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扬子西缘埃迪卡拉纪—寒武纪大地构造背景演化: 来自碎屑锆石 U-Pb 年代学证据

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Tectonic evolution of the western Yangtze Block during the Ediacaran–Cambrian: evidence from detrital zircon U-Pb geochronology

Abstract: [Objective] The Yangtze Block was a crucial component of the Gondwana supercontinent. During the Ediacaran–Early Cambrian, its western margin underwent a marked transition from carbonate- to siliciclastic-dominated depositional environments. However, the tectonic dynamics and geotectonic setting governing this pronounced sedimentary facies shift remain poorly constrained. Thick Lower Cambrian terrigenous clastic rocks widely exposed along the western margin of the Yangtze Block (Western Yangtze) serve as a key archive for tracing sediment provenance and deciphering Early Cambrian geotectonic evolution. [Methods] This study presents systematic detrital zircon U–Pb geochronological and whole-rock major- and trace-element geochemical analyses of the Lower Cambrian Qiongzhusi Formation in the Western Yangtze to constrain its provenance and tectonic background. [Results] Whole-rock geochemical data indicate that high-field-strength elements (HFSEs) and large-ion lithophile elements (LILEs; e.g., Th, Zr, Hf, Ba, Pb) in the Qiongzhusi Formation clastic rocks align closely with upper continental crust (UCC) values. Conversely, elements such as Co, Ni, Y, Nb, Cs, Hf, and Ta are depleted relative to UCC, with Co, Cs, and Ta showing the most significant depletion. Characteristics of immobile elements (Th, Sc, Hf, Zr, Ho) and rare earth elements (REEs; e.g., La, Ce, Yb) consistently indicate a predominantly felsic igneous source. Detrital zircon U–Pb age spectra exhibit two primary population peaks at ca. 590–500 Ma and ca. 880–720 Ma, alongside two subordinate clusters at ca. 1900–1500 Ma and ca. 2500–2400 Ma. [Conclusions] Integrated with regional geological evidence, we propose that the Early Cambrian detritus was primarily derived from Ediacaran–Early Cambrian magmatic rocks within the Longmenshan tectonic belt, as well as weathering products of late Neoproterozoic felsic magmatic rocks from the Panxi–Hannan and Ailaoshan magmatic arcs. Subduction of the Proto-Tethys Ocean beneath the Western Yangtze during the latest Ediacaran–Early Cambrian established a Late Ediacaran–Early Cambrian magmatic arc. This tectonic event converted the Western Yangtze from a passive margin into an active continental margin, supplying voluminous Early Cambrian detritus that drove the major depositional transition from carbonates to siliciclastics. [Significance] These findings establish key provenance links between the Western Yangtze and

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surrounding orogenic belts, providing critical constraints for reconstructing the tectonic and paleogeographic evolution of the South China Block during the Ediacaran–Early Cambrian transition.

Keywords: western Yangtze Block; Ediacaran–Cambrian; detrital zircon U–Pb geochronology; whole-rock geochemistry; magmatic arc

摘 要: 扬子地块是 Gondwana 超大陆的重要组成部分, 其西缘在埃迪卡拉纪—早寒武世期间经历了从碳酸盐岩相向碎屑岩相的显著转变, 但该转变的动力学机制及早寒武世的大地构造背景尚不明确。扬子地块西缘(扬子西缘)广泛出露巨厚的早寒武世陆源碎屑岩, 为示踪沉积物源和恢复构造背景提供了关键研究对象。文章对下寒武统筇竹寺组开展了碎屑锆石 U-Pb 年代学和全岩主、微量元素分析。结果表明: 碎屑岩中高场强元素和大离子亲石元素 Th、Zr、Hf、Ba、Pb 含量与上地壳相似, 而 Co、Ni、Y、Nb、Cs、Hf、Ta 等元素相对亏损, 以 Co、Cs、Ta 亏损显著; Th、Sc、Hf、Zr、Ho 等不活泼元素和 La、Ce、Yb 等稀土元素特征指示其物源主要来自长英质岩浆岩。碎屑锆石 U-Pb 年龄谱显示 ca. 590~500 Ma 和 ca. 880~720 Ma 2 个主峰, 以及 1900~1500 Ma 和 2500~2400 Ma 2 个次峰。结合区域资料和已有研究, 认为早寒武世碎屑物质主要来源于龙门山构造带埃迪卡拉纪—早寒武世岩浆岩, 以及攀西—汉南岩浆弧、哀牢山构造岩浆弧等新元古代晚期长英质岩浆岩的风化剥蚀。据此推断, 埃迪卡拉纪末期—早寒武世, 原特提斯洋向扬子西缘俯冲, 形成了 1 条同期岩浆弧, 不仅为寒武系碎屑岩提供了大量的物源, 还促使扬子西缘由被动大陆边缘转为活动大陆边缘, 并导致沉积相由碳酸盐岩向碎屑岩转变。上述结果揭示了扬子西缘与周缘造山带之间的物源联系, 为重建华南板块在该时期的构造—古地理演化提供了有效约束。

关键词: 扬子西缘; 埃迪卡拉纪—寒武纪; 碎屑锆石 U-Pb 定年; 全岩地球化学分析; 岩浆弧

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0 引言

新元古代晚期—古生代早期是全球从 Rodinia 超大陆裂解向 Gondwana 超大陆聚合转换的关键构造转换期(赵国春等, 2022)。华南板块的扬子地块作为 Rodinia 和 Gondwana 超大陆的重要组成部分, 记录了该时期地球—生命系统的协同演化过程, 并保存了大量沉积地层学、古生物学等证据(冯增昭等, 2001, 2002; Jiang et al., 2003, 2011)。该时期也对应着扬子地块从碳酸盐岩台地相向陆源碎屑岩相转变的关键时期, 然而控制其转变的构造动力学机制尚不清楚。目前学术界主要提出 3 种构造模式用以解释该转变: ①华南板块西缘与印度板块西北缘在晚埃迪卡拉世(0.56~0.54 Ga)碰撞形成造山带(Yang et al., 2020); ②华南板块与伊朗地体和印度板块西缘在晚埃迪卡拉世—早寒武世发生拼贴碰撞(Chen et al., 2021); ③原特提斯洋在早寒武世(ca. 530 Ma)俯冲于扬子西缘之下, 形成 1 条该时期岩浆弧(Gu et al., 2021, 2023)。厘清上述分歧, 将有助于深入理解 Rodinia–Gondwana 超大陆旋回过程, 为该时期地球—生命系统协同演化提供相应线索和证据。

虽然扬子地块内部及其边缘发育大量新元古代晚期岩浆岩, 但埃迪卡拉纪—寒武纪岩浆活动记录较为有限(周明忠等, 2011; Zhou et al., 2018; Deng et al., 2025), 难以提供充足的直接证据约束上述问题。相比之下, 扬子地块内部广泛保存的新元古代晚期—古生代早期(南华纪—寒武纪)沉积序列, 则记录了该时期构造演化以及地球—生命系统协同演化的重要信息(Jiang et al., 2003, 2011), 其中以埃迪卡拉纪—早寒武世陆源碎屑岩及其相关碳酸盐岩沉积相最为关键。文章选取扬子西缘的东川区娜姑镇和易门县为研究区, 以埃迪卡拉系—下寒武统筇竹寺组碎屑沉积岩为研究对象, 系统开展了沉积相分析、碎屑锆石 U-Pb 年代学和全岩地球化学等研究, 旨在揭示该时期扬子地块的沉积物源演化特征, 并探讨其构造演化及动力学过程。

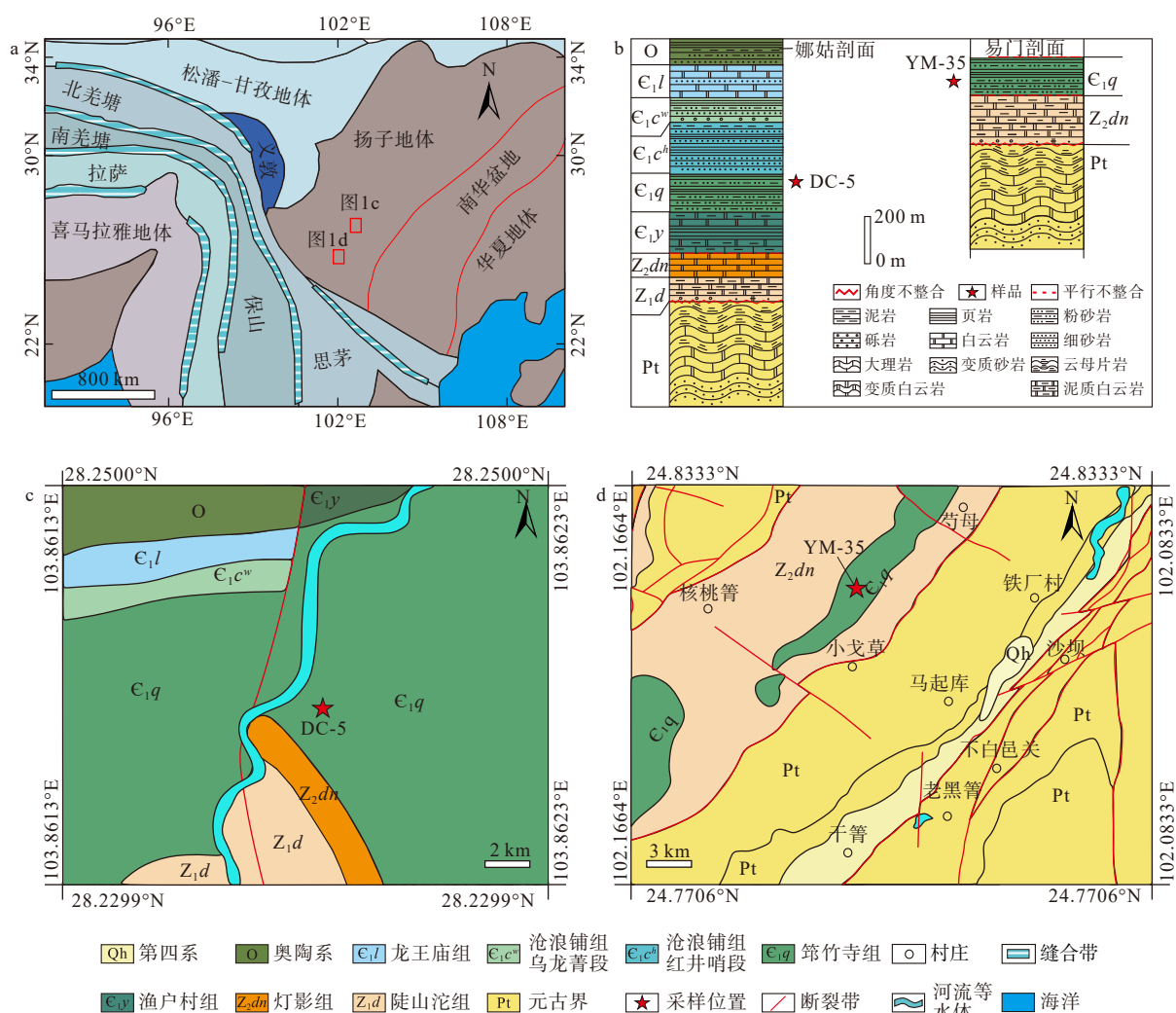
1 区域地质背景和样品特征

1.1 区域地质背景

华南板块夹持于秦岭—大别—苏鲁造山带、哀牢山—Song Ma 断裂带和龙门山断裂带之间, 主要由扬子地块与华夏地块碰撞拼合而成(图 1a)。学界对二

者碰撞拼合时间仍存在分歧,主要有2种观点:① ca. 820 Ma 的晋宁期拼合 (Zhao et al., 2018); ② ca. 420 Ma 的加里东晚期或更晚时期的最终拼合 (何卫红等, 2014; 张克信等, 2015, 2023; Wang et al., 2023; Lin et al., 2024)。伴随 Rodinia 超大陆的解体, 华南板块内部发育了一系列裂谷盆地 (齐靛等, 2023; 张克信等, 2023)。其中, 扬子地块周缘广泛发育了一系列新元古代 (ca. 880~700 Ma) 岩浆岩, 代表性岩带有: 西北缘的攀西-汉南岩浆弧 (ca. 880~700 Ma)、西缘的哀牢山岩浆带 (ca. 840~730 Ma), 以及南缘的江南造山带岩浆带 (ca. 840~740 Ma; Cai et al., 2014, 2015;

