## Degree of Brine Evaporation and Origin of the Mengyejing Potash Deposit: Evidence from Fluid Inclusions in Halite

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Abstract: The Mengyejing potash deposit is located in the southern port of the Simao Basin, Yunnan Province, and is hosted in mid-Cretaceous strata. The chemical compositions of fluid inclusions in halite crystals, collected from the level-610 adit in the deposit, were analysed by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). The results show that the brine is of the Na-K-Mg-Ca-Cl type and has K concentrations that are distinctly higher than those of Mg and Ca, unlike normal brines associated with Cretaceous halite. The high K concentrations indicate that the degree of evaporation of the ancient Mengyejing saline lake was very high, reaching the sylvite deposition stage but rarely reaching the carnallite deposition stage. The trajectory of the H and O isotopic compositions of the brines in the halite-hosted fluid inclusions corresponds to intense evaporation, indicating that the net evaporation exceeded the net inflow of brines. These brine compositions in halite-hosted fluid inclusions were likely formed by the dissolution of previously deposited K-bearing minerals by fresh continental and/or seawater, forming a type of modified seawater, with deep hydrothermal fluids potentially supplying additional potassium. The basin likely experienced multiple seawater incursion, dissolution and redeposition events in a high-temperature environment with high evaporation rates.

Key words: Cretaceous, halite fluid inclusions, H and O isotopic compositions, brine chemical compositions, Mengyejing potash deposit, Yunnan Province

## **1** Introduction

The Mengyejing potash deposit is located in the southern port of the Simao Basin, Yunnan Province (Fig. 1). It has aroused continuous and long-term disputes, particularly concerning the origin of the deposit. According to the findings of Qu Yihua et al. (1998), the Mengyejing potash deposit formed in a continental environment, and these findings are supported by evidence from sedimentary characteristics, facies associations, and fossils. Nevertheless, the geochemical features of rock salts (e.g., the high bromide content of the halite) in the Mengyejing potash deposit and mineral assemblages (e.g., a lack of mirabilite minerals and a dominance of chloride minerals) indicate that the potash deposit appears to be

The Simao Basin is adjacent to the Khorat Basin in Thailand and the Sakon Nakhon Basin in Laos, both of which contain giant potash deposits within continental red beds (El Tabakh, 1999). These three basins were regarded

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very closely related to seawater. Previous researchers proposed a variety of origins for the Mengyejing potash deposit, such as evaporated seawater mixed with hydrothermal fluids (Xia Wenjie and Li Xiuhua, 1983); hydrothermal fluids formed from deep circulation of seawater (Shuai Kaiye, 1987); remnant ancient seawater with additional sources from continental waters, hydrothermal fluids, weathering products of volcanic rocks and ancient salts (Zhang Congwei et al., 2010); and the interaction between an ore body and Jurassic saltbearing strata (Zheng Mianping et al., 2014), among others (see Table 1). Thus, there is no consensus regarding the genesis of the potash deposit.

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Fig. 1. Major tectonic units in the SE Tibetan Plateau (after Metcalfe, 2011) and regional geological setting of the study area.

SCB: South China Block; QSB: Qamdo-Simao Block.

as a series of evaporite basins that shared the same tectonic zone, ore-forming age and provenance (Wang et al., 2014; IMR, CAGS, 2015; Wang et al., 2015). Compared with the giant potash deposits in the Khorat and Sakon Nakhon basins, both of which contain a large amount of carnallite, bischofite and tachyhydrite, the Mengyejing potash deposit consists mainly of sylvite, with little carnallite. This difference indicates that the brines forming the giant potash deposits in the Khorat and Sakon Nakhon basins were more concentrated than those forming the Mengyejing potash deposit (Qu Yihua, 1997).

