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吕梁地区古元古代花岗片麻岩成因及变质时代:锆石和独居石 U-Pb 年龄及锆石 Hf 同位素证据*

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Abstract The Lüliang area, occupying an important position in the Precambrian research on the North China Craton (NCC), developed extensive Palaeoproterozoic metamorphic supracrustal rocks and granitic rocks. It is of great significance to study the paleoproterozoic geological evolution of the NCC. This paper presents zircon and monazite U-Pb ages and zircon Hf isotopes of Palaeoproterozoic Baijiatan granitic gneisses in the Lüliang area. Two granitic gneiss samples obtain LA-ICP-MS zircon U-Pb ages of 2182 ± 16Ma and 2185 ± 24Ma, respectively, representing their emplacement ages. New LA-ICP-MS dating of monazites from two samples yielded U-Pb ages of 1898 ± 7Ma and 1899 ± 14Ma, respectively, which are much younger than the concordant $^{207}Pb/^{206}Pb$ ages (2180 ~ 2032Ma) of zircon overgrowth rims. It indicates that monazites thoroughly suffered from the late metamorphism and their U-Pb ages showed the granitic gneiss underwent ~1900Ma metamorphism, which is synchronous with the metamorphic age of the Central Zone of the NCC. Zircon depleted mantle model ages are 2473 ~ 2598Ma and two-stage model ages are 2646 ~ 2839Ma, which are distinctively older than the zircon U-Pb ages. Zircon $\varepsilon_{Hf}(t)$ values are −1.2 ~ +1.8 and −1.3 ~ +1.4, respectively, suggesting the granitic gneiss were originated from partial melting of the late Archean crustal materials, without any mantle-derived materials input. Combined with the available zircon Hf isotopic data from middle Palaeoproterozoic (2.2 ~ 2.1Ga) magmatic rocks, the Late Archean crust of the NCC suffered from extensive remelting effect during 2.2 ~ 2.1Ga. The 2.2 ~ 2.1Ga magmatic activity widely distributed in the Lüliang, Zhongtiao, Wutai and Jiao-Liao-Ji areas and elsewhere in the NCC, which may develop in an intracontinental rift setting.

Key words North China Craton; Lüliang area; Palaeoproterozoic; Granitic gneisses; Zircon and monazite U-Pb ages

摘 要 吕梁地区在华北克拉通前寒武纪研究中具有重要位置,出露大量的古元古代变质表壳岩和花岗质岩石,对研究华北克拉通古元古代地质演化历史具有重要意义。本次研究选择吕梁地区白家滩花岗片麻岩进行锆石和独居石 U-Pb 年代学

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以及锆石 Hf 同位素研究,2 个花岗片麻岩的岩浆锆石 U-Pb 年龄分别为 2182 ± 16Ma 和 2185 ± 24Ma,代表了其侵位时代。独居石 U-Pb 年龄分别为 1898 ± 7Ma 和 1899 ± 14Ma,明显比锆石增生边的谐和 $^{207}Pb/^{206}Pb$ 年龄(2180 ~ 2032Ma)年轻,说明独居石对后期变质作用的响应程度比锆石强,其 U-Pb 年龄更能反映白家滩花岗片麻岩经历了 ~1900Ma 的退变质作用,与华北克拉通中部造山带的变质作用时间一致。花岗片麻岩的锆石 Hf 同位素亏损地幔模式年龄(t_{DM})为 2473 ~ 2598Ma,两阶段亏损地幔模式年龄($t_{DM}{}^{C}$)分别为 2646 ~ 2839Ma,$\varepsilon_{Hf}(t)$ 值分布于 -1.3 ~ +1.8 之间,未显示同期幔源物质的加入,而是新太古代地壳物质部分熔融的产物,结合已有的古元古代中期(2.2 ~ 2.1Ga)的岩浆岩锆石 Hf 同位素数据,华北克拉通新太古代地壳在 2.2 ~ 2.1Ga 期间发生了广泛的重熔作用,这期岩浆活动在华北克拉通吕梁、中条、五台以及胶-辽-吉等地区广泛发育,可能形成于陆内裂谷环境。

关键词 华北克拉通;吕梁地区;古元古代;花岗片麻岩;锆石和独居石 U-Pb 年龄

中图法分类号 P588.345; P597.3

华北克拉通在古太古代已经形成陆核,然后由多个独立块体拼贴形成规模较大的陆块(沈其韩等, 1992; 赵宗溥, 1993; 白瑾等, 1993, 1996; 伍家善等, 1998; 翟明国, 2004, 2019),但是对于其拼合机制和拼合时间还存在很大的争议。翟明国和卞爱国(2000)将华北克拉通基底划分为六个微陆块,在新太古代末期通过陆-陆或弧-陆碰撞拼合在一起,形成华北克拉通的基本轮廓,并在古元古代经历了裂谷、增生和碰撞过程后完成最终的克拉通化(1.95 ~ 1.82Ga)(沈其韩和钱祥麟, 1995; 伍家善等, 1998; Zhai *et al.*, 2000, 2005; Zhai and Santosh, 2011; Zhai, 2011; 翟明国, 2010, 2012)。赵国春等(2002)提出华北克拉通基底是由东部陆块、西部陆块和中部造山带三个主要构造单元组成(图 1a),东部陆块和西部陆块在 1.85Ga 沿中部造山带发生碰撞拼合,最终形成完整的克拉通。而有学者认为东部陆块和西部陆块在 2.5Ga 发生碰撞拼合(Kusky and Li, 2003; Kusky *et al.*, 2007; Kusky, 2011)。华北克拉通中部造山带古元古代演化过程对于不同构造演化模式具有关键意义(Zhao *et al.*, 2003, 2007; Kusky *et al.*, 2007; 杜利林等, 2018),关乎华北克拉通早前寒武纪地质演化历史的建立和哥伦比亚超大陆的重建模式。

大量年代学和同位素数据表明华北克拉通最强烈的岩浆活动和变质作用发生在 ~2.50Ga 和 ~1.85Ga(Zhao, 2001; Liu *et al.*, 2004, 2010, 2011; Wilde *et al.*, 2002; Kröner *et al.*, 2006; 赵国春, 2009; 耿元生等, 2010; Yang *et al.*, 2008; Wan *et al.*, 2011; Wang *et al.*, 2011),在 2.45 ~ 2.35Ga 之间存在一个短暂的静寂期之后(翟明国和彭澎, 2007),华北克拉通广泛发育 2.35 ~ 1.85Ga 的火山-沉积建造和花岗质-镁铁质侵入体,目前对于 2.35 ~ 1.85Ga 长达 5 亿年的时间间隔里所发生的构造-热事件的期次、性质、影响范围一直缺乏详细的了解(Zhao *et al.*, 2006, 2007),对该时期所处的构造演化机制,也一直存在与古元古代末哥伦比亚超大陆聚合相关联的俯冲-碰撞(Zhao *et al.*, 2002, 2005, 2007; Kröner *et al.*, 2005, 2006)、陆内裂谷的打开和闭合(Luo *et al.*, 2004; Zhao *et al.*, 2005; Li and Zhao, 2007)、陆-弧-陆碰撞事件(白瑾等, 1993; 贺高品和叶慧文, 1998; Faure *et al.*, 2004)、活动带/裂陷带的破裂和边缘增生(翟明国, 2004)以及岛弧地体的汇聚和拼贴(Kusky and Li, 2003)等争议。因此,对华北克拉通古元古代地质事件的性质进行深入研究将有助于更好地揭示华北克拉通古元古代的构造演化历史。

吕梁地区在华北克拉通早前寒武纪构造演化格架中占据重要位置(刘树文等, 2009),"吕梁运动"在此命名,在前寒武纪研究中具有重要意义。该地区发育典型的早前寒武纪岩浆-沉积组合,主要为太古宙-古元古代变质表壳岩和古元古代花岗岩类侵入体(耿元生等, 2000; 万渝生等, 2000)。一般而言,TTG 岩石和变质表壳岩记录了早期陆壳的增生-活化过程,花岗质岩石记录了早期陆壳的再造-稳定化过程,可以为早期陆壳演化的动力学机制提供制约。近些年来,前人对于吕梁地区以及华北克拉通其它地区古元古代岩浆活动作了大量年代学和同位素地球化学研究,但该时期岩浆事件的性质和构造背景仍存在较大争议(Li and Zhao, 2007; Liu *et al.*, 2011; 杜利林等, 2012, 2018; 杨崇辉等, 2011, 2017),这一期岩浆活动之后紧随 1.95 ~ 1.80Ga 变质热事件,为 Columbia 超大陆聚合时的全球性碰撞造山事件的一部分。因此,研究该地区古元古代岩浆作用及其变质改造历史,有助于理解华北克拉通古元古代地质演化过程及其与哥伦比亚超大陆的关系。本文通过对吕梁地区白家滩花岗片麻岩进行锆石和独居石 U-Pb 年代学以及锆石 Hf 同位素分析,以确定花岗片麻岩的原岩成因、侵位时代以及后期变质历史,并对比独居石和锆石对华北克拉通古元古代变质作用的不同响应程度。结合已有的华北克拉通同时期的岩浆活动和变质作用记录,综合讨论华北克拉通古元古代构造演化历史。

1 地质背景

山西吕梁地区是我国前寒武纪地质研究的重要地区,位于华北克拉通中部构造带的西侧,出露广泛的太古宙-古元古代变质结晶基底,以吕梁杂岩为主。吕梁杂岩可分为花岗闪长质-花岗质侵入体和变质表壳岩两大类(耿元生等, 2000; 万渝生等, 2000)。其中,大量的花岗岩类侵入体(2.5 ~ 1.8Ga)形成于古元古代构造运动的不同阶段,耿元生等

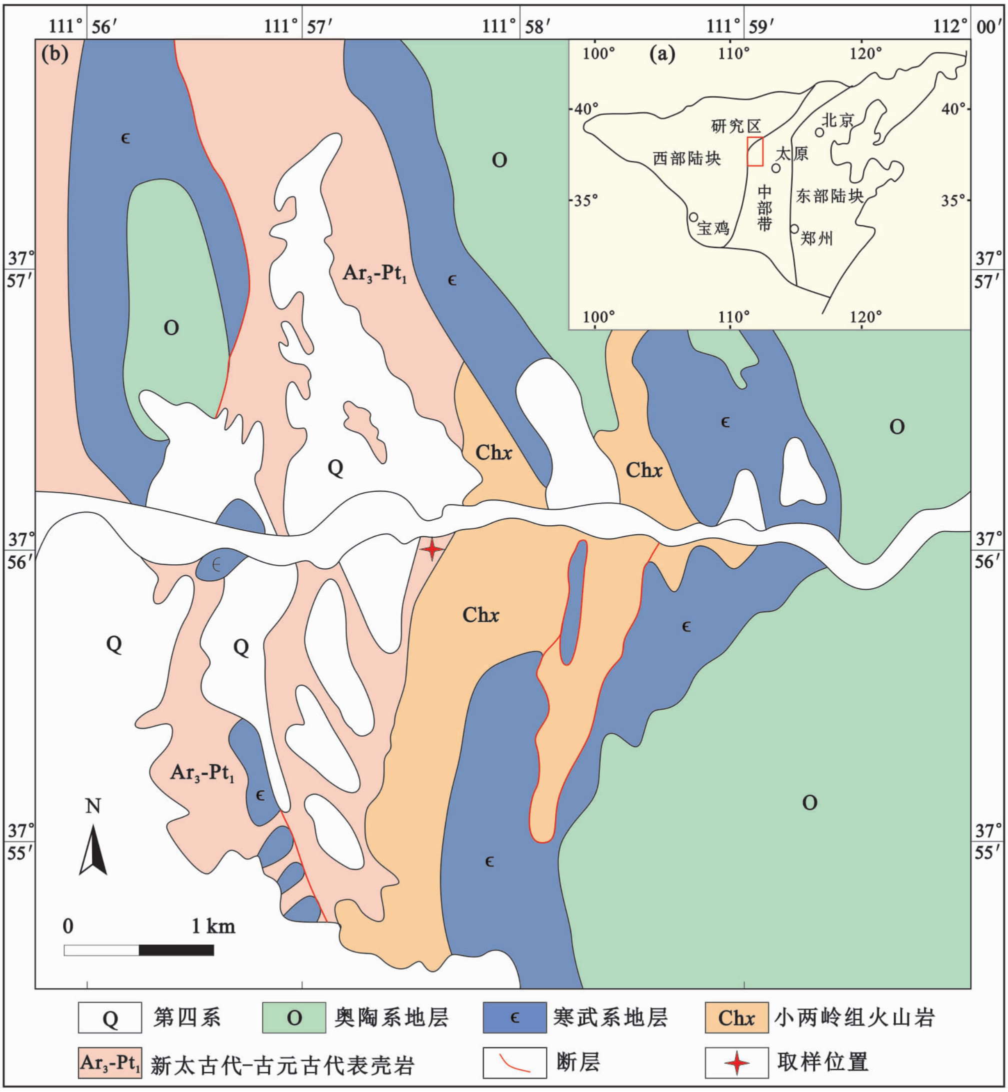

图 1　华北克拉通吕梁地区地质简图(据山西省地质调查院,2010①修改)

