

# 火山活动影响下的碱湖优质烃源岩成因及其对页岩油气勘探和开发的启示

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**摘要:**为明确火山活动控制陆相含油气盆地优质烃源岩发育的作用机制,对古今火山、碱湖以及优质烃源岩这三者的相互联系进行广泛的文献调研,认为碱湖是联系火山活动与优质烃源岩发育的中间场所。火山活动喷发的CO<sub>2</sub>进入热液、地下水或河流中,加速硅酸盐水解,产生大量HCO<sub>3</sub><sup>-</sup>,输入湖泊中导致水体pH值升高,形成碱湖。而碱湖中高pH值可以活化Mo、磷酸盐和硅酸盐等多种营养元素和化合物,提高水体的初级生产力;同时也可以使硅质在水体中的溶解度呈指数增大,这种溶解的硅质在有机质初始降解等pH值降低过程中易发生沉淀,形成硅质保护层,避免有机质的进一步降解。由此提出火山活动-碱湖-优质烃源岩的成因链模式,该模式形成的页岩油气储集层微晶白云石等矿物含量高,凝灰物质易发生蒙脱石—沸石—钾长石—钠长石转变,可以有效增加页岩油气储集层的脆性和微孔隙。

**关键词:**初级生产力;硅化;优质烃源岩;火山活动;碱湖

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## Genesis of high-quality source rocks in volcano-related alkaline lakes and implications for the exploration and development of shale oil and gas

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**Abstract:** In order to clarify the controlling mechanisms of volcanic activities on the development of high-quality source rocks in non-marine petroliferous basins, this study summarizes the relationships between volcanic activity, alkaline lakes and high-quality source rocks through an extensive review of previous studies and proposes that alkaline lakes act as a vital link between volcanic activities and source rocks. It is suggested that large amount of CO<sub>2</sub> emitted by volcanic activities would enter hydrothermal fluids, underground waters or rivers and then produce a large amount of HCO<sub>3</sub><sup>-</sup> through accelerated silicate hydrolysis process, leading to the formation of alkaline lakes. The high pH in alkaline lakes would activate a variety of nutrient elements and compounds such as Mo, phosphate and silicate, thus improving the primary productivity of water body. In addition, the high pH also would lead to an exponential increase of silica solubility in alkaline waters. During the process of pH decrease by initial degradation of organic matter, the dissolved silica would precipitate and form a siliceous layer, which could effectively prevent further degradation of organic matter. Based on these assumptions, this study proposes a genetic model for volcanism-alkaline lake-high-quality source rocks chain, which is the main reason of the occurrence of brittle and porous shale reservoirs for oil due to a high content of microcrystalline dolomite and tuff materials that are easily converted from montmorillonite to zeolite, potassium feldspar, and sodium feldspar.

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火山活动喷发的火山灰物质,降落到附近的湖泊或海洋表面能迅速发生水解,释放大量的营养物质和金属元素,短时间内可以引起水体中浮游藻类勃发<sup>[1-5]</sup>,提高水体的初级生产力。沉积盆地优质烃源岩的发育,往往需要异常丰富的有机质来源,因此火山-热液活动常被认为是优质烃源岩发育的有利条件之一<sup>[6-7]</sup>。这种理论背景下,火山灰对应的沉积层内应具有较高的有机质含量。然而,绝大多数湖相沉积岩中纯凝灰岩层的有机质含量并不丰富,如美国西部始新统绿河组云质油页岩有机质非常丰富(*TOC*高达20%),但其中的凝灰岩夹层几乎不含有有机质<sup>[8]</sup>。沉积盆地中与火山岩同期的沉积地层也并非极富有机质。这些都说明了火山-热液活动造成的同期短暂生物勃发并不是湖盆优质烃源岩发育的主要原因,上述模式忽略了火山活动对伴生或相邻湖泊性质的改变。事实上,火山灰喷发具有事件性、间歇性,而沉积盆地优质烃源岩的形成是由季节性生物发育积累而成,需要长期稳定、利于生物勃发和有机质保存的湖泊环境。研究火山-热液活动与优质烃源岩的联系,应重点关注火山活动对湖盆性质的长期改变。

对现代火山岩区的文献调研发现,火山活跃区常伴生一类特殊的湖泊,其湖水呈碱性( $\text{pH}>9$ ),盐度较高,是世界上初级生产力(含碳)最高的水生环境之一<sup>[9-13]</sup>。一般河流和湖泊的初级生产力平均值仅为 $0.6 \text{ g/m}^2 \cdot \text{d}$ ,而碱湖的初级生产力却可超过 $10 \text{ g/m}^2 \cdot \text{d}$ <sup>[14-15]</sup>。地质历史上,发育优质烃源岩的碱性湖盆亦往往与火山活动密切相关,如世界著名的美国绿河组(*TOC*=4.1%~19.0%)<sup>[16]</sup>、南襄盆地泌阳凹陷核桃园组(平均*TOC*>1.82%)<sup>[17]</sup>、准噶尔盆地西北缘二叠系风城组(平均*TOC*>1.0%)<sup>[18]</sup>等。为此本文提出碱湖可能是火山活动与陆相优质烃源岩关联的中间介质,火山活动借助于形成碱湖造就了优质烃源岩的形成。

## 1 碱湖的界定及古老碱湖识别

自然界湖泊水体中主要有8种离子: $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Mg}^{2+}$ ,  $\text{Ca}^{2+}$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{CO}_3^{2-}$ ,  $\text{HCO}_3^-$ 。前苏联科学家瓦里亚特科根据湖水中主要离子的相对含量将湖泊划分为硫酸盐型( $\text{Na-K-Mg-Cl-SO}_4$ )、氯化物型( $\text{Na-K-Mg-Ca-Cl}$ )和碳酸盐型( $\text{Na-K-Mg-Cl-SO}_4\text{-CO}_3$ )3种类型。碱湖属于碳酸盐型湖泊,湖水 $\text{pH}$ 值大于9,阴离子主要为 $\text{CO}_3^{2-}$ 和 $\text{HCO}_3^-$ 。自然界中盐湖多以硫酸盐型为主,

