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晚古生代秦岭造山带构造演化：西秦岭碎屑锆石 U-Pb 年代学的制约与启示

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Late Paleozoic tectonic evolution of the Qinling Orogenic Belt: Constraints and insights from detrital zircon U–Pb geochronology in the Western Qinling

Abstract: ［**Objective**］The Qinling Orogenic Belt, positioned between the Yangtze and North China cratons, has undergone a multi-stage evolution from the Paleozoic to the Early Mesozoic, fully documenting the collisional orogenic history between both cratons. Substantial research achievements have been accumulated in fields such as provenance, lithogeochemistry, magmatic activity, and tectonics. However, key issues regarding the Early Paleozoic tectonic framework and Late Paleozoic ocean basin evolution of the Qinling Orogenic Belt remain controversial, primarily including the

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following aspects: The Shangdan Ocean may have closed during the Early Silurian, Carboniferous, or Indosinian periods; the subduction of the Mianlue Ocean may have initiated in the Early Carboniferous, Late Permian, end of the Late Permian, or later than the Early Triassic. The Zhaishang area in Minxian County, located within the Western Qinling Orogenic Belt, shows extensive Paleozoic strata and serves as a critical window for studying the tectonic evolution history of the Qinling Orogenic Belt. ［**Methods**］ Systematic sampling was conducted on the exposed Devonian, Carboniferous, and Permian strata in this area. The procedures included zircon single-mineral separation, target preparation, polishing, and cathodoluminescence (CL) imaging, followed by zircon U–Pb isotope analysis using LA–ICP–MS (Laser Ablation Inductively Coupled Plasma Mass Spectrometry). Based on these experimental results, detrital zircon U–Pb chronology was performed for the Devonian, Carboniferous, and Permian strata exposed in the Zhaishang area of Minxian County, Western Qinling, to constrain the Paleozoic tectonic evolution history and sedimentary processes of the Qinling Orogenic Belt. ［**Results**］ Results of detrital zircon U-Pb chronology show that the Shuanglanggou Formation of the Xihan Shui Group and the Badu Formation in the Zhaishang area of Minxian County exhibit similar detrital zircon age compositions. Detrital zircons from the Shuanglanggou Formation (Devonian Xihanshui Group) are characterized by the dominant age peak at 794 Ma, belonging to a Neoproterozoic age group (880～746 Ma), and the youngest age peak at 448 Ma. Detrital zircons from the Lower Carboniferous Badu Formation display Neoproterozoic age groups (901～750 Ma), the dominant age peak at 818 Ma, and the youngest age peak at 390 Ma. Detrital zircons from the middle member of the Lower Permian Shilidun Formation exhibit the dominant and likewise youngest age peak at 443 Ma, belonging to an Early Paleozoic age group (464～409 Ma). ［**Conclusion**］ Through comparing the relative probability distribution curves of detrital zircon U–Pb ages of the Devonian, Carboniferous, and Permian strata, as well as the correlation diagrams between detrital zircon age peaks and tectonic settings (including the northern Qinling Orogenic Belt, North China Craton, and Yangtze Craton as comparison targets), it is revealed that: The Devonian Shuanglanggou Formation and the Carboniferous Badu Formation in the Zhaishang area share a consistent detrital provenance, primarily the Yangtze Craton, followed by the northern Qinling Orogenic Belt; both tectonic settings are classified as rift basins. The detrital materials of the middle member of the Permian Shilidun Formation stem predominantly from the northern Qinling Orogenic Belt and correspond to a back-arc basin tectonic setting. By integrating the research results with the relative positions of the Qinling Orogenic Belt, the North China Craton, the Yangtze Craton, the Shangdan Ocean, and the Mianlue Ocean, it is concluded that the Zhaishang area in Minxian County was in a rift basin environment from the Late Devonian to the Early Carboniferous, and transitioned to a back-arc basin in the Early Permian. This transition marks the completion of the Mianlue Ocean's evolution from oceanic expansion to subduction and demise. Additionally, the study constrains that: The Mianlue Ocean opened after the Early Carboniferous; the Shangdan Ocean closed before the Late Devonian. ［**Significance**］ This study provides new evidence and chronological constraints for the tectonic evolution of the Qinling Orogenic Belt, as well as the closure time of the Shangdan Ocean and the initial subduction time of the Mianlue Ocean, helping to reconstruct and restore the tectonic evolution process of the Qinling Orogenic Belt.

Keywords: detrital zircon; LA–ICP–MS U–Pb geochronology; provenance; depositional environment; western Qinling Orogenic Belt

摘　要：秦岭造山带位于扬子与华北克拉通之间，经历了古生代—早中生代多阶段演化过程，完整记录了扬子−华北克拉通的碰撞造山历史。在物源、岩石地球化学、岩浆活动及大地构造等领域已积累大量研究成果，但秦岭造山带早古生代构造格局及晚古生代洋盆演化等关键问题仍存争议，主要有以下观点：商丹洋的闭合时间为早志留世、石炭纪与印支期；勉略洋初始俯冲时间为早石炭世、晚二叠世、晚二叠世末以及晚于早三叠世。岷县寨上地区位于西秦岭造山带，古生代地层广泛发育，是研究秦岭造山带构造演化历史的重要窗口。对该区出露的泥盆系、石炭系和二叠系开展系统采样，依次实施锆石单矿物分选、制靶、抛光及阴极发光（CL）图像拍摄，利用 LA-ICP-MS 进行锆石 U-Pb 年代学分析。通过分析实验结果，对西秦岭岷县寨上地区出露的泥盆系、石炭系和二叠系开展碎屑锆石 LA-ICP-MS U-Pb 年代学研究，以限定秦岭造山带古生代构造演化历史及沉积过程。碎屑锆石 U-Pb 年代学研究结果表明，岷县寨上地区西汉水群双狼沟组和巴都组具有相似的碎屑锆石年龄组成。泥盆系西汉水群双狼沟组碎屑锆石的主要年龄峰值为 794 Ma，最年轻年龄峰值为 448 Ma，以新元古代年龄组（746～880 Ma）为特征。下石炭统巴都组碎屑锆石主要年龄峰值为 818 Ma，最年轻年龄峰值为 390 Ma，以新元古代年龄组（750～901 Ma）为特征。下二叠统十里墩组中段碎屑锆石主要年龄峰值为 443 Ma，最年轻年龄峰值为 443 Ma，以早古生代年龄组（409～464 Ma）为特征。通过对比泥盆系、石炭系、二叠系碎屑锆石 U-Pb 年龄相对概率分布曲

线及碎屑锆石年龄峰与构造背景关系图（对比对象包括北秦岭造山带、华北克拉通和扬子克拉通）发现：寨上地区泥盆系双狼沟组与石炭系巴都组具有一致的碎屑物质来源，其物源主要来自扬子克拉通，其次来自北秦岭造山带，且构造背景均属于裂谷盆地。而二叠系十里墩组中段碎屑物质则主要来源于北秦岭造山带，其构造背景为弧后盆地。结合研究结果以及秦岭造山带、华北克拉通、扬子克拉通、商丹洋和勉略洋的相对位置综合判断可知，岷县寨上地区在晚泥盆世—早石炭世期间处于裂谷盆地环境，至早二叠世转变为弧后盆地，这标志着勉略洋在此期间完成了由大洋扩张到大洋俯冲消亡的转换。此外，还限定勉略洋打开时间晚于早石炭世，商丹洋闭合时间早于晚泥盆世。这为秦岭造山带构造演化过程以及商丹洋的闭合时间和勉略洋初始俯冲时间提供了新的证据和年代学约束，有助于帮助恢复构建秦岭造山带的构造演化过程。

关键词：碎屑锆石；LA-ICP-MS U-Pb 年代学；物质来源；沉积环境；西秦岭造山带

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0　引言

锆石因其高稳定性，能在复杂环境中保存并记录岩浆岩和变质岩的结晶年龄，是年代学研究的重要工具(Andersen, 2005)。碎屑锆石 U-Pb 年代学技术的进步，显著推动了沉积盆地物源分析的发展(Dickinson and Gehrels, 2008a; Cawood et al., 2012; Nie et al., 2012; Gehrels, 2014; Horton et al., 2015; Han et al., 2016; 郭佩等, 2017; Liang et al., 2025)。碎屑锆石 U-Pb 年代学分析通过测定沉积岩中锆石的 U-Pb 年龄分布峰值，结合可能源区岩浆作用时代，可以确定地层碎屑物质来源及最大沉积年龄，为盆地沉积充填和构造−沉积演化研究提供关键约束(Cawood et al., 2003; Andersen, 2005; Moecher and Samson, 2006; Dickinson and Gehrels, 2008b, 2010; Pullen et al., 2014; Han et al., 2016; Sharman and Malkowski, 2020; 董晓朋等, 2023; 宋仁龙等, 2024; Liang et al., 2025)。此外，利用碎屑锆石的 U-Pb 年代学进行物源分析，能够为区域构造演化研究提供重要的约束条件(邬光辉等, 2007; 王杰等, 2013; 李孟芸, 2018; Agnihotri et al., 2018; Kent et al., 2018)。

