

# 新疆莎车拗陷晚白垩世吐依洛克组 古盐湖卤水浓缩阶段及成钾指示

——来自石盐流体包裹体的证据

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**内容提要:**石盐流体包裹体成分记录着古盐湖卤水的成分信息,可以揭示古盐湖卤水浓缩是否达到钾盐沉积阶段,从而进行盐湖成钾预测。新疆莎车拗陷位于塔里木盆地西南部,晚白垩世末期发育的吐依洛克组上部为石盐岩透镜体,已知最大纯盐厚度 264 m,被认为是找钾的有利层位。近年来,中国大部分古蒸发岩盆地中石盐流体包裹体成分已获得并进行成钾预测,但唯独没有对莎车拗陷石盐中流体包裹体成分开展测试。笔者等利用激光剥蚀电感耦合等离子体质谱法对莎车拗陷中喀拉塔勒盐点和塔什米里克盐点的石盐中流体包裹体成分进行测试,结果显示:喀拉塔勒盐点和塔什米里克盐点的 Br 平均含量分别为 65.50 mg/L、243.95 mg/L;  $Mg^{2+}/Ca^{2+}$  值分别为 0.43、0.32,反映了拗陷晚白垩世古盐湖沉积处于地质历史上的“方解石海”时期;平均溴氯系数分别为 0.11 和 0.39,揭示了莎车拗陷晚白垩世古盐湖卤水演化在塔什米里克盐点区域达到了钾盐沉积阶段。因此塔什米里克盐点所在区域具有良好的成钾前景,对今后在该拗陷钾盐成矿靶区圈定及古盐湖卤水演化研究具有重要的指示意义。

**关键词:**莎车拗陷;塔里木盆地;石盐;流体包裹体;卤水;浓缩阶段

古代钾盐找矿是一项艰巨而紧迫的任务(刘成林等,2016)。钾盐成矿与古环境密切相关(李皓楠等,2016),有利的成盐成钾环境一般受控于盆内次级凹陷、干旱气候条件以及古盐湖浓缩中心的变迁(曹养同等,2010)。莎车拗陷作为塔里木盆地中两大次级盆地之一,中新生代以来受多期次特提斯洋海水侵入影响,发育多期蒸发岩沉积旋回(Cao Yangtong, 2022)。拗陷前期找钾研究主要集中在盆地构造、蒸发岩地层及岩相特征、卤水地球化学及同位素、盐湖古环境以及古气候等方面(雍天寿,1984;雍天寿等,1986;陈荣林,1996;邵龙义等,2006;庄红红等,2013;桑洪等,2014;张亮等,2015;曹养同等,2011,2016;Liu Chenglin et al., 2018;王占兵等,2021;Liu Yidong et al., 2023),认为莎车拗陷具有优越的成钾条件和钾盐找矿潜力,特别是乌帕地区被认为是该拗陷有利的找钾区(刘成林等,2010;曹养同等,2021)。

由于蒸发岩中丰富的古环境信息(Boschetti et al., 2011),特别是石盐中的流体包裹体,其化学组成基本反映了古盐湖演化过程中古卤水的成分,即原生石盐流体包裹体不但记录了古盐湖的温度、化学组分,而且可以揭示大气成分的信息,为古环境研究提供直接地质记录(孟凡巍等,2018),从而被广泛用于研究盐湖沉积条件和重建特定地质时期海水的化学成分(Sun Xiaohong et al., 2013; Galamay et al., 2020)。通过对石盐流体包裹体成分研究来获取石盐沉积时期的卤水成分信息,判断古盐湖演化是否达到钾盐沉积阶段,已经在国内多个蒸发岩盆地测试,如四川盆地(孙小虹等,2016)、柴达木盆地(张星,2020;胡宇飞等,2021)、江汉盆地(Meng Fanwei et al., 2014;颜开,2024)、库车拗陷(徐洋等,2021)等,但对于莎车拗陷,没有开展此类工作,一般通过研究莎车拗陷野外露头及卤水的化学成分来揭示沉积阶段及成钾可能性(谭红兵等,2004,

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2005; 马万栋等, 2007; 伯英等, 2013; 曹养同等, 2021)。因此, 利用石盐流体包裹体成分来研究莎车拗陷古盐湖卤水的浓缩程度, 判断古盐湖演化是否达到钾盐沉积阶段, 具有重要意义。