碳酸盐型和氯化物型较为少见。硫酸盐型湖泊在地质记录中同样数量上占优势,因此以往研究也多关注于该类咸化湖盆。始新世中国大陆发育多个咸化湖盆,如柴达木盆地,东营凹陷、东濮凹陷、潜江凹陷以及泌阳凹陷等,仅泌阳凹陷发育碳酸盐型湖泊,其余均发育硫酸盐型湖泊。相对于硫酸盐矿物而言,碱性矿物非常罕见<sup>[19]</sup>。虽然碱湖数量很少,但其不仅发育优质烃源岩,而且还发育具有重要经济价值的天然碱矿和硼矿,因而极具研究价值。

古老碱湖的识别主要基于沉积物中盐类矿物类型。水体中离子的活性顺序是 $\text{K}^+>\text{Na}^+>\text{Mg}^{2+}>\text{Ca}^{2+}$ ,  $\text{Cl}^->\text{SO}_4^{2-}>\text{HCO}_3^->\text{CO}_3^{2-}$ ,离子活性越大,越不易从水体中析出沉淀。硫酸盐型和碳酸盐型湖泊在蒸发早期,沉淀矿物均以方解石和白云石为主;中期两者开始显现差异,硫酸盐型湖泊的碳酸根离子消耗殆尽,开始沉淀硫酸盐矿物,而碱湖由于碳酸根离子仍然富存,待 $\text{Ca}^{2+}$ 和 $\text{Mg}^{2+}$ 消耗完后,开始沉降Na的碳酸盐矿物;蒸发晚期两种盐湖均以氯盐和钾盐为主。因此,富钠碳酸盐矿物( $\text{Na-carbonate}$ )为碱湖的特征矿物,常见类型见表1。泡碱( $\text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O}$ )、天然碱 $[(\text{Na}_3(\text{HCO}_3)(\text{CO}_3)2\text{H}_2\text{O})]$ 和苏打石( $\text{NaHCO}_3$ )是3类主要的富钠碳酸盐矿物,其形成环境存在差异:苏打石形成于高 $\text{CO}_2$ 分压环境下,对温度要求不高;天然碱形成于低温、低 $\text{CO}_2$ 分压背景中;而泡碱形成于略高温、低 $\text{CO}_2$ 分压背景中。因此,碱湖沉积物中不同的富钠碳酸盐矿物富集,可以指示温度和大气中的 $\text{CO}_2$ 分压。除了上述富钠碳酸盐矿物外,碱湖沉积物中还发育碳酸钠钙石 $[(\text{Na}_2\text{Ca}_2(\text{CO}_3)_3 \cdot \text{H}_2\text{O})]$ 、钙水碱 $[(\text{Na}_2\text{Ca}(\text{CO}_3)_2 \cdot 2\text{H}_2\text{O})]$ 、单斜钠钙石 $[(\text{Na}_2\text{Ca}(\text{CO}_3)_2 \cdot 5\text{H}_2\text{O})]$ <sup>[20]</sup>、氯碳钠镁石 $[(\text{Na}_3\text{MgCl}(\text{CO}_3)_2)]$ 、碳钠镁石 $[(\text{Na}_2\text{Mg}(\text{CO}_3)_2)]$ 以及磷钠镁石 $[(\text{Na}_3\text{Mg}(\text{PO}_4)(\text{CO}_3))]$ 等其他类型富钠碳酸盐矿物。

对于尚未达到饱和、没有富钠碳酸盐和氯盐沉淀的碱性湖泊,如土耳其现代湖泊Lake Van和早白垩世南大西洋处的裂谷湖泊,主要处于Ca-Mg碳酸盐沉淀的早期蒸发阶段,富镁粘土矿物的出现和富集可以作为重要识别标志。碱湖环境中常出现的富镁粘土矿物包括:坡缕石 $[\text{palygorskite}, (\text{Mg}, \text{Al})_5(\text{Si}, \text{Al})_8\text{O}_{20}(\text{OH})_2 \cdot 8\text{H}_2\text{O}]$ 、海泡石 $[(\text{sepiolite}, \text{Mg}_4\text{Si}_6\text{O}_{15}(\text{OH})_2 \cdot 6\text{H}_2\text{O})]$ 、皂石 $[(\text{saponite}, \text{Ca}_{0.25}(\text{Mg}, \text{Fe})_3(\text{Si}, \text{Al})_4\text{O}_{10})(\text{OH})_2 \cdot n\text{H}_2\text{O})]$ 、硅镁石 $[(\text{stevensite}, (\text{Ca}, \text{Na})_x\text{Mg}_{3-x}(\text{Si}_4\text{O}_{10})(\text{OH})_2)]$ 、蜡蛇纹石 $[(\text{kerolite}, \text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2 \cdot n\text{H}_2\text{O})]$