位于华北克拉通和扬子克拉通之间的秦岭造山带，是具有长期演化历史且重要的复合大陆造山带(张国伟等, 1995, 2019; 董云鹏等, 2003a; Wang et al., 2009; Dong et al., 2022; 俞胜等, 2023; Peng et al., 2024)。在物源、岩石地球化学、岩浆活动及大地构造等领域已积累大量研究成果，但对于晚古生代—早中生代期间商丹洋的闭合和勉略洋初始俯冲的精确时限仍存争议(张宏飞等, 2005; Dong et al., 2011a; 吴树宽, 2013; 董云鹏等, 2019; 王艳鹏, 2019; 张国伟等, 2019; 俞胜等, 2023)，主要有以下观点：①商丹洋的闭合时间存在早志留世(孟庆任, 2017)、石炭纪(Yan et al., 2012; Chen et al., 2014; 赵淑娟等, 2016)和印支期(陈世悦, 2000; 李三忠等, 2017)等观点；②勉略洋初始俯冲时间存在早石炭世(李曙光等, 2003; 张思敏等, 2014)、晚二叠世(赖绍聪等, 2003; 张国伟等, 2004)、晚二叠世末(Dong and Santosh, 2016)和晚于早三叠世(Lai et al., 2008; 杨文涛等, 2014)等观点。西秦岭作为秦岭、祁连山、松潘−甘孜造山带及扬子克拉通的交汇区(王阿特, 2016)，地层年代学研究相对薄弱，这制约了对整个秦岭造山带构造演化的理解(Dong et al., 2011a; 张国伟等, 2019)。岷县寨上地区位于西秦岭北部，晚古生代沉积地层发育，记录了该区岩浆、沉积、构造和盆山耦合信息。研究该区晚古生代地层具有重要价值，有助于恢复秦岭造山带演化、丰富区域地质资料、明确沉积特征和环境、追溯物源以及分析盆地演化。

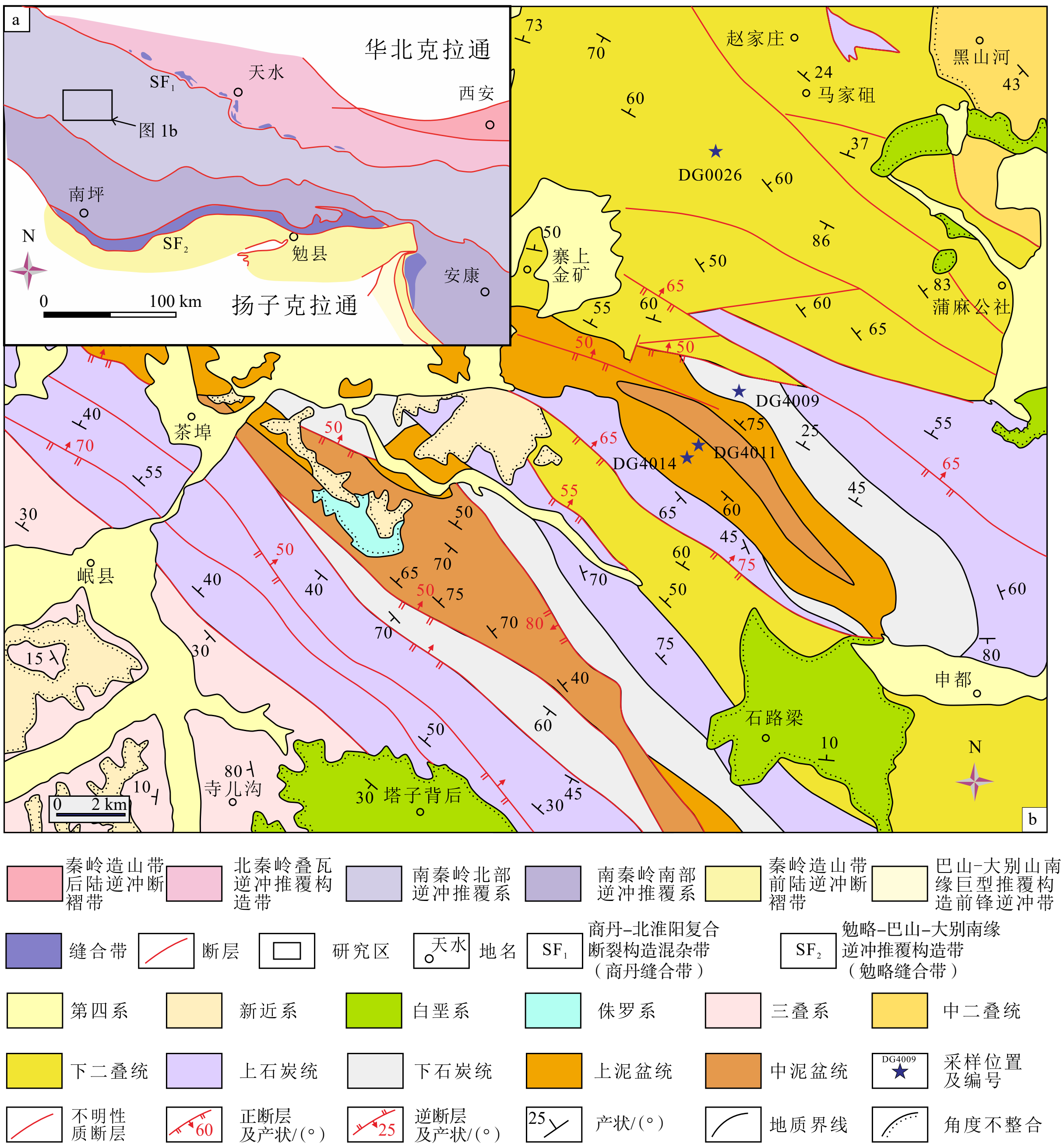
因此，针对西秦岭造山带广泛发育的古生代地层，选取了岷县寨上地区的泥盆系、石炭系和二叠系砂岩进行锆石 U-Pb 同位素测试，旨在约束地层沉积年代并分析其沉积物源，探讨西秦岭造山带的构造演化、相关地层的沉积环境，进而为秦岭造山带晚古生代的构造演化提供证据。

1　区域地质概况

秦岭造山带作为华北克拉通与扬子克拉通之间的重要造山带，经历了多期构造演化阶段：从 Rodinia 超大陆裂解、古大洋形成、板块俯冲−碰撞造山，到板内伸展及陆内叠覆造山(张国伟等, 1996; 董云鹏等, 2003a; 王宗起等, 2009; 王阿特, 2016; 高翔宇等, 2019; 张国伟等, 2019; 张逸鹏等, 2021; 李康宁等, 2024; 刘志慧等, 2024)。西秦岭造

山带作为秦岭造山带的西延部分，主要由晚古生代的碎屑岩和碳酸盐岩（形成于稳定的弧后陆棚和台地环境），以及三叠纪的碎屑岩夹碳酸盐岩（形成于前陆盆地和裂陷盆地环境）构成（冯益民等，2003；董云鹏等，2008；王阿特，2016；高翔宇等，2019）。

西秦岭出露的晚古生代地层主要包括泥盆系（西汉水群、大草滩组、舒家坝群、当多组、普莱组和陡石山组等）、石炭系（巴都组、下加岭组、岷河组和略阳组等）和二叠系（十里墩组、石关组、大关山组、迭山组和尕拉组）（高翔宇，2019）。岷县寨上地区古生代地层主要包括泥盆系、石炭系和二叠系（图 1）。区内泥盆系以双狼沟组为代表，下部为灰—



a—西秦岭造山带地质简图（据张国伟等，2019 修改）；b—岷县寨上地区区域地质简图及采样位置图

图 1　西秦岭造山带地质简图及岷县寨上地区区域地质简图及采样位置图

Fig. 1　Geological sketch map of the western Qinling Orogenic Belt and regional geological map of the Zhaishang area in Min County with sampling locations (slightly modified from Zhang et al., 2019).

(a) Geological sketch map of the western Qinling Orogenic Belt; (b) Regional geological map of the Zhaishang area in Min County with sampling locations

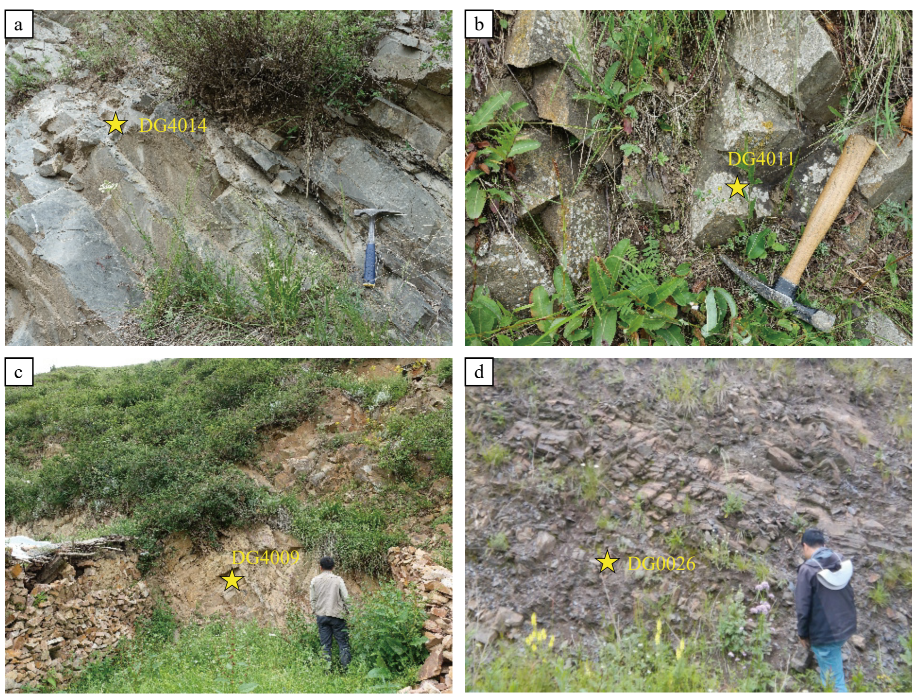
灰绿色板岩、钙质板岩、粉砂质板岩夹粉砂岩和细粒石英砂岩；上部为灰—灰绿色中厚层—块状细粒岩屑石英砂岩、石英砂岩粉砂岩及板岩灰岩。石炭系以下石炭统巴都组为代表，其以灰黑—深灰色薄层状泥质板岩、粉砂质板岩、粉砂岩为主夹中薄层状石英细砂岩及少量浅灰—深灰色中薄层状含生物碎屑灰岩。二叠系主要以下二叠统十里墩组为代表，下部为灰—灰黑色中粗粒长石石英砂岩、岩屑石英砂岩与粉砂岩、粉砂质板岩互层或夹层，含少量炭质板岩；中部以中—薄层状中细粒岩屑石英砂岩、含炭板岩、细砂岩互层或互为夹层为主，夹少量含炭粉砂岩和灰岩透镜体；上部为薄层灰岩、泥质灰岩和板岩，灰绿—灰黄色细—中粒砂岩和砂岩，夹杂色砾岩。

