A tuff interlayer in deep potash-bearing salt rocks and its implication for potash mineralization in the Simao Basin, southwestern China

Zhong-ying Miao (zhymiao@foxmail.com)
Institute of Mineral Resources, CAGS

Mian-ping Zheng
Institute of Mineral Resources, CAGS

Peng-cheng Lou
China University of Geosciences

Dong Wang
Institute of Mineral Resources, CAGS

Qi-hui Xu
China University of Geosciences

Jian-ming Xu
Institute of Mineral Resources, CAGS

Research Article

Keywords: Simao Basin, Potash deposit, Deep potash, Tuff, Element geochemistry, Tethys

Posted Date: May 11th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1591244/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License
Abstract

The lithology and genesis of a dark gray clastic interlayer firstly and only encountered within the deepest potassium-rich salt body in the Simao Basin, southwestern China, were analyzed with SEM and ICP-MS. The petrology, mineralogy, element geochemistry analyses of the layer reveal that: 1) the layer contains crystal fragments with irregular cracks, angular volcanic glasses as well as quartz crystals with gulf corrosion edge and explosion cracks. 2) The main mineral components are chlorite, illite, biotite, quartz, crystal fragments, glass shard, anhydrite, gypsum, magnesite, pyrite, molybdenite, clinopyroxene, and zircon. 3) The rare earth element patterns, Zr/TiO₂ and Nb/Y diagrams as well as boron content, all indicate a volcanic origin of the layer. Based on these observations, the layer is suggested to be an altered tuff associated with variety of volcanic fragments dominated by chlorite and formed after alteration of a parent tuff in an alkaline, salty, and low-temperature water body. The discovery of the layer not only indicates that the potash-bearing salt rocks could have taken in volcanic materials during these volcanic activities, but also provides a possibility of reliable zircon U-Pb dating for the absolute age of the host rock, which is vital for the genetic mechanism study of this deeply buried salt body. Furthermore, the layer may carry with it valuable information of volcanic and tectonic activities triggered by the closure of Meso-Tethys.

1. Introduction

Previous studies have shown that evaporite basins are often accompanied by volcanic activities during salt precipitation and that the activities contribute to salt provencances for the basins. Examples of this basin-volcanic activity ‘partnership’ can be found in many locations around the world, including the Paleogene evaporite Shahejie Formation (Fm.) in the Dongpu Sag, Bohai Bay Basin (Xue and Gao 2011), and the Paleocene evaporite layers in the Jiangling Sag, Jianghan Basin (Wang et al. 2015b) in East Asia; the giant evaporite Neogene belt in the central Andes (Alonso et al. 1991) in South America, and the Neogene evaporite basin in western Turkey (Erkül et al. 2005). However, pyroclastic-interlayer formed by co-deposition of pyroclastics and evaporite is rarely covered by these studies, except for Gong et al. (2021), who reported a tuff interlayer in the Triassic polyhalite-bearing salt rocks in the Sichuan Basin and Zhang et al. (2010), who described in their study a basalt-andesitic pyroclastic rock interlayer in the salt rocks of Mengyejing potash deposit in the Simao Basin. Pyroclastic interlayers of salt rocks not only indicate the contribution of volcanic sources for the salt deposit, but also have important chronological significance for constraining the salt deposit model (Yamamoto et al. 1986; Erkül et al. 2005; Szakács et al. 2012), thus are important research object of mineral deposits.

The deepest potash-bearing salt body up to date is buried between 2397 m to 2650 m as revealed by borehole MK-3 in the Simao Basin, southwestern China. It hosts a lithologically unique interlayer at depth 2594.4 – 2594.7 m that is lithologically different from the surrounding rocks. However, the layer shares the similar characteristics with shallow pyroclastic rocks as described by previous studies. This paper aims to confirm the pyroclastic lithology of the layer and discusses its genesis through analyses of petrology, mineralogy, element geochemistry, thus laying a foundation on which more accurate dating of metallogenesis and further determination of genesis of the salt body as well as the establishment of a genetic relationship between deep and shallow potash deposit are possible.

2. Geological Setting

Simao Basin is located in the north Indochina Block and bounded by the Jinshajiang-Alaoshan suture zone on the east and by the Lancangjiang suture zone on the west (Metcalf 2002; Xu et al. 2013). Influenced by the subduction of the Indian Plate to the Eurasian Plate (Cong et al. 1993), the formations and main faults in the basin are generally NW-SE oriented (Shuai 2000; Wu et al. 2003). In the Middle-Late Triassic, the basin had the characteristics of a rift basin (Zhu et al. 1997; Liao and Chen 2005) with volcanic rocks developed in the basin margin (Liao et al. 2003); In Jurassic-Cretaceous, the basin took the shape an intracontinental depression basin (Zhu et al. 1997).

The Middle-Upper Triassic in the basin contains a variety of marine clastics and carbonates. Overlaying the Upper Triassic are coastal swamp clastic rocks and coal seams with the edge of the basin being topped by alkaline, high-aluminum series and intermediate-basic volcanic rocks (Zhu et al. 1997; Tan 2002). The Lower Jurassic mainly hosts fine clastic rocks of tidal flat and lagoon facies. The Middle Jurassic contains barrier beaches and shell beaches in the western part of the basin, and tidal flats behind beaches in the east part of the basin. The Upper Jurassic is largely continental red fine clastic rock. The Cretaceous is a set of typical fluvial-lacustrine sandstone, shale, and conglomerate (Chen et al. 2004; Liao and Chen 2005).

Up to now, only one potash deposit, the "Mengyejing potash deposit" in the Mengyejing Formation, has been discovered in the Simao Basin. The deposit is buried between 27 m and 1251 m. It is a chloride-type potassium salt deposit, containing such mineral assemblages as NaCl, KCl, KCl-MgCl₂-6H₂O, CaSO₄, and MgCO₃. With an average content of KCl of 8.81%, the deposit hosts 1.676 billion tons of KCl.
resource. Zheng et al. (2014, 2015) suggested that the deposit was solid salt diapirs migrated from deep due to tectonic activities. Li et al. (2015) suggested that the potash deposit was of continental origin with a remnant seawater trace. Ma et al. (2019) proposed a metallogenic model for the deposit, suggesting seawater migration and metamorphism in multistage basins. Miao et al. (2020) suggested that the deposit was sourced from a deep marine stratum with the metallogenic epoch during the clastics depositional stage of the Mengyejing Fm.

With very little diagnostic evidence being previously published, the Mengyejing Fm. is yet to be chronostratigraphically determined. Based on sporopollen assemblage analysis, Yuan et al. (2013) suggested that the Mengyejing Fm. was between Aptian and Albian. Wang et al. (2015a) zircon SHRIMP U-Pb dated the formation to be 100 Ma to 110 Ma based on an interbedded tuff in the upper part of the formation, and thus estimated the formation was formed from the Albian to the Cenomanian. Yan et al. (2021a) obtained the first known age sequence of > 112 Ma to ca. 63 Ma for the Mengyejing Fm., via detrital zircon U-Pb geochronologic-magnetostratigraphic dating. Available data show that the Middle Jurassic Hepingxiang Fm. is another stratum of exploratory value for potash deposits and its salt-bearing layers are most likely to be deposited in a salt sag on tidal flat (i.e., the intertidal depression or supratidal salt marsh).

