

西秦岭临潭地区下白垩统一上新统陆相地层 碎屑锆石 U-Pb 年代学及其物源分析

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内容提要:选取西秦岭造山带临潭地区下白垩统磨沟组和新近系上新统临夏组碎屑岩为研究对象, 运用 LA-ICP-MS 锆石 U-Pb 同位素年代学方法, 探讨磨沟组和临夏组的物质来源。结果显示, 碎屑锆石年龄谱可分为 6 组: ①新太古代—古元古代(2627~1676 Ma); ②中元古代(1487~1035 Ma); ③新元古代(996~812 Ma); ④早古生代(534~425 Ma); ⑤晚古生代(409~252 Ma); ⑥早中生代(250~197 Ma)。其中, 新太古代—古元古代(2627~1676 Ma)的年龄数据约占总体的 50.31%, 所占比例最大, 其余年龄段所占比例则较少。下白垩统磨沟组和上新统临夏组中蕴含的锆石年龄信息分布特征较为一致, 均有新元古代、早古生代、早中生代年龄峰值, 以及华北板块特有的 1.8 Ga 和 2.5 Ga 年龄峰值。下白垩统磨沟组和上新统临夏组具有近源堆积为主的特征, 合作—岷县断裂北侧的中秦岭构造带为其提供了物源, 碎屑锆石年龄谱特征记录了物源区地质体中的再旋回年龄信息。本研究对西秦岭中新生代的构造演化研究具有重要意义。

关键词: 西秦岭; 下白垩统一上新统; 锆石 U-Pb 年代学; 碎屑锆石; 物源分析

西秦岭造山带为秦岭造山带的西延, 是中央造山系的重要组成部分。西秦岭造山带大致以武山—天水断裂为北界, 以玛沁—迭部断裂为南界; 东以徽成盆地与东秦岭造山带相接, 西以共和盆地与东昆仑造山带、柴达木地块和柴北缘构造带相邻。西秦岭造山带处于南北构造带与中央造山系的复合交接部位, 是华北板块、扬子板块、祁连造山带、秦岭微板块以及巴颜喀拉造山带在地质历史上长期相互作用的部位(图 1a), 使得西秦岭造山带成为不同构造阶段、不同构造性质的构造带相互叠加、交接转换的复合区域(Peng Yuanqiao and Yin Hongfu, 1995; Zhang Guowei et al., 2004), 在经历了中—晚三叠世(印支期)主碰撞造山后, 进入了陆内演化阶段(Mattauer et al., 1985; Hsu et al., 1987; Meng

Qingren and Zhang Guowei, 1999; Pei Xianzhi, 2001; Zhang Guowei et al., 2001; Pei Xianzhi et al., 2002; Feng Yimin et al., 2003; Dong Yunpeng and Safonova, 2016; Dong Yunpeng et al., 2017)。新生代以来印度与欧亚板块持续而强烈的碰撞汇聚, 使其成为青藏高原构造系统的组成部分(L. Jijun et al., 1996; Yin and Harrison, 2000; Tapponier et al., 2001; Liu Shaofeng et al., 2007; Guo Jinjing and Han Wenfeng, 2008; Guo Jinjing et al., 2009, 2013, 2018; Wang Chengshan et al., 2009; Yin, 2010)。

西秦岭造山带北部地区分布着不同地质特征的下白垩系—古近系—新近系红层沉积地层, 在区域上, 这些中新生代地层之间以及与下伏地层之间多以角

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度不整合接触,局部靠近断裂带的地方呈断层接触。这些红层沉积地层是西秦岭中—新生代陆内构造过程客观的地质记录,而且也可作为印度-欧亚板块汇聚碰撞过程在青藏高原东北缘的远程地质响应(Bureau of Geology and Mineral Resources of Gansu Province, 1989; Zhang Erpeng et al., 1992; 甘肃省地质调查院, 2007^①; Guo Jinjing and Han Wenfeng, 2008; Guo Jinjing et al., 2014, 2015, 2016)。前人的研究较多地集中在岩石组合划分、沉积相与沉积环境分析(Bureau of Geology and Mineral Resources of Qinghai Province, 1991, 1997; Yan Zhen et al., 2002; 甘肃省地质调查院, 2007^①; Xu Xueyi et al., 2007; Li Rongshe et al., 2008)、岩石地球化学(Zhang Yingli and Wang Zongqi, 2011)、古生物研究和构造研究(Shi Wei et al., 2006; Guo Jinjing and Han Wenfeng, 2008; Guo Jinjing et al., 2009; Xin Peng et al., 2017; Li Zuochen et al., 2019),对于沉积地层的物源分析相对薄弱。沉积岩中的碎屑锆石能够抗风化和磨蚀,并且能保持 U-Pb 同位素体系较高的封闭温度,通常可以保存源区曾经存在的岩石的年龄记录,在搬运过程不易受其他地质作用影响,将其应用于年代学研究可以建立碎屑锆石的年龄分布特征从而判断其物质来源。因此,本文试图通过对西秦岭临潭地区分布的下白垩统磨沟组和新统临夏组的碎屑岩进行 LA-ICP-MS 锆石 U-Pb 定年分析,探讨碎屑锆石蕴含的年龄信息,这对进一步研究物质来源显得尤为必要,为西秦岭中新生代的构造演化、物质来源,恢复古地理构造格局提供新的证据。

1 区域地质背景

研究区地处秦岭造山带西段,大地构造位置处于秦岭造山带西段南秦岭被动陆缘带之次级单元裂陷盆地内。区内出露地层主要为晚古生代—中生代地层和新生代地层,由老到新出露有上泥盆统大草滩组(D_3dc)、下石炭统巴都组(C_1b)、上石炭统下加岭组(C_2x)、中上二叠统十里墩组(P_{2-3sl})、下三叠统隆务河组(T_1l)、中三叠统光盖山组(T_2gg)、上三叠统大河坝组(T_3d)、下白垩统磨沟组(K_1m)、上新统临夏组(N_2l)、第四系(Q)。以洮河复式向斜和美武新寺-大草滩背斜为主的大型褶皱构造、北北西-南东东向合作-岷县多条断裂带组成大型逆冲推覆构造共同构成了研究区的构造格局(图 1b),各地层之间多以断层接触(图 1b, 图 2)。美武复式岩体出

露于研究区北部,主要岩石类型为石英闪长岩、花岗闪长岩和黑云母正长花岗岩,侵位年龄为 242~245Ma,属印支早期(Luo Biji et al., 2012)。

下白垩统磨沟组(K_1m)在研究区主要分布于合作-岷县断裂(F_1)和临潭北断裂(F_6)之间,北侧多角度不整合于上三叠统大河坝组、下三叠统隆务河组及石炭系之上,局部可见下三叠统隆务河组(图 3a)、中上二叠统十里墩组逆冲于磨沟组之上;南侧与上新统临夏组呈断层接触(图 3b)。根据岩石组合特征将磨沟组划分为两个岩性段:磨沟组一段(K_1m^1)由灰紫色块状砾岩—灰紫色粗粒砂岩—灰紫色泥岩组成的基本层序;磨沟组二段(K_1m^2)由灰紫色砂岩—灰紫色泥岩组成基本层序,与一段呈整合接触。磨沟组向上厚度变薄,粒度变细,至顶部泥岩层增多,砂岩中发育粒序层理、平行层理及交错层理,泥岩发育水平层理。厚层状粗砂岩间夹砾岩,砾岩中砾石以砂岩为主,其中砂岩自下而上逐渐减少,砂岩比例由 69% 减少到 54%,脉石英由 12% 增加到 28%,上部层位中见有少量花岗岩砾石,约占 7% (图 4a, 4b)。砾石的磨圆度较差,多呈次棱角状,且次棱角状、棱角状砾石约占 69%~91% (图 4c, 4d)。本组岩石颜色以紫红色为主,构成一套在热带、亚热带气候条件下,以氧化为主的河湖相碎屑沉积(甘肃省地质调查院, 2007^①)。

上新统临夏组(N_2l)主要分布于临潭北断裂(F_6)以南,与磨沟组呈断层接触(图 2, 3b)。根据岩石组合特征可分为三段:临夏组一段(N_2l^1)为一套砖红色-土黄色砂砾岩,砾石磨圆度一般,多呈次棱角状,分选性差,砾石成分复杂,见有砂岩、灰岩、板岩、脉石英等;临夏组二段(N_2l^2)为一套砖红色泥岩夹少量灰绿色薄层中粗粒长石石英砂岩的岩石组合,局部见单层巨厚层灰绿色长石砂岩,总体向上砂岩变厚,与一段呈整合接触;临夏组三段(N_2l^3)主要为一套青灰—灰白色钙质粉砂岩、泥岩、灰岩,夹有少量砖红色泥岩,与二段呈整合接触。该组为干旱炎热强氧化环境下的内陆湖泊相沉积,垂向上自下而上岩性由粗变细,为一由砾岩→砂岩→砂质黏土岩→灰岩的相变过程,是湖泊由浅变深过程中的产物(Bureau of Geology and Mineral Resources of Qinghai Province, 1991, 1997; Xu Xueyi et al., 2007; Li Rongshe et al., 2008)。

2 样品位置及岩石学特征

本次研究所获下白垩统磨沟组(样品 PM404-

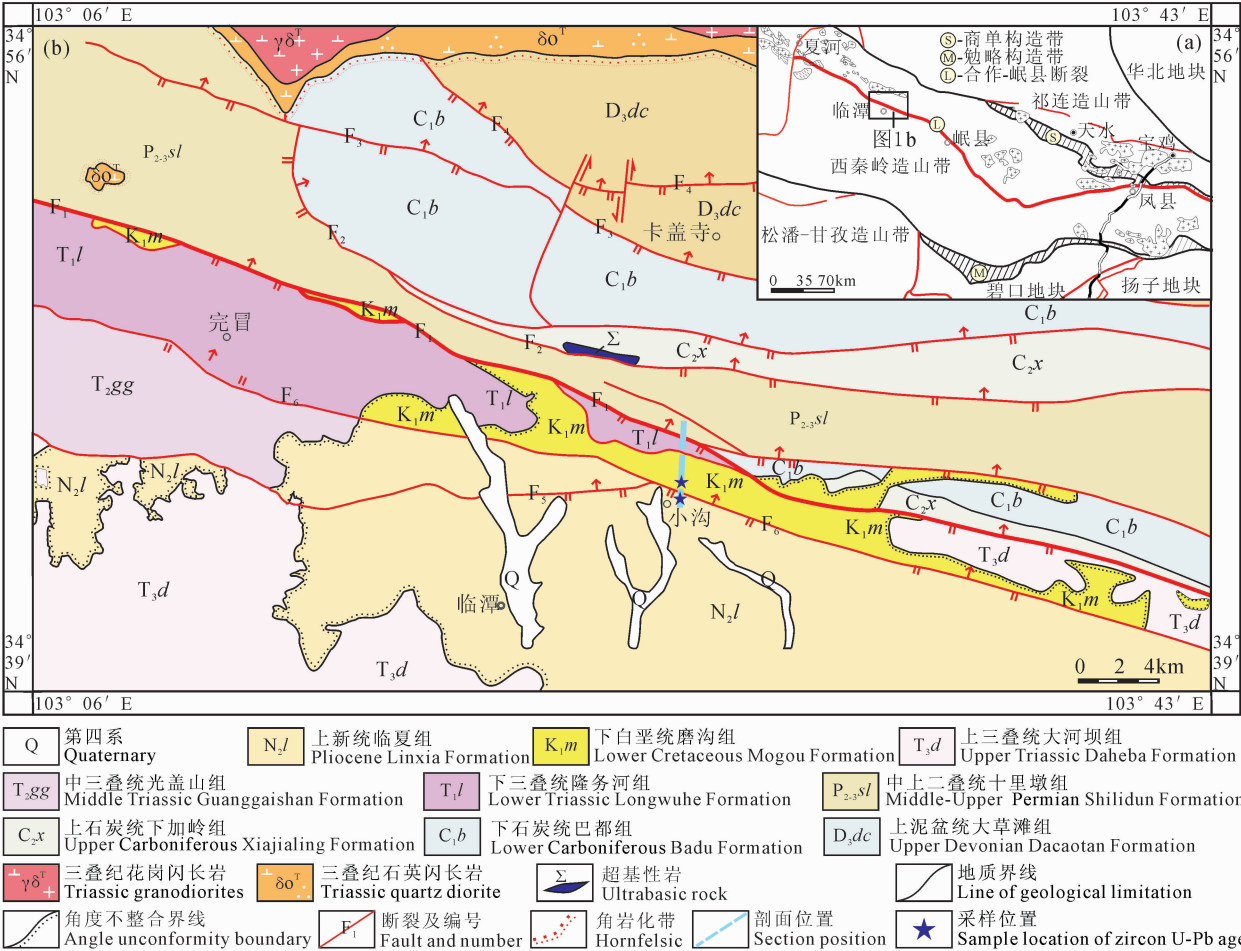


图 1 西秦岭造山带构造位置图(a)(据 Zhang Guowei et al. , 2001 修改)和西秦岭造山带临潭地区区域地质简图(b)
Fig. 1 Tectonic location of the West Qinling orogenic belt (a) (modified after Zhang Guowei et al. , 2001) and geological sketch map at Lintan area in the West Qinling orogenic belt (b)

F₁—合作-岷县断裂;F₂—恰龙断裂;F₃—恰盖南断裂;F₄—恰盖北断裂;F₅—临潭西断裂;F₆—临潭北断裂
F₁—Hezu-Minxian fault; F₂—Qialong fault; F₃—Southern of Qiagai fault;
F₄—Northern of Qiagai fault; F₅—Western of Lintan fault; F₆—Northern of Lintan fault