Fig. 1　Simplified geological map of Lüliang area in the North China Craton

(2006)根据花岗岩岩石组合和年代学资料把吕梁地区古元古代的花岗质岩浆事件分为早期拉张、拉张-挤压转化和中期挤压以及晚期拉张四个阶段。吕梁变质表壳岩主要由太古宙-古元古代界河口群、古元古代吕梁群和野鸡山群层状变质岩系组成(山西省地质矿产局, 1989; 耿元生等, 2000; 万渝生等, 2000)。

界河口群主要由一套变质的泥砂质岩石和大理岩以及少量的斜长角闪岩类组成,主体呈近南北向分布于吕梁杂岩的西北部界河口-郝家岔一带,被野鸡山群不整合覆盖(万渝生等, 2000; 耿元生等, 2000)。界河口群在吕梁地区出露面积最大,地层连续,自下而上分为奥家滩组、小蛇头组、黑崖寨组、马国寨组和烧炭沟组(山西省地质矿产局, 1989)。奥家滩组是一套由变质程度较高的富铝片岩夹变粒岩、大理岩组成的变质沉积岩;小蛇头组主要包括黑云斜长片麻岩、斜长角闪岩、变粒岩、绿泥片岩和少量的石英岩、大理岩等;黑崖寨组的岩石组合以浅粒岩、绢云黑云长英片岩、混合岩化片麻岩、斜长角闪岩为主,夹少量的石英岩和大理岩;马国寨组主要为黑云斜长片麻岩、黑云变粒岩、斜长角闪岩、夕线片岩;烧炭沟组则由条带状混合岩化黑云斜长片麻岩和斜长角闪岩组成,夹少量浅粒岩和绿泥黑云片岩(山西省地质矿产局, 1989)。关于界河口群的形成时代,通常认为形成于新太古代(山西省地质矿产局, 1989)或新太古代-古元古代早期(2.6 ~ 2.4Ga, 耿元生等, 2003)。万渝生等(2000)认为界河口群具有孔兹岩系的性质,在变泥砂质岩石中获得 2.03 ± 0.05Ga 的碎屑锆石年龄认为其形成于古元古代。刘超辉等(2013)通过界河口群奥家滩组变质沉积岩的碎屑锆

① 山西省地质调查院. 2010. 1 : 5 万岔口幅(J49E013016)地质图及说明书

石年龄研究和斜长角闪岩的变质作用限定了界河口群形成时代为2.00～1.85Ga。

吕梁群出露于吕梁山区中部,近南北走向,岩石组合主要为下部的变质碎屑岩和上部的变质火山岩,自下而上分为袁家村组、裴家庄组、近周营组和杜家沟组(于津海等, 1997a, b)。袁家村组主要由磁铁石英岩、绿泥千枚岩、片岩和杂砂岩组成,是铁矿床的主要赋存层位,该组岩石均受到不同程度的变质作用,由北到南从低绿片岩相到角闪岩相递增;裴家庄组是一套巨厚的浅变质沉积岩系,以千枚岩为主,夹变质砂岩和石英岩;近周营组的岩石组合主要为上部的基性火山岩和下部的变质碎屑岩,变质碎屑岩自下而上为长石石英岩夹变质砾岩、长石石英岩和变质粉砂岩等,基性火山岩已变质成斜长角闪岩、角闪片岩等,在部分火山岩中能够分辨出气孔和杏仁构造;杜家沟组主要由变流纹岩组成,流纹构造和斑状构造保存良好(山西省地质矿产局, 1989; 于津海等, 1997a)。吕梁群曾被认为形成于太古宙(张其春等, 1988; 山西省地质矿产局, 1989),于津海等(1997b)根据吕梁群上部基性火山岩(2051±68Ma)和变质流纹岩的锆石年龄(2099±41Ma)认为吕梁群形成于古元古代。耿元生等(2000)从吕梁群近周营组的变质流纹岩中获得了2360±95Ma的锆石U-Pb年龄,认为近周营组火山岩应该形成于2360～2350Ma。

野鸡山群变质岩系分布在吕梁杂岩的中西部,呈北东-南西向分布,自下而上划分为青杨树湾组、白龙山组和程道沟组(山西省地质矿产局, 1989)。青杨树湾组分布在野鸡山群构成的复向斜的东西两翼,以长石石英岩为主夹千枚岩和大理岩等,石英岩条带状构造发育,局部见有交错层理,千枚岩以粉砂岩为主,记录了滨海-浅海向的沉积环境(刘树文等, 2009);白龙山组分布在复向斜的核部,主要由基性火山岩组成,夹薄层千枚岩、长石石英岩和大理岩等,火山岩经变质成为角闪变粒岩、斜长角闪岩等,杏仁和气孔构造保存较好;程道沟组构成复向斜的核部,岩性以千枚岩为主,条带状构造发育,条带由粉砂质、泥质或碳酸盐岩小韵律组成,具有复理石建造特征。耿元生等(2000, 2003)获得了野鸡山群白龙山组变质火山岩的锆石U-Pb年龄为2124±38Ma,并通过沉积环境和火山岩的地球化学分析认为吕梁群和野鸡山群火山岩形成于陆内或大陆边缘裂谷环境。刘树文等(2009)综合地质学、岩石学和地球化学研究结果认为野鸡山群变质火山岩组合可能形成于大陆边缘岛弧的弧后靠近岛弧一侧的构造环境。Liu *et al.* (2011)通过野鸡山群变碎屑沉积岩最年轻的碎屑锆石年龄～1843Ma,并结合吕梁杂岩中的花岗岩的侵入年龄,认为野鸡山群的沉积时代为1840～1800Ma。

吕梁地区中元古代火山-沉积岩系出露范围较小(图1b),主要为汉高山群火山-沉积岩系和小两岭组火山岩(徐勇航等, 2007),但同期的基性岩墙群较为发育(侯贵廷等, 2001; 彭澎等, 2004)。汉高山群角度不整合于界河口群之上,其上被寒武系砂岩角度不整合覆盖。汉高山群为一套陆源碎屑岩-火山岩为主,未发生变质作用,自下而上可划分为三个组:第一组岩性主要为砾岩、砂岩和(砂质)页岩;第二组不整合于第一组砂岩之上,主要为灰白色、浅红色中粗粒含砾石英砂岩夹薄层灰绿色页岩;第三组底部发育砾岩,中部为安山岩,发育杏仁构造,上部为砾岩和页岩互层。小两岭组火山岩角度不整合覆盖于花岗片麻岩之上,其上被寒武系砂岩角度不整合覆盖,小两岭组火山岩主要由玄武-安山岩和英安-流纹岩组成,上部夹少量紫红色页岩。小两岭组火山岩的锆石U-Pb年龄为1779±20Ma(徐勇航等, 2007)和1776±6Ma(Yang *et al.*, 2019),相当于汉高山群第三组火山岩(山西省地质矿产局, 1989),与豫西地区熊耳群火山岩(1.80～1.75Ga, 赵太平等, 2002, 2004; Wang *et al.*, 2010a)相当,可能是同期岩浆活动在不同空间的产物(徐勇航等, 2007)。

2 样品及其岩相学特征

本文用于锆石和独居石U-Pb年龄分析的2个样品采自山西省吕梁市白家滩村公路附近(图1b,经纬度: 37°56′3.89″N、111°57′37.42″E),采样位置相距约20m,岩性为二云母花岗片麻岩,具有片麻状构造,发生角闪岩相变质作用(图2a, b),山西省地质调查院(2010)填图认为其形成于新太古代。该地区二云母花岗片麻岩被小两岭组火山岩角度不整合覆盖(图2c),小两岭组火山岩主要由玄武-安山岩和英安-流纹岩组成,上部夹有薄层紫红色页岩,火山岩气孔发育(图2d)。

二云母花岗片麻岩样品(17J101)具有鳞片粒状变晶结构,片麻状构造,主要矿物包括钾长石(～35%)、斜长石(～30%)、石英(～25%)、白云母(～3%)和黑云母(～5%)。钾长石和斜长石粒径多在0.3～1mm之间,多已发生不同程度蚀变,少数斜长石可见聚片双晶。石英多呈他形粒状结构,粒径变化较大(0.2～2mm),部分石英沿片麻理拉长,长宽比为2:1～3:1。黑云母呈半自形-他形鳞片状,多数已经发生明显退变,形成绿泥石。少量白云母与黑云母一起构成片麻理(图3a, b)。

二云母花岗片麻岩样品(17J102)具有鳞片粒状变晶结构,片麻状构造,主要矿物包括钾长石(～25%)、斜长石(～35%)、石英(～25%)、白云母(～10%)和黑云母(～5%),岩石蚀变程度较弱。钾长石为微斜长石,具有明显格子双晶。斜长石颗粒较大,可达～1mm,可见聚片双晶,发生一定程度蚀变。石英多呈他形粒状,粒径0.2～1.5mm,定向排列,部分石英含有轻微蚀变的长石包裹体。白云母含量较多,保存较好,单偏光下无色长片状,正交偏光下具有鲜亮的二级蓝-绿干涉色。黑云母呈短片状或细长片状,部分黑云母已蚀变为绿泥石(图3c, d)。

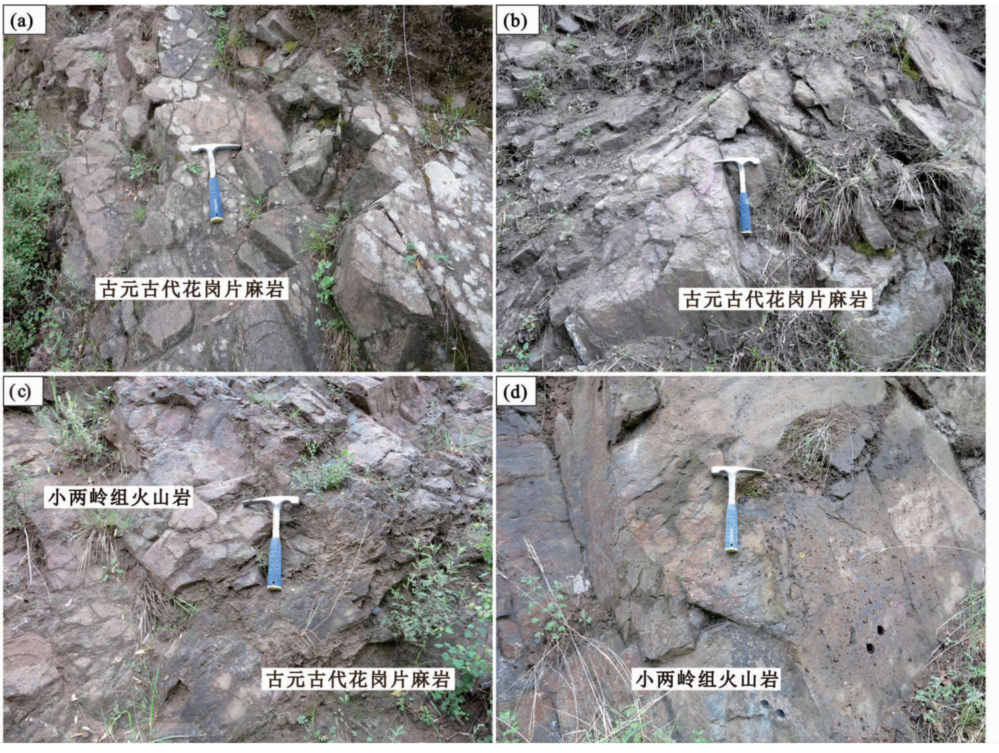

图 2 吕梁地区古元古代花岗片麻岩和小两岭组火山岩野外照片

Fig. 2 Representative field photographs of the Paleoproterozoic granitic gneiss and the volcanic rocks of the Xiaoliangling Formation in Lüliang area

