Origin of palaeo-waters in the Ordovician carbonates in Tahe oilfield, Tarim Basin: constraints from fluid inclusions and Sr, C and O isotopes

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ABSTRACT

Petrographic features, isotopes, and trace elements were determined, and fluid inclusions were analyzed on fracture-filling, karst-filling and interparticle calcite cement from the Ordovician carbonates in Tahe oilfield, Tarim basin, NW China. The aim was to assess the origin and evolution of palaeo-waters in the carbonates. The initial water was seawater diluted by meteoric water, as indicated by bright cathodoluminescence (CL) in low-temperature calcite. The palaeoseawater was further buried to temperatures from 57 to 110°C, nonluminescent calcite precipitated during the Silurian to middle Devonian. Infiltration of meteoric water of late Devonian age into the carbonate rocks was recorded in the first generation of fracture- and karst-filling dull red CL calcite with temperatures from <50°C to 83°C, low salinities (<9.0 wt%), high Mn contents and high 86Sr/87Sr ratios from 0.7090 to 0.7099. During the early Permian, 87Sr-rich hydrothermal water may have entered the carbonate rocks, from which precipitated a second generation of fracture-filling and interparticle calcite and barite cements with salinities greater than 22.4 wt%, and temperatures from 120°C to 180°C. The hydrothermal water may have collected isotopically light CO2 (possibly of TSR-origin) during upward migration, resulting in hydrothermal calcite and the present-day oilfield water having δ13C values from −4.3 to −13.8‰ and showing negative relationships of 87Sr/86Sr ratios to δ13C and δ18O values. However, higher temperatures (up to 187°C) and much lower salinities (down to 0.5 wt%) measured from some karst-filling, giant, nonluminescent calcite crystals may suggest that hydrothermal water was deeply recycled, reduced (Fe-bearing) meteoric water heated in deeper strata, or water generated from TSR during hydrothermal water activity. Mixing of hydrothermal and local basinal water (or diagenetically altered connate water) with meteoric waters of late Permian age and/or later may have resulted in large variations in salinity of the present oilfield waters with the lowest salinity formation waters in the palaeo-highs.

Key words: carbon isotopes, carbonates, fluid inclusion, fracture-filling, hydrothermal water, strontium isotopes, Tarim basin

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INTRODUCTION

The Tahe oilfield is located in the Tabei Uplift, north of the Tarim Basin, NW China, with giant volumes of petroleum reservoired in Ordovician carbonates with small volumes of condensate in the Cambrian dolomites at a depth of 8402 m in well TS1(Fig. 1). Abundant pores, fractures and vugs exist in the reservoirs even at 8400 m. Previous studies showed that the porosity in this area resulted from meteoric dissolution of carbonates during Caledonian and early Hercynian Orogenies (Yan 2002; Yu 2005; Qian et al. 2007; Zhang et al. 2007), when the strata were
uplifted and exposed to the surface. However, this mechanism alone cannot account for high porosity in the reservoirs away from the unconformities, where meteoric water supply would have been limited, or in the deep reservoirs (e.g. >6000 m), where most pore space is typically completely destroyed because of compaction and cementation (Halley & Schmoker 1983).

Carbonate dissolution by hydrothermal water has been invoked to explain “sag” occurrences above porous hydrothermal dolomite in deep carbonates in some petroleum-producing basins (Davies & Smith 2006). In the Central Tarim Basin, fracture-filling barite, fluorite, and pyrite probably originated from hydrothermal activity (Cai et al. 2008). However, it is not clear whether there has been hydrothermal activity in the Tahe oilfield, because the chemical and isotopic composition of Sr, C, and O and thus the source of hydrothermal water have not previously been characterized. The specific question being addressed in this study is the origin and evolution of palaeo-waters in the carbonates in the northern Tarim Basin.

To address this issue, this paper presents fluid-inclusion data, trace element compositions, and strontium, carbon, and oxygen isotopes from the fracture-filling, karst-filling and interparticle calcite cements and formation water in the Ordovician in Tahe area. Fluid-inclusion data can be used to indicate temperatures and salinities during mineralization, and Sr, C, and O isotopic compositions have widely been used to indicate the origin of waters, mixing of different water bodies, and cross-formation water flow (Worden & Matray 1995; Cai et al. 2001a,b, 2008; Schwinn et al. 2006; Worden et al. 2006; Sandstrom & Tullborg 2009). Analysis of these types of data is expected to supply reliable information to address the source and evolution of the water in this field.

**GEOLOGICAL SETTING**

The Tarim basin, which is located in northwest of China (Fig. 1), has a long history of successful petroleum exploration. Recently, giant petroleum resources have been found in reef-shoal facies limestone in the Ordovician in the Central Tarim and Tabei uplifts (Fig. 1). Detailed descriptions of the geological settings of the Tarim Basin have been published previously (Cai et al. 2001a,b, 2008). In brief, Upper Proterozoic (Sinian) beach to shallow marine facies siliciclastic rock and carbonates lie on Archean and Proterozoic crystalline basement. The overlying Cambrian and Ordovician strata are composed of platform facies limestone and dolomite, slope facies limestone and marlstone, and basinal facies mudstone, shale and marlstone. The Silurian to Carboniferous sequence consists of marine sandstone and mudstone. Permian strata are composed of lacustrine sediment and volcanic rock. Following the emergence of the sediments, Mesozoic and Cenozoic units are represented by nonmarine fluvial sandstone and mudstone.