Fluid inclusions in halite can record the composition of the brine fluids from which the halite precipitated, such as evaporated seawater or saline lake water (Kovalevich et al., 1998; Lowenstein et al., 2001; Timofeeff et al., 2001). Analyses of primary fluid inclusions supply the most reliable and direct information about the chemical composition of the brine from which the salt crystallized (Holser, 1979a; 1979b; Hardie, 1984). In this paper, we report detailed compositional data on single-phrase fluid inclusions that were analysed using the laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) method. These data provide key evidence about the origins of the parent brines of the Mengyejing potash deposit. The H and O isotopic compositions and the homogenization temperatures of fluid inclusions in halite can provide key information on the paleoclimate conditions and degree of brine evaporation (Roberts and Spencer, 1995; Benison and Goldstein, 1999; Zhang Hua et al., 2015; Li Minghui et al., 2016).

### 2 Geological Background

The Mengyejing potash deposit is limited to a region covering 3.5 square kilometres within the Simao Basin (No. 16 Geological Brigade of Yunnan Province, 1980), which is located in the southern part of the Qamdo-Simao block (Fig. 1). The block is bounded to the west by the Jingdong and Nan suture zone and to the east and south by the Ailaoshan and Song Ma sutures, respectively (Wang et al., 2000; Metcalfe, 2006; 2009; 2011; Sone and Metcalfe, 2008), and the Ailaoshan and Song Ma sutures is the boundary between the South China block and the Indochina block (Bui et al., 2016). After the Hercynian orogeny, the study area was elevated and then denuded in the Early Triassic. Rifting began on the eastern and western sides of the Simao Basin in the mid-Triassic, followed by a marine transgression. The Simao Basin became a Mesozoic-Cenozoic continental margin rift basin

Table 1 Different opinions on the genesis of the Mengyejing potash deposit

Viewpoints	Evidence	References
Evaporation of seawater mixed with hydrothermal fluids	Characteristics of salt minerals, trace elements, and sulfur isotopes indicate that the brine was mainly derived from seawater. Trace metals and volcanic rock intrusions in the same sequence of potash deposits indicate hydrothermal fluids could have provided subordinate materials	Xia Wenjie and Li Xiuhua, 1983
Deep hydrothermal circulation of seawater as the source of brines, which evolved into chloride-type	Could not find evidence of the existence of a transgression channel; several ephemeral seawater intrusions could not lead to evaporite deposits hundreds of metres in thickness; the mineral associations and ratios between minerals are much different from the original seawater.	Shuai Kaiye, 1987
Remnant ancient seawater supplemented with continental waters, hydrothermal fluids, volcanic rocks, ancient salt	Br geochemistry; C, B, Sr, S, Cl isotopes; heavy metals; widespread tuff beds co-exist with anhydrite in salt-bearing sequence and ancient salt in older layers.	Zhang Congwei et al., 2010
In addition to seawater, deep hydrothermal fluids played an important role in the formation of the potash deposit	The bromide content is higher than $200 \times 10^{-6} \ \mu g/g$ ; a small amount of glauconite, an indicative marine mineral, is present in the Pashahe formation, which underlies the Mengyejing formation, proving the marine origin of this deposit. Fracture-filling comblainite is very common in salt-bearing sequences, demonstrating that the elements of Cu, Co and Ni could have been provided by deep hydrothermal fluids.	Gao Xiang et al., 2013
Potash ore body interacted with salt-bearing strata in a Jurassic formation	Geological survey, sedimentary facies, salt structures, hydrochemistry, physical exploration and drill holes	Zheng Mianping et al., 2014

during the collision between the Eurasian and Indian plates (Liao Zongting and Chen Yuekun, 2005). The entire Mesozoic-Cenozoic sedimentary fill consists of a thick sequence (~10,000 m) of red beds that evolved from marine and marine-continental sediments in the Triassic period to continental sediments in the Jurassic-Cretaceous (Shuai Kaiye, 2000). These red beds are unconformably overlain by the Late Cretaceous continental evaporites and clastic deposits of the Mengyejing Formation (Chen et al., 1995). The Mengyejing Formation consists of the following layers, from bottom to top (Fig. 2): (1) red muddy conglomerate, fine-grained sandstone and evaporites with brown muddy fine-grained sandstone; (2) purplish fine-grained sandstone and mudstone; and (3) purplish conglomerate and medium- to fine-grained sandstone (Qu Yihua et al., 1998; Li et al., 2015).