3. Samples And Methods

3.1. Samples

From June 2018 to June 2019, a geological survey for potash through an exploratory well with a designed drilling depth of 2700 m had been carried out by the Institute of Mineral Resources under the Chinese Academy of Geological Sciences in areas outside the Mengyejing potash mining area, Jiangcheng Depression, Simao Basin. It was jointly funded by Geological Survey Project (DD20160054) and Potash Deep Field Special Project (2017YFC0602801). The exploratory well MK-3 was drilled at the coordinates of 101°37’43.5” E and 22°41’25.0” N, where outcropped strata was observed to be the Lower Cretaceous Nanxin Fm. (Fig. 1). Figure 2a shows the stratigraphic sequence of the Nanxin Fm., Jingxing Fm., Bazhulu Fm., Hepingxiang Fm. (from top to bottom) penetrated by the borehole MK-3.

Two layers of evaporite rock with an accumulative thickness of 149 m were drilled through by the well, with one layer being buried between 2397 m and 2443 m and the another between 2542 m and 2645 m. At a depth between 2594.4 m and 2594.7 m in the latter layer, a 30-centimeter-thick layer of dark gray “clastic rock” was found to be sandwiched between potash-bearing salt rocks and had a significantly larger diameter after being brought up to the surface and emptied from coring tube. On-site checking showed that the "clastic rocks" were barely rocks for they were not fully consolidated and covered with fissures filled by orange-red sylvite (Fig. 2b). The main mineral composition included quartz, anhydrite, clay mineral, and sylvite. This column of "clastic rock" has the characteristic of pyroclastic rock and is focus of this study and is taken sample labeled MK-3-T.

3.2. Contact relationship between the layer and salt rocks

The sample analyzed in this paper was from the lower part of the core gathered during the 906th coring trip into the well MK-3. The trip started at a depth of 2591.9 m and ended at a depth of 2594.9m. The interlayer (in-situ sediment) with a length of 0.30 m was found to be sandwiched between two salt rocks. The top is mud or gypsum-bearing salt rocks and potash-bearing salt rocks with a length of 2.5 m (from 2591.9 m to 2594.4 m) and the bottom is mud or gypsum-bearing salt rocks with a length of 0.2 m.

The well MK-3 was protected by a 146 mm inner intermediate casing from surface to a depth of 1900 m. The well then went successively through red, brown-red and purple-gray siltstone intercalated with 5 to 15 cm thick gray-green mudstone from 1900 m to 2397 m, dark gray potash-bearing salt rock from 2397 m to 2443 m, brown-red silty mudstone from 2443 m to 2535 m, black carbon mudstone from 2535 m to 2542 m, and mud-bearing salt rock or gypsum-bearing salt rocks from 2542 m to 2595 m. All these lithologies are quite different from those of the sample——thus eliminating the possibility of falling bits or blocks from these rocks being mingled into the sample.

After being brought up to the surface, the sample expanded due to pressure release, making the contact relationship between the sample and the overlying salt layers difficult to identify. However, the contact relationship between the sample and the underlying salt layer was clear (Fig. 2b), serving as another piece of evidence for the sample being an in-situ sediment from the perspective of sedimentology.

In conclusion, drilling engineering, petrology and sedimentology show that the sample is a “clastic rock” deposited in-situ between salt layers, laying a solid foundation for further exploration of its geological significance through sedimentological, petrological, and mineralogical analyses.

3.3. Methods
3.3.1. Transmitted light microscope
Fix the sample on the glass slide with epoxy resin as adhesive, grind the sample to a thickness of 0.03 mm with saturated saline, and bond the cover glass for observation under a Leica 2700P polarizing microscope with the LED light source and a LAS imaging system.

3.3.2. Scanning electron microscope (SEM)
A Field Emission Scanning Electron Microscope (FESEM) of Zeiss Ultra Plus with accelerating potential of 15 kV is used to perform the observation of prepared slices made from the sample. The mineral composition of the sample is obtained with an Oxford X-MaxN80 dual-detector EDS (X-ray Energy Dispersive Spectrometer).

Some debris are adhered on the sample tray and tested with a TM3030 scanning electron microscope and an XFlash MINSVE energy spectrometer.

3.3.3. Rare earth element analysis
The rare earth elements (REE) in the sample are determined with an ELEMENT XR Inductively Coupled Plasma Mass Spectrometry (ICP-MS) at the ambient temperature of 23.5°C and the relative humidity of 41%.

The analysis procedure begins with weighing 250.0 mg (up to 0.01 mg) of powdered sample (< 74 µm in size) and putting it into a Teflon vessel insert. Dissolve the powder with about 1 mL of HF (1.16 g/mL) and ca. 0.5 mL of nitric acid (1.42 g/mL). Seal the insert and put it into an oven, where the insert is heated up to 185 ± 5°C for 24 hours. Take out the insert after it is cooled down and heat it to nearly dry on an electric hot plate. Add another 0.5 mL of nitric acid (1.42 g/mL) into the tank and wait for it to evaporate to be nearly dry. Repeat the step once. Again add 5 mL of nitric acid (1 + 1) into the insert and seal it. Put it into the oven and heat at 130°C for 3 hours. Take out the insert, and transfer the solution quantitatively to a 25 mL plastic bottle, where the solution is diluted to 25 mL with deionized water. Shake the bottle well and prepare for ICP-MS measurements.

4. Results

4.1. Petrology
The sample is not well consolidated but with cracks of 0.1 mm to 2 mm wide, filled with orange-red sylvite (Fig. 2b). Under the polarizing microscope, the sample is made up of very small sized particles with undistinguishable single minerals (Fig. 3a). Alpha-quartz (ca. 120µm in size) with perfect crystal structure can be occasionally found in the argillaceous basement (Fig. 3b). Clay minerals are mostly 0.1 mm to 1.2 mm sized clastic particles (Clast-Clay) (Figs. 3a, 3c), among which 0.4 mm to 0.8 mm sized crystal fragments with irregular cracks are observed (Figs. 3c‒e); The sample has extremely low textural maturity, with 0.3 mm to 0.4 mm sized quartz and 0.1 mm to 0.4 mm sized anhydrite occasionally being observed to be gathered and distributed among debris particles bonded by clay (Fig. 3f).

4.2. Mineralogy
The sample mainly contains clay minerals, quartz, gypsum, anhydrite, biotite, pyrite, zircon, clinopyroxene, monazite, molybdenite, and magnesite, of which, clay minerals dominate and are largely composed of chlorite, illite, and biotite. Chlorite crystal grains are fine, generally ranging from 2 µm to 5 µm, and flaky with aggregations of scale and petal shape (Figs. 4a, 4b). Flaky illites of various crystal size ranging from 2 µm to 16 µm are dispersed in chlorite, with some individual flakes developing threadlike edges pointing towards pores among the mineral grains. Aggregated illites are granular and thin and may be the results of feldspar alteration or chlorite transformation (Figs. 4b, 4c). Biotites are rarely seen but aggregated of biotites can be occasionally spotted with cross-sections being measured to be about 4×27 µm (Fig. 4d).