Various orogenic events have led to nine recognized unconformities in the basin (Table 1). In the Tabei area, thrusting and uplift in the north of the Tahe area was significantly greater than in the south as a result of different structural stresses during the late Caledonian Orogeny at
the end of Ordovician. Thus, Middle-Upper Ordovician strata in the north were completely removed by erosion, whereas the strata remain in the south (Fig. 2). No Devonian or Silurian strata remain in the majority of the Tabei area as a result of the early Hercynian Orogeny at the end of the Devonian. Multiple-stage orogenies in the Tabei area also created abundant polyphase faults besides the unconformities. During the Sinian to late Cambrian stages, the study area was in a continental rift setting. Accordingly, a series of NW, NE, EW, and SN strike normal faults developed under the control of NE-SW, NNE-SSW, NNW-SSE trending primary stresses. Subsequently, as a result of middle-late Caledonian Orogeny, Cambro-Ordovician formations were in an extensional setting instead of the previous compressive environment. Extensive NW, NE, EW, and SN strike thrust faults developed. The orientation of the faults formed during the middle-late Caledonian Orogeny is consistent with that of the faults formed during the Sinian to late Cambrian. Therefore, a complex of deep-seated faults existed which affected the Cambro-Ordovician formations in the Tahe oilfield.

Burial and thermal history modeling of Wells S109 in the south and S75 in the north of the Tahe area, using Thermodel software (Hu & Zhang 1998) and calibrated with vitrinite reflectance (Ro) data, shows that rapid sedimentation took place during the late Ordovician to early Silurian, late Devonian to early Carboniferous, and late Permian to the Neogene. Significant uplift occurred during the late Silurian, the end of the Devonian to early Carboniferous, and the late Permian (Fig. 3). The Ordovician strata did not experience temperatures more than 110°C prior to the late Hercynian Orogeny during the late Permian and exceeded this temperature only after the Eocene. Present-day temperatures of Ordovician strata have temperatures up to 130°C in the north and up to 150°C in the south.

Table 1 Synthetic stratigraphy for Tahe area, Tabei Uplift.

<table>
<thead>
<tr>
<th>System</th>
<th>Series</th>
<th>Stage</th>
<th>Thickness (m)</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cenozoic Quaternary</td>
<td>Q</td>
<td>16–63</td>
<td>Grayish-yellow sand and clay</td>
<td></td>
</tr>
<tr>
<td>Neogene Pliocene</td>
<td>N2k</td>
<td>1522–2009</td>
<td>Gray siltstone and brownish yellow mudstone</td>
<td></td>
</tr>
<tr>
<td>Miocene</td>
<td>N1k</td>
<td>732–1052</td>
<td>Gray siltstone and brown mudstone</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N1j</td>
<td>329–674</td>
<td>Gray and grayish-green mudstone, siltstone and sandstone</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N1s</td>
<td>38–326</td>
<td>Light yellow, brown fine-grained sandstone and siltstone</td>
<td></td>
</tr>
<tr>
<td>Paleogene</td>
<td>K2–E</td>
<td>614–745</td>
<td>Brownish-red sandstone, mudstone and siltstone</td>
<td></td>
</tr>
<tr>
<td>Mesozoic Cretaceous Upper</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>K1kp</td>
<td>298–436</td>
<td>Tan silty-mudstone, mudstone and grayish-green sandstone</td>
</tr>
<tr>
<td>Jurassic Lower</td>
<td>J1</td>
<td>42–76</td>
<td>Gray fine-grained sandstone, mudstone, silty stone with thin layer of coal</td>
<td></td>
</tr>
<tr>
<td>Triassic Upper</td>
<td>T3h</td>
<td>98–174</td>
<td>Dark gray, gray mudstone, blacks and fine-grained sandstone</td>
<td></td>
</tr>
<tr>
<td>Middle</td>
<td>T2a</td>
<td>176–298</td>
<td>The upper part is dark gray and black mudstone, and the lower is sandstone</td>
<td></td>
</tr>
<tr>
<td>Paleozoic Carboniferous Lower</td>
<td>C1kl</td>
<td>370–537</td>
<td>Gray, tawny brown mudstone, light gray sandstone and marlstone</td>
<td></td>
</tr>
<tr>
<td>Ordovician Upper</td>
<td>O3b</td>
<td>76–235</td>
<td>Gray micrite, motley sandstone, mudstone, and grainstone</td>
<td></td>
</tr>
<tr>
<td></td>
<td>O4s</td>
<td>0–500</td>
<td>Grayish green and gray mudstone and micritic limestone</td>
<td></td>
</tr>
<tr>
<td></td>
<td>O4l</td>
<td></td>
<td>The middle-upper part is grayish green silty-mudstone, silty-micrite and micrite, and the lower is deep grey bioclastic marlstone and micrite</td>
<td></td>
</tr>
<tr>
<td></td>
<td>O3q</td>
<td>&gt;427</td>
<td>Motley packstone and micrite</td>
<td></td>
</tr>
<tr>
<td>Middle</td>
<td>O2yj</td>
<td></td>
<td>Gray-brownish gray calcarenite, bioclastic marlstone, oolitic limestone</td>
<td></td>
</tr>
<tr>
<td>Lower</td>
<td>O1yp</td>
<td></td>
<td>The upper part is gray micrite and calcarenite, and the lower is interbeded limestone and dolostone</td>
<td></td>
</tr>
<tr>
<td>Cambrian Upper</td>
<td>r2q1</td>
<td>1524</td>
<td>Gray argillaceous dolomite and fine to coarse-crystalline dolomite</td>
<td></td>
</tr>
</tbody>
</table>
SAMPLING AND ANALYTICAL METHODS

Thirty-nine core samples from seventeen wells across the whole Tahe oilfield (Fig. 1) were collected from the Ordovician strata. The samples with veins, giant calcite crystals, or different generations of cements were chosen from the petroleum reservoirs. Petrographic and cathodoluminescence (CL) analyses were performed on 23 thin sections. A cold cathode luminescence microscope was used with a beam voltage of 16.3 kV, a current of 325 μA and a beam diameter of 4 mm. Fluid inclusions were observed under a Linkam THMSG 600 fitted a UV lamp to determine whether they were oil or aqueous inclusions. Micro-thermometric measurements were conducted using the THMSG 600 freezing/heating stage with precision of ±1°C. Salinity was calculated based on the ice final melting temperature measurement using the following equation:

\[
\text{Salinity} = 0.00 + 1.78T_m - 0.0442T_m^2 + 0.000557T_m^3
\]

(Bodnar 1993), where \(T_m\) is the depression of the freezing point in degrees Celsius (°C).