岷县寨上地区构造复杂，主要包括卓落-国营牛场背斜、北西—北西西向断裂（主干断裂为层间滑动容矿断裂）、近南北向和北东向断裂，以及节理、劈理和次级小褶皱等（图 1）。该区域自泥盆纪以来经历了多期构造变形作用，其中以泥盆纪—三叠纪时期的构造活动最为强烈，奠定了岷县寨上地区的构造格架，最后叠加了新生代以来的改造（陈泽华，2023）。岷县寨上地区内未见发育有岩浆岩。

2　样品与分析方法

2.1　样品采集

全部样品均采自西秦岭岷县寨上地区，包括泥盆系西汉水群双狼沟组上段灰色砂岩（样品编号 DG4011、DG4014）、下石炭统巴都组土黄色砂岩（样品编号 DG4009）以及下二叠统十里墩组中段土黄色中粗粒砂岩（样品编号 DG0026）（图 2，图 3）。采样位置、矿物组成和年龄信息详见表 1。



a—样品 DG4014 采样位置；b—样品 DG4011 采样位置；c—样品 DG4009 采样位置；d—样品 DG0026 采样位置

图 2　岷县寨上地区典型沉积岩露头及采样位置照片

Fig. 2　Outcrop photographs of typical sedimentary rocks and sample locations, Zhaishang Area, Min County

(a) Sampling location of Sample DG4014; (b) Sampling location of Sample DG4011; (c) Sampling location of Sample DG4009; (d) Sampling location of Sample DG0026

2.2　锆石 U-Pb 同位素测试

首先，在河北廊坊市宇能岩石矿物分选技术服务有限公司进行锆石单矿物分选，流程包括：样品破碎至 80～120 目（120～180 μm），淘洗除尘，去除磁性矿物，重液分选，双目镜下人工挑选锆石。然后，由锆年领航科技有限公司完成锆石制靶、抛光，并进行透反射及阴极发光（CL）图像拍摄。在自然资源部古地磁与古构造重建重点实验室利用 LA-ICP-MS 对锆石进行 U-Pb 年代学分析。LA-ICP-MS 配备美国 ESL 公司 NWR193HE 激光剥蚀系统（主要参

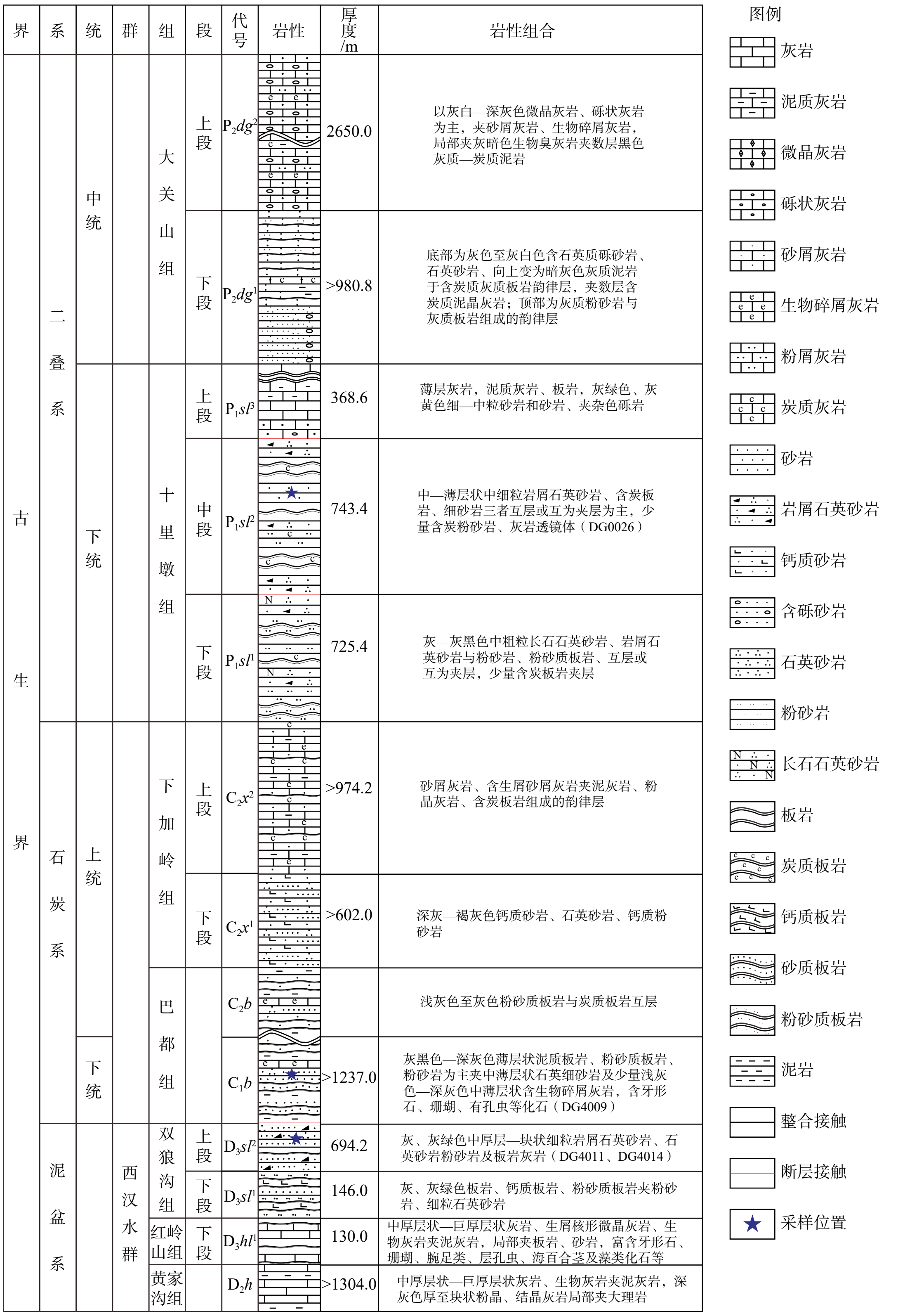


图 3 岷县寨上地区及邻区晚古生代地层柱状图

Fig. 3 Stratigraphic column diagram of the Late Paleozoic in the Zhaishang area, Min County, and adjacent regions

数：激光波长为 193 nm，束斑直径为 30 μm，能量密度为 3.0 J/cm²）和德国耶拿分析仪器股份公司 PQ-MS 质谱仪，使用氦气作为载气。

锆石 U-Pb 定年采用 91500（1065.4±0.6 Ma；Wiedenbeck et al.，1995）作为外标进行基体校正，QingHu（159.5±0.2 Ma；李献华等，2013）作为盲样，

表 1　岷县寨上地区古生代沉积岩采样位置、岩性特征及年龄特征

Table 1　Sampling locations, lithological characteristics, and age characteristics of Paleozoic sedimentary rocks in the Zhaishang area, Min County