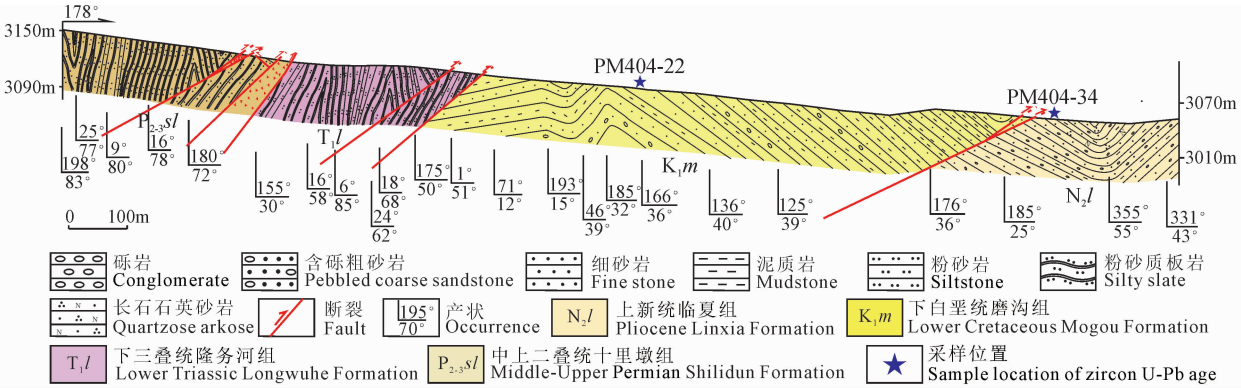


图 2 西秦岭造山带临潭地区小沟地质剖面图

Fig. 2 Section of the Xiaogou at Lintan area in the West Qinling orogenic belt

22)和临夏组(样品 PM404-34) 2 个样品均采自临潭县长川乡阳坡山—木地坡村(剖面 PM404),采样点地理坐标分别为 N34° 44′ 49.901″, E103° 27 34.068″, H3092m 和 N34° 44′ 12.610″, E103° 27

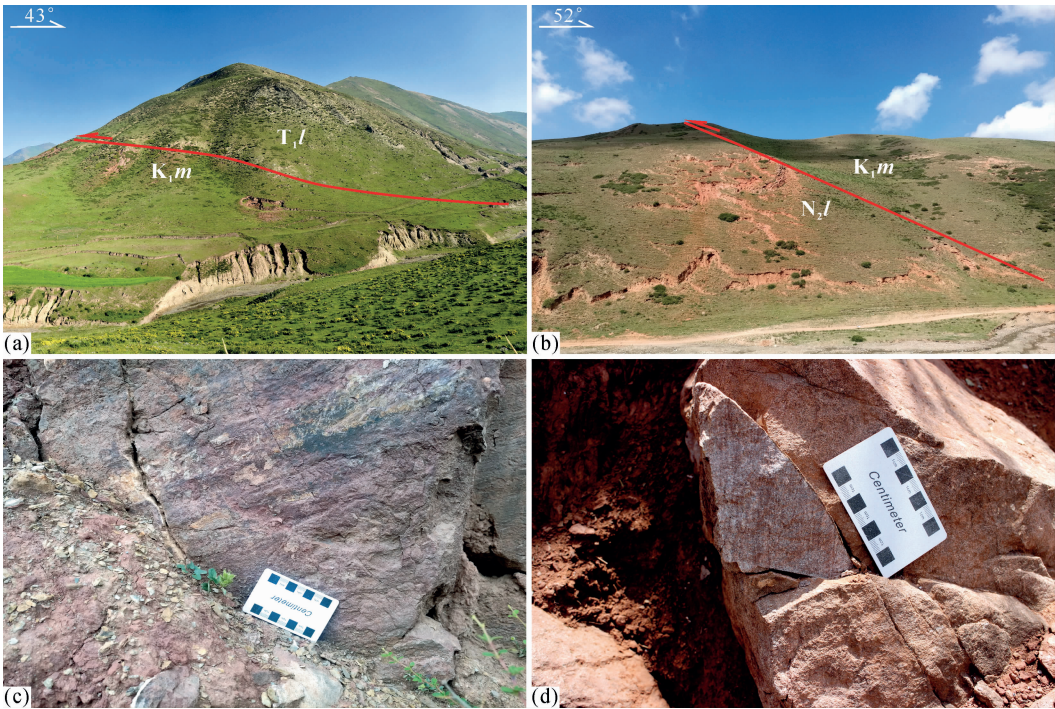


图 3 西秦岭造山带临潭地区下白垩统磨沟组(a, c)和上新统临夏组(b, d)野外照片

Fig. 3 Field photographs from the Lower Cretaceous Mogou Formation (a, c) and Pliocene Linxia Formation (b, d) at Lintan area in the West Qinling orogenic belt

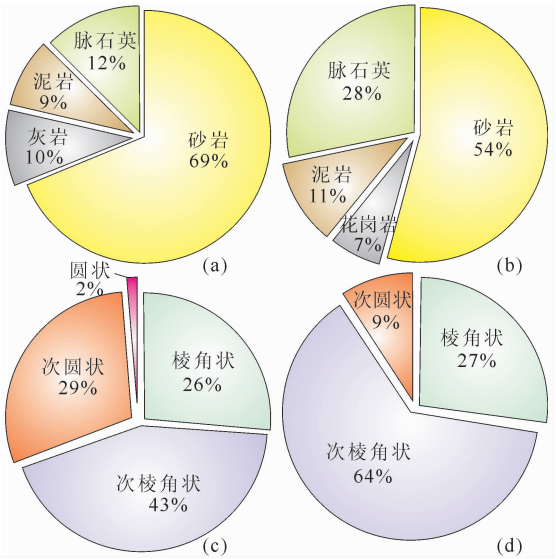


图 4 西秦岭造山带临潭地区下白垩统磨沟组砾石成分和磨圆度统计图(a, c 为下部层位, b, d 为上层层位)
Fig. 4 Composition and roundness of gravels counting from the Lower Cretaceous Mogou Formation at Lintan area in the West Qinling orogenic belt (a and c from the lower Mogou Formation, b and d from the upper Mogou Formation)

(图 3c),新鲜面为紫红色,砂质结构,厚层状构造,层厚 100~120cm。粒径 0.0039~0.065mm,砂质含量在 50%以上,粉砂质成分以石英为主,其次为白云母和长石,岩屑少见。

上新统临夏组(样品 PM404-34)样品岩性为紫红色厚层状粉砂岩(图 3d),新鲜面为砖红色,粉砂质结构,层状构造,层厚 100~150cm。粒径 0.0039~0.0625mm,砂质含量在 50%以上,粉砂成分以石英为主,其次为白云母和长石,岩屑少见,碎屑的磨圆度较差,多呈棱角状,显示出近源堆积为主的特征。

3 实验分析方法

样品先采用常规方法粉碎至 80~100 目,并用常规浮选和电磁选方法进行分选,再在双目镜下挑选出晶形和透明度较好的锆石颗粒作为测定对象。将锆石颗粒粘在双面胶上,然后用无色透明的环氧树脂固定,待环氧树脂充分固化后,对其表面进行抛光至锆石内部暴露,然后进行反射光和透射光照相。阴极发光图像在北京锆年领航科技有限公司的扫描电镜加载阴极发光仪上完成。锆石原位 U-Pb 同位素年龄分析在北京科荟测试技术有限公司的 LA-ICP-MS 仪器上用标准测定程序进行,分析仪器激

35.900", H3011m(图 1b)。其中下白垩统磨沟组(样品 PM404-22)样品岩性为紫红色厚层状粗砂岩

光剥蚀斑束直径为 $30\mu\text{m}$, 激光剥蚀深度为 $20\sim 40\mu\text{m}$ 。锆石年龄计算采用标准锆石 91500 作为外标, 元素含量采用美国国家标准物质局人工合成硅酸盐玻璃 NiSTSRM610 作为外标, ^{29}Si 作为内标原素进行校正。样品的同位素比值和元素含量数据处理采用 GLITTER(4.0 Macquarie University) 版软件并采用 Andersen(2002) 软件对测试数据进行普通铅校正, 所得数据通过 Isoplot 宏程序(Ludwig, 2003) 计算完成。对于谐和度小于 90% 的锆石点本文舍弃不作讨论, 同时对小于 1.0Ga 的锆石采用 $^{206}\text{Pb}/^{238}\text{U}$ 年龄; 对于大于 1.0Ga 的锆石采用 $^{207}\text{Pb}/^{206}\text{Pb}$ 年龄(Griffin et al., 2004)

4 锆石 U-Pb 年代学结果

4.1 碎屑锆石特征

下白垩统磨沟组(样品 PM404-22)砂岩样品中挑选出的锆石为自形晶(图 5a), 多呈透明一半透明短柱状、次圆状等, 粒径介于 $80\sim 200\mu\text{m}$ 之间, 晶体长宽比为 $1:1\sim 3:1$ 。晶体中可见凹坑、沟槽及断口磨蚀痕迹, 大多数锆石不同程度地保留有岩浆结晶成因特征的振荡环带, 部分锆石颗粒具有窄的浅

色边, 但核部仍显示出典型的生长韵律环带及明暗相间的条带特征, 表明浅色边为变质的增生边。从锆石形态上可以判断, 这些锆石包含了多种成因类型的锆石, 而不同性质的锆石反映了其物源区的复杂性。锆石稀土元素球粒陨石标准化模式图(图 6a, 附表 1) 具有轻稀土元素(LREE) 含量低, 重稀土元素(HREE) 富集的左倾模式, 且 Ce 正异常和 Eu 负异常十分突出。锆石 Th 含量为 $15.14\times 10^{-6}\sim 738.81\times 10^{-6}$, U 含量为 $11.50\times 10^{-6}\sim 789.45\times 10^{-6}$ (附表 2), 锆石 Th/U 比值介于 $0.16\sim 1.89$ 之间, 其中有 73 颗锆石(占 85.88%) Th/U 比值大于 0.4(图 6c), 说明绝大多数锆石为岩浆结晶锆石(Hoskin and Black, 2000)。

上新统临夏组(样品 PM404-34)样品中挑选出的锆石为自形晶(图 5b), 多呈透明一半透明短柱状、次圆状等, 粒径介于 $90\sim 250\mu\text{m}$ 之间, 晶体长宽比为 $1:1\sim 3:1$ 。锆石内部结构复杂, 成因多样。部分锆石具有残留的核部, 为继承核或捕获核。部分锆石颗粒也具有窄的浅色边, 但核部仍显示出典型的生长韵律环带及明暗相间的条带特征, 表明浅色边为变质的增生边。从锆石形态上可以判断, 这

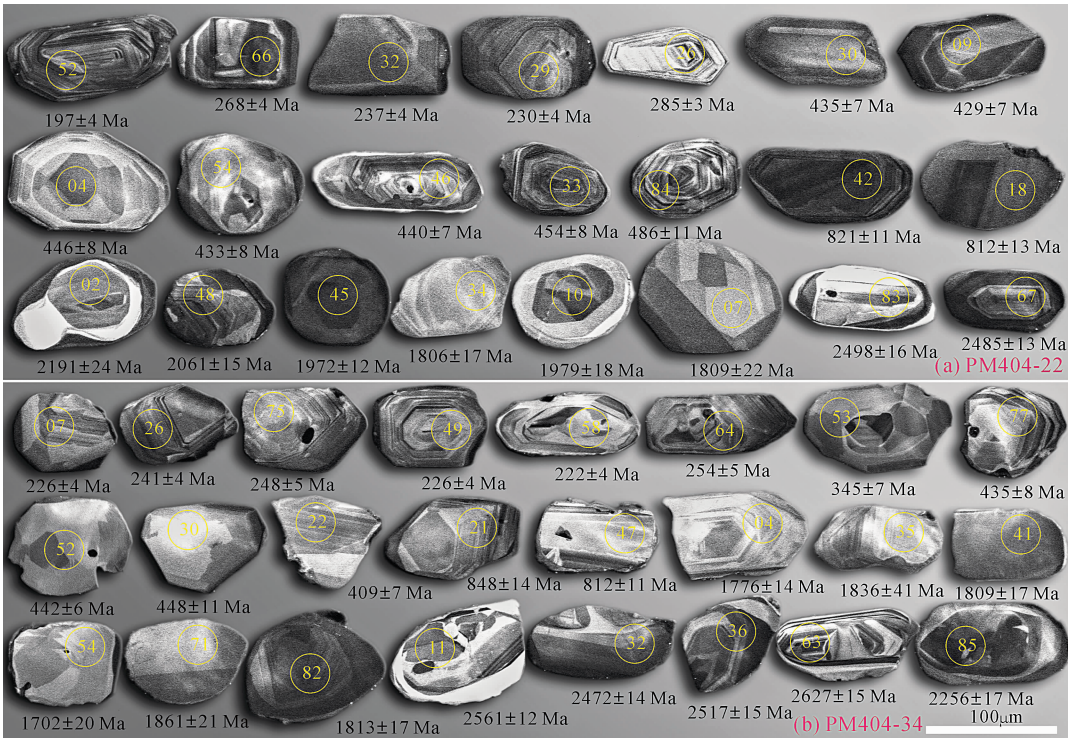


图 5 西秦岭造山带临潭地区下白垩统磨沟组(a)(样品 PM404-22)和上新统临夏组(b)(样品 PM404-34)典型碎屑锆石阴极发光图像和 $^{206}\text{Pb}/^{238}\text{U}$ 年龄值

Fig. 5 CL images and $^{206}\text{Pb}/^{238}\text{U}$ ages of the typical detrital zircons from the Lower Cretaceous Mogou Formation (a) (sample PM404-22) and the Pliocene Linxia Formation (b) (sample PM404-34) at Lintan area in the West Qinling orogenic belt

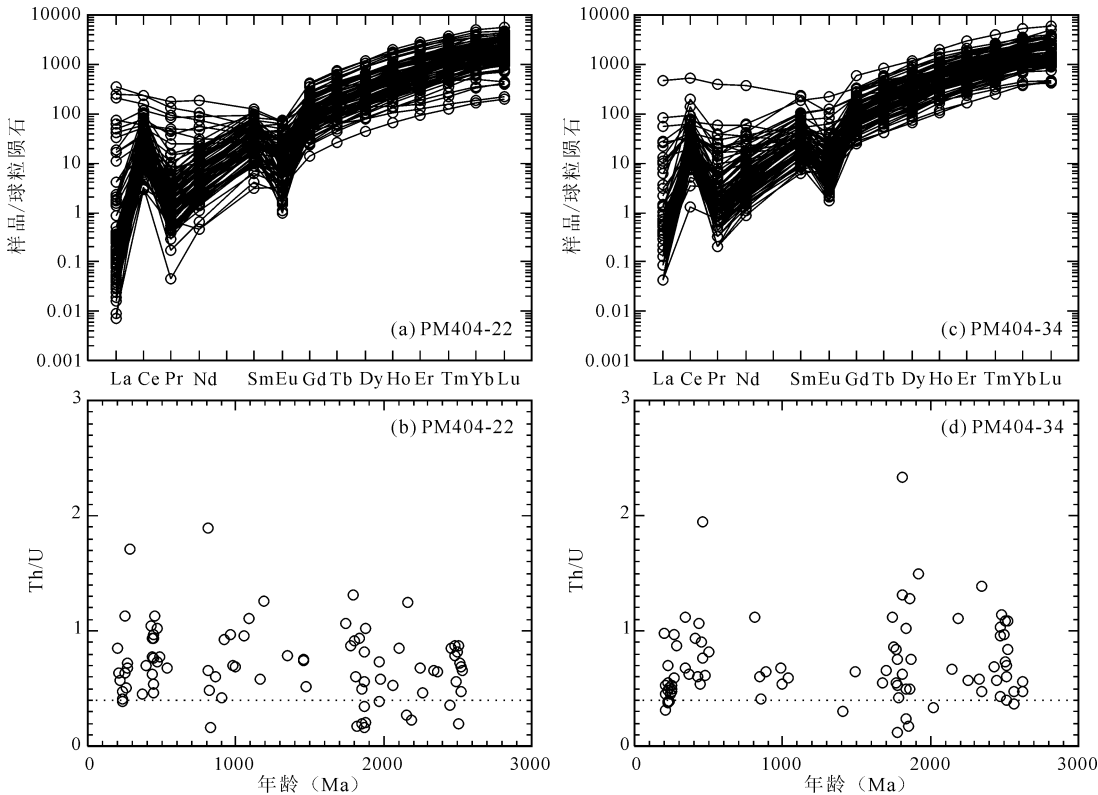


图 6 西秦岭造山带临潭地区下白垩统磨沟组(样品 PM404-22)和上新统临夏组(样品 PM404-34)碎屑锆石球粒
陨石标准化配分及年龄分布图(球粒陨石标准化数据据 Sun and McDonough, 1989)

