

云南永善水竹地区宣威组底部 稀土元素赋存状态研究

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内容提要: 本文采用基本化学分析、X射线衍射分析、扫描电子显微镜分析、稀土浸出实验等多种岩矿测试技术手段, 对云南昭通永善莲峰地区古陆相沉积型稀土矿进行详尽的矿物学研究。分析结果表明, 稀土氧化物总量平均质量分数为0.12%~0.21%, 单样最高为0.23%, 轻重稀土比值在1.55~2.88之间, 具有以轻稀土为主的特点, 轻稀土占稀土总量的61%~73%。矿物组成以黏土矿物为主, 含量合计约75%, 其中主要为高岭石(含量45%), 其次为蒙脱石(含量36%)、绿泥石(含量19%)。其他矿物含量微少, 含有稀土独立矿物极少。通过浸出试验和测定, 其离子吸附相占稀土总量的0.94%~3.86%, 呈离子相的稀土较少, 研究结果表明, 样品中的稀土元素可能以富稀土的纳米矿物颗粒赋存于高岭石等黏土矿物中。

关键词: 二叠系宣威组; 沉积型稀土矿; 赋存状态; 云南昭通永善

稀土矿床主要包含低温作用形成的离子吸附型(Bao Zhiwei et al., 2008; 张保涛, 2020; 周美夫等, 2020; 夏小洪等, 2022), 独居石、磷钇矿冲积砂矿和海滨砂矿型等(Xie Yuling et al., 2016), 以及高温地质过程形成碱性岩型(Xu Cheng et al., 2008)、碳酸岩型(Liu Yan et al., 2017; 许丹妮等, 2024)。近年来, 深海富稀土软泥(Kato et al., 2011)与铝土矿尾矿(Boni et al., 2013)、沉积型磷矿(Emsbo et al., 2015)、煤系地层(Dai Shifeng et al., 2017; 杨瑞东等, 2021)共伴生的稀土等新类型稀土资源的成矿理论研究更是成为了国际关注热点。多位学者报道显示, 川滇黔相邻区二叠系宣威组底部的层状黏土岩中稀土元素超常富集(曾励训, 1989; 杨瑞东等, 2006; Yang Ruidong et al., 2008; 张海, 2014; Zhao Lixin et al., 2016; Dai et al., 2017; 文俊等, 2021; 谯文浪等, 2023), 具有鲜明的沉积成因特征, 显著与古陆相沉积作用有关, 成因上与目前全球已报道的任何一种稀土矿床类型均不符合, 是一种罕见的稀土资源新类型, 被命名为“古陆相沉积型稀

土矿”(田恩源等, 2021; 龚大兴等, 2023; 罗香建等, 2023)。该类型稀土矿化分布广泛, 连续性好, 并伴生铌、镓等稀有金属资源, 具有极大的开发利用前景(Zhao Lixin et al., 2017; Gong Daxing et al., 2020)。目前, 该新类型稀土矿床的赋存状态、富集规律、成矿物质来源等方面尚不明朗, 严重制约了对该地区稀土矿的勘探与开发利用。因此, 本文拟对川滇黔相邻区内滇东北水竹地区宣威组底部古陆相沉积型稀土矿中的稀土元素开展赋存状态研究, 为研究区及国内同类型沉积型稀土矿床找矿及资源综合利用提供重要的线索和科学依据。

1 地质背景

本文研究样品来自云南昭通永善水竹地区, 选取中国地质调查局昆明自然资源综合调查中心所承担的地调项目“滇东—黔西黄葛树等4幅1:5万矿产地质调查”的部分样品进行相关研究。水竹地区大地构造上位于小江断裂东部、水城—紫云断裂西部, 处于扬子地台西南边缘的滇黔北拗陷—昭通凹

注: 本文为地质调查项目“滇东—黔西黄葛树等4幅1:5万矿产地质调查”(编号:DD20220967), “云南乌蒙山苞谷脑等3幅1:5万矿产地质调查”(编号:DD20240207104)的成果。

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陷(王东晖等,2024)。区域内下古生界寒武系、奥陶系、志留系、二叠系及三叠系地层较为发育,缺失中晚泥盆世和石炭世地层。晚二叠世峨眉山玄武岩岩浆大量喷溢在区域内形成了大面积的峨眉山溢流玄武岩(何斌等,2006),为稀土提供成矿物质来源。区内宣威组主要沿嵩枝坝向斜分布,其平行不整合覆盖于峨眉山玄武岩之上,上与下三叠统飞仙关组整合接触,为一套三角洲相沉积(图1)。含铈—稀土黏土岩系主要位于宣威组底部,峨眉山玄武岩不整合面之上,岩性主要为铝土质泥岩、粉砂质泥岩。矿体呈层状、似层状产出,产状与围岩一致,层厚1~5 m。该潜在关键金属矿层分布面积广、延伸稳定、厚度较大,有着可以作为新类型的稀土资源矿床的

巨大潜力,具有相当重要的研究价值。

2 样品特征及分析方法

2.1 矿石特征

矿石样品主要采集于昭通市永善县水竹乡一带,根据项目工区内的工程控制,圈定稀土矿层一层,在剥土工程及钻孔里面选取具有代表性的矿石样品,样品编号分别为 BT102-SD32、BT516b1、ZK70001b2、ZK70001b3(图2)。其中,BT102-SD32为黄色泥岩,泥质成分>90%。BT516b1为灰白色铝土质泥岩,黏土矿物约70%,铝土质约30%,为工作区内主要的稀土矿石类型之一。ZK70001b2为灰色铝土质泥岩,黏土矿物约50%,铝土质成分约25%,

