

文章编号: 1000-0550(2025)06-2237-12

川中地区中侏罗统沙溪庙组一段物源分析

曹甲新¹, 徐文礼^{1,2}, 曹脊翔³, 郭佩^{1,2}, 文华国^{1,2}

1. 成都理工大学沉积地质研究院, 成都 610059

2. 成都理工大学油气藏地质及开发工程全国重点实验室, 成都 610059

3. 西南油气田分公司致密油气勘探开发项目部, 成都 610066

摘要 【目的】川中地区中侏罗统沙溪庙组是四川盆地重要的致密气勘探开发层系, 目前沙溪庙组一段(沙一段)的油气勘探开发处于初期阶段, 整体研究薄弱, 特别是对优质砂体分布起控制作用的物源研究缺乏系统性认识。【方法】以岩石学分析为基础, 结合元素地球化学特征, 对川中地区沙一段物源进行了研究。【结果】(1)川中地区沙一段的砂岩主要发育长石岩屑和岩屑长石砂岩, 火成岩岩屑以安山岩为主, 安山岩岩屑在下伏地层中较少发育, 川东北和川东南地区沙一段中常见; (2)川中地区沙一段重矿物以石榴子石和绿帘石为主, 绿帘石在下伏地层中少见, 但在川东北和川东南大量发育; (3)F1-F2、SiO₂-TiO₂、La/Th-Hf、Co/Th-La/Sc 判别图显示, 川中地区沙一段源岩主要为长英质火山岩, 少量沉积岩。【结论】川中地区沙一段砂岩物源主要来自川东北大巴山, 盆地周缘其他方向物源供给有限。该认识为四川盆地致密气有利区的划分以及勘探开发提供了有力支撑。

关键词 四川盆地; 沙溪庙组; 物源分析; 安山岩岩屑; 绿帘石

第一作者简介 曹甲新, 男, 1997年出生, 博士研究生, 储层沉积学, E-mail: caojiaxin1217@163.com

通信作者 徐文礼, 男, 副教授, E-mail: xuwenli5@163.com

中图分类号 P618.13 **文献标志码** A

DOI: 10.14027/j.issn.1000-0550.2023.116

CSTR: 32268.14/j.cjxb.62-1038.2023.116

0 引言

致密气已成为国内外非常规油气勘探的重要新领域^[1-2]。我国四川、松辽、渤海湾和鄂尔多斯等盆地的致密油气勘探均获得了突破。四川盆地经过多年的油气勘探开发, 已经在侏罗系发现了多个含气构造^[3], 展现出巨大的勘探潜力。其中, 四川盆地中侏罗统沙溪庙组纵向上发育多期叠置河道, 下部沙溪庙组一段(简称沙一段)的多套砂组相对富含油气^[4], 而河道砂体的展布又受到物源的影响, 物源的性质及方向控制了沙溪庙组砂岩的展布方向及规模。目前, 针对四川盆地沙溪庙组的物源研究主要集中在川西和川北—川东北地区, 认为川西地区沙溪庙组的物源主要来自西侧龙门山和北侧米仓山^[5-10], 川北—川东北地区沙溪庙组的物源主要由北侧米仓山和大巴山提供。然而, 针对川中地区沙一段物源研究较为薄弱, 缺乏整体认识, 这制约了沙一段砂岩的

分布规律研究, 也影响了川中地区致密砂岩油气的进一步勘探与开发。

因此, 本文以岩石学为基础, 结合元素地球化学特征, 对川中地区沙一段物源进行研究, 深入探讨物源区性质, 为川中地区沙一段沉积演化、砂体展布规律及有利区带预测奠定基础, 推动和加快了川中地区致密气勘探开发的步伐。

1 地质背景

四川盆地位于中国西南地区, 整体上呈北东—南西向展布。印支晚期, 盆地西缘松潘—甘孜造山带隆升, 形成了龙门山体系, 扬子板块和华北板块的逆冲碰撞形成了川北秦岭造山带, 川东南江南古陆—雪峰山的构造运动, 在盆地周缘构造带共同作用下形成了陆相盆地的边界^[11]; 燕山早期, 川北—川东北米仓山—大巴山运动剧烈, 沉降中心由川西转至川北^[12]。燕山晚期, 龙门山运动加剧, 盆地受多个

收稿日期: 2023-09-04; 修回日期: 2023-11-06; 录用日期: 2024-01-08; 网络出版日期: 2024-01-08

基金项目: 国家自然科学基金项目(41972109) [Foundation: National Natural Science Foundation of China, No. 41972109]

方向构造运动联合控制。喜山期盆地构造格局基本定型^[13]。四川盆地北东方向为米仓山隆起带和大巴山断褶带,西邻龙门山断褶带,南部为娄山褶皱带,东部靠近川湘拗陷断褶带^[14-15]。川中地区位于四川盆地中部,北东起盐亭—西充,南西至简阳,是川中致密气的重点研究区域^[16-18]。沙溪庙组沉积时期,四川盆地周缘山体均已隆起,可为四川盆地提供物源^[19-20]。

川中地区沙溪庙组为一套陆相碎屑岩沉积,岩性主要为紫红色、灰绿色泥岩和浅灰—灰色砂岩组合(图1),区域上广泛发育的叶肢介泥页岩将沙溪庙组分为一段和二段^[21-23]。其中,沙一段与下伏千佛崖组、上覆沙二段均为整合接触,地层厚度一般为250~450 m^[24-25],横向上分布较为稳定。底部通常发育一套较厚的细砂岩,被称为“关口砂岩”^[26],向上发育一系列不等厚互层的紫红色、浅灰绿色泥岩、砂岩以及粉砂岩,顶部为薄层的黑色叶肢介泥页岩,强烈的冲刷导致局部地区叶肢介泥页岩缺失^[14];沙二段厚度一般为1 000~1 200 m,底部通常发育较稳定的一套细粒长石石英砂岩^[27](“嘉祥寨砂岩”),中下部发育灰绿色泥岩、紫红色泥岩,偶夹灰色粉砂岩和砂岩,上部发育厚度较大砂岩,指示该时期湖泊面积逐渐缩小,具有由湖泊向三角洲演化的沉积特点^[28-29]。

2 样品采集及实验方法

本次研究样品采集于川北地区的金溪、陈家岭剖面,川东地区的滩子、玉峡村剖面,川东北地区的上河坝、土黄镇剖面,川西—川西南地区的石牛角、两河口、沙坪村、观化村和川主河剖面,川南地区的中梗村、圆山坡、火把桥和德耀镇剖面以及川中地区的永浅1井、永浅2井、永浅3井和永浅6井钻井岩心(图1)。野外剖面采样挑选出露好且风化较弱的位置,钻井岩心从底部至顶部依次进行描述采样,所有样品均间隔采样,确保收集到的样品具有能代表沙一段沉积分布特征。从所有样品中挑选薄片样品240件,重矿物分析样品30件,主、微量元素及稀土元素分析样品25件。

在成都理工大学油气藏地质及开发工程全国重点实验室使用尼康E600型高级偏光显微镜完成薄片鉴定及照相。在河北省廊坊市科大岩石矿物分选技术服务有限公司完成重矿物分选工作。单个样品重量均在1~2 kg。首先将样品清洗晾干,取约1 kg的样品粉碎后过筛、清洗晾干并称重。在分离轻矿物与重矿物后通过磁选将重矿物分为磁性重矿物和非磁性重矿物,最后称重、鉴定,并统计每种重矿物颗粒含量,实验误差为3%~5%。主、微量元素及稀土元素在成都理工大学油气藏地质及开发工程全国重点