Fig. 6 Chondrite-normalized REE patterns and ages distribution of the detrital zircons from the Lower Cretaceous Mogou
Formation (sample PM404-22) and the Pliocene Linxia Formation (sample PM404-34) at Lintan area in the West Qinling
orogenic belt (chondrite data for normalization taken from Sun and McDonough, 1989)

些锆石包含了多种成因类型的锆石,而不同性质的
锆石反映了其物源区的复杂性。锆石稀土元素球粒
陨石标准化模式图(图 6c, 附表 1)显示和下白垩统
磨沟组样品相似的特征,均具有 Ce 正异常和 Eu 负
异常的特征。锆石 Th 含量为 $6.11 \times 10^{-6} \sim 839.13$
 $\times 10^{-6}$, U 含量为 $8.77 \times 10^{-6} \sim 1574.49 \times 10^{-6}$,
Th/U 比值为 0.12~2.33,其中有 75 颗锆石(占
88.24%)的 Th/U 比值大于 0.4(图 6d, 附表 2),指
示样品中锆石以岩浆成因锆石为主(Hoskin and
Black, 2000)。

4.2 碎屑锆石年龄谱特征

下白垩统磨沟组(样品 PM404-22)共测试了 85
个点,挑选谐和度>90%的 82 个测点进行年龄统计
(图 7a)。Th/U 比值为 0.16~1.89,年龄在 2531~
197 Ma 之间,主要有 2531~1744 Ma、1457~1057
Ma、996~812 Ma、534~429 Ma、396~252 Ma、250
~197 Ma 共 6 个年龄组(附表 2)。其中 250~197
Ma 年龄组有 6 颗,占 7.32%,峰值年龄 237 Ma;
396~252 Ma 年龄组有 7 颗,占 8.54%,无明显峰

值;534~429 Ma 年龄组有 14 颗,占 17.07%,峰值
年龄 447 Ma;996~812 Ma 年龄组有 10 颗,占
12.20%,峰值年龄 880 Ma;1457~1057 Ma 年龄组
有 7 颗,占 8.54%,无明显峰值;2531~1744 Ma 年
龄组有 38 颗,占 46.34%,出现两个年龄峰值,分别
为 1920 Ma、2435 Ma。

上新统临夏组(样品 PM404-34)测试了 85 个
点,挑选谐和度>90%的 79 个测点进行年龄统计
(图 7b)。Th/U 比值为 0.12~1.95,年龄在 2627~
202 Ma 之间,主要有 2627~1676 Ma、1487~1035
Ma、994~812 Ma、502~425 Ma、409~254 Ma、248
~202 Ma 共 6 个年龄组(附表 2)。其中 248~202
Ma 年龄组有 14 颗,占 17.72%,峰值年龄 223 Ma;
409~254 Ma 年龄组有 6 颗,占 7.59%,无明显峰
值;502~425 Ma 年龄组有 8 颗,占 10.13%,峰值
年龄 426 Ma;994~812 Ma 年龄组有 5 颗,占
6.33%,峰值年龄 900 Ma;1487~1035 Ma 年龄组
有 3 颗,占 3.80%,无年龄峰值;2627~1676 Ma 年
龄组有 43 颗,占 54.43%,也出现两个年龄峰值,分

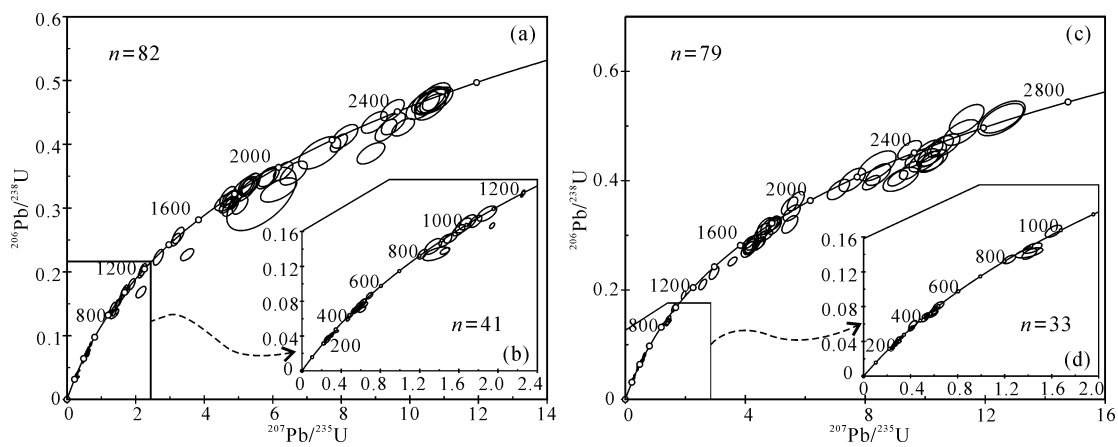


图 7 西秦岭造山带临潭地区下白垩统磨沟组(a, b)(样品 PM404-22)和上新统临夏组(c, d)(样品 PM404-34)碎屑锆石 U-Pb 年龄谐和图

Fig. 7 Zircon U-Pb concordia diagram from the Lower Cretaceous Mogou Formation (a, b) (sample PM404-22) and the Pliocene Linxia Formation (c, d) (sample PM404-34) at Lintan area in the West Qinling orogenic belt

别为 1795 Ma、2424 Ma。

5 讨论

5.1 新太古代—古元古代年龄信息

下白垩统磨沟组和上新统临夏组 2 个样品获得的该段的年龄数据最多,共有 81 个测点,年龄在 2627~1676 Ma 之间,占锆石总数的 50.31%。其中下白垩统磨沟组样品 PM404-22 的峰值年龄为 2435 Ma 和 1920 Ma;上新统临夏组样品 PM404-34 峰值年龄分别为 2424 Ma 和 1795 Ma,显然这两个样品具有相似的物源区(图 8a, 8b)。Shen Qihan et al. (2005)对华北板块早前寒武纪锆石的年龄进行统计研究,发现峰值以 2.5~2.55 Ga 最为突出,2.7 Ga、2.85~2.8 Ga 次之;Geng Yuansheng et al. (2002, 2010)指出华北板块在前寒武纪阶段,2.5 Ga、2.7 Ga 是 2 个主要的火山活动峰期,并认为变质基底中正片麻岩的主体年龄为 2.6~2.45 Ga;He Yanhong et al. (2005a)获得秦祁结合部位陇山岩群中花岗质片麻岩年龄有 1.90 Ga、2.35 Ga、2.50 Ga 峰值年龄和 Wang Yinchuan et al. (2012)在陇山岩群中获得花岗质片麻岩年龄为 1765±57 Ma;Pei Xianzhi et al. (2012)认为北祁连造山带结晶基底和华北板块基底岩系具有亲缘性;Pei Xianzhi et al. (2007)对西秦岭北缘构造带葫芦河群浅变质砂岩的碎屑锆石进行 U-Pb 测年,获得了 2578~2302 Ma 的年龄结果,并认为可能存在古元古代—新太古代结晶基底杂岩。在秦岭造山带及华北板块南缘亦有古元古代晚期的岩浆事件发生。太白岩基巩坚沟变形侵入体和宝鸡岩基胡店变形侵入体的结晶年龄分

别是 1741±12 Ma 和 1770±13 Ma,其形成时代和岩浆构造属性与 Columbia 超大陆汇聚具有极强的相关性,亦是吕梁运动在北秦岭西段的响应(Wang Hongliang et al., 2008)。而华北板块在吕梁造山运动后,华北板块约在 1.6~1.8 Ga 期间发育了一系列非造山裂解事件的岩浆活动(Lu Songnian et al., 2002, 2010; Zhai Mingguo and Peng Peng, 2007; Zhao Guochun, 2009)。因此,这些古老碎屑锆石年龄应反映了典型的祁连造山带、华北板块、北秦岭构造带结晶基底岩石信息。

5.2 中元古代年龄信息

下白垩统磨沟组样品 PM404-22 和上新统临夏组样品 PM404-34 获得中元古代年龄数据共 10 个,年龄在 1487~1035 Ma 之间,占锆石总数的 6.21%。该年龄段数据较分散,2 个样品均无明显的峰值年龄。

在祁连造山带获得的该阶段的年龄有马街山群(1192±38 Ma, Wang Hongliang et al., 2007)、兴隆山岩群(1172 Ma, Xu Xueyi et al., 2008)、化隆南片麻状正长花岗岩和永靖黑云斜长片麻岩(1470 Ma 和 1570 Ma, Wan Yusheng et al., 2003)。表明西秦岭地区下白垩统磨沟组和上新统临夏组的中元古代碎屑锆石有来自于祁连造山带、基底岩系的可能。

5.3 新元古代年龄信息

新元古代年龄数据共有 15 个,年龄在 996~812 Ma 之间,占锆石总数的 9.32%。下白垩统磨沟组样品 PM404-22 的峰值年龄为 880 Ma,上新统临夏组样品 PM404-34 的年龄峰值为 900 Ma(图

8a, 8b)。2 个样品的峰值年龄非常接近。

已有研究表明,受新元古代 Rodinia 超大陆的聚合和裂解活动的影响,在祁连造山带和西秦岭北缘产生一系列构造岩浆活动。1000~800 Ma 是 Rodinia 超大陆的聚合阶段,而 800~700 Ma 是 Rodinia 超大陆的裂解阶段 (Pei Xianzhi et al., 2012)。祁连造山带与 Rodinia 超大陆聚合和裂解有关的岩浆活动有:向河岩体 (917 ± 12 Ma, Guo Jinjing et al., 1999);中祁连东段的五峰村、五间房、日月亭和向河花岗岩体 (846 ± 2 Ma、 853 ± 2 Ma、 756 ± 2 Ma、 888 ± 3 Ma, Yong Yong et al., 2008);化隆岩群副片麻岩和侵入其中的片麻状花岗岩 ($940 \sim 850$ Ma, Xu Wangchun et al., 2007; Yan Zhen et al., 2015);兴隆山岩群火山岩 ($723 \sim 824$ Ma, Xu Xueyi et al., 2008)。

西秦岭北缘在同时期亦有新元古代构造岩浆事件发生。天水地区新阳细尾子沟花岗质片麻岩 ($981 \pm 5 \sim 938 \pm 4$ Ma, Ding Saping et al., 2006; 978.5 ± 4.8 Ma 和 935.5 ± 3.1 Ma, Pei Xianzhi et al., 2007);元龙花岗质片麻岩 (924.2 ± 2.7 Ma, Liu Huibin et al., 2006; 914.7 ± 7.6 Ma, Pei Xianzhi et al., 2007);社棠郭家坪花岗质片麻岩 (953.4 ± 14 Ma, Lu Songnian et al., 2003);武山北花岗质片麻岩 (951 ± 18 Ma, Li Wangye, 2008);木其滩岩组斜长角闪岩 (762.5 ± 4.6 Ma, Zhang Zhiguo et al., 2011)。

因此,下白垩统磨沟组和新统临夏组碎屑锆石中的新元古代年龄信息可能为祁连造山带和西秦岭北缘构造带在新元古代构造岩浆事件的物质记录。

5.4 早古生代年龄信息

早古生代获得 22 个年龄数据,年龄在 534~425 Ma 之间,占锆石总数的 13.66%。下白垩统磨沟组样品 PM404-22 有 12 个年龄数据,其峰值年龄为 447 Ma,上新统临夏组样品 PM404-34 有 8 个年龄数据,其峰值年龄为 426 Ma (图 8a, 8b)。前人对北祁连造山带东段加里东期岩浆活动研究得到了诸多成果,获得一批同位素年龄数据,时代主要集中在 $440.2 \pm 0.92 \sim 452.8 \pm 1.7$ Ma 之间 (He Yanhong et al., 2005a, 2005b; Chen Junlu et al., 2006, 2007; Zhang et al., 2006; He Shiping et al., 2007; Pei Xianzhi et al., 2007; Li Wangye, 2008; Wei Fanhui et al., 2012)。而在西秦岭北缘构造带在早古生代时期岩浆活动复杂,并广泛发育俯冲-碰撞型

花岗质岩浆岩。基性岩浆岩年龄集中在 $449.7 \pm 3.1 \sim 548.7 \pm 1.8$ Ma 之间 (长安大学地质调查研究院, 2004^②, Pei Xianzhi et al., 2005, 2007; Yang Zhao et al., 2006; Wang Hongliang et al., 2007; Li Wangye, 2008; Gao Jingmin et al., 2012; Wang Jiangbo et al., 2018);中酸性岩浆岩的年龄在 $438 \pm 3 \sim 454.0 \pm 1.7$ Ma 之间 (Pei Xianzhi et al., 2004; Chen Junlu et al., 2008; Wang Jing et al., 2008)。

下白垩统磨沟组和新统临夏组 2 个样品中 426 Ma 和 447 Ma 峰值年龄可能与祁连造山带与西秦岭微板块在加里东期向北俯冲而产生的构造岩浆事件具有相关性,表明祁连造山带和西秦岭北缘构造带存在为下白垩统磨沟组和新统临夏组沉积提供物源的可能性。