The sample also contains a large number of quartz particles, only next to clay minerals. The quartz particles or crystals, largely 130 µm to 145 µm big, are mostly angular and poorly rounded (Fig. 5). A few cube-shaped crystals with cylindrical and pyramidal faces can be observed. Some crystals are having gulf corrosion (Figs. 5b, 5d, 5f, 5g) and cracks (Figs. 5c, 5e). Volcanic glass pieces with the same chemical composition as quartz crystals are also present, the biggest pieces are as large as about 220 µm and the smallest less than 100 µm.

Gypsum and anhydrite are abundant in the sample, though not as abundant as clay minerals or quartz. Their energy spectrums reveal elemental composition to be mostly S, O, and Ca, and chemical composition to be CaSO₄. The needle-shaped or long columns are gypsums particles and the diamond-shaped and near cubic ones are anhydrite crystals.
Scattering among the clay minerals are monazite, pyrite, molybdenite, magnesite, zircon and clinopyroxene. The monazite and molybdenite grains are rather small, only about 10 µm to 20 µm big, and have poor crystal form. The magnesite grains are about 25 µm crystals of well-developed form with some cracks. The pyrite crystals are relatively large, about 100 µm in size, and have a perfect diamond shape.

Zircon is associated with clinopyroxene (Fig. 6). Zircon crystals are mostly a combination of double prisms and bipyramids, similar to those formed in alkaline rocks or meta-alkalescence granite. Their size is ca. 8×20 µm. Clinopyroxene crystals are also short columnars with a size of about 3×10 µm.

### 4.3. Rare-earth element

The total REE content of the sample is 141.9 µg/g, significantly higher than that of basalts in Jingdong and Mojiang (within the basin) but significantly lower than that of granite from the Lincang at the basin margin and PAAS (Table 1). The sample contains more LREE over HREE, with a LREE/HREE ratio of 8.35 (Table 2), which is similar to that of Lincang granite and PAAS and significantly higher than that of Mojiang Basalts and Jingdong Basalts.

The chondrite-normalized REE curves of the sample as well as of basalts in Jingdong and Mojiang and granite in Lincang are shown in Fig. 7a. The curves are dipping to the right as a whole, with (La/Yb)_N and (La/Sm)_N values of the sample respectively at 7.19 and 2.97, both are higher than those of basalt from Jingdong and Mojiang basalts, but lower than those of granite from Lincang and PAAS, indicating a relatively weak LREE differentiation. The (Gd/Yb)_N of the sample is at 1.39, similar to that of Jingdong and Mojiang basals as well as PAAS, but significantly lower than that of Lincang granite, indicating a weak HREE differentiation. The sample has a δCe, at 1.0, similar to chondrites, PAAS, and Jingdong -Mojiang basalts, but slightly higher than Lincang granite. It has a δEu, at 0.70, similar to PAAS, significantly higher than Lincang granite, and lower than Jingdong and Mojiang basalts.

Figure 7b shows the PAAS-normalized REE curves. The curves reveal that (1) REE in the sample are generally lower than that in PAAS, and their ratios to the corresponding elements in PAAS are between 0.62 and 0.96. (2) The sample is relatively rich in MREE (Sm, Eu, Gd) and HREE (Er, Tm, Yb), resulting in a M-shaped distribution (curve). (3) The sample differs from Lincang granite in that the sample has a relatively flat PAAS-normalized curve while the granite’s curve is above the PAAS (indicating higher content of REE than that of PAAS) and with an apparent negative Eu anomaly. (4) The sample’s curve is also different from Jingdong and Mojiang basalts, whose PAAS-normalized curves, an inverted “L” shape, indicate lower LREE and higher MREE (Eu) than PAAS, and a similar HREE to PAAS.

| Sample No. | LREE/µg/g | HREE/µg/g |
|------------|-----------|-----------|
|            | La        | Ce        | Pr        | Nd        | Sm        | Eu        | Gd        | Tb        | Dy        | Ho        | Er        | Tm        | Yb        | Lu        | Y         |
| MK-3-T     | 24.00     | 49.90     | 5.62      | 25.10     | 5.09      | 1.06      | 3.87      | 0.59      | 3.31      | 0.65      | 1.99      | 0.33      | 2.25      | 0.28      | 17.90     |
| Jingdong Basalt | 8.66     | 20.53     | 2.87      | 13.68     | 3.63      | 1.31      | 4.63      | 0.78      | 5.04      | 1.03      | 3.03      | 0.44      | 2.67      | 0.38      | 33.69     |
| Mojiang Basalt | 5.97     | 14.81     | 2.19      | 10.69     | 2.82      | 1.03      | 3.53      | 0.57      | 3.65      | 0.75      | 2.17      | 0.31      | 1.94      | 0.29      | 23.49     |
| Lincang Granite | 55.59    | 103.76    | 12.17     | 45.28     | 8.73      | 1.33      | 7.64      | 1.20      | 7.06      | 1.32      | 3.86      | 0.58      | 3.62      | 0.52      | 38.40     |
| Chondrite   | 0.31      | 0.81      | 0.12      | 0.60      | 0.20      | 0.07      | 0.26      | 0.05      | 0.32      | 0.07      | 0.21      | 0.03      | 0.21      | 0.03      | 1.96      |
| PAAS        | 38.00     | 80.00     | 8.80      | 32.00     | 5.60      | 1.10      | 4.70      | 0.77      | 4.40      | 0.99      | 2.85      | 0.40      | 2.80      | 0.43      | 27.00     |

Table 1

Relative content of REE in sample MK-3-T

Notes: modified after Dong et al. (2000) (Jingdong and Mojiang Basalts), Kong et al. (2012) (Lincang Granite), Boynton (1984) (Chondrite), and Mclennan (1989) (PAAS). PAAS (Post Archean Australian Shale).
5. Discussion

5.1. Rock genesis revealed by mineral assemblage characteristics

Mineral assemblage characterization was performed to reveal the lithology of the sample studied. Polarizing microscope observation shows that the sample mainly contains clay mineral and a small amount of anhydrite, quartz, and crystal fragments with irregular cracks - typically found in debris from volcanic eruption (Zhong et al. 2016). Minerals with typical pyroclastic characteristics such as volcanic glass, crystal fragment, and quartz crystals with gulf erosion can also be observed under SEM. Mineral assemblages such as pyrite, clinopyroxene, and molybdenite were observed and their existence generally indicates a supply of hydrothermal fluid minerals from deep volcanic activities (Feng et al. 2009; Cai et al. 2020; Li et al. 2019). So, all of these suggest that the lithology of the sample is pyroclastic.

SEM also reveals typical evaporite mineral such as magnesite, anhydrite, and gypsum dispersing in the sample. Combined with the observation that cracks in clastic rocks are filled with orange-red potash salt, it is concluded that the pyroclastic was co-deposited with saline minerals in an evaporite basin.