表1 古老碱湖中常见的富钠碳酸盐矿物

Table 1 Main sodium carbonate minerals common in ancient alkaline lakes

| 矿物类型               | 化学式                                                                | 现代碱湖是否存在 | 成因            | 文献      |
|--------------------|--------------------------------------------------------------------|----------|---------------|---------|
| 天然碱(trona)         | $\text{Na}_3(\text{HCO}_3)(\text{CO}_3) \cdot 2\text{H}_2\text{O}$ | 是        | 水体蒸发浓缩, 浅水    | [21]    |
| 苏打石(nahcolite)     | $\text{Na}(\text{HCO}_3)$                                          | 是        | 原生或成岩转化       | [22-24] |
| 泡碱(natron)         | $\text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O}$                | 是        | 原生或成岩转化       | [25]    |
| 碳酸钠钙石(shortite)    | $\text{Na}_2\text{Ca}_2(\text{CO}_3)_3 \cdot \text{H}_2\text{O}$   | 否        | 钙水碱失水转化       | [24]    |
| 钙水碱(pirssonite)    | $\text{Na}_2\text{Ca}(\text{CO}_3)_2 \cdot 2\text{H}_2\text{O}$    | 否        | 斜碳钠钙石成岩转化     | [24]    |
| 单斜钠钙石(gaylussite)  | $\text{Na}_2\text{Ca}(\text{CO}_3)_2 \cdot 5\text{H}_2\text{O}$    | 是        | 水体蒸发浓缩        | [24]    |
| 磷钠镁石(bradleyite)   | $\text{Na}_3\text{Mg}(\text{PO}_4)(\text{CO}_3)$                   | —        | 成岩作用          | [26]    |
| 氯碳酸钠镁石(northupite) | $\text{Na}_3\text{MgCl}(\text{CO}_3)_2$                            | 是        | 原生或碳酸钠钙石与石盐接触 | [21]    |
| 碳镁钠石(eitelite)     | $\text{Na}_2\text{Mg}(\text{CO}_3)_2$                              | —        | 原生或成岩转化       | [27]    |

注:以美国绿河盆地 Green River 组、土耳其 Bepazari 盆地 Bepazari 组和中国准噶尔盆地风城组为例。

等。这些镁粘土矿物主要在地表或近地表环境下形成,并且除坡缕石和皂石外,其余镁粘土矿物均不含铝。这主要是由于在粘土矿物晶体结构中, Mg-O 链比 Si-O 和 Al-O 链更易遭受破坏,因此镁粘土矿物相较铝粘土矿物更易遭受溶解风化<sup>[28-29]</sup>。

## 2 火山活动控制碱湖的形成

### 2.1 现今碱湖与火山活动的联系

现今世界上大多数碱湖均分布于受火山活动影响的亚热带副高压干旱或半干旱区域(图1;表2),并且主要聚集在以下3个火山活跃带<sup>[30]</sup>。1)东非裂谷系:碱湖主要分布于东非裂谷系东部分支富年轻火山岩区(喷发时间为渐新世至今,以第四纪以来为主),大多为浅水湖,直接接受热液供给,沉积物中含有丰富的火山物质,如 Lake Bogaria 湖泊,其湖缘断裂周围发育约200处热泉<sup>[31]</sup>,温度在36~100℃,盐度为1~15 g/L, pH 值为7~9.9,水体为 $\text{NaHCO}_3$ 型<sup>[32]</sup>;而东非裂谷西部分支新近纪期间火山活动弱,湖泊以淡水深湖为主,湖底沉积物中没有火山物质<sup>[33]</sup>。2)北美西南部和南美安第斯造山带:碱湖主要位于太平洋东部火山活动活跃区,如 Mono Lake, Albert Lake, Lake Atlacoy 等。3)亚洲中部:碱湖聚集区向西延伸到里海,向东延伸到中国西藏和青海地区,如中国西藏羌南碳酸盐型盐湖带。青藏高原湖泊根据水化学性质可分为5个带,最南部是碱湖带,其形成与地热水直接补给有关<sup>[34]</sup>,且该区域新近纪火山岩分布广泛<sup>[35]</sup>,水体中 B, Li, Cs, K 元素表现为高异常。除了上述区域外,其他火山活跃区也零星存在碱湖。世界上最大的碱湖 Lake Van 位于土耳其 Eastern Anatolia 高原,面积3 522 km<sup>2</sup>,最深处可达460 m<sup>[36]</sup>,湖水 pH 值为9.5~9.9,盐度为21‰~24‰,

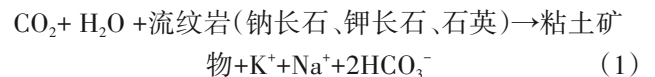
碱度为155 mmol/L<sup>[37]</sup>。Lake Van 湖泊的碱化与附近 Nemrut 火山喷发密切相关,湖底沉积物广泛记录了 Nemrut 火山喷发事件,含有至少12层熔结凝灰岩和40层火山碎屑<sup>[28-39]</sup>。

### 2.2 地质历史时期碱湖与火山活动的联系

地质历史时期,碱性含油气湖盆同样与火山或热液活动有关(表2)。世界上研究程度最高的碱性湖盆位于美国西部,主要地层为始新统绿河组,该组发育世界上最大碱矿,含有6层标志性凝灰岩层<sup>[55]</sup>。虽然在绿河组湖盆邻近地区并未发现同时期的火山活动,但 Hammond 等人(2019)利用碎屑锆石进行物源分析时发现,距离湖盆约200 km 的 Colorado Mineral Belt 是湖盆的主物源之一,该造山带在始新世火山活动强烈,可为湖盆提供岩浆和热液水<sup>[63]</sup>。世界上第二大碱矿发育于土耳其 Bepazari 盆地的中新统,该套地层中同样含有多套凝灰岩夹层<sup>[26]</sup>。中国准噶尔盆地玛湖凹陷下二叠统风城组为含碱地层,其下部地层发育玄武岩、安山岩以及熔结凝灰岩,上部地层同样发育有丰富的凝灰物质<sup>[64-65]</sup>。

### 2.3 火山活动控制下碱湖的形成机制

碱湖与火山活动的密切联系说明,除气候因素外,火山活动是造成湖泊水体呈碱性的主要原因。碱湖的主要特征是水体中 $(\text{HCO}_3^- + \text{CO}_3^{2-})$ 含量高于 $\text{Ca}^{2+}$ 的含量。花岗质和流纹质岩石化学风化可生成 $\text{HCO}_3^-$ ,流入湖泊后发生水解生成 $\text{OH}^-$ ,提高水体的 pH 值。然而,在漫长的地质历史中,以花岗质或流纹质岩石为物源的湖泊并不少见,但碱湖却较为罕见<sup>[19]</sup>。