## **3** Materials and Methods

Thirty-eight samples, consisting mainly of halite and a few potash minerals, were collected and examined from the 610-level adit in the Mengyejing potash deposit (Fig. 2 and Fig. 3). Suitable fluid inclusions, defined as those larger than 50 microns, were found in two halite samples. Potash mineral samples with very fine crystals were not suitable for this analysis.

Most of the halite crystals are grey in colour and euhedral (Fig. 3a) to anhedral granular in form (Fig. 3b). All the fluid inclusions in the halite have a cubic shape. The fluid inclusions are of two types: (1) single-phase (liquid) inclusions (Fig. 3c) or (2) two-phase (liquid and vapour) inclusions (Fig. 3d). Most of the fluid inclusions are single phase. The fluid inclusions range in size from several microns to 60 microns and are evenly distributed throughout clear halite crystals. According to Kovalevich et al. (1998), three types of halite are usually distinguished based on the crystal habits and fluid inclusion distribution. The first type includes chevron or hopper crystals or their relics; such crystals in primary-bedded evaporites are the only sedimentary halite that contains inclusions that fully record the chemical composition of the sedimentary brine. The second type is represented by transparent portions of halite crystals in primary-bedded halite and occasionally contains large (>250  $\mu$ m) brine inclusions. The third type of halite is represented by wholly transparent halite crystals with large (often >250 µm) inclusions, which formed during the recrystallization of sedimentary halite during different post-sedimentary stages. Fluid inclusions in recrystallized salt minerals record the conditions at which recrystallization occurred (Mernagh, 2015). The two-phase fluid inclusions are interpreted to have resulted from the modification of originally single-phase inclusions, despite the small size of the fluid inclusions (Goldstein, 2001), or from the entrapment of fluid during recrystallization (Chipley and Kyser, 1989).

We utilized an Element 2 plasma mass spectrometer (Germany Finnian) interfaced with a UP 213 laser (New Wave) to analyse the concentrations of major ions  $(K^+)$ .  $Ca^{2+}$ ,  $Mg^{2+}$  and  $SO_4^{2-}$  but not  $Na^+$  and  $Cl^-$ ) in the fluid inclusions, following the same method described by Sun Xiaohong et al. (2013). The laser wavelength was 213 nm, and the pulse width was 4 ns. Several single crystal slices were obtained from the halite. The ICP-MS parameters were optimized before the analyses for optimal sensitivity and stability. The spot size and ablation time varied for different samples. The preablation laser warm-up took approximately 15 s. The signal acquisition time was 60 s, and the signal measurement of the ICP-MS was controlled at a rate of 60 laser firings per minute. External and internal standards were used for calibration. Solutions with different concentrations of K, Ca, Mg, Sr, Rb, Li and Br were sealed into quartz microcapillary tubes to create artificial fluid inclusions, which were placed in the laser ablation sample chamber together with the untested samples as the external standard. The Na content was selected to be the internal standard in halite inclusions, which is 39.34% according to the standard theoretical value. This technique can analyse fluid inclusions greater than 30 microns in size; however, to obtain optimal results, the inclusions close to 50 microns in diameter were analysed.