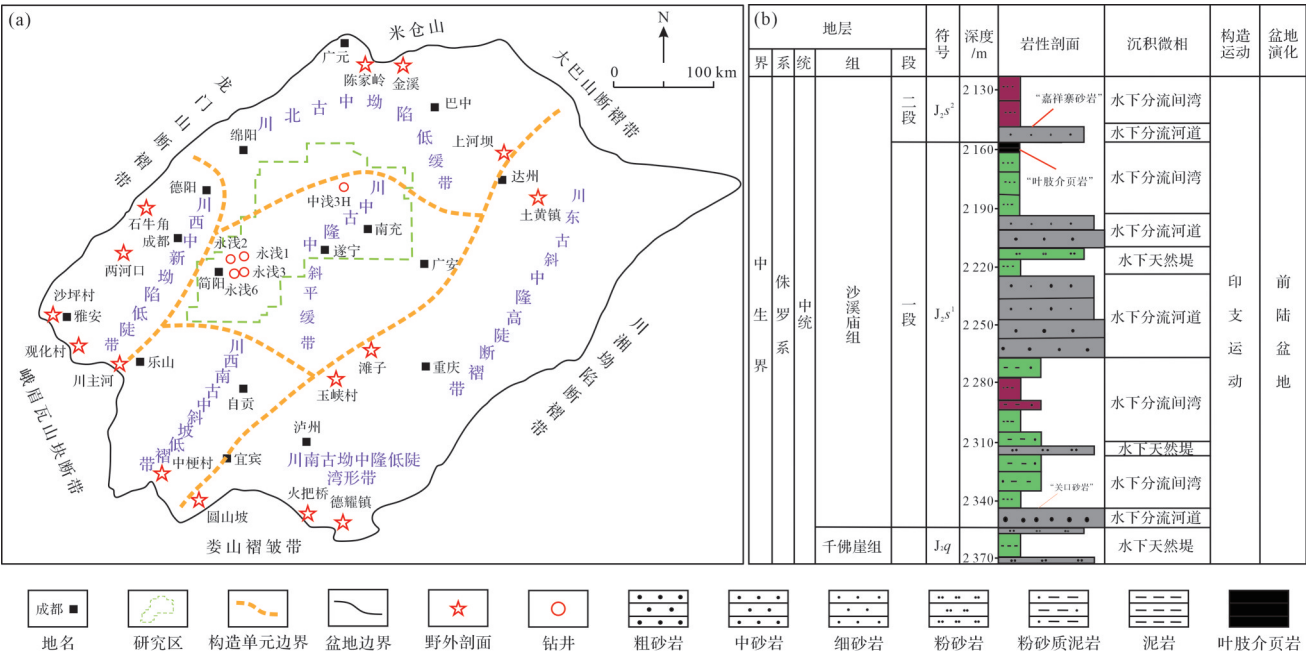


图1 四川盆地沙一段构造(a)及地层发育(b)简图(据文献[21]修改)

Fig.1 Simplified diagram of the structural development (a) and stratigraphic evolution (b) of the First member of the Shaximiao Formation, Sichuan Basin (modified from reference [21])

实验室完成。样品清洗烘干研磨至200目,微量和稀土元素分析采用Agilent7900等离子体质谱仪完成,仪器精度优于5%。

3 结果

3.1 轻矿物组分

川中地区沙一段砂岩碎屑组分含量较稳定,石英约占55%,长石和岩屑含量相当,岩屑以变质岩岩屑(图2a,b)为主,占总岩屑含量40%~50%,主要为千枚岩岩屑和片岩岩屑,火成岩岩屑(图2c,d)和沉积岩岩屑(图2e,f)含量相当,占总岩屑含量25%~30%,火成岩岩屑中以安山岩岩屑为主,占80%~90%,沉积岩岩屑中以泥岩岩屑为主,占60%~70%。盆地边缘沙一段砂岩碎屑组分含量差异较大,石英

含量约占39%,长石含量略大于岩屑含量,岩屑以变质岩岩屑和沉积岩岩屑为主,含少量火成岩岩屑。Q-F-R图解显示,川中地区及盆缘沙一段砂岩以长石岩屑砂岩和岩屑长石砂岩为主(图3)。

结合前人针对四川盆地沙一段砂岩的岩屑组分含量统计结果^[3,6,8-9],发现四川盆地沙一段岩屑组分呈现明显的分区特征(图4a):川西北广元地区,岩屑以变质岩岩屑为主,含少量沉积岩岩屑,火成岩岩屑极少或不发育;川西北绵阳地区,以富含沉积岩岩屑为特征;德阳—成都—自贡—宜宾一带,三种岩屑均发育,含量相当;川西南雅安—乐山地区,主要发育沉积岩岩屑和变质岩岩屑,沉积岩岩屑以碳酸盐岩岩屑为主;川东北—川中的巴中—南充—遂宁一带,以发育沉积岩岩屑和火成岩岩屑为特征;川东—川东北的重庆—达州地区,以变质岩岩屑和沉积岩岩屑为主。

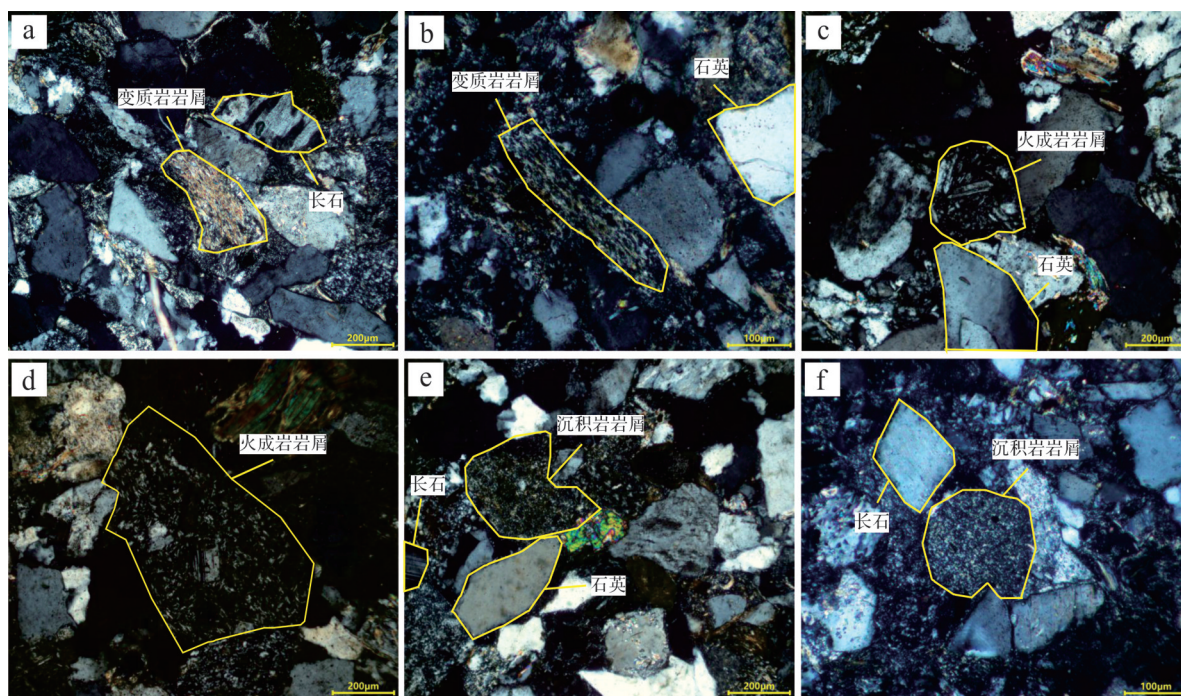


图2 川中地区及盆缘沙一段主要岩屑类型

(a)永浅3井,1930.70 m,中粒长石岩屑砂岩,变质岩岩屑较发育,主要为变质程度低—中等的千枚岩岩屑;(b)金溪剖面,JX-10,细粒长石岩屑杂砂岩,变质岩岩屑较发育,以变质程度较低的板岩岩屑为主;(c)永浅1井,2190.20 m,中粒长石岩屑砂岩,岩屑成分仍以变质岩岩屑为主,同时出现中—酸性火成岩岩屑;(d)永浅2井,2261.73 m,粗粒长石岩屑砂岩,发育中—酸性火成岩岩屑;(e)永浅6井,2119.45 m,中粒岩屑长石砂岩,三种岩屑均发育,沉积岩岩屑以泥岩岩屑为主;(f)陈家岭剖面,CJL-9,细—中粒长石岩屑砂岩,以发育变质岩岩屑为主,同时发育泥岩岩屑

Fig.2 Main lithic types in the First member of the Shaximiao Formation in central Sichuan Basin and its peripheral

(a) well YQ3, 1930.70 m, medium-grained feldspathic litharenite sandstone, with well-developed metamorphic rock clasts, mainly consisting of low to medium-grade phyllite clasts; (b) JX section, JX-10, fine-grained feldspathic litharenite arkose, with well-developed metamorphic rock clasts, predominantly composed of low-grade slate clasts; (c) well YQ1, 2190.20 m, medium-grained feldspathic litharenite sandstone, with predominant metamorphic rock clasts and the occurrence of intermediate to acidic igneous rock clasts; (d) well YQ2, 2261.73 m, coarse-grained feldspathic litharenite sandstone, with developed intermediate to acidic igneous rock clasts; (e) well YQ6, 2119.45 m, medium-grained lithic feldspar sandstone, with the development of all three types of clasts, with shale clasts being predominant; (f) CJL section, CJL-9, fine to medium-grained feldspathic litharenite sandstone, with well-developed metamorphic rock clasts and the presence of shale clasts