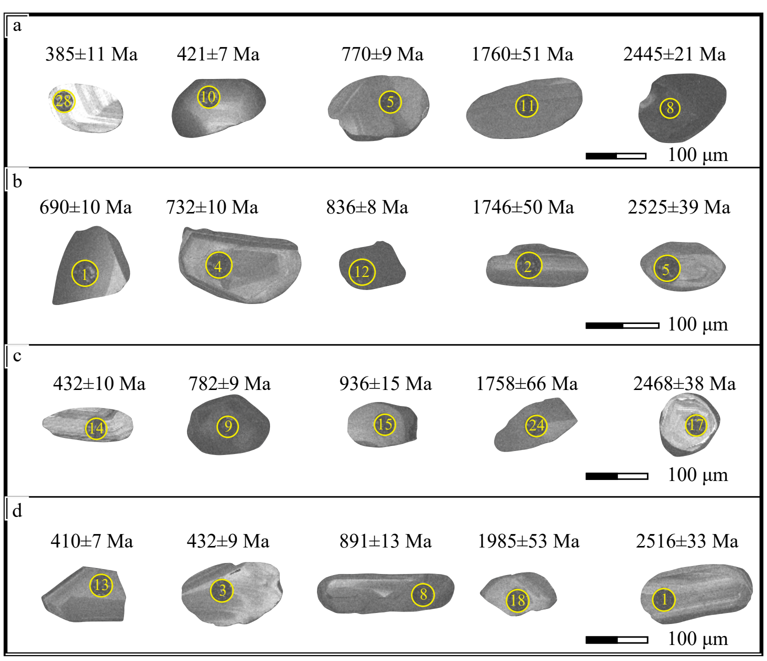
样品号	采样位置	采样地层时代	经/纬度	岩性	碎屑组分特征	峰值年龄/Ma	最年轻峰值年龄/Ma
DG4009	国营牛场东北	C_1b	34°29′50.68″N/ 104°18′04.94″E	土黄色砂岩	颗粒棱角分明，主要为棱角状—次棱角状石英、斜长石，含一定量岩屑，次棱角状—次圆状；钙质胶结	419、818、1901和2517	390
DG4011	国营牛场西南	D_3sl^2	34°28′57.01″N/ 104°16′57.46″E	灰色砂岩	颗粒棱角分明，主要为次棱角状石英、斜长石；含有一定量的岩屑和少量云母；钙质胶结	450、832、1749和2525	450
DG4014	毛茨沟口义东北	D_3sl^2	34°28′36.91″N/ 104°16′32.13″E	灰色砂岩	颗粒棱角分明，主要为次棱角状石英、斜长石；含有一定量的岩屑和少量云母；钙质胶结	434、784、1228、1826和2430	392
DG0026	大滩子东南	P_1sl^2	34°34′57.33″N/ 104°17′23.94″E	土黄色中粗粒砂岩	颗粒棱角明显，以石英和斜长石为主，为次棱角状，含有一定量的岩屑和少量云母；钙质胶结	443、738、932和2511	443

注：C_1b—巴都组；D_3sl^2—双狼沟组上段；P_1sl^2—十里墩组中段

NIST SRM 610 作为外标，Si 和 Zr 分别作为内标标定 Pb 元素含量和微量元素（Liu et al., 2010）。数据处理使用 iolite4 软件（Paton et al., 2011），U-Pb 谐和图、年龄分布频率图和年龄权重平均计算使用 Ludwig 的 Isoplot 软件（Ludwig, 2003）。

3　分析结果

每个样品测试 120 个点，统计谐和度>90% 的数据点。对于 $^{206}Pb/^{238}U$ 年龄≤1000 Ma 的点取 $^{206}Pb/^{238}U$ 年龄，$^{206}Pb/^{238}U$ 年龄 >1000 Ma 的点取 $^{207}Pb/^{206}Pb$ 年龄。从锆石 CL 图像看，锆石均具有一定磨圆度，具沉积岩碎屑锆石特征。其中绝大部分锆石 Th/U 比值较高（>0.1），震荡环带清晰，指示其为岩浆成因（图 4）；个别锆石具较窄生长边，属变质成因（Vavra et al., 1996, 1999; Rubatto et al., 1998; Hermann et al., 2001; 吴元保和郑永飞, 2004）。测试均针对岩浆型锆石进行测定。在绘制碎屑锆石 U-Pb 年龄频率分布直方图时使用的参数如下：带宽（bandwidth）为 20，组距（binwidth）为 70。



a—样品 DG4009 代表性锆石 CL 图像及年龄；b—样品 DG4011 代表性锆石 CL 图像及年龄；c—样品 DG4014 代表性锆石 CL 图像及年龄；d—样品 DG0026 代表性锆石 CL 图像及年龄

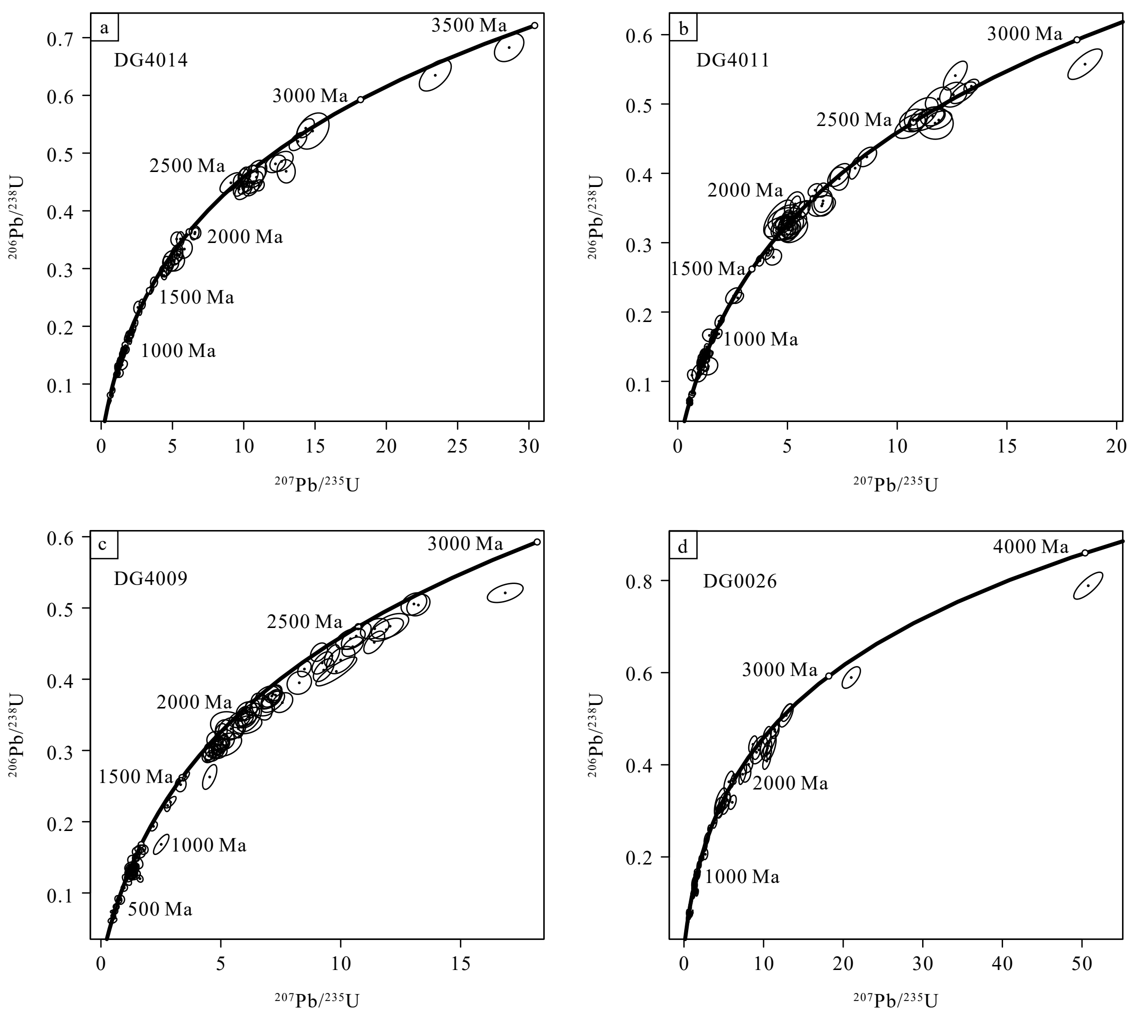
图 4　岷县寨上地区沉积岩中碎屑锆石的 CL 图像及年龄值

Fig. 4　CL images and age values of detrital zircons from sedimentary rocks in the Zhaishang area, Min County

(a) Representative zircon CL images and age values of Sample DG4009; (b) Representative zircon CL images and age values of Sample DG4011; (c) Representative zircon CL images and age values of Sample DG4014; (d) Representative zircon CL images and age values of Sample DG0026

(1)岷县寨上泥盆统灰色砂岩

样品 DG4014 中锆石呈棱柱状—次圆状，粒径为 50～180 μm，长宽比为 1.1～3。LA-ICP-MS 测得 120 个锆石年龄数据，去除谐和度<90% 的 11 个点后，剩余 109 个有效数据。Th/U 为 0.09～1.99(绝大部分>0.40；图 4；测试数据见文后 OSID 码)。主要年龄峰值为 784 Ma，次要峰值分别为 434 Ma、1228 Ma、1826 Ma 和 2430 Ma。最年轻锆石年龄为 394 Ma，最小年龄峰值为 434 Ma(图 5a，图 6a)。



a—样品 DG4014U-Pb 年龄谐和图；b—样品 DG4011U-Pb 年龄谐和图；c—样品 DG4009U-Pb 年龄谐和图；d—样品 DG0026U-Pb 年龄谐和图

图 5 岷县寨上地区沉积岩中碎屑锆石的 U-Pb 年龄谐和图

Fig. 5 U–Pb concordia diagrams of detrital zircons from sedimentary rocks in the Zhaishang area, Min County

(a) U–Pb concordia diagram for Sample DG4014; (b) U–Pb concordia diagram for Sample DG4011; (c) U–Pb concordia diagram for Sample DG4009; (d) U–Pb concordia diagram for Sample DG0026