Twenty-six halite samples were analysed to determine the H and O isotopic compositions of the fluid inclusions in the halite. For the H isotope analysis, thermal decomposition of the fluid inclusions at a temperature of 550°C was used to extract the brines. H<sub>2</sub> was obtained by exposing the brines to zinc. For the O isotope analysis, the brines in the halite inclusions were reacted with BrF5 in a constant ambient temperature of 300°C under vacuum for 20 minutes to produce O<sub>2</sub>, which was then purified via freezing. The purified O2 was reacted with carbon at 700°C to form CO<sub>2</sub>, which was then used in the O isotopic composition analysis. The H and O isotope analyses were performed using a MAT-253 gas isotope ratio mass spectrometer. The O isotope standards used for analysis were GBW-04409 and GBW-04410, with theoretical values of 11.11±0.06‰ and -1.75±0.08‰, respectively. The analytical precisions were  $\pm 2\%$  for  $\delta D$ and  $\pm 0.2\%$  for  $\delta^{18}$ O, respectively. Here,  $\delta^{18}$ O and  $\delta$ D are respectively the deviations in parts per thousand of the ratios <sup>18</sup>O/<sup>16</sup>O and <sup>2</sup>H/<sup>1</sup>H of the material analysed with respect to the international standard VSMOW (Vienna Standard Mean Ocean Water).



Fig. 2. Lithostratigraphic column of the Mengyejing Formation from which samples were collected (modified from Wang et al., 2014).



Fig. 3. Characteristics of fluid inclusions in halite from the Mengyejing potash deposit. (a), Lath-shaped euhedral halite crystal; (b), Relatively large subhedral to anhedral halite crystals; (c), Single-phase fluid inclusions; (d), Two-phase fluid inclusions.

## 4 Results

# 4.1 H and O isotopic compositions of the fluid inclusions

The H and O isotopic compositions of fluid inclusions in halite from the Mengyejing potash deposit are shown in Table 2 and are plotted in Fig. 4. All samples have  $\delta D_{VSMOW}$  values ranging from -86.5‰ to -44.9‰ and  $\delta^{18}O_{VSMOW}$  values ranging from 0.3‰ to 8.2‰, with average values of -72.4‰ and 3.5‰, respectively. As shown in Fig. 4, the isotopic compositions of the fluid inclusions in the Mengyejing potash deposit lie to the right of the meteoric water line and modern seawater, which indicates that the brines in halite fluid inclusions are enriched in <sup>18</sup>O relative to Standard Mean Ocean Water and meteoric water.

#### 4.2 Chemical compositions of fluid inclusions

The cation concentrations of the fluid inclusions in halite are listed in Table 3. The fluid inclusions are quite scattered in composition, but they are of the Na-Mg-K-Ca-Cl type. The K concentrations of the fluid inclusions in samples MY17 and MY101 range from 20299 to 55984 mg/l and from 16764 to 66382 mg/l, with average values of 42739 mg/l and 33266 mg/l, respectively. The Mg concentrations ranged from 927 to 20011 mg/l and from 8876 to 15713 mg/l, with averages of 10404 mg/l and 12669 mg/l, respectively. The Ca concentrations ranged from 485 to 9057 mg/l and from 4545 to 22191 mg/l, with averages of 5011 mg/l and 10758 mg/l, respectively. The calculation errors are relatively high for the Rb concentrations due to the low signal intensities. The fluid inclusions contain relatively high concentrations of Ca, and their SO<sub>4</sub> concentration is below the detection limit of LA-ICP-MS. These fluid composition characteristics are consistent with the absence of magnesium sulfate minerals and with the presence of carnallite and sylvite in the potash deposit. Furthermore. Mengyejing these characteristics are similar to those found in the giant potash deposit in the Khorat Basin, Thailand, which is believed to have formed from the same sources as the Mengyejing potash deposit (Qu Yihua, 1997).