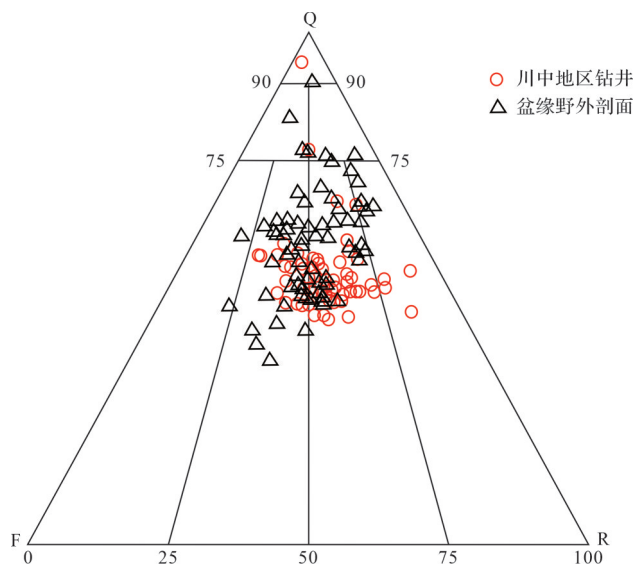


图3 川中及盆缘沙一段砂岩矿物组成

Q.石英;F.长石;R.岩屑

Fig.3 Mineral composition of sandstone in the First member of the Shaximiao Formation in central Sichuan Basin and peripheral basins

Q. quartz; F. feldspar; R. rock fragments

3.2 重矿物组分

川中地区沙一段重矿物主要包括锆石、磷灰石、金红石、电气石、绿帘石、石榴子石、榍石、钛铁矿、白钛石和磁铁矿等,以石榴子石和绿帘石为主(附表1)^①。

结合前人针对四川盆地沙一段砂岩重矿物数据统计结果^[3,30-34]发现,重矿物组分存在明显分区特征(图4b):雅安—成都地区,以发育锆石和石榴子石为主;德阳地区以发育石榴石、锆石和褐铁矿为主;巴中—秋林地区以发育褐铁矿、磁铁矿和石榴石为特征;广元地区以绿帘石、褐铁矿和石榴子石为主;盆地中东部地区以发育绿帘石和石榴子石为特征。

3.3 元素地球化学特征

主量、微量及稀土元素测试数据见附表2、附表3和附表4^①。

3.3.1 主量元素特征

沙一段泥岩样品的SiO₂含量为57.29%~64.72%(平均值为62.73%),略低于上地壳平均含量(66.00%);Al₂O₃含量为5.25%~17.24%(平均值为15.33%),略高于上地壳平均含量(15.20%);MgO含量为0.94%~2.25%(平均值为1.79%)略低于上地壳平均含量(2.20%);Na₂O含量为0.18%~1.92%(平均值为1.01%),明显低于上地壳平均含量(3.90%);K₂O含量为0.95%~4.11%(平均值为3.17%),略低于上地壳平均含量(3.40%);P₂O₅含量为0.051%~0.264%(平均值为0.13%);TiO₂含量为0.22%~0.85%(平均值为0.75%),略高于上地壳平均含量(0.50%);CaO含量为0.48%~6.96%(平均值为1.38%),明显低于上地壳平均含量(4.20%);Fe₂O₃含量为1.51%~

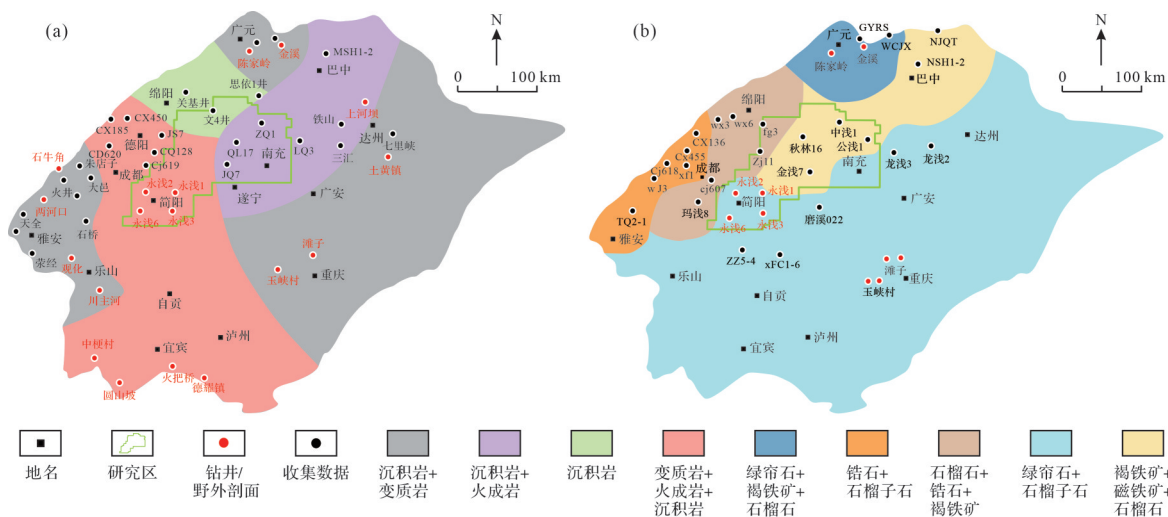


图4 四川盆地沙一段砂岩岩屑与重矿物组分分布特征(部分数据引自文献[3,30-34])

(a)岩屑组分;(b)重矿物组分

Fig.4 Compositions characteristic of lithic and heavy mineral in the First member of the Shaximiao Formation, Sichuan Basin (partial data from references [3,30-34])

(a) lithic composition; (b) heavy mineral composition

^①<http://www.cjxb.ac.cn/cn/article/doi/10.14027/j.issn.1000-0550.2023.116>

8.6% (平均值为 6.34%), 略高于上地壳平均含量 (5.04%); MnO 含量为 0.037%~0.759% (平均值为 0.13%), 略高于上地壳平均含量 (0.10%)。主量元素各项分析结果与上地壳平均值^[35]相比无较大变化。

3.3.2 微量元素

沙一段泥岩样品的微量元素数据采用原始地幔含量标准化后显示^[36], 川中地区与川北、川东地区沙一段标准化曲线特征相似 (图 5a), 具有大离子亲石元素 Rb、La、Nd 富集, 高场强元素 P、Nb、Hf 和 Ta 相对亏损的特征, 表现出与上地壳基本相近的特点^[37]。

3.3.3 稀土元素

沙一段 Σ REE 为 $(104.3\sim402.1)\times 10^{-6}$ (图 5b), 平均值为 247.9×10^{-6} ; δ Eu 具有中等的负异常, 为 0.59~0.72, 平均值为 0.66, δ Ce 为 0.38~0.96, 平均值为 0.80, 具有较弱的负异常; LREE/HREE 为 6.15~11.44, 平均值为 8.66; $(La/Yb)_N$ 为 7.96~16.65, 平均值为 10.33, 轻、重稀土元素分异明显, 轻稀土元素富集, 重稀土元素相对亏损; $(La/Sm)_N$ 为 3.39~5.56, 平均值为 4.34, 轻稀土分馏中等; $(Gd/Yb)_N$ 为 1.15~2.27, 平均值为 1.56, 重稀土分馏程度低。前人研究认为, 长英质岩石具有 LREE/HREE 高和负 Eu 异常的特点, 而铁镁质岩石具有 LREE/HREE 低、弱或者无 Eu 异常的特点^[38-39]。

4 物源分析及研究意义

4.1 岩屑组分分析

将川中地区与盆地沙一段岩屑组成进行对比后发现, 川中地区与盆地西缘龙门山前和盆地东南缘岩屑组成相似 (图 4a), 具有变质岩岩屑含量略高或

三种岩屑含量相当的特征, 指示川中地区沙一段物源可能来源于川西龙门山和川东南地区。另外, 川中地区沙一段与下伏地层相比, 岩屑中富含火成岩岩屑, 且以安山岩岩屑为主。四川盆地安山岩岩屑主要分布于盆地东北部和南部 (图 6a), 表明沙一段物源可能来自盆地东北部和南部。