5.5 晚古生代年龄信息

晚古生代年龄数据获得 13 个,年龄在 409~252 Ma 之间,占锆石总数的 8.07%。2 个样品均没有明显的峰值。

在北、中秦岭及周缘地区均有晚古生代岩浆岩的分布,均可能是该年龄段的锆石来源。Xu Xueyi et al. (2014) 获得西秦岭中川、江里沟花岗岩体年龄分别为 264.4 ± 1.3 Ma、 264 ± 1.4 Ma,地球化学特征显示其具活动大陆边缘岩浆岩特征,并认为这一时期存在板块的俯冲作用,该组碎屑锆石年龄与西秦岭构造带的岩浆事件具相关性,反映这些年龄与古特洋盆俯冲作用相关。在西秦岭地区西北缘夏河县甘家乡一带发现有中二叠世发生拉张环境的玄武岩 (LA-ICP-MS 锆石 U-Pb 年龄为 267.7 Ma^③),断裂带西延在隆务峡的小型超基性岩体 (LA-ICP-MS 锆石 U-Pb 年龄为 $251.4 \pm 0.7 \sim 256.2 \pm 3.1$ Ma^④),在研究区的北侧发现有凉帽山超基性岩体和东侧的下拉地超基性岩体,推测两者可能为一期构造岩浆事件,侵入时代为二叠纪 (Fei Yiqing and Zhou Xianjun, 2012)。

5.6 早中生代年龄信息

早中生代年龄数据获得 20 个,年龄在 250~197 Ma 之间,占锆石总数的 12.42%。下白垩统磨沟组样品 PM404-22 有 6 个年龄数据,其峰值年龄为 237 Ma;上新统临夏组样品 PM404-34 有 14 个年龄数据,其峰值年龄为 223 Ma (图 8a, 8b)。

在研究区合作-岷县断裂北侧的中秦岭构造带中出露的美武岩体、早子沟闪长玢岩、岗岔岩体、五朵金花岩体群 (教场坝、柏家庄、碌础坝、吴茶坝和正

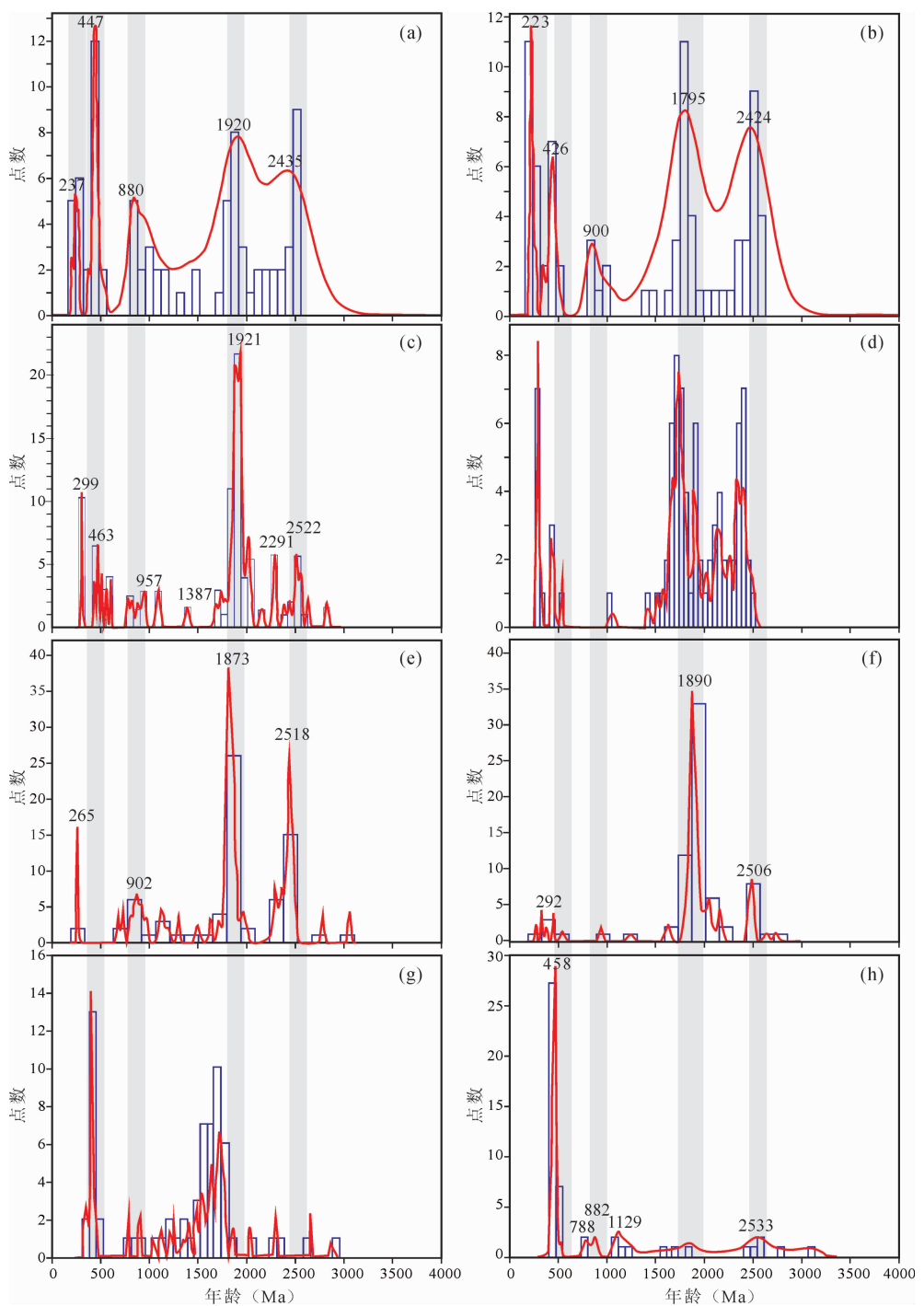


图 8 西秦岭造山带临潭及周缘地区锆石 U-Pb 年龄直方图及概率密度曲线

Fig. 8 Histograms and probability density curve at Lintan and its surrounding areas in the West Qinling orogenic belt
(a)—下白垩统磨沟组(样品 PM404-22);(b)—上新统临夏组(样品 PM404-34);(c)—下三叠统隆务河组(临潭县小沟剖面 PM404),据 Li Zuochen et al. ,待发表;(d)—下三叠统隆务河组(合作南),据 Chen Yuelong et al. ,2008;(e, f)—中上二叠统十里墩组(临潭县小沟剖面 PM404),据 Gao Xiangyu et al. , 2019;(g)—上泥盆统大草滩组 c 岩组(漳县大草滩),据 Chen Yibing et al. , 2010;(h)—上泥盆统大草滩组 b 岩组(天水皂郊镇),据 Wu Shukuan et al. , 2012
(a)—Lower Cretaceous Mogou Formation (sample PM404-22); (b)—Pliocene Linxia Formation (sample PM404-34); (c)—Lower Triassic Longwuhe Formation (Xiaogou, Lintan County, PM404), after Li Zuochen et al. , unpublished; (d)—Lower Triassic Longwuhe Formation (South of Hezuo), after Chen Yuelong et al. ,2008; (e, f)—Middle and Upper Permian Shilidun Formation (Xiaogou, Lintan County, PM404), after Gao Xiangyu et al. , 2019; (g)—Formation C of Upper Devonian Dacatou Formation (Dacaotan, Zhangxian County), after Chen Yibing et al. , 2010; (h)—Formation B of Upper Devonian Dacatou Formation (Zaojiao, Tianshui), after Wu Shukuan et al. , 2012

沟)、温泉岩体等花岗岩体,这些岩体的侵位年龄为245~211 Ma(Feng Yimin et al., 2003; Jin Weijun et al., 2005; Wang Huiqing et al., 2010; Liu Chunxian et al., 2011; Luo Biji et al., 2012; Wu Guoli et al., 2014; Zhang Dexian et al., 2015; Li Jinchun et al., 2016; Zhang Yongming et al., 2017; Wang Meng et al., 2019),下白垩统磨沟组和新统临夏组2个样品中的三叠纪年龄记录了该期构造岩浆事件的信息。

5.7 物源分析

下白垩统磨沟组的砾石成分以砂岩为主,脉石英次之,其中砂岩砾石的含量自下而上逐渐减少,比例由69%减少到54%,脉石英则相反,由12%增加到28%,下部层位含有少量灰岩,约占10%,上部层位中见有少量花岗岩砾石,约占7%(图4a, 4b),泥岩含量较为稳定,在9%~11%之间。砾石的磨圆度较差,多呈次棱角状,显示出近源堆积为主的特征,且次棱角状砾石比例自下而上由43%逐渐增多,达到64%,棱角状砾石比例相对稳定在26%~27%之间,圆状一次圆状砾石则由31%减少到9%(图4c, 4d),表明砾石搬运的距离逐渐减小。在区域上磨沟组主要分布在合作-岷县断裂两侧,以及与商丹缝合带之间的中秦岭构造带内,其地层包括泥盆系一中上二叠统的一套碎屑岩、灰岩,侵入有较多的印支期花岗岩体。南侧的三叠纪地层岩性也主要是一套碎屑岩,表明这些砾石均来自于周缘的泥盆纪—三叠纪地层,花岗岩砾石可能来自于研究区北部的美武岩体。

而锆石的耐久性一方面能使其在沉积环境中经历了风化、搬运、埋藏后仍能保持晶体内部U-Pb系统的稳定,从而能记录最初形成时的年龄(Dickinson et al., 2009);另一方面,也暗示其在经历多次沉积旋回后仍能留于沉积物中,即较老沉积物中的碎屑锆石可再次出现在年轻的沉积物中(Thomas et al., 2004; Link et al., 2005; Guo Pei et al., 2017)。因此,沉积岩碎屑锆石具有多来源和多成因的特点,碎屑锆石年龄谱的研究可以提供蚀源区构造-热事件演化、沉积物源等丰富的地质信息。下白垩统磨沟组和新统临夏组样品中挑选出的锆石为自形晶(图5a, 5b),多呈透明一半透明短柱状、次圆状等,晶体中可见凹坑、沟槽及断口磨蚀痕迹。从锆石形态上可以判断,这些锆石包含了多种成因类型的锆石,而不同性质的锆石反映了其物源区的复杂性。碎屑锆石阴极发光图像(图5a, 5b)

显示,古老的锆石多显示为次圆状,因此,根据锆石所具有的次圆状形态和晶体中可见凹坑、沟槽及断口磨蚀痕迹,也可推测有相当数量的锆石可能为再沉积的锆石(Gärtne et al., 2017)。而早中生代的锆石则大多显示出柱状,表明这些锆石可能来自于北侧印支期岩体。

从区域地层分布来看,在研究区合作-岷县断裂以南主要沉积了下三叠统隆务河组(T_1l)、中三叠统光盖山组(T_2gg)、上三叠统大河坝组(T_3d),三叠纪西秦岭地区总体为一套半深海到浅海沉积组合。而在岷县-合作断裂以北仅在中秦岭构造带的夏河县以西一带沉积了三叠纪地层,而在研究区北侧的则没有三叠纪沉积。表明研究区北部自中晚二叠世之后已隆升遭受剥蚀,为随后的沉积盆地提供物源。在锆石U-Pb年龄直方图上(图8a, 8b),下白垩统磨沟组和新统临夏组中锆石所蕴含的年龄分布特征总体较为一致,均有华北板块特有的1.8 Ga和2.5 Ga年龄数据,且占锆石总数的50.31%。这与研究区北侧已有的下三叠统隆务河组和中上二叠统十里墩组的碎屑锆石年龄谱相似(图8c~8f)(Chen Yuelong et al., 2008; Gao Xiangyu et al., 2019; L. Zuo Chen et al., 待发表)。下白垩统磨沟组和新统临夏组中早古生代的碎屑锆石年龄谱与上泥盆统大草滩组碎屑锆石年龄分布特征相似(图8g, 8h)(Chen Yibing et al., 2010; Wu Shukuan et al., 2012)。早中生代年龄信息则与中秦岭构造带中出露的印支期花岗岩体相关(245~211 Ma, Feng Yimin et al., 2003; Jin Weijun et al., 2005; Wang Huiqing et al., 2010; Liu Chunxian et al., 2011; Luo Biji et al., 2012; Wu Guoli et al., 2014; Zhang Dexian et al., 2015; Li Jinchun et al., 2016; Wang Meng et al., 2019)。

因此,在中—晚三叠世(印支期)主碰撞造山后,西秦岭地区处于伸展体制阶段,形成沿断裂带分布的小型陆内断陷盆地,沉积下白垩统磨沟组陆相碎屑岩,与下伏地层为角度不整合接触。晚白垩世—古近纪末期,西秦岭经历了一次较强烈的地壳缩短,导致前古近纪地层形成了北西向的平缓褶皱和逆冲推覆构造。燕山晚期西秦岭造山带发生伸展构造作用,沿新生的NE-NEE方向的左行走滑构造带产生具有拉分盆地性质的晚白垩世—古近纪红色陆相断陷盆地沉积,区域上呈斜列式展布(Guo Jinjing and Han Wenfeng, 2008; Guo Jinjing et al., 2009, 2016)。研究区合作-岷县断裂北侧的中秦岭构造带

为断陷盆地提供了物源,下白垩统磨沟组和新统临夏组多个分组的年龄谱特征记录了物源区地质体中的再旋回年龄信息。

6 结论

(1)临潭地区下白垩统磨沟组和新统临夏组碎屑锆石年龄谱 2627~1676 Ma、1487~1035 Ma、996~812 Ma、534~425 Ma、409~252 Ma、250~197 Ma 共 6 个年龄组。对应于西秦岭地区新太古代—古元古代、中元古代、新元古代、早古生代、晚古生代、早中生代 6 个演化阶段的年龄信息。

(2)下白垩统磨沟组和新统临夏组中锆石年龄分布特征较为一致,均有新元古代、早古生代、早中生代年龄峰值,以及华北板块特有的 1.8 Ga 和 2.5 Ga 年龄峰值。

(3)下白垩统磨沟组和新统临夏组的物源具有近源堆积为主的特征,合作—岷县断裂北侧的中秦岭构造带为其提供了物源,碎屑锆石年龄谱特征记录了物源区地质体中的再旋回年龄信息。

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注 释

① 甘肃省地质调查院. 2007. 1: 250000 合作镇幅区域地质调查报告.
② 长安大学地质调查研究院. 2004. 天水市幅(148C002003)1: 250000 区域地质调查(修测)成果报告.
③ 中国地质大学(武汉)地质调查研究院. 2006. 1: 250000 临夏市幅区域地质调查报告.