### 1 地质背景

新疆莎车拗陷位于塔里木盆地西南部(图 1), 是在前震旦纪结晶基底上发育起来经后期构造叠加改造形成的前陆拗陷(胡望水等, 1997; 张玉宾, 1999)。该拗陷早白垩世为继承性走滑—断陷盆地, 晚白垩世—古近纪为前陆拗陷发展阶段, 拗陷沉降和沉积中心主要沿着西昆仑及南天山山前分布(王永等, 1996)。新生代以来, 拗陷在受到印度板块与亚洲板块碰撞所产生的远距离效应作用下, 发育了多个沉降中心及沉积盖层(曲国胜等, 2005)。拗陷晚白垩世—古近纪受特提斯海的影响, 经历了多次海侵—海退事件, 海侵范围逐渐从西昆仑山及南天山山前扩散至麦盖提斜坡带, 海相沉积逐渐转化为陆相沉积, 从而发育多套蒸发岩系地层(曹养同等, 2016; 王占兵等, 2021; Liu Yidong et al.,

2023), 其中主要的蒸发岩地层为上白垩统吐依洛克组和古新统阿尔塔什组。拗陷内吐依洛克组岩盐层在横向分布上呈不连续状。吐依洛克组发育早期, 随着海水逐渐从莎车拗陷退出, 在拗陷西南部受西昆仑山阻挡, 形成了长条形潟湖, 从而在西昆仑山前沉积了含膏泥岩夹石膏层、灰绿色、褐红色泥岩; 晚期海水继续西退, 莎车拗陷西部发育几个小盐湖, 在干旱气候条件下发育石盐岩透镜体沉积(张华等, 2012; 曹养同等, 2016)。因此, 吐依洛克组下部基本为泥岩、膏泥岩夹石膏, 偶夹灰岩, 在阿克彻依、克里阳、和田一带相变为砂砾岩、砾岩(郭宪璞等, 2008); 上部基本为石盐岩透镜体, 集中分布在西昆仑山前, 其中塔什米里克盐点具有最大规模。吐依洛克组上覆地层为阿尔塔什组, 发育巨厚的石膏岩、硬石膏岩, 几乎遍布整个莎车拗陷(Cao Yangtong, 2022)。