## **5** Discussion

#### 5.1 Paleo-evaporation conditions

Evaporites, especially potash minerals, form under arid climatic conditions, where the net evaporation (NE) exceeds the net inflow (NF) of solute-bearing waters (Hardie, 1990). Therefore, the formation of potash-bearing evaporites requires not only an arid environment but also progressively increasing degrees of evaporation reaching Table 2 Hydrogen and oxygen isotopic compositions of fluid inclusions in halite from the Mengyejing potash deposit

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Sample name	$\delta^{18}$ O-VPDB	$\delta^{18}$ O-VSMOW	$\delta$ D-VSMOW
670-S1-10	-29.7	0.3	-78.3
670-S1-05	-29	1	-80.2
670-S1-36	-27.6	2.5	-64.4
670-S1-12	-26	4.1	-77.3
670-S1-37	-26.9	3.2	-70.7
670-S1-14	-25.8	4.4	-65.2
670-S1-21	-27.3	2.7	-69.5
670-S1-25	-27.9	2.1	-68.4
628-S1-10	-25.8	4.3	-72.8
628-S1-02	-27.2	2.8	-68.9
628-S1-08	-25.6	4.5	-75.1
628-S1-12	-22	8.2	-79.6
628-S1-05	-25.8	4.3	-86.5
628-S1-13	-24.8	5.4	-64.2
628-S1-01	-27.5	2.5	-44.9
628-S1-03	-28.1	1.9	-72.8
670-S2-20	-28.9	1.2	-80.4
670-S2-14	-25	5.1	-64.2
670-S2-08	-25.9	4.2	-76.8
670-S2-06	-25.3	4.8	-73
670-S2-13	-27.1	2.9	-70.6
670-S2-17	-26.6	3.5	-75.7
670-S2-28	-27.5	2.5	-72.6
670-S2-41	-26.9	3.1	-83.3
670-S2-07	-28.1	1.9	-75.5
670-S2-37	-29.2	0.8	-68
MK-61	-25.4	4.7	-69.6
MK-57	-24.9	5.2	-75
MK-032	-24.1	6.1	-76.8
average	-26.6	3.5	-72.4



Fig. 4. Isotopic compositions ( $\delta D$  versus  $\delta^{18}O$ ) of brines in halite fluid inclusions from the Mengyejing potash deposit (modified from Knauth and Beeunas, 1986; Kendal and McDonnell, 1998; Zhang Hua et al., 2015).

Dataset of Lop Nur salt lake is from Liu Chenglin et al. (1999); dataset of the fluid inclusions in Messinian halite, Sicitly is from Rigaudier er al. (2011).

NE>NF. Thus, appropriate paleoclimatic conditions and degrees of brine evaporation are crucial for the formation of potash deposits.

Relative to the meteoric water line, the dataset shows a very narrow range of  $\delta D$  values from -64.2% to -86.5%,

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Inclusion No.	Concentration (ppm)						Salinity	Mg+K+Ca	
inclusion No.	Li	В	Mg	K	Ca	Rb	Sr	(g/kg H <sub>2</sub> O)	(mmol/kg H <sub>2</sub> O)
MY17-4	_	1	7794	43447	8264	16	66	499	1646
MY17-7	1	1	3737	40010	1246	9	11	457	1213
MY17-10	7	1	20011	55985	9057	37	55	573	2496
MY17-13	2	6	17279	49853	3990	32	28	537	2098
MY17-14	2	3	16077	46514	4147	27	24	526	1966
MY17-16	_	_	7008	43066	7708	21	47	493	1589
MY17-17	_	_	928	20300	486	2	2	406	571
Average	3	2	10405	42739	5011	20	33	499	1654
MY101-2	_	_	12185	66383	22192	106	394	599	2765
MY101-3	_	_	13903	26479	6750	25	86	486	1427
MY101-5	_	_	8876	16764	4545	20	58	442	913
MY101-6	_	_	15713	23438	9545	38	144	495	1494
Average	_	_	12669	33266	10758	47	170	506	1650