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Detrital zircon U-Pb age and provenance analysis of Lower Cretaceous-Pliocene continental strata at Lintan area in the West Qinling orogenic belt

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Abstract

With clastic rocks of the Lower Cretaceous Mogou Formation and the Pliocene Linxia Formation at Lintan area in the West Qinling orogenic belt as the study object, the authors used LA-ICP-MS zircon U-Pb isotope geochronological method to explore the provenance of Mogou Formation and Linxia Formation, which has important significance of study of Meso-Cenozoic tectonic evolution of the West Qinling orogenic belt. The results show that the detrital zircon ages are divided into 6 groups: (1) The Neoproterozoic (2627~1676 Ma); (2) The Mesoproterozoic (1487~1035 Ma); (3) The Neoproterozoic (996~812 Ma); (4) The Early Paleozoic (534~425 Ma); (5) The Late Paleozoic (409~252 Ma); (6) The Early Mesozoic (250~197 Ma), of which, the Neoproterozoic (2627~1676 Ma) ages data possess the largest proportion, accounting for about 50.31% of the total data. The other ages possess a smaller proportion. The provenance source of Mogou Formation and Linxia Formation were much more complicated and characterized by obvious diversity. The Zircon age distribution of the two samples was consistent, with the Indosinian, Caledonian, and Neoproterozoic age peaks, as well as the unique peaks of 1.8 Ga and 2.5 Ga in the North China Block. The Lower Cretaceous Mogou Formation and the Pliocene Linxia Formation are characterized by proximal deposition. The Middle Qinling tectonic belt provides provenance, and the age patterns of the detrital zircon recorded the age information of multi-recycling zircons in the geological bodies of the provenance area.

Key words: West Qinling orogenic belt; Lower Cretaceous-Pliocene; zircon U-Pb age; detrital zircon; provenance analysis

附表 1 西秦岭临潭地区下白垩统磨沟组砂岩 (样品 PM404-22) 和上新统临夏组砂岩 (样品 PM404-34) 锆石微量元素 ($\times 10^{-6}$) 分析结果

Appendix 1 Zircon trace element data ($\times 10^{-6}$) results for sandstone from the Lower Cretaceous Mogou Formation (sample PM404-22) and the Pliocene Linxia Formation (sample PM404-34) in the West Qinling orogenic belt

样品	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	ΣREE	δEu	δCe
PM404-22																	
PM404-22-01	0.02	15.64	0.37	7.53	15.14	0.41	78.86	25.70	304.51	112.36	471.74	95.83	834.98	139.71	2102.81	0.03	12.75
PM404-22-02	0.01	7.45	0.02	0.31	1.03	0.31	4.74	1.66	20.04	7.56	35.00	9.08	97.17	19.52	203.92	0.36	112.30
PM404-22-03	0.02	23.53	0.11	1.84	3.19	0.18	10.71	3.31	36.45	12.11	52.96	11.59	114.61	18.54	289.16	0.08	60.93
PM404-22-04	0.03	12.89	0.24	3.74	5.78	0.97	24.96	7.43	81.78	29.17	125.81	28.23	263.61	46.88	631.54	0.21	15.53
PM404-22-05	0.03	12.32	0.04	0.73	1.60	0.32	8.99	3.14	36.28	13.49	61.79	14.26	139.27	25.05	317.31	0.20	71.67
PM404-22-06	0.01	9.26	0.04	0.86	2.03	0.15	11.25	4.18	50.72	19.40	85.81	19.24	183.39	30.91	417.27	0.08	60.46
PM404-22-07	0.01	4.51	0.23	3.47	6.68	1.73	21.36	5.66	52.93	15.69	60.49	12.15	104.43	17.53	306.85	0.40	6.03
PM404-22-08	17.05	35.56	4.05	14.29	4.51	0.67	19.08	5.14	55.86	19.84	87.38	18.47	162.26	30.39	474.55	0.19	1.01
PM404-22-09	0.01	14.09	0.12	2.48	4.56	0.89	23.21	8.10	95.82	36.79	164.31	37.69	361.11	62.99	812.17	0.21	35.32
PM404-22-10	0.20	5.25	0.58	8.86	12.19	0.84	55.78	15.51	150.41	46.57	169.04	31.12	255.09	41.71	793.15	0.08	2.47
PM404-22-11	0.00	6.33	0.05	0.97	2.64	0.10	16.43	6.23	75.67	27.62	118.48	26.16	220.83	35.74	537.23	0.03	39.87
PM404-22-12	0.03	7.73	0.19	2.88	6.01	0.14	32.02	10.93	123.31	43.98	180.44	37.84	327.13	51.18	823.82	0.03	12.18
PM404-22-13	0.01	8.02	0.06	1.30	3.61	0.17	21.34	7.27	89.65	33.59	148.06	31.90	291.79	48.67	685.44	0.05	39.83
PM404-22-14	0.03	12.23	0.04	0.80	2.17	0.10	10.66	3.87	48.63	19.15	85.12	18.81	171.79	27.63	401.05	0.05	76.00
PM404-22-15	0.95	9.65	0.57	6.26	8.27	0.95	38.45	12.59	140.44	49.02	199.81	40.29	348.34	56.04	911.63	0.14	3.16
PM404-22-16	0.01	58.07	0.21	3.36	7.06	2.35	27.72	9.33	99.17	33.29	139.65	30.73	290.35	48.94	750.23	0.45	84.58
PM404-22-17	0.01	6.22	0.07	1.09	2.79	0.06	13.77	5.16	64.60	24.23	107.21	24.25	227.72	37.64	514.82	0.02	26.10
PM404-22-18	0.02	8.59	0.45	6.90	9.08	0.70	31.06	8.92	95.16	33.36	147.46	32.33	310.38	52.47	736.88	0.11	5.78
PM404-22-19	0.09	19.54	0.14	2.35	3.53	1.25	15.85	5.16	62.05	25.37	127.63	32.06	355.24	73.27	723.52	0.43	34.63
PM404-22-20	0.04	3.55	0.30	4.63	8.43	0.29	42.66	13.48	155.79	54.06	222.94	47.34	418.41	69.25	1041.17	0.04	3.54
PM404-22-21	0.02	21.11	0.26	3.84	6.35	2.65	25.87	7.80	85.51	29.97	128.25	28.69	272.19	46.54	659.05	0.54	24.64
PM404-22-22	0.49	23.43	0.31	2.69	3.90	0.79	18.82	5.99	66.59	22.41	95.40	19.77	179.19	29.94	469.74	0.23	14.43
PM404-22-23	0.03	2.87	0.10	1.95	6.10	0.28	30.90	5.98	35.71	8.00	26.43	5.74	57.77	10.61	192.47	0.05	8.18
PM404-22-24	0.01	15.67	0.05	1.05	1.46	0.41	6.29	2.13	24.48	9.53	43.69	10.45	109.27	19.76	244.24	0.35	98.40
PM404-22-25	0.07	60.34	0.37	4.34	6.51	2.57	25.14	8.78	93.36	30.25	130.61	29.47	289.10	54.75	735.66	0.54	47.24
PM404-22-26	0.02	37.26	0.08	1.35	3.36	1.19	17.12	5.76	73.93	28.90	139.86	34.22	355.66	67.18	765.87	0.39	130.56
PM404-22-27	0.06	51.87	0.13	2.21	3.85	0.96	16.31	4.56	50.30	17.36	73.69	16.51	160.82	27.26	425.89	0.32	106.15
PM404-22-28	0.02	8.90	0.21	3.35	8.64	3.56	49.83	12.95	107.70	26.19	74.69	11.60	82.01	10.90	400.56	0.41	12.83
PM404-22-29	0.05	11.40	0.04	0.82	1.74	0.27	10.09	3.42	38.85	14.60	63.03	14.28	132.05	23.23	313.88	0.16	58.62
PM404-22-30	0.06	17.52	0.57	9.38	16.75	3.86	86.72	26.97	296.59	102.15	414.06	84.29	735.99	121.78	1916.69	0.25	9.14
PM404-22-31	0.03	9.03	0.27	4.03	6.86	0.65	28.24	9.08	98.26	34.56	142.33	30.01	264.06	44.01	671.41	0.12	10.01
PM404-22-32	0.00	11.07	0.04	1.01	2.73	0.28	13.46	4.35	48.61	18.39	78.93	17.43	164.01	27.85	388.18	0.12	83.42
PM404-22-33	0.44	46.09	0.26	2.90	4.96	2.17	21.83	7.51	85.28	30.97	140.19	32.95	328.77	60.82	765.13	0.54	32.42

续附表 1

样品	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	ΣREE	δEu	δCe
PM404-22-34	0.33	10.04	0.38	5.69	8.02	0.98	35.71	10.45	111.74	38.76	156.80	33.35	289.69	47.37	749.31	0.15	6.11
PM404-22-35	4.00	24.09	1.41	7.92	5.40	0.55	22.16	6.86	74.56	27.04	114.34	24.60	229.78	38.97	581.69	0.13	2.48
PM404-22-36	0.03	8.74	0.31	5.29	8.17	0.61	38.54	12.09	137.15	48.71	203.50	41.41	370.02	62.00	936.58	0.09	8.35
PM404-22-37	0.01	15.40	0.05	0.80	1.30	0.44	6.87	2.32	26.03	10.43	48.86	12.34	133.65	26.13	284.63	0.36	84.01
PM404-22-38	0.03	1.85	0.13	2.71	7.48	0.10	49.75	19.48	242.30	90.15	376.13	77.90	676.32	109.14	1653.47	0.01	4.07
PM404-22-39	0.37	49.04	0.17	2.04	3.94	0.80	20.50	7.49	89.91	34.17	155.35	36.16	354.84	61.43	816.22	0.22	47.66
PM404-22-40	0.01	2.03	0.00	0.21	0.46	0.19	2.87	0.96	10.94	3.81	15.28	3.10	27.97	5.11	72.96	0.39	87.42
PM404-22-41	0.07	12.26	0.03	0.70	1.70	0.31	11.54	4.10	51.11	19.73	90.16	21.46	211.72	37.85	462.72	0.16	66.44
PM404-22-42	82.39	146.23	12.41	48.38	8.69	1.72	15.37	4.30	45.99	16.35	74.42	18.73	196.70	38.12	709.81	0.45	1.00
PM404-22-43	0.05	16.07	0.36	5.63	9.74	2.89	43.77	14.31	157.93	56.81	240.87	51.86	481.42	84.69	1166.40	0.36	13.30
PM404-22-44	0.41	14.14	0.67	5.91	9.71	2.85	39.24	14.43	163.06	55.64	244.82	61.04	627.71	112.00	1351.63	0.39	5.24
PM404-22-45	0.01	11.05	0.09	1.70	3.51	0.62	16.24	5.25	61.84	23.18	107.19	25.36	253.20	47.29	556.54	0.21	35.01
PM404-22-46	49.18	93.16	8.77	33.76	6.28	0.89	10.06	2.69	30.76	11.71	56.67	14.46	157.95	31.49	507.84	0.34	1.02
PM404-22-47	0.01	20.97	0.07	1.48	2.80	0.89	13.17	3.99	44.05	16.01	67.47	14.97	140.91	24.98	351.77	0.37	91.24
PM404-22-48	7.86	32.73	2.31	11.74	4.15	0.29	15.63	5.18	64.74	25.10	113.72	26.70	253.49	44.78	608.42	0.10	1.86
PM404-22-49	0.08	5.32	0.11	2.56	7.75	0.54	40.72	13.55	154.51	53.53	218.17	46.15	402.64	63.28	1008.90	0.07	11.28
PM404-22-50	0.03	7.62	0.14	2.12	3.23	0.89	16.60	5.13	61.22	23.08	103.74	25.21	255.72	48.00	552.74	0.30	15.38
PM404-22-51	0.01	22.50	0.09	1.51	3.39	0.82	19.14	6.49	80.33	30.68	136.89	31.85	296.32	52.24	682.25	0.25	73.03
PM404-22-52	4.38	64.47	1.47	10.27	11.23	3.51	53.90	16.29	172.20	58.36	236.37	50.89	467.04	77.53	1227.92	0.36	6.20
PM404-22-53	0.04	10.49	0.04	0.69	1.76	0.20	10.42	3.99	51.80	21.07	95.27	23.53	235.94	41.18	496.41	0.11	56.20
PM404-22-54	0.02	16.67	0.12	1.85	4.71	1.06	25.70	8.42	95.51	34.54	144.93	32.05	293.42	52.82	711.83	0.23	38.95
PM404-22-55	0.08	32.81	0.12	1.83	3.23	1.42	18.07	5.95	72.14	27.15	122.11	28.95	280.02	51.71	645.59	0.45	67.69
PM404-22-56	0.02	24.74	0.24	5.12	10.61	0.29	56.91	18.61	217.68	80.06	328.14	70.32	612.84	100.84	1526.41	0.03	31.38
PM404-22-57	58.66	147.07	16.16	84.59	19.11	3.99	31.09	7.02	71.52	25.40	107.25	23.65	218.20	39.76	853.48	0.50	1.15
PM404-22-58	0.06	4.07	0.04	0.51	0.97	0.21	5.06	1.88	21.06	7.54	30.84	6.75	59.36	9.78	148.14	0.24	20.96
PM404-22-59	1.00	18.16	0.42	5.49	8.88	1.48	40.13	12.79	146.38	52.37	219.68	47.86	440.93	76.08	1071.64	0.20	6.85
PM404-22-60	11.67	48.80	3.55	25.99	5.70	0.89	17.13	5.43	64.51	24.78	108.68	24.95	232.88	42.53	617.50	0.25	1.84
PM404-22-61	3.86	21.57	1.01	9.34	12.54	4.16	45.44	15.29	154.21	46.51	181.61	39.61	363.91	62.62	961.67	0.47	2.62
PM404-22-62	0.04	14.41	0.25	3.94	6.01	1.36	26.61	7.33	80.82	29.66	129.28	29.48	278.02	51.54	658.75	0.28	16.56
PM404-22-63	0.05	10.99	0.04	0.72	1.59	0.20	8.60	3.06	37.53	14.30	65.13	15.02	142.74	26.83	326.80	0.13	61.51
PM404-22-64	0.07	8.41	0.22	2.96	4.71	1.68	16.61	5.20	57.29	21.08	96.16	26.30	284.15	54.24	579.07	0.52	10.61
PM404-22-65	0.54	58.67	0.56	6.61	10.58	1.75	47.41	14.93	167.26	60.22	256.77	56.82	520.98	92.22	1295.32	0.20	23.56
PM404-22-66	0.03	20.68	0.31	5.83	11.88	0.73	70.05	23.72	268.19	95.64	378.82	74.60	607.09	100.28	1657.87	0.06	20.22
PM404-22-67	0.01	30.37	0.07	1.38	2.92	1.34	16.46	5.34	63.00	25.30	120.46	29.28	302.21	61.36	659.51	0.47	135.21
PM404-22-68	0.01	2.98	0.07	0.21	0.63	0.14	5.39	2.18	29.73	11.96	62.25	16.43	175.35	36.78	344.12	0.16	13.29
PM404-22-69	14.92	72.20	7.69	40.84	14.05	1.34	36.39	10.21	107.76	38.23	164.90	36.79	337.03	63.19	945.58	0.17	1.64