Fracture-fillings with a width of more than 2 mm were extracted from core using a dentist’s drill and subject to trace element analyses and carbon, oxygen, and strontium isotope measurement. For carbon and oxygen isotope analyses, about 30–50 mg of samples was reacted overnight with 100% phosphoric acid at 25°C under vacuum to release CO\(_2\) from calcite. The CO\(_2\) was then analyzed for carbon and oxygen isotopes on a Finnigan MAT251 mass
spectrometer standardized with NBS-18. All carbon and oxygen data are reported in per mil relative to the Vienna Peedee Belemnite (VPDB) standard, respectively. The precision for δ13C and δ18O measurement is ±0.1‰. For strontium isotope analyses, 50–100 mg of sample powders was dissolved in 2.5 N HCl, and the strontium was then extracted using the conventional cation exchange procedures. The ⁸⁷Sr/⁸⁶Sr ratios were measured on a Finnigan MAT-261 mass spectrometer. The ⁸⁷Sr/⁸⁶Sr ratios were corrected relative to the NBS987 standard. The precision for ⁸⁷Sr/⁸⁶Sr measurement is ±0.00003–0.00007, respectively. Trace elements were analyzed using a Finnigan ICP-MS. Repeated analysis on standards and samples gives precisions better than ±8%. Mn was measured using an AA2610 atomic absorption spectrometer with a detection limit of 0.01% and precisions better than ±8%, and Fe was measured by colorimetry using RPA-100 Fe equipment with a detection limit of 5 μg g⁻¹ and precisions better than ±13%.

RESULTS

Petrology of fracture-fillings and cements
Calcite and a small amount of barite were observed to occur as fracture-, karst-, and vug-fillings or as interparticle cement. There are three different types of fractures, which are as follows: type I occurs in irregular shapes and is distributed as networks (Fig. 4A), type II and type III have straight and elongated shapes with type II fracture-filling.
crosscut by type III (Fig. 4C–D). Type I fracture-filling calcite occurs as fine crystals and type II and type III fracture-filling as fine to coarse euhedral crystals. Under cathodoluminescence (CL), type I calcite is dull red, type II calcite is nonluminescent and has a Mn content of 89 μg g⁻¹ and Fe of 300 μg g⁻¹ in well S65 (Tables 2 and 3), and type III calcite is dull red with Mn of 106 μg g⁻¹ and Fe 200 μg g⁻¹ in well S76 (Fig. 4C–F).

Karst-filling calcite is calcite that has grown in a palaeocave with a diameter more than 6 to 15 mm (Ford & Ewers 1978); it shows giant forms with crystal sizes from about 1–5 mm (Fig. 4B) and were found in the Lower to Middle Ordovician from wells S65, S72, S75, and S85 with a thickness up to 6 m. The calcites have two different CL responses: nonluminescent CL in wells S65 and S75 with Mn from 83 to 91 l (n = 9, Table 2) and Fe from 400 to 700 μg g⁻¹, and dull red – orange yellow CL in wells S72, S78, and S85 with Mn 232 μg g⁻¹ and Fe from 498 to 797 μg g⁻¹ (Fig. 4C, D–G).

Barite occurs as tabular, vug-fillings, and crosscuts karst-filling giant calcite crystals (Fig. 4K).

Interparticle calcite cements are present in three stages. Stage I-1 calcite is cloudy, fibrous or radial fibrous and nonluminescent (Fig. 4M, N); this type of calcite has been reported from normal marine diagenetic environments (Moore 2001). Stage I-2 calcite is bladed and granular and nonluminescent (Fig. 4M, N); this type of calcite has been reported from normal marine diagenetic environments (Moore 2001). Stage I-3 calcite is dull red with Mn of 106 l in well S65 (Fig. 4O, P). Stage I-1 calcite was infrequently followed by stage I-2 calcites. Stage II occurs as blocky crystals (>0.1 mm) in the center of pores and dull red CL (Fig. 4O, P). Stage III calcite occurs as coarse crystals and is nonluminescent under CL.

### Homogenization temperature (HT) and salinity

Seventeen samples were doubly polished and analyzed for fluid inclusions. Abundant fluid inclusions were observed in fracture-, karst-fillings and calcite cements (collectively called diagenetic calcite). Most of the inclusions occur in planar arrays along growth banding and appear to be primary and therefore were probably trapped during primary crystal growth of the minerals. Some of the inclusions are distributed across CL-defined growth banding and thus are secondary. Although some monophase, liquid aqueous inclusions were observed in type I fracture-filling calcite and late calcite fluid-inclusion assemblages (FIAs), most of the fluid inclusions are 2-phase aqueous vapor–liquid. In the following section, only aqueous 2-phase primary inclusions were measured for homogenization temperatures and salinities.

The type I fracture-filling calcite contains a few fluid inclusions. The fluid inclusions occur mainly as single-phase aqueous inclusions and have sizes <4 μm in general, which are too small to be measured for salinities. Small proportions of the fluid inclusions occur as aqueous 2-phase inclusions and have homogenization temperatures ranging from 57 to 83.4°C (n = 9). None of the fluid inclusions show UV fluorescence revealing that there was no petroleum present at the time these cements grew.

Type II fracture-filling calcite contains abundant single-phase aqueous and vapor–liquid 2-phase fluid inclusions. The latter fluid inclusions have low vapor to liquid ratios (<15%) and homogenization temperatures from 105.8 to 178.7°C (n = 25) and salinities from 4.0 to 10.9 wt% NaCl equiv (n = 8). A small fraction of the fluid inclusions show orange to yellow UV fluorescence emission colors.

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### Table 2 Mn and Fe contents of different calcites.