Table 3 Calculated ion concentrations (in µg/g) of brines from the Mengyejing Formation halite

except for an extremely high value of -44.9‰ from one sample, whereas the  $\delta^{18}$ O values have a relatively wide range, from +0.3‰ to +8.2‰. Fig. 4 shows that the dataset of H and O isotopic compositions lies on the lower right side of the meteoric water line (MWL). Based on the pioneering work of Knauth and Beeunas(1986), highly evaporated seawater can have an isotopic composition identical to that of highly evaporated meteoric water. Thus, the H and O isotopic compositions cannot be convincingly used to discriminate between marine and meteoric waters. Nonetheless, the slope of the trend line of the isotopic compositions is smaller than the evaporation line of meteoric water and seawater, indicating an environment (Kendall intensely evaporative and McDonnell, 1998).

This is also illustrated by the evaporation process of modern Quaternary saline lakes and ancient seawater, based on the research on H and O isotopes in the Lop Nur saline lake and fluid inclusions in Messinian halite from Sicily. The saline water in the Lop Nur saline lake and parent brines derived from seawater in the Mediterranean during the Messinian salinity crisis have undergone intense evaporation, forming enriched K-bearing brines in Lop Nur and a thick layer of evaporites and potash deposit in Sicily (Liu Chenglin et al., 1999; Rigaudier et al., 2011). Compared with the more concentrated distribution of H and O isotopic compositions of the Lop Nur saline lake water, the values of the halite fluid inclusions in the Mengyejing potash deposit show a continuous distribution with a positive correlation, resembling those in the Messinian halite in Sicily but with a smaller slope for the  $\delta D - \delta^{18} O$ evaporation trend (Fig. 4). The results indicate that the brines that formed the evaporites in the Mengyejing potash deposit experienced intense evaporation and that the evaporation intensity increased gradually.

#### 5.2 The evaporation stage of saline lake water

Given that the brines in the halite fluid inclusions in the potash deposits contain a very small amount of  $SO_4$  and

relatively high concentrations of Ca, the brines are characterized as the Na-K-Mg-Ca-Cl type (Khmelevska et al., 2000; Galamay et al., 2003; Kovalevych et al., 2006), similar to that of Cretaceous seawater (Timofeeff et al., 2006).

Because Na is used as an internal standard and because the Na content is, in practice, not always constant, ion ratios are more useful than the absolute ion concentrations for characterizing brine evolution. K versus Mg (Fig. 5a), K versus Ca (Fig. 5b), K versus Rb (Fig. 5c) and K versus Sr (Fig. 5d) are plotted as a set of bivariate diagrams. All of the plots show a great deal of scatter, even for some data from the same sample. However, the plots from the same samples show positive correlations, suggesting that the analysed inclusion fluids are not homogeneous and have experienced a progressive evaporation process.

On the Jänecke diagrams (Fig. 6a), the brine compositions of the Mengyejing halite show a relatively wide range. This dataset suggests that the brines varied in composition during the deposition of the evaporites. However, all the points are situated in the sylvite field and outside the range for Ca- and Mg-bearing salts (i.e., carnallite, antarcticite, tachyhydrite and bischofite). The brine compositions of the halite inclusions in sample MY17 are all associated with sylvite precipitation and evolved toward the carnallite zone with increasing total concentrations of the three major ions (Mg+K+Ca). With increasing evaporation, the major ion concentrations became enriched until sylvite precipitated from the brines. Subsequently, as shown by sample MY101, more K ions were removed from the brines, thus causing a decrease in the concentration of the three major ions (Mg, K, and Ca). However, based on the findings of this study, the brines associated with evaporite deposition only barely reached the stage of carnallite precipitation.

#### 5.3 Formation of the Mengyejing potash deposit

The brines of the Mengyejing potash deposit have been determined to be at least partly continental in origin based



Fig. 5. Relationships between major cations (K, Mg, Ca, Rb and Sr).