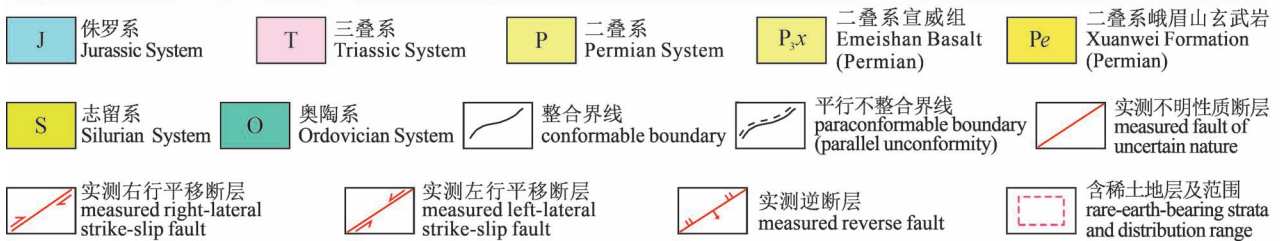
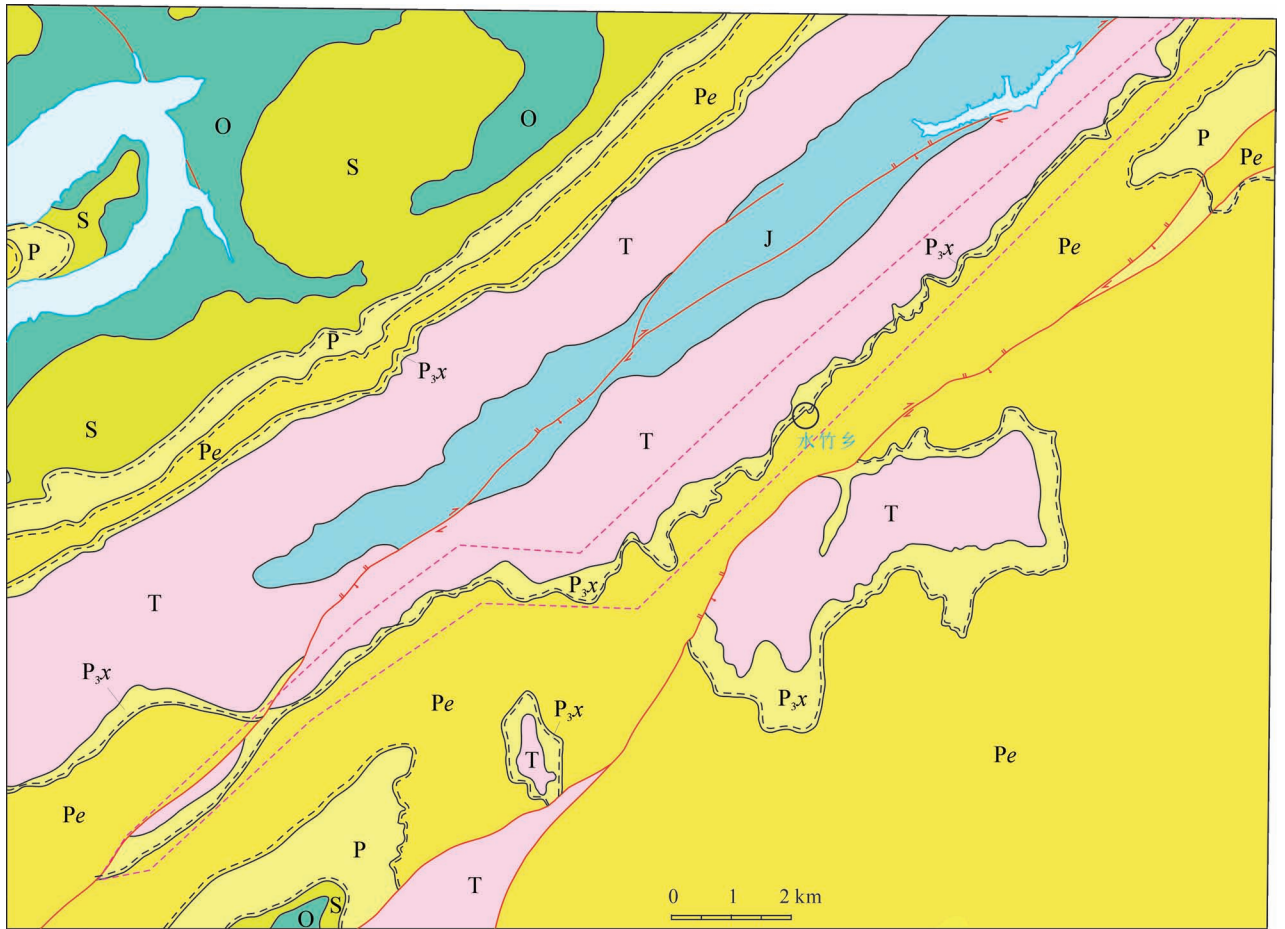


图1 云南永善水竹地区地质简图

Fig. 1 Geological sketch map of the Shuizhu area, Yongshan County, Yunnan Province