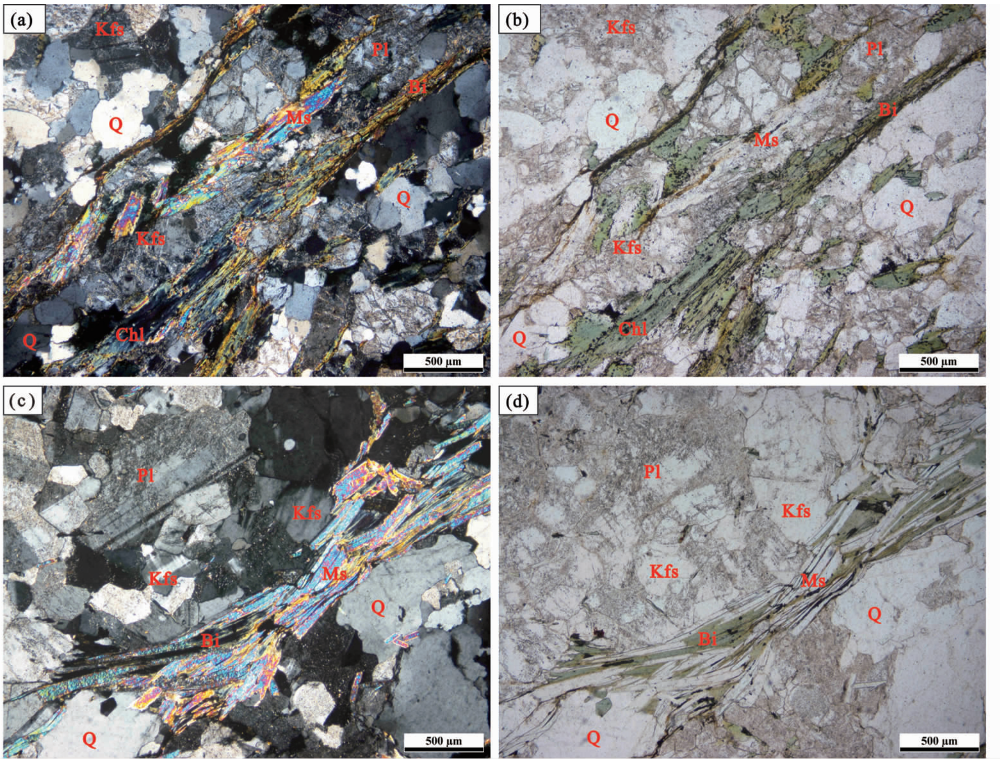

图 3 吕梁地区白家滩花岗片麻岩正交偏光(a、c)和单偏光(b、d)显微照片

Q-石英；Kfs-钾长石；Pl-斜长石；Ms-白云母；Bi-黑云母；Chl-绿泥石

Fig. 3 The cross-polarized light (a, c) and plane-polarized light (b, d) micrographs of the Baijiatan granitic gneiss in Lüliang area

Q-quartz; Kfs-K-feldspar; Pl-plagioclase; Ms-muscovite; Bi-biotite; Chl-chlorite

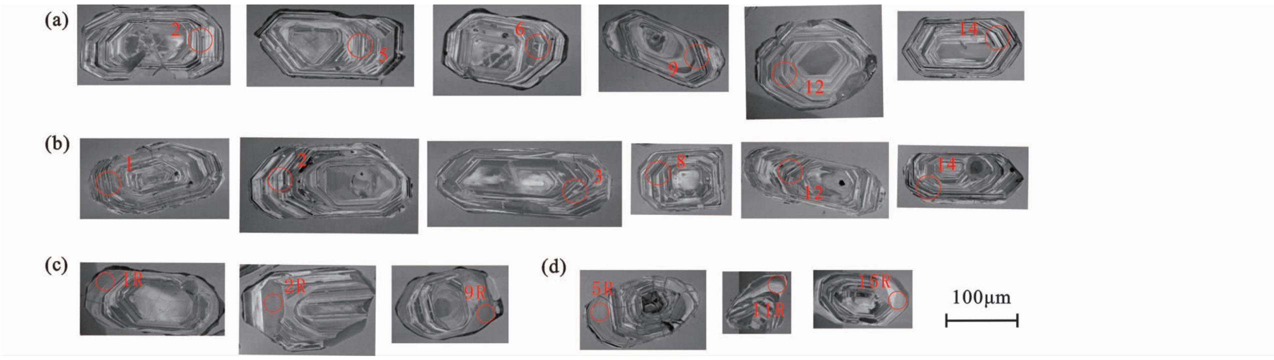

图4 吕梁地区白家滩花岗片麻岩锆石CL图像

(a、c)样品17J101；(b、d)样品17J102. 红色数字为测点号,图6同

Fig. 4 Representative CL images for zircons from the Baijiatan granitic gneiss in Lüliang area

Red circles indicate the in-situ analytical spots and the numbers refer to the LA-ICP-MS U-Pb analyses spot numbers, also in Fig. 6

3 分析方法

本次研究选取2个花岗片麻岩样品进行锆石和独居石U-Pb定年以及锆石原位Hf同位素分析。将样品破碎到40~60目,然后用常规方法分选锆石,并在双目镜下挑纯。将锆石颗粒置于环氧树脂中,抛光使锆石露出核部,用于阴极发光照相及LA-ICP-MS分析。测试前用体积百分比为3%的HNO_3清洗样品表面,以除去样品表面的污染。锆石阴极发光和独居石背散射照相在武汉上谱分析科技有限责任公司完成。

锆石的U-Pb同位素分析是在武汉上谱分析科技有限责任公司通过Agilent 7700e型ICP-MS加载COMPexPro 102 ArF 193nm准分子激光器完成的。采用的激光束斑直径和剥蚀频率分别为32μm(锆石增生边采用24μm的激光束斑直径)和5Hz,能量密度为$8J/cm^2$,每个样品的测试包括大约20s的背景值的采集和50s的样品数据采集。详细的仪器参数和分析流程见Zong *et al.* (2017)。U-Pb同位素分析采用国际标准锆石91500和NIST 610作外标进行校正,数据处理采用软件ICPMSDataCal(Liu *et al.*, 2008, 2010)完成。锆石年龄计算和谐和图绘制使用Isoplot软件(ver 3.0)完成(Ludwig, 2003)。

独居石U-Pb同位素定年在武汉上谱分析科技有限责任公司利用LA-ICP-MS分析完成。实验中使用的激光剥蚀系统由COMPexPro 102 ArF 193nm准分子激光器和MicroLas光学系统组成,ICP-MS型号为Agilent 7700e。本次分析的激光束斑和频率分别为16μm和2Hz,激光能量为80mJ。U-Pb同位素定年处理中采用独居石标准物质44069和玻璃标准物质NIST610作外标分别进行同位素和微量元素分馏校正。对分析数据的离线处理(包括对样品和空白信号的选择、仪器灵敏度漂移校正、元素含量及U-Th-Pb同位素比值和年龄计算)采用软件ICPMSDataCal(Liu *et al.*, 2008, 2010)完成。独居石样品的U-Pb年龄谐和图绘制和年龄加权平均计算采用Isoplot软件(ver 3.0)(Ludwig, 2003)完成。

锆石原位Hf同位素分析是通过武汉上谱分析科技有限责任公司的Neptune Plus(Thermo Fisher Scientific,德国)MC-ICP-MS加载Geolas HD(Coherent,德国)193nm激光剥蚀系统完成的。锆石Hf同位素分析点位与具有振荡环带的岩浆锆石的剥蚀位置相同。分析过程同时配备了信号平滑装置以提高信号稳定性和同位素比值测试精密度(Hu *et al.*, 2012a)。激光实际输出能量密度为$5.3J/cm^2$,束斑直径为44μm。详细仪器操作条件和分析方法参照Hu *et al.* (2012b)。实验中使用$^{176}Yb/^{173}Yb=0.79639$(Fisher *et al.*, 2014)来扣除^{176}Yb对^{176}Hf的同量异位干扰。使用$^{176}Lu/^{175}Lu=0.02656$(Blichert-Toft *et al.*, 1997)来扣除干扰程度相对较小的^{176}Lu对^{176}Hf的同量异位干扰。数据处理采用软件ICPMSDataCal(Liu *et al.*, 2010)完成。91500和GJ-1两个国际锆石标准与样品同时分析,91500进行外标校正,GJ-1作为第二标样监控数据校正质量。2个标样的外部精密度(2SD)优于0.000020。

4 分析结果

4.1 锆石U-Pb年龄

吕梁地区白家滩花岗片麻岩的岩浆锆石LA-ICP-MS U-Pb年龄分析结果见表1。样品17J101和17J102的锆石大多数为自形,呈长柱状,长轴粒径在100~200μm之间,长宽比在1∶1到2∶1之间,CL图像显示大部分锆石具有明显的振荡环带(图4a, b),部分锆石具有宽约5~40μm的变质增生边(图4c, d)。对2个样品均选择30颗具有较好振荡环带的锆石进行测试,结果表明样品17J101的锆石Th、U含量分别为71.8×10^{-6}~722×10^{-6}、130×10^{-6}~1031×10^{-6},Th/U比值为0.30~2.41;样品17J102的锆石Th、U含量分别为116×10^{-6}~897×10^{-6}、272×10^{-6}~1418×10^{-6},其Th/U比

表 1 吕梁地区白家滩花岗片麻岩岩浆锆石 LA-ICP-MS U-Pb 年龄分析结果

Table 1 LA-ICP-MS U-Pb dating results for magmatic zircons from Baijiatan granitic gneiss samples in Lüliang area

测点号	^{232}Th	^{238}U	Th/U	$^{207}Pb/^{206}Pb$		$^{207}Pb/^{235}U$		$^{206}Pb/^{238}U$		$^{207}Pb/^{206}Pb$ (Ma)		$^{207}Pb/^{235}U$ (Ma)		$^{206}Pb/^{238}U$ (Ma)		谐和度
	($\times10^{-6}$)			比值	±1σ	比值	±1σ	比值	±1σ	年龄	±1σ	年龄	±1σ	年龄	±1σ	
17J101 花岗片麻岩																
-01	195	356	0.54	0.1347	0.0025	7.5903	0.1602	0.4080	0.0056	2161	32	2184	19	2206	26	98%
-02	211	432	0.48	0.1310	0.0026	6.4944	0.1387	0.3597	0.0047	2111	35	2045	19	1981	22	96%
-03	235	522	0.45	0.1290	0.0028	5.9531	0.1357	0.3342	0.0041	2084	34	1969	20	1859	20	94%
-04	231	417	0.55	0.1292	0.0025	6.2500	0.1455	0.3494	0.0050	2087	34	2011	20	1932	24	95%
-05	229	556	0.41	0.1296	0.0022	6.3256	0.1185	0.3526	0.0035	2094	31	2022	17	1947	17	96%
-06	175	328	0.53	0.1384	0.0023	7.7862	0.1412	0.4069	0.0047	2207	23	2207	16	2201	22	99%
-07	503	261	1.91	0.1310	0.0023	6.2659	0.1191	0.3460	0.0040	2122	32	2014	17	1915	19	94%
-08	310	1031	0.30	0.0971	0.0021	2.4339	0.0482	0.1815	0.0022	1569	41	1253	14	1075	12	84%
-09	170	278	0.61	0.1289	0.0024	6.2509	0.1253	0.3507	0.0045	2083	33	2012	18	1938	21	96%
-10	276	506	0.54	0.1273	0.0023	6.0981	0.1136	0.3458	0.0033	2061	33	1990	16	1915	16	96%
-11	686	282	2.41	0.1354	0.0023	7.4135	0.1273	0.3952	0.0033	2169	30	2163	15	2147	15	99%
-12	82.6	139	0.59	0.1376	0.0022	7.6349	0.1258	0.4016	0.0044	2198	27	2189	15	2176	20	99%
-13	371	617	0.60	0.1156	0.0019	4.2477	0.0764	0.2652	0.0022	1900	31	1683	15	1516	11	89%
-14	370	580	0.63	0.1211	0.0019	4.3126	0.0699	0.2579	0.0027	1973	27	1696	13	1479	14	86%
-15	208	429	0.48	0.1344	0.0022	7.3868	0.1190	0.3975	0.0029	2167	28	2159	15	2158	13	99%
-16	241	542	0.44	0.1233	0.0022	5.0875	0.0902	0.2985	0.0024	2006	31	1834	15	1684	12	91%
-17	71.8	166	0.43	0.1388	0.0029	7.7166	0.1570	0.4026	0.0035	2213	36	2199	18	2181	16	99%
-18	269	283	0.94	0.1382	0.0024	7.8363	0.1327	0.4108	0.0044	2206	30	2212	15	2219	20	99%
-19	722	569	1.26	0.1227	0.0019	4.6836	0.0862	0.2756	0.0031	1995	33	1764	16	1569	16	88%
-20	168	339	0.49	0.1381	0.0021	7.7208	0.1207	0.4043	0.0035	2203	26	2199	14	2189	16	99%
-21	263	531	0.49	0.1218	0.0022	4.6746	0.0876	0.2777	0.0027	1983	34	1763	16	1580	14	89%
-22	118	245	0.48	0.1390	0.0024	7.8748	0.1463	0.4098	0.0049	2217	34	2217	17	2214	23	99%
-23	253	511	0.49	0.1235	0.0024	5.1960	0.1113	0.3035	0.0031	2007	35	1852	18	1709	15	91%
-24	101	130	0.77	0.1387	0.0028	7.7964	0.1565	0.4058	0.0035	2211	40	2208	18	2196	16	99%
-25	133	281	0.47	0.1349	0.0025	7.0380	0.1282	0.3768	0.0032	2165	32	2116	16	2061	15	97%
-26	337	758	0.44	0.1120	0.0020	3.3977	0.0579	0.2191	0.0017	1832	33	1504	13	1277	9	83%
-27	317	552	0.57	0.1180	0.0021	4.5324	0.0790	0.2773	0.0023	1928	32	1737	15	1578	12	90%
-28	375	712	0.52	0.1164	0.0020	3.8289	0.0778	0.2375	0.0031	1902	31	1599	16	1374	16	84%
-29	485	678	0.71	0.1105	0.0022	3.5482	0.0759	0.2309	0.0022	1809	36	1538	17	1339	11	86%
-30	261	508	0.51	0.1278	0.0022	6.1518	0.1063	0.3472	0.0031	2078	31	1998	15	1921	15	96%
17J102 花岗片麻岩																
-01	243	512	0.47	0.1182	0.0023	4.0721	0.0719	0.2497	0.0027	1929	35	1649	14	1437	14	86%
-02	274	695	0.39	0.1238	0.0021	5.3495	0.1064	0.3114	0.0039	2013	31	1877	17	1748	19	92%
-03	681	318	2.13	0.1325	0.0023	7.0235	0.1362	0.3823	0.0044	2131	31	2114	17	2087	20	98%
-04	239	598	0.40	0.1172	0.0019	4.3148	0.0678	0.2661	0.0025	1914	29	1696	13	1521	13	89%
-05	116	272	0.42	0.1346	0.0023	7.7411	0.1507	0.4157	0.0054	2158	30	2201	18	2241	25	98%
-06	376	610	0.61	0.1180	0.0022	3.7784	0.0834	0.2323	0.0040	1928	33	1588	18	1346	21	83%
-07	137	299	0.46	0.1359	0.0025	7.7076	0.1557	0.4100	0.0054	2176	31	2197	18	2215	25	99%
-08	369	698	0.53	0.1245	0.0023	4.5882	0.0882	0.2665	0.0029	2021	33	1747	16	1523	15	86%
-09	234	447	0.52	0.1287	0.0024	5.3674	0.1426	0.3011	0.0063	2081	32	1880	23	1697	31	89%
-10	140	350	0.40	0.1305	0.0021	5.9767	0.1104	0.3313	0.0038	2106	28	1972	16	1845	18	93%
-11	349	729	0.47	0.1160	0.0019	4.3808	0.0819	0.2727	0.0025	1896	30	1709	16	1555	13	90%
-12	897	473	1.88	0.1242	0.0024	4.8810	0.0992	0.2843	0.0029	2018	34	1799	17	1613	14	89%
-13	618	299	2.05	0.1380	0.0024	7.4557	0.1368	0.3916	0.0041	2203	30	2168	16	2130	19	98%
-14	272	668	0.40	0.1141	0.0021	3.6964	0.0777	0.2347	0.0030	1866	33	1571	17	1359	16	85%
-15	165	279	0.59	0.1335	0.0024	7.8050	0.1588	0.4240	0.0052	2144	27	2209	18	2279	23	96%
-16	213	488	0.43	0.1293	0.0021	5.9874	0.1118	0.3359	0.0044	2089	28	1974	16	1867	21	94%
-17	240	568	0.42	0.1319	0.0020	6.9061	0.1126	0.3798	0.0038	2124	27	2099	15	2075	18	98%
-18	137	370	0.37	0.1375	0.0022	8.2068	0.1360	0.4333	0.0051	2196	33	2254	15	2320	23	97%