<table>
<thead>
<tr>
<th>Well</th>
<th>Depth (m)</th>
<th>Occurrence</th>
<th>Mn (μg g⁻¹)</th>
<th>Fe (μg g⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S65</td>
<td>5732.21</td>
<td>Frac. Cc-2</td>
<td>89</td>
<td>300</td>
</tr>
<tr>
<td>S76</td>
<td>5744.8</td>
<td>Frac. Cc-3</td>
<td>106</td>
<td>200</td>
</tr>
<tr>
<td>S85</td>
<td>5964.6</td>
<td>Frac. Cc-1</td>
<td>232</td>
<td>498</td>
</tr>
<tr>
<td>S78</td>
<td>5329.2</td>
<td>Karst Cc-1</td>
<td>232</td>
<td>797</td>
</tr>
<tr>
<td>S65</td>
<td>5532.79</td>
<td>Karst Cc-2</td>
<td>83</td>
<td>700</td>
</tr>
<tr>
<td>S65</td>
<td>5732.24</td>
<td>Karst Cc-2</td>
<td>91</td>
<td>400</td>
</tr>
</tbody>
</table>

### Table 3 Sr contents, ⁸⁷Sr/⁸⁶Sr, homogenization temperatures and salinities of fluid inclusions and CL colors of different cements.

<table>
<thead>
<tr>
<th>Cements</th>
<th>Sr contents (μg g⁻¹)</th>
<th>⁸⁷Sr/⁸⁶Sr</th>
<th>Homogenization temperatures (°C)</th>
<th>Salinities (wt% equiv. NaCl)</th>
<th>CL colors</th>
</tr>
</thead>
</table>
| Frac. Cc-1 | 59.2–99.9 | 0.7087–0.7096 | 57–83.4 | - | -
| Frac. Cc-2 | 204.3–648.9 | 0.7090–0.7099 | 105.8–178.7 | 4.0–10.9 | Dull red
| Frac. Cc-3 | 111.2–158.5 | 0.7090–0.7096 | 63.4–121.1 | 3.7–8.6 | Nonluminescent
| Karst Cc-1 | 101.0–151.0 | 0.7091–0.7099 | 65.9–117.7 | 3.2–9.0 | Dull red to orange yellow
| Karst Cc-2 | 223.8–1091.0 | 0.7091–0.7097 | 110.2–187.1 | 0.5–9.5 | Nonluminescent
| Cement -1-1 | - | - | - | - | -
| Cement -1-2 | - | - | - | - | Nonluminescent
| Cement -2 | 59.5 | - | 57–107.9 | 3.6–7.2 | Red to orange yellow
| Cement -3 | 161.5 | - | 134.6–198.9 | 3.7–11.5 | Nonluminescent
| Barite | - | - | 120–154 | 15.0–22.4 | -
| Fluorite | - | - | 84–116 | 18.6–20 | -

*No measurement available.

From all-liquid fluid inclusions.
suggesting that some low to moderate maturity oil was present at the time these minerals grew.

Type III fracture-filling calcite contains only a few fluid inclusions, dominated by vapor-liquid 2-phase fluid inclusions with some gas-phase fluid inclusions. The fluid inclusions have regular shapes and show higher vapor to liquid ratios (20–30%) and homogenization temperatures from 63.4 to 121.1°C (n = 30), and salinities from 3.7 to 8.6 wt% NaCl equiv (n = 5). Associated with 2-phase aqueous inclusions are abundant oil inclusions, which have yellow to blue-white UV fluorescence emission colors.

Karst-filling, giant calcite crystal with dull red to orange yellow CL contains abundant monophase, liquid fluid inclusions and small amounts of 2-phase aqueous fluid inclusions with regular to irregular shapes. Oil-filled fluid inclusions were only rarely observed and showed orange to yellow UV fluorescence. The calcite shows a wide homogenization temperature range between 65.9 and 117.7°C (n = 49, Fig. 5) and wide salinities from 3.4 to 9.0 wt% NaCl equiv.

Nonluminescent karst-filling calcite contains less abundant fluid inclusions. The fluid inclusions are regularly shaped and dominated by 2-phase aqueous fluid inclusions with vapor to liquid ratios from 5% to 40% and have homogenization temperatures from 110.2 to 187.1°C (n = 60, Fig. 5) and salinities from 4.2 to 9.5 wt% NaCl equiv (n = 35, Fig. 4). The fluid inclusions are closely associated with abundant petroleum fluid inclusions with yellow to blue-white UV fluorescence emission colors.

Karst-filling, giant calcites in the Lower Ordovician in well S75 show four growth zones:

1. Aqueous fluid inclusions in the innermost zone have a vapor to liquid ratio of <15%, sizes of 3 to 11 μm, homogenization temperatures mainly from 123 to 140°C (n = 7), and salinities from 1.4 to 9.2% (n = 5).

2. Aqueous fluid inclusions in the second zone are abundant and have sizes from 3 to 14 μm, vapor to liquid ratio <15% in general, homogenization temperatures from 148 to 160°C, and salinities from 0.7 to 5.0 wt% NaCl.

![Fig. 5. Histograms showing homogenization temperatures and salinities measured from fluid inclusions of fracture-, karst- and interparticle cement from the Ordovician.](image-url)
(3) Aqueous fluid inclusions in the third zone are dominated by 2-phase vapor–liquid fluid inclusions with small numbers of gas-phase fluid inclusions. Most of the fluid inclusions have vapor to liquid ratios <15% and 3 to 14 µm in size. The fluid inclusions have a wide range of homogenization temperatures from 117 to 140°C (n = 10) and salinities from 0.5 to 3.4 wt% NaCl (n = 4).

(4) Aqueous fluid inclusions in the outermost zone have sizes from 3 to 6 µm. Most of the fluid inclusions are all-liquid and only a few occur as gas–liquid fluid inclusions. The vapor–liquid fluid inclusions have homogenization temperatures from 165 to 180°C (n = 3) and salinities from 0.7 to 1.2 wt% NaCl (n = 4).

Giant form calcite from innermost zone to outer zone in well S75 have homogenization temperatures varying from 123 to 140°C, 148 to 160°C to 117 to 140°C, and salinities mostly less than present seawater (3.5 wt%).