4.2 重矿物分析

川中地区沙一段重矿物主要为石榴子石和绿帘石。下伏千佛崖组砂岩中重矿物以锆石+磷灰石+石榴子石为主^[40], 须家河组砂岩的重矿物组合以金红石+锆石+电气石为主^[41]; 上覆遂宁组砂岩的重矿物组合以锆石+电气石+石榴子石为主^[32], 蓬莱镇组砂岩的重矿物组合以锆石+电气石+石榴子石+磁铁矿为主^[42]。由此可见, 富绿帘石是沙一段砂岩的独有特征之一。

四川盆地沙一段绿帘石分布特征显示 (图 6b), 北东缘和南东缘沙一段砂岩中富含大量绿帘石, 特征与川中地区相似, 且川东北和川东南地区同时也是火成岩岩屑较为发育的区域, 绿帘石和火成岩岩屑在物质来源上具有一致性, 说明绿帘石可能来自川东北和川东南地区。

ZTR 指数是指稳定重矿物锆石、电气石和金红石在透明矿物组分中所占的百分含量, ZTR 值越高, 说明成熟度越高, 反之则成熟度低。因此, 源区至沉积区 ZTR 指数通常应呈现逐渐增大的趋势。川中、川北和川东地区的 ZTR 平均值 (详细数据见附表 1) 分别为 0.098、0.113 和 0.280, 川北和川东地区 ZTR 值略高于川中地区, 因此川北和川东地区可能并非源区。金红石和锆石在搬运和沉积过程中具有相似的水力分选和埋藏成岩过程, 因此可利用金红石和锆

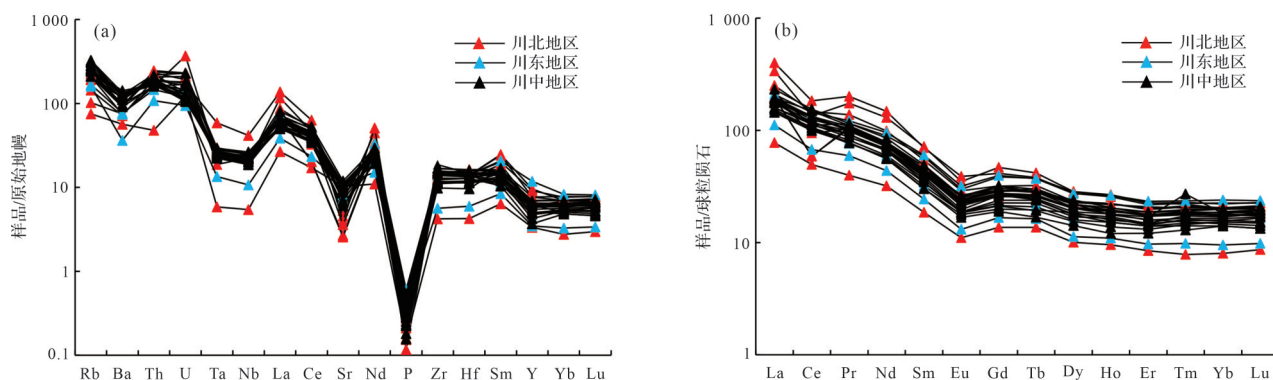


图5 微量元素及稀土元素标准化配分模式图

(a)微量元素原始地幔标准化配分模式图;(b)稀土元素球粒陨石标准化配分模式图

Fig.5 Standardized distribution pattern of trace elements and REE (Rare Earth Element)

(a) trace element spider diagram normalized to primitive mantle; (b) chondrite-normalized REE distributions

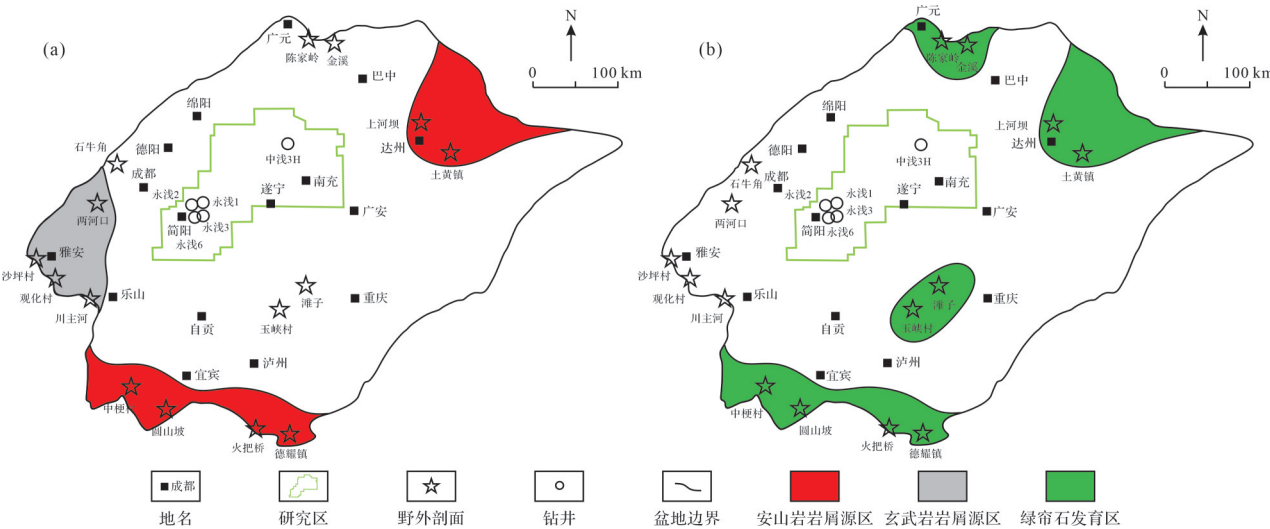


图6 四川盆地沙一段火山岩岩屑与重矿物中绿帘石发育特征图

(a)火山岩岩屑发育特征图;(b)重矿物中绿帘石发育特征图

Fig.6 Development feature maps of volcanic lithic and epidote in heavy minerals in the First member of the Shaximiao Formation, Sichuan Basin

(a) development features of volcanic lithic development; (b) development features of epidote in heavy minerals

石的相对含量(RuZi 指数)来指示物源信息^[43]。高 RuZi 指数指示源区金红石含量较高,如变质泥岩等,低 RuZi 指数则指示源区金红石含量较低,如火成岩等。川中地区样品 RuZi 指数(详细数据见附表1)为 0~31.65,平均值为 15.02,整体偏低,说明源区金红石含量较低,可能发育火成岩。

4.3 元素地球化学分析

4.3.1 物源区母岩性质分析

Rorer *et al.*^[44]根据已知碎屑岩的构造背景提出了

应用于砂岩—泥岩的判别图,并划分出四个不同的主要源区:长英质火成物源区(成熟的大陆边缘和大陆转换边缘)、中性火成物源区(其中主要是安山岩,属于成熟的岩浆弧和成熟的大陆边缘岩浆弧)、石英质沉积物源区(属于成熟的大陆源区)、镁铁质火成物源区(属于不成熟的海洋岛弧)。F1-F2 判别图显示(图 7a),研究区样品主要落在成熟度较高的石英质沉积物源区,表明川中地区沙一段物源区可能为古老的地质体、克拉通或是再旋回造山带^[45]。

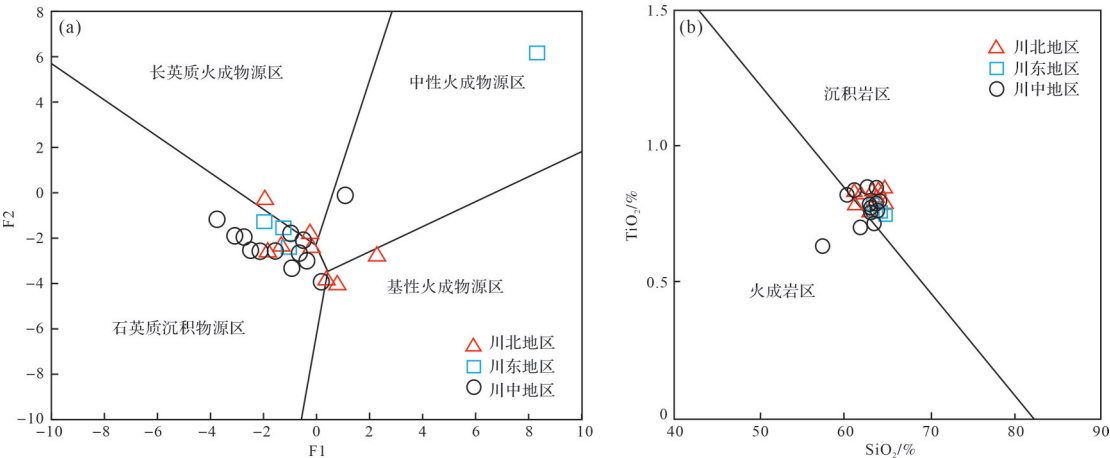


图7 四川盆地沙一段 F1-F2 判别图(据文献[44]修改)与 TiO₂-SiO₂ 判别图(据文献[46]修改)

$$F1 = -1.773TiO_2 + 0.607Al_2O_3 + 0.76Fe_2O_3(总) - 1.5MgO + 0.616CaO + 0.509Na_2O - 1.224K_2O - 9.09$$
$$F2 = 0.445TiO_2 - 0.07Al_2O_3 - 0.25Fe_2O_3(总) - 1.142MgO + 0.438CaO + 0.475Na_2O + 1.426K_2O - 6.861$$