Fig. 6. (a), Brine composition in halite fluid inclusions from the Mengyejing potash deposit in the Mg-Ca-2K Jänecke diagrams saturated with respect to halite at 25°C (Eugster, et al., 1980); (b), Ca/Mg ratios of halite fluid inclusions from the Sergipe, Khorat and Simao Basins.

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on the  $\delta^{34}$ S and  ${}^{87}$ Sr/ ${}^{86}$ Sr values of the evaporites (Li et al., 2015). Depending on the study, the Br values of the evaporites range from 89.08 to 555.45 ppm (Li et al., 2015) or from 143 to 1,886 ppm (Gao Xiang et al., 2013). These ranges are higher than the bromide contents of halite derived from seawater (40-200 ppm). These values are interpreted to be partly due to the presence of certain amounts of potash minerals (primarily sylvite) in the halite samples because sylvite more readily accommodates Br compared to halite and carnallite (Braitsch, 2012). However, continental waters are thought to be poor in Br compared to seawater and its brines, such that non-marine halite contains lower Br contents than marine halite (Valyashko, 1956; Patterson and Kinsman, 1977). Additionally, recrystallized halite derived from a secondcycle (typically non-marine) solution of older salt rocks tends to have an even lower bromide content that can be less than 20 ppm (Holser, 1966; Holser, 1979b). The close relationship between the Mengyejing potash deposit and the Cretaceous Maha Sarakham potash deposit in the Khorat Basin in Thailand, which is thought to be derived from Cretaceous seawater (Qu Yihua, 1997; Zhang Hua et al., 2014; Wang et al., 2015), suggests that seawater was likely the major source for the formation of the Mengyejing potash deposit.

The Ca and Mg concentrations of evaporated seawater trapped in halite are generally higher than the K concentrations, but in the Mengyejing potash deposit, the concentrations of K are distinctly higher than the expected concentrations of Mg and Ca (Fig. 6a). Therefore, processes other than simple evaporation of seawater likely occurred. One of the possible explanations for high K concentrations in halite fluid inclusions is the recycling of evaporites in basins. Research by Taberner et al. (2000) on the southern Pyrenean foreland basin and Messinian evaporites in the Lorca Basin demonstrates that the recycling of evaporites can be a major process in restricted basins. These basins experienced multiple separate incursions of fresh continental water or seawater, each of which may have dissolved and redeposited some of the salt (Holser, 1966). The dissolution preferentially increases the proportion of the ions of the more soluble saline minerals (e.g., Na and Cl from halite; K, Mg, and Cl from carnallite), forming a type of modified seawater. Evaporative concentration of this altered seawater produces halite-hosted fluid inclusions with a chemical composition that differs from that of brines evolved from unaltered parent seawater (Timofeeff et al. 2001). The fluid inclusions in marine halite from many Cretaceous evaporite deposits, including those in the Sergipe, Congo and Khorat basins, have been analysed in previous studies (Timofeeff et al.,

2006). The Ca/Mg ratios of fluid inclusions in Cretaceous halite that did not experience syndepositional modification are variable, but the variation is not significant (Fig. 6b). For example, the Ca/Mg ratios of the Sergipe and Khorat basins range from 0.78 to 1.30 and from 0.35 to 0.89, respectively. This variation may have been caused by secular changes in seawater chemistry due to fluctuations in the release of mid-ocean ridge hydrothermal brines (Hardie, 1996). The Ca/Mg ratios of the brines trapped in fluid inclusions in the Mengyejing halite range from 0.23 to 1.10, with an outlier value of 1.82 from one sample. These values are somewhat similar to those of Cretaceous evaporated seawater, indicating that even if the parent seawater experienced various alterations, the relationship between Ca and Mg does not appear to have changed notably. The Ca/Mg ratios appear to be related to the lithologies in which the halite occurs: fluid inclusions that formed during cycles with abundant dolomitized carbonates have high Ca/Mg ratios, whereas fluid inclusions that formed during cycles with no associated carbonates have low Ca/Mg values (Bein et al., 1991). The limited presence of dolomite in the saltbearing sequence of the Mengyejing Formation (Liang Wanxue et al., 1983; Qu Yihua, 1997) suggests that no significant changes occurred in the Ca/Mg ratios of the brines, which is in accordance with the Ca/Mg ratios of the Mengyejing fluid inclusions.