No measurable fluid inclusions were observed in stage 1–1 and 1–2 calcite cements (Cement 1–1 and Cement 1–2). Fluid inclusions in stage II calcite cements (Cement-2) have sizes from 4 to 10 µm, and show homogenization temperatures from 57 to 107.9°C (n = 27) and salinities from 3.6 to 7.2 wt% NaCl (n = 7). Stage III cements (Cement-3) show high homogenization temperatures from 134.6 to 198.9°C (n = 12) and salinities from 3.7 to 11.5 wt% NaCl (n = 9) (Fig. 4, Table 3).

Large oil inclusions (up to 50 µm) are ubiquitous in barite (Fig. 4I) and only a few small aqueous vapor–liquid inclusions are present. Barite shows a narrow homogenization temperature range from 120 to 154°C (n = 14) and salinities from 15.0 to 22.4 wt% NaCl (n = 8) (Fig. 5). Coexisting with barite is fluorite with homogenization temperatures of 84–116°C and salinities of 18.6–20.0 wt% (n = 6).

Relationship between homogenization temperatures and salinities of fluid inclusions show that an increase in homogenization temperatures and salinities from Karst Cc-1 and Frac. Cc-3, cement -2 to fluorite and barite. Frac. Cc-2, cement -3 and Karst Cc-2 have a similarly wide homogenization temperatures range, but Karst Cc-2 show significantly lower salinities (<3.5 wt%) than Frac. Cc-2 and cement -3 (Fig. 6).

**Sr, 87Sr/86Sr, δ18O and δ13C of fracture-fillings**

The trace element and isotopic compositions of the calcite are listed in Table 4. Twenty fracture-filling calcite crystals and karst-filling giant calcite crystals from the Ordovician have 87Sr/86Sr ratios from 0.7085 to 0.7099, most of which are significantly higher than bulk carbonate and contemporary seawater 87Sr/86Sr ratios (0.7060–0.7090) (Fig. 7).

Type I fracture-filling calcite has low Sr contents from 59.2 to 111.1 µg g⁻¹ (n = 4) and low Ba, Pb, and Zn contents. Type II fracture-filling calcite has Sr content varying between 92.6 and 648.9 µg g⁻¹ (n = 8) and Ba contents up to 12760 µg g⁻¹. Karst-filling, giant form calcite has Sr contents mainly from 101 to 244 µg g⁻¹ with a maximum of 1091 µg g⁻¹ (n = 6). Two calcite cement samples have Sr contents of 59.5 µg g⁻¹ and 161.5 µg g⁻¹, respectively.

Most of the diagenetic calcite samples show more negative carbon isotopes (as low as ~8.3‰) than bulk carbonates in the Ordovician in the basin (Jiang et al. 2001). Giant form calcite from well T417 has light δ13C values (~3.7‰ and ~5.9‰) and light δ18O values at about ~11.0‰ (n = 2). These values are close to the ~1.7 to ~5.1‰ for δ13C values and ~13.7 to ~16.6‰ for δ18O values of giant calcite from well S85, respectively (Qian et al. 2009). δ18O values for the calcites range from ~8.3‰ to ~16.8‰. There is a positive correlation between δ13C and δ18O values (Fig. 8A) and negative correlation relationships of 87Sr/86Sr ratios to δ18O and δ13C values for the calcite (Fig. 8A).

**Chemistry, δ13C_HCO₃⁻ and 87Sr/86Sr of formation water**

Total dissolved solids (TDS) of formation waters in the Tabei area range from 61 000 to 297 200 mg l⁻¹.
Formation waters with relatively high TDS occur mainly in the areas of wells S67-S79-S65-T601-S88-S85 and T204-T205-TS1 (>160 000 mg l\(^{-1}\)) in the southwest of the Tahe area, and low TDS waters are mostly present in Lunnan area (<160 000 mg l\(^{-1}\)) in the northeast (palaeohighs) (Fig. 9).

Table 4 Trace elements contents, and Sr, C and O isotopic compositions of fracture- and Karst-filling calcite and cement.

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Well</th>
<th>Formation</th>
<th>Depth (m)</th>
<th>Occurrence</th>
<th>Zn (µg g(^{-1}))</th>
<th>Sr (µg g(^{-1}))</th>
<th>Ba (µg g(^{-1}))</th>
<th>Pb (µg g(^{-1}))</th>
<th>(\delta^{13}C) (‰)</th>
<th>(\delta^{18}O) (‰)</th>
<th>(87\text{Sr}/86\text{Sr})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S106-4</td>
<td>O(_{1yj})</td>
<td>6001.5</td>
<td>Frac. Cc-1</td>
<td>2.16</td>
<td>111.18</td>
<td>13.25</td>
<td>0.82</td>
<td>-3.21</td>
<td>-12.77</td>
<td>0.70936</td>
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<tr>
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<td>O(_{1yj})</td>
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<td>99.53</td>
<td>28.04</td>
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<td>4.26</td>
<td>14.17</td>
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</tr>
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<td>99.53</td>
<td>28.04</td>
<td>0.56</td>
<td>4.26</td>
<td>14.17</td>
<td>0.70871</td>
</tr>
<tr>
<td>4</td>
<td>T739</td>
<td>O(_{1yj})</td>
<td>6141</td>
<td>Frac. Cc-1</td>
<td>2.15</td>
<td>59.21</td>
<td>11.24</td>
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<td>-</td>
<td>-</td>
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<td>Frac. Cc-2</td>
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<td>414.37</td>
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<td>5.36</td>
<td>-14.91</td>
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<td>158.51</td>
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<td>648.90</td>
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<td>Frac. Cc-2</td>
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<td>Frac. Cc-3</td>
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<td>5560.1</td>
<td>Frac. Cc-2</td>
<td>-</td>
<td>-</td>
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<td>Frac. Cc-2</td>
<td>2.24</td>
<td>126.22</td>
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<tr>
<td>18</td>
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<td>O(_{1yj})</td>
<td>5506.92</td>
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<td>223.83</td>
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<td>Cement-2</td>
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<td>10.74</td>
<td>0.28</td>
<td>-</td>
<td>-</td>
<td>0.70899</td>
</tr>
</tbody>
</table>

*No measurement.