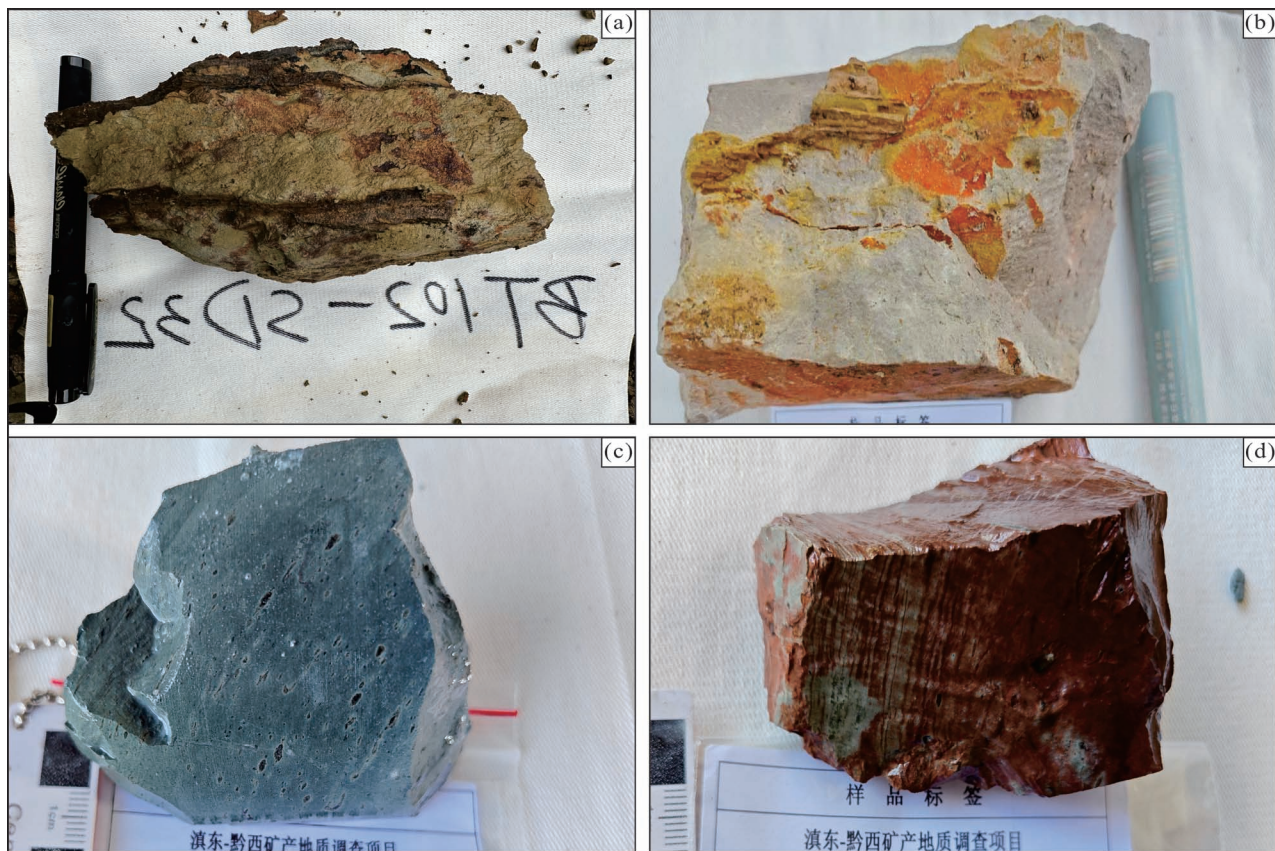


图2 昭通永善水竹地区沉积型稀土矿矿石样品照片

Fig. 2 Sample photos of sedimentary-type rare earth ore in Shuizhu area, Yongshan County, Zhaotong City
(a) 样品 BT102-SD32, 黄色泥岩; (b) 样品 BT516b1, 灰白色铝土质泥岩; (c) 样品 ZK70001b2, 灰色铝土质泥岩;
(d) 样品 ZK70001b3, 浅肉红色砂质铁质泥岩

(a) The sample BT102-SD32, yellow mudstone of ; (b) the sample BT516b1, grayish-white bauxitic mudstone; (c) the sample ZK70001b2, gray bauxitic mudstone; (d) the sample ZK70001b3, light flesh-red arenaceous ferruginous mudstone

为工作区内主要的矿石类型之一。ZK70001b3 为浅肉红色砂质铁质泥岩,黏土矿物约 45%,岩屑约 25%,不透明矿物约 30%。

2.2 分析方法

样品实验分析由中国地质调查局昆明自然资源综合调查中心、中国冶金地质总局山东局集团测试有限公司和武汉中地大环境地质研究院完成。

矿石的基本化学分析由中国地质调查局昆明自然资源综合调查中心完成,主要分析矿石的稀土各氧化物的含量(质量分数),检测依据为《硅酸盐岩石化学分析方法第 30 部分:44 个元素量测定》;主要仪器为 iCAP QC 电感耦合等离子质谱仪。

矿石矿物研究采用 X 射线衍射分析(X 射线衍射仪)、扫描电镜(SUPRA55 热场发射扫描电子显微镜)和能谱分析(均由中国冶金地质总局山东局集团测试有限公司完成)。最后采用稀土浸出实验,测得稀土矿石中所含的离子吸附相(由武汉中地大

环境地质研究院完成)。稀土浸出实验检测方法为:按照固液比 1:1 的比例,将溶液(硫酸铵:氯化铵=1:1,pH=6~7)与矿样混合后,在常温下搅拌 3 小时进行稀土浸出,后进行过滤及固液分离,将浸出液和浸出渣分别进行化验分析,计算浸出率。

3 实验分析

3.1 矿石化学组成

通过选取两个剥土工程(BT102、BT516)及一个钻孔(ZK70001)的样品进行基本化学分析(表 1)。

根据基本化学分析及稀土配分结果显示,稀土平均品位为 0.12%~0.21%,达到沉积型稀土矿的边界品位[稀土矿以《黔西北地区沉积型稀土普查阶段一般工业指标论证报告》中建议的一般工业指标(TREO 露天开采边界品位 0.12%、最低工业品位 0.26%)进行评价]。其中,样品中稀土质量分数最高可达 3877.97×10^{-6} 。

表2 云南永善水竹地区矿石轻、重稀土总量及占比

Table 2 Total amount and proportion of light, heavy rare earth elements of the ores from Shuizhu area, Yongshan County, Yunnan Province