### 2 研究方法

#### 2.1 石盐样品及其流体包裹体观察

选取的石盐岩露头主要分布于莎车拗陷的西北部, 即西昆仑山前构造带(图 1), 自乌恰西部沿西昆

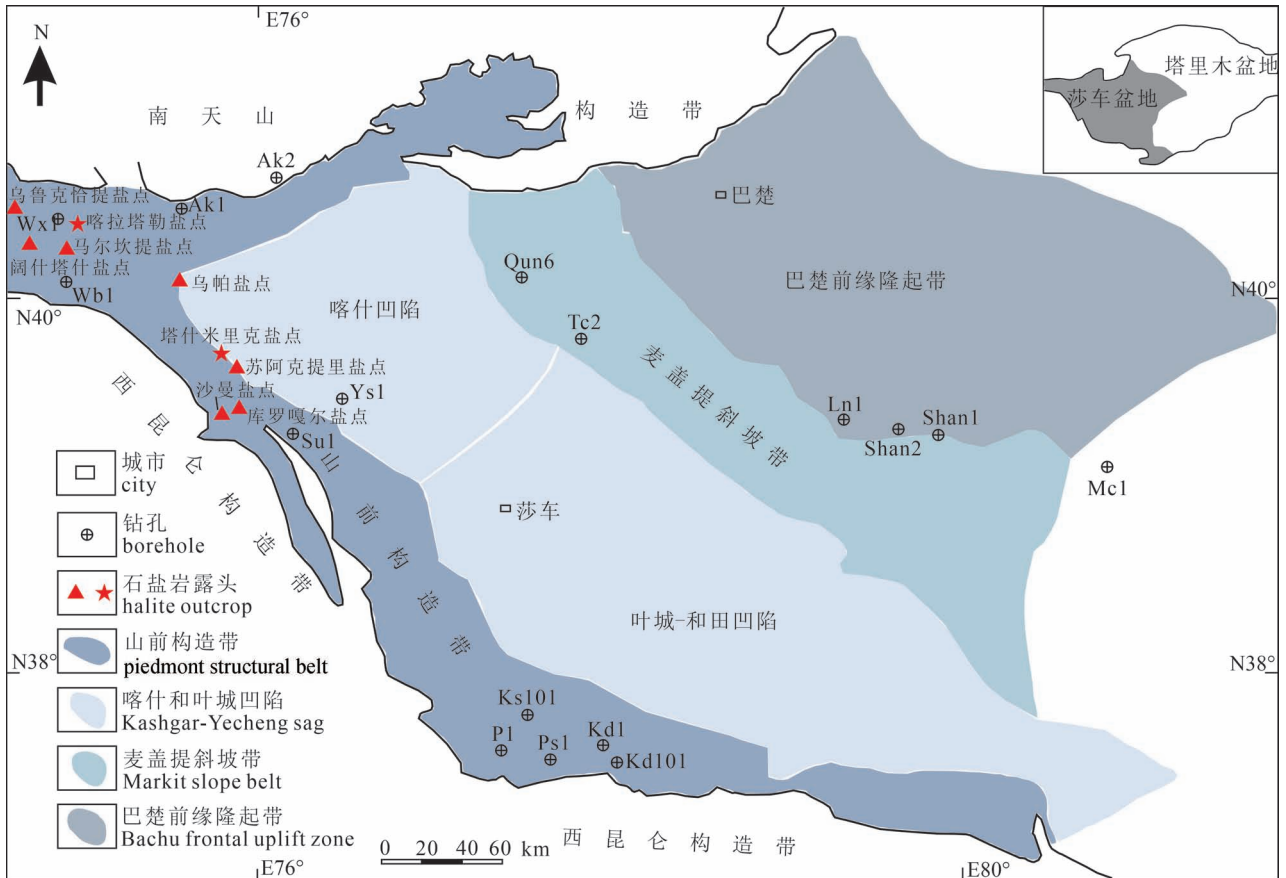


图 1 新疆莎车拗陷构造及主要石盐岩露头(据曹养同等, 2021)

Fig. 1 Structure and principal outcrops of evaporites in the Shache (Yarkand) Depression(from Cao Yangtong et al., 2021&)



图 2 新疆莎车拗陷喀拉塔勒盐点和塔什米里克盐点露头岩性:(a) 喀拉塔勒盐点露头;(b) 灰白色石盐岩(喀拉塔勒盐点露头);(c) 塔什米里克盐点露头;(d) 褐红色含石膏、泥砾石盐岩(塔什米里克盐点露头)

Fig. 2 The outcrop lithology of Kalatale salt point and Tashimilike salt point in the Shache Depression: (a) Kalatale salt point outcrop; (b) off-white rock salt(outcrops named Kalatale); (c) Tashimilike salt point outcrop; (d) maroon gypsum or boulder clay-bearing rock salt (outcrops named Tashimilike)

仑山前延续至喀什西南部一带。依据蒸发岩遥感地质解译及野外地质调查验证,共有 9 处石盐岩露头,其赋存层位为上白垩统吐依洛克组上段,表现为石盐岩透镜体沉积,在拗陷中横向上分布不连续,宽度和长度从数米到上百米不等。本次实验样品取自其中的喀拉塔勒盐点( $E74^{\circ}45'52''$ ,  $N39^{\circ}48'30''$ )和塔什米里克盐点(坐标  $E75^{\circ}39'00''$ ,  $N39^{\circ}04'01''$ )。喀拉塔勒盐点位于乌恰康苏—乌鲁克恰提公路旁边,山坡上无石盐岩出露,但见有人工挖掘的矿洞,受大气降水淋滤的影响,山坡上见白色盐霜及结晶盐壳,矿洞内岩性主要为灰白色含膏石盐岩(图 2a、b),呈透镜体状产出;塔什米里克盐点位于塔什米里克乡南约 2 km 处,面积约 0.4 km<sup>2</sup>,其岩性主要为褐红色含石膏、泥砾石盐岩(图 2c、d),多与泥砾、石膏等混

杂产出,部分会因泥质物浸染呈棕红色,受后期构造作用影响较小。喀拉塔勒盐点和塔什米里克盐点的部分样品分别见图 3a 和 3c。

显微镜下观察到的石盐流体包裹体包括纯液相和气液两种包裹体,但主要以单一液相为主。流体包裹体呈正方体或长方体,其组合以人字形或堆积型为主(图 3b、d)。喀拉塔勒盐点石盐流体包裹体大小多在 20~60  $\mu\text{m}$ ,最大可达 108  $\mu\text{m}$ ,而塔什米里克盐点的则多数在 10~50  $\mu\text{m}$ 。

## 2.2 石盐流体包裹体化学成分测定

选取莎车拗陷塔什米里克盐点 2 个样品(编号为 TSMLK-1, TSMLK-2)和喀拉塔勒盐点 2 个样品(编号为 KLTL-4, KLTL-5)用于分析,由于石盐样品中有青灰色和褐红色泥砾,为消除测试过程中杂质