样品 DG4011 中锆石呈棱柱状—次圆状，粒径为 70～180 μm，长宽比为 1.1～2.3。LA-ICP-MS 测得 120 个锆石年龄数据，去除谐和度<90% 的 10 个点后，剩余 110 个有效数据，Th/U 为 0.04～2.26(绝大部分>0.40；图 4；测试数据见文后 OSID 码)。主要年龄峰值为 832 Ma，次要峰值分别为 450 Ma、1749 Ma 和 2525 Ma。最年轻锆石年龄为 428 Ma，最小年龄峰值为 450 Ma(图 5b，图 6b)。

(2)岷县寨下石炭统土黄色砂岩

样品 DG4009 中锆石呈棱柱状—次圆状，粒径为 60～160 μm，长宽比为 1.2～3。LA-ICP-MS 测得 120 个锆石年龄数据，去除谐和度<90% 的 6 个点后，剩余 114 个有效数据。Th/U 比为 0.13～3.09(绝大部分>0.40；图 4；测试数据见文后 OSID 码)。主要年龄峰值为 818 Ma，次要峰值分别为 419 Ma、1901 Ma 和 2571 Ma。最年轻锆石年龄为 385 Ma，最小年

龄峰值为 419 Ma(图 5c, 图 6c)。

(3)岷县寨上下二叠统土黄色中粗粒砂岩

样品 DG0026 中锆石呈棱柱状—次圆状, 粒径为 80～200 μm, 长宽比为 1～3.3。LA-ICP-MS 测得 120 个锆石年龄数据, 去除谐和度<90% 的 17 个点后, 剩余 103 个有效数据。Th/U 比为 0.01～5.01(绝大部分>0.40; 图 4; 测试数据见文后 OSID 码)。主要年龄峰值为 443 Ma, 次要峰值分别为 738 Ma、932 Ma 和 2511 Ma。最年轻锆石年龄为 410 Ma, 最小年龄峰值为 443 Ma(图 5d, 图 6d)。

4　讨论

4.1　沉积时限

碎屑锆石年龄常用于限定地层沉积时代上限, 因为地层沉积时代与碎屑形成时代相近或稍晚(Cawood et al., 2012)。岷县寨上地区古生代地层单元主要为近滨—浅海陆棚相细碎屑岩夹泥质岩、海陆过渡相碎屑岩、板岩夹灰岩以及滨海相砂岩、板岩, 岩性包括石英砂岩、板岩、粉砂岩和灰岩等。野外地质调查结果显示, 泥盆系与石炭系为构造接触关系, 石炭系与二叠系为整合接触关系。

利用 LA-ICP-MS U-Pb 定年技术, 对岷县寨上地区 4 个沉积岩样品开展碎屑锆石年代学分析。在 2 个泥盆纪西汉水群双狼沟组上段灰色砂岩中, DG4014 样品中最年轻年龄峰值为 434 Ma, 单个最年轻锆石年龄为 394 Ma, 2σ 为 13, 谐和度为 95%; DG4011 样品中最年轻年龄峰值为 450 Ma, 单个最年轻锆石年龄为 428 Ma, 2σ 为 18, 谐和度为 92%(图 6a、6b, 表 1)。1 个下石炭统巴都组土黄色砂岩样品的最年轻年龄峰值为 419 Ma, 单个最年轻锆石年龄为 385 Ma, 2σ 为 21, 谐和度为 97%(图 6c, 表 1)。1 个下二叠统十里墩组中段土黄色中粗粒砂岩样品的最年轻年龄峰值为 443 Ma, 单个最年轻锆石年龄为 410 Ma, 2σ 为 14, 谐和度为 98%(图 6d, 表 1)。

已有资料显示岷县西汉水群生物丰富, 以腕足类、珊瑚类和牙形石为主, 次为层孔虫、苔藓和双壳类等, 偶见海百合茎和三叶虫碎片, 指示该群沉积时代为泥盆纪。下石炭统巴都组发现珊瑚、非虫筳有孔虫和牙形刺等化石, 指示早石炭世。十里墩组区域上采得蜓类(如 *Neoschwagerrina* sp., *Misellina claudiae*., *Schwagerrina* sp., *Neomisellina* 等)及植物碎片, 确定其时代为早二叠世(吴树宽, 2013; 王阿特, 2016; 常亮, 2019)。

碎屑锆石年代学结果结合已有资料表明, 岷县寨上地区泥盆纪西汉水群双狼沟组上段、下石炭统巴都组和下二叠统十里墩组中段的沉积作用分别持续至晚泥盆世、早石炭世和早二叠世, 从而限定了这些地层沉积时代的最晚时间。

4.2　沉积物源

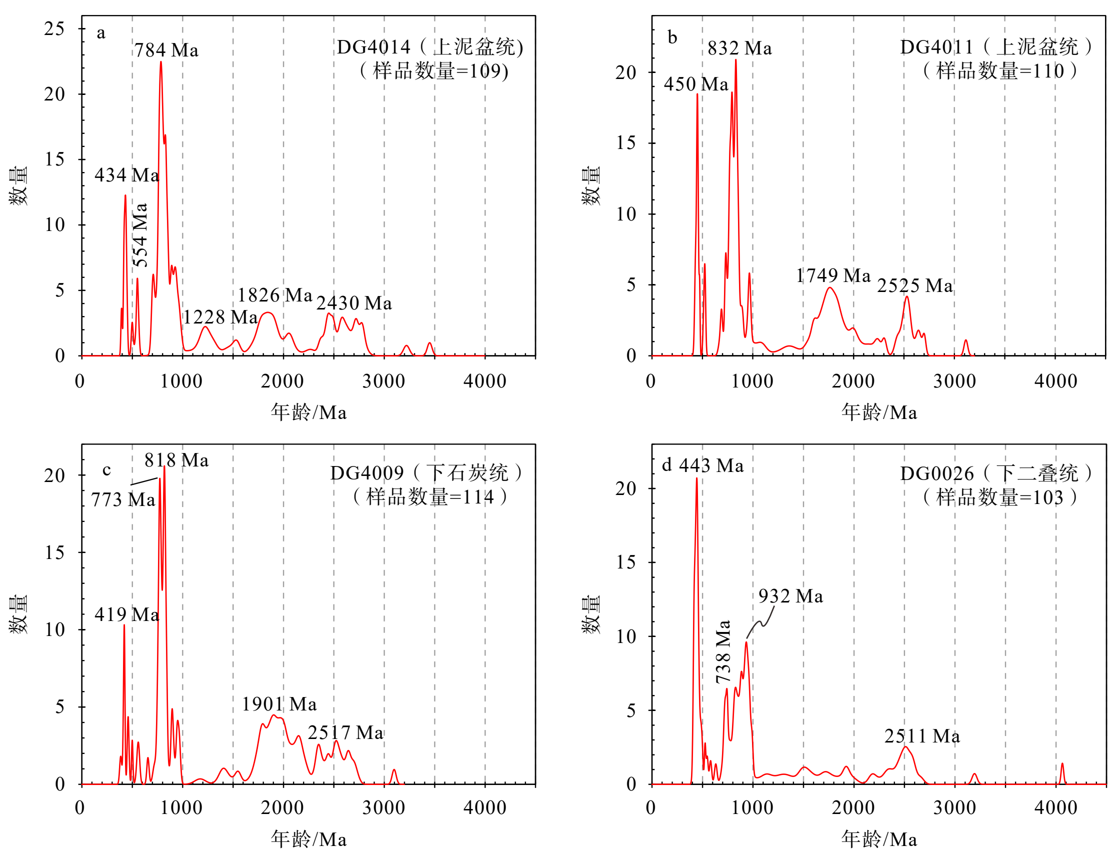
Diwu et al.(2012)对华北克拉通、扬子克拉通及北秦岭造山带进行了碎屑锆石年龄分析(图 7)。华北克拉通的碎屑锆石 U-Pb 年龄谱表现出显著的～2500 Ma 和～1800 Ma 年龄峰值, 这些峰值与该地块记录的 2600～2400 Ma 和 2000～1700 Ma 的太古宙晚期和古元古代—中元古代构造-岩浆-热事件在时间上具有成因联系(钱祥麟, 1996; 翟明国和卞爱国, 2000; 耿元生等, 2002, 2010; 万渝生等, 2003; Zhang et al., 2022)。扬子克拉通的碎屑锆石 U-Pb 年龄谱在～800 Ma 附近呈现显著峰值, 与新元古代 Rodinia 超大陆裂解期间发生的岩浆作用(793～841 Ma)在时间上具有良好的对应关系(Yan et al., 2003; 闫全人等, 2007; 裴先治等, 2009; 林振文等, 2013; Zhang et al., 2022)。北秦岭造山带的碎屑锆石 U-Pb 年龄谱以～400 Ma 的峰值为特征, 指示了早古生代寒武纪—志留纪造山运动期间的岩浆活动(507～400 Ma), 可能与弧后盆地或同碰撞环境下的岩浆作用有关(Wang et al., 2009, 2013; 王宗起等, 2009; Dong et al., 2011a; Wang et al., 2013; 张成立等, 2013; Dong and Santosh, 2016; 刘志慧等, 2018)。结合研究结果, 分析如下。