SEM shows that the clay minerals are mainly chlorite, with a small amount of illite and mica. This is different from other clastic rocks in the study area (Miao et al. 2015; Lou et al. 2021), thus serving as another piece of evidence for the pyroclastic identity of the sample.

Based on the combination characteristics of clastic minerals, clay minerals, and evaporite minerals, the sample is highly likely a pyroclastic rock that was possibly deposited syngenetically with evaporite rocks. According to the pyroclastic grain size description standard, the sample can be defined as tuff. However, due to the special preservation condition (i.e., wrapped within salt rocks), the tuff was altered but not well consolidated.

5.2. Genesis of chlorite

Chlorite is one of the Fe- and Mg-rich aluminosilicate clay minerals and has a generalized chemical formula of \((X, Y)_{4-6}(Si, Al)_{4}O_{10}(OH, O)_{8}\), in which \(X\) and \(Y\) represent divalent or trivalent ions including Fe\(^{2+}\), Fe\(^{3+}\), Mg\(^{2+}\), or Al\(^{3+}\). Chlorite in sedimentary rocks is formed as a diagenesis product from transition of detrital Fe-rich berthierine and Mg-rich smectite or from the reaction of kaolinite with Fe and the breakdown of volcanic grains (Berger et al. 2009; Worden et al. 2020; Šegvić et al. 2020). Plagioclase, pyroxene, hornblende, biotite, Fe- and Mg-rich mafic minerals commonly seen in the igneous rock, can also turn into chlorite by hydrothermal alteration (Yang et al. 2002; Worden et al. 2020).

Volcanic rock fragments have long been proposed as a way of delivering the key ingredients for the formation of authigenic chlorite (Berger et al. 2009). Glassy components in tuffs could be devitrificated and form smectite, which then could react with iron oxide and saline water to produce chlorite (Bloch et al. 2002), if in an environment with proper alkaline (pH ca. 8), temperature (30 – 55°C), and water depth (shallow) (Cicerali et al. 2020). Robinson et al (2002) described the process in this neutral or weak alkaline environment as: Ca\(^{2+}\) and Na\(^+\) are removed from montmorillonite layers, and Fe\(^{2+}\) and Mg\(^{2+}\) in the environmental fluid are combined with the OH\(^{-}\) of the...

### Table 2

| Sample No. | \(\sum\text{REE}\) | \(\sum\text{LREE}\) | \(\sum\text{HREE}\) | \(\text{LREE/HREE}\) | \((\text{La/Yb})_N\) | \((\text{La/Sm})_N\) | \((\text{Gd/Yb})_N\) | \(\delta\text{Eu}_1\) | \(\delta\text{Eu}_2\) | \(\delta\text{Ce}_1\) | \(\delta\text{Ce}_2\) |
|-----------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| MK-3-T    | 141.94         | 110.77         | 31.17          | 8.35           | 7.19           | 2.97           | 1.39           | 0.70           | 0.73           | 1.00           | 1.03           |
| Jingdong Basalt | 102.35         | 50.67          | 17.99          | 2.82           | 2.19           | 1.50           | 1.40           | 0.98           | 0.98           | 0.99           | 0.99           |
| Mojiang Basalt | 74.22          | 37.51          | 13.22          | 2.84           | 2.07           | 1.33           | 1.47           | 1.00           | 1.00           | 0.99           | 0.99           |
| Lincang Granite | 291.04         | 226.85         | 25.79          | 8.80           | 10.35          | 4.01           | 1.70           | 0.49           | 0.50           | 0.92           | 0.96           |
| Chondrite  | 5.25           | 2.11           | 3.14           | 1.78           | 1.00           | 1.00           | 1.00           | 1.00           | 1.00           | 1.00           | 1.00           |
| PAAS      | 209.84         | 165.50         | 44.34          | 9.54           | 9.15           | 4.27           | 1.35           | 0.64           | 0.66           | 1.02           | 1.05           |

Notes: \(\sum\text{REE}: \text{La}+\text{Lu}+\text{Y}; \sum\text{LREE}: \text{La}+\text{Eu}; \sum\text{HREE}: \text{Gd}+\text{Lu}; \text{LREE/HREE}=\sum\text{LREE}/\sum\text{HREE}; (\text{La/Yb})_N=\text{La}_N/\text{Yb}_N; \delta\text{Eu}_1=2\text{Eu}_N/(\text{Sm}_N+\text{Gd}_N); \delta\text{Eu}_2=\text{Eu}_N/(\text{Sm}_N\times\text{Gd}_N)^{1/2}; \delta\text{Ce}_1=2\text{Ce}_N/(\text{La}_N+\text{Pr}_N); \delta\text{Ce}_2=\text{Ce}_N/(\text{La}_N\times\text{Pr}_N)^{1/2}; \) Corner mark "N" is chondrite-normalized.
aqueous solution to form the brucite-like layer, which enters the montmorillonite layer in the form of octahedral sheets and combines with
the original montmorillonite structure to form a 2:1:1 chlorite.

The Simao Basin was within a hot subtropical zone near 29° N during the Mesozoic (Yang and Besse 1993; Li et al. 2005). Research on
the homogenization temperature of salt rock fluid inclusions shows that the paleotemperature during the salt evolution period was
between 35°C to 65°C (Zhang et al. 2015). Magnesite found in the sample indicates a slightly alkaline sedimentary environment. A
relatively high salinity water body can be inferred from the existence of potash-bearing salt rocks that wrap the sampling layer. Volcanic
activities may serve as carriers of Fe²⁺ and Mg²⁺ into the environmental fluid. As a result, the study area had the ideal temperature, salinity,
pH, and provenance conditions for an alteration of tuff to chlorite. To be more specific, the glass fragments in the tuff were devitrified into
montmorillonite, which then chloritized in a Fe- and Mg-rich environment. While the main body underwent chloritization, individual crystals
were illitized because of the presence of K⁺ in the environment.

5.3. Geochemical characteristics of REE

REE in sedimentary rocks are mainly controlled by provenances, less by diagenesis and alteration, and therefore can be used to reveal the
characteristics of REE in parent rocks (Nesbitt 1979; McLennan 1989; Yang and Li 1999).

The chondrite-normalized and PAAS-normalized distribution curves of REE in the sample are somewhere between those of Lincang granite
on the basin edge and those of Jingdong and Mojiang basalts within the basin, indicating a neutral volcanic rock origin. Previous works
also show that acid rocks have obvious negative δEu anomalies (Kong et al. 2012; Zhao et al. 2018; Yuan et al. 2021), and basic rocks
have weak negative or positive δEu anomalies (Dong et al. 2000; Liu et al. 2011; Zhang et al. 2012), both at the edge of and inside the
Simao Basin. The sample analyzed has δEu values between the acid rocks and basic rocks, another evidence showing that the sample
has the characteristics of a neutral rock. The Zr/TiO₂ and Nb/Y scatter diagrams of the elements further identify the nature of the parent
source for the sample to be andesite with typical extrusive rock characteristics (Figs. 8).