对结果的影响,在测试之前首先挑选晶体形态较好的纯净石盐,使用无水乙醇对样品进行清洗,将石盐表面清洗干净。然后用小刀将处理好的石盐样品沿着其解理面切开,切至1~2 mm厚,之后进行显微镜岩相学观察,记录石盐中流体包裹体的大小、形态和分布特征,分析并挑选出原生石盐流体包裹体,将挑选好的原生石盐晶体用塑料自封袋封好,放入干燥剂中保存。

石盐原生流体包裹体成分的测试分析在中国地质科学院国家地质实验测试中心完成。测试所使用仪器为激光剥蚀电感耦合等离子体质谱仪(LA-ICP-MS),其型号为德国Finnigan公司制造的Element 2,激光器为NewWave公司的UP 213型,激光波长为213 nm。进行激光剥蚀采样时,使用高纯度的氦气

作为载气,从而提高剥蚀和传输效率。激光采样过程中采用点剥蚀模式,每个分析点总分析时间为90 s。首先在遮挡激光束使激光能量达到稳定的同时进行空白计数15 s,之后对样品中的一个点位进行连续剥蚀60 s,停止剥蚀后用氦气继续吹扫进样系统15 s,这样完成一个流体包裹体的测试。通过内外标结合的方法对石盐流体包裹体含量进行分析计算。

### 3 实验结果

在对4个石盐样品流体包裹体成分分析过程中,共对77个石盐流体包裹体进行了LA-ICP-MS测试。由于部分测试的包裹体位置可能离样品表面较远,激光束剥蚀不到,故检测不到包裹体的信息