(1)岷县地区泥盆系—石炭系

泥盆系西汉水群双狼沟组的 2 个样品综合年龄谱图显示, 该地层碎屑锆石的主要年龄峰值为 794 Ma, 次要峰值为 448 Ma、1808 Ma 和 2530 Ma(图 7a)。碎屑锆石年龄主体峰值为新元古代, 集中于 794 Ma, 区间为 746～880 Ma, 该主要年龄峰值可能代表了 Rodinia 超大陆的聚合阶段(800～1000 Ma)和裂解阶段(700～800 Ma)在西秦岭地区的响应(图 7a; 裴先治等, 2012)。综合年龄图谱对比结果显示, 岷县寨上地区泥盆系碎屑锆石的主要年龄峰值与扬子克拉通高度一致, 这与扬子克拉通存在的大量与 Rodinia 超大陆汇聚与裂解相关的岩浆活动事件相吻合(793±11～841Ma; 图 7; 闫全人等, 2007; 裴先治等, 2009; 林振文等, 2013)。此外, 已有研究表明南秦岭造山带是扬子克拉通北缘的组成

部分（Dong and Santosh, 2016; 董云鹏等, 2022），且南秦岭造山带与扬子克拉通之间的勉略洋打开时代为泥盆纪（张国伟等, 1997; Wu and Zheng, 2013; 张国伟, 2015; 高翔宇, 2019），因此扬子克拉通可以成为南秦岭造山带泥盆系的沉积物质潜在物质来源；泥盆系碎屑锆石年龄的次要年龄峰值代表为 448 Ma，区间为 420～460 Ma，该年龄峰值可能反映了早古生代岩浆的侵位的时代。综合年龄图谱对比结果显示，该次要年龄峰值与北秦岭造山带高度一致，这与北秦岭造山带在寒武纪—志留纪发生构造运动所产生的岩浆活动相吻合（507～470 Ma、460～422 Ma 和 415～400 Ma; 图 7; Wang et al., 2009; 王宗起等, 2009; Dong et al., 2011a; 张成立等, 2013; Dong and Santosh, 2016; 刘志慧等, 2018）。综合已有研究结果表明，南秦岭造山带与北秦岭造山带于早泥盆世已经拼合在一起（李伍平等, 2001; Dong and Santosh, 2016; Dong et al., 2018, 2021; 董云鹏等, 2022），故北秦岭造山带可以是南秦岭造山带的潜在物质来源。并且沉积岩中碎屑颗粒呈棱角状、磨圆度较差以及锆石形态均表明其具有近缘沉积的特点（闫臻等, 2018）。因此，该次要年龄峰值更有可能来自于相邻的北秦岭造山带而非华北克拉通。故综合认为在这个时期岷县寨上地区沉积物质主要来源于扬子克拉通，其次来自北秦岭造山带，具有多源性的特点。

下石炭统巴都组样品年龄图谱显示，该地层碎屑锆石主要年龄峰值为 818 Ma，次要峰值为 419 Ma、1901 Ma 和 2517 Ma（图 6c）。碎屑锆石年龄主体峰值为新元古代，集中于 818 Ma，区间为 750～901 Ma（图 6c）。下石炭统巴都组碎屑锆石年龄图谱与泥盆系西汉水群双狼沟组年龄图谱高度一致，且两者的主要年龄峰值和次要年龄峰值基本一致（图 7），



a—样品 DG4014 U-Pb 年龄频率分布直方图；b—样品 DG4011 U-Pb 年龄频率分布直方图；c—样品 DG4009 U-Pb 年龄频率分布直方图；d—样品 DG0026 U-Pb 年龄频率分布直方图

图 6 岷县寨上地区沉积岩中碎屑锆石 U-Pb 年龄频率分布直方图

Fig. 6 U–Pb age frequency histograms of detrital zircons from sedimentary rocks in the Zhaishang area, Min County

(a) U–Pb age frequency histogram for Sample DG4014; (b) U–Pb age frequency histogram for Sample DG4011; (c) U–Pb age frequency histogram for Sample DG4009; (d) U–Pb age frequency histogram for Sample DG0026

因此认为两者的主要沉积物质来源一致,沉积物质主要来源于扬子克拉通,其次来自北秦岭造山带(沉积物质来源的讨论与泥盆系沉积物质来源的讨论一致);且地层沉积时的构造背景没有发生巨大变化。

(2)岷县寨上地区下二叠统

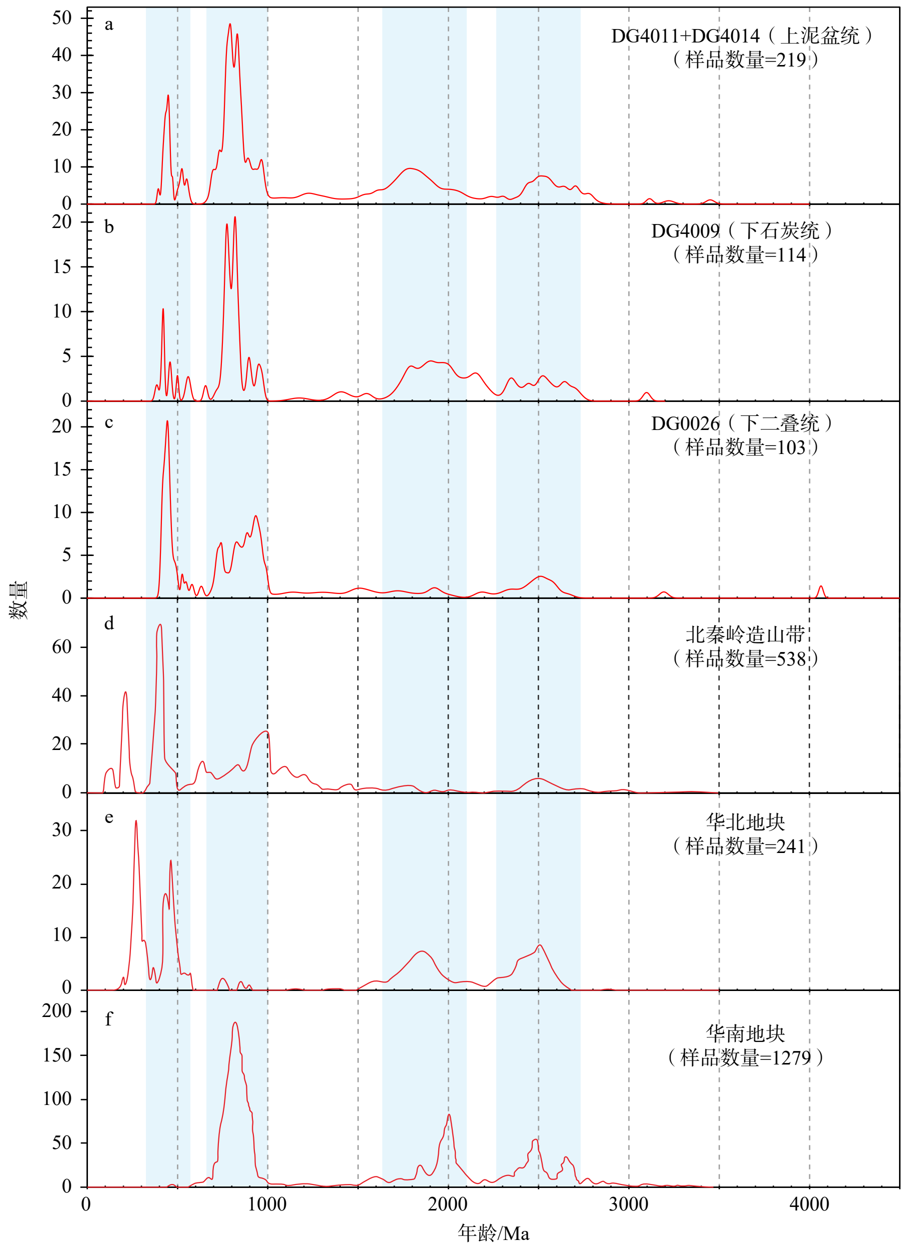
岷县寨上地区下二叠统十里墩组中段样品年龄图谱显示,该地层碎屑锆石主要年龄峰值为 443 Ma,次要峰值为 738 Ma、932 Ma 和 2511 Ma(图 6d)。碎屑锆石年龄主体峰值为早古生代,集中于 443 Ma,区间为 409～464 Ma,该年龄峰值可能反映了早古生代岩浆的侵位的时代(图 6d)。综合年龄图谱对比结果显示,岷县寨上地区二叠系碎屑锆石年龄谱图与北秦岭造山带一致,这与北秦岭造山带在寒武纪—志留纪发生构造运动所产生的岩浆活动相吻合(507～470 Ma、460～422 Ma 和 415～400 Ma; 图 7; Wang et al., 2009; 王宗起等, 2009; Dong et al., 2011a; 张成立等, 2013; Dong and Santosh, 2016; 刘志慧等, 2018);且南秦岭造山带与北秦岭造山带自早泥盆世就已经拼合在一起了(李伍平等, 2001; Dong and Santosh, 2016; Dong et al., 2018, 2021; 董云鹏等, 2022),故早二叠世时北秦岭造山带也可以为南秦岭造山带提供沉积物质。下二叠统十里墩组碎屑锆石的次要年龄峰值为 932 Ma,区间为 857～965 Ma,这个次要年龄峰值可能代表了 Rodinia 超大陆的聚合阶段(800～1000 Ma)在西秦岭的响应(裴先治等, 2012)。年龄图谱对比结果显示,该次要年龄峰值同样与北秦岭造山带的年龄图谱相一致,且在区域伸展背景下,勉略洋盆在石炭纪—早二叠世为最大的扩张期,但至迟于早二叠世晚期开始进入俯冲消减阶段(赖绍聪等, 1997; 张国伟等, 1997, 2003, 2015; 裴先治, 2001; 赖绍聪等, 2002; 董云鹏等, 2003b, 2007; 闫臻等, 2007; 徐亚军, 2010; Wu and Zheng, 2013; 颜全治, 2017; 高翔宇等, 2019; 高翔宇, 2019; Dong et al., 2022),以至于二叠系的沉积物质不可能来源于被勉略洋隔开的扬子克拉通(图 7)。此外,古生代时沉积盆地的地形为北高南低(闫臻等, 2007; 徐亚军, 2010; 颜全治, 2017; 高翔宇等, 2019; 高翔宇, 2019),古流向为由北向南(闫臻等, 2007; 徐亚军, 2010; 颜全治, 2017)。综上所述,岷县寨上地区二叠系沉积物源主要来自北秦岭造山带。这与在其他地区的已有研究结果(物质来源主要为扬子克拉通和秦岭造山带; 王阿特, 2016)不同,可能反映了岷县寨上地区不同部位在二叠纪时期的物源供给系统存在空间分异。

