

# 吉泰盆地石炭系黄龙组黑色碳质泥岩物源、 构造背景与古风化作用：来自稳定元素 地球化学的证据

颜 开<sup>1)</sup>, 王春连<sup>1)\*</sup>, 王九一<sup>1)</sup>, 沈立建<sup>1)</sup>, 余小灿<sup>1)</sup>, 孟令阳<sup>2)</sup>

1) 中国地质科学院矿产资源研究所, 自然资源部成矿作用与资源评价重点实验室, 北京 100037;

2) 江西省地质矿产勘查开发局 902 地质队, 江西新余 338099

**摘 要:** 吉泰盆地在白垩纪—古近纪时期, 沉积了巨量的富锂钾卤水, 同时富含硼、铷、铯、溴、碘等新兴矿产资源, 综合利用价值高。本文采用 X 射线荧光光谱(XRF)和电感耦合等离子体质谱(ICP-MS)分析了吉泰盆地石炭系黄龙组黑色碳质泥岩的主、微量和稀土元素地球化学特征。通过对其物源、构造背景及古风化作用的详细分析, 探讨了其对上覆卤水矿层的影响。吉泰盆地 M2 钻孔底部细碎屑岩具有 LREE 富集, HREE 较平缓的特征, 且均表现明显的 Eu 负异常, 综合 La/Th-Hf 和 Zr-TiO<sub>2</sub> 图解, 认为其主要来自长英质/基性岩浆岩和古老沉积组分的混合源区, 为卤水形成带来了丰富的深源物质。微量元素和稀土元素的含量和比值(La/Th、Cr/Th、Th/Sc), 反映出被动大陆边缘的构造背景特征。通过计算化学风化指数(CIA、CIW、PIA 和 ICV)及 Al<sub>2</sub>O<sub>3</sub>-(CaO+Na<sub>2</sub>O)-K<sub>2</sub>O 图解, 表明其化学风化程度较高, 有利于元素的迁移和富集, 为卤水矿床的形成提供了丰富的成矿元素。

**关键词:** 吉泰盆地; 地球化学; 物质来源; 构造演化; 风化作用

中图分类号: P619.211 文献标志码: A doi: 10.3975/cagsb.2022.030401

## Provenance, Tectonic Setting and Palaeo-weathering of Black Carbonaceous Mudstones from Carboniferous Huanglong Formation in the Jitai Basin: Evidence from Stable Element Geochemistry

YAN Kai<sup>1)</sup>, WANG Chun-lian<sup>1)\*</sup>, WANG Jiu-yi<sup>1)</sup>, SHEN Li-jian<sup>1)</sup>, YU Xiao-can<sup>1)</sup>, MENG Ling-yang<sup>2)</sup>

1) MNR Key Laboratory of Metallogeny and Mineral Assessment, Institute of Mineral Resources,  
Chinese Academy of Geological Sciences, Beijing 100037;

2) 902 Geological Brigade of Jiangxi Bureau of Exploration and Development for Geology and Mineral Resources,  
Xinyu, Jiangxi 338099

**Abstract:** In the Cretaceous–Paleogene period, a huge amount of lithium-potassium rich brine was deposited in the Jitai Basin, which is rich in boron, rubidium, cesium, bromine, iodine and other emerging mineral resources, with high comprehensive utilization value. In this paper, the major, trace and rare earth element geochemical characteristics of Carboniferous Huanglong Formation black carbonaceous mudstone in the Jitai Basin were analyzed by X-ray fluorescence spectrometry (XRF) and inductively coupled plasma mass spectrometry (ICP-MS). Based on the detailed analysis of its provenance, tectonic setting and paleo-weathering, the influence of it on the overlying brine ore bed is discussed. The fine clastic rocks in the lower part of the M2 borehole in the Jitai Basin are characterized by LREE enrichment and gentle HREE, and they all show obvious negative

本文由中央级公益性科研院所基本科研业务费专项(编号: KK2005; KK2016)、国家 973 计划项目(编号: 2011CB403007)和中国地质调查局地质矿产调查评价专项项目(编号: DD20190437; DD20190606)联合资助。

收稿日期: 2021-11-18; 改回日期: 2022-03-01; 网络首发日期: 2022-03-08。责任编辑: 张改侠。

第一作者简介: 颜开, 男, 1992 年生。博士研究生。矿物学、岩石学、矿床学专业。E-mail: yankai\_ytq@sina.com。

\*通讯作者: 王春连, 男, 1983 年生。博士, 研究员。主要从事矿床学方面的研究。通讯地址: 100037, 北京市西城区百万庄大街 26 号。  
E-mail: wangchunlian312@163.com。

Eu anomaly. Based on La/Th-HF and Zr-TiO<sub>2</sub> diagram, they are mainly from the mixed source area of felsic/basic magmatic rocks and ancient sedimentary components, which brings abundant deep source materials for the formation of brine. The contents and ratios of trace elements and rare earth elements (La/Th, Cr/Th, Th/Sc) reflect the tectonic background characteristics of passive continental margin. The chemical weathering index (CIA, CIW, PIA and ICV) and the diagram of Al<sub>2</sub>O<sub>3</sub>-(CaO+Na<sub>2</sub>O)-K<sub>2</sub>O show that the chemical weathering degree is high, which is conducive to the migration and enrichment of elements, and provides rich ore-forming elements for the formation of brine deposits.

**Key words:** Jitai Basin; geochemistry; provenance; tectonic evolution; weathering

碎屑岩地球化学特征作为地质信息的重要载体, 真实详细地记录了物源、构造、环境和生态演化等重要信息(王春连等, 2022)。在沉积的过程中, 水体和沉积物中对氧化还原敏感的微量元素的分布、循环和分异(亏损和富集)不仅与它们自身的化学性质有关, 而且还受沉积介质的物理化学条件和古气候条件的控制(Nameroff et al., 2004; Tribovillard et al., 2004, 2006; Zhang et al., 2016; 兰叶芳等, 2022; 游超等, 2022; 周博文等, 2022)。因此, 一些溶解于水且对气候变化敏感的主微量元素可以作为研究古气候演化的重要代用指标。

中生代是华南乃至整个东亚大陆构造剧烈变化的时期, 也是东亚构造发展的转折点(任纪舜, 1990; 赵越等, 2004; 董树文等, 2007, 2010; Rodríguez-López and Wu, 2020)。白垩纪—古近纪时期, 华南中部形成了江汉盆地、吉泰盆地等一系列断陷盆地。此时, 这些盆地中的大多数湖泊演化成盐湖, 并沉积了大量的盐岩和其他盐类矿物(姚秋昌和楼基胜, 2008)。目前, 在吉泰盆地周田组晚白垩世地层发现深层卤水, 富含钾、锂、硼、铷、铯、溴、碘等高价值新兴战略矿产资源, 其中 NaCl 的品位为工业品位的 2.6 倍, LiCl 的品位为工业品位的 3.8 倍, 具有较大的工业价值(刘成林等, 2009; 刘成林, 2013; 周敏娟等, 2017; 王春连等, 2020; 马厚明等, 2021)。

深部卤水沉积的形成受物质来源、沉积期古气候条件和盆地构造条件等因素的控制(刘成林等, 2010; 魏海成等, 2016; Sun et al., 2017; 王春连等, 2018, 2021)。目前吉泰盆地的基础地质研究还显薄弱, 现有资料不足以揭示深层卤水的形成机理。为了更好地了解吉泰盆地深层卤水的成因, 各成矿元素的来源及富集程度, 本文报道了黄龙组黑色碳质泥岩的主、微量、稀有元素地球化学数据, 探讨其对上层周田组卤水矿产的影响。

## 1 地质背景

吉泰盆地位于江西中部隆起与西南凹陷的过渡地带, 在中生代燕山运动时该区陆壳在隆起的背景上表现为急剧而广泛的差异性断块运动, 并在先期和新生断裂的影响与制约下, 形成了吉泰断陷盆

地。盆地长约 120 km, 宽 10~30 km, 面积约 1850 km<sup>2</sup>(图 1, 余心起等, 2005)。盆地基底因地区而异, 北部以晚古生代地层为主, 南部以早古生代浅变质岩系为主。盆地及周边地层发育, 除奥陶、志留系缺失外均有出露。盆地基底为震旦系—寒武系的巨厚地槽型复理石建造, 泥盆系为陆相—滨海相碎屑岩沉积, 石炭系为陆相含煤和碳酸盐建造, 二叠系为浅海相碎屑岩, 下三叠统以碳酸盐岩为主, 上三叠统为含火山碎屑的陆相沉积物, 侏罗系发育劣质煤层和火山碎屑岩。白垩纪地层在盆地内部主要出露厚达几千米的白垩纪陆相红色地层(卢秋芽, 1991)。盆内蕴藏着较丰富的石膏、石盐等重要矿产资源, 富锂矿赋存于上白垩统周田组(周敏娟等, 2017; 王春连等, 2020)。盆地的生成和发展受到盆缘断裂和控盆断裂的控制, 盆地界限由赣江大断裂、吉水大断裂、遂川大断裂、永新—峡江断裂以及遂川—兴深断裂构成(王春连等, 2020)。M2 井位于盆地中下部, 主要由下部的深灰色含碳粉砂质泥岩和上部的紫红色粉砂岩组成, 根据盆地内的地层对比, 下部可能为石炭系黄龙组, 上部应为上白垩统周田组。

## 2 样品采集和分析方法

本文共采集来自吉泰盆地 M2 钻孔黄龙组的黑色碳质泥岩样品 29 件。黄龙组的岩心以灰色和深灰色为主, 岩性以碳质泥岩或粉砂岩为主, 构造不发育(图 2)。通过岩心编录和野外照片, 可以观察到大量黄铁矿和脉状石英的存在。为了使实验结果更具代表性, 样品按照一定的间隔和岩性变化进行挑选(图 1)。同时, 为了不受次生沉积物的影响, 所挑选的样品均不存在脉石英。

本次实验采用 X 射线荧光光谱法(XRF)测定了 SiO<sub>2</sub>、TiO<sub>2</sub>、Al<sub>2</sub>O<sub>3</sub>、Fe<sub>2</sub>O<sub>3</sub>、FeO、MnO、MgO、CaO、Na<sub>2</sub>O、K<sub>2</sub>O、P<sub>2</sub>O<sub>5</sub> 等主要元素的氧化物。采用电感耦合等离子体质谱仪(ICP-MS)测定痕量稀土元素的含量。用碱熔法将样品熔成玻璃片, 并在连续 X 射线荧光光谱仪(AB104L, Axios-mAX)上进行测试。采用电感耦合等离子体质谱仪(ELEMENT XR)测定溶出的微量元素和稀土元素。所有实验均在北京核工业地质研究院分析实验室进行。