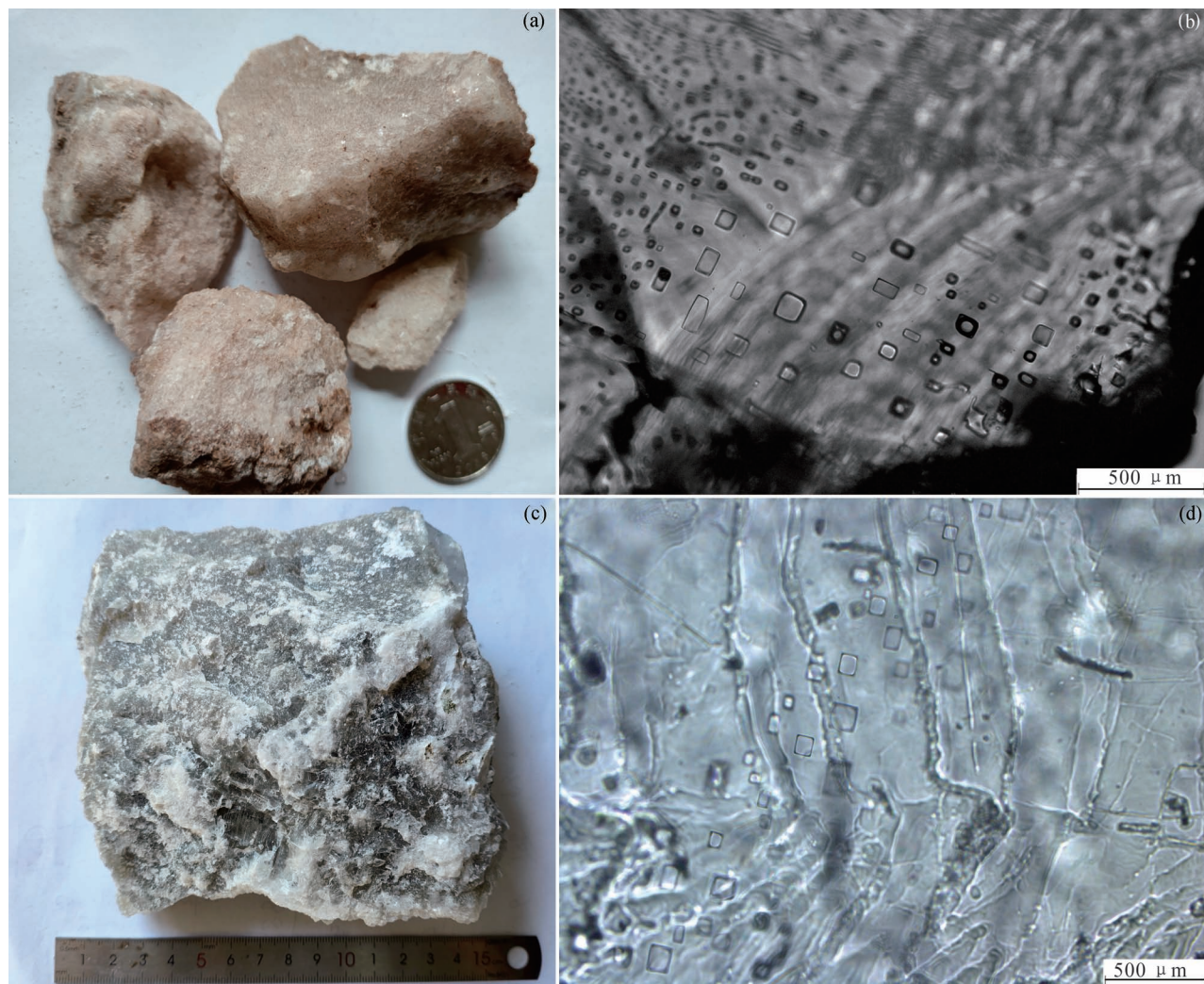


图3 莎车拗陷样品及石盐流体包裹体:(a) 喀拉塔勒石盐岩;(b) 喀拉塔勒石盐流体包裹体;  
(c) 塔什米里克石盐岩;(d) 塔什米里克石盐流体包裹体

Fig. 3 Sample and fluid inclusion of halite from the Shache Depression; (a) Kalatale halite; (b) fluid inclusion of Kalatale halite; (c) Tashimilike halite; (d) fluid inclusion of Tashimilike halite

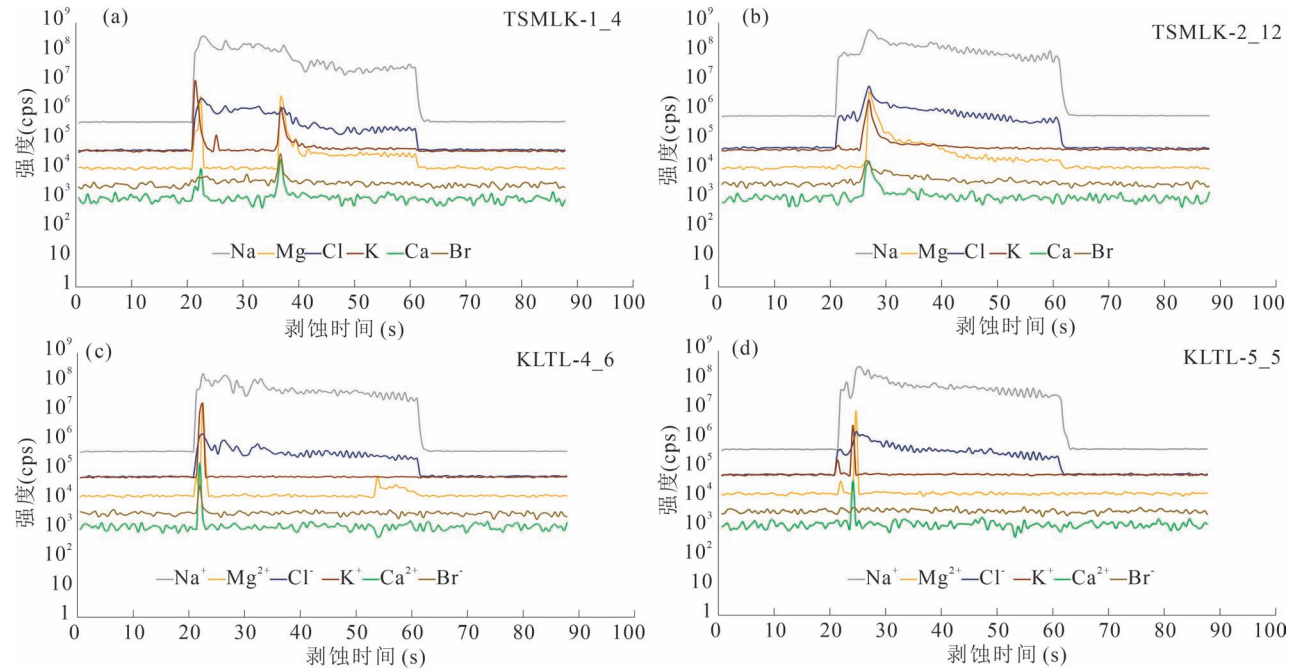


图 4 莎车拗陷石盐流体包裹体质谱信号强度随时间变化

Fig. 4 MS signal intensity vs. time for the fluid inclusion in halite from the Shache Depression