4.3　区域构造意义

Cawood et al.(2012)通过分析碎屑锆石 U-Pb 年龄数据,构建了碎屑锆石年龄峰值与构造背景关系图(图 8)。将岷县寨上地区上泥盆统和下石炭统碎屑锆石 U-Pb 年龄频率分布直方图和碎屑锆石年龄峰值与构造背景关系图进行对比显示,上泥盆统和下石炭统的碎屑锆石 U-Pb 年龄频率分布直方图与裂谷盆地的碎屑锆石 U-Pb 年龄频率分布直方图相一致,推测晚泥盆世—早石炭世时岷县寨上地区构造背景为裂谷盆地(图 7, 图 8; Cawood et al., 2012)。碎屑锆石以新元古代年龄为主,峰值区间为 746～880Ma,集中于794Ma。该年龄峰值可能反映了Rodinia 超大陆聚合(800～1000 Ma)及随后的裂解过程(700～800 Ma)在西秦岭地区的响应(裴先治等, 2012)。而西秦岭北缘发育的同时期蛇绿岩和同期周缘的造山带(祁连造山带)中广泛的同期基性岩同样记录了该期广泛发育的区域裂解事件,可能代表商丹洋初始扩张的岩浆响应(裴先治等, 2005; Pei et al., 2007; 刘军锋等, 2007; 李王晔, 2008; Xia et al., 2012; 郭周平等, 2015; Yan et al., 2019; 董云鹏等, 2022)。

秦岭古洋盆自新元古代末(600 Ma)形成,于 520 Ma 开始俯冲消减(Shi et al., 2013),经历多期弧陆碰撞,最终于早泥盆世沿商丹一线闭合(图 9; 李伍平等, 2001; Dong and Santosh, 2016; Dong et al., 2018, 2021; 董云鹏等, 2022)。即此时南秦岭造山带随着“商丹洋”洋壳北向俯冲,并于早泥盆世时与北秦岭造山带拼合在一起,南秦岭造山带在泥盆纪—石炭纪时可以接收来自北秦岭造山带的物源。同时,扬子克拉通西北缘和碧口地块是 Rodinia 超大陆汇聚和裂解时期岩浆活动的另一重要场所(陆松年等, 2003; 闫全人等, 2003; 夏林圻等, 2007; Dong et al., 2011b; 王梦玺等, 2012; 邓奇等, 2013; 平先权等, 2014)。甘肃迭部—舟曲一带在奥陶纪—早志留世为陆缘裂谷盆地(段亮, 2010; 徐通等, 2013)。晚志留世扬子克拉通西北缘相对隆升(刘宝星等, 2020),且沉积岩中碎屑颗粒呈棱角状、磨圆度较差以及锆石形态均表明其具有近缘沉积的特点(闫臻等, 2018)。

早二叠世,岷县寨上地区碎屑锆石以早古生代年龄为主,峰值区间为 409～464 Ma,集中于 443



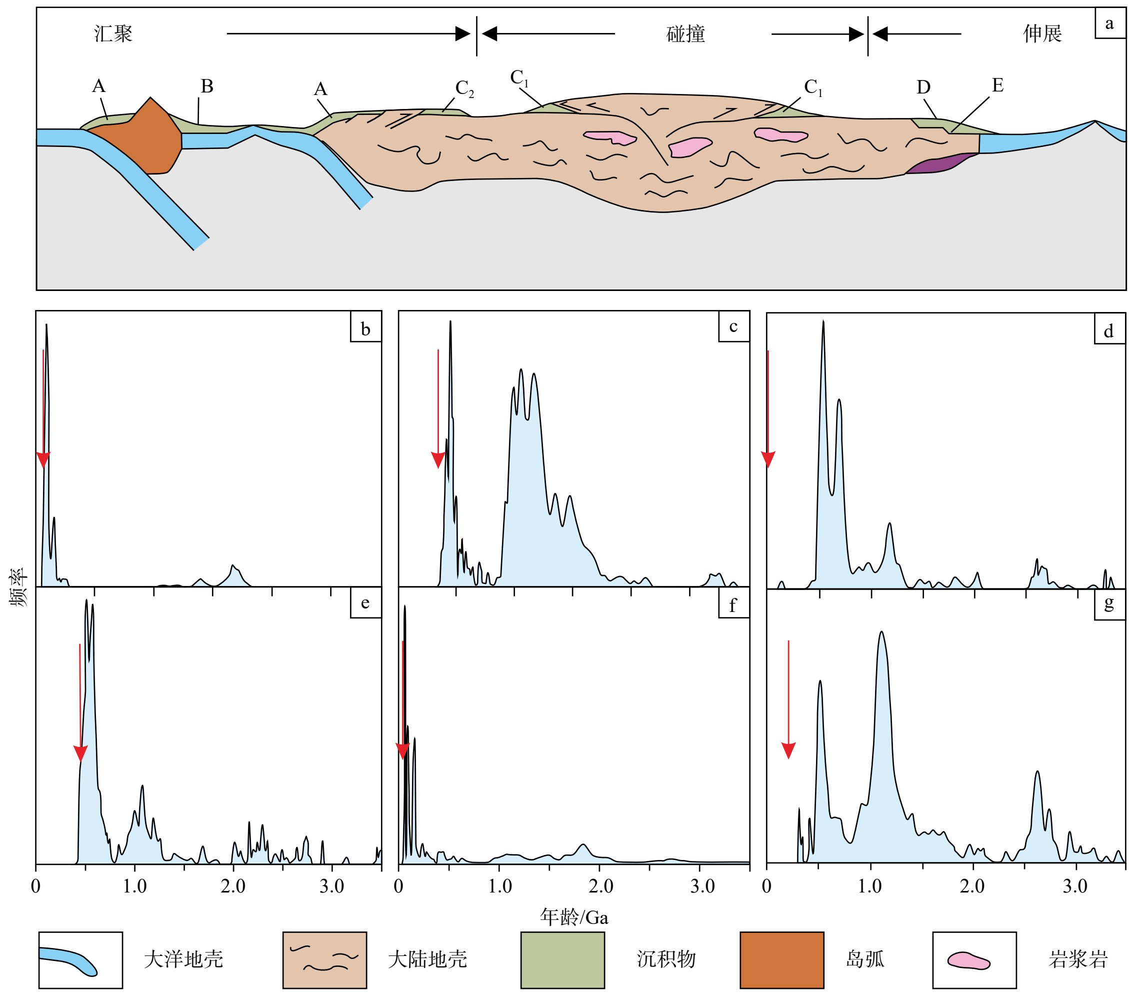
a—样品 DG4014 和样品 DG4011 综合年龄相对概率分布图；b—样品 DG4009U-Pb 年龄相对概率分布图；c—样品 DG0026U-Pb 年龄相对概率分布图；d—北秦岭造山带年龄相对概率分布图（据 Diwu et al., 2012）；e—华北克拉通年龄相对概率分布图（据 Diwu et al., 2012）；f—扬子克拉通年龄相对概率分布图（据 Diwu et al., 2012）

图 7　岷县寨上地区及其邻区 U-Pb 年龄相对概率分布图

Fig. 7　Relative probability plots of zircon U–Pb ages for the Zhaishang area, Min County, and adjacent areas

(a) Relative probability plot of U–Pb ages for samples DG4014 and DG4011 combined; (b) Relative probability plot of U–Pb ages for Sample DG4009; (c) Relative probability plot of U–Pb ages for Sample DG0026; (d) Relative probability plot of ages from the northern Qinling Orogenic Belt (after Diwu et al., 2012); (e) Relative probability plot of ages form the North China Craton (after Diwu et al., 2012); (f) Relative probability plot of ages from the Yangtze Craton (after Diwu et al., 2012)

Ma。该年龄峰值记录的早古生代岩浆侵位时代，与北秦岭造山带寒武纪—志留纪岩浆活动（507～400 Ma）对应良好（Wang et al., 2009, 2013; 王宗起等，2009; Dong et al., 2011a; 张成立等，2013; Dong and Santosh, 2016; 刘志慧等，2018）。将岷县寨上地区下二叠统年龄图谱与构造背景判别年龄图谱对比显示，下二叠统的年龄图谱与弧后盆地的年龄图谱相一致，早二叠世时岷县寨上地区构造背景为弧后盆