| 样品编号 | 稀土总量 ($\times 10^{-6}$) | 轻稀土 ($\times 10^{-6}$) | 重稀土 ($\times 10^{-6}$) | 轻稀土占比 (%) | 重稀土占比 (%) | 轻稀土/ 重稀土 | (La,Ce,Nd) ₂ O ₃ 占比(%) |
|-----------|------------------------------|-----------------------------|-----------------------------|--------------|--------------|-------------|---|
| ZK70001H1 | 960.04 | 754.89 | 205.15 | 78.63 | 21.37 | 3.68 | 72.39 |
| ZK70001H2 | 732.81 | 592.69 | 140.12 | 80.88 | 19.12 | 4.23 | 72.60 |
| ZK70001H3 | 1105.93 | 892.64 | 213.29 | 80.71 | 19.29 | 4.19 | 72.16 |
| ZK70001H4 | 1037.33 | 825.37 | 211.96 | 79.57 | 20.43 | 3.89 | 71.72 |
| ZK70001H5 | 2251.07 | 1636.01 | 615.06 | 72.68 | 27.32 | 2.66 | 66.63 |
| ZK70001H6 | 956.79 | 646.91 | 309.88 | 67.61 | 32.39 | 2.09 | 61.46 |
| ZK70001H7 | 596.00 | 520.33 | 75.67 | 87.30 | 12.70 | 6.88 | 81.64 |
| ZK70001H8 | 2291.51 | 1393.77 | 897.74 | 60.82 | 39.18 | 1.55 | 53.72 |
| ZK70001H9 | 359.38 | 246.32 | 113.06 | 68.54 | 31.46 | 2.18 | 59.96 |
| BT102H26 | 2572.47 | 2249.10 | 323.37 | 87.43 | 12.57 | 6.96 | 78.60 |
| BT102H27 | 1809.69 | 1502.65 | 307.04 | 83.03 | 16.97 | 4.89 | 74.87 |
| BT102H28 | 905.34 | 713.70 | 191.64 | 78.83 | 21.17 | 3.72 | 71.24 |
| BT102H29 | 902.38 | 727.66 | 174.72 | 80.64 | 19.36 | 4.16 | 72.59 |
| BT102H30 | 1097.34 | 839.40 | 257.94 | 76.49 | 23.51 | 3.25 | 69.08 |
| BT102H31 | 1406.32 | 1043.34 | 362.98 | 74.19 | 25.81 | 2.87 | 67.34 |
| BT102H32 | 3877.97 | 3255.90 | 622.07 | 83.96 | 16.04 | 5.23 | 76.46 |
| BT102H33 | 756.20 | 542.61 | 213.59 | 71.75 | 28.25 | 2.54 | 63.34 |
| BT102H34 | 636.28 | 547.15 | 89.13 | 85.99 | 14.01 | 6.14 | 78.71 |
| BT102H35 | 990.53 | 882.99 | 107.54 | 89.14 | 10.86 | 8.21 | 80.66 |
| BT102H36 | 2578.14 | 2390.70 | 187.44 | 92.73 | 7.27 | 12.75 | 80.25 |
| BT102H37 | 818.66 | 648.67 | 169.99 | 79.24 | 20.76 | 3.82 | 68.28 |
| BT516H6 | 1154.24 | 860.90 | 293.34 | 74.59 | 25.41 | 2.93 | 66.36 |
| BT516H7 | 1505.51 | 1033.72 | 471.79 | 68.66 | 31.34 | 2.19 | 61.24 |
| BT516H8 | 643.59 | 493.12 | 150.47 | 76.62 | 23.38 | 3.28 | 68.58 |
| BT516H9 | 841.71 | 754.74 | 86.97 | 89.67 | 10.33 | 8.68 | 81.98 |
| BT516H10 | 988.92 | 901.76 | 87.16 | 91.19 | 8.81 | 10.35 | 83.22 |
| BT516H11 | 1881.88 | 1724.90 | 156.98 | 91.66 | 8.34 | 10.99 | 80.24 |
| BT516H12 | 317.21 | 203.69 | 113.52 | 64.21 | 35.79 | 1.79 | 54.57 |

选取达到工业边界品位的样品中,所含轻稀土总量为 $1154.24 \times 10^{-6} \sim 3255.90 \times 10^{-6}$,重稀土总量为 $156.98 \times 10^{-6} \sim 897.74 \times 10^{-6}$ 。其中,轻稀土氧化物元素中氧化镧、氧化铈及氧化钕占比最高,合计占到稀土总量的 53.72%~80.25%。

3.2 XRD 衍射分析

本文选取 BT102 剥土工程的 1 件稀土矿石样品进行了 X 射线衍射分析,样品 BT102-X32 分析结果表明:稀土矿石主要组成为黏土矿物(含量 75%)、一水软铝石(含量 16%)及少量石英(含量 9%)(表 3)。黏土矿物组成主要有高岭石(含量 45%)、蒙脱石(含量 36%)、绿泥石(含量 19%)(图 3,表 4)。

3.3 扫描电镜

通过矿石矿物种类分析,样品 BT102-SD32 中

表3 云南永善水竹地区样品 BT102-X32 主要物相及半定量结果分析结果表

Table 3 Analysis results of main phases and semi-quantitative results of sample BT102-X32 from Shuizhu area, Yongshan County, Yunnan Province

| 分析编号 | 送样号 | 主要物相及半定量结果(%) | | | | | |
|---------|------------|---------------|-----|-----|-----|-------|------|
| | | 石英 | 斜长石 | 黄铁矿 | 赤铁矿 | 一水软铝石 | 黏土矿物 |
| D246758 | BT102-SD32 | 9 | — | — | — | 16 | 75 |

Nd(平均 6.85%),总质量百分比为 43.23%~47.57%,平均稀土元素质量百分比为 45.4%。Al 平均质量百分比为 8.67%、P 平均质量百分比为 11.62%、Si 平均质量百分比为 5.11%。根据其成分特点,推测为独居石。独居石化学式 $Ce(PO_4)$ 或