化学反应式(1)中, $\text{CO}_2$ 含量的大量增加可以加速

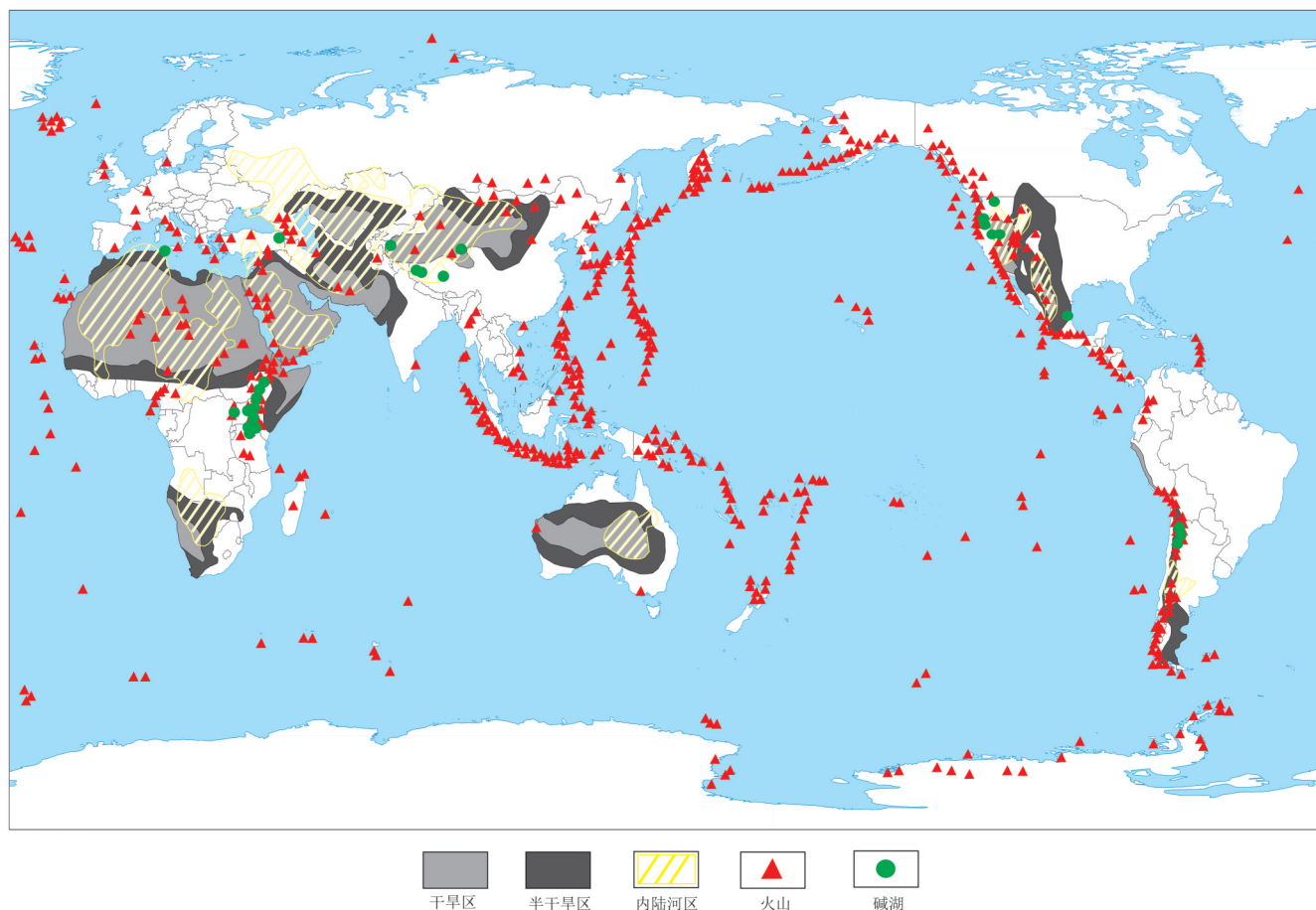


图1 全球碱湖分布(据文献[30]绘制)

Fig. 1 Global distribution of alkaline lakes (according to reference[30])

流纹质母岩的化学风化,提高物源水体中 $\text{HCO}_3^-$ 含量,进而导致湖泊水体大幅度碱化。Earman 等人(2005)通过对比北美洲 San Bernardino 盆地与周围盆地的地下水化学物质组成,发现仅 San Bernardino 盆地的地下水呈碱性,而该盆地与周围盆地经历了相同的构造-气候演化,唯一区别在于 San Bernardino 盆地周围山体发育新近纪—第四纪玄武火山活动,由此提出了大量 $\text{CO}_2$ 的输入是自然界湖泊呈碱性和天然碱形成的必要条件<sup>[66]</sup>。幔源或岩浆 $\text{CO}_2$ 溶解到热液、地下水或河流中,加速硅酸盐矿物的化学风化,产生大量 $\text{HCO}_3^-$ ,进而提高了地下水和地表水中 $\text{Na}^+$ 和 $\text{CO}_3^{2-}$ 的含量<sup>[23, 54-55, 66]</sup>。美国加利福尼亚 Searles Lake 700 m 的岩心中,291 m 以下部分以硫酸盐矿物为主,发育硬石膏、钙芒硝和石盐,而 291 m 以上部分以含钠碳酸盐矿物为主,发育钙水碱、天然碱和石盐。Lowenstein 等人(2016)通过研究石盐包裹体成分证明了 291 m 处湖泊类型的转变与当时热泉和岩浆活动携带的大量 $\text{CO}_2$ 溶解到湖水有关<sup>[52]</sup>。岩浆成因的 $\text{CO}_2$ 溶解到源头水系,同样也是美国绿河组湖泊呈碱性的主要原因。中国泌阳凹陷核桃

园组沉积时期,凹陷附近没有火山岩,可能是凹陷北部的源区秦岭造山带存在同期火山活动,喷发的大量 $\text{CO}_2$ 溶解到源头水系,造成湖水碱化。

火山活动常伴随地层的局部抬升,造成湖泊水体封闭,这是湖泊水体能够保持碱性的另一重要原因。土耳其 Lake Van 一直以淡水沉积为主,大约 0.03 Ma,由于湖泊西部的 Nemrut 火山强烈喷发,火山口及其周围的穹隆强烈隆升,造成 Van Basin 封闭, Lake Van 水体才发生碱化<sup>[39]</sup>。东非裂谷处的 11 个湖泊也正因为是内流型湖盆,无水体流出才演变为碱湖<sup>[67]</sup>。