续附表 1

样品	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	ΣREE	δEu	δCe
PM404-22-70	0.04	16.43	0.12	2.29	3.68	0.86	17.33	5.33	64.57	25.96	127.87	30.69	310.62	63.48	669.27	0.27	39.14
PM404-22-71	0.10	17.31	0.82	12.54	17.30	0.38	70.07	20.86	220.56	76.80	309.86	62.19	511.66	88.43	1408.85	0.03	6.22
PM404-22-72	0.02	34.28	0.19	3.29	6.13	1.68	31.20	10.70	128.19	48.29	214.50	46.17	430.67	81.06	1036.39	0.30	53.69
PM404-22-73	9.54	36.19	4.62	21.44	13.04	0.76	44.15	13.14	140.62	50.17	214.06	45.03	396.81	71.65	1061.22	0.09	1.33
PM404-22-74	0.03	5.03	0.09	1.51	2.39	0.77	11.31	3.53	42.48	16.95	80.46	19.59	201.01	42.23	427.39	0.38	14.88
PM404-22-75	0.01	14.37	0.04	0.63	1.47	0.11	8.81	3.29	39.22	15.95	75.97	17.68	170.72	33.09	381.33	0.07	117.33
PM404-22-76	0.54	31.19	0.19	2.11	2.66	1.17	10.72	4.08	40.72	12.95	54.39	12.79	124.76	25.04	323.33	0.58	23.70
PM404-22-77	0.00	1.80	0.05	0.92	3.25	0.09	23.16	8.79	97.54	31.66	121.56	23.13	191.03	32.84	535.81	0.02	10.44
PM404-22-78	0.00	12.65	0.07	1.19	2.32	0.37	9.21	2.30	20.23	5.95	21.05	4.01	32.29	5.66	117.31	0.21	55.99
PM404-22-79	0.01	4.58	0.08	1.53	4.45	0.06	27.21	10.19	114.02	38.57	147.46	27.39	215.78	33.45	624.77	0.01	17.03
PM404-22-80	0.04	11.60	0.07	1.36	3.53	0.30	19.81	6.69	76.82	28.44	123.65	25.67	226.78	41.42	566.19	0.09	41.81
PM404-22-81	0.20	8.39	0.32	4.10	6.42	0.73	27.48	7.95	82.47	28.68	115.48	23.40	200.93	35.64	542.19	0.14	6.43
PM404-22-82	2.64	16.26	0.78	4.49	3.37	0.37	20.00	7.89	104.83	44.34	211.64	48.10	455.58	87.85	1008.15	0.11	2.75
PM404-22-83	0.04	18.93	0.44	7.26	12.27	0.93	48.95	14.50	148.90	50.24	206.06	40.55	353.89	61.82	964.79	0.10	12.94
PM404-22-84	0.13	16.95	0.07	0.95	1.48	0.50	7.75	2.78	34.89	14.37	74.29	18.48	200.87	44.39	417.90	0.37	42.34
PM404-22-85	0.06	35.33	0.17	2.33	3.38	0.82	13.09	3.65	38.84	14.03	63.77	14.61	140.58	27.73	358.37	0.33	56.88
PM404-34																	
PM404-34-01	0.02	11.13	0.06	0.95	2.68	0.51	13.28	5.00	57.12	22.57	103.33	24.02	234.47	40.04	515.18	0.21	50.80
PM404-34-02	0.07	13.87	0.06	1.08	2.80	0.27	14.04	4.40	51.42	18.56	79.38	17.57	163.40	27.35	394.27	0.11	48.90
PM404-34-03	1.49	29.84	0.61	4.48	3.70	0.25	15.40	5.20	62.34	23.94	110.16	25.59	251.58	44.78	579.36	0.09	7.67
PM404-34-04	0.01	9.20	0.06	1.44	2.56	0.14	12.75	4.09	47.65	17.25	74.67	16.21	150.87	25.63	362.53	0.06	44.62
PM404-34-05	3.01	11.74	0.04	0.84	1.29	0.67	7.47	2.77	37.69	16.74	86.74	23.76	272.33	57.05	522.14	0.52	2.92
PM404-34-06	3.01	49.12	0.93	5.33	3.18	1.40	17.58	6.04	78.36	32.68	165.42	43.66	487.29	96.32	990.32	0.45	7.14
PM404-34-07	12.74	38.25	3.67	16.31	4.15	0.19	11.80	4.05	52.55	22.53	112.00	28.85	305.92	55.24	688.25	0.08	1.35
PM404-34-08	0.09	16.74	0.25	2.46	4.93	2.98	25.40	6.81	68.49	25.08	121.51	31.02	327.68	61.32	694.76	0.66	18.17
PM404-34-09	0.05	2.07	0.31	5.75	12.10	0.21	67.41	21.90	224.58	72.17	266.89	51.59	435.36	66.15	1226.54	0.02	1.95
PM404-34-10	0.03	9.85	0.03	0.56	1.54	0.33	11.58	4.13	51.10	19.18	85.42	19.68	185.14	33.93	422.50	0.17	72.77
PM404-34-11	0.02	7.34	0.07	1.10	2.24	0.36	14.80	4.77	54.27	20.47	89.10	20.68	207.25	37.03	459.50	0.14	29.21
PM404-34-12	0.01	9.40	0.05	1.19	2.47	0.45	13.06	4.00	46.14	16.81	69.27	15.13	140.80	23.45	342.23	0.19	54.03
PM404-34-13	0.01	4.79	0.05	0.89	2.22	0.10	13.46	4.46	54.73	21.04	93.38	21.04	195.82	33.58	445.57	0.04	27.53
PM404-34-14	0.09	26.78	0.09	1.37	2.26	0.74	10.10	2.81	31.10	11.26	50.13	12.25	129.21	24.30	302.49	0.40	65.94
PM404-34-15	0.03	58.01	0.14	2.38	3.93	0.98	17.36	5.04	54.73	19.08	81.55	18.79	178.52	31.24	471.78	0.31	118.46
PM404-34-16	0.01	6.00	0.08	1.52	3.12	0.74	17.38	5.97	76.31	29.60	135.71	32.76	333.46	61.13	703.79	0.24	22.17
PM404-34-17	0.01	12.16	0.04	0.68	1.10	0.32	4.97	1.53	16.43	6.02	26.68	6.27	63.53	11.34	151.08	0.35	85.78
PM404-34-18	0.01	20.91	0.10	1.64	4.55	0.57	26.55	8.78	107.56	39.04	170.66	39.39	380.11	61.73	861.60	0.12	62.41
PM404-34-19	6.40	43.10	5.57	27.40	5.71	1.19	12.78	4.75	61.19	24.84	122.54	30.75	347.30	54.60	748.12	0.41	1.64

续附表 1

样品	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	ΣREE	δEu	δCe
PM404-34-20	0.87	123.27	3.41	28.84	28.67	12.45	66.35	17.57	151.09	41.93	157.68	33.15	304.09	49.95	1019.32	0.84	10.18
PM404-34-21	0.24	6.11	0.15	1.97	3.83	0.27	20.24	6.89	82.68	30.10	129.28	29.23	271.99	45.50	628.48	0.08	7.70
PM404-34-22	0.09	16.89	0.51	7.71	8.99	1.88	36.13	9.21	102.81	37.38	162.67	35.97	338.81	61.74	820.79	0.28	9.60
PM404-34-23	110.73	312.25	38.38	174.17	36.03	1.29	48.23	10.31	102.51	37.46	162.94	37.97	355.69	63.37	1491.33	0.09	1.17
PM404-34-24	0.01	27.91	0.04	0.92	1.83	0.34	9.41	3.04	35.75	13.62	62.63	14.55	145.53	26.56	342.14	0.20	196.89
PM404-34-25	0.03	5.58	0.21	3.99	5.14	0.31	15.75	3.90	34.95	10.60	39.07	7.77	68.24	10.85	206.39	0.10	7.80
PM404-34-26	0.72	10.01	0.30	3.13	4.83	0.64	30.23	11.04	140.56	55.21	246.00	55.21	501.46	91.01	1150.35	0.12	5.28
PM404-34-27	0.15	12.15	0.19	2.61	4.64	0.30	23.76	7.40	89.43	33.12	148.49	33.80	326.26	61.69	743.99	0.07	15.08
PM404-34-28	0.01	13.25	0.06	1.62	3.03	0.19	15.37	5.32	61.14	22.59	97.17	21.48	196.64	33.95	471.82	0.07	64.27
PM404-34-29	0.03	19.26	0.19	4.24	8.49	0.28	39.05	12.87	155.56	58.36	260.70	62.62	588.72	97.90	1308.27	0.04	29.60
PM404-34-30	0.03	16.27	0.16	3.19	5.56	1.23	22.64	6.43	66.32	22.10	92.89	19.44	176.59	31.59	464.44	0.29	29.36
PM404-34-31	0.01	9.52	0.08	1.23	2.29	0.25	12.52	3.92	46.32	17.19	73.93	16.79	155.03	26.83	365.91	0.11	35.18
PM404-34-32	0.02	30.34	0.06	0.83	1.50	0.38	7.84	2.68	32.17	12.56	59.24	15.22	155.23	28.50	346.57	0.27	138.48
PM404-34-33	0.05	11.08	0.47	7.40	11.15	0.48	43.70	12.81	133.86	45.24	180.41	37.49	339.02	53.34	876.50	0.06	7.02
PM404-34-34	0.10	11.67	0.11	1.06	2.37	0.24	9.85	3.37	42.48	16.46	78.24	19.29	190.35	35.57	411.16	0.13	24.14
PM404-34-35	0.04	38.41	0.13	2.67	4.41	1.34	19.30	6.10	62.72	22.33	90.30	20.79	186.18	31.84	486.56	0.38	81.66
PM404-34-36	0.02	8.13	0.02	0.40	1.14	0.61	5.85	1.94	22.33	9.14	43.66	10.78	117.57	23.40	244.99	0.59	90.09
PM404-34-37	0.01	37.42	0.09	1.95	6.01	0.17	30.79	9.74	98.96	30.58	109.06	20.14	177.33	33.52	555.77	0.03	123.58
PM404-34-38	0.08	21.95	0.30	4.96	7.17	2.08	26.24	7.35	80.07	29.01	128.76	30.44	310.33	60.36	709.10	0.41	20.52
PM404-34-39	0.09	14.75	0.13	2.30	4.88	0.39	23.36	7.11	79.81	29.46	125.12	27.35	252.05	44.08	610.88	0.09	27.57
PM404-34-40	0.04	15.47	0.48	8.16	13.45	0.77	63.45	19.58	220.84	78.72	314.80	61.49	511.67	82.89	1391.81	0.07	9.68
PM404-34-41	0.31	27.37	1.32	19.40	32.94	5.94	121.47	31.41	301.43	92.06	347.47	67.65	577.69	90.71	1717.17	0.25	5.88
PM404-34-42	0.12	11.93	0.25	3.93	6.84	1.62	31.47	9.99	112.94	41.59	187.59	42.98	414.30	75.23	940.78	0.28	12.42
PM404-34-43	0.05	46.10	0.52	7.26	7.89	3.60	21.17	5.24	43.45	12.72	45.35	8.74	74.27	11.80	288.16	0.80	26.50
PM404-34-44	5.31	25.97	1.60	7.97	4.21	0.36	16.11	4.79	54.09	19.77	85.17	18.72	173.73	30.55	448.35	0.12	2.16
PM404-34-45	0.03	12.02	0.16	2.68	4.58	0.67	21.98	6.82	74.25	26.78	114.36	24.34	223.93	39.55	552.15	0.17	21.69
PM404-34-46	0.02	15.37	0.14	2.24	3.65	0.39	17.33	5.27	57.89	20.48	89.44	19.88	191.30	34.19	457.59	0.12	32.24
PM404-34-47	0.02	3.16	0.29	5.46	9.80	1.41	57.69	20.35	268.46	108.84	478.46	100.85	904.22	148.40	2107.41	0.14	3.29
PM404-34-48	6.06	19.76	2.02	10.37	4.83	0.18	17.83	5.70	65.79	23.38	98.74	21.19	194.95	33.09	503.89	0.05	1.38
PM404-34-49	0.13	14.27	0.15	2.83	5.10	0.77	24.49	7.64	82.78	29.24	121.30	26.04	239.33	40.36	594.43	0.17	21.92
PM404-34-50	0.07	26.78	0.48	7.85	14.39	2.24	57.04	15.73	160.24	53.94	210.99	43.66	389.85	65.89	1049.15	0.21	16.36
PM404-34-51	2.27	24.17	1.90	12.95	8.70	1.37	28.52	8.31	88.27	31.42	134.70	29.19	269.12	45.77	686.66	0.24	2.67
PM404-34-52	0.01	7.74	0.02	0.51	0.95	0.43	6.13	2.08	26.69	11.05	56.46	14.39	156.43	31.97	314.86	0.41	100.09
PM404-34-53	0.03	26.81	0.09	1.21	2.83	0.63	13.74	4.75	55.37	22.57	108.95	26.84	276.01	52.20	592.03	0.25	81.58
PM404-34-54	0.01	16.98	0.13	2.72	5.14	0.26	25.66	8.05	84.77	30.37	118.99	23.00	195.77	31.96	543.81	0.06	39.34
PM404-34-55	1.88	26.85	1.13	8.05	6.47	0.65	25.12	7.69	84.98	30.51	130.02	27.88	255.22	44.95	651.40	0.14	4.43