Except for REE characteristics, the boron content can also indicate the volcanic origin of the sample. The content of boron in the sample is
580 µg/g, which is abnormally high comparing with the results of salt and clastic rocks at Mengyejing area (Xu and Wu 1983) (Table 3).
Some researchers suggest that this is likely to be caused by the introduction of hydrothermal fluids or hot spring through volcanic
activities (Zheng et al. 1983; Liu et al. 2007; Zheng et al. 2007). This also supports the understanding of the sample being clastic deposit
formed by volcanic eruptions.

| Lithology  | Sample number | B content/ppm |
|------------|---------------|---------------|
|            |               | Range | Average |
| Sylvite rock | 95           | 0 ~ 472 | 96.8 |
| Halite rock  | 176          | 0 ~ 250 | 57.3 |
| Clastic rock | 15           | 97 ~ 260 | 144 |
| Anhydrite    | 7            | 13 ~ 300 | 89 |

REE parameters like δCe are generally used to reflect the redox potential of sedimentary environment (Mongelli et al. 2014; Costa et al.
2021; Wang et al. 2021). In an oxidizing setting, Ce in water is more likely to migrate and settle in underwater sediments, resulting in an
accumulation of Ce in clastic sediments that presents itself as positive δCe anomalies; while in a reducing environment, Ce is not likely to
migrate to underwater sediments and causing δCe negative anomalies (Bolhar et al. 2004). The δCe₁ and δCe₂ values of the samples are
1.00 and 1.03, respectively, and shows no obvious δCe-related anomalies, reflecting a weak oxidation-reduction condition. This is further
confirmed by mineral assemblages in the sample, where anhydrite coexists with pyrite, molybdenite, and other sulfides.

5.4. Genetic model and geological significance

Based on the above analyses, the genesis of this inter-salt tuff may be described as the following: When so concentrated as to precipitate
sylvite, brine water body in this evaporite basin of Simao shrunk a great deal but still maintain a redox interface, below which a (at least)
15 cm high accommodation space can be inferred from the thickness of the sample. The basin had been supplied from time to time with
terrigenous freshwater as their footprint was recorded by terrigenous clastic materials commonly seen in evaporite salt rocks in the basin.
Volcanic ash from volcanic eruption was sent to float over the basin where it was drawn down by gravity and deposited as pyroclastic rocks near the redox interface. The rocks were then altered in an alkaline, hyperhaline, low temperature, and water environment, with volcanic glasses in them first turning into montmorillonite and then to chlorite with a small amount of illite. As the alteration going on, newly-formed potash-bearing evaporite rocks overlay and wrapped these pyroclastic rocks together with underlaying potash-bearing evaporite layers. During the process, water adsorbed by clay minerals in these pyroclastic rocks was also sealed within and had been keeping these fragmented rocks from final diagenesis even with a burial depth up to ca. 2600 m, formation temperature ranging between 96.2°C and 96.6°C and period of more than 100 Ma long. This may explain the coexisting gypsum and anhydrite as well as the abnormally high loss on ignition of major elements in the sample.

The material sources of the evaporite in the Simao Basin are still a focus of dispute. Some suggest seawater being the primary source (Wang et al. 2018; Ma et al. 2019), some propose terrestrial water (Li et al. 2015; Yan et al. 2021b). Miao et al. (2019a, 2019b) analyzed the anhydrite sulfur isotopes in these evaporite rocks and found that volcanic activities had an important impact on the material supply for the evaporite rocks. After analyzing hydrochemical characteristics of spring water and genesis of surface potassium anomalies, Bo et al. (2021) inferred that the deep volcanic rocks were one of the important material sources of the evaporite rather than supplying of volcanic activities during evaporite precipitation.

This study moves forward by identifying the direct evidence of volcanic activities during the salt rock deposition period and confirm the contribution of volcanic activities to the formation of evaporite rocks. The pyroclastic layer itself is chronologically significant for a more accurate dating of the potash salt deposits. Furthermore, considering the fact that no evidence so far showing volcanic eruption inside the Simao Basin during the Jurassic-Cretaceous (indicating a relatively stable structure and deposition of the basin during the period), these pyroclastic rocks are very likely to be the result of structural movements and volcanic activities triggered by Tethys closure in the periphery of the basin.

6. Conclusion

Petrology, mineralogy and element geochemistry analyses all indicate that the sample studied is a tuff. A reasonable inference of the genesis of the tuff is that: (1) During the precipitation of potash-bearing salt, volcanic eruption that was probably triggered by the closure of the Meso-Tethys occurred outside the Simao Basin. (2) Tephra ejected from volcanic eruption eventually settled down in the evaporite basin and was later altered in an alkaline, hyperhaline, and low temperature water environment to form a tuff layer. (3) The tuff layer wrapped up by potash-bearing salt rocks was then buried with it under later deposited clastic rocks.

The discovery of the tuff layer not only suggests a volcanic material supply for the potash-bearing salt rocks, but also provides an opportunity for performing a reliable zircon dating for the absolute age (of the tuff), which then could be used to explore the genesis of the salt rocks.

Declarations

CRediT authorship contribution statement

Zhong-ying Miao conceived of the presented idea. Jian-ming Xu contributed to sample preparation. Zhong-ying Miao, Peng-cheng Lou, Dong Wang, Qi-hui Xu carried out the experiment. Dong Wang contributed to the interpretation of the results. Zhong-ying Miao wrote the manuscript with support from Peng-cheng Lou and Qi-hui Xu. Mian-ping Zheng supervised the project. All authors discussed the results and contributed to the final manuscript.

Declaration of competing interest

The authors declare no conflicts of interest.

Acknowledgments

This research was jointly supported by the project of China Geological Survey (DD20201115 and DD20221913), the National Key Research and Development Program (2017YFC0602801). The authors are indebted to Prof. Hong-Yan Li and Prof. Zhen-yu Chen for help on experiment. This manuscript has benefited from valuable advice from reviews expert.
References

1. Alonso RN, Jordan TE, Tabbutt KT, Vandervoort DS (1991) Giant evaporite belts of the Neogene central Andes. Geology, 19(4), 401–404. https://doi: 10.1130/0091-7613(1991)019<0401:GEBOTN>2.0.CO;2

2. Berger A, Gier S, Kros P (2009) Porosity-preserving chloride cements in shallow-marine volcaniclastic sandstones: Evidence from Cretaceous sandstones of the Sanaw gas field, Pakistan. AAPG Bulletin, 93(5), 595–615. doi: 10.1306/01300908096

3. Bloch S, Lander RH, Bonnell L (2002) Anomalously high porosity and permeability in deeply buried sandstone reservoirs: Origin and predictability. AAPG Bulletin, 86(2), 301–328. doi: 10.1306/61EEDABC-173E-11D7-8645000102C1865D

4. Bolhar R, Kamber BS, Moorbath S, Fedo CM, Whitehouse MJ (2004) Characterisation of early Archaean chemical sediments by trace element signatures. Earth and Planetary Science Letters, 222(1), 43–60. doi: 10.1016/j.epsl.2004.02.016