Yao et al., 2019; 张克信等, 2023)。在沉积建造方面, 扬子地块由新元古代早期裂谷盆地的火山岩组合及沉积充填序列和埃迪卡拉纪-古生代早期陆源碎屑-碳酸盐岩台地相沉积序列组成, 主要发育南华纪早期碎屑岩夹火山岩建造、南华纪晚期冰碛岩建造、震旦纪 (对应国际地层学中的埃迪卡拉纪; ca. 635~541 Ma) 盖帽碳酸盐岩建造, 以及寒武纪-奥陶纪碎屑岩和碳酸盐岩建造。震旦纪之后地层中火山物质含量稀少 (冯增昭等, 2001, 2002; Jiang et al., 2003, 2011; 张克信等, 2023)。扬子地块南缘的南华裂谷盆地主要发育斜坡相和深水沉积体系。



a—华南板块及其邻区构造简图 (据 Liu et al., 2023; 刘兵兵等, 2025 修改); b—东川区娜姑镇和易门县埃迪卡拉纪-奥陶纪地层柱状图 (据熊家铺等, 1980 修改); c—东川区娜姑镇地质简图 (据熊家铺等, 1980 修改); d—易门县地质简图 (据熊家铺等, 1980 修改)

图 1 研究区区域地质和采样简图

Fig. 1 Regional geotectonic framework and simplified geological maps of the study area

(a) geotectonic map of South China and adjacent regions (modified from Liu et al., 2023; Liu et al., 2025); (b) Ediacaran-Ordovician stratigraphic columns in the Nagu and Yimen areas (modified from Xiong et al., 1980); (c) Simplified geological map of the Nagu area, Dongchuan (modified from Xiong et al., 1980); (d) Simplified geological map of the Yimen area (modified from Xiong et al., 1980)

其中,斜坡相带北界大致沿蒙自—贵阳—花垣—张家界—岳阳—九江—常州—线展布,南界则沿广南—文山—凯里—镇远—铜仁—吉首—常德—武宁—岳阳—宣城—无锡—宜兴—线延伸,沉积物以南华纪陆源碎屑岩—火山碎屑岩—冰川砾岩、震旦纪浊积岩—泥质岩—页岩—碳酸盐,以及寒武纪泥灰岩—泥质岩为主。深水相带北界与斜坡南界重合,南界沿南宁—象州—道县—耒阳—萍乡—南昌—万年—杭州—线展布,沉积以南华纪陆源碎屑岩—火山碎屑岩—冰川砾岩和埃迪卡拉纪—早寒武世炭质黏土岩—硅质泥质岩为主(冯增昭等, 2001, 2002; Jiang et al., 2003, 2011; Wang and Li, 2003)。

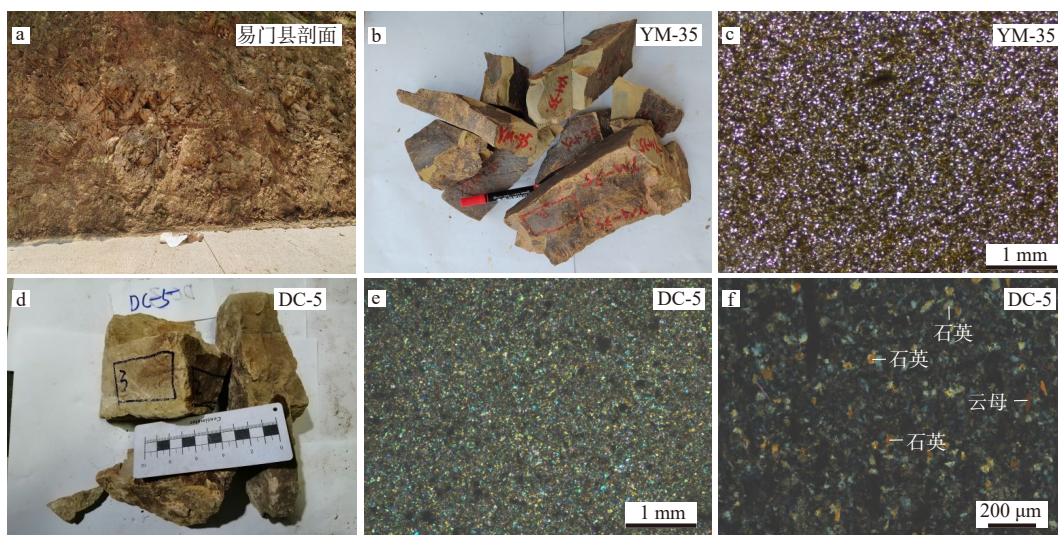
研究区位于扬子西缘的东川区娜姑镇和易门县(图 1a)。娜姑镇主要出露埃迪卡拉系浅海相碳酸盐岩与寒武系滨海相碎屑岩,前者包括陡山沱组和灯影组,后者包括渔户村组、筇竹寺组、沧浪铺组和龙王庙组,各组之间多为整合接触(熊家镛等, 1980; 云南省地质矿产局, 1990; 图 1b)。其中,陡山沱组主要发育白云岩,局部夹泥质岩;灯影组主要为浅灰白色的块状富磷白云岩,局部含硅质条带白云岩和含磷白云岩(熊家镛等, 1980);渔户村组岩性主要包括白云岩、硅质岩、粉砂岩和灰岩等;筇竹寺组下部发育粉—细砂岩与黑色页岩,中上部为

黄绿色页岩;沧浪铺组下段(红井哨段)以细砂岩和泥页岩为主,上段(乌龙箐段)由砾岩、细砂岩和泥页岩组成;龙王庙组主要发育白云岩和白云质灰岩(图 1c; 熊家镛等, 1980)。

易门县基底由中元古界浅变质岩系构成,其上覆有埃迪卡拉系—二叠系陆表海沉积盖层(熊家镛等, 1980)。区内出露地层自下而上依次为:中元古界,岩性以变质砂岩、变质白云岩、大理岩和板岩为主;埃迪卡拉系灯影组,不整合覆盖于中元古地层之上,主要岩性为白云岩;下寒武统筇竹寺组,整合上覆于灯影组,主要发育粉砂质页岩和粉砂岩(图 1d; 徐云飞, 2018; 王雅萍等, 2024)。

1.2 样品特征

研究区样品(DC-5、YM-35)分别采自东川区娜姑镇及易门县的下寒武统筇竹寺组(图 1)。样品 DC-5 为灰黑色粉砂岩(采样点: 26.493371°N, 103.200043°E),重量约 5 kg;岩性为含粉砂黏土,粉砂含量约 15%~20%、黏土含量约 80%~85%,粉砂碎屑以石英和云母为主。样品 YM-35 为黄色粉砂质页岩(采样点: 26.489570°N, 103.205050°E),重量同样约 5 kg;岩性为粉砂质黏土,粉砂含量约 40%~45%、黏土含量约占 55%~60%,粉砂组分亦以石英和云母为主(图 2)。



a—样品 YM-35 野外露头; b—样品 YM-35 手标本; c—样品 YM-35 单偏光镜下照片; d—样品 DC-5 手标本; e—样品 DC-5 单偏光镜下照片; f—样品 DC-5 正交光镜下照片

图 2 样品野外露头、手标本及镜下照片

Fig. 2 Field outcrops, hand specimens and thin-section photomicrographs of representative samples

(a) Field outcrop photograph of sample YM-35; (b) Hand specimen of sample YM-35; (c) Plane-polarized light (PPL) photomicrograph of sample YM-35; (d) Hand specimen of sample DC-5; (e) PPL photomicrograph of sample DC-5; (f) Cross-polarized light (XPL) photomicrograph of sample DC-5

2 分析方法

为厘定扬子西缘埃迪卡拉纪—早寒武世地层的矿物组成、化学组成和碎屑物源,对碎屑岩样品(YM-35和DC-5)开展了岩相学观察、碎屑锆石U-Pb定年分析,另外对样品YM-35开展了全岩主、微量元素测定。具体实验流程详述。

2.1 锆石 U-Pb 同位素定年

碎样、岩石薄片磨制、淘洗、锆石分选及制靶等前处理流程均由河北省廊坊市宇恒岩矿技术有限公司完成。抛光好的锆石靶先进行透射/反射光显微照相,随后送至重庆宇劲科技有限公司完成锆石阴极发光(CL)成像。根据上述显微图像和CL图像,识别锆石内部的裂隙或包裹体,并优选结构完整、无干扰的锆石颗粒及分析点位。

锆石U-Pb同位素定年在东华理工大学核资源与环境国家重点实验室完成,采用激光剥蚀电感耦合等离子体质谱(LA-ICP-MS)技术,仪器由美国Resonetics公司的Resolution S-155激光剥蚀系统与Agilent 7500型ICP-MS联机。分析过程中,采用He作为剥蚀物质的载体。锆石测试参数为:激光能量90 mJ,能量密度4 J/cm²,激光频率6 Hz、He流量600 sccm(Standard Cubic Centimeter per Minute,标准立方厘米每分钟)、补偿气流量0.8 L/min、激光束斑直径44 μm。U-Pb同位素定年采用标准锆石91500、Qinghu、TanZ、Jilin和PL作为年龄校正标样,以BCR-2G、BHVO-2G、BIR-1G和SRM 612作为微量元素校正标样。详细实验流程参考Liu et al.(2010),普通Pb校正方法和流程参考Andersen(2002)。随后的数据处理采用ICP-MS DataCal软件,具体操作流程参考Liu et al.(2010)。锆石U-Pb年龄谐和图和频谱图分别采用Isoplot 3.0(Ludwig, 2003)和Density Plotter(Vermeesch, 2012)程序绘制。

2.2 全岩主、微量元素分析

全岩样品的主量和微量元素分析测试在澳实矿物实验室(广州)完成。主量元素分析流程为:首先将风干后的全岩粉末样品于900℃下加热90 min,以去除碳酸盐和有机质;然后准确称取0.50 g经加热处理后的样品,与4.00 g Li₂B₄O₇混合均匀,于1200℃下熔融制成玻璃熔片,备用分析。主量元素含量采用Rigaku ZSX100e X射线荧光光谱仪(XRF)测定,分析精度优于1%。微量元素分析时,将准确

称量的粉末样品与四硼酸锂混合,于1025℃下熔融,随后加入HF-HCl-HNO₃混合物,于180℃下完全消融。稀释后,采用Agilent7900x电感耦合等离子体质谱(ICP-MS)测定。所有元素的分析准确度和精密密度均优于10%(王三达等, 2023)。