续表 1

Continued Table 1

测点号	^{232}Th	^{238}U	Th/U	$^{207}Pb/^{206}Pb$		$^{207}Pb/^{235}U$		$^{206}Pb/^{238}U$		$^{207}Pb/^{206}Pb$ (Ma)		$^{207}Pb/^{235}U$ (Ma)		$^{206}Pb/^{238}U$ (Ma)		谐和度
	($\times 10^{-6}$)			比值	±1σ	比值	±1σ	比值	±1σ	年龄	±1σ	年龄	±1σ	年龄	±1σ	
-19	195	544	0.36	0.1268	0.0019	5.8752	0.1056	0.3362	0.0048	2053	26	1958	16	1868	23	95%
-20	135	276	0.49	0.1374	0.0023	6.3943	0.1137	0.3378	0.0043	2194	34	2031	16	1876	21	92%
-21	198	475	0.41	0.1359	0.0021	6.1739	0.1156	0.3285	0.0040	2176	27	2001	16	1831	20	91%
-22	336	294	1.14	0.1416	0.0024	8.3989	0.1611	0.4288	0.0051	2247	30	2275	17	2300	23	98%
-23	125	321	0.39	0.1334	0.0023	7.1593	0.1597	0.3892	0.0070	2143	25	2131	20	2119	32	99%
-24	458	598	0.76	0.1253	0.0021	5.2401	0.0943	0.3024	0.0032	2033	29	1859	15	1703	16	91%
-25	327	608	0.53	0.1303	0.0022	5.7860	0.1124	0.3209	0.0039	2102	29	1944	17	1794	19	91%
-26	397	477	0.83	0.1312	0.0024	5.8964	0.1239	0.3244	0.0034	2113	33	1961	18	1811	17	92%
-27	188	285	0.65	0.1374	0.0022	7.7783	0.1673	0.4100	0.0069	2194	28	2206	19	2215	31	99%
-28	164	425	0.38	0.1367	0.0020	7.4677	0.1201	0.3955	0.0039	2187	25	2169	14	2148	18	99%
-29	174	383	0.45	0.1388	0.0020	7.2034	0.1179	0.3757	0.0039	2213	26	2137	15	2056	18	96%
-30	753	1418	0.53	0.0957	0.0025	1.5399	0.0437	0.1161	0.0012	1543	50	946	17	708	7	71%

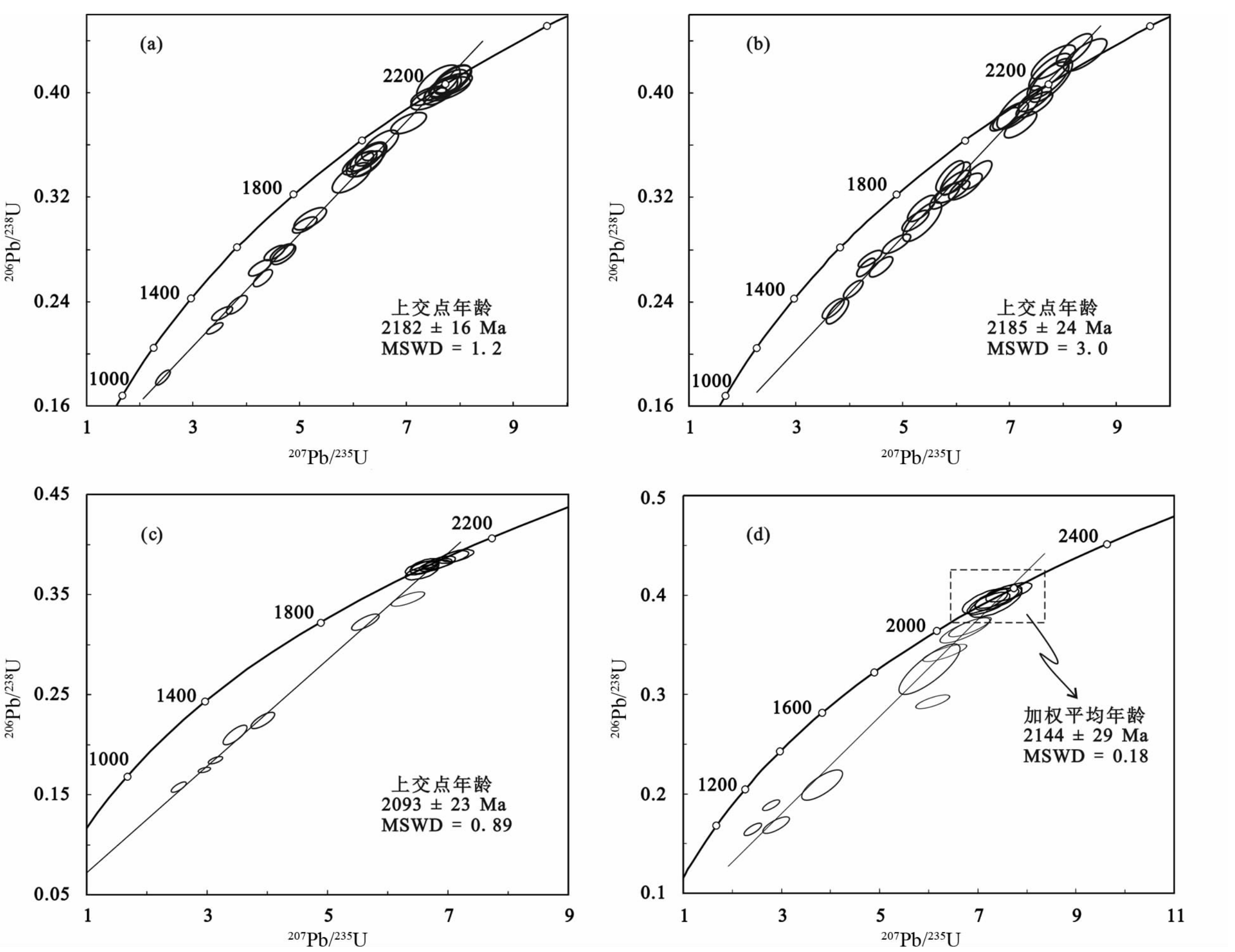

图 5 吕梁地区白家滩花岗片麻岩锆石 U-Pb 年龄谐和图

(a、b)具有明显振荡环带的锆石;(c、d)锆石增生边

Fig. 5 U-Pb concordia diagrams for zircons from the Baijiatan granitic gneiss in Lüliang area

(a, b) represent zircons with good zoning structures; (c, d) zircon rims

表 2 吕梁地区白家滩花岗片麻岩的锆石增生边 LA-ICP-MS U-Pb 年龄分析结果

Table 2 LA-ICP-MS U-Pb dating results for zircon overgrowth rims from Baijiatan granitic gneiss samples in Lüliang area

测点号	^{232}Th	^{238}U	Th/U	$^{207}Pb/^{206}Pb$		$^{207}Pb/^{235}U$		$^{206}Pb/^{238}U$		$^{207}Pb/^{206}Pb$ (Ma)		$^{207}Pb/^{235}U$ (Ma)		$^{206}Pb/^{238}U$ (Ma)		谐和度
	($\times 10^{-6}$)			比值	$\pm 1\sigma$	比值	$\pm 1\sigma$	比值	$\pm 1\sigma$	年龄	$\pm 1\sigma$	年龄	$\pm 1\sigma$	年龄	$\pm 1\sigma$	
17J101 花岗片麻岩																
-01R	48.1	191	0.25	0.1315	0.0042	6.1676	0.1872	0.3364	0.0045	2118	56	2000	27	1870	22	93%
-02R	50.8	207	0.25	0.1312	0.0036	7.2274	0.1825	0.3951	0.0038	2115	48	2140	23	2146	18	99%
-03R	92.7	168	0.55	0.1303	0.0033	7.2407	0.1780	0.3987	0.0042	2102	44	2142	22	2163	19	99%
-04R	61.9	118	0.52	0.1294	0.0033	6.9754	0.1758	0.3875	0.0042	2100	78	2108	22	2111	20	99%
-05R	63.3	125	0.51	0.1293	0.0033	6.8183	0.1625	0.3793	0.0037	2100	44	2088	21	2073	17	99%
-06R	160	590	0.27	0.1181	0.0030	4.0064	0.1082	0.2444	0.0040	1928	45	1636	22	1410	21	85%
-07R	140	283	0.49	0.1252	0.0029	6.6598	0.1525	0.3818	0.0040	2032	41	2067	20	2085	19	99%
-08R	268	702	0.38	0.1230	0.0028	3.0440	0.0755	0.1774	0.0025	2067	40	1419	19	1053	14	70%
-09R	92	162	0.57	0.1255	0.0030	6.6752	0.1587	0.3811	0.0037	2036	43	2069	21	2082	18	99%
-10R	159	355	0.45	0.1258	0.0029	5.2076	0.1331	0.2966	0.0048	2040	41	1854	22	1674	24	89%
-11R	143	815	0.18	0.1219	0.0031	3.0519	0.0754	0.1793	0.0020	1984	44	1421	19	1063	11	71%
-12R	178	288	0.62	0.1272	0.0036	6.7098	0.1878	0.3773	0.0048	2061	50	2074	25	2063	23	99%
-13R	114	124	0.92	0.1258	0.0039	6.7624	0.2050	0.3849	0.0047	2040	55	2081	27	2099	22	99%
-14R	84.9	211	0.40	0.1306	0.0035	7.0550	0.1858	0.3862	0.0038	2106	48	2118	23	2105	18	99%
-15R	308	1422	0.22	0.1174	0.0027	2.0478	0.0538	0.1247	0.0018	1918	42	1132	18	757	11	60%
-16R	257	672	0.38	0.1301	0.0030	4.2654	0.1302	0.2343	0.0049	2099	40	1687	25	1357	26	78%
17J102 花岗片麻岩																
-01R	167	579	0.29	0.1494	0.0034	6.0825	0.1364	0.2925	0.0028	2339	39	1988	20	1654	14	81%
-02R	60.1	131	0.46	0.1336	0.0034	6.8425	0.1722	0.3676	0.0038	2146	44	2091	22	2018	18	96%
-03R	85.0	164	0.52	0.1305	0.0036	7.1492	0.1908	0.3938	0.0051	2106	48	2130	24	2141	24	99%
-04R	66.7	139	0.48	0.1342	0.0036	7.3602	0.2175	0.3926	0.0061	2153	46	2156	26	2135	28	99%
-05R	30.4	144	0.21	0.1342	0.0035	7.4216	0.1930	0.3972	0.0051	2154	46	2164	23	2156	23	99%
-06R	1315	329	4.00	0.1490	0.0038	7.5463	0.1918	0.3626	0.0032	2344	38	2178	23	1995	15	91%
-07R	57.3	285	0.20	0.1324	0.0033	7.2200	0.1783	0.3914	0.0045	2131	43	2139	22	2129	21	99%
-08R	147	932	0.16	0.1225	0.0033	2.9117	0.1085	0.1687	0.0037	1992	49	1385	28	1005	20	68%
-09R	105	229	0.46	0.1329	0.0040	6.3148	0.1830	0.3411	0.0036	2137	52	2021	25	1892	17	93%
-10R	248	520	0.48	0.1312	0.0040	3.8255	0.1702	0.2070	0.0065	2113	52	1598	36	1213	35	72%
-11R	142	293	0.49	0.1328	0.0038	6.7304	0.1982	0.3634	0.0046	2135	50	2077	26	1998	22	96%
-12R	174	910	0.19	0.1064	0.0027	2.7900	0.0723	0.1881	0.0021	1739	46	1353	19	1111	11	80%
-13R	180	907	0.20	0.1056	0.0027	2.4204	0.0733	0.1641	0.0025	1724	48	1249	22	979	14	75%
-14R	99	221	0.45	0.1363	0.0034	7.6331	0.1920	0.4027	0.0039	2180	44	2189	23	2182	18	99%
-15R	48.5	74.6	0.65	0.1326	0.0041	6.0137	0.2527	0.3256	0.0097	2132	55	1978	37	1817	47	91%
-16R	130	246	0.53	0.1341	0.0033	7.3925	0.1820	0.3968	0.0041	2152	42	2160	22	2154	19	99%