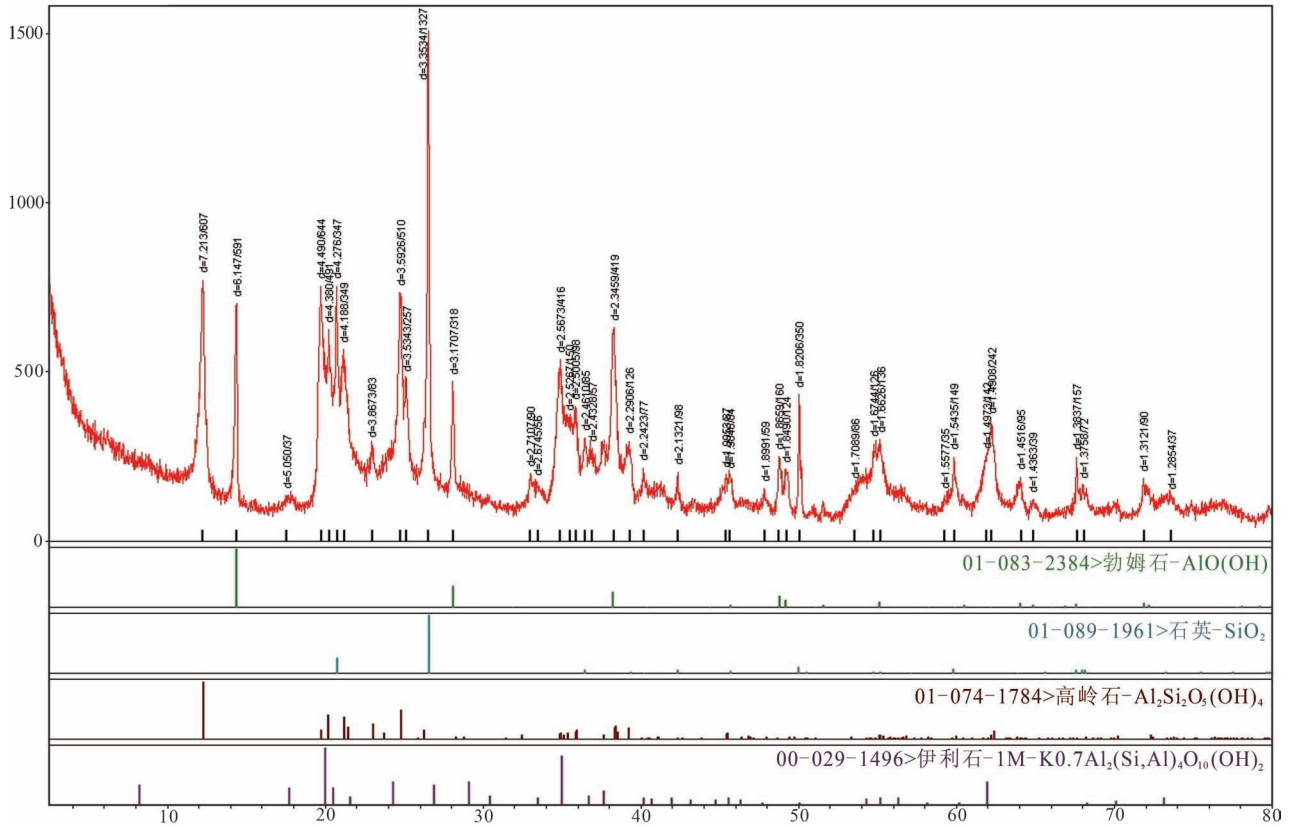


图3 样品 BT102-X32 X 射线分析图谱

Fig. 3 X-ray analysis spectrum of sample BT102-X32

(Ce,La)PO₄,属三单斜晶系,单晶体呈板状或似楔形,或各向等长状,呈浅黄色至浅红褐色,强玻璃光泽或树脂光泽至蜡状光泽,微透明至透明。硬度5~5.5,密度4.9~5.5 g/cm³,晶体形状或是板状或是柱状,单斜晶系,斜方柱晶类。独居石一般呈细微粒状嵌布于黏土矿物集合体中,粒度微细,粒径在2000 nm,个别不规则集合体粒度为20000 nm。

表4 云南永善水竹地区样品 BT102-X32

黏土矿物相对含量分析结果表

Table 4 Analysis results of relative contents of clay minerals in sample BT102-X32 from Shuizhu area, Yongshan County, Yunnan Province

| 分析编号 | 送样号 | 黏土矿物相对含量(%) | | | | | | 混层比(%) | |
|---------|-----------|-------------|-----|----|-----|----|-----|--------|-----|
| | | S | I/S | It | Kao | C | C/S | I/S | C/S |
| D246758 | BT102-X32 | — | 36 | — | 45 | 19 | — | 25 | — |

注:S—蒙皂石;I/S—伊/蒙混层;It—伊利石;Kao—高岭石;C—绿泥石;C/S—绿/蒙混层。

3.4 稀土浸出实验

为了研究矿石中稀土元素的赋存状态,本文仅

在 BT102 剥土工程中采集了稀土品位相对较高的样品进行了浸出试验和测定。浸出结果表明,离子吸附相仅占稀土总量的 2.94%,结果表明呈离子相的稀土含量较少(表 5)。

表5 云南永善水竹地区稀土浸出试验结果表

Table 5 Results of rare earth leaching tests for the ores from Shuizhu area, Yongshan, Yunnan

| 样品编号 | 稀土总量 TREO($\times 10^{-6}$) | 离子型稀土总量 SREO($\times 10^{-6}$) | SREO/TREO (%) |
|-----------|----------------------------------|-------------------------------------|------------------|
| BT102-ZH1 | 1890 | 55.6 | 2.94 |

4 讨论

前人对该地区稀土元素的赋存状态主要有以下几种认识:① 与高岭石等黏土矿物含量密切相关,主要由离子吸附相和富含稀土元素的残余独立矿物相组成(Zhao Lixin et al., 2017);② 在高岭石质黏土岩中以类质同象为主,含离子吸附相(约 20%)两种形式赋存(徐莺等,2018;文俊等,2021b);③ 高岭石硬质黏土岩中包含离子吸附态、胶体吸附态等的

