–2460.
51. Sun, X.; Liu, F. Chemical Behavior and Geological Significance of Formation Water in Sedimentary Basins. *Nat. Gas Explor. Dev.* **2001**, *24*, 47–53.
52. Ni, X.; Zhang, L.; Shen, A.; Qiao, Z. Characteristics and Genesis of Ordovician Carbonate Karst Reservoir in Yingmaili-Halahatang Area, Tarim Basin. *Acta Sedimentol. Sin.* **2011**, *29*, 465–474.
53. Zhang, Z.H.; Deng, Z.Y.; Shui-Ping, W.U.; Chang, X.C. Geochemical Alteration of Hydrocarbon Compositions During Migration and Accumulation and its Controlling Factors. *Geol. J. China Univ.* **2003**, *4*, 484–493.
54. Shi, J.; Jiang, J.; Zhang, F.; Jia, Y. Relation Between Hydro-Geologic Characteristics of Formation Water and Oil Migration and Accumulation in Damintun Depression. *Mar. Geol. Lett.* **2003**, *11*, 24–30.
55. Zhang, Z.; Ming, Z.; Gao, C. Hydrochemical Characteristics and Hydrocarbon Accumulation in the Chengbei Fault Terrace Zone of Dagang Oilfield. *Oil Gas Geol.* **2009**, *30*, 268–274.
56. Yang, S.I.; Zhang, W.; Luo, A.; Sun, B.; Zhu, Y. Hydrochemical Feature Genesis and Hydrocarbon Exploration Significance of Chang 8 Tight Sandstone Reservoir in Longdong Area, Ordos Basin. *Geoscience* **2019**, *33*, 1106–1117.
57. Ye, S.; Rong, L.; Zhang, S. Chemical Characteristics of Jurassic Formation Water and its Relationship with Hydrocarbon Migration and Accumulation in Middle Part of Western Sichuan Depression. *Pet. Geol. Exp.* **2014**, *36*, 487–494.
58. Li, S.; Zhang, B.; Xing, L.; Hao, S.; Yuan, X. Geochemical Features of Deep Hydrocarbon Migration and Accumulation in Halahatang-Yingmaili Area of the Northern Tarim Basin. *Acta Pet. Sin.* **2015**, *36*, 92–101.
59. Fang, R. *Geochemistry of Polycyclic Aromatic Hydrocarbons and Nonhydrocarbons: Tracing Markers for Oil Filling Orientations and Pathways*; China University of Petroleum: Beijing, China, 2016.
60. Seyler, D.B. Chemical Composition and Geologic History of Saline Waters in Aux Vases and Cypress Formations, Illinois Basin. *Aquat. Geochem.* **1999**, *5*, 281–331.
61. Stueber, A.M.; Walter, L.M.; Huston, T.J.; Pushkar, P. Formation Waters from Mississippian-Pennsylvanian Reservoirs, Illinois Basin, Usa: Chemical and Isotopic Constraints on Evolution and Migration. *Geochim. Cosmochim. Acta* **1993**, *57*, 763–784. [[CrossRef](#)]
62. Cai, L.; Qian, Y.; Liu, G. The Isotopes Composition Formation Waters in Akekule and Adjacent, Tarim. *Nat. Gas Geosci.* **2005**, *16*, 503–506.
63. Chen, J. Iodine-129 Chronological Study of Brines from an Ordovician Paleokarst Reservoir in the Lunnan Oilfield, Tarim Basin. *Appl. Geochem.* **2016**, *65*, 14–21. [[CrossRef](#)]