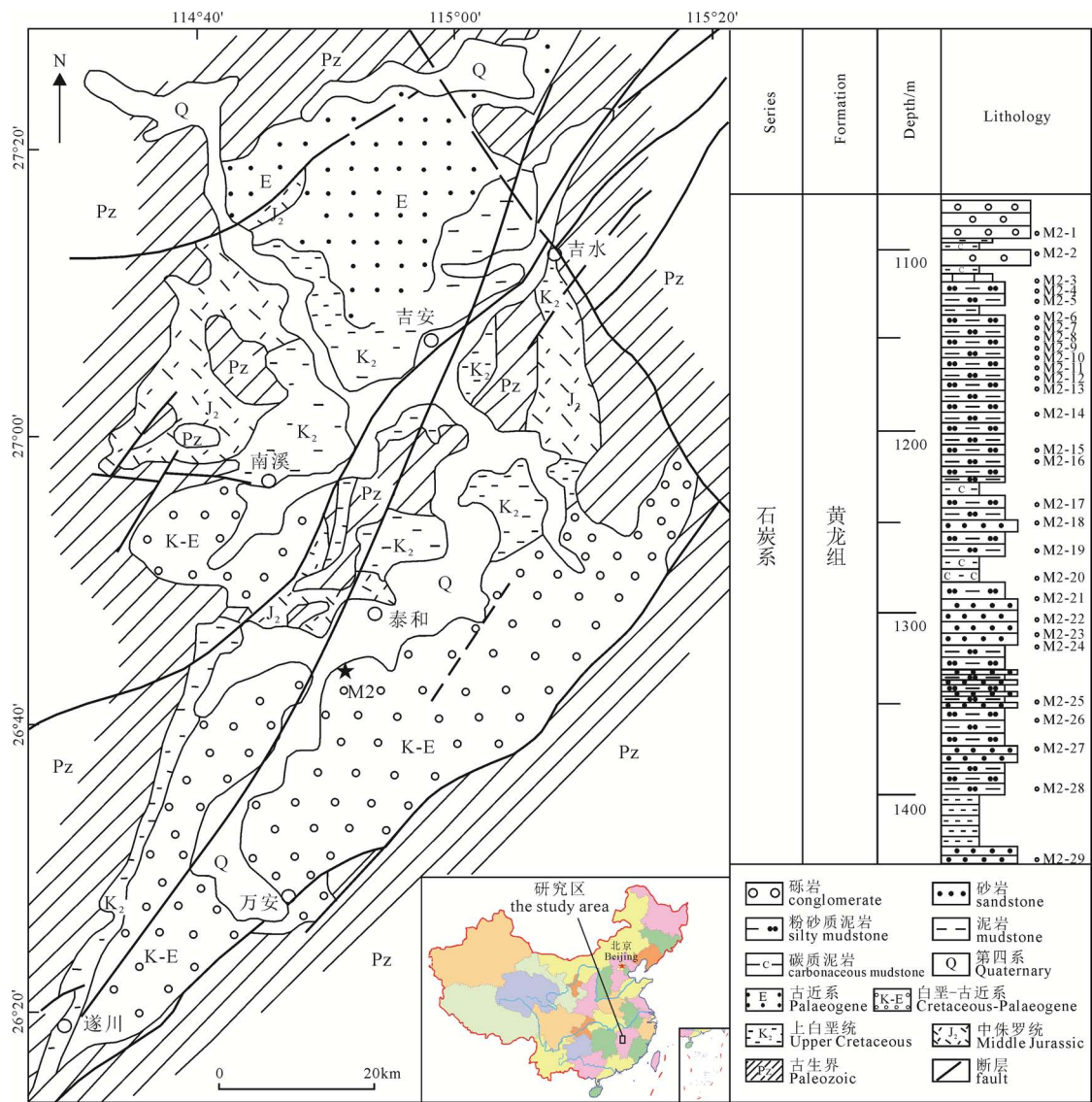


图 1 吉泰盆地地质构造简图(改自余心起等, 2005)  
Fig. 1 Geological structure diagram of the Jitai Basin (modified from YU et al., 2005)

样品制备前, 用微钻除去外表风化面, 并将其研磨至 200 目。所有的地球化学分析样品都被粉碎并研磨到小于 200 目。XRF 的测试方法如下: 首先, 在镍锅中混合 0.4 g 粉末样品和无水  $\text{Li}_2\text{B}_4\text{O}_7$ , 并用合适的氧化剂和浓度为 120 mg/mL 的  $\text{NH}_4\text{Br}$  液体稀释混合物。然后, 根据测试仪器的程序指示, 将镍罐放置在名为 CLAISSIE 的取样机上, 之后得到高温液化的熔体, 并将其放在模具中, 冷却后, 装入密封的塑料袋中, 储存在干燥器中, 待测。ICP-MS 的测试方法如下: 首先, 称重约 2.5 g 的粉末样品, 将其放入耐高压烧杯中, 并加入溶液  $\text{HF-HNO}_3$  和烧杯的比例是 1:1 把搅拌均匀。在  $80^\circ\text{C}$  下加热 24 小时蒸发液体。第二, 在溶液蒸发到接近干燥后, 分别加入 0.5 mL  $\text{HClO}_4$ , 1.5 mL  $\text{HF}$  和 1.5 mL  $\text{HNO}_3$ 。第三, 把盛有溶液的烧杯放进去烤箱  $180^\circ\text{C}$  加热至少 48 小时, 以确保样品完全溶解。最后, 稀释溶液至 50 mL 并加入 1% 的  $\text{HNO}_3$ , 用于测量。

蚀变化学指标( $\text{CIA}=\text{Al}_2\text{O}_3/(\text{Al}_2\text{O}_3+\text{CaO}^*+\text{Na}_2\text{O}+\text{K}_2\text{O})\times 100$ )、风化化学指标( $\text{CIW}=\text{Al}_2\text{O}_3/(\text{Al}_2\text{O}_3+\text{CaO}+\text{Na}_2\text{O})\times 100$ )、斜长石蚀变指标( $\text{PIA}=(\text{Al}_2\text{O}_3-\text{K}_2\text{O})/(\text{Al}_2\text{O}_3+\text{CaO}^*+\text{Na}_2\text{O}-\text{K}_2\text{O})\times 100$ )以及成分变异指标( $\text{ICV}=(\text{Fe}_2\text{O}_3+\text{K}_2\text{O}+\text{Na}_2\text{O}+\text{CaO}+\text{MgO}+\text{TiO}_2)/\text{Al}_2\text{O}_3$ ), 反映了长石向黏土矿物的转化, 可用于追溯源区的风化历史(Nesbitt and Young, 1982; Harnois, 1988; Fedo et al., 1995; Cox et al., 1995)。  $\text{CaO}^*$ (硅酸盐相中  $\text{CaO}$  含量) =  $\text{CaO}-10/3\times\text{P}_2\text{O}_5$  (McLennan et al., 1993)。

3 分析结果

3.1 主量元素地球化学

主量元素的含量见表 1。在所有的测试样品中,  $\text{SiO}_2$  是主要的氧化物, 其含量在 43.87%~86.46%, 平均为 64.02%。 $\text{Al}_2\text{O}_3$  (7.05%~31.12%, 平均 18.44%) 和  $\text{Fe}_2\text{O}_3$  (1%~26.81%) 含量次之。相比之下,  $\text{CaO}$  (0.094%~2.15%)、 $\text{MgO}$  (0.323%~2.91%)、

$\text{Na}_2\text{O}$  (0.085%~0.483%)、 $\text{K}_2\text{O}$  (0.68%~5.88%)、 $\text{TiO}_2$  (0.199%~1.25%)的含量占比偏少。含量最少的主量元素是  $\text{MnO}$  (0.008%~0.099%) 和  $\text{P}_2\text{O}_5$  (0.022%~0.376%)。黄龙组样品具有低  $\text{Al}_2\text{O}_3/\text{SiO}_2$ , 高  $\text{Al}_2\text{O}_3/\text{TiO}_2$ , 高  $\text{K}_2\text{O}/\text{Na}_2\text{O}$  的特征。

### 3.2 微量元素地球化学

所有测试样品的微量元素含量见表2。微量元素含量的范围跨度较大, 在上地壳平均标准化图谱中

(图3), 大部分元素的含量低于上地壳(UCC)的平均值。其中含量最高的微量元素是 Ba ( $134 \times 10^{-6} \sim 712 \times 10^{-6}$ , 平均  $478.38 \times 10^{-6}$ ), 其次是 Zr ( $155 \times 10^{-6} \sim 492 \times 10^{-6}$ , 平均  $295.28 \times 10^{-6}$ ); 含量最低的微量元素为 Ta ( $0.426 \times 10^{-6} \sim 2.24 \times 10^{-6}$ , 平均  $1.44 \times 10^{-6}$ )。在上地壳标准化图解中, 样品具有 V 元素相对富集和 Sr 元素亏损的特征。部分微量元素与稀土元素的比值见表4。

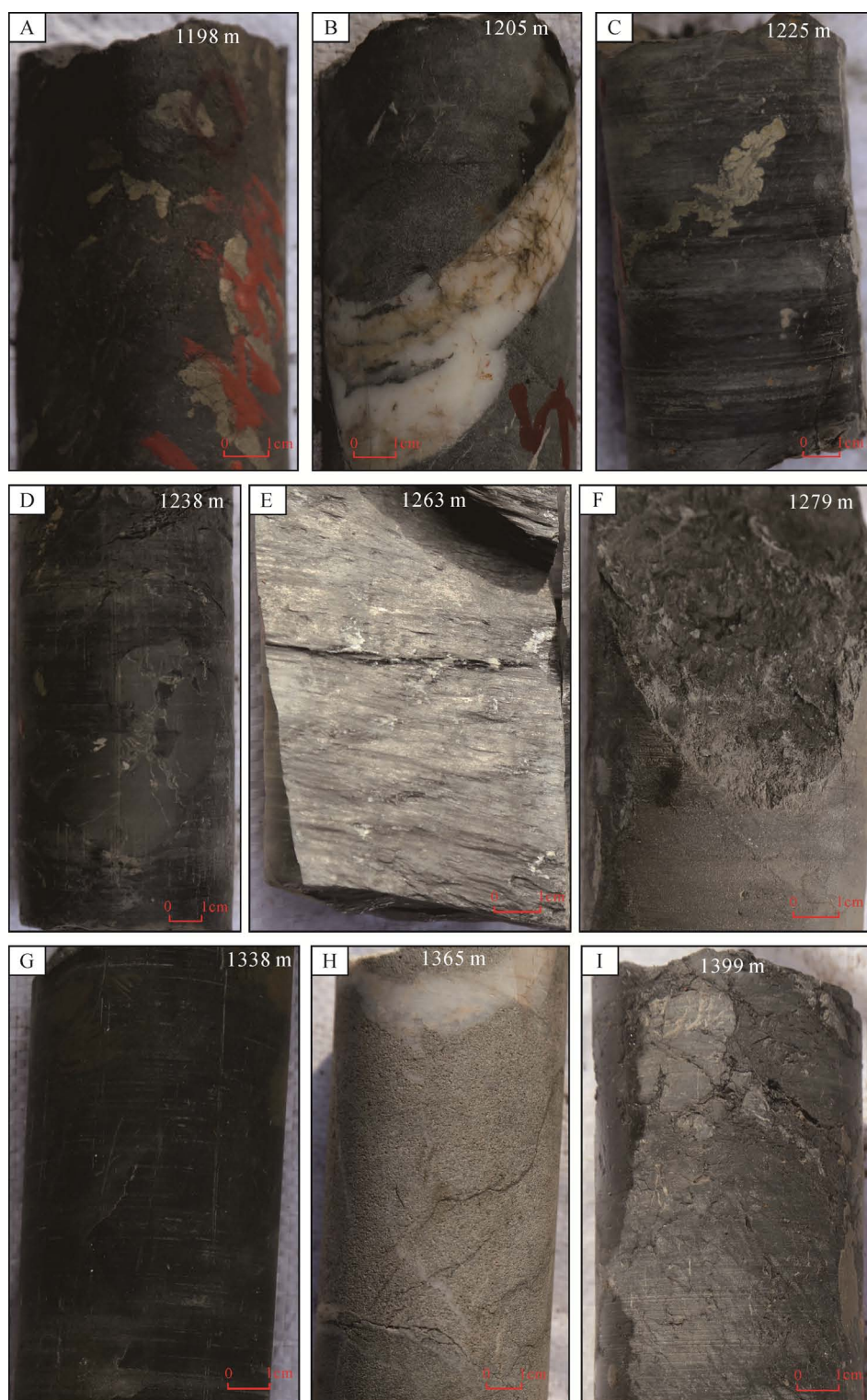


图2 M2井黄龙组部分岩心照片

Fig. 2 Some photographs of Huanglong Formation in Well M2

表 1 吉泰盆地黄龙组主量元素含量/%  
Table 1 Content of major elements /% in Huanglong Formation, Jitai Basin