Fig.7 Discrimination diagrams of F1-F2 (modified from reference [44]) and TiO₂-SiO₂ (modified from reference [46]) in the First member of the Shaximiao Formation, Sichuan Basin

Roser^[46]根据砂岩、泥岩提出的 $\text{SiO}_2\text{-TiO}_2$ 图解也可判断源区特征,研究区样品落在火成岩区和沉积岩区(图7b),表明川中地区沙一段物源存在沉积岩和火成岩两种源岩。

La/Th-Hf 和 Co/Th-La/Sc 图解也可以判别源岩性质。 La/Th-Hf 判别图^[47]显示(图8a),样品处于长英质酸性岛弧物源区; Co/Th-La/Sc 图解^[48]显示(图8b),样品主要落在长英质火山岩附近。另外, La/Th 值(2.23~5.84,平均值为2.99)低于5, Hf 含量(1.31~5.04,平均值为4.02)整体偏低, δEu 存在明显的负异常,综合表明川中地区沙一段物源主要来自长英质物源区^[39]。

4.3.2 化学风化作用

物源区母岩中的稳定氧化物和不稳定氧化物在遭受风化过程中含量会发生变化,其中CIA指数常被用来判断化学风化程度^[49]。CIA值在50左右时,代表源区岩石未遭受风化,CIA值介于50~100时,代表源区岩石遭受了不同程度的风化,CIA值越接近100指示源区岩石遭受风化程度越大。川中地区样品CIA值(详细数据见附表1)介于55.52~76.81,平均值为72.00,反映源区遭受了中等偏高的风化程度,表明川中地区沉积物经历了较长距离的搬运。

4.4 物源综合分析及意义

综上所述,川中地区沙一段富含安山岩岩屑,碳酸盐岩岩屑、玄武岩岩屑和花岗岩岩屑不发育,且重矿物中发育绿帘石。盆地西缘的构造活动导致碳酸盐岩露出地表,并遭受剥蚀,因此川西龙门山前发育大量碳酸盐岩岩屑。龙门山在印支—燕山期经历过强烈的岩浆活动,广泛分布花岗岩^[50-51],川西南地区

发育玄武岩岩屑。由此可见,川西地区基本未对川中地区沙一段提供物源,盆地北部米仓山物源主要影响川西北部—米仓山前缘^[31],对川中地区贡献较小。川东北地区(大巴山)和川东南地区富含火成岩岩屑,且绿帘石较发育,与川中地区沙一段特征相似,表明川东北和川东南地区均可能为川中地区沙一段提供物源。中侏罗世时期强烈的构造活动导致川东北大巴山的强烈隆升^[52],基底岩浆岩、侵入岩暴露而成为母岩区进而为川中供源。江南造山带作为我国华南地区的古陆剥蚀区之一,位于扬子板块和华夏板块之间,被认为是扬子板块与华夏板块碰撞后,由岛弧—弧后盆地组成的洋陆碰撞造山带,虽然江南造山带在演化过程中也存在中酸性岩浆岩^[53],但江南造山带在侏罗纪时期已经基本定型,处于微弱隆起且相对稳定状态,加之源区化学风化作用较强,所以江南造山带可能并非主要源区^[54]。由此可见,川中地区在沙一段时期主要由川东北大巴山进行供源。

通过对川中地区不同物源沉积岩石样品的物质组成、颜色、形态等特征分析,我们了解到川中地区沙一段物源主要来自盆地东北部。利用地震资料对川中地区砂体进行刻画,发现河道展布特征明显(图9a),可以确定川中地区沙一段发育三角洲体系,三角洲沉积物质主要由大巴山供给(图9b)。研究成果不仅指明了碎屑物质的主要搬运方向,为四川盆地致密气有利区的划分以及勘探开发提供了有力支撑,也为研究隆升山体周缘地区沉积环境、沉积速率和沉积特征等相关关系奠定了基础,这对研究“盆—山”耦合关系意义重大^[55-56]。

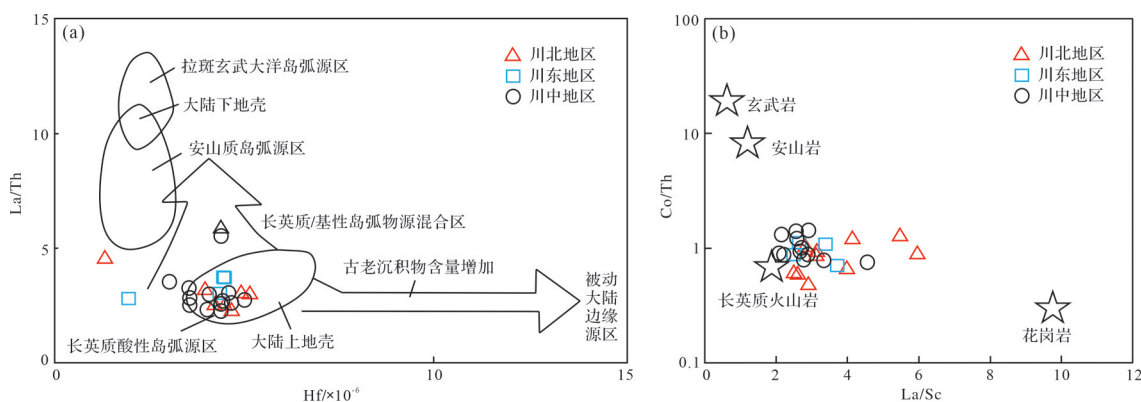


图8 四川盆地沙一段 La/Th-Hf 判别图(据文献[47]修改)与 Co/Th-La/Sc 判别图(据文献[48]修改)

Fig.8 Discrimination diagrams of La/Th-Hf (modified from reference [47]) and Co/Th-La/Sc (modified from reference [48]) in the First member of the Shaximiao Formation, Sichuan Basin

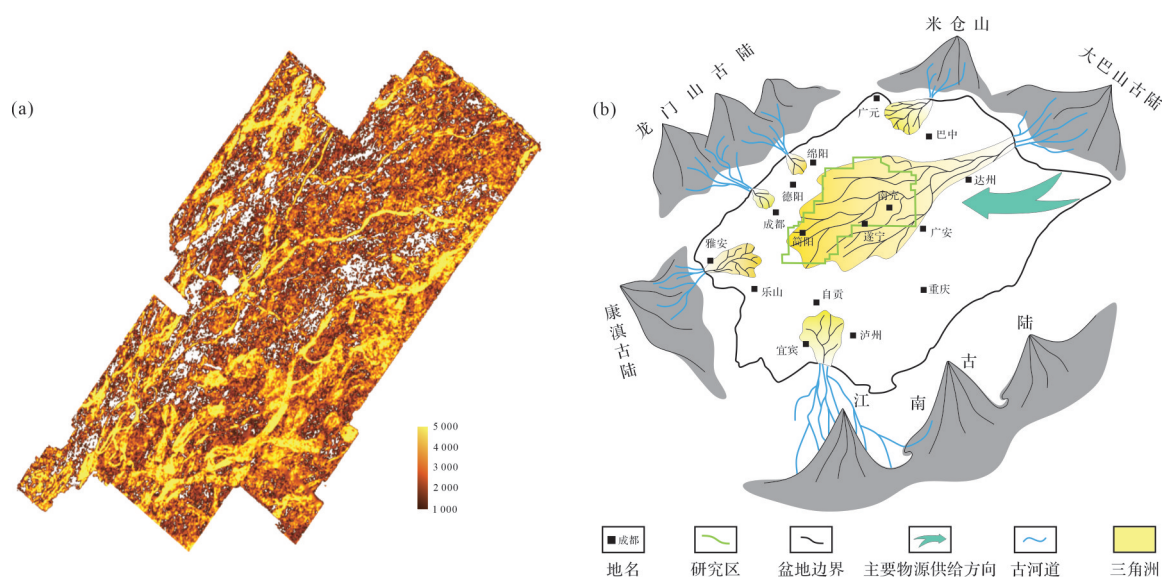


图9 (a)川中地区沙一段砂体平面分布图;(b)四川盆地沙一段沉积模式图

Fig.9 (a) Plan view of sand bodies in the First member of the Shaximiao Formation in central Sichuan Basin; (b) schematic of sedimentary patterns in the First member of the Shaximiao Formation, Sichuan Basin