(图 4), 因此所有样品测试完后, 共获得流体包裹体成分数据 32 个, 分别为喀拉塔勒盐点 13 个, 塔什米里克盐点 19 个。统计特征见表 1 和表 2。

通过对成分数据分析可知: 喀拉塔勒盐点石盐

表 1 新疆莎车拗陷喀拉塔勒盐点石盐流体包裹体成分  
Table 1 The composition of fluid inclusions in halite of Kalatale salt point in the Shache (Yarkand) Depression

编号	$\rho$ (mg/L)					$1000\rho$ (Br <sup>-</sup> )
	Mg <sup>2+</sup>	Cl <sup>-</sup>	K <sup>+</sup>	Ca <sup>2+</sup>	Br <sup>-</sup>	$\rho$ (Cl <sup>-</sup> )
#-4_1	120	580418	1052	718	171	0.29
#-4_2	259	606609	1367	820	93.80	0.15
#-4_3	1405	615677	33.00	252	38.20	0.06
#-4_5	45.40	646305	20.10	106	59.40	0.09
#-4_6	1.60	552193	2.26	93.20	60.02	0.11
#-4_8	1513	580415	4350	2257	67.80	0.12
#-4_9	1701	630049	1818	4489	7.01	0.01
#-5_1	102	603194	142	124	49.40	0.08
#-5_3	41.30	665525	132	487	94.01	0.14
#-5_5	2562	636711	4102	17190	93.20	0.15
#-5_6	4.29	612063	3909	1729	65.50	0.11
#-5_9	4792	585656	23.50	131	40.10	0.07
#-5_10	0.24	600859	12.60	483	12.10	0.02
平均值	965.14	608898	1304	2221	65.50	0.11
最大值	4792	665525	4350	17190	171	0.29
最小值	0.24	552193	2.26	93.20	7.01	0.01

注: 编号栏的“#”=“KLTL”。

流体包裹体的质量浓度分别为: Cl<sup>-</sup>平均值为 608898 mg/L, 最大值为 665525 mg/L, 最小值为 552193 mg/L; K<sup>+</sup>平均值为 1304 mg/L, 最大值为 4350 mg/L, 最小值为 2.26 mg/L; Mg<sup>2+</sup>平均值为 965 mg/L, 最大值为 4792 mg/L, 最小值为 0.24 mg/L; Ca<sup>2+</sup>平均值为 2221 mg/L, 最大值为 17190 mg/L, 最小值为 93.20 mg/L; Br<sup>-</sup>平均值为 65.50 mg/L, 最大值为 171 mg/L, 最小值为 7.01 mg/L。

塔什米里克盐点石盐流体包裹体的质量浓度分别为: Cl<sup>-</sup>平均值为 624347 mg/L, 最大值为 671515 mg/L, 最小值为 599094 mg/L; K<sup>+</sup>平均值为 511.90 mg/L, 最大值为 4346 mg/L, 最小值为 6.37 mg/L; Mg<sup>2+</sup>平均值为 912.62 mg/L, 最大值为 3481 mg/L, 最小值为 9.52 mg/L; Ca<sup>2+</sup>平均值为 2827.38 mg/L, 最大值为 35342 mg/L, 最小值为 41.20 mg/L; Br<sup>-</sup>平均值为 243.95 mg/L, 最大值为 488 mg/L, 最小值为 80.1 mg/L。

## 4 讨论

钾(K<sup>+</sup>)是评价蒸发岩层钾矿化的关键指标。通常情况下, 捕获在石盐流体包裹体中的蒸发海水 Ca<sup>2+</sup>和 Mg<sup>2+</sup>的质量浓度高于 K<sup>+</sup>质量浓度。当 K<sup>+</sup>质量浓度高于 Ca<sup>2+</sup>和 Mg<sup>2+</sup>质量浓度时, 表明除了存在简单的海水蒸发作用之外, 还可能存在其他复杂的