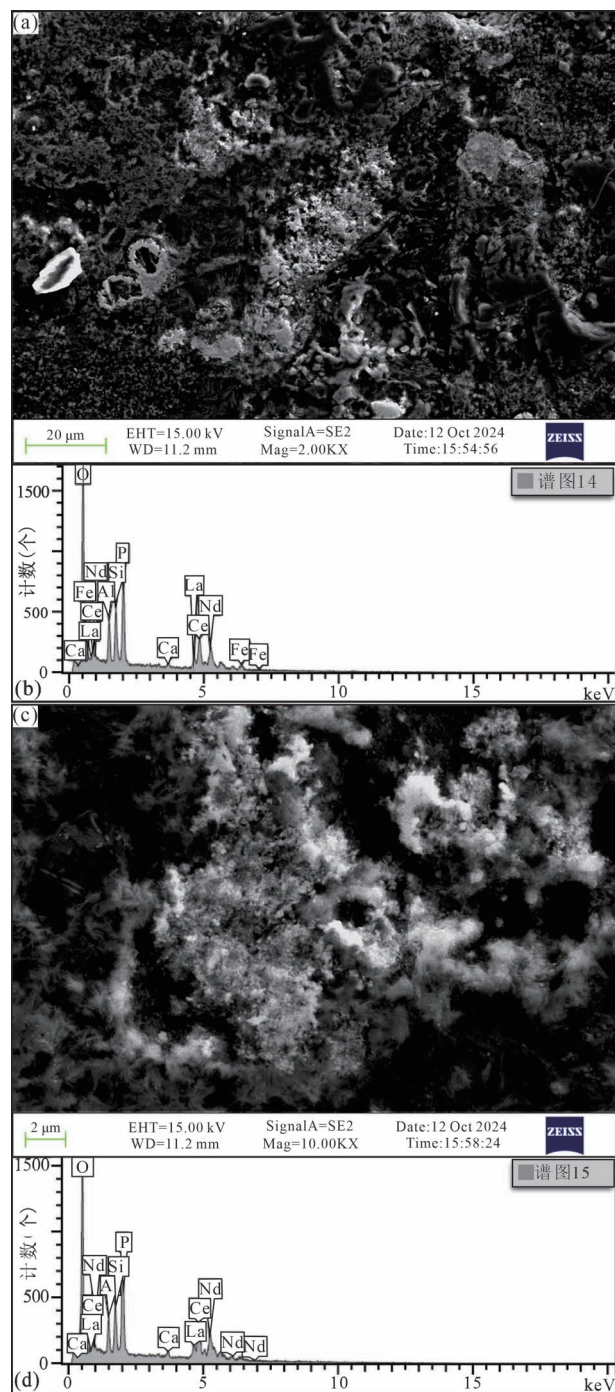


图4 样品 BT102-SD32 独居石的背散射图(a,c)及能谱图谱(b,d)

Fig. 4 Backscattered electron images (a, c) and energy dispersive spectroscopy (EDS) spectra (b, d) of monazite from sample BT102-SD32

混合态稀土;④ 富稀土的纳米矿物颗粒被高岭石及伊利石等层状硅酸盐矿物“束缚”在黏土矿物层状结构中(龚大兴等,2023)。

样品 X 射线衍射分析结果表明,稀土矿石主要

矿物成分及质量分数如下:黏土矿物(含量 75%)、一水软铝石(含量 16%)及少量石英(含量 9%),黏土矿物组成主要有高岭石(含量 45%)、蒙脱石(含量 36%)、绿泥石(含量 19%),并没有发现稀土的独立矿物。通过扫描电镜研究发现,岩石中含有少量细微粒状独居石矿物,占整体矿物比重不足 50%,所提供的稀土元素较少,并不能支撑如此高的稀土总量。因此,独立矿物并不是该类型稀土的主要赋存形式,稀土元素应该以离子形式被高岭石等黏土矿物吸附于表面,或进入矿物晶格(徐莺等,2018)。同时,对稀土品位相对较高的样品进行浸出试验和测定,离子吸附相仅占稀土总量的 2.94%,表明呈离子相稀土较少。龚大兴等(2023)发现高岭石及伊利石中存在大量粒径在 100~300 nm 的富稀土矿物,认为该类型沉积型稀土具有特殊的赋存状态,富稀土的纳米矿物颗粒被高岭石及伊利石等层状硅酸盐矿物“束缚”在黏土矿物层状结构中。水竹地区与威宁地区稀土类型一致,应与其赋存方式相似,可能以纳米级颗粒赋存于高岭石等黏土矿物中。

5 结论

(1)永善水竹地区沉积型型稀土矿石稀土总量 $1154.24 \times 10^{-6} \sim 3877.97 \times 10^{-6}$ 不等,整体具轻稀土富集、重稀土亏损的特征。

(2)通过 X 衍射分析,矿石矿物主要以黏土矿物为主,黏土矿物又以高岭石和蒙脱石为主;通过能谱分析,矿石矿物中存在少量细微粒状稀土独立矿物,根据其成分推测为独居石,但其含量极少;浸出实验表明,离子相稀土矿物较少。

综合样品测试分析结果,呈离子相和矿物相的稀土元素含量较少,稀土可能主要以纳米颗粒赋存于以高岭石为主的黏土岩中。

参 考 文 献 / References

- (The literature whose publishing year followed by a “&” is in Chinese with English abstract; The literature whose publishing year followed by a “#” is in Chinese without English abstract)
- 龚大兴, 田恩源, 肖斌, 惠博, 赖杨, 徐璐, 王晓慧, 徐莺, 秦建华, 黄庆, 何良伦, 覃英, 张嘉玮. 2023. 川滇黔相邻区古陆相沉积型稀土的发现及意义. 矿床地质, 42(5): 1025~1033.
- 何斌, 徐义刚, 肖龙, 王雅玫, 王康明, 沙绍礼. 2006. 峨眉山地幔柱上升的沉积响应及其地质意义. 地质论评, 52(1): 30~37.
- 罗香建, 覃英, 卢树藩, 符宏斌, 刘国栋, 陈武. 2023. 赫章辅处地区沉积型富稀土岩系地球化学特征及物源分析. 矿物学报, 43(6): 758~770.
- 谯文浪, 杨瑞东, 季国松, 龙建喜, 陈登. 2023. 黔北上二叠统底部发现 REY、Nb、Zr 和 Li 等关键金属异常富集层. 地质论评, 69(6):