5 结论

(1) 川中地区沙一段砂岩以长石岩屑砂岩和岩屑长石砂岩为主,安山岩岩屑和绿帘石在沙一段下伏地层较少发育,川东北和川东南地区沙一段中常见。

(2) 川中地区沙一段物源主要来自盆地东北部大巴山,源区母岩主要为长英质火山岩,同时含有少量沉积岩,盆缘其他方向物源供给有限。

致谢 感谢成都理工大学沉积地质研究院徐文礼老师和郭佩老师的悉心指导,感谢审稿专家提出的宝贵意见。

参考文献 (References)

- [1] 邹才能,翟光明,张光亚,等. 全球常规—非常规油气形成分布、资源潜力及趋势预测[J]. 石油勘探与开发, 2015, 42(1): 13-25. [Zou Caineng, Zhai Guangming, Zhang Guangya, et al. Formation, distribution, potential and prediction of global conventional and unconventional hydrocarbon resources[J]. Petroleum Exploration and Development, 2015, 42(1): 13-25.]
- [2] 孙龙德,邹才能,贾爱林,等. 中国致密油气发展特征与方向[J]. 石油勘探与开发, 2019, 46(6): 1015-1026. [Sun Longde, Zou Caineng, Jia Ailin, et al. Development characteristics and orientation of tight oil and gas in China[J]. Petroleum Exploration and Development, 2019, 46(6): 1015-1026.]
- [3] 刘柏,樊仕海,张本健,等. 川西坳陷南段中侏罗统沙溪庙组多物源特征探讨[J]. 油气藏评价与开发, 2016, 6(5): 16-20. [Liu Bai, Fan Shihai, Zhang Benjian, et al. Discuss on multiple prove-

nance characteristics of Shaximiao Formation of Middle Jurassic in the south of western Sichuan Depression[J]. Reservoir Evaluation and Development, 2016, 6(5): 16-20.]

- [4] 姚文礼. 四川盆地须家河组致密砂岩物源体系的控储作用[J]. 地质科技通报, 2021, 40(5): 223-230. [Yao Wenli. Reservoir control of tight sandstone provenance system in Xujiahe Formation, Sichuan Basin[J]. Bulletin of Geological Science and Technology, 2021, 40(5): 223-230.]
- [5] 王大洋,王峻. 川西前陆盆地侏罗系沉积体系及沉积模式研究[J]. 地质学刊, 2010, 34(2): 123-129. [Wang Dayang, Wang Jun. Study on sedimentary system and sedimentary model of Jurassic in foreland basin of western Sichuan[J]. Journal of Geology, 2010, 34(2): 123-129.]
- [6] 李夏. 川西坳陷侏罗系沉积相研究[D]. 荆州:长江大学, 2014. [Li Xia. A sedimentary facies study of Jurassic in western Sichuan sedimentary depression[D]. Jingzhou: Yangtze University, 2014.]
- [7] 王丽英,王琳,张渝鸿,等. 川西地区侏罗系沙溪庙组储层特征[J]. 天然气勘探与开发, 2014, 37(1): 1-4, 9, 95. [Wang Liying, Wang Lin, Zhang Yuhong, et al. Reservoir characteristics of Jurassic Shaximiao Formation, western Sichuan Basin[J]. Natural Gas Exploration and Development, 2014, 37(1): 1-4, 9, 95.]
- [8] 汪超平,刘甜甜. 川西坳陷中段中侏罗统沙溪庙组沉积体系的新认识[J]. 沉积与特提斯地质, 2016, 36(2): 62-66. [Wang Chaoping, Liu Tiantian. Depositional systems in the Middle Jurassic Shaximiao Formation in the central part of Western Sichuan Depression[J]. Sedimentary Geology and Tethyan Geology, 2016, 36(2): 62-66.]
- [9] 邓莉,刘君龙,钱玉贵,等. 川西地区龙门山前带侏罗系物源与沉积体系演化[J]. 石油与天然气地质, 2019, 40(2): 380-391.

- [Deng Li, Liu Junlong, Qian Yugui, et al. Provenance and sedimentary system of the Jurassic successions in the front of Longmen Mountain in western Sichuan Basin[J]. Oil & Gas Geology, 2019, 40(2): 380-391.]
- [10] 王一帆,徐胜林,张兵,等. 川西坳陷西充—梓潼地区下沙溪庙组沉积微相特征[J]. 沉积与特提斯地质, 2020, 40(1): 35-44. [Wang Yifan, Xu Shenglin, Zhang Bing, et al. Sedimentary microfacies in the Lower Shaximiao Formation in the Xichong-Zitong region, Western Sichuan Depression[J]. Sedimentary Geology and Tethyan Geology, 2020, 40(1): 35-44.]
- [11] 张维宸. 四川盆地中生代区域构造格架与构造演化过程研究[D]. 北京:中国地质大学(北京), 2009. [Zhang Weichen. Tectonic framework and tectonic evolution of the Sichuan Basin in the Mesozoic and Cenozoic[D]. Beijing: China University of Geosciences (Beijing), 2009.]
- [12] 卿元华. 川中侏罗系凉上段—沙一段致密油储层形成机理[D]. 成都:成都理工大学, 2020. [Qing Yuanhua. Formation mechanism of tight oil reservoirs in Liangshang member and Shayi member of Jurassic, central Sichuan Basin[D]. Chengdu: Chengdu University of Technology, 2020.]
- [13] 魏嘉宝. 川中地区侏罗系凉高山组储层特征及含油性控制因素[D]. 成都:西南石油大学, 2015. [Wei Jiabao. Reservoir characteristics and controlling factors of oil bearing of Jurassic Lianggaoshan Formation in central Sichuan Basin[D]. Chengdu: Southwest Petroleum University, 2015.]
- [14] 杨跃明,王小娟,陈双玲,等. 四川盆地中部地区侏罗系沙溪庙组沉积体系演化及砂体发育特征[J]. 天然气工业, 2022, 42(1): 12-24. [Yang Yueming, Wang Xiaojuan, Chen Shuangling, et al. Sedimentary system evolution and sandbody development characteristics of Jurassic Shaximiao Formation in the central Sichuan Basin[J]. Natural Gas Industry, 2022, 42(1): 12-24.]
- [15] 张本健,潘珂,吴长江,等. 四川盆地金秋气田侏罗系沙溪庙组多期砂组天然气复合成藏机理及模式[J]. 天然气工业, 2022, 42(1): 51-61. [Zhang Benjian, Pan Ke, Wu Changjiang, et al. Compound gas accumulation mechanism and model of Jurassic Shaximiao Formation multi-stage sandstone formations in Jinqu gas field of the Sichuan Basin[J]. Natural Gas Industry, 2022, 42(1): 51-61.]
- [16] 欧莉华,钱利军,林良彪,等. 川西地区中侏罗统沙溪庙组砂岩地球化学特征及构造意义[J]. 科学技术与工程, 2016, 16(17): 1-8. [Ou Lihua, Qian Lijun, Lin Liangbiao, et al. Tectonic setting and geochemical characteristics of sandstone from Middle Jurassic of Shaximiao Formation in western Sichuan area[J]. Science Technology and Engineering, 2016, 16(17): 1-8.]
- [17] 杨春龙,苏楠,芮宇润,等. 四川盆地中侏罗统沙溪庙组致密气成藏条件及勘探潜力[J]. 中国石油勘探, 2021, 26(6): 98-109. [Yang Chunlong, Su Nan, Rui Yurun, et al. Gas accumulation conditions and exploration potential of tight gas reservoir of the Middle Jurassic Shaximiao Formation in Sichuan Basin[J]. China Petroleum Exploration, 2021, 26(6): 98-109.]
- [18] 吕松婷,时保宏. 四川盆地川中 YTB 地区沙溪庙组二段沉积微相研究[J]. 石油地球物理勘探, 2022, 57(增刊1): 122-129. [Lü Songting, Shi Baohong. Sedimentary microfacies of the Second member of Shaximiao Formation in YTB area of central Sichuan Basin[J]. Oil Geophysical Prospecting, 2022, 57(Suppl. 1): 122-129.]
- [19] 李英强,何登发. 四川盆地及邻区早侏罗世构造—沉积环境与原型盆地演化[J]. 石油学报, 2014, 35(2): 219-232. [Li Yingqiang, He Dengfa. Evolution of tectonic-depositional environment and prototype basins of the Early Jurassic in Sichuan Basin and adjacent areas[J]. Acta Petrolei Sinica, 2014, 35(2): 219-232.]
- [20] 马永生,陈洪德,王国力,等. 中国南方构造—层序岩相古地理图集(震旦纪—新近纪)[M]. 北京:科学出版社, 2009: 1-301. [Ma Yongsheng, Chen Hongde, Wang Guoli, et al. Tectonic sequence stratigraphy and lithofacies paleogeography of Sinian-Neogene in southern China[M]. Beijing: Chinese Science Publishing Company, 2009: 1-301.]
- [21] 肖富森,马廷虎. 川东北五宝场构造沙溪庙组气藏勘探开发认识[J]. 天然气工业, 2007, 27(5): 4-7. [Xiao Fusen, Ma Tinghu. Understanding of exploration and development of Shaximiao gas pool in Wubaochang structure, northeastern Sichuan Basin[J]. Natural Gas Industry, 2007, 27(5): 4-7.]
- [22] 韦腾强,张本健,王小娟,等. 四川盆地秋林地区侏罗系沙溪庙组二段河流相沉积特征及储集差异性分析[J]. 科学技术与工程, 2021, 21(29): 12438-12446. [Wei Tengqiang, Zhang Benjian, Wang Xiaojuan, et al. Sedimentary characteristics of fluvial facies and analysis of reservoir differences in the Second member of Jurassic Shaximiao Formation in Qiulin area, Sichuan Basin[J]. Science Technology and Engineering, 2021, 21(29): 12438-12446.]
- [23] 段文荣. 四川盆地中侏罗统下沙溪庙组致密气勘探潜力及有利方向[J]. 石油实验地质, 2021, 43(3): 424-431, 467. [Duan Wenshen. Exploration potential and favorable direction of tight gas in Middle Jurassic Xiashaximiao Formation in Sichuan Basin[J]. Petroleum Geology & Experiment, 2021, 43(3): 424-431, 467.]
- [24] 郭贵安,关旭,肖富森,等. 四川盆地中部侏罗系沙溪庙组致密砂岩气藏地震一体化描述技术[J]. 天然气工业, 2022, 42(1): 40-50. [Guo Gui'an, Guan Xu, Xiao Fusen, et al. Integrated seismic description technology for tight sandstone gas reservoir of Jurassic Shaximiao Formation in the central Sichuan Basin[J]. Natural Gas Industry, 2022, 42(1): 40-50.]
- [25] 付蕾,张本健,曹正林,等. 四川盆地川中地区侏罗系沙溪庙组不同类型砂体地质特征及地震精细雕刻[J]. 石油实验地质, 2022, 44(1): 85-93. [Fu Lei, Zhang Benjian, Cao Zhenglin, et al. Geological characteristics and seismic fine description of different types of sand bodies in Jurassic Shaximiao Formation in central Sichuan Basin[J]. Petroleum Geology & Experiment, 2022, 44(1): 85-93.]