3 分析结果

3.1 锆石年龄组成特征

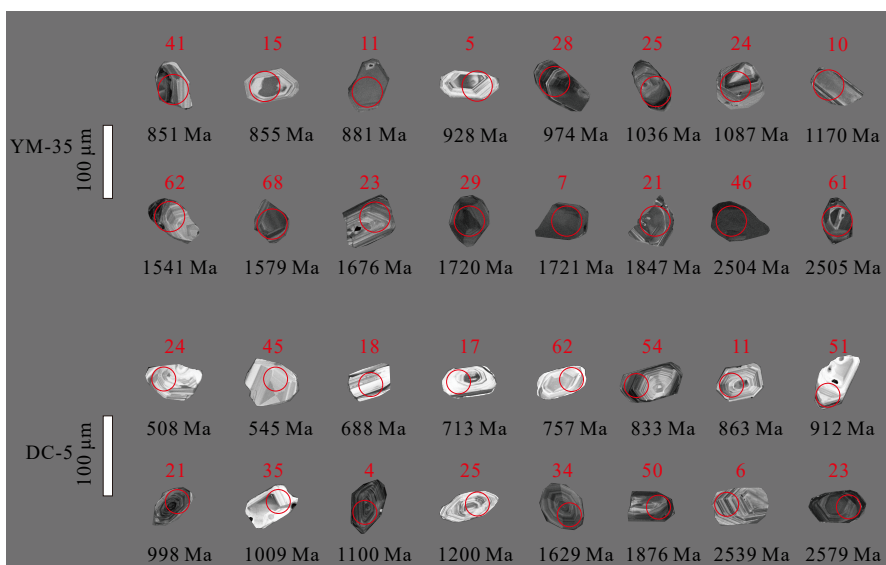
阴极发光(CL)图像显示,大多数锆石颗粒具有典型的韵律振荡环带结构,且Th/U值较高(>0.1;附表1,附表2),表明其为岩浆成因(吴元保和郑永飞, 2004)。少数锆石的CL图像整体较亮、内部成分较为均一,且Th/U值较低(<0.1),指示其为变质成因(吴元保和郑永飞, 2004;图3)。对于年龄小于1000 Ma的锆石,采用²⁰⁶Pb/²³⁸U年龄;对于年龄大于1000 Ma的锆石,则采用²⁰⁷Pb/²⁰⁶Pb年龄(Gehrels et al., 2006)。

样品DC-5共测定了64颗碎屑锆石,获得54个有效U-Pb年龄数据,年龄范围为2877~508 Ma(附表1)。锆石U-Pb年龄谐和图(图4a)与频谱图(图4b)显示,碎屑锆石年龄主要集中于612~508 Ma和868~704 Ma 2个区间,对应的主峰值分别为ca. 570 Ma和ca. 835 Ma;另有1083~912 Ma和2579~2477 Ma 2个次要年龄群,峰值年龄分别为ca. 997 Ma和ca. 2517 Ma。其中,868~508 Ma年龄区间内的锆石共32颗,占有有效数据总数的59%。

样品YM-35共测定了70颗碎屑锆石,获得64个有效U-Pb年龄数据,年龄范围为2618~842 Ma(附表1)。锆石U-Pb年龄谐和图(图4c)与频谱图(图4d)显示,碎屑锆石年龄主要集中于928~842 Ma,峰值为ca. 862 Ma;此外,还存在1868~1502 Ma和2532~2425 Ma 2个次要年龄群,峰值年龄分别为ca. 1686 Ma和ca. 2508 Ma。其中,928~842 Ma年龄区间内的锆石共20颗,占有有效数据总数的27.1%。

3.2 全岩地球化学特征

易门县5件筇竹寺组页岩样品(YM-35)的主、微量元素测试数据见表1。主量元素以氧化物形式给出,其中SiO₂含量为51.97%~54.00%,Al₂O₃为7.12%~7.41%,CaO为9.09%~9.80%,MgO为6.62%~7.10%,K₂O为2.10%~2.17%,Fe₂O₃为4.31%~4.84%;而TiO₂、P₂O₅、MnO含量均低于1%,分别为0.35%~0.36%、0.18%~0.19%和0.21%~0.23%(附表1)。样品的烧失量(LOI)较高,为15.05%~15.99%。



红圈代表 U-Pb 分析测点位置, 红色数字为测点编号; 锆石下方数字为对应测点 U-Pb 年龄; 束斑直径 44 μm

图3 东川区娜姑镇和易门县下寒武统碎屑岩代表性锆石 CL 图像

Fig. 3 Representative cathodoluminescence (CL) images of detrital zircons from the Lower Cambrian clastic rocks in Nagu Town, Dongchuan District and Yimen County

Red circles indicate U-Pb analytical spots, red numbers are spot IDs. Values below zircons represent corresponding U-Pb ages; laser beam diameter is 44 μm .

沉积岩中稀土元素含量主要受源区岩石的元素丰度及风化条件控制, 成岩作用及后期改造对其影响较小 (Bhatia, 1986; Taylor and McLennan, 1985)。5 件筇竹寺组页岩样品的微量元素蛛网图显示, 其配分模式与上地壳总体相似, 均富集高场强元素 (Zr) 及大离子亲石元素 (Ba、Pb、Th)。其中, Rb、Ba 呈轻微相对富集, 而 Ni、Sr、Y 等元素相对亏损, 以 Co、Cs、Ta 亏损最为显著 (图 5)。稀土元素总量 (ΣREE) 介于 $71.4 \times 10^{-6} \sim 74.0 \times 10^{-6}$, (La/Yb)_N 值为 4.97~5.51, LREE/HREE 值为 3.97~4.26 (平均 4.10)。球粒陨石标准化配分曲线整体呈右倾, 表现为轻稀土富集、重稀土分布平缓, 轻重稀土分异特征显著 (图 5)。 δEu 值为 0.70~0.90 (平均 0.76), 显示弱负 Eu 异常, Ce 异常不明显。此外, 样品相对亏损 Nb、Ta 等高场强元素, 相对富集 Ba、Sr 等大离子亲石元素和 La、Zr 等高场强元素。

4 讨论

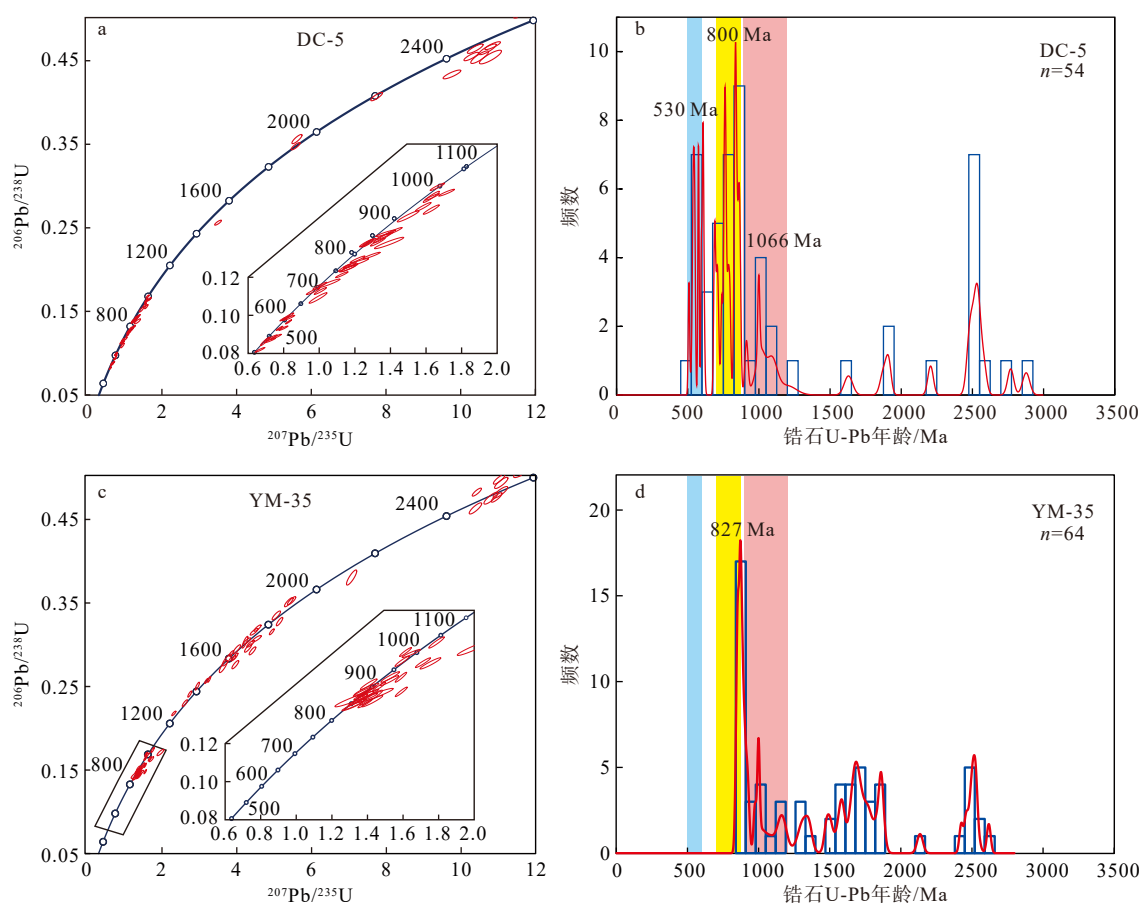
4.1 扬子西缘下寒武统地层碎屑物源分析

扬子西缘埃迪卡拉纪—早寒武世地层的碎屑物源和地球化学特征已有较多研究成果 (Xia et al., 2016; Yang et al., 2020; Gu et al., 2021, 2023; 刘兴源等, 2023; 刘兵兵等, 2025)。在此基础上, 结合碎屑

锆石 U-Pb 年代学和地球化学数据, 可进一步约束筇竹寺组的物源信息。

碎屑沉积岩的微量元素含量及元素组合已被广泛用于源区母岩性质的判别, 尤其是 Th、Sc、Hf、Zr、Ho 等不活泼元素和 La、Ce、Yb 等稀土元素。地球化学数据表明, 筇竹寺组粉砂质页岩物源主要来自大陆上地壳的长英质物质。在 La/Yb- ΣREE 图解中 (图 6a), 样品数据与已有研究成果一致, 均落在沉积岩与花岗岩的交汇区, 指示物源以上地壳陆源沉积物为主。微量元素判别图解进一步支持该结论: 在 Th/Sc-Zr/Sc 图解中 (图 6b), 样品主要落于长英质源区及部分沉积物再旋回的交汇区域; 在 La/Th-Hf 图解中 (图 6c), 样品主要落入酸性岩浆弧源区和长英质与基性混合源区; Co/Th-La/Sc 图解 (图 6d) 显示, 样品物源主要来自长英质、TTG 等中酸性物质。综合上述全岩地球化学数据, 筇竹寺组碎屑岩的原岩沉积物主要由中酸性岩浆岩风化剥蚀而成, 物源总体以长英质岩浆岩为主。

碎屑锆石 U-Pb 年龄频谱可以进一步揭示长英质物质的详细物源。整合已发表的下寒武统碎屑锆石 U-Pb 年龄数据, 共识别出 2 个主要年龄群 (ca. 880~725 Ma 和 ca. 590~500 Ma) 和 2 个次要年龄群 (ca. 2100~1500 Ma 和 ca. 2500~2400 Ma; 图 4), 各年



蓝色曲线为U-Pb谐和曲线; 曲线旁数字表示谐和年龄, Ma; 红色椭圆表示分析数据点及其 2σ 误差范围; 插图为数据点密集区域的局部放大图; n 代表有效锆石测点数量

a—样品 DC-5 U-Pb 年龄谐和图; b—样品 DC-5 锆石 U-Pb 年龄频谱图; c—样品 YM-35 U-Pb 年龄谐和图; d—样品 YM-35 锆石 U-Pb 年龄频谱图

图4 东川区娜姑镇和易门县筇竹寺组碎屑锆石U-Pb年龄谐和图和频谱图

Fig. 4 Detrital zircon U-Pb concordia diagrams and age probability density spectra for the Qiongzhusi Formation in Nagu Town, Dongchuan District and Yimen County

(a) Zircon U-Pb concordia diagram for sample DC-5; (b) Zircon U-Pb age probability density spectra for sample DC-5; (c) Zircon U-Pb concordia diagram for sample YM-35; (d) Zircon U-Pb age probability density spectra for sample YM-35

The blue curves represents the U-Pb concordia curve, and numbers along the concordia curve indicate concordia ages (Ma). Red ellipses represent analytical data points with 2σ uncertainties. The inset shows an enlarged view of the data-rich portion of the diagram. n represents the number of valid zircon analytical spots.