### 3 碱湖控制优质烃源岩的形成

相对于其他类型湖盆,碱湖中沉积的烃源岩具有有机质丰度高、类型好的特点,笔者通过分析研究认为这主要源于碱湖下列独有的特征。

#### 3.1 异常高的初级生产力

碱湖被看为自然界最富营养的水库<sup>[68]</sup>。碱湖异

表2 国内外典型碱湖发育背景及岩矿信息

**Table 2 Development background, rocks and minerals of typical alkali lacustrine deposits all over the world (all the alkali lakes have reached the precipitation salinity of Na-carbonate except for Lake Van and early Cretaceous rift lakes in the south Atlantic)**

| 湖泊或古老含碱地层                                   | 国家       | 时代          | 主要碱性矿物                                       | 气候背景                                                    | 火山碎屑    | 火山岩石类型                              | 热液影响                              | 文献来源       |
|---------------------------------------------|----------|-------------|----------------------------------------------|---------------------------------------------------------|---------|-------------------------------------|-----------------------------------|------------|
| Lake Van                                    | 土耳其      | 现代          | Calcite(碱湖早期)                                | 河流径流 2km <sup>3</sup> /a;<br>蒸发量 3.8 km <sup>3</sup> /a | 有, 12 层 | Nemrut 和 Süphan 两个火山口, 岩石类型为过碱性流纹岩  | 较少                                | [40-42]    |
| Specchio di Venere Lake                     | 意大利      | 更新世—现代      | aragonite, calcite, dolomite                 | 半干旱                                                     | 有       | 位于火山岛上, 富钠超碱性流纹岩                    | 第二来源                              | [30]       |
| Lake Natron                                 | 坦桑尼亚     | 现代          | Trona, gaylussite                            | 年降雨量 600 ~ 900 mm, 年蒸发量 2800 mm                         | 有       | Oldoinyo Lengai 火山口: 碱性硅酸盐岩浆, 碳酸盐熔岩 | 主要                                | [43]       |
| Lake Bogaria                                | 肯尼亚      | 全新世—现代      | Trona, nahcolite, gaylussite                 |                                                         | 有       | —                                   | 发育 200 多个 Na-HCO <sub>3</sub> 型热泉 | [44-47]    |
| Lake Magadi                                 | 肯尼亚      | 全新世—现代      | Trona, nahcolite,                            |                                                         | 有       | 玄武岩和碱性粗面岩                           | 主要来源                              | [48]       |
| Lake Searles                                | 美国加利福尼亚  | 更新世—现代      | Trona, nahcolite, halite, burkeite, shortite | 干旱气候                                                    | 有       | 硅质火山岩                               | 第二来源                              | [49-52]    |
| 青藏高原羌南碳酸盐型盐湖带                               | 中国西藏     | 现代          | 多种                                           | 干旱气候                                                    | 下部地层含有  | 钙碱性火山岩                              | 主要                                | [34-35]    |
| Beypazari 盆地中新统                             | 土耳其      | 中、晚中新世      | Trona, nahcolite, pirssonite                 | 研究薄弱                                                    | 有       | Teke 火山口, 安山和玄武岩熔岩                  | 研究薄弱                              | [26], [53] |
| Bridger 盆地绿河组 Wilkins Peak Member           | 美国怀俄明州   | 始新世         | Trona, nahcolite, shortite                   | 早始新世温室气候                                                | 有       | Absaroka 火山岩省和 Lowland Creek 火山口    | 争议较大, 直接证据少                       | [54]       |
| Piceance Greek 盆地绿河组 Parachute Greek Member | 美国科罗拉多高原 | 始新世         | Nahcolite, trona, dawsonit, halite           | 早始新世温室气候                                                | 有       | 研究薄弱                                |                                   | [55]       |
| 南襄盆地泌阳凹陷核桃园组                                | 中国河南     | 始新世         | Trona, nahcolite, halite                     | 争议较大                                                    | —       | 研究薄弱                                | 研究程度低                             | [56-58]    |
| 南大西洋下白垩统盐下碳酸盐地层                             | 巴西和安哥拉   | 早白垩世 Aptian | Stevensite                                   | 干旱气候                                                    | 有       | 粗面岩                                 | 影响较大                              | [29,59-60] |
| 准噶尔盆地玛湖凹陷风城组                                | 中国新疆     | 早二叠世        | Trona, shortite, searlesite                  | 研究薄弱                                                    | 有       | 研究薄弱                                | 研究程度低                             | [61-62]    |

注:除 Lake Van 和南大西洋早白垩世裂谷湖泊外,其余碱湖盐度均达到富钠碳酸盐沉淀盐度。

为方便检索和识别,国外盆地、湖泊及层位名称未翻译成中文,矿物英文名称对应的中文及组成见表1和表3。

常高的初级生产力与其独特的高 pH 水体化学性质密切相关,其控制机制如下:①CO<sub>2</sub>在碱湖水体中较为丰富,生物的光合作用可以不受 CO<sub>2</sub> 浓度限制<sup>[9,69]</sup>;②Mo 是有机体固定 N<sub>2</sub> 的固氮酶的重要组成元素,由于 Mo 在碱性环境下溶解度更大,因而在碱湖中含量更高<sup>[70]</sup>;③高的可溶性碳酸盐碱度和无机碳浓度更有利于自养生物的生存<sup>[67]</sup>;④碱湖环境中游离硫化物以 HS<sup>-</sup> 状态存在,对生物的毒性远小于 H<sub>2</sub>S 和多硫化合