地质过程。其中,石盐流体包裹体中高  $K^+$  质量浓度的可能解释之一是盆地中蒸发岩的再循环 (Taberner et al., 2002)。这种再循环往往发生于盆地经历多次不同大陆淡水或者海水入侵的情况下,每次入侵都可能溶解并重新沉积一些石盐 (Holser et al., 1966)。在高温气候条件下,盐水迅速蒸发,沉淀出钾盐,导致先前沉淀的钾盐矿物被新鲜的盐水溶解,从而  $K^+$  质量浓度增加。喀拉塔勒盐点石盐流体包裹体  $K^+$  质量浓度平均值高于  $Mg^{2+}$  质量浓度但低于  $Ca^{2+}$  质量浓度,塔什米里克盐点的石盐流体包裹体  $K^+$  质量浓度平均值都低于  $Mg^{2+}$  质量浓度和  $Ca^{2+}$  质量浓度。相比古新世阿尔塔什组,晚白垩世吐依洛克组缺失了石膏层。而在晚白垩世时期,莎车拗陷处于一个海退环境,发生了快速的海退事件 (Cao Yangtong et al., 2022)。这说明在这个时期,随着快速的海退,残留在拗陷中的海水没有得到新鲜海水的补充,在干旱气候条件下,经过蒸发浓缩作用后最终发育成石盐,形成了拗陷晚白垩世古卤水成分的特点。

地质历史时期,全球古海水成分演化经历了

表 2 新疆莎车拗陷塔什米里克盐点石盐流体包裹体成分  
Table 2 The composition of fluid inclusions in halite of Tashimilike salt point in Shache Depression

编号	$\rho$ (mg/L)					$\frac{1000\rho(Br^-)}{\rho(Cl^-)}$
	$Mg^{2+}$	$Cl^-$	$K^+$	$Ca^{2+}$	$Br^-$	
#-1_3	745	632888	58.4	337	194	0.31
#-1_4	222	606678	77.6	138	145	0.24
#-1_5	88.1	614053	40	463	230	0.37
#-1_6	298	599094	104	607	309	0.52
#-1_8	65.4	599914	41.4	276	186	0.31
#-1_10	141	652305	4346	35342	252	0.39
#-1_13	25.7	671515	804	2045	207	0.31
#-1_14	2146	622954	479	2050	160	0.26
#-2_1	2983	636027	322	468	236	0.37
#-2_2	9.52	624975	71.7	41.2	207	0.33
#-2_4	3481	629647	513	1668	363	0.58
#-2_5	996	603994	6.37	164	80.1	0.13
#-2_6	220	614439	1072	66	204	0.33
#-2_7	2176	607255	432	1335	255	0.42
#-2_8	384	655514	36.3	2190	246	0.38
#-2_9	193	639643	57.3	875	488	0.76
#-2_12	290	613547	133	489	289	0.47
#-2_13	1415	617897	767	3561	203	0.33
#-2_15	1461	620255	365	1605	381	0.61
平均值	912.62	624347	511.90	2827.4	243.95	0.39
最大值	3481	671515	4346	35342	488	0.76
最小值	9.52	599094	6.37	41.20	80.10	0.13

注:编号栏的“#”=“TSMILK”。

“方解石海”和“文石海”的周期性波动 (Sandberg, 1983)。在不同的地质历史时期,因海水的化学成分不同会形成不同的蒸发岩矿物 (孟凡巍等, 2012)。晚白垩世—古新世,受特提斯海水的影响,莎车拗陷发生多次大规模的海侵—海退事件,为蒸发岩提供了丰富的物质来源 (Cao Yangtong, 2022)。古海水  $Mg^{2+}/Ca^{2+}$  值小于 2,表明其属于“方解石海”时期 (Lowenstein et al., 2001)。喀拉塔勒盐点和塔什米里克盐点的石盐流体包裹体中  $Mg^{2+}/Ca^{2+}$  值分别为 0.43 和 0.32,表明其正处于“方解石海”时期。