龄群物源指示意义分述如下。

ca. 590~500 Ma 年龄群: 该期岩浆岩通常与 Gondwana 超大陆聚合过程的泛非期造山作用有关, 主要出露于印度板块东缘的 Kuunga 造山带和印度板块西缘包括伊朗俯冲带在内的 Cadomian 造山带 (图 7; Liu et al., 2020; Chen et al., 2021); 在华南板块内部, 该期岩浆-构造记录零星出露于云开-武夷地区, 并大量分布于龙门山构造带 (Li et al., 2017; Gu et al., 2023; Deng et al., 2025)。然而, 呈北东-南西向展布的南华-德里深水盆地 (北界: 广南-文山-凯里-镇远-铜仁-吉首-常德-武宁-岳阳-

宣城-无锡-宜兴; 南界: 南宁-象州-道县-耒阳-萍乡-南昌-万年-杭州) 主要发育黑色页岩、炭质页岩、硅质页岩等深水相沉积, 阻隔了华南板块的扬子地块与华夏地块以及印度板块东西两侧地体之间的物质交流 (冯增昭等, 2001, 2002; Liu et al., 2023)。据此推断, Kuunga 造山带和云开-武夷地区可能并非扬子地块下寒武统碎屑岩的主要碎屑物源。相比之下, 与原特提斯洋俯冲作用相关的岩浆带 (Cadomian 造山带以及龙门山地区) 更可能是其主要碎屑物源 (Deng et al., 2025)。结合研究区内下寒武统碎屑岩中该期碎屑锆石多呈棱角状-次棱

表 1 易门县筇竹寺组全岩样品主量和微量元素分析结果

Table 1 Whole-rock major and trace element compositions from the Qiongzhusi Formation, Yimen County

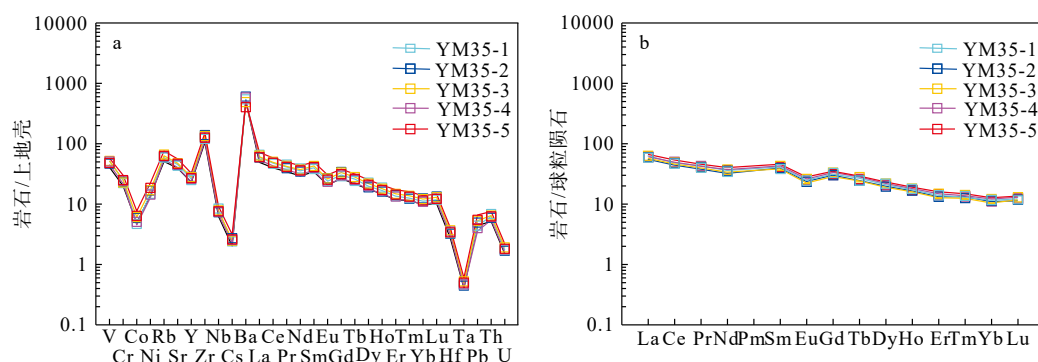
样品编号	Ag	Al	As	Be	Bi	Ca	Cd	Co	Cr	Cs	Cu	Fe	Ga	Ge	In	K	Li
YM-35-1	0.09	3.72	3.7	1.01	0.07	6.73	0.04	5.9	24	2.43	39.3	3.18	8.87	<0.05	0.116	1.72	53.5
YM-35-2	0.08	3.82	3.0	1.03	0.05	6.37	0.74	4.7	25	2.41	84.0	2.98	8.84	<0.05	0.160	1.76	55.5
YM-35-3	0.09	3.81	3.5	1.03	0.08	6.78	0.08	6.1	25	2.54	49.1	3.22	8.92	<0.05	0.126	1.76	53.8
YM-35-4	0.06	3.90	2.8	1.05	0.06	6.56	0.05	5.2	25	2.61	38.7	3.01	9.22	<0.05	0.122	1.80	56.0
YM-35-5	0.09	3.83	4.1	1.05	0.07	6.84	0.04	6.4	25	2.61	39.6	3.32	9.23	<0.05	0.122	1.77	53.3
样品编号	Mg	Mn	Mo	Na	Ni	P	Pb	Rb	Re	S	Sb	Sc	Se	Sn	Ta	Te	Ti
YM-35-1	4.08	1615	6.85	0.04	16.8	890	5.3	61.0	<0.002	0.44	0.60	5.8	1	1.3	0.49	<0.05	0.208
YM-35-2	3.86	1500	4.72	0.05	14.8	880	4.4	58.9	<0.002	0.27	0.49	5.8	<1	1.3	0.47	<0.05	0.214
YM-35-3	4.15	1615	8.98	0.05	17.0	880	5.3	63.2	<0.002	0.49	0.63	6.0	1	1.4	0.49	<0.05	0.214
YM-35-4	4.04	1575	5.75	0.05	14.7	890	4.1	63.4	<0.002	0.19	0.46	6.0	<1	1.4	0.48	<0.05	0.220
YM-35-5	4.14	1635	8.58	0.05	18.6	880	5.5	63.0	<0.002	0.54	0.70	6.0	<1	1.4	0.50	<0.05	0.212
样品编号	Tl	W	Zn	Ba	Ce	Dy	Er	Eu	Gd	Hf	Ho	La	Lu	Nb	Nd	Pr	Sm
YM-35-1	0.33	1.0	38	604	29.4	5.40	2.35	1.45	6.54	3.3	1.00	14.0	0.31	7.5	16.5	3.91	6.29
YM-35-2	0.31	0.9	419	544	29.2	5.02	2.24	1.39	6.22	3.3	0.95	14.2	0.30	7.7	16.6	3.91	6.11
YM-35-3	0.35	1.0	79	490	30.1	5.56	2.45	1.51	6.86	3.6	1.02	14.4	0.33	7.7	17.4	4.00	6.56
YM-35-4	0.31	1.0	39	597	30.2	5.17	2.26	1.39	6.28	3.6	0.97	14.6	0.32	7.7	16.9	4.04	6.28
YM-35-5	0.35	1.0	36	403	29.6	5.31	2.38	1.47	6.46	3.4	0.97	14.2	0.31	7.6	16.9	3.91	6.30
样品编号	Sr	Tb	Th	Tm	U	V	Y	Yb	Zr	Al ₂ O ₃	As ₂ O ₃	BaO	CaO	Cl	CoO	Cr ₂ O ₃	CuO
YM-35-1	47.5	0.97	6.22	0.35	1.81	49	27.6	2.02	127	7.12	<0.01	0.07	9.66	0.01	<0.01	<0.01	<0.01
YM-35-2	45.3	0.97	6.25	0.32	1.74	52	26.2	1.90	123	7.39	<0.01	0.06	9.09	0.01	<0.01	<0.01	<0.01
YM-35-3	47.5	1.05	6.47	0.35	1.92	52	28.0	2.06	134	7.33	<0.01	0.05	9.80	0.01	<0.01	<0.01	<0.01
YM-35-4	46.3	0.97	6.29	0.34	1.82	52	26.9	1.90	130	7.39	<0.01	0.07	9.20	0.01	<0.01	<0.01	<0.01
YM-35-5	46.6	0.98	6.27	0.34	1.82	48	27.0	1.95	126	7.41	<0.01	0.05	9.75	0.01	<0.01	<0.01	<0.01
样品编号	TFe ₂ O ₃	K ₂ O	MgO	MnO	Na ₂ O	NiO	P ₂ O ₅	PbO	SiO ₂	SnO ₂	SO ₃	SrO	TiO ₂	V ₂ O ₅	ZnO	ZrO ₂	LOI ₁₀₀₀
YM-35-1	4.67	2.10	6.97	0.22	0.05	<0.01	0.18	<0.01	52.54	<0.01	1.04	<0.01	0.35	<0.01	<0.01	0.01	15.72
YM-35-2	4.38	2.17	6.62	0.21	0.05	<0.01	0.19	<0.01	54.00	<0.01	0.64	<0.01	0.35	<0.01	0.04	0.01	15.05
YM-35-3	4.74	2.13	7.08	0.23	0.05	<0.01	0.18	<0.01	51.97	<0.01	1.15	<0.01	0.35	<0.01	<0.01	0.01	15.99
YM-35-4	4.31	2.16	6.75	0.21	0.04	<0.01	0.19	<0.01	53.68	<0.01	0.44	<0.01	0.36	<0.01	<0.01	0.01	15.55
YM-35-5	4.84	2.16	7.10	0.23	0.05	<0.01	0.19	<0.01	51.80	<0.01	1.28	<0.01	0.35	<0.01	<0.01	0.01	15.87

角状(图 3), 指示近源搬运特征, 进一步支持上述碎屑物质可能来自扬子西缘北侧的龙门山构造带或 Cadomian 造山带。

ca. 880~725 Ma 年龄群: 扬子地块广泛发育该期长英质岩浆岩, 主要包括攀西-汉南岩浆弧(ca. 725~888 Ma; Zhao et al., 2017, 2021)、西南缘哀牢山构造带(ca. 834~731 Ma; Cai et al., 2014, 2015)及东南缘江南造山带(ca. 840~742 Ma; Yao et al., 2019)。该时期碎屑锆石形态呈棱角一次棱角状, 指示近源搬运(图 3)。但沉积相分析表明, 江南造山带在该时期处于江南盆地深水区, 而攀西-汉南岩浆弧和哀牢山构造带则属于隆起区或者台地区, 因此后者更可能为扬子西缘提供该期碎屑锆石。

ca. 1860~1730 Ma 与 ca. 2500~2400 Ma 年龄群: ca. 1860~1730 Ma 岩浆岩记录在扬子西缘昆阳群火山岩中已被大量报道(Wang et al., 2012); ca. 2500~2400 Ma 岩浆岩则见于扬子地块崆岭地区(3.5~2.5 Ga)及越南西北部的西潘(Phan Si Pan)地区(2.6~2.1 Ga; Zhao et al., 2019)。这 2 期碎屑锆石普遍呈次圆—圆状(图 3), 表明其具有再循环成因, 可能源自扬子地块前寒武纪老地层的再循环。

综上, 扬子西缘下寒武统碎屑物质以近源沉积为主, 物源主要来自扬子西北缘的龙门山泛非期岩浆岩、新元古代攀西-汉南岩浆弧、扬子西缘哀牢山构造岩浆弧等长英质岩浆岩以及部分基性岩的风化剥蚀产物, 经搬运后沉积于扬子西缘各地区。