物<sup>[71]</sup>;⑤由于 CaCO<sub>3</sub> 在碱性条件下迅速沉淀,因此碱湖水体中 Ca<sup>2+</sup> 浓度远低于海水,从而大大减少了磷酸盐因 Ca<sup>2+</sup> 结合造成的损失,有利于形成磷酸盐生物聚合物<sup>[21,72]</sup>;⑥碱性环境能提高氰化氢聚合效率,促进氨基酸、核酶及多肽的合成<sup>[73-74]</sup>,因而有利于甲醛聚糖反应形成非生物碳水化合物;⑦碱湖中含有较高含量的溶解硅酸盐,有利于硅藻的富营养化和勃发<sup>[67,74]</sup>。因此,在相同的营养条件下,碱湖可活化营养元素,中和有害

物质,极大提高初级生产力,这也是绿河组、核桃园组极富有机质的主要原因之一。

### 3.2 有效的浅水有机质保存机制

一般湖泊中有机质的保存需要深水还原环境,而碱湖的特殊性还在于能有效保存浅水区的有机质。

#### 3.2.1 早期硅化

pH是湖水中控制硅质溶解度最为重要的因素,当pH值小于9时,硅质的溶解度较低,与pH值关系较小;当pH值大于9时,硅质溶解度随pH值呈指数增加。水体的pH值会随季节发生变化:在潮湿季节,生物新陈代谢强烈,会消耗水体中的 $\text{CO}_2$ ,使水体呈碱性,造成碎屑石英和硅酸盐矿物溶解;而在干旱季节,植物死亡及降解生成的有机酸,会降低水体pH值,造成硅质的沉淀。对碱湖而言,一次大规模的降水也会引起湖水pH值迅速降低,造成硅质大量沉淀。硅质的大量沉淀对有机质的保存,尤其是浅水区有机质的保存具有重要的意义,前期富有机质层若被硅质大量覆盖,可以有效阻止有机质的进一步降解<sup>[75]</sup>。在很多中新世的湖泊环境中,微生物席经历了早期的硅化作用,其中的细胞和EPS物质得到较好保存<sup>[76-77]</sup>。在Orca-dian盆地的Middle Old Red Sandstone湖相沉积中,最富有机质的层位中常常含有燧石沉积<sup>[78]</sup>。玛湖凹陷

下二叠统风城组富有机质层也常见被层状硅质覆盖。

#### 3.2.2 热泉输入

发育于火山活跃区的碱湖,湖盆周围常伴有常年性热泉的输入。如位于肯尼亚中央裂谷的Bogoria湖,其周围分布有220个热泉。热泉的输入与河流不同,河流流量在气候干旱时期会大大减少,使得湖泊面积缩小,造成边缘地区的有机质暴露于地表而遭受氧化破坏。而热泉的流量基本不受气候的控制,即便在干旱时期仍能为湖泊输入水量,使得碱湖的热液输入区很少经历大规模的暴露剥蚀,有利于有机质的保存。东非裂谷区的Baringo湖,受热泉输入的控制<sup>[79]</sup>,虽然湖水仅6 m深,但在过去的0.3 Ma期间,却只经历了2次暴露剥蚀<sup>[80]</sup>。同样受热泉影响的准噶尔盆地玛湖凹陷风城组湖盆,即使位于东北部边缘区域,也很少发育红层。