- [26] 黄东,李育聪,刘敏,等. 川中地区中侏罗统沙溪庙组一段油气藏特征及勘探潜力评价[J]. 中国石油勘探, 2017, 22(2): 44-49. [Huang Dong, Li Yucong, Liu Min, et al. Reservoir features and exploration potential of the 1st member of Shaximiao Formation of Middle Jurassic in central Sichuan Basin[J]. China Petroleum Exploration, 2017, 22(2): 44-49.]
- [27] 方锐,蒋裕强,陈沁,等. 川东北五宝场地区侏罗系沙溪庙组沉积特征[J]. 岩性油气藏, 2023, 35(2): 47-58. [Fang Rui, Jiang Yuqiang, Chen Qin, et al. Sedimentary characteristics of Jurassic Shaximiao Formation in Wubaochang area, northeastern Sichuan Basin[J]. Lithologic Reservoirs, 2023, 35(2): 47-58.]
- [28] 李朝辉. 四川盆地侏罗纪岩相古地理研究[D]. 成都: 成都理工大学, 2016. [Li Zhaohui. Study on the Jurassic lithofacies and paleogeography of Sichuan Basin[D]. Chengdu: Chengdu University of Technology, 2016.]
- [29] 王锦西. 川中公山庙地区沙溪庙组沉积相与储层特征研究[D]. 成都: 成都理工大学, 2019. [Wang Jinxi. Sedimentary facies and reservoir characteristics of Shaximiao Formation in Gongshanmiao area, central Sichuan[D]. Chengdu: Chengdu University of Technology, 2019.]
- [30] 黄滢竹,龚文平,张方. 成都凹陷下沙溪庙组物源分析[J]. 长江大学学报(自科版), 2014, 11(31): 35-38. [Huang Yingzhu, Gong Wenping, Zhang Fang. Study on provenance of Lower Shaximiao Formation in Chengdu Sag[J]. Journal of Yangtze University (Natural Science Edition), 2014, 11(31): 35-38.]
- [31] 钱利军,欧莉华,郝强,等. 川西—川北地区中侏罗统千佛岩组物源分析及沉积相展布[J]. 科学技术与工程, 2016, 16(8): 79-86. [Qian Lijun, Ou Lihua, Hao Qiang, et al. Provenance and sedimentary facies evolution of the Middle Jurassic Qianfuyan Formation in the western-northern Sichuan[J]. Science Technology and Engineering, 2016, 16(8): 79-86.]
- [32] 安红艳. 川西坳陷中段侏罗系沙溪庙组和遂宁组物源分析及油气地质意义[D]. 成都: 成都理工大学, 2011. [An Hongyan. Provenance analysis and its oil-gas significance of Jurassic Shaximiao Formation and Suining Formation in the middle part of West Sichuan Depression[D]. Chengdu: Chengdu University of Technology, 2011.]
- [33] 杨祥菊. 川西坳陷马井—什邡中侏罗统沙溪庙组沉积相研究[D]. 成都: 成都理工大学, 2014. [Yang Xiangju. Research on depositional facies of the Middle Jurassic Shaximiao Formation in Majing-Shifang area, Western Sichuan Depression[D]. Chengdu: Chengdu University of Technology, 2014.]
- [34] 付菊,伍玲,李刚,等. 川西坳陷中段合兴场: 丰谷地区沙溪庙组沉积相研究[J]. 岩性油气藏, 2014, 26(1): 75-79. [Fu Ju, Wu Ling, Li Gang, et al. Sedimentary facies of Shaximiao Formation in Hexingchang-Fenggu area at the middle part of Western Sichuan Depression[J]. Lithologic Reservoirs, 2014, 26(1): 75-79.]
- [35] Rudnick R L, Gao S. Composition of the continental crust[M]// Holland H D, Turekian K K. Treatise on geochemistry. Amsterdam: Elsevier, 2003.
- [36] Taylor S R, McLennan S M. The continental crust: Its composition and evolution[M]. Oxford: Blackwell Scientific Publications, 1985: 1-312.
- [37] 李振宏,董树文,渠洪杰,等. 宁武—静乐盆地侏罗系碎屑岩地球化学特征及地质意义[J]. 地质论评, 2013, 59(4): 637-655. [Li Zhenhong, Dong Shuwen, Qu Hongjie, et al. Geochemistry of Jurassic detrital rocks and geological significance in Ningwu-Jingle Basin[J]. Geological Review, 2013, 59(4): 637-655.]
- [38] 呼其图,关平,王大华,等. 柴达木盆地北缘东段中侏罗统物源分析: 来自重矿物、元素地球化学及碎屑锆石年代学的证据[J]. 沉积学报, 2024, 42(2): 466-485. [Hu Qitu, Guan Ping, Wang Dahua, et al. Provenance analysis of the Middle Jurassic in northeastern Qaidam Basin: Evidence from heavy minerals, elemental geochemistry and detrital zircon U-Pb geochronology[J]. Acta Sedimentologica Sinica, 2024, 42(2): 466-485.]
- [39] Cullers R L. The geochemistry of shales, siltstones and sandstones of Pennsylvanian-Permian age, Colorado, USA: Implications for provenance and metamorphic studies[J]. Lithos, 2000, 51(3): 181-203.
- [40] 张楚越. 元坝地区中侏罗统千佛崖组储层特征[D]. 成都: 成都理工大学, 2016. [Zhang Chuyue. Research on reservoir characteristics of Middle Jurassic Qianfoya Formation in the Yuanba area of northeast Sichuan Basin, China[D]. Chengdu: Chengdu University of Technology, 2016.]
- [41] 胡诚. 四川盆地川中地区须家河组物源区分析及岩相古地理特征[D]. 成都: 成都理工大学, 2011. [Hu Cheng. Provenance analysis and lithofacies palaeogeographic characteristics of Xujiahe Formation in middle of Sichuan Basin[D]. Chengdu: Chengdu University of Technology, 2011.]
- [42] 叶素娟,李嵘,张庄. 川西坳陷中段上侏罗统蓬莱镇组物源及沉积体系研究[J]. 沉积学报, 2014, 32(5): 930-940. [Ye Sujuan, Li Rong, Zhang Zhuang. Provenance analysis and depositional system of the Upper Jurassic Penglaizhen Formation in the middle part of western Sichuan, China[J]. Acta Sedimentologica Sinica, 2014, 32(5): 930-940.]
- [43] 刘腾,陈刚,徐小刚,等. 物源分析方法及其发展趋势[J]. 西北地质, 2016, 49(4): 121-128. [Liu Teng, Chen Gang, Xu Xiaogang, et al. Methods and development trend of provenance analysis[J]. Northwestern Geology, 2016, 49(4): 121-128.]
- [44] Roser B P, Korsch R J. Provenance signatures of sandstone-mudstone suites determined using discriminant function analysis of major-element data[J]. Chemical Geology, 1988, 67(1/2): 119-139.
- [45] 田洋,谢国刚,王令占,等. 鄂西南齐岳山须家河组物源及构造背景: 来自岩石学、地球化学和锆石年代学的制约[J]. 地球科学: 中国地质大学学报, 2015, 40(12): 2021-2036. [Tian Yang, Xie Guogang, Wang Lingzhan, et al. Provenance and tectonic settings of Triassic Xujiahe Formation in Qiyueshan area,