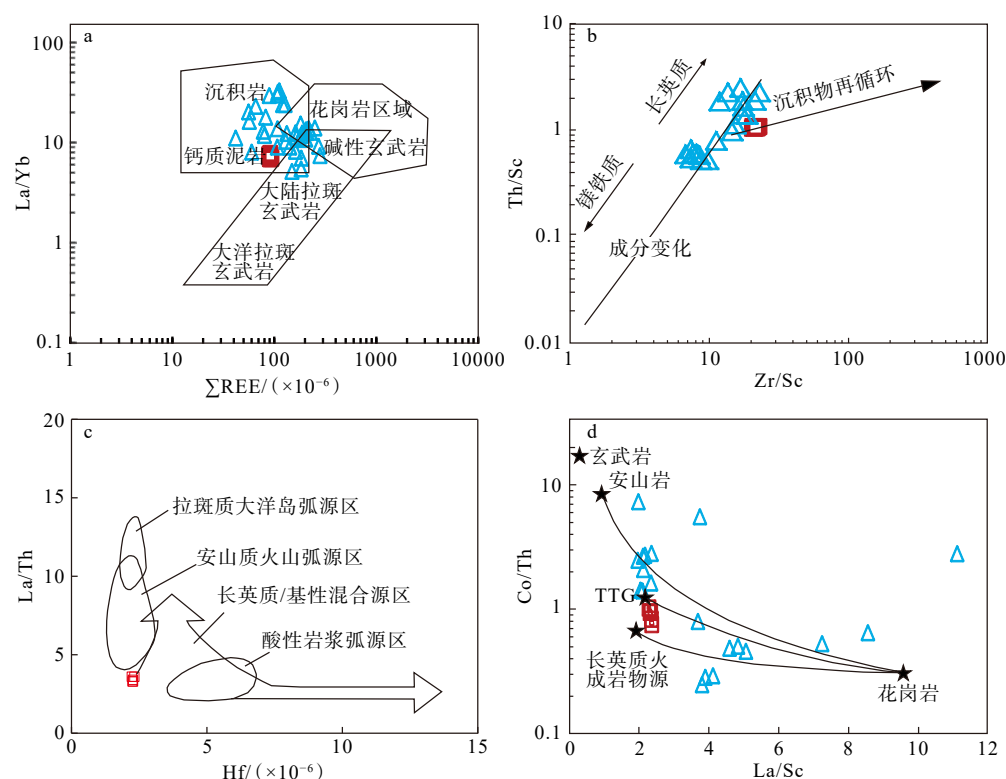


a—微量元素上地壳标准化蛛网图；b—稀土元素球粒陨石标准化配分模式图

图5 易门县筇竹寺组页岩微量元素上地壳标准化蛛网图和稀土元素球粒陨石标准化配分模式图（球粒陨石数据引自 McDonough and Sun, 1995；上地壳数据引自 Rudnick and Gao, 2014）

Fig. 5 Upper continental crust (UCC)-normalized trace element spider diagrams and chondrite-normalized rare earth element (REE) distribution patterns of shales from the Qiongzhusi Formation, Yimen County (Chondrite normalizing values are from McDonough and Sun, 1995; upper continental crust normalizing values are from Rudnick and Gao, 2014)

(a) UCC-normalized trace element spider diagram; (b) Chondrite-normalized REE pattern



红色方框代表文中数据，蓝色三角代表已发表数据（陈思达等, 2023；杨永祯等, 2024；刘慧萍等, 2025）

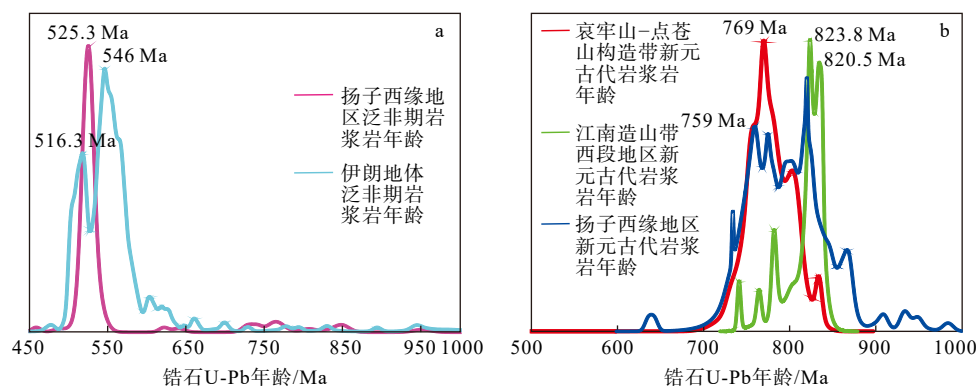
a—La/Yb vs. REE (底图引自 Taylor and McLennan, 1985)；b—Th/Sc vs. Zr/Sc (底图引自 McLennan et al., 1993)；c—La/Th vs. Hf (底图引自 Floyd and Leveridge, 1987)；d—Co/Th vs. La/Sc (底图引自 Wronkiewicz and Condie, 1987)

图6 扬子西缘下寒武统碎屑沉积岩物源性质判别图解

Fig. 6 Geochemical provenance discriminant diagrams for Lower Cambrian clastic sedimentary rocks on the western margin of the Yangtze Block

(a) La/Yb vs. REE (basemap from McLennan et al., 1993); (b) Th/Sc vs. Zr/Sc (basemap from McLennan et al., 1993); (c) La/Th vs. Hf (basemap from Floyd and Leveridge, 1987); (d) Co/Th vs. La/Sc (basemap from Wronkiewicz and Condie, 1987)

Red squares denote data from this study; blue triangles denote literature data from Chen et al., 2023; Yang et al., 2024; Liu et al., 2025.



a—泛非期潜在物源岩浆岩年龄频谱; b—新元古代潜在物源岩浆岩年龄频谱

图7 潜在物源区岩浆岩锆石 U-Pb 年龄频谱图 (数据引自宋昊等, 2015; Shafaii Moghadam et al., 2017; Shahzeidi et al., 2017; Moradi et al., 2022; 刘兴源等, 2023; 占沈薇, 2023; 邓藤丽等, 2025; Deng et al., 2025; 李亚博等, 2025)

Fig. 7 Zircon U-Pb age probability density spectra for magmatic rocks from potential provenance areas (Data from Song et al., 2015; Shafaii Moghadam et al., 2017; Shahzeidi et al., 2017; Moradi et al., 2022; Liu et al., 2023; Zhan et al., 2023; Deng et al., 2025; Deng et al., 2025; Li et al., 2025)

(a) Pan-African magmatic rocks; (b) Neoproterozoic magmatic rocks

4.2 扬子西缘埃迪卡拉纪—早寒武世构造转换机制

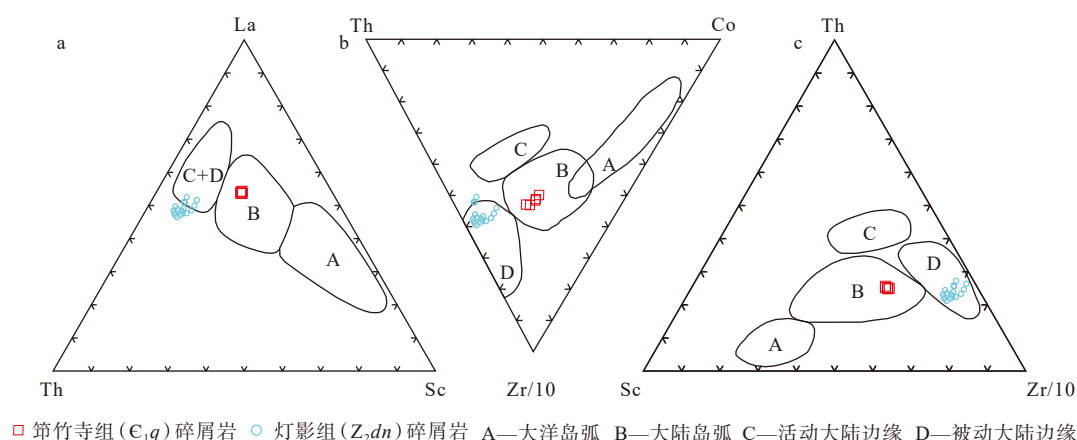
埃迪卡拉纪—寒武纪是扬子西缘由碳酸盐岩沉积相向碎屑岩沉积相转变的关键时期(冯增昭, 2001, 2002; Jiang et al., 2003, 2011), 但驱动这一沉积相转变的深部构造动力学机制尚不明确。文章在现有研究成果的基础上, 从沉积相、碎屑锆石 U-Pb 年代学和全岩地球化学角度, 对上述问题进行了探讨。

埃迪卡拉纪时期, 扬子西缘发育以碳酸盐岩为主的巨厚沉积序列, 厚度约 800~1500 m, 包括陡山沱组和灯影组(图 1b)。碳酸盐岩层系中夹有薄层粉砂岩和页岩, 其地球化学特征显示轻稀土元素(LREE)富集、重稀土元素(HREE)配分模式平坦及明显的 Eu 负异常, 具有典型的被动大陆边缘地球化学特征(McLennan, 1989; Gu et al., 2023), 与后太古宙澳大利亚页岩(PAAS)具有高度相似性。在 Th-Co-Zr/10 构造判别图解中, 样品均落入被动大陆边缘区域(图 8; Gu et al., 2023), 表明扬子西缘当时可能处于被动大陆边缘环境。此外, 埃迪卡拉纪碎屑岩中碎屑锆石 U-Pb 年龄谱系显示 880~720 Ma 的单峰分布特征(图 9)。结合巨厚的碳酸盐岩沉积序列, 共同表明扬子西缘在埃迪卡拉纪早—中期处于相对稳定的构造环境, 缺乏显著的埃迪卡拉纪岩浆活动, 具有典型的被动大陆边缘构造属性。

埃迪卡拉纪末期—早寒武世, 扬子西缘经历了被动大陆边缘向活动大陆边缘的构造体制转换, 主

要体现在以下 3 个方面。①以碳酸盐岩为主的埃迪卡拉纪沉积序列(如陡山沱组、灯影组)被早寒武世以陆源碎屑岩为主的沉积体系替代(图 1b), 可能反映了区域构造背景的调整。②早寒武世碎屑锆石 U-Pb 年龄谱显示 2 个主要峰值(ca. 520 Ma 和 ca. 800 Ma; 图 9), 表明扬子西缘下寒武统除了接受来自攀西—汉南岩浆弧和哀牢山构造带持续输入的新元古代(ca. 800 Ma)碎屑物质外, 还接受了大量的泛非期(ca. 530 Ma)的碎屑物质, 且后者的沉积年龄接近其地层沉积年龄, 符合汇聚大陆边缘环境碎屑锆石 U-Pb 年龄分布特征(图 9; Cawood et al., 2012)。此外, 文中样品及已有的早寒武世地层中的泛非期(590~500 Ma)碎屑锆石具有较低的 Nb/Hf 值和较高的 U/Yb 值(图 10, 附表 2), 指示其源区母岩可能与弧岩浆作用有关。③尽管碎屑岩样品的烧失量(LOI)较高, 但 La、Ce、Nd、Th、Zr、Hf、Nb、Ti 等不活泼微量元素(在水体中滞留时间短、稳定性强)仍可有效指示物源构造环境。在 La-Th-Sc 和 Th-Sc-Zr/10 构造判别图解中(Bhatia, 1983), 5 件碎屑岩样品的数值均落在活动大陆边缘的范围内(图 8)。上述证据都表明, 扬子西缘早寒武世地层的碎屑物源与泛非期弧岩浆作用具有强烈相关性(张帅等, 2025)。

古水流资料表明扬子西缘早寒武世的碎屑物质可能主要来自北侧地区, 比如龙门山一带(张英利等, 2018; 张冬孟等, 2023; Deng et al., 2025)。近