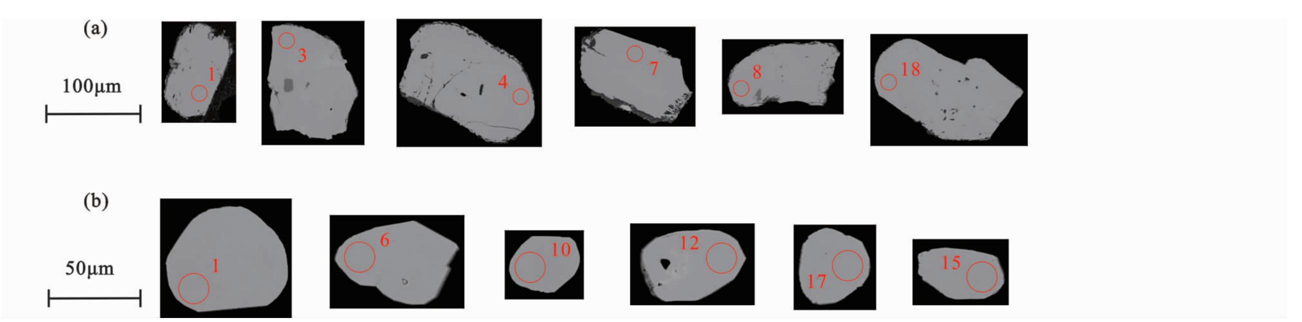

图 6 吕梁地区白家滩花岗片麻岩独居石 BSE 图像

Fig. 6 Representative BSE images for monazites from the Baijiatan granitic gneiss in Lüliang area

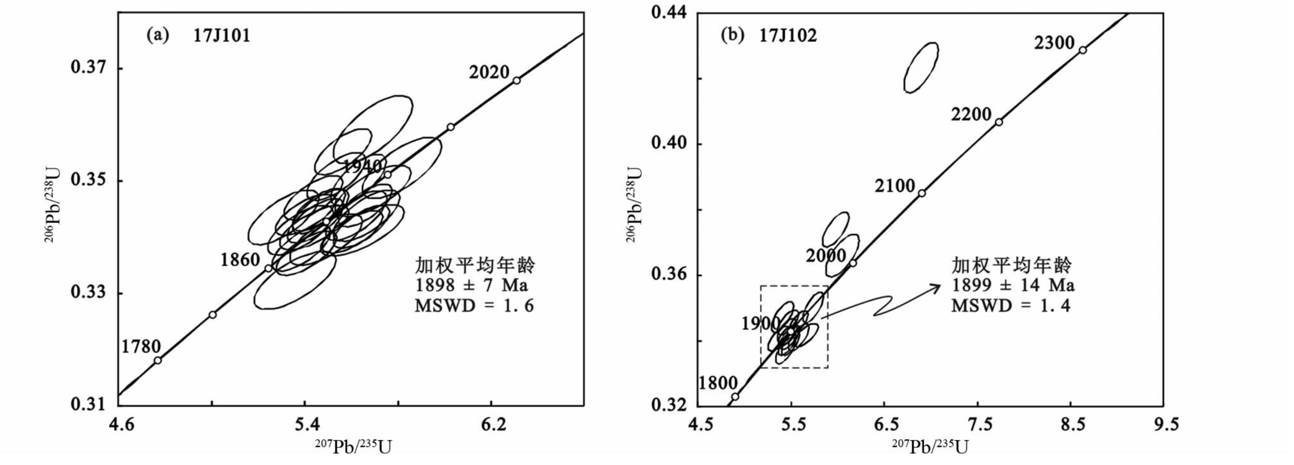

图7 吕梁地区白家滩花岗片麻岩独居石 U-Pb 年龄谐和图

Fig. 7 U-Pb concordia diagrams for monazites from the Baijiatan granitic gneiss in Lüliang area

值为0.36~2.13;为典型的岩浆成因锆石。2个样品的30个分析点给出的上交点年龄分别为2182±16Ma(MSWD=1.2)(图5a)和2185±24Ma(MSWD=3.0)(图5b),二者在误差范围内一致,可代表白家滩花岗片麻岩的原岩形成时代。

本次研究选择2个花岗片麻岩的锆石增生边进行LA-ICP-MS U-Pb年龄分析,结果见表2。对2个样品分别测试了16个点,部分锆石Pb丢失明显,约一半测试点的谐和度优于90%。样品17J101的锆石增生边的Th、U含量分别为$48.1\times10^{-6}\sim308\times10^{-6}$、$118\times10^{-6}\sim1422\times10^{-6}$,Th/U比值为0.18~0.92,Th含量和Th/U比值整体上比岩浆锆石低。样品17J101所有测点的谐和线上交点年龄为2093±23Ma(MSWD=0.89)(图5c),其中10颗谐和锆石的$^{207}Pb/^{206}Pb$年龄范围为2032~2118Ma,明显小于核部具有振荡环带的锆石年龄(2182±16Ma)。样品17J102的部分测试点在谐和图中分布较为分散,剔除普通Pb含量较高(12.2×10^{-6})的点06R,其余15个测试点的Th、U含量分别为$30.4\times10^{-6}\sim248\times10^{-6}$、$74.6\times10^{-6}\sim932\times10^{-6}$,其Th/U比值为0.16~0.65,小于岩浆锆石的Th、U含量和Th/U比值,该15个分析点得到的不一致线的交点年龄(2185±53Ma,MSWD=9.1)较差,其中10颗谐和锆石的$^{207}Pb/^{206}Pb$年龄范围为2106~2180Ma,其加权平均年龄为2144±29Ma(MSWD=0.18)(图5d),比花岗片麻岩的岩浆锆石年龄(2185±24Ma)略小。

4.2 独居石 U-Pb 年龄

2个花岗片麻岩的独居石LA-ICP-MS U-Pb年龄分析结果见表3。样品17J101的独居石颗粒为半自形-他形,粒径约50~150μm,BSE图像显示独居石为均匀的灰白色,没有分带现象(图6a)。对该样品选择24颗独居石进行测试,结果表明独居石的Th和U含量均较高,分别为$4437\times10^{-6}\sim68615\times10^{-6}$、$626\times10^{-6}\sim4740\times10^{-6}$,Th/U比值为1.17~72.85,24个分析点的谐和度较好,$^{207}Pb/^{206}Pb$年龄集中于1832~1951Ma,其加权平均年龄为1898±7Ma(MSWD=1.6)(图7a)。样品17J102的独居石颗粒较小,呈次圆状-圆状,粒径约20~70μm,BSE图像显示均为灰白色,没有环带(图6b)。对该样品共分析18个点,其中2个点(17J102-2和17J102-5)不是独居石(P_2O_5含量分别为0.28%和0.38%),还有3个点(17J102-3、17J102-8和17J102-13)的$^{206}Pb/^{238}U$年龄和$^{207}Pb/^{235}U$年龄较大,其余13个测试点在谐和图中分布较为集中,Th($484\times10^{-6}\sim93720\times10^{-6}$)和U($2850\times10^{-6}\sim11043\times10^{-6}$)含量变化较大,Th/U比值为0.06~9.93,该13个点的加权平均年龄为1899±14Ma(MSWD=1.4)(图7b),与样品17J101的独居石年龄结果一致,代表了花岗片麻岩的变质作用时间。

4.3 锆石 Lu-Hf 同位素

2个样品的锆石Lu-Hf同位素分析结果见表4。其中,锆石颗粒17J102-30被打穿,信号极差,去除该数据。样品17J101和17J102的锆石的$^{176}Lu/^{177}Hf$比值分别为0.000759~0.001735和0.000514~0.002056,除17J102-06的锆石$^{176}Lu/^{177}Hf$比值(0.002056)大于0.002,其他58个点的$^{176}Lu/^{177}Hf$比值均小于0.002,表明锆石结晶后,放射性成因Hf的积累基本没有或较少,测得的$^{176}Hf/^{177}Hf$比值基本代表了其形成时体系中的Hf同位素组成(Patchett *et al.*, 1981)。2个样品的锆石$^{176}Hf/^{177}Hf$比值为0.281403~0.281483和0.281408~0.281493,$\varepsilon_{Hf}(t)$值变化范围较小,分别为−1.2~+1.8和−1.3~+1.4,集中分布于−0.2~1.2之间,远低于同时代的亏损地幔$\varepsilon_{Hf}(t)$值(图8)。2个样品的Hf同位素单阶段亏损地幔模式年龄(t_{DM})分别为2473~2587Ma和2490~2598Ma,两阶段亏损地幔模式年龄($t_{DM}{}^{C}$)分布于2646~2828Ma和2674~2839Ma之间,明显大于花岗片麻岩的原岩形成年龄(~2180Ma),表明花岗片麻岩的原岩是较

表 3　吕梁地区白家滩花岗片麻岩独居石 LA-ICP-MS U-Pb 年龄分析结果

Table 3　LA-ICP-MS U-Pb dating results for monazites from Baijiatan granitic gneiss samples in Lüliang area