5. Bo Y, Cao YT, Lü FL (2021) Hydrochemical characteristics of spring water and genesis of surface potassium anomaly in the Mengyejing potash deposit and its surrounding areas in Yunnan Province. Acta Geologica Sinica, 92(8), 2193–2204 (in Chinese with English abstract). doi: 10.19762/j.cnki.dizhixuebao.2021190

6. Boynton WV (1984) Cosmochemistry of the rare earth elements: Meteorite studies. Developments in Geochemistry, 2, 63–114. doi: 10.1016/B978-0-444-42148-7.50008-3

7. Cai YY, Han XQ, Qiu ZY, Wang YJ, Li M, Popoola SO (2020) Characteristics, distribution and implication of hydrothermal minerals in Tianxiu Hydrothermal Field, Carlsberg Ridge, northwest Indian Ocean. Marine Geology and Quaternary Geology, 40(5), 36–45 (in Chinese with English abstract). doi: 10.16562/j.cnki.0256-1492.2019101201

8. Chen YK, Liao ZT, Wei ZH, Li MH (2004) Characteristics and tectonic evolution of the Lanping-Simao Mesozoic Basin. Petroleum Geology and Experiment, 26(3), 219–222 (in Chinese with English abstract). https://doi: 10.3969/j.issn.1001-6112.2004.03.001

9. Cicerali D, Arslan M, Yazar EA, Yücel C, Temizel I, Park S, Schroeder PA (2020) Mineralogy, chemistry, and genesis of zeolitization in Eocene tuffs from the Bayburt area (NE Turkey): Constraints on alteration processes of acidic pyroclastic deposits. Journal of African Earth Sciences, 162, 103690. doi: 10.1016/j.jafrearsci.2019.103690

10. Cong BL, Wu GY, Zhang Q, Zhang RY, Zhai MG, Zhao DS, Zhang WH (1993) Petrotectonic evolution of the paleotethys tectonic belt in western Yunnan, China. Science in China (Series B), 23(11), 1202–1205 (in Chinese). https://doi: CNKI:SUN:JBMK.0.1993-11-012

11. Costa L, Johannesson K, Mirlean N, Quintana G (2021) Rare earth element distributions in salt marsh sediment cores reveal evidence of environmental lability during diatom burial and diagenetic processes. Chemical Geology, 584, 120503. doi: 10.1016/j.chemgeo.2021.120503

12. Dong YP, Zhu BQ, Chang XY, Deng SX (2000) Geochemistry of the two-type volcanic rocks from Ailaoshan suture zone and their tectonic implication. Geochimica, 29(1), 6–13 (in Chinese with English abstract). doi: 10.19700/j.0379-1726.2000.01.002

13. Erkül F, Helvaci C, Sozbilir H (2005) Stratigraphy and geochronology of the early Miocene volcanic units in the Bigadi Borate Basin, western Turkey. Turkish Journal of Earth Sciences, 14(3), 227–253. doi: 10.1117/12.623445

14. Feng J, Xue CJ, Wang XL, Zhang B, Xu SQ, Zhou CP (2009) Geological characteristics of Chahansala gold deposit of Xinjiang and its ore genesis analysis. Xinjiang Geology, 27(2), 127–130 (in Chinese with English abstract). doi: 10.1002/9780470611807.ch2

15. Gong DX, Xiao B, Bagas L, Li D, Zhao Y, Zou H (2021) Origin of the Early to Middle Triassic polyhalite minerals in the Sichuan Basin, SW China: New evidence from calcium and sulphur isotopes and microfabrics. Ore Geology Reviews, 139, 104439. doi: 10.1016/j.oregeorev.2021.104439

16. Kong HL, Dong GC, Mo XX, Zhao ZD, Zhu DC, Wang S, Li R, Wang QL (2012) Petrogenesis of Lincang granites in Sanjiang area of SW China: New evidence from calcium and sulphur isotopes and microfabrics. Ore Geology Reviews, 139, 104439. doi: 10.1016/j.oregeorev.2021.104439

17. Li MH, Yan MD, Wang ZR, Liu XM, Fang XM, Li J (2015) The origins of the Mengye potash deposit in the Lanping–Simao Basin, Yunnan Province, Western China. Ore Geology Reviews, 69, 174–186. doi: 10.1016/j.oregeorev.2015.02.003

18. Li PW, Gao R, Cui JW, Guan Y (2005) Paleomagnetic results from the Three Rivers Region, SW China: Implications for the collisional and accretionary history. Acta Geoscientica Sinica, 26(5), 387–404 (in Chinese with English abstract). doi: 10.3321/j.issn:1006-3021.2005.05.001

19. Li SY, Yu KF, Zhang Y, Tao SC, Yan HQ (2019) Mineral chemistry of clinopyroxene in pyroclastic rocks of the Xisha Islands and their geological significance. Acta Oceanologica Sinica, 41(7), 65–76 (in Chinese with English abstract). doi: 10.3969/j.issn.0253-4193.2019.07.006

20. Liao ZT, Chen YK (2005) Nature and evolution of Lanping-Simao Basin prototype. Journal of Tongji University (Natural science), 33(11), 1527–1531 (in Chinese with English abstract). https://doi: 10.3321/j.issn:0253-374X.2005.11.022
21. Liao ZT, Chen YK, Wei ZH, Li MH (2003) Tectonic Evolution Since Late Palaeozoic Era in West Yunnan. Journal of Tongji University (Natural science), 31(9), 1029–1033 (in Chinese with English abstract). https://doi.org/10.1016/S0955-2219(02)00073-0

22. Liu C, Deng JF, Liu JL, Shi YL (2011) Characteristics of volcanic rocks from Late Permian to Early Triassic in Ailaoshan tectono-magmatic belt and implications for tectonic settings. Acta Petrologica Sinica, 27(12), 3590–3602 (in Chinese with English abstract). doi: 10.1080/00288306.2011.590212

23. Liu XF, Zheng MP, Qi W (2007) Sources of ore-forming materials of the superlarge B and Li deposit in Zabuye Salt Lake, Tibet, China. Acta Geologica Sinica, 81(12), 1709–1715 (in Chinese with English abstract). https://doi: US20100305279 A1

24. Lou PC, Miao ZY, Zheng MP, Zhang XF, Ruan Z, Xu QH (2021) Paleogeographic characteristics of the Mengyejing Formation in the Simao Basin during its depositional period and its indication of potash mineralization: A case study of MZK-3 well. Minerals, 11(4), 338. doi: 10.3993/min11040338

25. Ma HZ, Li YS, Cheng HD, Qing XW, Zhang XY, Miao WL, Xu JX, Li BK, Hai QY (2019) Metallogenic model and processes of the Cretaceous potassium-bearing evaporites involving Changdu, Lanping-Simao and Khorat Basin. Journal of Salt Lake Research, 27(1), 1–11. doi: 10.12119/j.yhyj.201901001

26. McElheny SM (1989) Rare earth elements in sedimentary rocks: influence of provenance and sedimentary processes. Reviews in Mineralogy and Geochemistry, 21(1), 169–200. doi: 10.1007/BF00209706