续附表 1

样品	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	ΣREE	δEu	δCe
PM404-34-56	0.09	12.20	0.11	1.93	4.27	0.16	26.85	8.88	99.61	36.50	145.40	28.73	253.28	40.62	658.63	0.03	25.93
PM404-34-57	0.01	0.79	0.07	1.45	5.10	0.13	37.68	14.37	170.47	61.63	244.27	47.91	405.24	65.81	1054.93	0.02	3.31
PM404-34-58	0.03	17.61	0.05	1.16	2.13	0.71	13.89	4.66	59.47	23.87	103.84	22.58	206.96	39.26	496.22	0.30	88.14
PM404-34-59	0.01	12.39	0.03	0.68	1.45	0.43	5.65	1.57	18.23	6.70	27.73	6.46	63.22	11.67	156.22	0.40	113.11
PM404-34-60	0.51	18.90	1.82	14.23	16.14	7.19	44.18	12.21	95.96	23.72	77.65	14.30	119.34	19.03	465.18	0.77	2.90
PM404-34-61	0.17	14.72	0.45	7.36	11.20	4.72	45.28	12.24	124.95	45.49	201.36	45.00	449.44	88.71	1051.09	0.55	8.82
PM404-34-62	0.01	13.83	0.11	2.55	5.48	0.44	32.07	10.92	126.99	47.50	196.80	39.27	334.50	56.13	866.60	0.08	37.66
PM404-34-63	2.53	25.64	2.71	17.05	8.68	1.35	23.21	6.86	77.52	29.59	135.56	32.61	319.39	63.85	746.55	0.27	2.14
PM404-34-64	0.08	15.75	0.10	1.41	3.16	0.38	16.27	5.42	60.21	22.57	95.79	20.60	187.20	34.36	463.30	0.13	37.02
PM404-34-65	19.57	55.95	2.34	7.79	3.11	0.46	15.82	5.22	61.56	23.83	106.43	22.78	213.94	39.73	578.53	0.16	1.71
PM404-34-66	0.01	11.13	0.10	2.18	4.37	0.70	22.48	6.80	72.85	25.78	107.60	22.21	197.77	36.24	510.22	0.17	33.22
PM404-34-67	0.14	13.78	0.10	1.05	1.73	0.37	9.20	2.83	33.48	12.62	56.93	12.58	127.36	23.91	296.08	0.23	27.40
PM404-34-68	0.01	7.11	0.09	1.55	4.35	0.13	24.82	9.76	121.11	45.59	198.39	43.18	380.63	67.88	904.60	0.03	23.48
PM404-34-69	0.01	6.43	0.05	0.74	1.34	0.10	6.95	2.35	27.61	11.02	54.37	13.21	116.91	21.91	263.00	0.08	36.96
PM404-34-70	0.13	10.01	0.73	11.13	13.71	0.87	55.27	15.47	156.66	53.70	213.50	41.50	358.49	63.51	994.68	0.08	3.97
PM404-34-71	0.01	13.18	0.05	0.78	1.93	0.95	11.49	4.05	49.22	18.91	87.08	19.73	200.84	39.66	447.88	0.48	75.76
PM404-34-72	0.09	21.65	0.64	7.85	10.20	1.55	36.83	10.37	108.96	37.90	158.77	33.24	303.98	57.71	789.74	0.22	9.94
PM404-34-73	0.01	21.24	0.20	3.86	7.60	0.92	39.09	13.81	160.54	60.92	264.23	57.04	525.93	94.25	1249.64	0.13	32.32
PM404-34-74	0.02	13.47	0.08	1.44	2.55	0.12	16.53	5.73	66.02	25.57	114.81	25.13	229.17	43.17	543.81	0.04	47.51
PM404-34-75	0.12	16.25	0.16	1.61	2.46	0.41	12.61	4.06	44.23	16.41	71.59	15.58	139.77	26.60	351.86	0.18	24.24
PM404-34-76	0.01	8.40	0.02	0.91	1.91	0.61	13.44	5.00	65.70	27.71	142.80	35.28	374.87	82.95	759.61	0.27	108.62
PM404-34-77	0.01	21.88	0.13	1.86	2.58	1.03	10.65	2.83	29.90	10.72	48.89	11.29	115.22	23.94	280.93	0.52	50.69
PM404-34-78	0.02	12.87	0.09	1.83	3.84	0.55	19.29	6.11	67.87	24.26	104.97	21.82	198.64	37.40	499.56	0.16	40.76
PM404-34-79	0.21	84.05	1.39	13.14	15.19	7.18	42.72	13.95	139.40	45.17	209.51	52.42	569.83	127.13	1321.29	0.81	17.70
PM404-34-80	0.35	4.57	0.43	6.39	11.38	0.56	57.04	17.73	198.89	70.77	293.60	57.72	496.99	91.39	1307.81	0.05	2.49
PM404-34-81	0.01	12.28	0.06	1.18	2.44	0.28	14.02	4.71	51.53	19.03	85.30	18.11	161.98	29.93	400.86	0.11	59.56
PM404-34-82	0.02	26.21	0.19	3.46	6.25	0.80	32.40	10.71	124.11	46.29	206.39	44.15	405.81	76.40	983.19	0.14	41.09
PM404-34-83	0.02	13.76	0.11	2.30	4.91	0.62	24.54	7.97	86.51	30.78	130.96	27.21	245.03	44.95	619.67	0.14	36.20
PM404-34-84	0.33	13.81	0.27	3.31	5.59	1.46	27.34	8.58	94.97	35.27	155.10	33.75	323.57	65.37	768.72	0.30	10.66
PM404-34-85	0.31	14.30	0.09	1.20	2.23	0.27	11.24	3.65	41.98	16.31	75.10	16.75	161.49	32.08	377.00	0.13	20.72

注:δCe= $\text{Ce}_\text{N}/(\text{La}_\text{N} \times \text{Pr}_\text{N})^{0.5}$; δEu = $\text{Eu}_\text{N}/(\text{Sm}_\text{N} \times \text{Gd}_\text{N})^{0.5}$, 球粒陨石标准化数据据 Sunand McDonough, 1989。

附表 2 西秦岭临潭地区下白垩统磨沟组砂岩 (样品 PM404-22) 和上新统临夏组砂岩 (样品 PM404-34) LA-ICP-MS 锆石 U-Pb 同位素分析结果

Appendix 2 LA-ICP-MS detrital zircon U-Pb dating results for sandstone from the Lower Cretaceous Mogou Formation (sample PM404-22) and the Pliocene Linxia Formation (sample PM404-34) in the West Qinling orogenic belt

测点	元素含量($\times 10^{-6}$)				同位素比值						同位素年龄 (Ma)				谐和度 (%)		
	Pb	Th	U	Th/U	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	1σ	$^{207}\text{Pb}/^{206}\text{Pb}$	1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$			
						1σ	1σ	1σ	1σ	1σ	1σ						
PM404-22																	
PM404-22-01	97.31	215.57	285.97	0.75	0.0914	0.0012	3.2446	0.0687	0.2572	0.0052	1455	24	1468	16	1476	27	99
PM404-22-02	132.88	65.51	281.60	0.23	0.1370	0.0019	7.3649	0.2512	0.3867	0.0104	2191	24	2157	31	2108	48	97
PM404-22-03	5.34	15.14	11.50	1.32	0.1096	0.0038	4.6996	0.1602	0.3107	0.0062	1792	63	1767	29	1744	31	98
PM404-22-04	15.44	147.50	157.55	0.94	0.0567	0.0008	0.5604	0.0111	0.0716	0.0013	480	27	452	7	446	8	98
PM404-22-05	11.70	86.91	119.06	0.73	0.0559	0.0009	0.5827	0.0127	0.0754	0.0014	450	37	466	8	469	8	99
PM404-22-06	40.59	90.97	154.99	0.59	0.0787	0.0008	2.2125	0.0434	0.2034	0.0039	1165	20	1185	14	1194	21	99
PM404-22-07	16.74	24.58	41.01	0.60	0.1106	0.0013	4.6397	0.0828	0.3030	0.0044	1809	22	1756	15	1706	22	97
PM404-22-08	23.76	44.71	52.45	0.85	0.1302	0.0015	5.6710	0.4136	0.3144	0.0203	2102	20	1927	63	1762	100	91
PM404-22-09	13.01	134.76	129.28	1.04	0.0570	0.0010	0.5423	0.0118	0.0688	0.0012	494	39	440	8	429	7	97
PM404-22-10	61.24	72.92	126.02	0.58	0.1216	0.0012	5.8812	0.1246	0.3491	0.0064	1979	18	1958	18	1930	31	98
PM404-22-11	41.94	131.12	187.19	0.70	0.0716	0.0008	1.6910	0.0356	0.1707	0.0035	976	22	1005	13	1016	19	98
PM404-22-12	72.01	285.54	299.63	0.95	0.0746	0.0007	1.7705	0.0263	0.1718	0.0028	1057	19	1035	10	1022	16	98
PM404-22-13	124.46	160.89	285.36	0.56	0.1145	0.0009	5.3432	0.1096	0.3374	0.0071	1872	15	1876	18	1874	34	99
PM404-22-14	77.91	90.89	183.33	0.50	0.1131	0.0012	5.1631	0.1472	0.3293	0.0079	1850	20	1847	24	1835	39	99
PM404-22-15	47.48	205.40	211.43	0.97	0.0716	0.0006	1.5996	0.0256	0.1615	0.0026	976	13	970	10	965	15	99
PM404-22-16	46.26	379.39	496.74	0.76	0.0586	0.0005	0.5777	0.0094	0.0713	0.0011	550	20	463	6	444	7	95
PM404-22-17	83.27	194.81	458.29	0.43	0.0706	0.0006	1.4624	0.0268	0.1499	0.0028	946	17	915	11	900	16	98
PM404-22-18	55.20	210.66	321.42	0.66	0.0662	0.0006	1.2276	0.0201	0.1342	0.0023	813	19	813	9	812	13	99
PM404-22-19	21.29	204.02	200.52	1.02	0.0605	0.0008	0.6367	0.0134	0.0759	0.0013	622	28	500	8	472	8	94
PM404-22-20	35.09	154.90	167.33	0.93	0.0716	0.0008	1.5169	0.0273	0.1529	0.0025	976	22	937	11	917	14	97
PM404-22-21	49.73	69.75	82.50	0.85	0.1597	0.0016	9.3007	0.1293	0.4220	0.0071	2454	17	2368	13	2269	32	95
PM404-22-22	20.31	86.53	68.63	1.26	0.0793	0.0009	2.1625	0.0360	0.1971	0.0027	1189	56	1169	12	1160	15	99
PM404-22-23	180.57	78.93	492.94	0.16	0.1141	0.0009	4.8508	0.0545	0.3072	0.0037	1866	13	1794	10	1727	18	96
PM404-22-24	31.98	56.03	76.99	0.73	0.1200	0.0012	5.0485	0.0932	0.3044	0.0057	1967	19	1828	16	1713	28	93
PM404-22-25	29.28	393.24	682.15	0.58	0.0643	0.0021	0.3151	0.0161	0.0347	0.0008	754	70	278	12	220	5	76
PM404-22-26	11.31	263.06	153.45	1.71	0.0560	0.0012	0.3499	0.0089	0.0452	0.0006	450	16	305	7	285	3	93
PM404-22-27	36.48	72.26	87.80	0.82	0.1141	0.0009	4.7695	0.0978	0.3028	0.0063	1865	15	1780	17	1705	31	95
PM404-22-28	16.30	137.40	197.58	0.70	0.0558	0.0008	0.4893	0.0107	0.0633	0.0011	456	31	404	7	396	7	97
PM404-22-29	12.76	113.80	290.88	0.39	0.0510	0.0007	0.2561	0.0050	0.0364	0.0006	239	64	231	4	230	4	99
PM404-22-30	39.99	394.89	421.72	0.94	0.0551	0.0006	0.5311	0.0100	0.0698	0.0012	417	24	433	7	435	7	99
PM404-22-31	15.37	65.48	58.92	1.11	0.0756	0.0010	1.8855	0.0410	0.1807	0.0036	1085	32	1076	14	1071	20	99
PM404-22-32	18.89	170.59	410.61	0.42	0.0501	0.0006	0.2593	0.0047	0.0375	0.0006	211	30	234	4	237	4	98

续附表 2

测点	元素含量($\times 10^{-6}$)				同位素比值				同位素年龄 (Ma)				谐和度 (%)				
	Pb	Th	U	Th/U	$^{207}\text{Pb}/^{235}\text{U}$	$^{206}\text{Pb}/^{238}\text{U}$	1σ	1σ	$^{207}\text{Pb}/^{206}\text{Pb}$	1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ		$^{206}\text{Pb}/^{238}\text{U}$	1σ		
PM404-22-33	68.85	738.81	654.24	1.13	0.0006	0.0583	0.0006	0.5899	0.0138	0.0013	539	22	471	9	454	8	96
PM404-22-34	24.69	50.48	55.15	0.92	0.0011	0.1103	0.0011	4.7708	0.0870	0.0053	1806	17	1780	15	1756	26	98
PM404-22-35	22.26	237.58	504.68	0.47	0.0007	0.0515	0.0007	0.2579	0.0132	0.0018	261	34	233	11	230	11	98
PM404-22-36	114.34	128.09	185.26	0.69	0.0011	0.1662	0.0011	9.8022	0.1361	0.0056	2520	12	2416	13	2291	25	94
PM404-22-37	248.44	263.85	364.58	0.72	0.0011	0.1660	0.0011	10.7718	0.1967	0.0084	2518	11	2504	17	2480	37	99
PM404-22-38	156.12	126.97	365.96	0.35	0.0008	0.1141	0.0008	5.2481	0.0907	0.0057	1865	14	1860	15	1852	28	99
PM404-22-39	11.01	208.56	185.35	1.13	0.0009	0.0553	0.0009	0.3042	0.0051	0.0005	433	35	270	4	252	3	93
PM404-22-40	94.99	29.83	153.62	0.19	0.0015	0.1646	0.0015	10.6270	0.1965	0.0080	2503	15	2491	17	2470	35	99
PM404-22-41	37.09	80.95	108.73	0.74	0.0008	0.0914	0.0008	3.1697	0.0558	0.0041	1457	17	1450	14	1441	21	99
PM404-22-42	137.24	380.83	789.45	0.48	0.0006	0.0728	0.0006	1.3674	0.0217	0.0020	1009	17	875	9	821	11	93
PM404-22-43	88.50	234.96	297.25	0.79	0.0007	0.0865	0.0007	2.6634	0.0591	0.0050	1350	-18	1318	16	1297	27	98
PM404-22-44	122.93	124.95	765.85	0.16	0.0008	0.0766	0.0008	1.4594	0.0199	0.0015	1110	16	914	8	832	9	90
PM404-22-45	201.18	181.69	462.64	0.39	0.0008	0.1211	0.0008	5.8083	0.1163	0.0068	1972	12	1948	17	1919	32	98
PM404-22-46	16.94	90.39	196.41	0.46	0.0007	0.0566	0.0007	0.5532	0.0125	0.0012	472	23	447	8	440	7	98
PM404-22-47	73.47	78.09	118.90	0.66	0.0014	0.1673	0.0014	10.6013	0.1856	0.0085	2531	14	2489	16	2434	37	97
PM404-22-48	141.90	165.06	309.53	0.53	0.0011	0.1273	0.0011	6.3025	0.1151	0.0060	2061	15	2019	16	1972	29	97
PM404-22-49	23.05	144.05	316.97	0.45	0.0010	0.0576	0.0010	0.4699	0.0070	0.0008	522	37	391	5	371	5	94
PM404-22-50	36.60	124.76	205.42	0.61	0.0007	0.0677	0.0007	1.3384	0.0359	0.0037	859	23	863	16	862	21	99
PM404-22-51	53.40	113.94	110.90	1.03	0.0012	0.1147	0.0012	5.3031	0.1027	0.0061	1876	19	1869	17	1860	30	99
PM404-22-52	25.30	509.13	600.12	0.85	0.0008	0.0535	0.0008	0.2299	0.0054	0.0006	350	31	210	4	197	4	93
PM404-22-53	77.75	71.49	150.52	0.47	0.0019	0.1662	0.0019	8.8635	0.1650	0.0069	2519	20	2324	17	2104	32	90
PM404-22-54	20.48	148.43	235.42	0.63	0.0007	0.0559	0.0007	0.5386	0.0140	0.0014	450	30	438	9	433	8	98
PM404-22-55	11.14	171.41	267.52	0.64	0.0009	0.0515	0.0009	0.2336	0.0052	0.0006	261	41	213	4	209	4	97
PM404-22-56	6.51	85.21	118.36	0.72	0.0012	0.0528	0.0012	0.3100	0.0074	0.0007	320	19	274	6	269	4	97
PM404-22-57	12.07	104.90	55.53	1.89	0.0016	0.0729	0.0016	1.3677	0.0548	0.0032	1010	44	875	23	813	18	92
PM404-22-58	99.05	50.53	249.18	0.20	0.0010	0.1149	0.0010	5.3662	0.1091	0.0068	1880	16	1879	17	1876	33	99
PM404-22-59	170.94	182.92	279.64	0.65	0.0022	0.1493	0.0022	8.9634	0.1548	0.0070	2339	20	2334	16	2326	31	99
PM404-22-60	17.76	149.27	191.64	0.78	0.0010	0.0586	0.0010	0.5657	0.0116	0.0012	550	32	455	8	436	7	95
PM404-22-61	67.33	172.68	334.55	0.52	0.0015	0.0923	0.0015	2.1555	0.0596	0.0037	1476	31	1167	19	1002	20	84
PM404-22-62	94.47	114.05	145.91	0.78	0.0016	0.1626	0.0016	10.5437	0.2011	0.0088	2482	17	2484	18	2479	38	99
PM404-22-63	170.86	111.27	309.56	0.36	0.0021	0.1595	0.0021	9.5170	0.1441	0.0071	2450	23	2389	14	2316	32	96
PM404-22-64	173.12	106.02	394.27	0.27	0.0015	0.1345	0.0015	6.6091	0.1622	0.0077	2157	19	2061	22	1958	37	94
PM404-22-65	103.73	260.26	208.18	1.25	0.0023	0.1351	0.0023	6.1720	0.2160	0.0078	2166	29	2000	31	1831	38	91
PM404-22-66	14.19	181.27	265.94	0.68	0.0007	0.0529	0.0007	0.3104	0.0055	0.0007	324	30	274	4	268	4	97
PM404-22-67	174.64	241.48	276.67	0.87	0.0013	0.1628	0.0013	10.3773	0.1994	0.0090	2485	13	2469	18	2444	40	98