- southwest Hubei: Evidences from petrology, geochemistry and zircon U-Pb ages of clastic rocks[J]. *Earth Science: Journal of China University of Geosciences*, 2015, 40(12): 2021-2036.]
- [46] Roser B P, Korsch R J. Determination of tectonic setting of sandstone-mudstone suites using SiO_2 content and $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratio[J]. *The Journal of Geology*, 1986, 94 (5): 635-650.
- [47] Floyd P A, Winchester J A, Park R G. Geochemistry and tectonic setting of Lewisian clastic metasediments from the Early Proterozoic Loch Maree Group of Gairloch, NW Scotland[J]. *Precambrian Research*, 1989, 45(1/2/3): 203-214.
- [48] Floyd P A, Leveridge B E. Tectonic environment of the Devonian Gramscatho Basin, South Cornwall: Framework mode and geochemical evidence from turbiditic sandstones[J]. *Journal of the Geological Society*, 1987, 144(4): 531-542.
- [49] Nesbitt H W, Young G M. Early Proterozoic climates and plate motions inferred from major element chemistry of Lutites[J]. *Nature*, 1982, 299(5885): 715-717.
- [50] 黄永健,张成江,汪云亮,等. 龙门山造山带中生代花岗岩带成因及其构造意义[J]. *成都理工学院学报*, 2002, 29(1): 69-73. [Huang Yongjian, Zhang Chengjiang, Wang Yunliang, et al. Genesis and tectonic significance of the Mesozoic era granite terrain in Longmen mountains orogen[J]. *Journal of Chengdu University of Technology*, 2002, 29(1): 69-73.]
- [51] 胡健民,孟庆任,石玉若,等. 松潘—甘孜地体内花岗岩锆石 SHRIMP U-Pb 定年及其构造意义[J]. *岩石学报*, 2005, 21(3): 867-880. [Hu Jianmin, Meng Qingren, Shi Yuruo, et al. SHRIMP U-Pb dating of zircons from granitoid bodies in the Songpan-Ganzi terrane and its implications[J]. *Acta Petrologica Sinica*, 2005, 21(3): 867-880.]
- [52] 沈传波,梅廉夫,徐振平,等. 四川盆地复合盆山体系的结构构造和演化[J]. *大地构造与成矿学*, 2007, 31(3): 288-299. [Shen Chuanbo, Mei Lianfu, Xu Zhenping, et al. Architecture and tectonic evolution of composite basin-mountain system in Sichuan Basin and its adjacent areas[J]. *Geotectonica et Metallogenia*, 2007, 31(3): 288-299.]
- [53] 王坤,张嘉玮,向华,等. 江南造山带中部存在约 860 Ma 隐伏花岗岩:来自湖南宁乡云影窝钾镁煌斑岩捕虏晶的证据[J]. *矿物岩石地球化学通报*, 2024, 43:151-166. [Wang Kun, Zhang Jiangwei, Xiang Hua, et al. The existence of the ca. 860 Ma concealed granite in the central Jiangnan Orogen: Evidence from the xenocrysts in lamproite at Yunyingwo, Ningxiang, Hunan province[J]. *Bulletin of Mineralogy, Petrology and Geochemistry*: 2024, 43: 151-166.]
- [54] 廖子宽. 四川板块构造的演化与地势形成[J]. *重庆师范学院学报(自然科学版)*, 1990, 7(1): 45-50. [Liao Zikuan. The changes of the plate structure and the formation of the physical features of Sichuan province[J]. *Journal of Chongqing Teachers College (Natural Science Edition)*, 1990, 7(1): 45-50.]
- [55] 汪正江,陈洪德,张锦泉. 物源分析的研究与展望[J]. *沉积与特提斯地质*, 2000, 20(4): 104-110. [Wang Zhengjiang, Chen Hongde, Zhang Jinquan. Provenance analysis: Perspectives[J]. *Sedimentary Geology and Tethyan Geology*, 2000, 20(4): 104-110.]
- [56] 杨仁超,李进步,樊爱萍,等. 陆源沉积岩物源分析研究进展与发展趋势[J]. *沉积学报*, 2013, 31(1): 99-107. [Yang Renchao, Li Jinbu, Fan Aiping, et al. Research progress and development tendency of provenance analysis on terrigenous sedimentary rocks[J]. *Acta Sedimentologica Sinica*, 2013, 31(1): 99-107.]

Provenance Analysis of the First Member of the Middle Jurassic Shaximiao Formation in Central Sichuan Basin

CAO JiaXin¹, XU WenLi^{1,2}, CAO JiXiang³, GUO Pei^{1,2}, WEN HuaGuo^{1,2}

1. Institute of Sedimentary Geology, Chengdu University of Technology, Chengdu 610059, China

2. State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Chengdu University of Technology, Chengdu 610059, China

3. Tight Oil and Gas Exploration and Development Project Department of Southwest Oil and Gas Field Branch, Chengdu 610066, China

Abstract: [Objective] The Shaximiao Formation of Middle Jurassic in the central Sichuan Basin represents a key tight gas reservoir target. Currently, exploration and development of the First member of the Shaximiao Formation remain in early stages, with comprehensive research still limited, especially in systematic provenance studies controlling the distribution of high-quality sand bodies. [Methods] Integrating petrological analysis and elemental geochemistry, this study investigates the provenance of the First member of the Shaximiao Formation in central Sichuan Basin. [Results] (1) The sandstone of the First member of the Shaximiao Formation is mainly composed of feldspathic litharenite and lithic arkose. The igneous rock fragments are predominantly andesite, which is rarely found in the underlying strata but is common in northeastern and southeastern Sichuan Basin. (2) The dominant heavy minerals are garnet and epidote. The latter is scarce in the lower strata but is well-developed in northeastern and southeastern Sichuan Basin. (3) Discrimination diagrams of F1-F2, SiO₂-TiO₂, La/Th-Hf and Co/Th-La/Sc indicate that the provenance of the First member of the Shaximiao Formation is mainly felsic volcanic rocks, with minor sedimentary rocks. [Conclusions] The sandstone of the First member of the Shaximiao Formation in central Sichuan Basin is primarily sourced from the Dabashan Orogenic Belt in the northeastern part of the basin, with limited contribution from surrounding areas in other directions. This understanding provides strong support for delineating favorable tight gas zones and guiding exploration and development activities in the Sichuan Basin.

Key words: Sichuan Basin; Shaximiao Formation; provenance analysis; andesite fragments; epidote