27. Metcalfe I (2002) Permian tectonic framework and palaeogeography of SE Asia. Journal of Asian Earth Sciences, 20, 551–566. doi: 10.1016/S1367-9120(02)00022-6

28. Miao WL, Ma HZ, Zhang XY, Shi HY, Li YS, Rong ZM (2015) Mineralogical and geochemical characteristics of detrital rocks in the Mengyejing Formation and evolution of the sedimentary environment of paleolake in Simao Basin, Yunnan Province. Acta Geologica Sinica, 89(11), 2096–2107 (in Chinese with English abstract). doi: 10.3975/cagsb.2013.05.04

29. Miao ZY, Zheng MP, Lou PC, Zhang XF, Sun HT, Zhang Z, Xu QH, Du XM (2020) A new genetic model for potash deposits of the Simao Basin, Yunnan: Evidence from Sr isotope. Geology in China, https://kns.cnki.net/kcms/detail/11.1167.P.20201207.1635.006.html

30. Miao ZY, Zheng MP, Zhang XF, Zhang Z, Gao YZ (2019a) Geochemistry of sulfur isotope in evaporite and its sedimentology significance: a case study from the well MZK-3 in the Simao basin, southwestern China. Acta Geologica Sinica, 93(5), 1166–1179 (in Chinese with English abstract). doi: 10.19762/j.cnki.dizhixuebao.2019047

31. Miao ZY, Zheng MP, Zhang XF, Zhang Z, Liu JH, Gao YZ, Zhai XF (2019b) Sulfur isotope geochemistry of the Lower Cretaceous evaporite and its significance for potash mineralization in the Simao Basin, Southwest China. Acta Geoscientia Sinica, 40(2), 279–290 (in Chinese with English abstract). doi: 10.3975/cagsb.2019.011701

32. Mongelli G, Boni M, Buccione R, Simisi R (2014) Geochemistry of the Apulian karst bauxites (southern Italy): Chemical fractionation and parental affinities. Ore Geology Reviews, 63, 9–21. doi: 10.1016/j.oregeorev.2014.04.012

33. Nesbitt H (1979) Mobility and fractionation of rare earth elements during weathering of a granodiorite. Nature, 279, 206–210. doi: 10.1038/279206a0

34. Robinson D, Schmidt ST, Zamora AS (2002) Reaction pathways and reaction progress for the smectite-to-chlorite transformation: Evidence from hydrothermally altered metabasites. Journal of Metamorphic Geology, 20(1), 167–174. doi: 10.1046/j.0263-9292.2001.00361.x

35. Šegvić B, Zanoni G, Moscariello A (2020) On the origins of eogenetic chloride in verdine facies sedimentary rocks from the Gabon Basin in West Africa. Marine and Petroleum Geology, 112, 104064. doi: 10.1016/j.marpetgeo.2019.104064

36. Shuai KY (2002) A new interpretation of Mesozoic and Cenozoic Lanping-Simao Basin. Earth Science Frontiers, 7(4), 380 (in Chinese).

37. Szakács A, Pécskay Z, Silye L, Balogh K, Vlad D, Fülöp A (2012) On the age of the Dej Tuff, Transylvanian Basin (Romania). Geologica Carpathica, 63(2), 139–148. doi: 10.2478/v10096-012-0011-9

38. Tan FW (2003) The sedimentary characteristics of Simao Triassic Rear Arc Foreland Basin, Yunnan Province. Acta Sedimentologica Sinica, 20(4), 560–567 (in Chinese with English abstract). https://doi: 10.1007/s11769-002-0045-5

39. Wang LC, Liu CL, Fei MM, Shen LJ, Zhang H, Zhao YJ (2015a) First SHRIMP U-Pb zircon ages of the potash-bearing Mengyejing Formation, Simao Basin, southwestern Yunnan, China. Cretaceous Research, 52, 238–250. doi: 10.1016/j.cretres.2014.09.008

40. Wang CL, Liu CL, Liu BK, Shen LJ, Cai XL, Yu XC, Xie TX, Wang LC, Zhao YJ, Xuan ZQ (2015b) The discovery of carnallite in paleocene Jiangling Depression and its potash searching significance. Acta Geologica Sinica, 89(1), 129–136 (in Chinese with English abstract). doi: https://doi.org/10.1007/s11769-013-0676-9

41. Wang LC, Liu CL, Shen LJ, Bo Y (2018) Research advances in potash forming of the Simao Basin, Eastern Tethyan Realm. Acta Geologica Sinica, 92(8), 1707–1723 (in Chinese with English abstract). https://doi: 10.3969/j.issn.0001-5717.2018.08.012
42. Wang LY, Guo QJ, Zhao CQ, Wei RF, Deng YN, Han XK, Tian LY, Kong J, Yang X (2021) Trace and rare earth elements geochemistry of sedimentary rocks in the Ediacaran-Cambrian transition from the Tarim Basin, Northwest China: Constraints for redox environments. Precambrian Research, 352, 105942. doi: 10.1016/j.precamres.2020.105942.

43. Winchester JA, Floyd PA (1977) Geochemical discrimination of different magma series and their differentiation products using immobile elements. Chemical Geology, 20, 325–343. doi: 10.1016/0009-2541(77)90057-2.

44. Worden RH, Griffiths J, Wooldridge LJ, Utley JEP, Lawan AY, Muhammed DD, Simon N, Armitage PJ (2020) Chlorite in sandstones. Earth-Science Reviews, 204, 103105. doi: 10.1016/j.earscirev.2020.103105.

45. Wu NP, Jiang SY, Liao QL, Pan JY, Dai BZ (2003) Lead and sulfur isotope geochemistry and the ore sources of the vein-type copper deposits in Lanping-Simao Basin, Yunnan province. Acta Petrologica Sinica, 19(4), 799–807 (in Chinese with English abstract). doi: 10.3321/j.issn:1000-0569.2003.04.023.

46. Xu XS, Wu JL (1983) Potash deposits in Mengyejing, Yunnan: A study of certain characteristics, geochemistry of trace elements and genesis of the deposits. Acta Geoscientifica Sinica, 5(5), 17–36 (in Chinese with English abstract). https://doi: CNKI:SUN:DQXB.0.1983-01-001.

47. Xu ZQ, Yang JS, Li WC, Li HQ, Cai ZH, Yan Z, Ma CQ (2013) Pako-Tethys system and accretionary orogen in the Tibet Plateau. Acta Petrologica Sinica, 29(6), 1847–60 (in Chinese with English abstract). https://doi: CNKI:SUN:YSXB.0.2013-06-002.

48. Xue GG, Gao JZ (2011) Volcanism and Halite Genesis in Shahejie Formation of Paleogene in Dongpu Depression. Journal of Oil and Gas Technology, 33(1), 53–56 (in Chinese with English abstract). https://doi: 10.1007/s11589-011-0776-4.

49. Yamamoto K, Sugisaki R, Arai F (1986) Chemical aspects of alteration of acidic tuffs and their application to siliceous deposits. Chemical Geology, 55(1–2), 61–76. doi: 10.1016/0009-2541(86)90128-2.