红色方框代表文中数据, 绿色圆圈数据来自 Gu et al., 2023; 底图引自 Bhatia, 1983

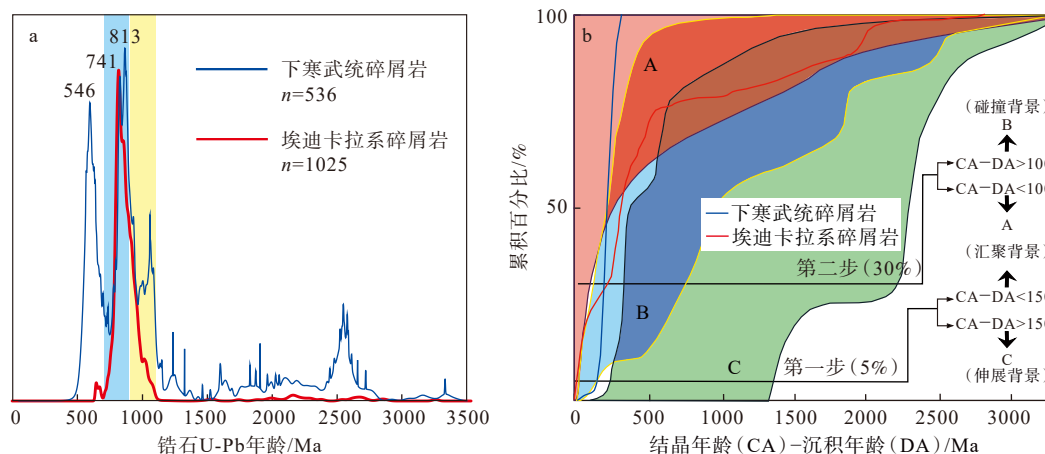
a—La—Th—Sc; b—Th—Co—Zr/10; c—Th—Sc—Zr/10

图 8 扬子西缘埃迪卡拉系—下寒武统碎屑沉积岩物源区构造背景微量元素判别图解

Fig. 8 Trace element tectonic setting discrimination diagrams for Ediacaran–Lower Cambrian clastic sedimentary rocks on the western margin of the Yangtze Block

(a) La–Th–Sc; (b) Th–Co–Zr/10; (c) Th–Sc–Zr/10

Red squares denote data from this study; green circles denote literature data from Gu et al., 2023; base maps are from Bhatia, 1983.



n 代表有效锆石测点数量

a—碎屑锆石 U–Pb 年龄频谱图; b—碎屑锆石结晶年龄 (CA)–沉积年龄 (DA) 的累积分布曲线图

图 9 扬子西缘埃迪卡拉系—下寒武统碎屑锆石 U–Pb 年龄频谱图和累积分布曲线图 (数据来源: Wang et al., 2012; Chen et al., 2016; Tian et al., 2020; Gu et al., 2023; 刘兴源等, 2023; 底图引自 Cawood et al., 2012)

Fig. 9 Detrital zircon U–Pb age probability density spectra and cumulative distribution plot for the Ediacaran–Lower Cambrian on the western margin of the Yangtze Block (Data from Wang et al., 2012; Chen et al., 2016; Tian et al., 2020; Gu et al., 2023; Liu et al., 2023; modified from Cawood et al., 2012)

(a) Detrital zircon U–Pb age probability density spectrum; (b) Cumulative probability distribution curves of detrital zircon crystallization age (CA) minus depositional age (DA)

n represents the number of valid zircon analytical spots.

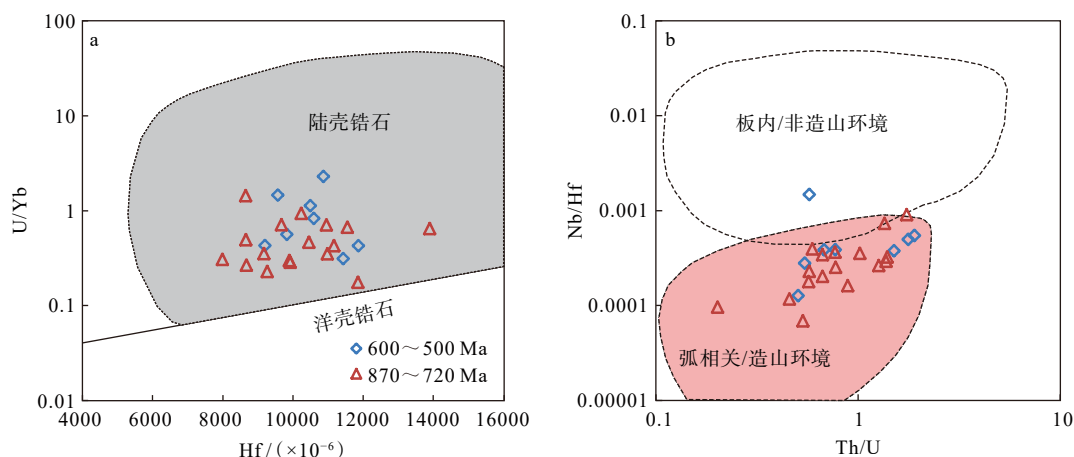
期, Gu et al. (2021, 2023) 在龙门山地区识别出数百米厚的早寒武世火山岩及火山碎屑沉积序列 (ca. 526 Ma) 和辉长岩 (ca. 528 Ma; Deng et al., 2025), 其地球化学组成富集轻稀土和大离子亲石元素、亏损

Nb、Ta 和 Ti 等元素, 符合弧岩浆特征, 表明龙门山地区早寒武世早期的岩浆作用形成于原特提斯洋的俯冲过程。

综上, 扬子西缘在埃迪卡拉纪末期—早寒武世

期间经历了从被动大陆边缘向活动大陆边缘的构造体制转换, 并可能发育了1条与原特提斯洋俯冲

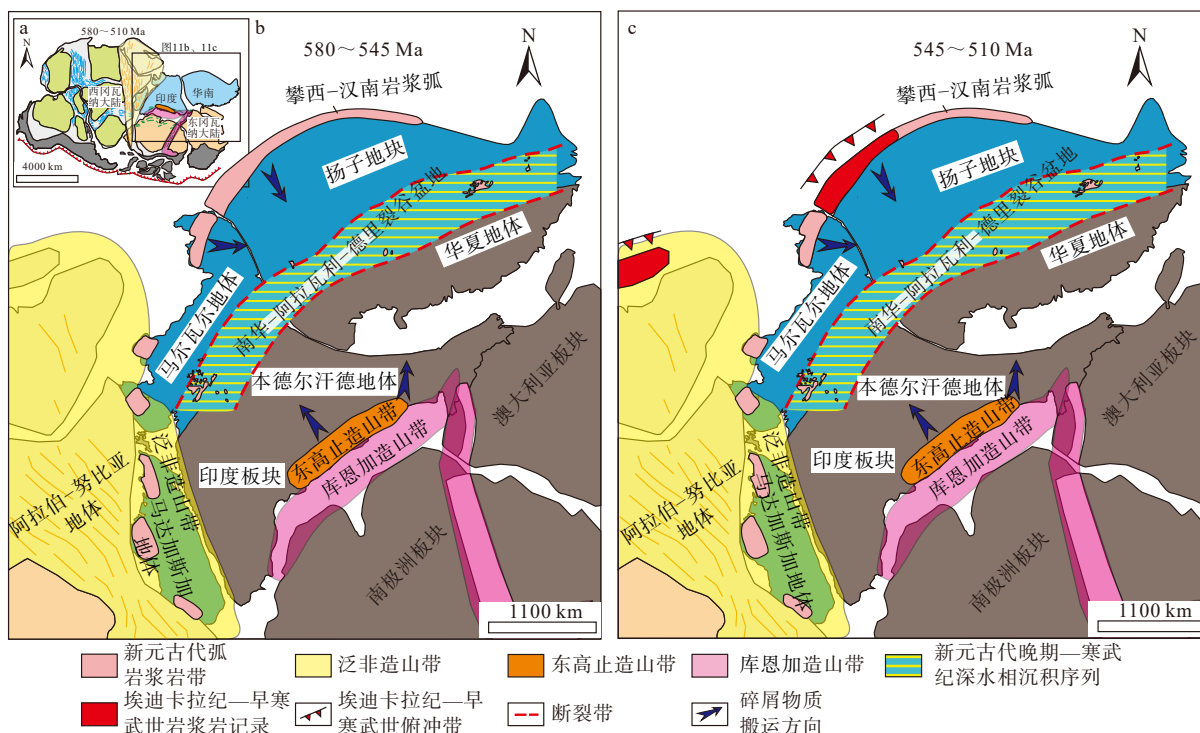
相关的岩浆弧, 持续为扬子西缘寒武纪碎屑岩提供大量碎屑物质(图11)。



a—锆石 Hf-U/Yb 结晶环境判别图解(底图引自 Grimes et al., 2007); b—锆石 Th/U-Nb/Hf 构造环境判别图解(底图引自 Yang et al., 2012)

图10 筇竹寺竹寺组样品碎屑锆石微量元素结晶与构造判别图解

Fig. 10 Trace element tectonic discriminant diagrams of crystallization and tectonic setting for detrital zircons from the Qiongzhusi Formation (a) Zircon Hf vs. U/Yb crystallization environment discrimination diagram (base map after Grimes et al., 2007); (b) Zircon Th/U vs. Nb/Hf tectonic setting discrimination diagram (base map after Yang et al., 2012)



a—冈瓦纳大陆埃迪卡拉纪—早寒武世构造格局图(据 Zhao et al., 2018 修改); b—华南—印度联合地体埃迪卡拉纪—中期构造格局图(据刘兴源等, 2023 修改); c—华南—印度联合地体埃迪卡拉末—早寒武世构造格局图(据刘兴源等, 2023 修改)

图11 华南—印度联合地体埃迪卡拉纪—早寒武世构造格局演化图

Fig. 11 Tectonic evolution of the South China-India terrane during the Ediacaran-Early Cambrian

(a) Tectonic framework of Gondwana during the Ediacaran-Early Cambrian (modified after Zhao et al., 2018); (b) Tectonic framework of the united South China-India terrane during the early-middle Ediacaran (modified after Liu et al., 2023); (c) Tectonic framework of the united South China-India terrane during the latest Ediacaran-Early Cambrian (modified after Liu et al., 2023)

5 结论

(1) 扬子西缘筇竹寺组粉砂质页岩富含 Th、Sc、Hf、Zr、Ho 等不活泼元素和 La、Ce、Yb 等稀土元素, 地球化学数据指示其物源主要来自长英质岩浆岩的风化剥蚀。碎屑锆石 U-Pb 年龄数据显示出 ca. 590~500 Ma 和 ca. 880~720 Ma 2 个主要年龄群, 以及 ca. 1900~1500 Ma 和 ca. 2500~2400 Ma 2 个次要年龄群。其早寒武世碎屑物质以近源为主, 主要源自扬子西缘龙门山地区的泛非期岩浆岩、新元古代攀西—汉南岩浆弧、哀牢山构造岩浆弧等上地壳长英质岩浆岩, 以及部分基性岩的风化剥蚀产物。

(2) 埃迪卡拉纪—早寒武世, 原特提斯洋板片俯冲于扬子西缘之下, 诱发龙门山地区形成同时期的岩浆弧。该弧岩浆作用不仅驱动沉积盆地由被动陆缘向活动陆缘构造体制转换, 同时也为同期寒武系碎屑岩系提供了大量具泛非期年龄的火山—深成碎屑物质, 导致扬子西缘在埃迪卡拉纪末期—早寒武世期间发生沉积相分异与碎屑物源的显著转变。
附加材料: 附表由作者提供, 数据真实性由作者负责, 在线查看网址: <https://journal.geomech.ac.cn/cn/article/doi/10.12090/j.issn.1006-6616.2025065>

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Author's Contributions: SHI Zhiqiang and ZHANG Hong conceived the study, performed data analysis, designed the research methodology, and drafted the manuscript; SUN Le and PEI Jinyun participated in data analysis, practical application of technical approaches, and figure generation; LI Wei were involved in data analysis, refinement of the research methodology, and manuscript revision. All authors have read and approved the submission and publication of the manuscript.