| No.   | SiO <sub>2</sub> | Al <sub>2</sub> O <sub>3</sub> | Fe <sub>2</sub> O <sub>3</sub> | TiO <sub>2</sub> | MnO   | CaO   | MgO   | K <sub>2</sub> O | Na <sub>2</sub> O | P <sub>2</sub> O <sub>5</sub> | FeO   | LOI   | Total |
|-------|------------------|--------------------------------|--------------------------------|------------------|-------|-------|-------|------------------|-------------------|-------------------------------|-------|-------|-------|
| M2-1  | 66.74            | 18.34                          | 1.56                           | 0.786            | 0.008 | 0.577 | 0.834 | 4.36             | 0.327             | 0.036                         | 0.65  | 6.34  | 100.6 |
| M2-2  | 76.03            | 11.95                          | 4.34                           | 0.672            | 0.016 | 0.208 | 0.541 | 1.51             | 0.165             | 0.027                         | 2.60  | 4.54  | 102.6 |
| M2-3  | 75.32            | 11.22                          | 5.13                           | 0.680            | 0.014 | 0.153 | 0.720 | 1.80             | 0.179             | 0.022                         | 3.60  | 4.35  | 103.2 |
| M2-4  | 43.87            | 28.36                          | 9.66                           | 1.040            | 0.023 | 0.219 | 1.410 | 4.28             | 0.390             | 0.119                         | 6.35  | 10.53 | 106.3 |
| M2-5  | 44.00            | 14.90                          | 26.81                          | 0.580            | 0.099 | 0.508 | 2.910 | 0.68             | 0.137             | 0.376                         | 19.24 | 8.43  | 118.7 |
| M2-6  | 62.57            | 22.31                          | 3.68                           | 1.070            | 0.013 | 0.094 | 0.806 | 3.04             | 0.267             | 0.043                         | 2.72  | 6.06  | 102.7 |
| M2-7  | 66.59            | 19.79                          | 3.76                           | 1.000            | 0.018 | 0.148 | 0.966 | 2.96             | 0.249             | 0.046                         | 2.71  | 4.41  | 102.6 |
| M2-8  | 60.71            | 22.10                          | 5.45                           | 1.040            | 0.020 | 0.138 | 1.360 | 2.79             | 0.229             | 0.036                         | 3.87  | 6.07  | 103.8 |
| M2-9  | 69.22            | 17.42                          | 3.76                           | 0.952            | 0.012 | 0.106 | 0.769 | 2.32             | 0.210             | 0.032                         | 2.50  | 5.15  | 102.5 |
| M2-10 | 59.93            | 21.17                          | 5.93                           | 1.050            | 0.024 | 0.134 | 1.100 | 2.79             | 0.229             | 0.041                         | 3.67  | 7.41  | 103.5 |
| M2-11 | 58.36            | 25.79                          | 3.94                           | 1.150            | 0.013 | 0.107 | 0.742 | 2.99             | 0.232             | 0.051                         | 2.72  | 6.57  | 102.7 |
| M2-12 | 50.89            | 28.00                          | 3.95                           | 1.100            | 0.008 | 0.116 | 0.699 | 3.57             | 0.292             | 0.044                         | 1.37  | 11.30 | 101.3 |
| M2-13 | 64.90            | 21.18                          | 3.67                           | 0.997            | 0.016 | 0.145 | 0.836 | 2.24             | 0.201             | 0.031                         | 2.33  | 5.76  | 102.3 |
| M2-14 | 58.55            | 24.53                          | 4.95                           | 1.090            | 0.014 | 0.100 | 1.010 | 2.60             | 0.252             | 0.047                         | 3.31  | 6.86  | 103.3 |
| M2-15 | 65.65            | 8.05                           | 10.36                          | 0.823            | 0.008 | 0.159 | 0.323 | 1.11             | 0.191             | 0.029                         | 1.76  | 13.20 | 101.7 |
| M2-16 | 65.17            | 19.01                          | 4.77                           | 0.934            | 0.025 | 0.120 | 0.914 | 2.18             | 0.211             | 0.035                         | 3.46  | 6.56  | 103.4 |
| M2-17 | 49.73            | 29.83                          | 4.91                           | 1.220            | 0.006 | 0.100 | 0.634 | 3.36             | 0.432             | 0.050                         | 2.08  | 9.72  | 102.1 |
| M2-18 | 57.59            | 19.52                          | 8.20                           | 0.954            | 0.099 | 1.240 | 1.710 | 2.18             | 0.206             | 0.152                         | 5.14  | 8.12  | 105.1 |
| M2-19 | 49.86            | 25.77                          | 7.19                           | 0.998            | 0.037 | 0.632 | 1.530 | 2.95             | 0.330             | 0.130                         | 4.75  | 10.53 | 104.7 |
| M2-20 | 64.78            | 22.60                          | 3.17                           | 1.010            | 0.010 | 0.136 | 0.356 | 1.61             | 0.234             | 0.068                         | 2.08  | 6.00  | 102.1 |
| M2-21 | 50.20            | 31.12                          | 2.41                           | 1.250            | 0.009 | 0.418 | 0.837 | 5.64             | 0.483             | 0.053                         | 1.34  | 7.49  | 101.3 |
| M2-22 | 86.46            | 7.08                           | 1.00                           | 0.324            | 0.024 | 0.461 | 0.371 | 1.88             | 0.125             | 0.034                         | 0.73  | 2.14  | 100.6 |
| M2-23 | 73.71            | 12.58                          | 4.33                           | 0.568            | 0.069 | 0.933 | 1.340 | 3.39             | 0.147             | 0.084                         | 2.46  | 2.37  | 102.0 |
| M2-24 | 76.59            | 12.04                          | 2.86                           | 0.504            | 0.022 | 0.330 | 1.060 | 3.07             | 0.139             | 0.088                         | 2.22  | 2.88  | 101.8 |
| M2-25 | 80.50            | 7.75                           | 2.32                           | 0.199            | 0.016 | 1.790 | 1.240 | 1.77             | 0.085             | 0.144                         | 1.87  | 3.76  | 101.4 |
| M2-26 | 74.54            | 9.13                           | 3.81                           | 0.432            | 0.065 | 2.150 | 2.000 | 2.41             | 0.107             | 0.156                         | 2.91  | 5.10  | 102.8 |
| M2-27 | 61.24            | 19.26                          | 5.40                           | 0.818            | 0.009 | 0.172 | 2.160 | 5.88             | 0.154             | 0.059                         | 3.71  | 4.78  | 103.6 |
| M2-28 | 72.60            | 12.19                          | 3.69                           | 0.592            | 0.016 | 1.100 | 1.770 | 3.31             | 0.114             | 0.052                         | 2.83  | 4.10  | 102.4 |
| M2-29 | 70.15            | 11.71                          | 2.93                           | 0.565            | 0.086 | 1.900 | 1.940 | 3.66             | 0.133             | 0.183                         | 2.34  | 6.69  | 102.3 |

### 3.3 稀土元素地球化学

稀土元素的含量见表 3。稀土元素中 Ce 的含量最高, 在  $30.9 \times 10^{-6} \sim 131 \times 10^{-6}$ , 平均  $87.69 \times 10^{-6}$ , 含量最少的稀土元素是 Tm ( $0.13 \times 10^{-6} \sim 0.747 \times 10^{-6}$ , 平均  $0.383 \times 10^{-6}$ ) 和 Lu ( $0.134 \times 10^{-6} \sim 0.635 \times 10^{-6}$ , 平均  $0.384 \times 10^{-6}$ )。稀土总量( $\Sigma$ REE)变化较大, 含量在  $71.52 \times 10^{-6} \sim 323 \times 10^{-6}$  之间, 平均  $207.5 \times 10^{-6}$ 。轻稀土元素(LREE)的含量在  $66.3 \times 10^{-6} \sim 297.1 \times 10^{-6}$  之间, 平均  $190.1 \times 10^{-6}$ 。重稀土元素(HREE)的含量在  $5.2 \times 10^{-6} \sim 29.2 \times 10^{-6}$  之间, 平均  $17.4 \times 10^{-6}$ 。在球粒陨石标准化图解中(图 4), 测试样品的稀土元素呈现明显的 Eu 负异常, 所有稀土元素的值表明了轻稀土元素(LREE)的富集和重稀土元素(HREE)的平缓。

## 4 讨论

### 4.1 物源

地球化学数据为表征沉积物源和源区提供了线索(Roser and Korsch, 1986; Cullers, 2000)。主微量元素, 如 TiO<sub>2</sub>、La、Sc、Hf、Th、Zr, 由于在沉积过程

中具有较低的潜在流动性, 在风化和搬运过程中被定量地输送到沉积物中, 因此能够反映其母岩的特征(Bhatia and Crook, 1986), 而稀土元素在解释沉积物来源和组成方面起着重要作用(McLennan et

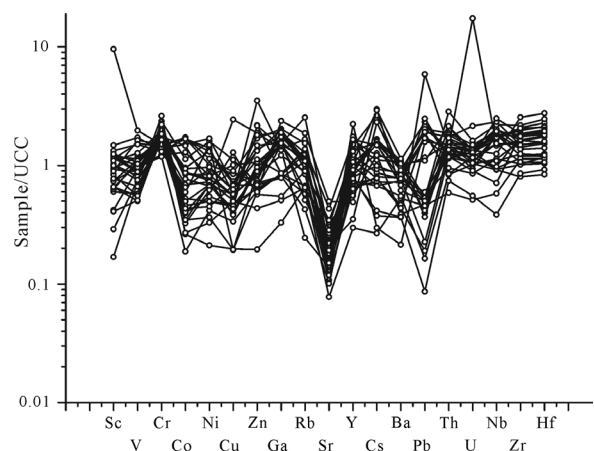


图 3 M2 井碳质泥岩微量元素 UCC 标准化 (Taylor and McLennan, 1985)

Fig. 3 UCC-normalized trace-element diagram of carbonaceous mudstones in Well M2 (after Taylor and McLennan, 1985)

表 2 吉秦盆地黄龙组微量元素含量/ $10^{-6}$   
Table 2 Content of trace elements / $10^{-6}$  in Huanglong Formation, Jitai Basin