测点号	Th	U	Th/U	$^{207}Pb/^{206}Pb$		$^{207}Pb/^{235}U$		$^{206}Pb/^{238}U$		$^{207}Pb/^{206}Pb$ (Ma)		$^{207}Pb/^{235}U$ (Ma)		$^{206}Pb/^{238}U$ (Ma)		谐和度
	(×10⁻⁶)			比值	±1σ	比值	±1σ	比值	±1σ	年龄	±1σ	年龄	±1σ	年龄	±1σ	
17J101 花岗片麻岩																
-01	32856	664	49.5	0.1174	0.0027	5.3580	0.1165	0.3324	0.0034	1917	42	1878	19	1850	17	98%
-02	43321	4220	10.3	0.1151	0.0017	5.3847	0.0842	0.3382	0.0027	1883	27	1882	13	1878	13	99%
-03	35572	2494	14.3	0.1135	0.0017	5.4024	0.0854	0.3441	0.0024	1857	28	1885	14	1907	12	98%
-04	45095	1652	27.3	0.1134	0.0018	5.4361	0.0841	0.3471	0.0026	1855	28	1891	13	1921	13	98%
-05	33580	957	35.1	0.1120	0.0021	5.3074	0.1006	0.3436	0.0032	1832	33	1870	16	1904	16	98%
-06	32185	2102	15.3	0.1148	0.0016	5.4677	0.0802	0.3447	0.0026	1876	26	1896	13	1909	13	99%
-07	12840	3381	3.80	0.1145	0.0016	5.4609	0.0748	0.3450	0.0025	1873	25	1894	12	1911	12	99%
-08	33715	3421	9.86	0.1133	0.0016	5.5645	0.0809	0.3553	0.0027	1854	25	1911	13	1960	13	97%
-09	35850	3305	10.8	0.1142	0.0017	5.5352	0.0824	0.3509	0.0028	1866	27	1906	13	1939	13	98%
-10	43468	1862	23.3	0.1161	0.0019	5.4078	0.0862	0.3373	0.0026	1898	3	1886	14	1873	13	99%
-11	19725	1512	13.0	0.1151	0.0021	5.4398	0.0982	0.3418	0.0026	1881	32	1891	16	1895	12	99%
-12	22430	1958	11.5	0.1141	0.0020	5.3810	0.0932	0.3414	0.0029	1866	32	1882	15	1894	14	99%
-13	46747	1515	30.9	0.1147	0.0021	5.6921	0.1112	0.3592	0.0040	1876	32	1930	17	1978	19	97%
-14	47951	4740	10.1	0.1148	0.0017	5.4441	0.0798	0.3430	0.0026	1877	27	1892	13	1901	13	99%
-15	46143	2634	17.5	0.1163	0.0017	5.6296	0.0792	0.3503	0.0030	1902	26	1921	12	1936	14	99%
-16	4437	3777	1.17	0.1184	0.0016	5.6603	0.0764	0.3457	0.0025	1933	24	1925	12	1914	12	99%
-17	42090	1617	26.0	0.1192	0.0021	5.8154	0.1123	0.3524	0.0036	1946	27	1949	17	1946	17	99%
-18	25537	986	25.9	0.1170	0.0023	5.4908	0.1036	0.3397	0.0030	1922	35	1899	16	1885	14	99%
-19	30824	868	35.5	0.1196	0.0025	5.6467	0.1177	0.3414	0.0030	1951	37	1923	18	1893	15	98%
-20	49099	1694	29.0	0.1183	0.0019	5.6216	0.0865	0.3440	0.0029	1931	29	1919	13	1906	14	99%
-21	46748	1658	28.2	0.1190	0.0019	5.6048	0.0857	0.3410	0.0025	1943	28	1917	13	1891	12	98%
-22	68615	3660	18.7	0.1194	0.0017	5.6421	0.0789	0.3420	0.0025	1948	24	1923	12	1896	12	98%
-23	45601	626	72.8	0.1187	0.0024	5.6927	0.1069	0.3484	0.0030	1936	36	1930	16	1927	14	99%
-24	8814	2935	3.00	0.1193	0.0019	5.6644	0.0934	0.3440	0.0030	1946	29	1926	14	1906	14	98%
17J102 花岗片麻岩																
-01	4478	5404	0.83	0.1198	0.0018	5.6548	0.0869	0.3418	0.0023	1953	26	1924	13	1895	11	98%
-02	1179	2172	0.54	0.1378	0.0032	3.7279	0.1197	0.1959	0.0045	2211	40	1577	26	1153	24	68%
-03	1668	981	1.70	0.1200	0.0021	6.0528	0.1168	0.3661	0.0043	1955	31	1983	17	2011	20	98%
-04	7860	5342	1.47	0.1157	0.0014	5.4577	0.0671	0.3418	0.0020	1890	10	1894	11	1895	10	99%
-05	1022	3048	0.34	0.1475	0.0039	2.9668	0.1658	0.1484	0.0078	2318	45	1399	42	892	44	55%
-06	13353	8321	1.60	0.1146	0.0016	5.4641	0.0748	0.3458	0.0025	1873	24	1895	12	1914	12	98%
-07	1633	4857	0.34	0.1140	0.0016	5.3680	0.0767	0.3409	0.0025	1865	30	1880	12	1891	12	99%
-08	3117	1382	2.26	0.1159	0.0018	5.9780	0.0931	0.3742	0.0035	1894	27	1973	14	2049	17	96%
-09	6594	2850	2.31	0.1128	0.0015	5.4062	0.0761	0.3474	0.0031	1856	24	1886	12	1922	15	98%
-10	484	8651	0.06	0.1148	0.0013	5.4490	0.0649	0.3434	0.0023	1877	20	1893	10	1903	11	99%
-11	24269	9281	2.61	0.1164	0.0014	5.4559	0.0630	0.3390	0.0022	1902	21	1894	10	1882	11	99%
-12	51505	9721	5.30	0.1162	0.0015	5.4813	0.0681	0.3413	0.0024	1899	24	1898	11	1893	12	99%
-13	235	1459	0.16	0.1177	0.0017	6.8979	0.1208	0.4236	0.0050	1921	26	2098	16	2277	23	91%
-14	33766	11043	3.06	0.1165	0.0014	5.4343	0.0700	0.3372	0.0026	1903	22	1890	11	1873	12	99%
-15	4370	5996	0.73	0.1170	0.0014	5.4913	0.0621	0.3394	0.0024	1911	16	1899	10	1884	11	99%
-16	502	6372	0.08	0.1183	0.0014	5.7303	0.0725	0.3503	0.0031	1931	21	1936	11	1936	15	99%
-17	10762	6827	1.58	0.1165	0.0013	5.5762	0.0654	0.3458	0.0024	1906	21	1912	10	1914	12	99%
-18	93720	9436	9.93	0.1182	0.0014	5.5822	0.0725	0.3413	0.0027	1929	22	1913	11	1893	13	98%

表 4 吕梁地区白家滩花岗片麻岩岩浆锆石 Lu-Hf 同位素分析结果

Table 4 Zircon Lu-Hf data from Baijiatan granitic gneiss samples in Lüliang area

测点号	年龄 (Ma)	$\frac{^{176}Yb}{^{177}Hf}$	$\frac{^{176}Lu}{^{177}Hf}$ (m)	$\frac{^{176}Hf}{^{177}Hf}$ (m)	1σ	$\frac{^{176}Hf}{^{177}Hf}(t)$	$\varepsilon_{Hf}(t)$	t_{DM} (Ma)	$t_{DM}{}^{C}$ (Ma)	$f_{Lu/Hf}$
17J101 花岗片麻岩										
-01		0.022151	0.000892	0.281462	0.000011	0.281425	1.2	2494	2683	-0.97
-02		0.024669	0.000974	0.281455	0.000010	0.281414	0.8	2510	2706	-0.97
-03		0.019124	0.000793	0.281449	0.000010	0.281416	0.9	2506	2702	-0.98
-04		0.034261	0.001348	0.281472	0.000010	0.281416	0.9	2511	2703	-0.96
-05		0.024708	0.000987	0.281463	0.000009	0.281422	1.1	2499	2689	-0.97
-06		0.027477	0.001077	0.281448	0.000011	0.281403	0.4	2526	2731	-0.97
-07		0.027857	0.001035	0.281423	0.000010	0.281380	-0.4	2556	2780	-0.97
-08		0.038450	0.001441	0.281448	0.000011	0.281388	-0.1	2550	2764	-0.96
-09		0.025188	0.001008	0.281483	0.000010	0.281441	1.8	2473	2646	-0.97
-10		0.022584	0.000894	0.281451	0.000010	0.281413	0.8	2510	2708	-0.97
-11		0.028776	0.001073	0.281403	0.000010	0.281358	-1.2	2587	2828	-0.97
-12		0.019764	0.000792	0.281433	0.000012	0.281400	0.3	2527	2737	-0.98
-13		0.026945	0.001068	0.281462	0.000010	0.281417	0.9	2506	2699	-0.97
-14		0.043293	0.001644	0.281458	0.000011	0.281389	-0.1	2550	2760	-0.95
-15		0.022623	0.000885	0.281449	0.000009	0.281413	0.7	2511	2710	-0.97
-16	2182	0.033035	0.001307	0.281451	0.000011	0.281397	0.2	2536	2744	-0.96
-17		0.019834	0.000759	0.281461	0.000011	0.281430	1.3	2487	2673	-0.98
-18		0.021361	0.000859	0.281454	0.000011	0.281419	1.0	2502	2696	-0.97
-19		0.026850	0.001016	0.281434	0.000012	0.281391	0.0	2541	2756	-0.97
-20		0.024988	0.001019	0.281460	0.000011	0.281417	0.9	2506	2699	-0.97
-21		0.040413	0.001534	0.281456	0.000011	0.281393	0.0	2545	2753	-0.95
-22		0.023004	0.000935	0.281459	0.000011	0.281420	1.0	2502	2694	-0.97
-23		0.026622	0.001045	0.281458	0.000010	0.281415	0.8	2509	2705	-0.97
-24		0.019778	0.000796	0.281450	0.000010	0.281417	0.9	2505	2700	-0.98
-25		0.039509	0.001490	0.281466	0.000010	0.281404	0.4	2529	2729	-0.96
-26		0.029016	0.001161	0.281446	0.000011	0.281397	0.2	2534	2743	-0.97
-27		0.045685	0.001735	0.281441	0.000011	0.281369	-0.8	2579	2804	-0.95
-28		0.038666	0.001516	0.281455	0.000010	0.281392	0.0	2545	2754	-0.95
-29		0.045760	0.001727	0.281446	0.000011	0.281375	-0.6	2571	2792	-0.95
-30		0.024605	0.000971	0.281476	0.000011	0.281435	1.6	2481	2660	-0.97
17J102 花岗片麻岩										
-01		0.020340	0.000782	0.281442	0.000012	0.281409	0.7	2515	2715	-0.98
-02		0.022874	0.000954	0.281431	0.000010	0.281391	0.1	2541	2754	-0.97
-03		0.034573	0.001229	0.281442	0.000011	0.281391	0.0	2544	2755	-0.96
-04		0.033084	0.001275	0.281471	0.000010	0.281418	1.0	2507	2696	-0.96
-05		0.021947	0.000868	0.281449	0.000010	0.281412	0.8	2511	2708	-0.97
-06		0.055463	0.002056	0.281493	0.000011	0.281408	0.6	2528	2718	-0.94
-07		0.020596	0.000812	0.281440	0.000011	0.281406	0.6	2519	2721	-0.98
-08		0.023217	0.000911	0.281466	0.000012	0.281428	1.4	2490	2674	-0.97
-09		0.035632	0.001381	0.281457	0.000011	0.281399	0.3	2534	2737	-0.96
-10		0.029962	0.001152	0.281430	0.000011	0.281382	-0.3	2556	2775	-0.97
-11		0.022029	0.000918	0.281427	0.000011	0.281388	0.0	2544	2760	-0.97
-12		0.024742	0.000950	0.281438	0.000011	0.281398	0.3	2531	2739	-0.97
-13		0.022604	0.000826	0.281408	0.000010	0.281374	-0.6	2563	2792	-0.98
-14		0.030600	0.001227	0.281439	0.000011	0.281388	0.0	2547	2760	-0.96
-15	2185	0.019910	0.000789	0.281443	0.000010	0.281410	0.7	2513	2712	-0.98
-16		0.025451	0.001020	0.281446	0.000010	0.281403	0.5	2525	2728	-0.97
-17		0.024775	0.000981	0.281448	0.000010	0.281407	0.6	2519	2719	-0.97
-18		0.012240	0.000514	0.281410	0.000011	0.281389	0.0	2540	2759	-0.98
-19		0.032172	0.001239	0.281444	0.000012	0.281392	0.1	2542	2752	-0.96
-20		0.035175	0.001348	0.281421	0.000011	0.281365	-0.9	2581	2812	-0.96
-21		0.021587	0.000851	0.281428	0.000011	0.281392	0.1	2538	2752	-0.97
-22		0.037736	0.001334	0.281408	0.000011	0.281352	-1.3	2598	2839	-0.96
-23		0.042769	0.001662	0.281478	0.000012	0.281409	0.7	2522	2715	-0.95
-24		0.020340	0.000819	0.281429	0.000011	0.281395	0.2	2535	2747	-0.98
-25		0.020792	0.000852	0.281454	0.000011	0.281418	1.0	2503	2695	-0.97
-26		0.022372	0.000897	0.281460	0.000011	0.281422	1.2	2498	2686	-0.97
-27		0.020587	0.000819	0.281461	0.000011	0.281427	1.3	2491	2676	-0.98
-28		0.019611	0.000790	0.281443	0.000010	0.281410	0.7	2514	2713	-0.98
-29		0.018481	0.000746	0.281442	0.000010	0.281411	0.8	2512	2711	-0.98