## 4 火山活动-碱湖-优质烃源岩成因链模式

经过上述火山活动-碱湖、碱湖-优质烃源岩这两部分的综述研究,可以很清晰地形成一种火山活动-碱湖-优质烃源岩成因链模式(图2)。

优质烃源岩的形成至少需要两个要素:第一是异常高的初级生产力;第二是良好的有机质保存条件。

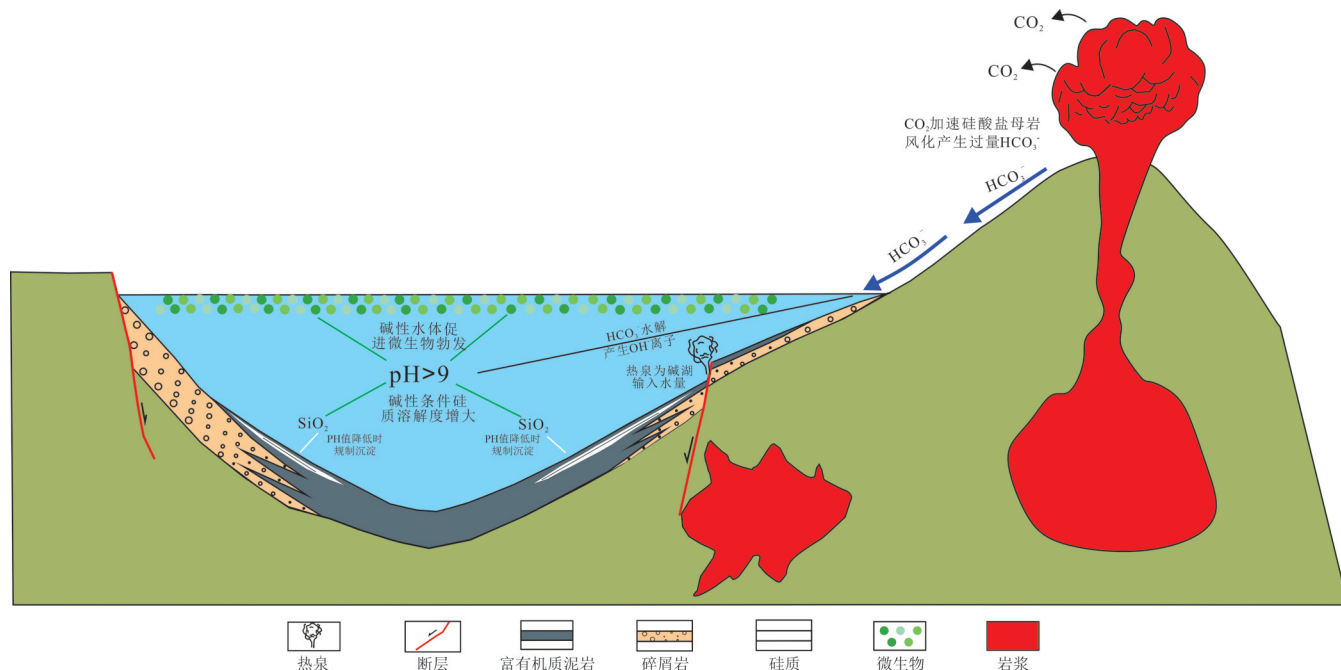


图2 火山活动-碱湖-优质烃源岩成因链模式

Fig. 2 Genetic model of volcanism-alkaline lake-high-quality source rock chain

火山活动喷发的大量  $\text{CO}_2$ , 通过加速硅酸盐母岩的风化产生大量  $\text{HCO}_3^-$ , 通过热液、地下水或者河流输入到湖泊水体中;  $\text{HCO}_3^-$  水解形成  $\text{OH}^-$ , 造成湖泊特有的碱性化学性质。在 pH 值增加的情况下, 水中部分离子、化合物的化学性质发生变化, 使得碱湖水体富营养化而具备异常高的初级生产力; 同时, 喷发的火山物质也会造成短暂性水体富营养化, 引起藻类等微生物勃发, 进一步提高了水体的初级生产力。火山附近的常年性热泉保证了碱湖具有稳定的水量输入, 不会随着旱季的到来而急剧萎缩, 为部分浅水区有机质的保存提供了稳定的水下环境; 另外浅水区硅质的沉降也为碱湖有机质的保存增添了一份保障。

由此可见, 火山活动可以通过碱湖这一介质场所为优质烃源岩的发育提供有利的物质保障和保存条件。因此, 火山活动-碱湖-优质烃源岩这条成因链可以较好的细化认识火山活动和优质烃源岩的联系, 指导油气勘探中优质烃源岩的成因及展布研究。

## 5 碱湖烃源岩特征

在全球油气需求量日益高涨的背景下, 常规油气资源后继乏力, 使得非常规油气资源特别是原本扮演烃源岩角色的泥页岩受到了越来越多的关注。碱湖烃源岩有着巨大的资源潜力和开发远景, 其除了有机质丰度高、类型好外, 还具有独特的矿物组成和相对较高的可压裂性和孔渗性。

### 5.1 独特的矿物组成

#### 5.1.1 (泥)微晶白云石

陆相碱湖烃源岩中普遍发育泥(微)晶白云石。中国泌阳凹陷核桃园组<sup>[81]</sup>、酒泉盆地青西凹陷下白垩统下沟组<sup>[82]</sup>、二连盆地下白垩统<sup>[83-84]</sup>、准噶尔盆地吉木萨尔和沙帐以及玛湖凹陷二叠系<sup>[85]</sup>以及美国 Piceance 盆地始新统绿河组<sup>[86]</sup>, 均含有一定量的(泥)微晶白云石。泥页岩中(泥)微晶白云石含量与方解石、文石的含量无相关性, 反而与有机质含量具有一定的正相关性<sup>[87-88]</sup>。美国绿河组泥页岩中有机质含量高的层位白云石尤其丰富<sup>[89]</sup>, 中国准噶尔盆地风城组藻纹层发育段是微晶白云石分布最密集的层段, 酒泉盆地地下沟组泥质白云岩相比白云质泥岩发育更多的有机纹层(藻纹层)且具有更高的生烃潜量<sup>[90-91]</sup>。上述现象说明碱湖烃源岩中白云石的含量与有机质关系密切。

碱湖烃源岩中白云石的成因争议较大。Desbo-

rough (1978) 认为有机质层中的白云石是生物有机成因, 湖泊中的蓝绿藻在新陈代谢过程中会优先吸收  $\text{Mg}^{2+}$ , 而在湖底降解过程中会释放  $\text{Mg}^{2+}$  促进自生或交代白云石的形成<sup>[92]</sup>。Slaughter 和 Hill (1991) 提出有机成因白云化作用 (organogenic dolomitization), 认为有机质降解过程中产生的  $\text{CO}_2$ , 提高了孔隙水中的碳酸盐碱度, 使文石和方解石发生白云石化作用; 这种白云石化作用产生的白云石与有机质含量相关<sup>[93]</sup>。Zhu 等人 (2017, 2019, 2020) 观察到碱湖沉积物中普遍含有火山灰及其蚀变产物 (如方沸石), 并且与白云石联系紧密, 因而提出产甲烷菌新陈代谢活动产生的  $\text{CO}_2$  参与蒙脱石伊利石化和绿泥石化过程, 产生  $\text{Fe}^{2+}$  和  $\text{Mg}^{2+}$ , 促使(铁)白云石形成<sup>[83-84, 94-95]</sup>。

#### 5.1.2 火山物质蚀变产物

碱湖环境独特的高盐度和富  $\text{HCO}_3^-$  水体环境使得火山玻璃以及不稳定的陆源硅酸盐矿物进入碱湖后很快发生水解作用, 形成次稳定的粘土矿物和沸石。在后期埋藏过程中, 这些矿物会发生溶蚀或被稳定矿物如石英、碱性长石和白云母替换交代<sup>[49, 64-65, 96]</sup>。因此, 沸石常在前中生代的碱湖烃源岩中普遍缺失<sup>[96-97]</sup>。不同的碱性环境, 火山物质的成岩演化产物亦不同(表3)。

在古老碱湖烃源岩中, 受沉积环境的影响, 自生硅酸盐矿物的空间分布具有分带性<sup>[31, 98]</sup>, 如科罗拉多高原上侏罗统 Morrison 组的 Brushy Basin Member, 从盆地边缘到中心, 分别为蒙脱石-斜发沸石-方沸石-钾长石-钠长石带<sup>[99]</sup>。碱湖烃源岩中不稳定的火山玻璃在碱性环境下可转变成沸石, 沸石可转变为钾长石和硅硼钠石, 而钾长石可进一步转变为钠长石<sup>[49, 100]</sup>。