50. Yan MD, Zhang DW, Fang XM, Zhang WL, Song CH, Liu CL, Zan JB, Shen MM (2021a) New insights on the age of the Mengyejing Formation in the Simao Basin, SE Tethyan domain and its geological implications. Science China Earth Sciences, 64. https://doi: 10.1007/s11430-020-9689-3.

51. Yan MD, Zhang DW, Li MH (2021b) Research progress and new views on the potash deposits in the Simao and Khorat Basins. Earth Science Frontiers, 28(6), 10–28. https://doi: 10.13745/j.esf.sf.2021.1.40.

52. Yang SY, Li CX (1999) Research progress in REE tracer for sediment source. Advance in Earth Sciences, 14(2), 164–167 (in Chinese with English abstract). https://doi: 10.11867/j.issn.1001-8166.1999.02.0164.

53. Yang XZ, Yang ZL, Tao KY, Wang LB (2002) Formation temperature of chlorite in oil-bearing basalt. Acta Mineralogica Sinica, 22(4), 365–70 (in Chinese with English abstract). https://doi: 10.16461/j.cnki.1000-4734.2002.04.013.

54. Yang ZY, Besse J (1993) Paleomagnetic study of permain and mesozoic sedimentary rocks from northern thailand supports the extrusion model for indochina. Earth and Planetary Science Letters, 117(3–4), 525–552. doi: 10.1016/0012-821X(93)90101-E.

55. Yuan Q, Qin ZJ, Wei HC, Sheng SR, Shan FS (2013) The ore-forming age and palaeoenvironment of the Mengyejing Formation in Jiangcheng, Yunnan Province. Acta Geoscientifica Sinica, 34(5), 631–637 (in Chinese with English abstract). doi: 10.19476/j.issn.1671-2552.2021.01.011.

56. Yuan X, Yang QJ, Lv Y, Pan M, Gao AY, Xu F (2021) Response of magmatic activity to the closure of Changning-Menglian Palaeothys in western Yunnan: Evidence from geochemical study on granite in southern section of Lincang pluton. Geological Bulletin of China, 40(1), 125–137 (in Chinese with English abstract). doi: 10.12097/j.issn.1671-2552.2021.01.011.

57. Zhang CH, Liu JS, Zhang HP, Liu WM, Wu ZC (2012) Geochemistry characteristics of late Triassic potash-rich volcanic rocks and their origins in southern Lancangjiang belt, western Yunnan Province, China. The Chinese Journal of Nonferrous Metals, 22(3), 669–679 (in Chinese with English abstract). doi: 10.1007/s11430-012-0004-4.

58. Zhang CW, Gao DL, Ma HZ, Han WX (2010) A tentative discussion on material source of potash deposit in Lanping-Simao Basin. Journal of Salt Lake Research, 18(4), 12–18 (in Chinese with English abstract). doi: 10.1016/S1876-3804(11)60004-9.

59. Zhang H, Liu CL, Zhao YJ, Mischke S, Fang X, Ding T (2015) Quantitative temperature records of mid Cretaceous hothouse: Evidence from halite fluid inclusions. Palaeogeography, Palaeoclimatology, Palaeoecology, 437, 33–41. doi: 10.1016/j.palaeo.2015.07.022.

60. Zhao F, Li GJ, Zhang PF, Wang CB, Sun ZB, Tang X (2018) Petrogenesis and tectonic implications of the Lincang batholith in the Sanjiang, Southwest China: Constraints by geochemistry, zircon U-Pb chronology and Hf isotope. Acta Petrologica Sinica, 34(5), 1397–1412 (in Chinese with English abstract). https://doi: CNKI:SUN:YSXB.0.2018-05-013.

61. Zheng MP, Hou XH, Yu CQ, Li HP, Yin HW, Zhang Z, Deng XL, Zhang YS, Guo TF, Wei Z, Wang XB, An LY, Nie Z, Tan XH, Zhang XF, Niu XS (2015) The Leading Role of Salt Formation Theory in the Breakthrough and Important Progress in Potash Deposit Prospecting. Acta Geoscientica Sinica, 36(2), 129–139 (in Chinese with English abstract). doi: 10.3975/cagbs.2015.02.01.
62. Zheng MP, Liu WG, Xiang J, Jiang ZT (1983) On saline lakes in Tibet, China. Acta Geological Sinica, (2), 184–194 (in Chinese with English abstract). https://doi: CNKI:SUN:DZXE.0.1983-02-007

63. Zheng MP, Liu XF, Zhao W (2007) Tectonogeochmical and biological aspects of salt lakes on the Tibetan Plateau. Acta Geologica Sinica, 81(12), 1698–1708 (in Chinese with English abstract).

64. Zheng MP, Zhang Z, Yin HW, Tan XH, Yu CQ, Shi LF, Zhang XF, Yang JX, Jiao J, Wu GP (2014) A new viewpoint concerning the formation of the Mengyejing Potash Deposit in Jiangcheng, Yunnan. Acta Geoscientia Sinica, 35(1), 11–24 (in Chinese with English abstract). doi: 10.3975/cagsb.2014.01.03

65. Zhong H, Gao XY, Wu Y (2016) Discussion on petrology and genesis of the pisolitic tuff in Xinmin Formation in Arhorqinqi, Inner Mongolia. Geology and Resources, 25(2), 121–124 (in Chinese with English abstract). doi: 10.13686/j.cnki.dzyzy.2016.02.004

66. Zhu CY, Xia WJ, Yi HS, Wei YJ (1997) The tectonic nature and evolution of Mesozoic Lanping-Simao Basin. Journal of Chengdu University of Technology, 24(4), 25–32 (in Chinese with English abstract). https://doi: CNKI:SUN:CDLG.0.1997-04-002

Figures

Figure 1

Geological sketch map of Mengyejing potash mining area and location of well MK-3
Figure 2

Stratigraphic characteristics. (a) Stratigraphic sequence penetrated by the borehole MK-3. (b) Lithology column and sampling locations in the salt-bearing section of well MK-3.
Figure 3

Photomicrographs showing typical characteristics of sample MK-3-T under polarized light. (a) very small-sized grains. (b) Monocrystalline α-quartz. (c) Crystal fragment with irregular cracks. (f) Crystals with larger-sized grains. Cry- crystal fragment, Qtz-quartz, Anh-anhydrite.
Note: “+” is point of energy spectrum analysis

**Figure 4**

SEM images showing textural features of clay minerals. (a) Dominant chlorite and flaky-petaloid texture. (b), (c) Illite size and crystal structure. (d) Close-up of biotite displaying crystal size and texture.

**Figure 5**

SEM images of quartz particles in sample MK-3-T

**Figure 6**

Electron microscope image and energy spectrums of zircon, gypsum, quartz, and clinopyroxene in sample MK-3-T
Figure 7

Distribution patterns of REE in sample MK-3-T, basalt from Jingdong and Mojiang and granite from Lincang

Figure 8

$Zr/TiO_2$ vs. $Nb/Y$ showing typical volcanic rock types (modified after Winchester and Floyd 1977)