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References

- ANDERSEN T, 2002. Correction of common lead in U-Pb analyses that do not report ^{204}Pb . *Chemical Geology*, 192(1-2): 59-79.
- BHATIA M R, 1983. Plate tectonics and geochemical composition of sandstones[J]. *The Journal of Geology*, 91(6): 611-627.
- BHATIA M R, CROOK K A W, 1986. Trace element characteristics of graywackes and tectonic setting discrimination of sedimentary basins[J]. *Contributions to Mineralogy and Petrology*, 92(2): 181-193.
- Bureau of Geology and Mineral Resources of Yunnan Province. 1990. *Regional Geology of Yunnan Province*[M]. Beijing: Geological Publishing House.
- CAI Y F, WANG Y J, CAWOOD P A, et al., 2014. Neoproterozoic subduction along the Ailaoshan zone, South China: geochronological and geochemical evidence from amphibolite[J]. *Precambrian Research*, 245: 13-28.
- CAI Y F, WANG Y J, CAWOOD P A, et al., 2015. Neoproterozoic crustal growth of the Southern Yangtze Block: geochemical and zircon U-Pb geochronological and Lu-Hf isotopic evidence of Neoproterozoic diorite from the Ailaoshan zone[J]. *Precambrian Research*, 266: 137-149.
- CAWOOD P A, HAWKESWORTH C J, DHUIME B, 2012. Detrital zircon record and tectonic setting[J]. *Geology*, 40(10): 875-878.
- CHEN Q, SUN M, LONG X P, et al., 2016. U-Pb ages and Hf isotopic record of zircons from the Late Neoproterozoic and Silurian-Devonian sedimentary rocks of the western Yangtze Block: implications for its tectonic evolution and continental affinity[J]. *Gondwana Research*, 31: 184-199.
- CHEN Q, ZHAO G C, SUN M, 2021. Protracted northward drifting of South China during the assembly of Gondwana: constraints from the spatial-temporal provenance comparison of Neoproterozoic-Cambrian strata[J]. *GSA Bulletin*, 133(9-10): 1947-1963.
- CHEN S D, XU Z Q, SONG H, et al., 2023. Geochemical characteristics and sedimentary environment of Qiongzhusi Formation in Daibuzhen, Huize Area, Yunnan Province[J]. *Sichuan Metallurgy*, 45(1): 12-21. (in Chinese with English abstract)
- DENG Q, WANG Z J, LIU H, et al., 2025. Subduction-collision and rapid uplift of the NW Yangtze Block during the Ediacaran-Cambrian transition: new evidence from the shoshonite series[J]. *International Geology Review*, 67(3): 331-351.
- DENG T L, PENG Y W, CHENG W B, et al., 2025. Geochronology, petrogenesis, and tin-tungsten metallogenic potential of the Neoproterozoic highly fractionated granites in the Mosuoying area, western margin of the Yangtze Block[J]. *Journal of Chengdu University of Technology (Science & Technology Edition)*, 52(3): 456-479. (in Chinese with English abstract)
- FENG Z Z, PENG Y M, JIN Z K, et al., 2001. Lithofacies palaeogeography of the Cambrian in South China[J]. *Journal of Palaeogeography*, 3(1): 1-14. (in Chinese with English abstract)
- FENG Z Z, PENG Y M, JIN Z K, et al., 2002. Lithofacies palaeogeography of the Early Cambrian in China[J]. *Journal of Palaeogeography*, 4(1): 1-12. (in Chinese with English abstract)
- FLOYD P A, LEVERIDGE B E, 1987. Tectonic environment of the Devonian

- an Gramscatho basin, south Cornwall: framework mode and geochemical evidence from turbiditic sandstones[J]. *Journal of the Geological Society*, 144(4): 531-542.
- GEHRELS G E, DECELLES P G, OJHA T P, et al., 2006. Geologic and U-Pb geochronologic evidence for Early Paleozoic tectonism in the Dadeldhura thrust sheet, far-west Nepal Himalaya[J]. *Journal of Asian Earth Sciences*, 28(4-6): 385-408.
- GRIMES C B, JOHN B E, KELEMEN P B, et al., 2007. Trace element chemistry of zircons from oceanic crust: a method for distinguishing detrital zircon provenance[J]. *Geology*, 35(7): 643-646.
- GU Z D, LONERGAN L, ZHAI X F, et al., 2021. The formation of the Sichuan Basin, South China, during the Late Ediacaran to Early Cambrian[J]. *Basin Research*, 33(4): 2328-2357.
- GU Z D, JIAN X, WATTS A B, et al., 2023. Formation and evolution of an Early Cambrian foreland basin in the NW Yangtze Block, South China[J]. *Journal of the Geological Society*, 180(3): jgs2022-127.
- HE W H, TANG T T, YUE M L, et al., 2014. Sedimentary and tectonic evolution of Nanhuan-Permian in South China[J]. *Earth Science—Journal of China University of Geosciences*, 39(8): 929-953. (in Chinese with English abstract)
- JIANG G Q, SOHL L E, CHRISTIE-BLICK N, 2003. Neoproterozoic stratigraphic comparison of the Lesser Himalaya (India) and Yangtze block (South China): paleogeographic implications[J]. *Geology*, 31(10): 917-920.
- JIANG G Q, SHI X Y, ZHANG S H, et al., 2011. Stratigraphy and paleogeography of the Ediacaran Doushantuo Formation (ca. 635-551 Ma) in South China[J]. *Gondwana Research*, 19(4): 831-849.
- LI L M, LIN S F, XING G F, et al., 2017. First direct evidence of Pan-African orogeny associated with Gondwana assembly in the Cathaysia block of southern China[J]. *Scientific Reports*, 7(1): 794.
- LI Y B, REN X, SAFONOVA I, et al., 2025. Early Neoproterozoic oceanic subduction along the western Yangtze Block: constraints from the genesis of Tianquan diorites in the western Sichuan[J]. *Journal of Chengdu University of Technology (Science & Technology Edition)*, 52(3): 480-501. (in Chinese with English abstract)
- LIN S F, WANG L J, XIAO W J, et al., 2024. The Early Paleozoic Wuyi-Yunkai orogeny in South China: a collisional orogeny with a major lag in time between onset of collision and peak metamorphism in subducted continental crust[M]//NANCE R D, STRACHAN R A, QUESADA C, et al. *Supercontinents, orogenesis and magmatism*. London: Geological Society, London, Special Publications: 649-641.
- LIU B B, PENG T P, FAN W M, et al., 2020. Tectonic evolution and paleo-position of the Baoshan and Lincang blocks of West Yunnan during the Paleozoic[J]. *Tectonics*, 39(10): e2019TC006028.
- LIU B B, PENG T P, FAN W M, et al., 2023. Correlation between South China and India and development of double rift systems in the South China-India Duo during late Neoproterozoic time[J]. *GSA Bulletin*, 135(1-2): 351-366.
- LIU B B, YAN Q H, SHI Z Q, et al., 2025. Late Neoproterozoic-Middle Cambrian tectonic affinity and paleogeographic position of the South China Block and its geotectonic significance[J]. *Geotectonica et Metallogenia*, 49(4): 975-988. (in Chinese with English abstract)
- LIU H P, RONG J, LIU Z L, et al., 2025. Element geochemical characteristics and geological significance of the Cambrian Qiongzhusi Formation in northern Guangyuan, Sichuan Basin[J]. *Natural Gas Geoscience*, 36(5): 936-952. (in Chinese with English abstract)
- LIU X Y, CAO J, LI S S, et al., 2023. Geochemical characteristics and geological significance of Neoproterozoic Qingmingshan granite in northern Guangxi[J]. *Journal of Guilin University of Technology*, 43(3): 351-363. (in Chinese with English abstract)
- LIU Y S, HU Z C, ZONG K Q, et al., 2010. Reappraisal and refinement of zircon U-Pb isotope and trace element analyses by LA-ICP-MS[J]. *Chinese Science Bulletin*, 55(15): 1535-1546.
- LUDWIG K R, 2003. User's manual for Isoplot 3.00: a geochronological toolkit for Microsoft Excel[M]. Berkeley: Berkeley Geochronology Center.
- MCDONOUGH W F, SUN S S, 1995. The composition of the Earth[J]. *Chemical Geology*, 120(3-4): 223-253.
- MCLENNAN S M, 1989. Rare earth elements in sedimentary rocks: influence of provenance and sedimentary processes. *Rev. Mineral.* 21: 169-200.
- MCLENNAN S M, HEMMING S, MCDANIEL D K, et al., 1993. Geochemical approaches to sedimentation, provenance, and tectonics[M]//JOHNSSON M J, BASU A. *Processes controlling the composition of clastic sediments*. Geological Society of America: 21-40.
- MORADI A, SHABANIAN N, DAVOUDIAN A R, et al., 2022. Zircon U-Pb and geochemistry of the north Shahrekord metamorphosed felsic rocks: implications for the Ediacaran-Cambrian tectonic setting of Iran[J]. *International Journal of Earth Sciences*, 111(7): 2239-2263.
- QI L, XU Y J, DU Y S, et al., 2023. Neoproterozoic sedimentary records in the Cathaysia Block and their implications for the supercontinent reconstruction[J]. *Sedimentary Geology and Tethyan Geology*, 43(1): 188-211. (in Chinese with English abstract)
- RUDNICK R L, GAO S, 2014. Composition of the continental crust[M]//HOLLAND H D, TUREKIAN K K. *Treatise on geochemistry*. Oxford: Elsevier: 1-51.
- SHAFARI MOGHADAM H, GRIFFIN W L, LI X H, et al., 2017. Crustal evolution of NW Iran: Cadomian arcs, Archean fragments and the Cenozoic magmatic flare-up[J]. *Journal of Petrology*, 58(11): 2143-2190.
- SHAHZEIDI M, MOAYYED M, MURATA M, et al., 2017. Late Ediacaran crustal thickening in Iran: geochemical and isotopic constraints from the ~550 Ma Mishu granitoids (northwest Iran)[J]. *International Geology Review*, 59(7): 793-811.
- SONG H, XU Z Q, NI S J, et al., 2015. Response of the Motianling granitic pluton in North Guangxi to the tectonic evolution in the southwestern section of the Jiangnan Orogenic Belt: constraints from neoproterozoic zircon geochronology[J]. *Geotectonica et Metallogenia*, 39(6): 1156-1175. (in Chinese with English abstract)
- TAYLOR S R, MCLENNAN S M, 1985. The continental crust: its composition and evolution[M]. Oxford: Blackwell Scientific Publications.
- TIAN Z D, LENG C B, and ZHANG, X C, 2020. Provenance and tectonic setting of the Neoproterozoic metasedimentary rocks at southeastern