续附表 2

测点	元素含量($\times 10^{-6}$)				同位素比值				同位素年龄 (Ma)				谐和度 (%)			
	Pb	Th	U	Th/U	$^{207}\text{Pb}/^{206}\text{Pb}$	1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	1σ	$^{207}\text{Pb}/^{206}\text{Pb}$	1σ				
PM404-22-68	147.05	91.34	518.42	0.18	0.1114	0.0015	3.5032	0.0787	0.2270	0.0038	1822	29	1528	18	20	85
PM404-22-69	176.68	237.13	270.30	0.88	0.1651	0.0014	10.7543	0.1596	0.4713	0.0075	2509	15	2502	14	33	99
PM404-22-70	112.01	139.45	206.07	0.68	0.1418	0.0012	8.0973	0.1578	0.4125	0.0076	2250	15	2242	18	35	99
PM404-22-71	43.54	105.44	99.40	1.06	0.1067	0.0011	4.6908	0.0953	0.3181	0.0065	1744	19	1766	17	32	99
PM404-22-72	143.05	284.48	324.23	0.88	0.1086	0.0014	4.7677	0.0950	0.3170	0.0045	1776	22	1779	17	22	99
PM404-22-73	93.15	102.15	156.91	0.65	0.1513	0.0014	9.4895	0.1409	0.4535	0.0069	2361	15	2387	14	30	98
PM404-22-74	7.36	76.62	150.91	0.51	0.0526	0.0011	0.2921	0.0073	0.0404	0.0010	322	50	260	6	6	98
PM404-22-75	120.05	107.92	235.18	0.46	0.1428	0.0014	7.9287	0.1016	0.4019	0.0057	2261	17	2223	12	26	97
PM404-22-76	34.06	354.93	364.45	0.97	0.0625	0.0008	0.6122	0.0152	0.0706	0.0014	700	26	485	10	9	90
PM404-22-77	104.36	52.80	269.05	0.20	0.1132	0.0010	5.2239	0.0735	0.3335	0.0048	1852	49	1857	12	23	99
PM404-22-78	32.51	203.39	301.70	0.67	0.0577	0.0007	0.6897	0.0132	0.0864	0.0015	517	21	533	8	9	99
PM404-22-79	119.51	397.23	573.19	0.69	0.0713	0.0006	1.6469	0.0333	0.1670	0.0035	965	19	988	13	19	99
PM404-22-80	21.97	285.60	448.26	0.64	0.0522	0.0009	0.2851	0.0068	0.0396	0.0009	300	39	255	5	5	98
PM404-22-81	24.45	50.27	53.72	0.94	0.1122	0.0012	5.2160	0.0889	0.3358	0.0057	1836	20	1855	15	27	99
PM404-22-82	29.69	184.04	341.90	0.54	0.0556	0.0007	0.5450	0.0099	0.0709	0.0013	435	28	442	7	8	99
PM404-22-83	107.86	132.88	162.06	0.82	0.1640	0.0015	10.6288	0.2024	0.4677	0.0088	2498	16	2491	18	39	99
PM404-22-84	37.22	289.41	374.11	0.77	0.0571	0.0007	0.6202	0.0150	0.0784	0.0018	494	21	490	9	11	99
PM404-22-85	149.94	126.36	225.28	0.56	0.1631	0.0016	10.6844	0.2017	0.4730	0.0096	2488	17	2496	18	42	99
PM404-34																
PM404-34-01	51.64	61.15	201.21	0.30	0.0891	0.0009	2.5801	0.0525	0.2101	0.0039	1406	19	1295	15	21	94
PM404-34-02	12.42	140.77	312.61	0.45	0.0499	0.0009	0.2236	0.0050	0.0324	0.0004	191	41	205	4	3	99
PM404-34-03	145.99	139.89	244.90	0.57	0.1593	0.0012	9.6684	0.1390	0.4402	0.0064	2450	12	2404	13	29	97
PM404-34-04	17.86	35.10	46.35	0.76	0.1085	0.0011	4.2606	0.1094	0.2844	0.0068	1776	14	1686	21	34	95
PM404-34-05	19.67	134.34	221.96	0.61	0.0572	0.0006	0.5370	0.0083	0.0681	0.0010	502	24	436	6	6	97
PM404-34-06	35.52	508.37	583.06	0.87	0.0525	0.0007	0.3227	0.0060	0.0446	0.0008	309	30	284	5	5	99
PM404-34-07	17.29	152.24	393.33	0.39	0.0534	0.0008	0.2630	0.0057	0.0358	0.0007	346	33	237	5	4	95
PM404-34-08	245.75	221.01	517.43	0.43	0.1617	0.0010	7.8205	0.1121	0.3506	0.0046	2473	10	2211	13	22	86
PM404-34-09	50.33	116.92	284.59	0.41	0.0718	0.0018	1.4082	0.0476	0.1418	0.0023	981	50	892	20	855	95
PM404-34-10	161.23	101.43	275.91	0.37	0.1711	0.0011	10.1859	0.1691	0.4315	0.0067	2569	11	2452	15	30	94
PM404-34-11	136.88	110.74	234.35	0.47	0.1702	0.0012	10.2655	0.1953	0.4372	0.0080	2561	12	2459	18	36	94
PM404-34-12	48.85	64.83	130.09	0.50	0.1137	0.0010	4.4855	0.0773	0.2861	0.0045	1861	16	1728	14	1622	23
PM404-34-13	19.48	65.65	101.12	0.65	0.0707	0.0011	1.4367	0.0330	0.1473	0.0024	950	36	904	14	886	14
PM404-34-14	122.36	119.01	198.83	0.60	0.1653	0.0011	10.2332	0.1936	0.4490	0.0090	2511	11	2456	18	40	97
PM404-34-15	49.56	86.68	114.37	0.76	0.1141	0.0010	4.9816	0.0916	0.3168	0.0062	1866	17	1816	16	30	97
PM404-34-16	12.86	104.23	329.52	0.32	0.0529	0.0010	0.2383	0.0052	0.0327	0.0005	324	43	217	4	3	95

续附表 2

测点	元素含量($\times 10^{-6}$)				同位素比值				同位素年龄 (Ma)				谐和度 (%)	
	Pb	Th	U	Th/U	$^{207}\text{Pb}/^{206}\text{Pb}$	1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ		
PM404-34-17	4.95	6.11	8.77	0.70	0.1656	0.0026	9.1826	0.2416	0.4024	0.0090	2513	27	2180	41
PM404-34-18	10.27	221.94	227.72	0.97	0.0543	0.0019	0.2387	0.0093	0.0319	0.0006	383	80	202	3
PM404-34-19	19.13	142.72	187.91	0.76	0.0583	0.0008	0.5936	0.0150	0.0740	0.0017	543	31	460	10
PM404-34-20	302.91	530.80	490.65	1.08	0.1650	0.0012	9.9597	0.2050	0.4372	0.0087	2509	12	2338	39
PM404-34-21	21.74	72.30	119.52	0.60	0.0729	0.0010	1.4107	0.0257	0.1406	0.0025	1013	30	848	14
PM404-34-22	11.70	119.08	127.82	0.93	0.0575	0.0010	0.5188	0.0115	0.0654	0.0011	522	39	409	7
PM404-34-23	175.09	339.97	298.34	1.14	0.1627	0.0012	9.0863	0.1361	0.4045	0.0058	2484	13	2190	26
PM404-34-24	27.63	34.80	47.31	0.74	0.1647	0.0015	9.5092	0.1507	0.4190	0.0068	2506	16	2256	31
PM404-34-25	18.75	290.96	149.10	1.95	0.0596	0.0008	0.6033	0.0099	0.0734	0.0009	591	28	456	5
PM404-34-26	17.38	173.58	378.56	0.46	0.0534	0.0008	0.2806	0.0063	0.0380	0.0006	346	33	241	4
PM404-34-27	111.57	94.85	282.23	0.34	0.1244	0.0009	5.4867	0.1084	0.3201	0.0066	2020	13	1790	32
PM404-34-28	26.61	59.43	69.19	0.86	0.1072	0.0010	4.2314	0.0859	0.2861	0.0054	1752	17	1622	27
PM404-34-29	111.33	174.46	317.65	0.55	0.1082	0.0012	4.1518	0.0818	0.2780	0.0046	1769	19	1582	23
PM404-34-30	12.26	118.50	130.53	0.91	0.0589	0.0009	0.5870	0.0186	0.0720	0.0018	565	33	448	11
PM404-34-31	19.99	30.07	56.99	0.53	0.1085	0.0013	4.1859	0.1004	0.2794	0.0061	1776	22	1588	31
PM404-34-32	95.26	150.16	145.16	1.03	0.1615	0.0013	10.1181	0.1931	0.4540	0.0084	2472	14	2446	18
PM404-34-33	26.58	55.76	66.22	0.84	0.1079	0.0009	4.5613	0.1049	0.3059	0.0066	1765	16	1742	19
PM404-34-34	71.06	74.03	176.96	0.42	0.1092	0.0010	4.7958	0.1151	0.3171	0.0063	1787	18	1776	31
PM404-34-35	15.26	36.86	36.14	1.02	0.1122	0.0026	4.6366	0.1143	0.2993	0.0044	1836	41	1756	21
PM404-34-36	41.63	26.91	67.81	0.40	0.1659	0.0015	11.1943	0.2378	0.4882	0.0096	2517	15	2539	20
PM404-34-37	25.72	72.82	48.73	1.49	0.1176	0.0013	5.5470	0.1160	0.3410	0.0060	1920	19	1908	18
PM404-34-38	101.80	147.95	153.28	0.97	0.1644	0.0013	10.5067	0.1789	0.4627	0.0080	2502	14	2481	16
PM404-34-39	75.40	101.18	151.40	0.67	0.1338	0.0012	7.1045	0.1526	0.3838	0.0076	2148	15	2125	19
PM404-34-40	98.03	104.51	180.63	0.58	0.1483	0.0013	8.4297	0.1708	0.4111	0.0081	2328	16	2278	18
PM404-34-41	200.32	603.91	460.43	1.31	0.1105	0.0010	4.5249	0.0677	0.2961	0.0043	1809	17	1736	12
PM404-34-42	16.96	159.56	233.53	0.68	0.0815	0.0032	0.5995	0.0191	0.0539	0.0010	1235	71	338	6
PM404-34-43	56.89	315.18	135.16	2.33	0.1108	0.0014	3.5600	0.0594	0.2327	0.0042	1813	23	1541	13
PM404-34-44	22.32	204.64	538.02	0.38	0.0530	0.0010	0.2613	0.0078	0.0355	0.0006	328	41	236	6
PM404-34-45	16.72	192.32	380.85	0.50	0.0513	0.0007	0.2587	0.0051	0.0366	0.0007	254	31	234	4
PM404-34-46	122.17	159.39	189.86	0.84	0.1661	0.0012	10.6674	0.2003	0.4648	0.0084	2520	12	2495	18
PM404-34-47	18.81	112.21	99.88	1.12	0.0669	0.0008	1.2401	0.0218	0.1342	0.0020	835	22	819	10
PM404-34-48	15.80	144.43	369.26	0.39	0.0517	0.0007	0.2663	0.0058	0.0373	0.0007	272	31	240	5
PM404-34-49	17.66	224.66	408.16	0.55	0.0515	0.0006	0.2527	0.0046	0.0356	0.0006	265	32	229	4
PM404-34-50	79.89	182.19	131.41	1.39	0.1500	0.0014	8.2023	0.1205	0.3965	0.0054	2346	15	2153	25
PM404-34-51	98.69	161.82	148.69	1.09	0.1668	0.0017	10.1032	0.1579	0.4394	0.0058	2526	17	2444	15