- 2111~2114.
- 田恩源, 龚大兴, 赖杨, 邱小龙, 谢华, 田康志. 2021. 贵州威宁地区沉积型稀土含矿岩系成因与富集规律. *地球科学*, 46(8): 2711~2731.
- 王东晖, 李德宗, 王万能. 2024. 云南永善地区铈—稀土矿赋存状态及富集机制研究. *云南地质*, 43(S1): 64~70.
- 文俊, 刘治成, 赵俊兴, 竹合林, 张航飞, 张金元, 陈东方, 钟海仁, 郭文彦, 游学军, 赵伟, 凌茂前, 李鹏程, 何永刚. 2022. 川南沐川地区宣威组底部铈—稀土多金属富集层富集规律、沉积环境与成矿模式. *地质学报*, 96(2): 592~615.
- 文俊, 竹合林, 张金元, 张航飞, 郭文彦, 游学军, 赵伟, 李鹏程, 陈东方. 2021. 川南沐川地区首次发现宣威组底部古风化壳—沉积型铈、稀土矿. *中国地质*, 48(3): 970~971.
- 夏小洪, 刘国强, 尹川, 杨伟, 谭洪旗, 周家云, 王成辉. 2022. 四川攀枝花—西昌地区离子吸附型(中—重)稀土矿床的首次发现及其重要意义. *地质论评*, 68(4): 1540~1543.
- 许丹妮, 宋文磊, 杨金昆, 陈倩, 刘涛涛, 徐亦桐. 2024. 内生碳酸岩型稀土矿床中磷酸盐作用研究综述. *地质论评*, 71(3): 1097~1112.
- 徐莺, 戴宗明, 龚大兴, 惠博. 2018. 贵州某地二叠系宣威组富稀土岩系稀土元素赋存状态研究. *矿产综合利用*, 39(6): 90~94+101.
- 杨瑞东, 王伟, 鲍森, 王强, 魏怀瑞. 2006. 贵州赫章二叠系玄武岩顶部稀土矿床地球化学特征. *矿床地质*, 25(S1): 205~208.
- 杨瑞东, 郑绿林, 程伟, 高军波, 陈军, 孙百川, 张衍. 2021. 黔北桐梓—金沙一带发现晚二叠世煤富集稀土、锂金属元素. *地质论评*, 67(5): 1543~1544.
- 曾励训. 1989. 贵州西部发现离子吸附型稀土矿. *贵州地质*, 6(3): 272.
- 张保涛, 蓝信杰, 金刚, 李星亮, 张永三, 胡兆国, 孙璐伟, 王向伟, 张修龙, 郭伟. 2020. 云南临沧花岗岩带回龙卡离子吸附型稀土矿床地质特征和控制因素. *地质论评*, 66(2): 380~392.
- 张海. 2014. 黔西北地区稀土矿床地质地球化学特征及其成矿机制研究. 导师: 何明友, 桑世华, 孟昌忠. 成都: 成都理工大学博士学位论文: 1~148.
- 周美夫, 李欣禧, 王振朝, 李晓春, 刘嘉成. 2020. 风化壳型稀土和钨矿床成矿过程的研究进展和展望. *科学通报*, 65(33): 3809~3824.
- Bao Zhiwei, Zhao Zhenhua. 2008. Geochemistry of mineralization with exchangeable REY in the weathering crusts of granitic rocks in South China. *Ore Geology Reviews*, 33(3~4): 519~535.
- Boni M, Rollinson G, Mondillo N, Balassone G, Santoro L. 2013. Quantitative mineralogical characterization of karst bauxite deposits in the southern Apennines, Italy. *Economic Geology*, 108(4): 813~833.
- Dai Shifeng, Ward C R, Graham I T, French D, Hower J C, Zhao Lei, Wang Xibo. 2017. Altered volcanic ashes in coal and coal-bearing sequences: A review of their nature and significance. *Earth-Science Reviews*, 175: 44~74.
- Emsbo P, McLaughlin P I, Breit G N, du Bray E A, Koenig A E. 2015. Rare earth elements in sedimentary phosphate deposits: Solution to the global REE crisis? *Gondwana Research*, 27(2): 776~785.
- Gong Daxing, Hui Bo, Dai Zongming, Lai Yang, Tian Enyuan. 2020. A new type of REE deposit found in clay rock at the top of the Permian Emeishan basalt in the Yunnan—Guizhou area. *Acta Geologica Sinica (English Edition)*, 94(1): 204~205.
- Gong Daxing, Tian Enyuan, Xiao Bin, Hui Bo, Lai Yang, Xu Lu, Wang Xiaohui, Xu Ying, Qin Jianhua, Huang Qing, He Lianglun, Qin Ying, Zhang Jiawei. 2023&. Significance and discovery of sedimentary REE deposits in adjacent areas of Sichuan, Yunnan and Guizhou. *Mineral Deposits*, 42(5): 1025~1033.
- He Bin, Xu Yigang, Xiao Long, Wang Yamei, Wang Kangming, Sha Shaoli. 2006&. Sedimentary responses to uplift of Emeishan mantle plume and its implications. *Geological Review*, 52(1): 30~37.
- Kato Y, Fujinaga K, Nakamura K, Takaya Y, Kitamura K, Ohta J, Toda R, Nakashima T, Iwamori H. 2011. Deep-sea mud in the Pacific Ocean as a potential resource for rare-earth elements. *Nature Geoscience*, 4(8): 535~539.
- Liu Yan, Hou Zengqian. 2017. A synthesis of mineralization styles with an integrated genetic model of carbonatite—syenite-hosted REE deposits in the Cenozoic Mianming—Dechang REE metallogenic belt, the eastern Tibetan Plateau, southwestern China. *Journal of Asian Earth Sciences*, 137: 35~79.
- Luo Xiangjian, Qin Ying, Lu Shufan, Fu Hongbin, Liu Guodong, Chen Wu. 2023&. Geochemical characteristics and provenance analysis of the sedimentary type REE-rich rock series in the Fuchu area, Hezhang County, Guizhou, China. *Acta Mineralogica Sinica*, 43(6): 758~770.
- Qiao Wenlang, Yang Ruidong, Ji Guosong, Long Jianxi, Chen Deng. 2023#. Discovery of super enrichment critical metals REY, Nb, Zr and Li in the base of the Upper Permian in northern Guizhou. *Geological Review*, 69(6): 2111~2114.
- Tian Enyuan, Gong Daxing, Lai Yang, Qiu Xiaolong, Xie Hua, Tian Kangzhi. 2021&. Genesis and enrichment of sedimentary rare earth in Weining area, Guizhou Province. *Earth Science*, 46(8): 2711~2731.
- Wang Donghui, Li Dezhong, Wang Wanneng. 2024&. Preliminary study on the occurrence and enrichment rules of niobium—rare earth deposits in Yongshan area, Yunnan. *Yunnan Geology*, 43(S1): 64~70.
- Wen Jun, Liu Zhicheng, Zhao Junxing, Zhu Helin, Zhang Hangfei, Zhang Jinyuan, Chen Dongfang, Zhong Hairan, Guo Wenyan, You Xuejun, Zhao Wei, Ling Maoqian, Li Pengcheng, He Yonggang. 2022&. Enrichment regularity, sedimentary environment and metallogenic model of niobium—rare earth polymetallic enrichment layer at the bottom of the Xuanwei Formation in Muchuan area, south Sichuan. *Acta Geologica Sinica*, 96(2): 592~615.
- Wen Jun, Zhu Helin, Zhang Jinyuan, Zhang Hangfei, Guo Wenyan, You Xuejun, Zhao Wei, Li Pengcheng, Chen Dongfang. 2021&. The first discovery of the paleo-weathering crust—sedimentary Nb and rare earth deposits at the bottom of Xuanwei Formation in the Muchuan area of southern Sichuan. *Geology in China*, 48(3): 970~971.
- Xia Xiaohong, Liu Tuqiang, Yin Chuan, Yang Wei, Tan Hongqi, Zhou Jiayun, Wang Chenghui. 2022#. First discovery of ion adsorption-type (medium—heavy) REE deposit in the Panzhuhua—Xichang area, Sichuan Province, and its significance. *Geological Review*, 68(4): 1540~1543.
- Xie Yuling, Hou Zengqian, Goldfarb R J, Guo Xiang, Wang Lei. 2016. Rare earth element deposits in China. *Reviews in Economic Geology*, 18: 115~136.
- Xu Cheng, Campbell I H, Kynicky J, Allen C M, Chen Yanjing, Huang Zhilong, Qi Liang. 2008. Comparison of the Daluxiang and Maoniuping carbonatitic REE deposits with Bayan Obo REE deposit, China. *Lithos*, 106(1~2): 12~24.
- Xu Danni, Song Wenlei, Yang Jinkun, Chen Qian, Liu Taotao, Xu Yitong. 2024&. A review on the role of phosphate in endogenous carbonatite-hosted REE deposits. *Geological Review*, 71(3): 1097~1112.