- Tibetan Plateau: Implications for the tectonic affinity of Yidun terrane: Precambrian Research, 344: 1–19.
- VERMEESCH P, 2012. On the visualisation of detrital age distributions[J]. Chemical Geology, 312-313: 190-194.
- WANG J, LI Z X, 2003. History of Neoproterozoic rift basins in South China: implications for Rodinia break-up[J]. Precambrian Research, 122(1-4): 141-158.
- WANG L J, YU J H, GRIFFIN W L, et al., 2012. Early crustal evolution in the western Yangtze Block: evidence from U-Pb and Lu-Hf isotopes on detrital zircons from sedimentary rocks[J]. Precambrian Research, 222-223: 368-385.
- WANG L J, LIN S F, XIAO W J, 2023. Yangtze and Cathaysia blocks of South China: their separate positions in Gondwana until early Paleozoic juxtaposition[J]. Geology, 51(8): 723-727.
- WANG S D, DUAN X X, CAI X B, et al., 2023. Enrichment and fractionation of REY in the weathering crust of metamorphic rocks in the Shiguan Area of the Dabie Orogenic Belt[J]. Geology and Exploration, 59(4): 828-851. (in Chinese with English abstract)
- WANG Y P, BAO Z D, ZHANG L J, et al., 2024. Diagenesis of microbial dolomite reservoirs in the second Member of Dengying Formation of Ediacaran in the Penglai area, Sichuan Basin: Insights into the formation and evolution of high-quality reservoirs[J]. Journal of Geomechanics, 30(4): 579-594. (in Chinese with English abstract)
- WRONKIEWICZ D J, CONDIE K C, 1987. Geochemistry of Archean shales from the Witwatersrand Supergroup, South Africa: source-area weathering and provenance[J]. Geochimica et Cosmochimica Acta, 51(9): 2401-2416.
- WU Y B, ZHENG Y F, 2004. Genesis of zircon and its constraints on interpretation of U-Pb age[J]. Chinese Science Bulletin, 49(15): 1554-1569.
- XIA X P, NIE X S, LAI C K, et al., 2016. Where was the Ailaoshan Ocean and when did it open: a perspective based on detrital zircon U-Pb age and Hf isotope evidence[J]. Gondwana Research, 36: 488-502.
- XIONG J Y, ZHANG Z B, LIU S R, 1980. The eighth team of Regional Geological Investigation Team, Geological Bureau of Yunnan Province. Regional Geological Survey Report of the People's Republic of China 1: 200000 Dongchuan G-48-XIV[R]. Yuxi: Geological Bureau of Yunnan Province (In Chinese).
- XU Y F, 2018. The Definition of the Paleoproterozoic Stratum and the prospecting significance in the Yimen area, central Yunnan Province[D]. Kunming: Kunming University of Science and Technology. (in Chinese with English abstract)
- YANG C, LI X H, LI Z X, et al., 2020. Provenance evolution of age-calibrated strata reveals when and how South China Block collided with Gondwana[J]. Geophysical Research Letters, 47(19): e2020GL090282.
- YANG J H, CAWOOD P A, DU Y S, et al., 2012. Large igneous province and magmatic arc sourced Permian-Triassic volcanogenic sediments in China[J]. Sedimentary Geology, 261-262: 120-131.
- YANG Y Z, GUO L, FANG Z X, et al., 2024. Weathering characteristics of sedimentary source area of Qiongzhusi Formation, eastern margin of Ancient Kangding-Yunnan Land: case study of the Wulongcun section of Wuding district, Chuxiong City, Yunnan province, China[J]. Acta Sedimentologica Sinica, 42(1): 324-341. (in Chinese with English abstract)
- YAO J L, CAWOOD P A, SHU L S, et al., 2019. Jiangnan Orogen, South China: a~970-820 Ma Rodinia margin accretionary belt[J]. Earth-Science Reviews, 196: 102872.
- ZHAN S W, 2023. Geochemical characteristics and geological significance of Lugu granite in the western margin of the Yangtze Block[D]. Chengdu: Chengdu University of Technology. (in Chinese with English abstract)
- ZHANG D M, CHENG X, WEI B T, et al., 2023. Magnetic fabric study of the Cambrian Stage 3 sedimentary rocks in Eastern Yunnan and its implications for paleocurrent direction[J]. Journal of Northwest University (Natural Science Edition), 53(4): 655-670. (in Chinese with English abstract)
- ZHANG K X, PAN G T, HE W H, et al., 2015. New division of tectonic-strata superregion in China[J]. Earth Science—Journal of China University of Geosciences, 40(2): 206-233. (in Chinese with English abstract)
- ZHANG K X, HE W H, XU Y D, et al., 2023. The division of Qingbaikouan-Triassic tectono-stratigraphic regions and their characteristics in South China[J]. South China Geology, 39(1): 1-23. (in Chinese with English abstract)
- ZHANG S, LUO B, WANG Z C, et al., 2025. Genesis of the Deyang-Anyue intracratonic rift in the Sichuan Basin and its connection with the Proto-Tethys Ocean[J]. Natural Gas Industry, 45(2): 37-50. (in Chinese with English abstract)
- ZHANG Y L, JIA X T, WANG Z Q, et al., 2018. New insights into provenance of Early Cambrian Xiannüdong Formation in the Micangshan Area: evidence from sedimentology, heavy mineral and detrital zircon chronology[J]. Acta Geologica Sinica, 92(9): 1918-1935. (in Chinese with English abstract)
- ZHAO G C, WANG Y J, HUANG B C, et al., 2018. Geological reconstructions of the East Asian blocks: from the breakup of Rodinia to the assembly of Pangea[J]. Earth-Science Reviews, 186: 262-286.
- ZHAO G C, HAN Y G, LI J H, et al., 2022. Environmental effects of assembly and breakup of supercontinents[J]. Acta Geologica Sinica, 96(9): 3120-3127. (in Chinese with English abstract)
- ZHAO J H, ASIMOW P D, ZHOU M F, et al., 2017. An Andean-type arc system in Rodinia constrained by the Neoproterozoic Shimian ophiolite in South China[J]. Precambrian Research, 296: 93-111.
- ZHAO J H, NEBEL O, JOHNSON T E, 2021. Formation and evolution of a Neoproterozoic continental magmatic arc[J]. Journal of Petrology, 62(8): egab029.
- ZHAO T Y, CAWOOD P A, ZI J W, et al., 2019. Early Paleoproterozoic magmatism in the Yangtze Block: evidence from zircon U-Pb ages, Sr-Nd-Hf isotopes and geochemistry of ca. 2.3 Ga and 2.1 Ga granitic rocks in the Phan Si Pan Complex, north Vietnam[J]. Precambrian Research, 324: 253-268.
- ZHOU M Z, LUO T Y, HUANG Z L, et al., 2011. Early Cambrian volcanic records in Guizhou Province, China and their geological significances[J]. Acta Mineralogica Sinica, 31(3): 453-461. (in Chinese with English abstract)
- ZHOU M Z, LUO T Y, HUFF W D, et al., 2018. Timing the termination of the Doushantuo negative carbon isotope excursion: evidence from U-Pb

ages from the Dengying and Liuchapo formations, South China[J]. Science Bulletin, 63(21): 1431-1438.

附中文参考文献

- 陈思达, 徐争启, 宋昊, 等, 2023. 云南省会泽地区待补镇筇竹寺组岩石地球化学特征及沉积环境分析[J]. 四川冶金, 45(1): 12-21.
- 邓藤丽, 彭义伟, 程文斌, 等, 2025. 扬子西缘摩挲营新元古代高分异花岗岩年龄、成因和锡钨成矿潜力[J]. 成都理工大学学报(自然科学版), 52(3): 456-479.
- 冯增昭, 彭勇民, 金振奎, 等, 2001. 中国南方寒武纪岩相古地理[J]. 古地理学报, 3(1): 1-14.
- 冯增昭, 彭勇民, 金振奎, 等, 2002. 中国早寒武世岩相古地理[J]. 古地理学报, 4(1): 1-12.
- 何卫红, 唐婷婷, 乐明亮, 等, 2014. 华南南华纪-二叠纪沉积大地构造演化[J]. 地球科学—中国地质大学学报, 39(8): 929-953.
- 李亚博, 任祥, SAFONOVA I, 等, 2025. 扬子西缘新元古代早期大洋俯冲作用: 来自川西天全冈长岩成因的制约[J]. 成都理工大学学报(自然科学版), 52(3): 480-501.
- 刘兵兵, 闫庆贺, 史志强, 等, 2025. 华南板块新元古代晚期-中寒武世古地理格局及其大地构造意义[J]. 大地构造与成矿学, 49(4): 975-988.
- 刘慧萍, 戎佳, 刘自亮, 等, 2025. 四川盆地广元北部寒武系筇竹寺组元素地球化学特征及地质意义[J]. 天然气地球科学, 36(5): 936-952.
- 刘兴源, 曹杰, 李赛赛, 等, 2023. 桂北新元古代清明山花岗岩地球化学特征及其地质意义[J]. 桂林理工大学学报, 43(3): 351-363.
- 齐靓, 徐亚军, 杜远生, 等, 2023. 华夏地块新元古代沉积记录与超大陆重建[J]. 沉积与特提斯地质, 43(1): 188-211.
- 宋昊, 徐争启, 倪师军, 等, 2015. 广西摩天岭岩体对江南造山带西南段构造演化的响应: 来自新元古代花岗岩锆石 U-Pb 年代学证据[J]. 大地构造与成矿学, 39(6): 1156-1175.
- 王三达, 段晓侠, 蔡晓兵, 等, 2023. 大别造山带石关地区变质岩风化壳中 REY 富集和分异研究[J]. 地质与勘探, 59(4): 828-851.
- 王雅萍, 鲍志东, 张连进, 等, 2024. 四川盆地蓬莱地区埃迪卡拉系灯影组二段微生物岩储层成岩作用: 对优质储层形成与演化的启示[J]. 地质力学学报, 30(4): 579-594.
- 吴元保, 郑永飞, 2004. 锆石成因矿物学研究及其对 U-Pb 年龄解释的制约[J]. 科学通报, 49(16): 1589-1604.
- 熊家镛, 张志斌, 刘世荣, 等, 1980. 中华人民共和国 1: 20 万区域地质调查报告(东川幅)[R]. 玉溪: 云南省地质局.
- 徐云飞, 2018. 滇中易门地区古元古界的厘定及区域找矿意义[D]. 昆明: 昆明理工大学.
- 杨永祯, 郭岭, 方泽鑫, 等, 2024. 康滇古陆东缘筇竹寺组沉积物源的风化特征: 以云南省楚雄市武定县乌龙村剖面为例[J]. 沉积学报, 42(1): 324-341.
- 云南省地质矿产局, 1990. 云南省区域地质志[M]. 北京: 地质出版社.
- 占沈薇, 2023. 扬子板块西缘泸沽花岗岩的地球化学特征及地质意义[D]. 成都: 成都理工大学.
- 张冬孟, 程鑫, 卫弼天, 等, 2023. 滇东地区寒武系第三阶沉积岩磁组构研究及其对古水流方向的启示[J]. 西北大学学报(自然科学版), 53(4): 655-670.
- 张克信, 潘桂棠, 何卫红, 等, 2015. 中国构造-地层大区划分新方案[J]. 地球科学—中国地质大学学报, 40(2): 206-233.
- 张克信, 何卫红, 徐亚东, 等, 2023. 华南青白口纪-三叠纪构造-地层区划及特征[J]. 华南地质, 39(1): 1-23.
- 张帅, 罗冰, 汪泽成, 等, 2025. 四川盆地德阳-安岳克拉通内裂陷成因及其与原特提斯洋的联系[J]. 天然气工业, 45(2): 37-50.
- 张英利, 贾晓彤, 王宗起, 等, 2018. 米仓山地区早寒武世仙女洞组沉积物源新认识: 沉积学、重矿物和碎屑锆石年代学的证据[J]. 地质学报, 92(9): 1918-1935.
- 赵国春, 韩以贵, 李建华, 等, 2022. 超大陆聚散的环境效应[J]. 地质学报, 96(9): 3120-3127.
- 周明忠, 罗泰义, 黄智龙, 等, 2011. 贵州早寒武世火山活动记录及其地质意义[J]. 矿物学报, 31(3): 453-461.