| No.   | Sc    | V     | Cr  | Co    | Ni   | Cu   | Zn    | Ga   | Rb    | Sr    | Y    | Cs    | Ba  | Pb    | Th   | U     | Nb   | Ta   | Zr  | Hf    | B     |
|-------|-------|-------|-----|-------|------|------|-------|------|-------|-------|------|-------|-----|-------|------|-------|------|------|-----|-------|-------|
| M2-1  | 12.9  | 85.8  | 143 | 5.95  | 32.7 | 68.3 | 126.0 | 24.0 | 140.0 | 67.4  | 7.4  | 11.30 | 540 | 34.40 | 15.0 | 47.00 | 17.6 | 1.39 | 313 | 8.31  | 79.5  |
| M2-2  | 9.2   | 48.6  | 168 | 9.08  | 23.2 | 13.3 | 42.9  | 14.6 | 48.4  | 45.3  | 13.9 | 3.56  | 450 | 9.40  | 10.0 | 2.31  | 13.6 | 1.06 | 199 | 6.19  | 52.0  |
| M2-3  | 11.7  | 53.5  | 206 | 7.93  | 23.3 | 12.6 | 146.0 | 14.9 | 56.3  | 34.5  | 14.8 | 3.79  | 290 | 32.00 | 8.8  | 2.75  | 13.6 | 1.17 | 307 | 9.28  | 89.8  |
| M2-4  | 15.9  | 149.0 | 133 | 29.90 | 53.5 | 24.6 | 113.0 | 35.5 | 129.0 | 72.4  | 30.5 | 12.90 | 563 | 34.40 | 19.7 | 4.03  | 22.3 | 1.67 | 233 | 6.34  | 60.7  |
| M2-5  | 20.7  | 167.0 | 122 | 29.00 | 66.0 | 16.3 | 236.0 | 23.6 | 20.6  | 44.1  | 46.9 | 1.46  | 134 | 26.90 | 15.8 | 2.80  | 11.0 | 0.93 | 155 | 4.46  | 24.4  |
| M2-6  | 17.0  | 86.2  | 188 | 15.10 | 36.3 | 15.7 | 56.5  | 26.2 | 96.0  | 56.6  | 28.4 | 7.55  | 570 | 9.77  | 17.7 | 3.73  | 21.7 | 1.66 | 343 | 10.10 | 78.7  |
| M2-7  | 16.2  | 85.0  | 154 | 8.60  | 32.3 | 11.1 | 68.9  | 26.3 | 97.6  | 60.1  | 31.6 | 5.44  | 669 | 6.74  | 15.1 | 3.49  | 19.9 | 1.62 | 403 | 12.10 | 99.9  |
| M2-8  | 17.5  | 103.0 | 163 | 14.60 | 39.3 | 15.6 | 90.8  | 31.6 | 95.2  | 49.3  | 18.3 | 8.16  | 638 | 8.56  | 13.2 | 2.83  | 21.6 | 1.69 | 273 | 8.23  | 74.0  |
| M2-9  | 14.3  | 78.6  | 194 | 13.30 | 31.5 | 16.0 | 56.2  | 21.3 | 73.9  | 48.4  | 25.6 | 4.24  | 482 | 10.10 | 13.3 | 3.18  | 18.3 | 1.50 | 290 | 8.12  | 75.4  |
| M2-10 | 16.3  | 96.8  | 113 | 22.30 | 38.2 | 28.2 | 71.4  | 27.9 | 88.1  | 57.0  | 17.4 | 6.20  | 610 | 19.80 | 16.0 | 3.63  | 20.8 | 1.61 | 381 | 11.30 | 97.9  |
| M2-11 | 13.3  | 114.0 | 145 | 6.87  | 25.7 | 12.8 | 57.5  | 30.5 | 90.7  | 58.1  | 20.2 | 7.91  | 656 | 6.77  | 19.0 | 3.79  | 24.2 | 1.90 | 317 | 9.42  | 90.2  |
| M2-12 | 12.5  | 158.0 | 138 | 29.50 | 47.4 | 23.7 | 49.8  | 34.7 | 78.1  | 40.7  | 19.2 | 8.00  | 691 | 39.50 | 12.0 | 3.75  | 24.4 | 1.84 | 275 | 8.12  | 80.0  |
| M2-13 | 10.3  | 109.0 | 162 | 15.00 | 35.1 | 10.7 | 64.5  | 26.1 | 70.8  | 38.0  | 13.3 | 3.93  | 489 | 8.43  | 14.7 | 2.53  | 21.6 | 1.76 | 234 | 6.64  | 92.4  |
| M2-14 | 16.8  | 110.0 | 156 | 16.50 | 62.3 | 20.5 | 88.6  | 34.8 | 94.2  | 64.4  | 34.2 | 5.92  | 707 | 9.04  | 29.8 | 4.36  | 26.4 | 2.06 | 421 | 13.00 | 116.0 |
| M2-15 | 8.4   | 55.8  | 217 | 19.50 | 75.3 | 31.2 | 47.6  | 14.2 | 35.7  | 32.2  | 17.0 | 1.84  | 227 | 99.80 | 15.1 | 3.62  | 15.0 | 1.39 | 492 | 14.60 | 178.0 |
| M2-16 | 14.0  | 73.0  | 144 | 11.90 | 34.1 | 14.2 | 145.0 | 25.3 | 71.3  | 49.9  | 36.7 | 4.55  | 543 | 7.07  | 16.5 | 3.84  | 20.6 | 1.62 | 397 | 11.10 | 101.0 |
| M2-17 | 8.8   | 106.0 | 129 | 26.00 | 79.4 | 19.1 | 56.9  | 34.0 | 85.8  | 70.4  | 22.1 | 7.79  | 568 | 32.50 | 18.2 | 5.80  | 28.0 | 2.06 | 286 | 8.43  | 89.3  |
| M2-18 | 134.0 | 191.0 | 138 | 28.90 | 61.4 | 19.5 | 98.8  | 27.2 | 42.8  | 64.6  | 16.8 | 4.87  | 517 | 29.30 | 14.2 | 3.35  | 22.0 | 1.71 | 337 | 9.74  | 86.0  |
| M2-19 | 18.6  | 146.0 | 120 | 11.30 | 43.8 | 17.4 | 121.0 | 33.2 | 107.0 | 101.0 | 27.6 | 7.75  | 645 | 18.60 | 22.4 | 3.62  | 22.5 | 1.75 | 264 | 7.42  | 79.7  |
| M2-20 | 5.9   | 91.5  | 167 | 6.95  | 31.9 | 12.0 | 44.1  | 26.0 | 52.4  | 106.0 | 11.7 | 5.96  | 242 | 7.98  | 14.1 | 4.03  | 23.2 | 2.01 | 350 | 10.50 | 104.0 |
| M2-21 | 10.3  | 93.4  | 109 | 3.25  | 19.6 | 9.4  | 40.9  | 41.5 | 157.0 | 159.0 | 10.3 | 14.60 | 383 | 8.51  | 22.5 | 3.19  | 29.9 | 2.24 | 357 | 10.60 | 133.0 |
| M2-22 | 2.4   | 70.4  | 240 | 4.55  | 10.0 | 5.5  | 13.1  | 5.8  | 55.0  | 24.8  | 6.3  | 1.31  | 329 | 7.76  | 6.2  | 1.38  | 6.9  | 0.62 | 217 | 6.02  | 84.4  |
| M2-23 | 9.1   | 99.7  | 161 | 25.30 | 31.1 | 25.1 | 41.5  | 14.5 | 105.0 | 48.2  | 20.7 | 3.30  | 465 | 28.80 | 12.1 | 3.46  | 11.4 | 0.88 | 222 | 6.07  | 128.0 |
| M2-24 | 15.3  | 123.0 | 182 | 7.48  | 21.2 | 19.0 | 45.9  | 13.7 | 91.1  | 61.5  | 15.4 | 3.30  | 344 | 2.79  | 8.9  | 3.20  | 11.1 | 0.89 | 196 | 5.51  | 102.0 |
| M2-25 | 4.1   | 73.1  | 205 | 4.66  | 15.5 | 13.9 | 29.1  | 8.9  | 54.5  | 82.6  | 16.2 | 2.03  | 229 | 1.47  | 7.8  | 1.50  | 4.6  | 0.43 | 165 | 4.89  | 68.4  |
| M2-26 | 5.7   | 49.2  | 203 | 5.63  | 29.1 | 36.0 | 38.1  | 9.6  | 75.1  | 110.0 | 23.5 | 3.82  | 273 | 3.23  | 12.5 | 2.43  | 8.5  | 0.74 | 349 | 9.55  | 123.0 |
| M2-27 | 17.4  | 85.4  | 139 | 10.30 | 70.1 | 5.4  | 59.4  | 26.9 | 213.0 | 85.9  | 22.4 | 14.30 | 712 | 6.26  | 17.9 | 2.90  | 18.4 | 1.43 | 206 | 5.63  | 204.0 |
| M2-28 | 10.8  | 64.4  | 170 | 16.20 | 45.4 | 17.6 | 75.2  | 15.0 | 112.0 | 90.9  | 19.2 | 7.40  | 425 | 42.10 | 12.4 | 2.83  | 13.1 | 1.05 | 241 | 6.44  | 119.0 |
| M2-29 | 9.2   | 53.8  | 151 | 6.01  | 17.1 | 5.5  | 40.0  | 15.0 | 115.0 | 138.0 | 34.6 | 7.24  | 482 | 3.85  | 14.2 | 3.14  | 11.7 | 0.99 | 340 | 10.30 | 204.0 |

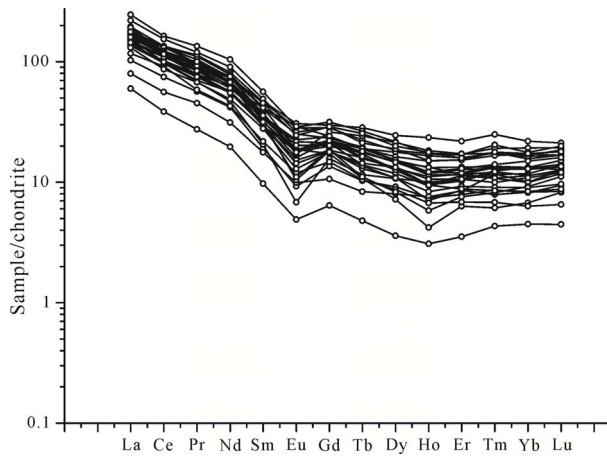


图 4 M2 井碳质泥岩稀土元素球粒陨石标准化  
(Taylor and McLennan, 1985)

Fig. 4 Chondrite-normalized rare-element diagram  
of carbonaceous mudstones in Well M2  
(after Taylor and McLennan, 1985)

al., 1993; 苏建超等, 2021)。通过  $\text{La/Th-Hf}$  和  $\text{Zr/10}^{-6}\text{-TiO}_2/\%$ 图解(图 5), 样品投点大多处于长英质/基性岩浆岩源区和古老沉积物组分增加的区域。沉积物中稀土元素的分布规律和 Eu 的异常特征为源区特征提供了线索。长英质源岩具有较高的轻稀土/重稀土比值和 Eu 负异常特征, 而基性源岩具有较低的轻稀土/重稀土比值和无明显 Eu 异常特征(Cullers, 1994; Wanas and Assal, 2021)。样品的 LREE/HREE 值为 7.17~18.15, 平均 11.35, 具有明显的 Eu 负异常。综合微量元素和稀土元素的地球化学特征, 吉泰盆地黄龙组沉积物主要来自长英质/基性岩和古老沉积物的混合区域。吉泰盆地基底石炭系黄龙组地层中的沉积物具有明显的深部来源特征, 这将为上覆白垩统周田组地层中的富钾锂卤水提供丰富的物质来源。

表 3 吉泰盆地黄龙组稀土元素含量/ $10^{-6}$   
Table 3 Content of rare elements / $10^{-6}$  in Huanglong Formation, Jitai Basin