Frac. Cc represents fracture-filling calcite; Karst Cc represents karst-filling giant crystalline calcite.

Fig. 7. \(87\text{Sr}/86\text{Sr}\) ratios of fracture-, and karst-filling calcite and present formation waters in comparison with bulk carbonate rocks in the Ordovician (Jiang et al. 2001) and seawater of Ordovician age (Burke et al. 1982).

DISCUSSION

Re-equilibration of fluid inclusions during subsequent heating events?

Several investigators (e.g. Goldstein 1986; Burruss 1987; Prezbindowski & Larese 1987) have suggested that homogenization temperatures of fluid inclusions in carbonates (specifically calcite) can be affected by re-equilibration during later heating events. Their studies indicate that re-equilibration may cause aqueous inclusions to yield a

\[ \delta^{13}C_{\text{HCO}_3} \]

values of the 24 formation water samples range from 6‰ to 13.8‰. The \(\delta^{13}C_{\text{HCO}_3}\) values of the water samples from different wells show that, compared to calcite samples, there is a linear positive correlation relationship between \(\delta^{13}C\) and \(\delta^{18}O\) values and a negative relationship between \(87\text{Sr}/86\text{Sr}\) ratios and \(\delta^{13}C_{\text{HCO}_3}\) values for the water samples (Fig. 8B).
poor record of their low-temperature history, but a useful record of the maximum temperature experienced by the host rock (Burruss 1987).

In the Tahe oilfield, most of the fluid inclusions are likely not re-equilibrated from existing inclusions caused by stretching when crystal growth and fluid inclusion assemblages are considered. This proposal is supported by the following lines of evidence on the basis of criterions of Goldstein & Reynolds (1994) and Worden et al. (1995) (i) most of the fluid inclusions have sizes in a narrow range and are small, mainly from 4 to 13 μm, (ii) no obvious correlation was observed between the size of an inclusion and its homogenization temperature, (iii) in giant calcite crystals from well S75, the inclusions can be segregated petrographically into different fluid-inclusion assemblages that each have different homogenization temperature ranges. HT ranges in the innermost zone and second zone are less than 15°C and thus are considered to be consistent (Goldstein & Reynolds 1994). Fluid inclusions in the outermost zone may have resulted from necking down. This is supported by two lines of evidence, (i) the fluid inclusions have significantly smaller sizes in this zone than in the other zones, and (ii) vapor–liquid 2-phase fluid inclusions with significantly higher homogenization temperatures (165–180°C) than those in other zones (123–160°C); however, the 2-phase fluid inclusions in the outermost zone coexist with monophase liquid fluid inclusions that are considered to have homogenization temperatures lower than 50°C (Goldstein & Reynolds 1994), and thus, homogenization temperatures in this zone are considered to be inconsistent (Goldstein & Reynolds 1994). Fluid inclusions in the outermost zone are ruled out for further discussion.

**Origin of 12C- and 87Sr-rich water**

Almost all of the 87Sr/86Sr measurements from brines and diagenetic calcite in the Tahe oilfield are higher than those of the Ordovician limestone and underlying Cambrian dolomite in the basin. This evidence indicates that
radiogenic Sr may have been derived from continental aluminosilicates, but not from carbonates in situ. $^{87}$Sr-rich water may have been derived from meteoric water which infiltrated the clastic rock in the surface, or from hyperthermal water which obtained $^{87}$Sr from the deeper strata in the basin.

$^{12}$C-rich HCO$_3^-$ may have a similar source to the radiogenic Sr as indicated by the negative correlation relationship between $^{87}$Sr/$^{86}$Sr ratios and $^{13}$C values of diagenetic calcite and formation waters. Isotopically light carbon in Frac. Cc-2 calcite (down to $-8.3_{\text{ppm}}$) and formation water ($-6.0_{\text{ppm}}$ to $-13.8_{\text{ppm}}$) were most likely derived from oxidation of organic matter (OM, i.e. petroleum and/or kerogen), perhaps by thermochemical sulfate reduction (TSR), and less likely from meteoric diagenetic environments. $^{13}$C values of meteoric diagenetic fluids are determined by the ratios of the amount of dissolved limestone and the amount of carbon from soil gas and have been shown to range from $11$ to $+1_{\text{ppm}}$; the calcites precipitated from these fluids have $^{13}$C values of $-10$ to $+2_{\text{ppm}}$ (Allan & Mathews 1982). These calcites show constant $^{18}$O and variable $^{13}$C values (Lohmann 1988). In the case of the Tahe area, (i) some of the formation waters have $^{13}$C$_{\text{HCO}_3^-}$ values lighter than that of the meteoric diagenetic fluids; (ii) the calcites analyzed do not show constant $^{18}$O values relative to their $^{13}$C values; and (iii) salinities of Frac. Cc-2 calcite with the lightest carbon range from 4.0 to 10.0 wt%, and salinities of the formation waters range from 42 530 mg l$^{-1}$ to 232 430 mg l$^{-1}$ with an average of 214 780 mg l$^{-1}$ ($n = 20$); these salinities are significantly higher than modern seawater (3.5 wt%). All these three lines of evidence argue against a source of isotopically light carbon coming mainly from meteoric diagenetic fluids. In contrast, isotopically light carbon may have been derived from organic matter oxidation possibly by TSR (Cai et al. 2003, 2004). That is, $^{87}$Sr-rich water has been derived from the area where OM was oxidized, or OM was oxidized during the flow of $^{87}$Sr-rich water.