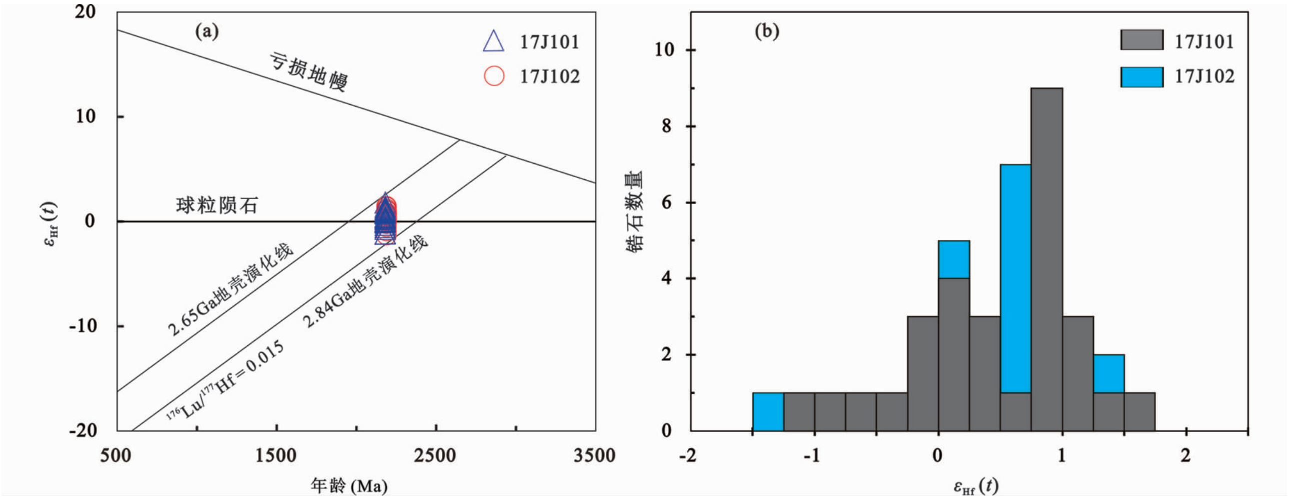

图 8　吕梁地区白家滩花岗片麻岩锆石 Hf 同位素特征

平均地壳的$^{176}Lu/^{177}Hf$比值取 0.015（Griffn *et al.*, 2002）

Fig. 8　Zircon Hf isotopic characteristics from the Baijiatan granitic gneiss in Lüliang area

The $^{176}Lu/^{177}Hf$ ratio of the average crust is characterized by 0.015（Griffn *et al.*, 2002）

老的地壳物质再循环的产物。

5　讨论

5.1　华北克拉通 2.2～2.1Ga 岩浆作用

吕梁地区出露的古元古代变质表壳岩主要包括界河口群、吕梁群和野鸡山群，并在吕梁杂岩中识别出大量古元古代花岗岩。界河口群由变质碎屑岩和少量的斜长角闪岩组成，总体上发生了角闪岩相变质作用（山西省地质矿产局，1989），变质沉积岩的碎屑锆石年龄和吕梁杂岩的主变质作用的时代限定了界河口群形成于 2.00～1.85Ga（万渝生等，2000；Zhao *et al.*, 2000, 2007；Xia *et al.*, 2009；刘超辉等，2013）。吕梁群上部近周营组和杜家沟组发育变基性火山岩和变质流纹岩，其单颗粒锆石 U-Pb 年龄分别为 2051±68Ma 和 2099±41Ma（于津海等，1997b），Liu *et al.*（2014a）在近周营组基性火山岩中也获得了 2209±20Ma、2178±6Ma 和 2196±8Ma 的岩浆年龄。野鸡山群中部白龙山组以浅变质玄武岩为主，其锆石 U-Pb 年龄为 2188±48Ma（Liu *et al.*, 2014b）和 2124±38Ma（耿元生等，2000）。以上研究结果表明吕梁地区变质火山岩的整体喷发时间介于 2.2～2.1Ga 之间。本次研究获得的白家滩花岗片麻岩的原岩年龄为 2182±16Ma 和 2185±24Ma，已有年龄资料表明吕梁地区赤坚岭英云闪长质片麻岩（刘超辉等，2013）、杜家沟长石斑岩和恶虎滩闪长质片麻岩（杜利林等，2012）、赤坚岭-关帝山花岗片麻岩（Zhao *et al.*, 2008）均形成于～2180Ma，耿元生等（2000, 2006）测得的赤坚岭条纹状角闪斜长片麻岩形成于 2151±12Ma，表明吕梁地区发育较多的 2.2～2.1Ga 的花岗质侵入体。

近年来，随着锆石 U-Pb 定年技术的广泛应用，华北克拉通范围内古元古代（2.2～2.1Ga）岩浆活动得到较多的识别，尤其是华北克拉通中部带和东部胶-辽-吉带的 2.2～2.1Ga 的岩浆活动被广泛发现，如中条地区绛县群变流纹质凝灰岩（孙大中等，1991；孙大中和胡维兴，1993）、铜矿峪组变火山岩（孙大中等，1991）、石英斑岩（杨崇辉等，2015；李宁波等，2013）、变质酸性火山岩（杨崇辉等，2015）；豫西地区侵入到太华群的片麻状花岗岩（Wan *et al.*, 2006a）、花岗片麻岩（杨长秀，2008）、石英二长岩（Zhou *et al.*, 2015），以及鲁山地区钾质花岗岩（Zhou *et al.*, 2014）；五台地区滹沱群玄武安山岩（Du *et al.*, 2010）和长英质凝灰岩（Wilde *et al.*, 2004），与五台地区大洼梁花岗岩（王凯怡和 Wilde，2002）、王家会花岗岩（王凯怡等，2000）、黄金山花岗斑岩（Du *et al.*, 2013）和基性岩墙（Peng *et al.*, 2005）年龄相当；赞皇地区甘陶河群玄武安山岩（Xie *et al.*, 2012）、流纹岩（Liu *et al.*, 2012a；Du *et al.*, 2016）以及华北克拉通北部恒山地区深熔花岗岩（Kröner *et al.*, 2005）和辉长岩（Wang *et al.*, 2010b）也都形成于 2.2～2.1Ga。此外，华北克拉通东部胶-辽-吉带的辽河群火山岩（Wan *et al.*, 2006b；Liu *et al.*, 2012b；Li and Chen, 2014；Hu *et al.*, 2015；陈斌等，2016）、～2.18Ga 的辽吉花岗岩（路孝平等，2004；Wan *et al.*, 2006b；Lu *et al.*, 2006；Li and Zhao, 2007；杨明春等，2015；陈斌等，2016；王欣平，2017）和同时期的基性岩床等（董春艳等，2012；Meng *et al.*, 2014；Yuan *et al.*, 2015；王欣平，2017）也广泛发育。同时，在鄂尔多斯盆地基底（钻孔）中也发现 2.2～2.0Ga 的花岗质岩石和碎屑锆石年龄记录（Wan *et al.*, 2013；Zhang *et al.*, 2015；张成立等，2018；Wang *et al.*, 2019）。本文通过对吕梁地区白家滩二云母花岗片麻岩的年龄研究（原岩年龄 2182±16Ma 和 2185±24Ma）以及华北克拉通不同地区古元古代岩浆活动的总结分析，认为 2.2

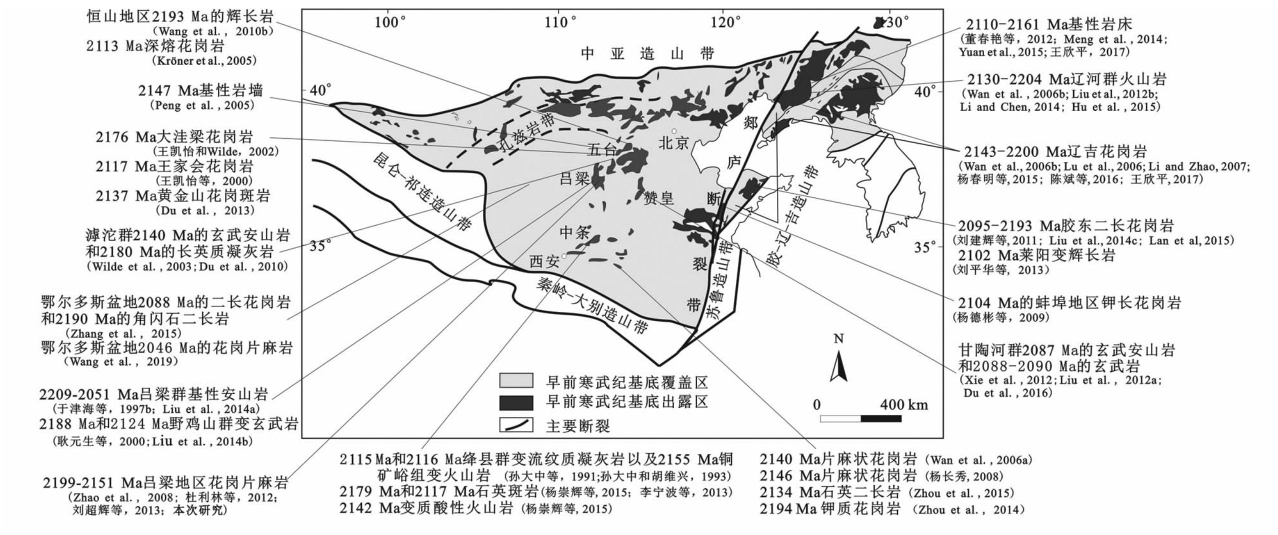

图9 华北克拉通2.2~2.1Ga岩浆岩分布图(据 Zhao *et al.*, 2005 修改)

Fig.9 The distribution of 2.2~2.1Ga magmatic rocks in the North China Craton (modified after Zhao *et al.*, 2005)

~2.1Ga的岩浆作用在华北克拉通豫西、中条山、吕梁山、五台山、和辽东等地区广泛发育(图9),呈面状分布,并且基性-酸性火山岩、花岗质侵入体和基性岩床共生,大多发生了角闪岩相变质作用。

5.2 华北克拉通~1.90Ga的变质作用

吕梁地区白家滩花岗片麻岩样品的锆石具有两种类型,一种具有明显振荡环带的岩浆锆石(图4a, b),另一种具有变质增生边的变质锆石(图4c, d),分别代表了原岩岩浆事件和后期变质改造事件。2个样品中锆石增生边的$^{207}Pb/^{206}Pb$年龄介于2180~2032Ma之间,样品17J101得到的不一致线的交点年龄约为2093±23Ma,样品17J102的$^{207}Pb/^{206}Pb$加权平均年龄为2144±29Ma,均小于花岗岩的结晶年龄(~2185Ma),可能由于锆石具有极高的稳定性和较高的U-Pb同位素体系封闭温度(>800℃, Cherniak and Watson, 2001; Cherniak, 2010),在变质作用过程中不完全重结晶而不能较好的记录变质作用的时间(Hawkesworth and Kemp, 2006; Moecher and Samson, 2006; Hawkesworth *et al.*, 2013),因此,锆石边部2180~2032Ma的$^{207}Pb/^{206}Pb$年龄和2093±23Ma的交点年龄可能是混合年龄,不能准确代表花岗片麻岩的变质作用时间。而独居石往往产于过铝质的火成岩和变质岩中(Spear and Pyle, 2002; Foster and Parrish, 2003; Williams *et al.*, 2007),具有非常高的Th和U含量以及很低的普通Pb含量,可以作为理想的U-Th-Pb年龄测定对象(Williams *et al.*, 2007)。同时,独居石在变质作用和流体作用过程中,对环境条件的变化更加敏感,比锆石更容易记录不同时期的改造历史(Gasser *et al.*, 2015; Shazia *et al.*, 2015; Wang *et al.*, 2017)。本次研究的吕梁地区2个花岗片麻岩样品的独居石U-Pb年龄分别为1898±7Ma和1899±14Ma,明显比原岩的岩浆锆石(交点年龄为~2.18Ga)和锆石增生边(2180~2032Ma)年轻,表明独居石受后期变质作用改造的明显影响,而锆石对后期变质作用的响应程度较弱,这种变质独居石所记录的U-Pb年龄比锆石年龄更低的现象一般出现在经历过退变质演化历史的岩石中(Ayers *et al.*, 2002)。与锆石较高的U-Pb体系封闭温度相比(T_C>800℃, Cherniak and Watson, 2001),独居石的U-Pb体系封闭温度相对较低(~700℃, Foster *et al.*, 2002; Kohn and Malloy, 2004),结合花岗片麻岩的锆石和独居石U-Pb年龄,其变质变形时代及冷却曲线如图10所示,表明白家滩花岗片麻岩经历了1.90Ga的变质作用,可能对应区域快速抬升冷却的退变质过程。

Rogers and Santosh (2002)提出哥伦比亚超大陆的存在,一般认为是由全球范围内2.1~1.8Ga的碰撞造山事件形成的,华北克拉通被认为是哥伦比亚超大陆的一部分(Zhao *et al.*, 2002, 2003)。华北东部陆块和西部陆块在~1.85Ga沿中部造山带最终碰撞拼合形成统一的克拉通(Zhao *et al.*, 2005),这一大规模的古元古代构造-热事件在华北克拉通得到了广泛的识别,如西部陆块的山西大同片麻岩(1861~1900Ma, Wan *et al.*, 2006b)、内蒙古凉城麻粒岩(1919±10Ma, Santosh *et al.*, 2007)、内蒙古千里山片麻岩和浅粒岩(1920~1955Ma, Yin *et al.*, 2009)、宁夏银川盆地基底麻粒岩(1895±36Ma, Wang *et al.*, 2017)等,东部陆块辽吉地区辽河群和基性岩床以及花岗岩中均发现有很多1.95~1.80Ga的变质年龄(Luo *et al.*, 2004, 2008; Lu *et al.*, 2006; Li and Zhao, 2007; Xie *et al.*, 2011; Hu *et al.*, 2015; Wang *et al.*, 2016),以及胶北地区1.90~1.85Ga峰期高压麻粒岩相变质和1.84~1.82Ga中低压麻粒岩-角闪岩相退变质作用(Zhou *et al.*, 2008; 刘建辉等, 2011; Tam *et al.*, 2012a, b; 刘平华等, 2013, 2015; Wu *et al.*, 2014)。中部