| No.   | La   | Ce    | Pr   | Nd   | Sm    | Eu   | Gd   | Tb   | Dy   | Ho   | Er   | Tm    | Yb   | Lu    | $\Sigma\text{REE}$ |
|-------|------|-------|------|------|-------|------|------|------|------|------|------|-------|------|-------|--------------------|
| M2-1  | 49.9 | 89.8  | 10.3 | 38.2 | 6.77  | 1.31 | 4.50 | 0.54 | 2.30 | 0.30 | 1.33 | 0.184 | 1.42 | 0.247 | 207.09             |
| M2-2  | 30.9 | 59.9  | 6.8  | 25.1 | 3.84  | 0.65 | 3.53 | 0.51 | 2.93 | 0.52 | 1.66 | 0.259 | 1.72 | 0.283 | 138.62             |
| M2-3  | 23.9 | 44.9  | 5.4  | 18.8 | 3.54  | 0.69 | 2.76 | 0.42 | 2.56 | 0.53 | 1.78 | 0.352 | 2.11 | 0.374 | 108.15             |
| M2-4  | 58.6 | 108.0 | 13.6 | 49.1 | 9.30  | 1.98 | 7.36 | 1.12 | 5.89 | 1.21 | 3.59 | 0.575 | 4.04 | 0.581 | 264.95             |
| M2-5  | 46.3 | 96.6  | 11.5 | 43.6 | 9.40  | 2.15 | 7.73 | 1.42 | 7.85 | 1.64 | 4.59 | 0.747 | 4.60 | 0.635 | 238.76             |
| M2-6  | 53.4 | 96.6  | 11.3 | 39.4 | 6.46  | 1.12 | 5.77 | 0.95 | 5.68 | 1.16 | 3.35 | 0.524 | 3.52 | 0.557 | 229.79             |
| M2-7  | 47.1 | 92.4  | 10.6 | 40.1 | 7.03  | 1.58 | 6.21 | 0.96 | 5.20 | 1.05 | 3.24 | 0.532 | 3.28 | 0.504 | 219.78             |
| M2-8  | 50.4 | 106.0 | 11.7 | 44.2 | 7.47  | 1.26 | 5.73 | 0.79 | 4.24 | 0.67 | 2.38 | 0.324 | 2.09 | 0.353 | 237.60             |
| M2-9  | 40.8 | 78.2  | 8.4  | 33.9 | 5.86  | 1.26 | 5.16 | 0.88 | 4.76 | 0.93 | 2.44 | 0.399 | 2.75 | 0.423 | 186.16             |
| M2-10 | 49.8 | 92.7  | 11.3 | 39.7 | 6.86  | 1.52 | 5.51 | 0.69 | 3.78 | 0.65 | 2.25 | 0.348 | 2.47 | 0.418 | 218.00             |
| M2-11 | 54.5 | 106.0 | 13.3 | 47.1 | 8.36  | 1.30 | 5.82 | 0.89 | 4.69 | 0.83 | 2.68 | 0.389 | 2.69 | 0.401 | 248.95             |
| M2-12 | 41.2 | 81.6  | 9.5  | 37.3 | 8.27  | 1.76 | 6.02 | 0.98 | 4.75 | 0.81 | 2.43 | 0.364 | 2.39 | 0.372 | 197.73             |
| M2-13 | 42.6 | 77.4  | 9.5  | 34.0 | 6.29  | 0.73 | 4.73 | 0.65 | 3.49 | 0.50 | 1.80 | 0.237 | 1.74 | 0.252 | 183.86             |
| M2-14 | 73.9 | 131.0 | 16.2 | 62.7 | 11.30 | 2.02 | 8.23 | 1.33 | 6.95 | 1.2  | 3.55 | 0.614 | 3.72 | 0.599 | 323.31             |
| M2-15 | 41.3 | 77.9  | 8.2  | 28.2 | 4.13  | 0.48 | 4.07 | 0.58 | 3.44 | 0.71 | 2.18 | 0.374 | 2.79 | 0.456 | 174.78             |
| M2-16 | 52.3 | 92.0  | 11.7 | 41.2 | 7.43  | 1.20 | 6.79 | 1.21 | 6.84 | 1.28 | 3.62 | 0.521 | 3.43 | 0.506 | 230.03             |
| M2-17 | 52.7 | 105.0 | 12.5 | 44.5 | 8.29  | 2.03 | 6.28 | 0.95 | 4.86 | 0.93 | 2.80 | 0.406 | 2.79 | 0.381 | 244.41             |
| M2-18 | 44.0 | 88.8  | 10.9 | 41.2 | 7.12  | 1.28 | 5.74 | 0.86 | 4.10 | 0.67 | 2.15 | 0.367 | 2.39 | 0.368 | 209.94             |
| M2-19 | 66.0 | 123.0 | 14.4 | 54.3 | 9.82  | 1.82 | 7.49 | 1.06 | 6.03 | 1.06 | 3.20 | 0.500 | 3.61 | 0.503 | 292.79             |
| M2-20 | 35.1 | 73.4  | 7.0  | 25.7 | 4.36  | 0.84 | 3.84 | 0.52 | 2.79 | 0.47 | 1.44 | 0.204 | 1.33 | 0.196 | 157.20             |
| M2-21 | 57.4 | 98.2  | 11.8 | 39.3 | 5.96  | 0.77 | 4.84 | 0.55 | 2.66 | 0.41 | 1.59 | 0.246 | 1.93 | 0.334 | 225.99             |
| M2-22 | 18.0 | 30.9  | 3.3  | 11.8 | 1.95  | 0.34 | 1.67 | 0.24 | 1.15 | 0.22 | 0.74 | 0.130 | 0.94 | 0.134 | 71.52              |
| M2-23 | 43.1 | 78.8  | 9.1  | 33.2 | 5.94  | 1.07 | 4.79 | 0.80 | 4.16 | 0.78 | 2.45 | 0.325 | 2.37 | 0.379 | 187.28             |
| M2-24 | 44.6 | 89.9  | 9.5  | 32.9 | 5.98  | 1.00 | 4.70 | 0.68 | 3.46 | 0.59 | 1.94 | 0.272 | 1.90 | 0.289 | 197.67             |
| M2-25 | 46.6 | 79.8  | 9.0  | 33.0 | 6.32  | 1.28 | 5.49 | 0.82 | 4.03 | 0.66 | 1.85 | 0.255 | 1.76 | 0.263 | 191.10             |
| M2-26 | 43.4 | 87.4  | 10.1 | 36.2 | 7.10  | 1.24 | 5.76 | 0.95 | 4.91 | 0.85 | 2.51 | 0.410 | 2.71 | 0.405 | 203.95             |
| M2-27 | 53.2 | 95.1  | 11.1 | 40.5 | 7.16  | 1.42 | 5.23 | 0.90 | 4.68 | 0.85 | 2.73 | 0.422 | 3.14 | 0.481 | 226.92             |
| M2-28 | 39.3 | 69.4  | 8.1  | 29.5 | 5.58  | 0.91 | 4.62 | 0.72 | 4.25 | 0.74 | 2.22 | 0.299 | 2.28 | 0.361 | 168.28             |
| M2-29 | 48.0 | 92.4  | 12.0 | 45.2 | 9.05  | 1.71 | 7.53 | 1.27 | 6.40 | 1.24 | 3.32 | 0.534 | 3.64 | 0.538 | 232.83             |

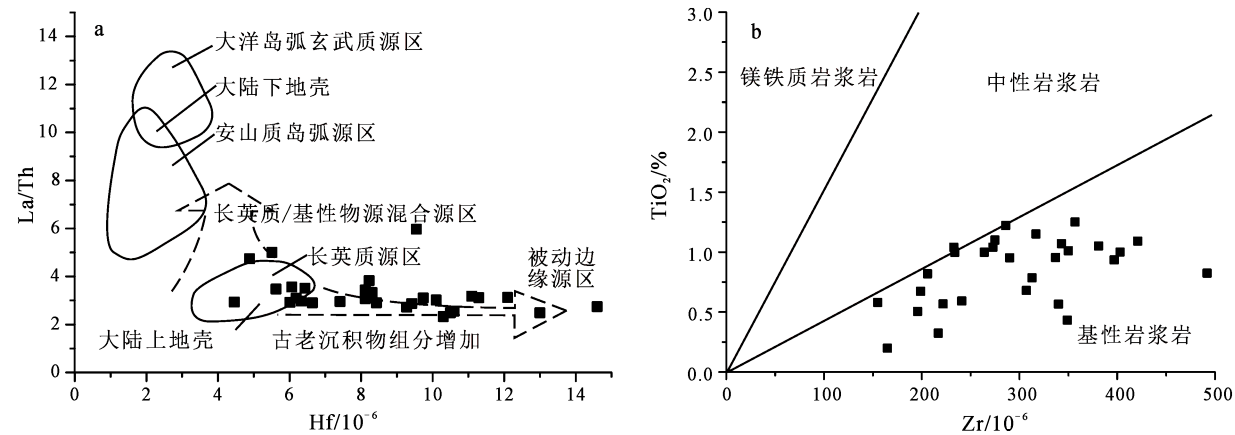
4.2 沉积构造背景

硅质碎屑沉积物的全岩地球化学可以用来区分沉积盆地的构造环境(Bhatia, 1983; Bhatia and Crook, 1986; Roser and Korsch, 1986; 严松涛等, 2020)。根据 Bhatia(1983), Bhatia and Crook(1986)

等人绘制的基于主要元素的判别图(图 6), 黄龙组的样品投点在  $\text{SiO}_2\text{-K}_2\text{O}/\text{Na}_2\text{O}$  图解中主要位于被动大陆边缘区域, 小部分样品处于活动大陆边缘区域, 在  $\text{K}_2\text{O}/\text{Na}_2\text{O}\text{-SiO}_2/\text{Al}_2\text{O}_3$  判别图中均处于被动大陆边缘区域。根据 Bhatia and Crook(1986)绘制的

表 4 吉泰盆地黄龙组部分元素比值  
Table 4 The value of elements in the Huanglong Formation, Jitai Basin

| No.   | $\text{Al}_2\text{O}_3/\text{SiO}_2$ | $\text{Al}_2\text{O}_3/\text{TiO}_2$ | $\text{K}_2\text{O}/\text{Na}_2\text{O}$ | CIA   | CIW   | PIA   | ICV  | La/Th | Cr/Th | Th/Sc | Zr/Sc |
|-------|--------------------------------------|--------------------------------------|------------------------------------------|-------|-------|-------|------|-------|-------|-------|-------|
| M2-1  | 0.275                                | 23.333                               | 13.333                                   | 78.10 | 95.30 | 94.69 | 0.46 | 3.33  | 9.53  | 1.16  | 24.26 |
| M2-2  | 0.157                                | 17.783                               | 9.152                                    | 86.95 | 96.97 | 97.36 | 0.62 | 3.09  | 16.80 | 1.08  | 21.56 |
| M2-3  | 0.149                                | 16.500                               | 10.056                                   | 84.50 | 97.13 | 97.33 | 0.77 | 2.72  | 23.46 | 0.75  | 26.24 |
| M2-4  | 0.646                                | 27.269                               | 10.974                                   | 86.33 | 97.90 | 99.13 | 0.60 | 2.97  | 6.75  | 1.24  | 14.65 |
| M2-5  | 0.339                                | 25.690                               | 4.964                                    | 99.52 | 95.85 | 99.05 | 2.12 | 2.93  | 7.72  | 0.76  | 7.49  |
| M2-6  | 0.357                                | 20.850                               | 11.386                                   | 87.26 | 98.41 | 98.88 | 0.40 | 3.02  | 10.62 | 1.04  | 20.18 |
| M2-7  | 0.297                                | 19.790                               | 11.888                                   | 86.07 | 98.03 | 98.57 | 0.46 | 3.12  | 10.20 | 0.93  | 24.88 |
| M2-8  | 0.364                                | 21.250                               | 12.183                                   | 87.92 | 98.37 | 98.74 | 0.50 | 3.82  | 12.35 | 0.75  | 15.60 |
| M2-9  | 0.252                                | 18.298                               | 11.048                                   | 87.32 | 98.22 | 98.63 | 0.47 | 3.07  | 14.59 | 0.93  | 20.28 |
| M2-10 | 0.353                                | 20.162                               | 12.183                                   | 87.53 | 98.31 | 98.78 | 0.53 | 3.11  | 7.06  | 0.98  | 23.37 |
| M2-11 | 0.442                                | 22.426                               | 12.888                                   | 89.09 | 98.70 | 99.26 | 0.36 | 2.87  | 7.63  | 1.43  | 23.83 |
| M2-12 | 0.550                                | 25.455                               | 12.226                                   | 87.96 | 98.56 | 98.94 | 0.35 | 3.43  | 11.50 | 0.96  | 22.00 |
| M2-13 | 0.326                                | 21.244                               | 11.144                                   | 89.51 | 98.39 | 98.73 | 0.38 | 2.90  | 11.02 | 1.43  | 22.72 |
| M2-14 | 0.419                                | 22.505                               | 10.317                                   | 89.77 | 98.59 | 99.12 | 0.41 | 2.48  | 5.23  | 1.77  | 25.06 |
| M2-15 | 0.123                                | 9.781                                | 5.812                                    | 85.52 | 95.83 | 96.48 | 1.61 | 2.74  | 14.37 | 1.79  | 58.50 |
| M2-16 | 0.292                                | 20.353                               | 10.332                                   | 88.81 | 98.29 | 98.74 | 0.48 | 3.17  | 8.73  | 1.18  | 28.36 |
| M2-17 | 0.600                                | 24.451                               | 7.778                                    | 88.90 | 98.25 | 98.64 | 0.36 | 2.90  | 7.09  | 2.08  | 32.61 |
| M2-18 | 0.339                                | 20.461                               | 10.583                                   | 86.22 | 93.10 | 94.86 | 0.74 | 3.10  | 9.72  | 0.11  | 2.51  |
| M2-19 | 0.517                                | 25.822                               | 8.939                                    | 88.11 | 96.40 | 97.74 | 0.53 | 2.95  | 5.36  | 1.20  | 14.19 |
| M2-20 | 0.349                                | 22.376                               | 6.880                                    | 92.80 | 98.39 | 99.32 | 0.29 | 2.49  | 11.84 | 2.39  | 59.42 |
| M2-21 | 0.620                                | 24.896                               | 11.677                                   | 83.02 | 97.19 | 97.24 | 0.35 | 2.55  | 4.84  | 2.18  | 34.66 |
| M2-22 | 0.082                                | 21.852                               | 15.040                                   | 75.06 | 92.36 | 91.67 | 0.59 | 2.92  | 38.90 | 2.60  | 91.56 |
| M2-23 | 0.171                                | 22.148                               | 23.061                                   | 75.01 | 92.09 | 91.99 | 0.85 | 3.56  | 13.31 | 1.32  | 24.29 |
| M2-24 | 0.157                                | 23.889                               | 22.086                                   | 78.77 | 96.25 | 98.08 | 0.66 | 5.01  | 20.43 | 0.58  | 12.81 |
| M2-25 | 0.096                                | 38.945                               | 20.824                                   | 71.00 | 80.52 | 81.08 | 0.96 | 4.74  | 33.86 | 1.93  | 27.32 |
| M2-26 | 0.122                                | 21.134                               | 22.523                                   | 68.77 | 80.18 | 79.46 | 1.19 | 5.97  | 26.25 | 2.19  | 40.74 |
| M2-27 | 0.315                                | 23.545                               | 38.182                                   | 76.22 | 98.34 | 99.04 | 0.76 | 3.47  | 16.24 | 1.03  | 61.01 |
| M2-28 | 0.168                                | 20.591                               | 29.035                                   | 73.70 | 90.94 | 89.51 | 0.87 | 3.51  | 15.29 | 1.15  | 55.41 |
| M2-29 | 0.167                                | 20.726                               | 27.519                                   | 69.73 | 85.21 | 84.98 | 0.95 | 2.32  | 14.60 | 1.54  | 14.74 |