$Br^-$  与  $Cl^-$  的化学行为极其相似,在自然界一般不以溴化物矿物产出,而是以类质同象的形式代替氯产出。因此,卤水或蒸发岩矿物中的  $Br^-$  是反映盐湖卤水蒸发程度和浓缩阶段的重要指标,其值越高通常表明盐湖蒸发越强烈 (Liu Chenglin et al., 2023)。正常海水逐渐蒸发沉淀的原生石盐中  $Br^-$  含量最小值一般为 65~75 mg/L (Bukowski et al., 2020)。对于喀拉塔勒盐点和塔什米里克盐点,石盐流体包裹体中的  $Br^-$  含量平均值分别为 65.50 mg/L、243.95 mg/L,表明莎车拗陷晚白垩世古盐湖卤水来源为海水。古盐湖卤水浓缩过程中,首先是石膏析出,然后是氯化物,如石盐、钾盐和光卤石,最后是共生结点。盐类矿物中溴的含量取决于卤水中溴的质量浓度 (Siemann, 2003)。因此,古盐湖卤水在浓缩过程中,卤水中  $Br^-$  的含量在不断变化,即使在卤水的同一浓缩阶段,不同的盐类矿物中,其溴含量也不一样。由于盐类矿物成因复杂,经常会有其他矿物或者杂质伴生,那么必然会影响到样品中  $Cl^-$  和  $Br^-$  的绝对含量。因此引入  $Br^- \times 10^3 / Cl^-$  值 (即溴氯系数) 来消除这一不利影响,从而反映古盐湖卤水蒸发浓缩的实际情况。通过对世界各地不同时代古盐湖中各个沉积阶段析出的石盐分析,在正常海水蒸发浓缩的各个阶段所形成的矿物,其溴氯系数范围各不相同,分别是:石盐阶段为 0.11~0.31、钾盐沉积阶段为 0.31~0.45、光卤石沉积阶段为 0.45~0.68,共结沉积阶段大于 0.68 (程怀德等, 2008; 胡挺等, 2011)。新疆库车拗陷石盐溴氯系数范围为 0.0002~0.0303 (刘群, 1981)。莎车拗陷乌帕地区盐泉水的溴氯系数达到 0.54,并且在地表的结晶盐壳中发现了光卤石 (曹养同等, 2021)。喀拉塔勒盐点溴氯系数范围为 0.01~0.29,平均值为 0.11;塔什米里克盐点溴氯系数范围为 0.13~0.76,平均值为 0.39,明显高于库车拗陷。这表明塔什米里克盐点所在区域古盐湖演化则达到了钾盐沉积阶

段,为有利的成钾指示。

## 5 结论

通过对莎车拗陷喀拉塔勒和塔什米里克这两处盐点的石盐中流体包裹体成分分析,获得以下认识:

(1)喀拉塔勒盐点和塔什米里克盐点石盐流体包裹体的  $Mg^{2+}/Ca^{2+}$  值分别为 0.43 和 0.32,表明莎车拗陷晚白垩世古盐湖沉积处于地质历史上的“方解石海”时期。

(2)喀拉塔勒盐点和塔什米里克盐点的  $Br^-$  含量平均值分别为 65.50 mg/L、243.95 mg/L,表明莎车拗陷古盐湖卤水来源为海水。喀拉塔勒盐点溴氯系数范围为 0.01~0.29,平均值为 0.11;而塔什米里克盐点溴氯系数范围为 0.13~0.76,平均值为 0.39,表明塔什米里克盐点所在区域古盐湖演化则达到了钾盐沉积阶段,为有利的成钾区。

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# Sedimentary stages and indications of potassium formation in Late Cretaceous Tuylock Formation in Shache (Yarkand) Depression

## —Evidence from fluid inclusions of halite

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**Objectives:** The composition of fluid inclusions of halite records the composition information of brine in ancient salt lake, which can reveal whether brine concentration reaches the stage of potassium salt deposition and predict potassium formation in salt lake. The Shache(Yarkand) Depression in Xinjiang is located in the southwest of Tarim Basin. The upper part of Tuylock Formation developed at the end of Late Cretaceous is a lens of rock salt with a maximum known pure salt thickness of 264 m, which is considered to be a favorable horizon for searching for potassium. In recent years, fluid inclusions in most ancient evaporite basins in China have been obtained and predicted for potassium formation, but the inclusions in Shache Depression have not been tested.

**Methods:** In this paper, the fluid inclusions in halite at Kalatale salt point and Tashimilike salt point in Shache Depression were measured by inductively coupled plasma mass spectrometry.

**Results:** The results show that the average  $\text{Br}^-$  content of Kalatale salt point and Tashimilike salt point is 65.50 mg/L and 243.95 mg/L, respectively. The  $\text{Mg}^{2+}/\text{Ca}^{2+}$  ratios were 0.43 and 0.32, respectively, reflecting that the Late Cretaceous palaeosalt lake deposits in the basin were deposited during the "calcite sea" period of geological history. The mean bromo—chlorine coefficients were 0.11 and 0.39, respectively. It is revealed that the Late Cretaceous ancient salt lake brine evolution in Shache Depression reached the potassium salt deposition stage in the Tashimilike salt point area.

**Conclusions:** The area where the Tashimilike salt point is located has a good potassium formation prospect, which is of great significance for the delineation of the potassium salt metallogenic target area in this basin and the study of the ancient salt lake brine evolution.

**Keywords:** Shache Depression; Tarim Basin; halite; fluid inclusions; brine; enrichment stage

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