- Xu Ying, Dai Zongming, Gong Daxing, Hui Bo. 2018&. Study on the Occurrence State of Rare Earth Elements of Rare earth-Enriched Rocks in the Permian Xuanwei Formation in Guizhou Province. *Multipurpose Utilization of Mineral Resources*, 6: 90~94.
- Yang Ruidong, Wang Wei, Bao Miao, Wang Qiang, Wei Huairui. 2006#. Geochemical character of rare earth mineral from the top of Permian basalt, Hezhang County, Guizhou Province. *Mineral Deposits*, 25(S1): 205~208.
- Yang Ruidong, Wang Wei, Zhang Xiaodong, Liu Ling, Wei Huairui, Bao Miao, Wang Jingxin. 2008. A new type of rare earth elements deposit in weathering crust of Permian basalt in western Guizhou, NW China. *Journal of Rare Earths*, 26(5): 753~759.
- Yang Ruidong, Zheng Lulin, Cheng Wei, Gao Junbo, Chen Jun, Sun Baichuan, Zhang Yan. 2021#. Rare earth and lithium elements enrichment found in Late Permian coals in Tongzi—Jinsha area, Northern Guizhou Province. *Geological Review*, 67(5): 1543~1544.
- Zeng Lixun. 1989#. Discovery of ion adsorption rare earth ore in western Guizhou. *Guizhou Geology*, 6(3): 272.
- Zhang Hai. 2014&. Geological and Geochemical Characteristics and Metallogenic Mechanism of REE Deposits, Northwestern Guizhou. Supervisor: He Mingyou. Chengdu: Chengdu University of Technology Doctoral Dissertation; 1~148.
- Zhang Baotao, Lan Xinjie, Jin Gang, Li Xingliang, Zhang Yongsan, Hu Zhaoguo, Sun Luwei, Wang Xiangwei, Zhang Xiulong, Guo Wei. 2020&. Geological characteristics and controlling factors of the Huilongka ion-adsorption type REE deposit in Lincang granite belt, Yunnan Province. *Geological Review*, 66(2): 380~392.
- Zhao Lixin, Dai Shifeng, Graham I T, Li Xiao, Liu Huidong, Song Xiaolin, Hower J C, Zhou Yiping. 2017. Cryptic sediment-hosted critical element mineralization from eastern Yunnan Province, southwestern China: Mineralogy, geochemistry, relationship to Emeishan alkaline magmatism and possible origin. *Ore Geology Reviews*, 80: 116~140.
- Zhao Lixin, Dai Shifeng, Graham I T, Li Xiao, Zhang Beibei. 2016. New insights into the lowest Xuanwei Formation in eastern Yunnan Province, SW China: Implications for Emeishan large igneous province felsic tuff deposition and the cause of the end-Guadalupian mass extinction. *Lithos*, 264: 375~391.
- Zhou Meifu, Li M Y H, Wang Zhenchao, Li Xiaochun, Liu Jiacheng. 2020&. The genesis of regolith-hosted rare earth element and scandium deposits: Current understanding and outlook to future prospecting. *Chinese Science Bulletin*, 65(33): 3809~3824.

Study on the occurrence state of rare earth elements at the bottom of the Xuanwei Formation in the Shuizhu area, Yongshan, Yunnan

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Objectives: This study intends to investigate the occurrence states of rare earth elements (REEs) in the paleo-terrestrial sedimentary rare earth deposits at the bottom of the Xuanwei Formation in the Shuizhu area, northeastern Yunnan, within the contiguous region of Sichuan, Yunnan and Guizhou. The research is expected to provide crucial clues and a scientific basis for mineral exploration and comprehensive resource utilization of the same type of sedimentary rare earth deposits in the study area and across China.

Methods: In this paper, a variety of rock and mineral testing techniques including basic chemical analysis, X-ray diffraction (XRD) analysis, scanning electron microscopy (SEM) analysis, and rare earth leaching experiments were employed to conduct an in-depth mineralogical study on the paleo-continental sedimentary rare earth deposits in the Lianfeng area of Yongshan County, Zhaotong City, Yunnan Province.

Results: The analysis results show that the average grade of total rare earth oxides (TREO) ranges from 0.12% to 0.21%, with the maximum content of a single sample reaching 0.23%. The ratio of light rare earths to heavy rare earths is between 1.55 and 2.88, indicating a light-rare-earth-dominated characteristic, where light rare earths account for 61%~73% of the total rare earth content. Mineralogically, the ore is dominated by clay minerals with a total content of approximately 75%, among which kaolinite is the predominant component (45%), followed by montmorillonite (36%) and chlorite (19%). The contents of other minerals are trace, and independent rare earth minerals are extremely scarce. Leaching tests and measurements reveal that the ion-adsorbed phase accounts for only 0.94% - 3.86% of the total rare earths, suggesting a relatively low content of ion-exchangeable rare earths. The results indicate that the rare earth elements in the samples are likely to occur as rare-earth-enriched

nanomineral particles hosted within clay minerals such as kaolinite.

Keywords: Permian Xuanwei Formation; sedimentary rare earth ore; occurrence state; Yongshan, Zhaotong, Yunnan

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