a—La/Th-Hf 判别图(Roser and Korsch, 1988); b—Zr/10<sup>-6</sup>-TiO<sub>2</sub>/ %判别图(Hayashi et al., 1997)。  
a—diagram of La/Th-Hf (after Roser and Korsch, 1988); b—diagram of Zr/10<sup>-6</sup>-TiO<sub>2</sub>/ % (after Hayashi et al., 1997).

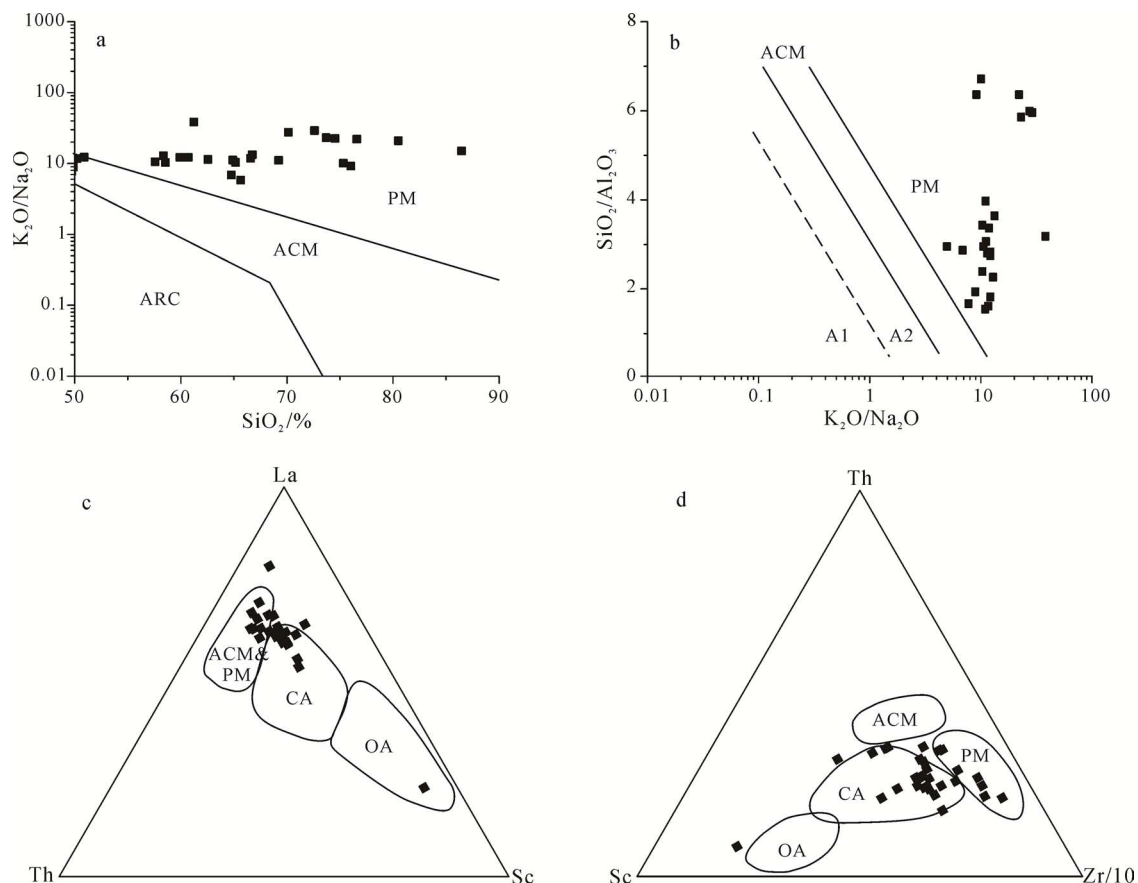
图 5 M2 井样品物源判别图  
Fig. 5 Provenance discrimination diagram of Well M2

La-Th-Sc 和 Th-Sc-Zr/10 图解, 黄龙组的样品投点主要处于被动大陆边缘区域和大陆岛弧区域。综合主微量元素、稀土元素的比值判别图, 吉泰盆地石炭系黄龙组碎屑岩的沉积构造背景以被动大陆边缘构造为主, 同时具有大陆岛弧构造的特征。舒良树等(2008)通过研究华南东段早古生代的沉积环境、火山岩、镁铁岩及早古生代造山带, 表明华南东段为被动大陆边缘浅海-半深海沉积环境。泥盆纪至三叠纪时期, 扬子板块为大西洋式被动大陆边缘; 从印支运动开始后, 逐渐由被动大陆边缘向主动大陆边缘演化(王鸿桢, 1986; 任纪舜, 1990)。在晚古生代时期, 华南陆块岩石学和沉积相特征表明, 由早期的陆内断陷演变成被动大陆边缘的陆表海环境(李双应和金福全, 1994; 吴大燮等, 1994)。舒良树等(2012)利用锆石 U-Pb 测年、沉积环境和地层对比等手段对华南地区构造演化的基本特征做了详细梳理, 认为在早古生代时期的板内构造事件使扬子块体和华夏块体再次聚合, 泥盆纪开始逐渐形成初步统一的中国南方岩相古地理格局。早石炭世一中三叠世时期, 整个华南基本处在一个稳定的

滨海-浅海环境没有出现大规模的火山活动及深海大洋的物质沉积。因此, 吉泰盆地石炭系黄龙组碳质泥岩具有被动大陆边缘的构造背景特征。

#### 4.3 源区古风化

化学风化作用在潮湿气候下起主导作用, 强烈地控制着硅质碎屑岩沉积物的主微量元素组成(Nesbitt and Young, 1982; Harnois, 1988; Middelburg et al., 1988; McLennan et al., 1993; Fedo et al., 1995)。而在干旱条件下, 原岩普遍存在物理风化作用, 既原岩被机械分解呈较小的颗粒, 但是矿物学和化学成分并没有发生重大变化。因此, 化学风化指数能够为源区古风化提供很好的测量手段。利用 A-CN-K(由  $\text{Al}_2\text{O}_3$ 、CaO、 $\text{Na}_2\text{O}$  和  $\text{K}_2\text{O}$  的分子比例分布和蚀变化学指标(CIA)构成)三元图可以确定化学风化和成岩过程中钾交代的元素迁移率(Nesbitt and Young, 1982, 1984)。此外, Harnois (1988)、Fedo et al.(1995)、Cox et al.(1995)利用 CIW、PIA、ICV 等化学风化指标评价源区的古风化作用, 同时避免了涉及钾富集的问题。



a— $\text{SiO}_2$ - $\text{K}_2\text{O}/\text{Na}_2\text{O}$  判别图; b— $\text{K}_2\text{O}/\text{Na}_2\text{O}$ - $\text{SiO}_2/\text{Al}_2\text{O}_3$  判别图(Roser and Korsch, 1986);

c—La-Th-Sc 判别图; d—Th-Sc-Zr/10 判别图(Bhatia and Crook, 1986);

ARC—岛弧; ACM—活动大陆边缘; PM—被动大陆边缘; CA—大陆岛弧; OA—大洋岛弧; A1—岛弧背景; A2—演化岛弧背景。

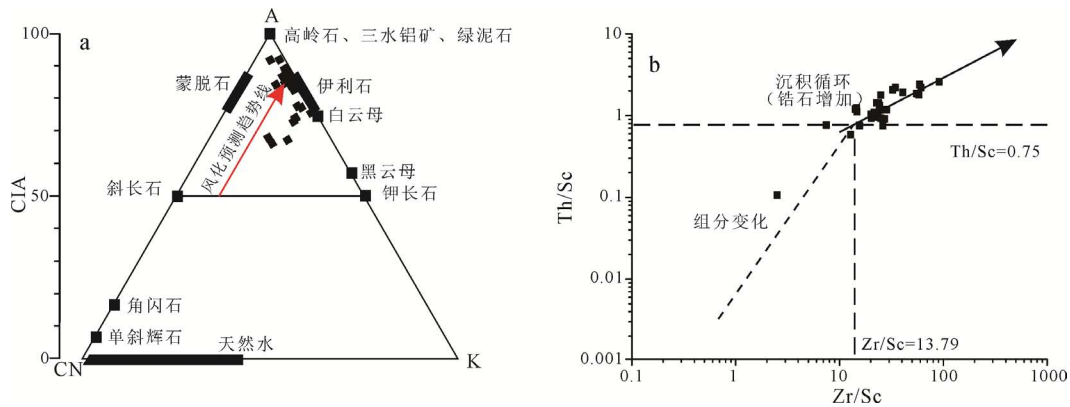
a—diagram of  $\text{SiO}_2$ - $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ; b—diagram of  $\text{K}_2\text{O}/\text{Na}_2\text{O}$ - $\text{SiO}_2/\text{Al}_2\text{O}_3$  (after Roser and Korsch, 1986); c—diagram of La-Th-Sc;

d—diagram of Th-Sc-Zr/10 (after Bhatia and Crook, 1986); ARC—Island arc; ACM—Active continental margin; PM—Passive margin;

CA—Continental island arc; OA—Oceanic island arc; A1—arc setting; A2—evolved arc setting.