Hydrothermal activity was widespread in the Simao Basin, as indicated by the presence of metallic mineral deposits, including large Zn-Pb and Cu deposits, in the basin (Wu Nanping et al., 2003; Wang Xiaohu et al., 2011). Heavy metals are enriched in the evaporites of the Mengyejing potash deposit and occur at much higher levels than those found in typical marine evaporites in Canada and the US (Shuai Kaiye, 1987). These results indicate that hydrothermal fluids might have been potential sources for potash formation. This could be another reason why the K content is higher than the Mg and Ca contents in the halite fluid inclusions.

Several researchers have presented estimates of the homogenization temperatures for the halite precipitation based on the study of the halite fluid inclusions in the Mengyejing potash deposit. In one estimate, the homogenization temperature generally ranged from  $45^{\circ}$ C to  $65^{\circ}$ C, with a maximum of  $80^{\circ}$ C (Yuan Jianqi et al., 1991). Zhao Yanjun et al. (2015) measured the homogenization temperature of fluid inclusions in halite from the Mengyejing potash deposit and obtained 20 values that ranged from 21.1 to 59.0°C, with a mean of  $38.3^{\circ}$ C. The maximum value in this estimate is similar to the extremely high temperature ( $61^{\circ}$ C) of the mid-Cretaceous greenhouse (Zhang et al., 2015). These results

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suggest that, during the deposition of the evaporites, the temperature of the brines was very high, resulting in strong evaporation. The concentration of K in brines in marine halite fluid inclusions has been used to determine the degree of evaporation based on the back-calculation of seawater composition during the Phanerozoic (Horita et al., 2002). The high concentrations of K in the brines in the Mengyejing halite fluid inclusions also indicate that the evaporation of the ancient Mengyejing saline lake was very high, reaching the deposition stage of potashmagnesia salts during most of the saline lake depositional period. In conclusion, the brine evaporated rapidly in a high-temperature climate, thereby precipitating late-stage potassium salts. The dissolution of previously deposited potash minerals by relatively fresh brines caused the K concentrations to increase, and hydrothermal fluids may have supplied additional K ions to the brines. These factors controlled the development of high K concentrations in the brines in the halite fluid inclusions in the Mengyejing potash deposit.

## **6** Conclusions

(1) The H and O isotopic compositions of the brines in the halite fluid inclusions indicate that the brines underwent an intensive evaporation process in which the net evaporation exceeded the net inflow of brines during the deposition of the Mengyejing potash deposit.

(2) The chemical compositions of the fluid inclusions in halite from the Mengyejing potash deposit show that the brine is of the Na-K-Mg-Ca-Cl type. The concentrations of K are distinctly higher than those of Mg and Ca, in contrast to primary brines in Cretaceous halite. The high K concentrations in the brines in the halite fluid inclusions indicate that the degree of evaporation of the ancient Mengyejing saline lake was very high, resulting in sylvite deposition but rarely resulting in carnallite deposition.

(3) The high K concentrations of the brines in the halite fluid inclusions might have been caused via the dissolution of previously deposited potash minerals and/or supplementation by hydrothermal fluids. The basin probably experienced multiple incursions involving dissolution and redeposition. The high K concentrations of the brines occurred progressively in association with a high evaporation rate in a high-temperature climate. These factors resulted in the precipitation of late-stage evaporites, i.e., sylvite and a small amount of carnallite. The conditions were favourable for potash formation in terms of the evaporation during the deposition of the Mengyejing formation, thus suggesting the potential for the discovery of new ancient potash deposits in the Simao Basin.

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