### 5.2 相对较高的可压裂性和孔渗性

脆性矿物含量越高的泥页岩脆性越强, 越容易在外力作用下产生天然裂缝和诱导裂缝, 越有利于泥页岩油气的开采<sup>[102]</sup>。李晓萌等 (2016) 对川南地区下古生界的筇竹寺组与龙马溪组页岩气储层进行对比研究, 认为筇竹寺组脆性矿物含量高于龙马溪组, 因而具有更大的开采潜力<sup>[103]</sup>。Jarvie 等 (2007) 认为对于页岩油气储层研究来说, 矿物学分析是不可缺少的, 脆性矿物含量是决定美国得克萨斯州中北部的密西西比系 Barnett 页岩以及其他泥页岩层系天然气产量的重要因素<sup>[104]</sup>。碱湖烃源岩中白云石以及后期由凝灰物质转变形成的稳定矿物如石英、碱性长石等的富集, 使得该类烃源岩脆性矿物含量较高, 因此天然裂缝以及受

表3 古老碱湖沉积物中常见的自生硅酸盐矿物

Table 3 Common authigenic silicate minerals in the deposits of ancient alkali lakes

| 矿物类型                     | 化学式                                                                                                                               | 成因                                                          | 文献                   |
|--------------------------|-----------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------|----------------------|
| 钙十字沸石(phillipsite)       | $(\text{Ca}, \text{Na}_2, \text{K}_2)_3\text{Al}_6\text{Si}_{10}\text{O}_{32} \cdot 12\text{H}_2\text{O}$                         | 硅质火山灰与高盐度、高碱性的孔隙流体                                          |                      |
| 钾长石(k-feldspar)          | $\text{KAlSi}_3\text{O}_8$                                                                                                        | 接触,按火山灰→钙十字沸石→钾长石→                                          | [26],[49],[99],[101] |
| 水硅硼钠石(searlesite)        | $\text{NaBSi}_2\text{O} \cdot \text{H}_2\text{O}$                                                                                 | 硅硼钠石的成岩序列演化                                                 |                      |
| 富镁蒙脱石(mg-rich smectites) | $(\text{Na}, \text{Ca})_{0.33}(\text{Al}, \text{Mg})_2[\text{Si}_4\text{O}_{10}](\text{OH})_2 \cdot n\text{H}_2\text{O}$          | 火山灰与中等盐度、略碱性的地层水接                                           |                      |
| 方沸石(analcime)            | $\text{NaAlSi}_2\text{O}_6 \cdot \text{H}_2\text{O}$                                                                              | 触,按火山灰→富镁蒙脱石→方沸石→斜                                          | [49]                 |
| 斜发沸石(clinoptilolite)     | $(\text{Na}, \text{K}, \text{Ca})_{2-3}\text{Al}_3(\text{Al}, \text{Si})_2\text{Si}_{13}\text{O}_{36} \cdot 12\text{H}_2\text{O}$ | 发沸石→蛋白石的成岩序列演化                                              |                      |
| 蛋白石(opal c-t)            | $\text{SiO}_2$                                                                                                                    |                                                             |                      |
| 钠长石(albite)              | $\text{NaAlSi}_3\text{O}_8$                                                                                                       | 钾长石转化,代表高温成岩产物                                              | [99]                 |
| 丝硅镁石(loughlinite)        | $\text{Na}_2\text{Mg}_3\text{Si}_6\text{O}_{16} \cdot 8\text{H}_2\text{O}$                                                        | 原生;含硅溶液与天然碱和白云石接触;碳酸钠钙石与含硅溶液接触, $\text{Mg}^{2+}$ 来源于有机物质的释放 | [21]                 |
| 片钠铝石(dawsonite)          | $\text{NaAl}(\text{OH})_2\text{CO}_3$                                                                                             | 一般与白云石共生                                                    | [101]                |

压裂后产生的人工裂缝发育程度高,油气初始产能高。泌阳凹陷核桃园组泥页岩中脆性矿物含量高,碳酸盐、长石、黄铁矿等脆性矿物含量为49.4%,石英平均含量为19.5%,因此裂缝非常发育,泌页HF1井初期产能达到了 $23.6 \text{ m}^3/\text{d}^{[105]}$ 。

此外,碱湖沉积物中的不稳定矿物和火山灰在成岩过程中会经历复杂的转变,这些过程会产生大量的无机孔,增加了泥页岩的孔渗性和含油气性。朱世发等(2011)认为准噶尔盆地西北缘二叠系风城组中大量火山玻璃物质在经历蚀变和多期转化后会形成沸石类、钠长石等矿物,而沸石类矿物在成岩期酸性环境中普遍发生溶蚀,极大改善了储层的质量<sup>[106]</sup>。巴西近海区域白垩系盐下的Barra Velha组是典型的碱湖沉积,受火山喷发物质的影响,初期含有大量的富镁粘土矿物。Tosca和Wright(2015)认为Barra Velha组储层中发育的大量次生孔隙就是富镁粘土矿物后期溶蚀形成的<sup>[28]</sup>。

## 6 结论

1)碱湖的形成与火山活动密切相关。在干旱-半干旱气候及湖泊封闭的背景下,湖泊水体pH值升高的主要原因是间歇性火山活动喷发的大量 $\text{CO}_2$ 进入热液、地下水或河流中,加速硅酸盐母岩的化学风化而产生大量的 $\text{HCO}_3^-$ ,进而输入到湖泊中造成水体碱化。

2)碱湖特有的水体性质(高pH值)可以活化多种营养元素和化合物,促进水体富营养化,使得碱湖具有异常高的初级生产力。同时火山附近的常年性热泉保证了碱湖具有稳定的水量输入,再加上碱湖特有的浅水硅化保存机制,使得有机质在碱湖中具有较好的保

存条件。

3)火山活动-碱湖-优质烃源岩的成因链模式,有助于深入认识火山活动和优质烃源岩的联系;该模式形成的烃源岩同样为优质的页岩油气储集层,微晶白云石、沸石、石英、碱性长石等矿物含量高,具有相对较高的可压裂性和孔渗性。

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