图 6 M2 井样品构造背景判别图

Fig. 6 Discriminant drawing of structural background, Well M2



a—A-CN-K 图解(Fedo et al., 1995); b—Zr/Sc-Th/Sc 图解(McLennan et al., 1993)。

a—diagram of A-CN-K (after Fedo et al., 1995); b—diagram of Zr/Sc-Th/Sc (after McLennan et al., 1993)。

图 7 M2 井样品风化、分选和再循环判别图

Fig. 7 Comparative diagrams showing influence of weathering, sorting and recycling for M2

未风化的岩石和 UCC 的平均 CIA 值在 50 左右或以下(Taylor and McLennan, 1985), 页岩 CIA 的值在 70~75 之间, 黏土的 CIA 值接近 100。黄龙组样品的 CIA 值在 68.77~99.52 之间, 平均 83.77, 表明了较大的化学风化程度差异。其中较低的化学风化主要出现在钻孔的下部(表 4), 岩性较粗以粉砂岩为主, 碳质含量较少, 而上部的泥岩和粉砂质泥岩则表现出重度化学风化程度。在风化过程中, CaO 和 Na<sub>2</sub>O 相对于 K<sub>2</sub>O 优先被去除, 因此斜长石比钾长石更容易被风化。黄龙组样品经历化学风化后, CaO 和 Na<sub>2</sub>O 含量降低, 投点大多处于 A-K 边界附近。而在沉积后的钾交代蚀变过程中, K 相对于 Al 表现出被去除, 从而使样品投点靠近 A(Al<sub>2</sub>O<sub>3</sub>)顶点附近。钾长石和其他不稳定矿物的逐渐枯竭导致黑云母、白云母和伊利石矿物的增加。最终随着风化作用的加深, 岩石组分将以高岭石、三水铝石和绿泥石富集为主。风化过程也可以由长英质岩石向蒙脱石转变, 再转向白云母、黑云母及伊利石, 最后转变为高岭石、三水铝石和绿泥石(图 7a)。通过计算, 黄龙组样品的 CIW 值为 80.18~98.70, 平均 95.24; PIA 的值为 79.46~99.36, 平均 95.91(表 4)。这些值都表明黄龙组沉积物有着强烈的化学风化作用(Harnois, 1988; Fedo et al., 1995), 有利于元素的迁移和富集, 为上覆卤水矿的形成提供了多样的成矿元素。对于 ICV 值而言, ICV 值小于 1, 表明沉积物可能经受强风化作用的首次沉积物或经历了再沉积的产物。Th/Sc 和 Zr/Sc 的比值暗示了沉积物的循环作用, 导致锆石等重矿物逐渐富集, 而锆石是 Zr 和 Th 的主要宿主(McLennan et al., 1993)。对比 Zr/Sc-Th/Sc 判别图(图 7b), 表明沉积物经历了再循环过程。地球化学特征表明黄龙组沉积物经历了较强的风化作用和再循环作用, 而且上部风化作用更为强烈, 气候也更为潮湿。

## 5 结论

(1)通过分析吉泰盆地 M2 井碳质泥岩样品 La/Th-Hf 和 Zr-TiO<sub>2</sub> 的比值, 轻稀土/重稀土比值和 Eu 的异常特征, 认为吉泰盆地黄龙组的物源主要为长英质/基性岩和古老沉积物的混合区域, 为富锂钾卤水矿提供了物质来源;

(2)通过主微量元素和稀土元素(TiO<sub>2</sub>、La、Sc、Hf、Th、Zr)的含量和比值, 反映出吉泰盆地黄龙组的碳质泥岩具有被动大陆边缘的构造背景特征;

(3)Th/Sc 和 Zr/Sc 的比值表明吉泰盆地黄龙组上部泥岩受到沉积再循环的影响。根据化学风化指数(CIA、CIW、PIA 和 ICV)及 Al<sub>2</sub>O<sub>3</sub>-(CaO+Na<sub>2</sub>O)-K<sub>2</sub>O 图解, 黄龙组碳质泥岩是在沉积源区经历了较为强烈的风化作用和再循环形成的沉积物。强烈的化学风化作用有利于元素的迁移和富集, 为卤水矿床的形成提供了丰富的成矿元素。

致谢: 野外工作中得到了江西省新余市地质矿产勘察开发局 902 地质队的大力支持和帮助, 样品挑选和预处理过程中得到了陈鹏等工作人员的帮助, 在此表示衷心的感谢。同时, 感谢评审专家提出富有建设性的宝贵意见。

## Acknowledgements:

This study was supported by Central Public-interest Scientific Institution Basal Research Fund (Nos. KK2005 and KK2016), National Program on Key Basic Research Project (973 Program) (No. 2011CB403007), and China Geological Survey (Nos. DD20190437 and DD20190606)。

## 参考文献:

董树文, 施炜, 张岳桥, 胡健民, 张忠义, 李建华, 武红岭, 田蜜, 陈虹, 武国利, 李海龙. 2010. 大巴山晚中生代陆内造

- 山构造应力场[J]. 地球学报, 31(6): 769-780.
- 董树文, 张岳桥, 龙长兴, 杨振宇, 季强, 王涛, 胡建民, 陈宣华. 2007. 中国侏罗纪构造变革与燕山运动新诠释[J]. 地质学报, 81(11): 1449-1461.
- 兰叶芳, 任传建, 李小彩, 任成明, 高柱. 2022. 黔西北毕节地区中二叠统碳酸盐岩岩石学、地球化学特征及意义[J]. 地球学报, 43(3): 309-324.
- 李双应, 金福全. 1994. 下扬子盆地石炭纪的岩石学特征及沉积相[J]. 安徽地质, 4(3): 36-47.
- 刘成林, 焦鹏程, 王弭力. 2010. 盆地钾盐找矿模型探讨[J]. 矿床地质, 29(4): 581-592.
- 刘成林, 王弭力, 焦鹏程, 陈永志. 2009. 罗布泊盐湖钾盐矿床分布规律及控制因素分析[J]. 地球学报, 30(6): 796-802.
- 刘成林. 2013. 大陆裂谷盆地钾盐矿床特征与成矿作用[J]. 地球学报, 34(5): 515-527.
- 卢秋芽. 1991. 江西吉泰盆地泰和坳陷白垩纪沉积特征[J]. 物探与化探, 15(5): 395-398.
- 马厚明, 赖志坚, 鄢新华, 廖绍平, 田立明. 2021. 江西吉泰盆地卤水锂矿床地球化学特征及远景分析[J]. 地球学报, 42(5): 617-627.
- 任纪舜. 1990. 论中国南部的大地构造[J]. 地质学报, 64(4): 275-288.
- 舒良树, 于津海, 贾东, 王博, 沈渭洲, 张岳桥. 2008. 华南东段早古生代造山带研究[J]. 地质通报, 27(10): 1581-1593.
- 舒良树. 2012. 华南构造演化的基本特征[J]. 地质通报, 31(7): 1035-1053.
- 苏建超, 李长安, 吴中海, 林旭, 李亚伟, 郭汝军. 2021. 江汉盆地周缘主要河流沉积物碎屑磷灰石的微量元素特征及其物源判别指标分析[J]. 地球学报, 42(5): 641-650.
- 王春连, 黄华, 王九一, 徐海明, 余小灿, 高超, 孟令阳, 蔡芃睿, 颜开, 方景玲. 2018. 江陵凹陷富钾锂卤水矿田地质特征及成藏模式研究[J]. 地质学报, 92(8): 1630-1646.
- 王春连, 刘丽红, 李强, 孟令阳, 刘成林, 张媛媛, 王九一, 余小灿, 颜开. 2020. 江西吉泰盆地卤水型锂钾矿物源区岩石地球化学特征及成因分析[J]. 岩石矿物学杂志, 39(1): 65-84.
- 王春连, 孟令阳, 刘成林, 余小灿, 颜开, 刘思晗, 游超, 栗克坤, 滕晓华. 2021. 江陵凹陷古新世地下卤水型硼成因研究[J]. 岩石矿物学杂志, 40(1): 1-13.
- 王春连, 王九一, 游超, 余小灿, 刘殿鹤, 颜开, 刘思晗, 薛燕, 刘延亭, 刘雪, 尹传凯. 2022. 战略性非金属矿产厘定、关键应用和供需形势研究[J]. 地球学报, 43(3): 267-278.
- 王鸿楫. 1986. 中国华南地区地壳构造发展的轮廓[M]//华南地区古大陆边缘构造史. 武汉: 武汉地质学院出版社.
- 魏海成, 樊启顺, 安福元, 山发寿, 马海州, 袁秦, 秦占杰. 2016. 94—9 ka 察尔汗盐湖的气候环境演化过程[J]. 地球学报, 37(2): 193-203.
- 吴大燮, 徐良发, 曹振秋, 叶德燎, 朱宏发. 1994. 扬子及周缘地区晚古生代总体沉积格局与含油气领域的探讨[J]. 石油实验地质, 16(1): 21-29.
- 严松涛, 谭昌海, 秦蒙, 李虎, 段阳海. 2020. 四川理塘地区二叠—三叠纪硅质岩的地球化学特征及地质意义[J]. 地球学报, 41(4): 504-514.
- 姚秋昌, 楼基胜. 2008. 洞庭盆地沅江凹陷油气成藏条件分析[J]. 天然气工业, 28(9): 37-40, 134.
- 游超, 王春连, 刘殿鹤, 余小灿, 颜开, 刘思晗, 周博文. 2022. 江西宁都坎田萤石矿床稀土元素地球化学特征及其指示意义[J]. 地球学报, 43(3): 359-370.
- 余心起, 舒良树, 邓国辉, 王彬, 祖辅平. 2005. 江西吉泰盆地碱性玄武岩的地球化学特征及其构造意义[J]. 现代地质, 19(1): 133-140.
- 赵越, 徐刚, 张拴宏, 杨振宇, 张岳桥, 胡健民. 2004. 燕山运动与东亚构造体制的转变[J]. 地学前缘, 11(3): 319-328.
- 周敏娟, 胡立, 黄小年, 韩雪平. 2017. 江西省泰和县梅岗含锂卤水矿成矿地质特征及开发利用前景[J]. 现代矿业, 33(11): 61-82.
- 周博文, 王春连, 游超, 刘殿鹤, 刘思晗, 余小灿, 颜开, 刘雪, 刘延亭. 2022. 福建邵武地区张厝萤石矿微量、稀土元素地球化学特征[J]. 地球学报, 43(3): 393-403.

## References:

- BHATIA M R, CROOK K A. 1986. Trace element characteristics of graywackes and tectonic setting discrimination of sedimentary basins[J]. Contributions to Mineralogy and Petrology, 92(2): 181-193.
- BHATIA M R. 1983. Plate tectonics and geochemical composition of sandstones[J]. Journal of Geology, 91(6): 611-627.
- COX R, LOWE D R, CULLERS R L. 1995. The influence of sediment recycling and basement composition on evolution of mudrock chemistry in the southwestern United States[J]. Geochimica et Cosmochimica Acta, 59(14): 2919-2940.
- CULLERS R L. 1994. The controls on the major and trace element variation of shales, siltstones, and sandstones of Pennsylvanian-Permian age from uplifted continental blocks in Colorado to platform in Kansas, USA[J]. Geochimica et Cosmochimica Acta, 58(22): 4955-4972.
- CULLERS R L. 2000. The geochemistry of shales, siltstones and sandstones of Pennsylvanian-Permian age, Colorado, USA: implications for provenance and metamorphic studies[J]. Lithos, 51(3): 181-203.
- DONG Shu-wen, SHI Wei, ZHANG Yue-qiao, HU Jian-min, ZHANG Zhong-yi, LI Jian-hua, WU Hong-ling, TIAN Mi, CHEN Hong, WU Guo-li, LI Hai-long. 2010. The tectonic stress field in the Dabashan orogen resulting from late Mesozoic intra-continental orogeny[J]. Acta Geoscientica Sinica, 31(6): 769-780(in Chinese with English abstract).