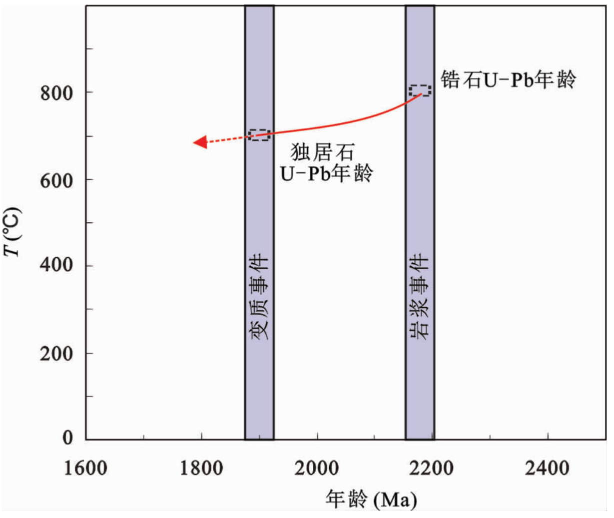

图 10 花岗片麻岩的矿物封闭温度-冷却年龄图解

锆石 U-Pb 体系封闭温度 $T>800$℃（Cherniak and Watson, 2001）；独居石的 U-Pb 体系封闭温度为 ~700℃（Foster *et al.*, 2002）

Fig. 10 Mineral closure temperature vs. cooling age plot for two granitic gneiss samples

Closure temperatures for zircon U-Pb system are higher than 800℃ (Cherniak and Watson, 2001), and closure temperatures for monazite U-Pb system are ~700℃ (Foster *et al.*, 2002)

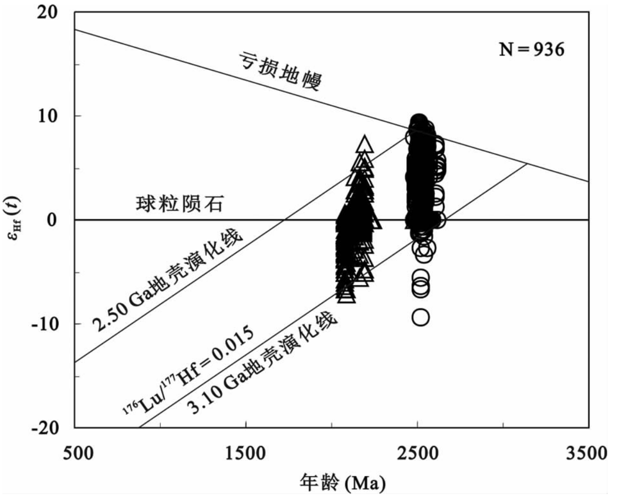

图 11 华北克拉通新太古代(~2.5Ga)和古元古代(2.2 ~2.1Ga)岩浆岩的锆石 Hf 同位素特征

~2.5Ga 岩浆岩的锆石 Hf 同位素数据引自 Diwu *et al.*, 2011；赵瑞福等, 2011；张瑞英等, 2013；Bai *et al.*, 2014；Shan *et al.*, 2015；杨崇辉等, 2017；Yang *et al.*, 2008；2.2 ~2.1Ga 岩浆岩的锆石 Hf 同位素数据引自杨德彬等, 2009；赵瑞福等, 2011；Du *et al.*, 2013；刘超辉等, 2013；颉颃强等, 2013；Zhou *et al.*, 2014, 2015；杜利林等, 2015, 2018；杨崇辉等, 2017 以及本文数据

Fig. 11 Zircon Hf isotopic characteristics from the Late Archean (~2.5Ga) and Paleoproterozoic (2.2 ~2.1Ga) magmatic rocks in the North China Craton

~2.5Ga zircon Hf isotopic data after Diwu *et al.*, 2011, Zhao *et al.*, 2011; Zhang *et al.*, 2013; Bai *et al.*, 2014; Shan *et al.*, 2015; Yang *et al.*, 2017; Yang *et al.*, 2008; 2.2 ~2.1Ga zircon Hf isotopic data after Yang *et al.*, 2009; Zhao *et al.*, 2011; Du *et al.*, 2013; Liu *et al.*, 2013; Xie *et al.*, 2013; Zhou *et al.*, 2014, 2015; Du *et al.*, 2015, 2018; Yang *et al.*, 2017 and this study

带河北淮安地区片麻岩(1946 ±26Ma)和麻粒岩(1947 ±22Ma)(Zhao *et al.*, 2010)、山西高压麻粒岩(1817 ~1856Ma, 郭敬辉和翟明国, 2000; Guo *et al.*, 2005)、吕梁营运闪长质片麻岩(1872 ±7Ma, Zhao *et al.*, 2008)、太行山地区片麻岩(1817 ±26Ma, Guan *et al.*, 2002)、豫西地区上太华群片麻岩(1.87 ~1.84Ga, Wan *et al.*, 2006a; 1912 ±13Ma, 时毓等, 2011)等。已有研究表明阴山陆块和鄂尔多斯陆块碰撞拼合形成西部陆块的时间在 1.96 ~1.95Ga(Zhao *et al.*, 2005, 2010; Yin *et al.*, 2009, 2014; Wang *et al.*, 2014a)，为造山初始阶段，而 1.92 ~1.88Ga 的超高温麻粒岩相变质作用(Santosh *et al.*, 2006; 2007; Yang *et al.*, 2014)一般认为是造山后伸展背景下幔源岩浆上涌的结果(赵国春, 2009)。本次研究确定了华北克拉通中部带吕梁地区存在 ~1.9Ga 的变质事件，与银川盆地的退变冷却时间(1895 ±36Ma 和 1892 ±14Ma, Wang *et al.*, 2017)和鄂尔多斯盆地 1880 ~1909Ma(Gou *et al.*, 2016; Wang *et al.*, 2019)的变质作用时间一致，可能均受到西部阴山陆块和鄂尔多斯陆块碰撞后的伸展构造影响。

5.3 花岗质岩浆的物质来源：新太古代地壳重熔

已有研究表明华北克拉通在太古宙经历了 ~2.7Ga 和 ~2.5Ga 两期明显的地壳生长(第五春荣等, 2012; 万渝生等, 2017)，形成了大量的 TTG 岩石，是陆壳增生时期岩浆作用的产物。TTG 岩石主要为新生地壳，也有相当部分为壳内再循环产物或形成过程中受到陆壳物质影响(万渝生等, 2017)。华北克拉通 ~2.7Ga 的岩石主要分布在豫西、中条山和鲁西地区等(Sun *et al.*, 1994; Liu *et al.*, 2009; 第五春荣等, 2010; Jahn *et al.*, 2008; Wan *et al.*, 2011; 万渝生等, 2017)，~2.5Ga 的岩石在华北克拉通中部带和东部带均有广泛出露，是华北克拉通新太古代末的主要构造-热事件。

吕梁地区白家滩花岗片麻岩的 Hf 同位素单阶段模式年龄为 2473 ~2598Ma，集中分布于 2500 ~2560Ma，明显大于花岗片麻岩的原岩年龄(~2.18Ga)，而两阶段模式年龄介于 2646 ~2839Ma，Hf 同位素组成均分布于 2.65 ~2.84Ga 古老地壳演化线范围内(图 8)，并且 $\varepsilon_{Hf}(t)$ 值介于 −1.3 ~ +1.8 之间(平均值为 0.4)，远小于同时期的亏损地幔的 $\varepsilon_{Hf}(t)$ 值，表明没有同期幔源物质的加入，而是新太古代地壳物质重熔的产物。结合华北克拉通其它地区 2.2 ~2.1Ga 岩浆岩的 Hf 同位素特征，其 $\varepsilon_{Hf}(t)$ 值主要介于 −6 ~ +5 之间，分布于 2.5 ~3.1Ga 的地壳演化线内，与华北克拉通 ~2.5Ga 岩浆岩的锆石 Hf 同位素亏损地幔两阶段模式年龄相似(图 11)，表

明华北克拉通该时期(2.2~2.1Ga)的岩浆岩来源于太古代地壳物质的再循环,新太古代地壳在2.2~2.1Ga发生了广泛的重熔作用。

5.4 构造背景

华北克拉通中部带发育大量的古元古代变质表壳岩,主要为吕梁地区的界河口群、吕梁群和野鸡山群,五台地区的滹沱群,赞皇地区的甘陶河群和中条地区的中条群,目前对这些表壳岩的形成环境仍有争议。吕梁地区的古元古代吕梁群和野鸡山群均由下部的碎屑沉积岩和上部的火山岩组成,火山岩的地球化学特征表明其形成于陆内或大陆边缘裂谷环境(耿元生等, 2003),界河口群变质沉积岩的REE特征与被动大陆边缘沉积很相似(刘超辉等, 2013),而且界河口群中的基性火山岩的地球化学特征表明其形成于大陆裂谷环境(刘建忠等, 2001)。颜耀阳和王汝铮(1996)以及杜利林等(2009)发现滹沱群中的玄武岩地球化学特征和岛弧型火山岩明显不同,具有板内裂谷火山岩的特征,郭进京等(2011)则认为滹沱群更可能形成于陆内裂谷盆地。中条地区的火山岩大多具有双峰式特征,孙大中等(1991)认为其很可能形成于拉张环境,颉颃强等(2013)通过研究表明这些双峰式火山岩在形成过程中受到了明显的地壳混染,其地球化学特征类似于陆内裂谷火山岩,暗示了甘陶河群的形成环境为大陆裂谷。也有部分研究认为华北克拉通中部带表壳岩形成于大陆边缘环境(Wilde *et al.*, 2004)、大陆岛弧环境(Li *et al.*, 2009; 刘树文等, 2009; Liu *et al.*, 2011)。颉颃强等(2013)认为这些古元古代火山-沉积建造中的火山岩多数具有双峰式特征,缺乏岛弧环境常见的安山岩,且火山岩中普遍存在2.5Ga的捕获锆石,在表壳岩基底中也存在大量2.7~2.5Ga的花岗质岩石,所以这套表壳岩最可能形成于板内拉张环境。

目前在这些古元古代表壳岩中发现的大量2.2~2.1Ga的花岗岩,如五台黄金山花岗岩(Du *et al.*, 2013)和大洼梁似斑状花岗岩、王家会黑云母二长花岗质片麻岩以及莲花山花岗岩(杜利林等, 2018)、赞皇许亭花岗岩(杨崇辉等, 2011)和恒山凌云口钾质花岗岩以及辽吉花岗岩(路孝平等, 2004; 杨明春等, 2015; 李超等, 2017)、五台黄金山花岗岩(Du *et al.*, 2013)等均具有A型花岗岩的特征,指示了伸展构造背景。豫西鲁山地区石英二长岩和钾质花岗岩的地球化学特征也表明其形成于陆内裂谷环境(Zhou *et al.*, 2014, 2015)。此外,华北东部发育有大量同时期的海城基性岩床群、五台横岭基性岩床、吕梁基性岩墙、赞皇基性岩床、胶东基性岩墙等(Peng *et al.*, 2012, 2017a, b; 刘平华等, 2013; Wang *et al.*, 2014b; 杨崇辉等, 2017; 王欣平, 2017),均侵入于古元古代火山沉积岩系中,地球化学特征表现为拉斑玄武质特征,与华北古元古代陆内裂谷活动有关。综上所述,华北克拉通古元古代表壳岩和2.2~2.1Ga期间的岩浆活动的特征表明其形成于伸展背景,可能与陆内裂谷环境有关,裂谷型岩浆作用的出现则表明新太古代晚期华北板块已经形成了一定规模的大陆地壳(耿元生等, 2003)。

6 结论

(1)吕梁地区白家滩二云母花岗片麻岩的岩浆锆石U-Pb年龄为2182±16Ma和2185±24Ma,代表其侵位时代。

(2)独居石U-Pb年龄(1898±7Ma和1899±14Ma)表明白家滩花岗片麻岩发生变质作用的时间为~1900Ma,与华北克拉通中部造山带的变质作用时间一致。锆石增生边的$^{207}Pb/^{206}Pb$年龄为2180~2032Ma,表明独居石对古元古代变质作用的响应程度比锆石强。

(3)2个花岗片麻岩的锆石Hf同位素两阶段模式年龄($t_{DM}{}^{C}$)分别为2646~2828Ma和2674~2839Ma,$\varepsilon_{Hf}(t)$值分别为-1.2~+1.8和-1.3~+1.4,表明其原岩是新太古代地壳物质部分熔融的产物。结合已有的古元古代中期(2.2~2.1Ga)的岩浆岩锆石Hf同位素数据,华北克拉通新太古代地壳在2.2~2.1Ga期间发生了广泛的重熔作用。

(4)结合已有研究资料,2.2~2.1Ga期间的岩浆岩在华北克拉通吕梁地区、中条地区、五台地区以及胶辽吉地区广泛发育,可能形成于陆内裂谷环境。

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