The $^{87}$Sr-rich water may have experienced high temperatures, as indicated by the fact that some calcite with high $^{87}$Sr/$^{86}$Sr ratios shows very light $^{13}$C values. Calcite with light $^{18}$O values may have precipitated either from low temperatures and meteoric water environment, or from an environment with relatively high temperatures and heavier $^{18}$O values. Palaeo-meteoric water has been shown to have heavier $^{18}$O and $^D$ values than present surface water as typified by Kongque River ($^D = -72_{\text{ppm}}$, $^{18}$O = $-11.5_{\text{ppm}}$; Cai 2000; Cai et al. 2001a). For example, meteoric water of Devonian age was shown to have a $^{18}$O value of $-5.5_{\text{ppm}}$ and $^D$ of $-35_{\text{ppm}}$ in the Tarim Basin (Cai et al. 2001a). The latitude of the Tarim area during the Paleozoic has been shown to be less than 30°N, which are lower than present-day latitude of 41.5°N (Fang et al. 1996). Thus, oxygen isotope values of freshwater of Permian age (Hercynian orogeny) can be estimated to be less negative than $-9.2_{\text{ppm}}$ PDB (or 14.6% SMOW) (Cai 2000). It is unlikely for relatively light $^{18}$O values (down to $-16.8_{\text{ppm}}$ PDB or 13.6% SMOW) of calcite to have been derived from the meteoric water of Permian age with temperatures <50°C, based on the oxygen isotope

Fig. 9. Mapped present formation water total dissolved solids (TDS, in g l$^{-1}$) for the Ordovician with the distribution of different types of oils and water.

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equilibrium fractionation equation between calcite and pure water: \(1000 \ln x = 2.78 \times 10^6/T^2 - 2.89\) (O’Neil et al. 1969) (Fig. 10). This line of argument suggests that at least some of the isotopically light oxygen in diagenetic calcite may have been derived from relatively high-temperature water.

Thus, enrichment in radiogenic Sr, light oxygen isotopes in some present formation water and palaeo-water may have been derived from relatively high-temperature interaction with aluminosilicates in deeper strata.

Isotopically light carbon measured from formation water and some calcite with homogenization temperatures higher than 120°C is most likely derived from TSR by petroleum in deeper strata in this area, as initially proposed by Cai et al. (2009), who has provided supporting evidence, including high H₂S contents in gas composition and gaseous phase fluid inclusions and heavy \(\delta^{34}S\) values (25–29‰) of fracture-filling pyrite and oils. However, no direct evidence indicates the isotopically light carbon and heavy sulfur are genetically linked; thus, the possibility that isotopically light carbon may have been directly derived from kerogen cracking cannot be ruled out.

**Water mixing and cross-formation flow**

Previous studies (Cai et al. 1997 and Jia et al. 2007) have shown that there is mixing between meteoric water and basin water in the Tabei area, based on the relationship between \(6D\) and \(\delta^{18}O\) values.

In this study, basinal water *in situ* or diagenetically altered connate water (Fisher & Boles 1990) is indicated by its \(^{87}Sr/^{86}Sr\) ratios from 0.7085 to 0.7090 inferred from two fracture-filling calcites (Table 4).

![Fig. 10. Cross plot of diagenetic water oxygen isotopes versus homogenization temperature of aqueous inclusions of calcites.](image)

A meteoric water end-member is indicated by three lines of evidence:

1. High \(^{87}Sr/^{86}Sr\) ratio but low Sr concentration (Table 4),
2. Low salinities (<3.5 wt% NaCl) in fluid inclusions in karst-filling giant calcite crystals (Karst Cc-1),
3. Precipitation temperatures below 50°C as inferred from all-liquid fluid inclusions (Goldstein & Reynolds 1994),
4. Generally low Sr, Ba, and Zn concentrations in type I fracture-filling calcite.

Hydrothermal calcite and barite are indicated by their homogenization temperatures about 5–20°C higher than what experienced by the carbonates as indicated by burial and thermal history in well S109 in the south and well S75 in the north (Fig. 2) (e.g. Machel & Lonnee 2002; Cai et al. 2008). Barite, stage III calcite cements, and part of type II fracture-fillings and karst-filling, giant calcite crystals have homogenization temperatures higher than 120°C in the Ordovician in the Tahe area, which were measured on nonreequilibrated or non-necked-down fluid inclusions as discussed in re-equilibration of fluid inclusions during subsequent heating events?

Hydrothermal calcite is rich in \(^{87}Sr\) with \(^{87}Sr/^{86}Sr\) ratios up to 0.7097 and Sr concentrations up to 1091 µg g⁻¹ in well S110 in the south. Thus, the hydrothermal water must have obtained radioactive Sr as well as Ba and Zn from deeper strata by interacting with \(^{87}Sr\)-rich minerals or detrital rocks.

Different from hydrothermal calcite in the south, fluid inclusions of some hydrothermal calcite from wells S75 and S65 in the north are shown to have low salinities but high homogenization temperatures, similar to fluid inclusions from wells S85 and S79 in this area (Qian et al. 2009). Fluid inclusions with high temperatures (120 to 187°C) and low salinities (about 5 wt% equiv. NaCl) were also reported from epigenetic dolomites in southeast Missouri (Shelton et al. 1992). This kind of calcite may have precipitated from a variety of processes:

1. Deeply recycled meteoric water,
2. Mixing of meteoric water with hydrothermal water,
3. Thermochemical sulfate reduction.

Deeply recycled water, i.e. meteoric water, could have flowed down along faults to deep strata and thus became significantly heated. Subsequently, the heated meteoric water underwent upward migration and led to the precipitation of hydrothermal calcite. This model of water flow was previously proposed by Qing & Mountjoy (1992) to explain variation of homogenization temperatures, \(^{87}Sr/^{86}Sr\) and \(\delta^{18}O\) values from saddle dolomite cements from the west toward the east in Western Canada sedimentary basin.

possible for similar model of water flow to have occurred in the two areas.

Alternatively, the hydrothermal calcite in the north may have precipitated from meteoric water mixed with hydrothermal fluids. Reservoirs in the north were covered directly by Carboniferous sediment and must have been infiltrated and thus dissolved by palaeo-meteoric water to some degree, resulting in the formation of karst which was subsequently connected by fractures to form networks (Zhang & Wang 2004; Jing et al. 2005; Qian et al. 2009). Similar karst reservoirs have been reported from around the world (Lohmann 1988; Lucia 1995; Louks 1999; Moore 2001); however, some of the cases have been debated and re-explained as a result of hydrothermal water activity (Qing & Mountjoy 1994; Davies & Smith 2006).