图中红色的箭头代表沉积物沉积时的年龄；A—海沟和弧前盆地；B—弧后盆地；C_1、C_2—前陆盆地；D—被动大陆边缘；E—裂谷盆地

a—构造背景环境及其对应的大地构造单元；b—海沟和弧前盆地 U-Pb 年龄频率分布直方图；c—前陆盆地（C_1）U-Pb 年龄频率分布直方图；d—被动大陆边缘 U-Pb 年龄频率分布直方图；e—弧后盆地 U-Pb 年龄频率分布直方图；f—前陆盆地（C_2）U-Pb 年龄频率分布直方图；g—裂谷盆地 U-Pb 年龄频率分布直方图；

图 8　碎屑锆石年龄峰与构造背景关系图（据 Cawood et al.，2012 修改）

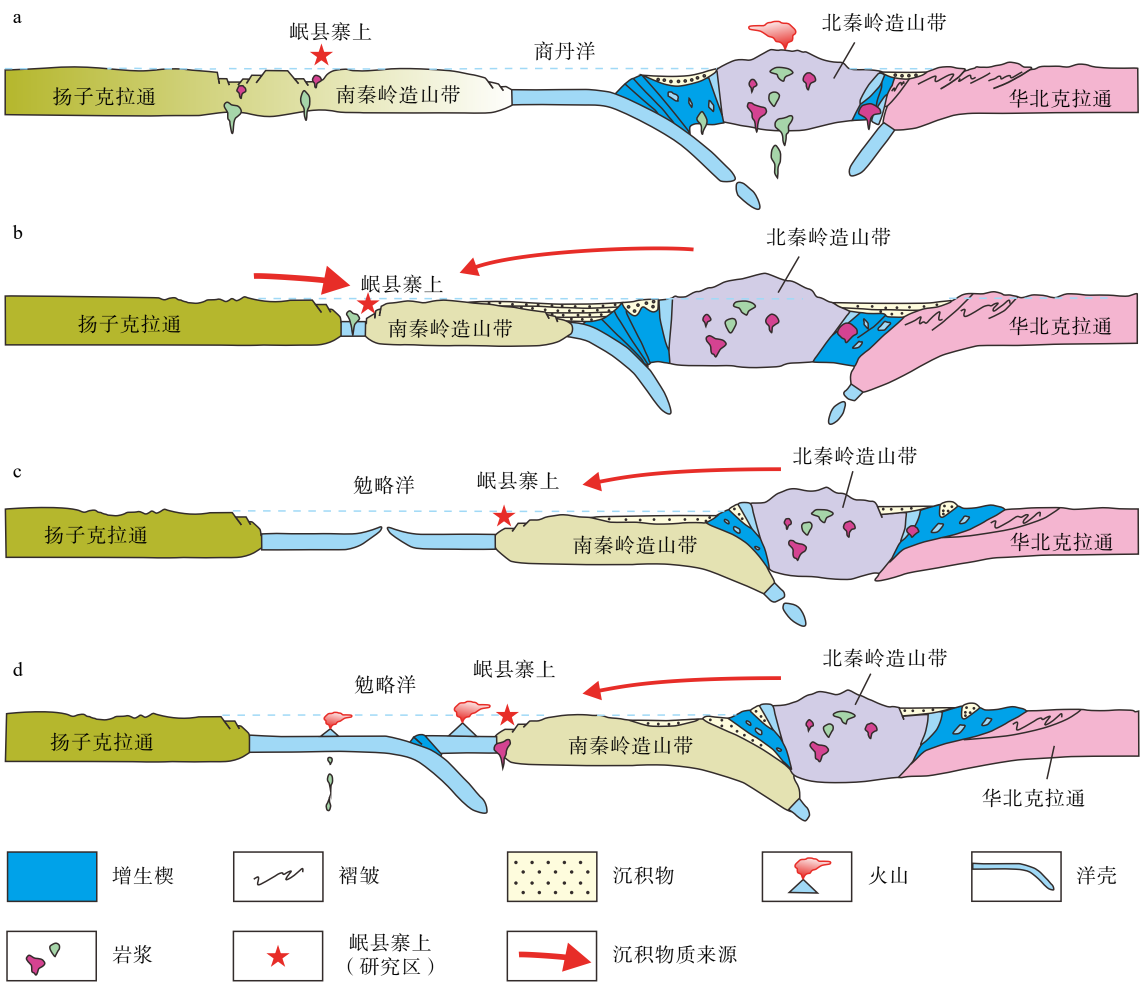
Fig. 8　Relationship between age peaks and tectonic settings of detrital zircon (modified after Cawood et al., 2012)

(a) Tectonic setting and corresponding tectonic units; (b) U–Pb age frequency histogram for the trench and forearc basin; (c) U–Pb age frequency histogram for the foreland basin (C_1); (d) U–Pb age frequency histogram for the assive margin; (e) U–Pb age frequency histogram for the backarc basin; (f) U–Pb age frequency histogram for the foreland basin (C_2); (g) U–Pb age frequency histogram for a rift basin

The red vertical arrows in the figure represent the age of sediment deposition; A–trench and forearc basin; B–backarc basin; C1, C2–foreland basin; D–passive continental margin; E–rift basin

地（Cawood et al., 2012）。受古特提斯洋扩张影响，泥盆纪—石炭纪—早二叠世时，勉略洋完成了洋盆打开和扩张，并于早二叠世开始进入俯冲消减阶段（图 7—图 9；赖绍聪等，1997，2002；张国伟等，1997，2003，2015；裴先治，2001；董云鹏等，2003b，2007；闫臻等，2007；徐亚军，2010；Wu and Zheng，2013；颜全治，2017；高翔宇等，2019；高翔宇，2019；Dong et al., 2022；Jia et al., 2024）。并且二叠系沉积时，商丹洋已经完全闭合（即南秦岭造山带已经完成了与北秦岭造山带的拼接），勉略洋盆扩张至最大（扬子克拉通与南秦岭造山带之间有较宽的洋壳阻隔了沉积物的远距离搬运）（张国伟等，1995；Wang et al., 2011；Dong et al., 2011a, 2011c, 2022；Wu and Zheng 2013；徐通，2016；王安琪，2020）。

综上，文章认为上泥盆统至下石炭统的沉积物源主要来自扬子克拉通，其次为北秦岭造山带；同时支持勉略洋的打开时间晚于早石炭世与商丹洋的闭合时间早于晚泥盆世的这一认识，这与已有的



a—奥陶纪—早泥盆世秦岭造山带构造格局；b—早泥盆世—早石炭世秦岭造山带构造格局；c—早石炭世—早二叠世秦岭造山带构造格局；d—二叠纪之后秦岭造山带构造格局

图 9 秦岭造山带构造演化图（据 Dong et al.，2022 修改）

Fig. 9 Tectonic evolution of the Qinling Orogenic Belt (modified after Dong et al., 2022)

(a) Tectonic framework of the Qinling Orogenic Belt from the Ordovician to the Early Devonian; (b) Tectonic framework of the Qinling Orogenic Belt from the Early Devonian to the Early Carboniferous; (c) Tectonic framework of the Qinling Orogenic Belt from the Early Carboniferous to the Early Permian; (d) Tectonic framework of the Qinling Orogenic Belt after the Permian

研究成果一致（Meng and Zhang, 1999；赖绍聪等，2003；张国伟等，2004；Lai, 2008；杨文涛等，2014；Dong and Santosh, 2016；孟庆任，2017；Yu et al., 2023）。然而，二叠系的物源分析显示，其沉积物主要来源于北秦岭造山带，这一认识虽与部分已有研究成果相符，但与王阿特（2016）的研究结果存在差异。王阿特（2016）认为二叠系十里墩组的物源具有双重性，既来自扬子克拉通，也来自秦岭造山带。这一差异可能反映了岷县寨上地区不同部位在二叠纪时期的物源供给系统存在空间分异。此外，甘肃岷县寨上地区晚泥盆统—早二叠统碎屑锆石年龄谱及物源分析表明，该时期沉积构造背景经历了从裂谷盆地向弧后盆地的转变，为勉略洋盆构造演化提供了重要依据。

5 结论

（1）岷县寨上地区西汉水群双狼沟组上段沉积持续至晚泥盆世，巴都组沉积持续至早石炭世，十里墩组中段沉积持续至早二叠世，从而限定了岷县寨上地区地层沉积时代上限。

（2）岷县寨上地区西汉水群双狼沟组和巴都组具有相似的碎屑锆石年龄组成，以新元古代年龄组（746～880 Ma 和 750～901 Ma）为特征，指示了其物源主要来自扬子克拉通，其次为北秦岭造山带。而

十里墩组碎屑锆石年龄组成具有明显变化，以早古生代年龄组（409～464 Ma）为特征，其物源主要来源于北秦岭造山带。

（3）甘肃岷县寨上地区晚泥盆统—早二叠统碎屑锆石年龄谱及物源分析结果表明，岷县寨上地区在晚泥盆世—早石炭世期间处于裂谷盆地环境，至早二叠世转变为弧后盆地环境，这一沉积–构造演化过程为勉略洋盆的构造演化提供了重要依据。同时，研究进一步限定勉略洋的打开时间晚于早石炭世，而商丹洋的闭合时间早于晚泥盆世，这些认识为区域构造演化研究提供了新的年代学约束。

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