- DONG Shu-wen, ZHANG Yue-qiao, LONG Chang-xing, YANG Zhen-yu, JI Qiang, WANG Tao, HU Jian-min, CHEN Xuan-hua. 2007. Jurassic tectonic revolution in China and new interpretation of the Yanshan Movement[J]. *Acta Geologica Sinica*, 81(11): 1449-1461(in Chinese with English abstract).
- FEDO C M, NESBITT H W, YOUNG G M. 1995. Unraveling the effects of potassium metasomatism in sedimentary rocks and paleosols, with implications for paleoweathering conditions and provenance[J]. *Journal of Geology*, 23(10): 921-924.
- HARNOIS L. 1988. The CIW index: A new chemical index of weathering[J]. *Sedimentary Geology*, 55(3-4): 319-322.
- HAYASHI K I, FUJISAWA H, HOLLAND H D, OHMOTO H. 1997. Geochemistry of ~1.9 Ga sedimentary rocks from northeastern Labrador, Canada[J]. *Geochimica et Cosmochimica Acta*, 61(19): 4115-4137.
- LAN Ye-fang, REN Chuan-jian, LI Xiao-cai, REN Shu-ming, GAO Zhu. 2022. Petrological and Geochemical Characteristics and Their Significance of Middle Permian Carbonate Rocks in Bijie Area, Northwestern Guizhou[J]. *Acta Geoscientica Sinica*, 43(3): 309-324(in Chinese with English abstract).
- LI Shuang-ying, JIN Fu-quan. 1994. Carboniferous petrographic features and depositional facies of the Lower Yangtze Basin[J]. *Geology of Anhui*, 4(3): 36-47(in Chinese with English abstract).
- LIU Cheng-lin, JIAO Peng-cheng, WANG Mi-li. 2010. A tentative discussion on exploration model for potash deposits in basins of China[J]. *Mineral Deposits*, 29(4): 581-592(in Chinese with English abstract).
- LIU Cheng-lin, WANG Mi-li, JIAO Peng-cheng, CHEN Yong-zhi. 2009. The probing of regularity and controlling factors of potash deposits distribution in Lop Nur salt lake, Xinjiang[J]. *Acta Geoscientica Sinica*, 30(6): 796-802(in Chinese with English abstract).
- LIU Cheng-lin. 2013. Characteristics and formation of potash deposits in continental rift basins: A review[J]. *Acta Geoscientica Sinica*, 34(5): 515-527(in Chinese with English abstract).
- LU Qiu-ya. 1991. Characteristics of Cretaceous Sedimentation in Taihe depression, Jitai Basin, Jiangxi Province[J]. *Geophysical and Geochemical Exploration*, 15(5): 395-398(in Chinese).
- MA Hou-ming, LAI Zhi-jian, YAN Xin-hua, LIAO Shao-ping, TIAN Li-ming. 2021. Geochemical characteristics and prospect analysis of brine lithium deposits in Jitai Basin, Jiangxi Province[J]. *Acta Geoscientica Sinica*, 42(5): 617-627(in Chinese with English abstract).
- MCLENNAN S M, HEMMING S, MCDANIEL D K, HANSON G N. 1993. Geochemical approaches to sedimentation, provenance, and tectonics[M]. Geological Society of America Special Paper, 284, USA: 21-40.
- MIDDELBURG J J, VAN DER WEIJDEN C H, WOITTEZ J R W. 1988. Chemical processes affecting the mobility of major, minor and trace elements during weathering of granitic rocks[J]. *Chemical Geology*, 68(3-4): 253-273.
- NAMEROFF T J, CALVERT S E, MURRAY J W. 2004. Glacial-interglacial variability in the eastern tropical North Pacific oxygen minimum zone recorded by redox-sensitive trace metals[J]. *Paleoceanography and Paleoclimatology*, 19(1): PA1010.
- NESBITT H W, YOUNG G M. 1982. Early Proterozoic climates and plate motions inferred from major element chemistry of lutites[J]. *Nature*, 299(5885): 715-717.
- NESBITT H W, YOUNG G M. 1984. Prediction of some weathering trends of plutonic and volcanic rocks based on thermodynamic and kinetic considerations[J]. *Geochimica Cosmochimica Acta*, 48(7): 1523-1534.
- REN Ji-shun. 1990. On the geotectonics of Southern China[J]. *Acta Geologica Sinica*, 64(4): 275-288(in Chinese with English abstract).
- RODRÍGUEZ-LÓPEZ J P, WU Chi-hua. 2020. Recurrent deformations of aeolian desert dunes in the Cretaceous of the South China Block: Trigger mechanisms variability and implications for aeolian reservoirs[J]. *Marine and Petroleum Geology*, 119: 104483.
- ROSER B P, KORSCH R J. 1986. Determination of tectonic setting of sandstone-mudstone suites using SiO<sub>2</sub> content and K<sub>2</sub>O/Na<sub>2</sub>O ratio[J]. *Journal of Geology*, 94(5): 635-650.
- SHU Liang-shu, YU Jin-hai, JIA Dong, WANG Bo, SHEN Wei-zhou, ZHANG Yue-qiao. 2008. Early Paleozoic orogenic belt in the eastern segment of South China[J]. *Geological Bulletin of China*, 27(10): 1581-1593(in Chinese with English abstract).
- SHU Liang-shu. 2012. An analysis of principal features of tectonic evolution in South China Block[J]. *Geological Bulletin of China*, 31(7): 1035-1053(in Chinese with English abstract).
- SU Jian-chao, LI Chang-an, WU Zhong-hai, LIN Xu, LI Ya-wei, GUO Ru-jun. 2021. Detrital apatite trace element characteristics of main rivers around Jiangnan Basin and an analysis of their provenance discriminant indicators[J]. *Acta Geoscientica Sinica*, 42(5): 641-650(in Chinese with English abstract).
- SUN Xiao-hong, ZHAO Yan-jun, LIU Cheng-lin, JIAO Peng-cheng, ZHANG Hua, WU Chi-hua. 2017. Paleoclimatic information recorded in fluid inclusions in halites from Lop Nur, Western China[J]. *Scientific Reports*, 7: 16411.
- TAYLOR S R, MCLENNAN S M. 1985. The continental crust: Its composition and evolution[M]. Oxford: Blackwell, Oxford

- University.
- TRIBOVILLARD N, ALGEO T J, LYONS T, RIBOULLEAU A. 2006. Trace metals as paleoredox and paleoproductivity proxies: An update[J]. *Chemical Geology*, 232((1-2): 12-32.
- TRIBOVILLARD N, AVERBUCH O, DELEESCHOUWER X, RACKI G, RIBOULLEAU A. 2004. Deep-water anoxia over the Frasnian-Famennian boundary (La Serre, France): A tectonically induced oceanic anoxic event?[J]. *Terra Nova*, 16(5): 288-295.
- WANAS H A, ASSAL E M. 2021. Provenance, tectonic setting and source area-paleoweathering of sandstones of the Bahariya Formation in the Bahariya Oasis, Egypt: An implication to paleoclimate and paleogeography of the southern Neo-Tethys region during Early Cenomanian[J]. *Sedimentary Geology*, 413: 105822.
- WANG Chun-lian, HUANG Hua, WANG Jiu-yi, XU Hai-ming, YU Xiao-can, GAO Chao, MENG Ling-yang, CAI Peng-rui, YAN Kai, FANG Jing-ling. 2018. Geological features and metallogenic model of K-and Li-rich brine ore field in the Ji-angling Depression[J]. *Acta Geologica Sinica*, 92(8): 1630-1646(in Chinese with English abstract).
- WANG Chun-lian, LIU Li-hong, LI Qiang, MENG Ling-yang, LIU Cheng-lin, ZHANG Yuan-yuan, WANG Jiu-yi, YU Xiao-can, YAN Kai. 2020. Petrogeochemical characteristics and genetic analysis of the source area of brine type lithium-potassium ore sources area in Jitai basin of Jiangxi Province[J]. *Acta Petrologica et Mineralogica*, 39(1): 65-84(in Chinese with English abstract).
- WANG Chun-lian, MENG Ling-yang, LIU Cheng-lin, YU Xiao-can, YAN Kai, LIU Si-han, YOU Chao, LI Ke-kun, TENG Xiao-hua. 2021. A study of the genesis of Paleocene underground brine boron deposits in Jiangling Depression[J]. *Acta Petrologica et Mineralogica*, 40(1): 1-13(in Chinese with English abstract).
- WANG Chun-lian, WANG Jiu-yi, YOU Chao, YU Xiao-can, LIU Dian-he, YAN Kai, LIU Si-han, XUE Yan, LIU Yan-ting, LIU Xue, YIN Chuan-kai. 2022. A Study on Strategic Non-metallic Mineral Definition, Key Applications, and Supply and Demand Situation[J]. *Acta Geoscientica Sinica*, 43(3): 267-278(in Chinese with English abstract).
- WANG Hong-zhen. 1986. Outline of tectonic evolution in the southern China[M]//Tectonic history of old continental margin at southern China. Wuhan: Wuhan College of Geology Press (in Chinese).
- WEI Hai-cheng, FAN Qi-shun, AN Fu-yuan, SHAN Fa-shou, MA Hai-zhou, YUAN Qin, QIN Zhan-jie. 2016. Chemical elements in core sediments of the Qarhan Salt Lake and palaeoclimate evolution during 94—9 ka[J]. *Acta Geoscientica Sinica*, 37(2): 193-203(in Chinese with English abstract).
- WU Da-xi, XU Liang-fa, CAO Zhen-qi, YE De-liao, ZHU Hong-fa. 1994. The Late Paleozoic sedimentary framework and the oil/gas potential of the Yangtze Block and its bordering areas[J]. *Experimental Petroleum Geology*, 16(1): 21-29(in Chinese with English abstract).
- YAN Song-tao, TAN Chang-hai, QIN Meng, LI Hu, DUAN Yang-hai. 2020. Geochemical characteristics and geological significance of Permian-Triassic siliceous rocks in Litang Area, Sichuan Province[J]. *Acta Geoscientica Sinica*, 41(4): 504-514(in Chinese with English abstract).
- YAO Qiu-chang, LOU Ji-sheng. 2008. An analysis of hydrocarbon pooling conditions in Yuanjiang sag, the Dongting Basin[J]. *Natural Gas Industry*, 28(9): 37-40(in Chinese with English abstract).
- YOU Chao, WANG Chun-lian, LIU Dian-he, YU Xiao-can, YAN Kai, LIU Si-han, ZHOU Bo-wen. 2022. REE Geochemistry of Fluorite from Kantian Fluorite Deposit and Its Geological Implications in Ningdu Area, Jiangxi Province[J]. *Acta Geoscientica Sinica*, 43(3): 359-370(in Chinese with English abstract).
- YU Xin-qi, SHU Liang-shu, DENG Guo-hui, WANG Bin, ZU Fu-ping. 2005. Geochemical features and tectonic significance of the alkaline-basalts from Ji'an-Taihe Basin, Jiangxi Province[J]. *Geoscience*, 19(1): 133-140(in Chinese with English abstract).
- ZHANG Lei, QIN Xiao-guang, LIU Jia-qi, SUN Chun-qing, MU Yan, GAO Jin-liang, GUO Wen-feng, AN Shi-kai, LU Chun-hui. 2016. Geochemistry of sediments from the Huaibei Plain (east China): Implications for provenance, weathering, and invasion of the Yellow River into the Huaihe River[J]. *Journal of Asian Earth Sciences*, 121: 72-83.
- ZHAO Yue, XU Gang, ZHANG Shuan-hong, YANG Zhen-yu, ZHANG Yue-qiao, HU Jian-min. 2004. Yanshanian movement and conversion of tectonic regimes in East Asia[J]. *Earth Science Frontiers*, 11(3): 319-328(in Chinese with English abstract).
- ZHOU Bo-wen, WANG Chun-lian, YOU Chao, LIU Dian-he, LIU Si-han, YU Xiao-can, YAN Kai, LIU Xue, LIU Yan-ting. 2022. Geochemical Characteristics of Trace Elements and REE in Zhangcuo Fluorite Deposit in Shaowu Area, Fujian Province[J]. *Acta Geoscientica Sinica*, 43(3): 393-403(in Chinese with English abstract).
- ZHOU Min-juan, HU Li, HUANG Xiao-nian, HAN Xue-ping. 2017. Metallogenic geological characteristics and prospect of development and utilization of Meigang Li-bearing Brine deposit in the Taihe County, Jiangxi Province[J]. *Modern Mining*, 33(11): 61-64(in Chinese with English abstract).