The karstic voids may have been full of meteoric water. Present oils in the Tahe oilfield are produced mainly from reservoirs with karstic voids or vugs connected by fractures at 100–150 m (not more than 230 m) below the Carboniferous–Ordovician unconformity. In the south, Lower Ordovician reservoirs are covered by the Middle and Upper Ordovician and thus much less influenced by palaeo-meteoric water. Consequently, reservoirs in the south have much less karst and smaller amounts of palaeo-meteoric water; thus, the water after mixing with hydrothermal water is expected to have higher salinities in the south than in the north. However, if this model applies, fluid inclusions with highest temperatures are expected to have the highest salinities rather than lowest salinities as found in this area.

The third possibility is that hydrothermal calcite with high homogenization temperatures and low salinities may have precipitated from TSR – derived water. This proposal is supported by the occurrence of TSR in this area (Section Origin of $^{12}$C- and $^{87}$Sr-rich water) and generation of water during TSR as proposed by Worden et al. (1996). Because this kind of calcite has homogenization temperatures significantly higher than temperatures ambient rock experienced, it is possible for $^{87}$Sr-rich hydrothermal water together with TSR-H$_2$S and CO$_2$ to have migrated from deeper strata. Alternatively, elevated temperatures from hydrothermal water activity resulted in TSR and the generation of TSR water in the Ordovician reservoirs. Further study on this aspect is needed.

**Palaeo-water evolution**

It has generally been demonstrated that inclusion oils of higher API gravity and maturity fluoresce in the blue end of the visible spectrum, whereas inclusion oils of lower API gravity and maturity fluoresce in the red region (Burruss et al. 1985; McLimans 1987; Bodnar 1990). Thus, visually determined fluorescence colors of inclusion oils, in combination with petrological observation, aqueous fluid-inclusion data and burial histories of the Tahe oilfield can be used to constrain the precipitation sequence of the diageneric calcite, barite, and fluorite, as is summarized in Fig. 11. Diagenetic water in this area may have evolved as follows.

![Synthetic paragenetic sequence shows main stages in the diagenetic evolution of Ordovician carbonates.](image-url)

The original water was seawater of Early to Middle Ordovician age, from which fibrous calcite precipitated (Cement 1-1). Subsequently, the sediments were exposed to vadose and phreatic zones and the water was diluted by meteoric water, from which bright CL (red to orange yellow) calcite (Cement 1-2) precipitated at <50°C under weak reducing environments (Muchez et al. 1998). During the Silurian to Middle Devonian, the sediments were buried to depths corresponding to temperatures from 57 to 110°C, the diagenetic environment became more reducing and thus more Fe(II) may have been released from detrital rocks, being similar to Ordovician oilfield waters of hydrothermal origin with salinity mainly from underlying Cambrian and pre-Cambrian evaporites and detrital rocks, being similar to Ordovician oilfield waters from Central Tarim (Cai et al. 2001a).

### CONCLUSIONS

1. In the Tahe oilfield, analyses of present formation water, cements, fracture- and karst-fillings and fluid inclusion indicate mixing between three different types of water, that is, local basinal water or diagenetically altered connate water, hydrothermal water, and several episodes of meteoric water influx during development of numerous unconformities.

2. Local basinal water is characterized by $^{87}$Sr/$^{86}$Sr ratios of 0.7085 to 0.7090 inferred from two fracture-filling calcites, relatively heavy $\delta^{13}$C and $\delta^{18}$O.

3. Hydrothermal water was enriched in Ba, $^{87}$Sr, and Zn had temperatures >154°C and salinities >22.4 wt% NaCl equivalent and may have been sourced from Cambrian and pre-Cambrian evaporites and detrital rocks and possibly entered the carbonate rocks during the early Permian.

4. Mixing of the hydrothermal water with basinal water in situ may have resulted in the precipitation of calcite and barite with more radiogenic Sr, lighter carbon and oxygen, and higher Ba and Zn concentrations than bulk limestone.

5. However, it is possible that the hydrothermal water was deeply recycled meteoric water that was heated in deeper strata, or water generated from TSR during hydrothermal water activity. The chemical composition of the hydrothermal water is still to be defined.

6. The meteoric water was $^{87}$Sr-rich but Ba- and Zn-depleted and may have infiltrated the carbonates during at least two periods (the late Devonian and the late Permian), as recorded in karst-filling giant calcite crystals (Karst Cc-2, Karst Cc-2 and Cement-3) suggests a reduced (possibly Fe-rich) water during this period. The reduced water coexisted with high mature oils with yellow to blue-white UV fluorescence emission colors. The chemical composition of the hydrothermal water is still to be defined.

Subsequently, the carbonates were uplifted during the late Permian, and meteoric water of this period may have infiltrated the carbonates as recorded in Frac. Cc-3 calcite with decreasing homogenization temperatures and salinities of fluid inclusions and increasing Mn to Fe ratio (dull red to orange yellow CL colors). Mixing with palaeometeoric water of this and/or later periods (Yanshanian to Himalayan orogenies, Cai et al. 2001a) to different extents may have resulted in large variations in salinity of the oilfield waters with the lowest value in palaeohighs. In the oilfield area, some present oilfield waters have TDS close to salinities of fluid inclusions of barite, suggesting that the oilfield waters are of hydrothermal origin with salinity mainly from underlying Cambrian and pre-Cambrian evaporites and detrital rocks, being similar to Ordovician oilfield waters from Central Tarim (Cai et al. 2001a).
(7) Mixing of palaeometeoric waters of the two periods and later (perhaps of late Cretaceous to Neogene age) with hydrothermal water and local basinal water may have resulted in present-day oilfield water salinity variations.

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REFERENCES


