华北克拉通南部熊耳盆地晚前寒武纪年代地层格架和演化

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内容提要：熊耳盆地发育华北克拉通最齐全的晚前寒武纪地层，是认识华北克拉通晚前寒武纪沉积和构造演化历史的理想地区。依据收集和自测的38个碎屑岩和23个岩浆岩样品的锆石年代学数据，结合岩相区域对比、沉积古地理格局继承关系等，细化年代地层格架和分析盆地构造属性，重塑熊耳盆地晚前寒武纪构造演化历史及沉积古地理格局。重新厘定的晚前寒武纪年代地层格架将熊耳盆地演化划分为六个阶段：早长城世裂陷、晚长城世断陷、蓟县纪坳陷、待建纪早期坳陷、青白口纪坳陷及晚震旦世冰期坳陷，以及早长城世末期、待建纪中晚期和南华纪—早震旦世三期重要的沉积间断。熊耳盆地存在晚长城世和青白口纪两期碰撞型—伸展型的盆地属性转换，支持北秦岭地体与华北克拉通多期拼贴—裂解的演化模式。中元古代早长城世—待建纪早期的火山-沉积岩系及1.64～1.47 Ga非造山岩浆事件是Columbia超大陆裂解的地质响应，青白口纪早期碰撞型沉积岩系和晚期伸展型火山-沉积岩系分别是Rodinia超大陆汇聚和裂解的地质响应。

关键词：晚前寒武纪；盆地构造属性；超大陆演化；熊耳盆地；北秦岭

华北克拉通发育多个晚前寒武纪沉积盆地(Peng Peng, 2015a; Zhai Mingguo et al., 2015; Guan Shuwei et al., 2017)，包括熊耳(或称豫陕—吕梁)盆地、燕辽盆地、北缘(或称渣尔泰—白云鄂博—化德)盆地、东缘(或称胶辽徐淮)盆地以及西缘(或称贺兰—定边—晋陕)盆地(图1a)。最新修订的晚前寒武纪年代地层格架打破了华北克拉通从长城纪到青白口纪近于连续沉积的传统认识(Li Huaikun et al., 2013; Su Wenbo, 2016)，这使人们不得不重新审视华北晚前寒武纪地层的时代归属、沉积大地构造背景和古大陆的重建方案等。

华北克拉通晚前寒武纪盆地的发育机制和演化过程存在多种解释(Qiao Xiufu et al., 2014; Zhai Mingguo et al., 2015; Zhong Yan et al., 2019和其引用文献)，主流观点认为华北地区始终处于反复扩张裂解状态(Zhang Guowei et al., 2001; Zhai Mingguo et al., 2015; Guan Shuwei et al., 2017)，是华北克拉通对哥伦比亚(Columbia)和罗迪尼亚(Rodinia)超大陆裂解过程的响应(Zhai Mingguo et al., 2015; Zhang Shuanhong et al., 2016a, 2016b; Zhao Taiping et al., 2016)；然而，华北克拉通周缘曾处于俯冲—碰撞构造环境的认识越来越多(Su Wenbo et al., 2008; Su Wenbo, 2016; Qiao Xiufu et al., 2014; Zhong Yan et al., 2019)，尤其是熊耳盆地(Zhao Guochun et al., 2003a; He Yanhong et al., 2009, 2010; Hu Guohui et al., 2012b; Meng Yao et al., 2018; Liu Xuefei et al., 2019; Li Zhensheng et al., 2020)。熊耳盆地发育机制和演化过程一直存在争议，例如，熊耳群火山岩具有“岛弧型”地球化学特征(Zhao Guochun et al., 2003a; Zhao Taiping et al., 2004; Meng Yao et al., 2018)，其成因及构造属性有同造山B型或安

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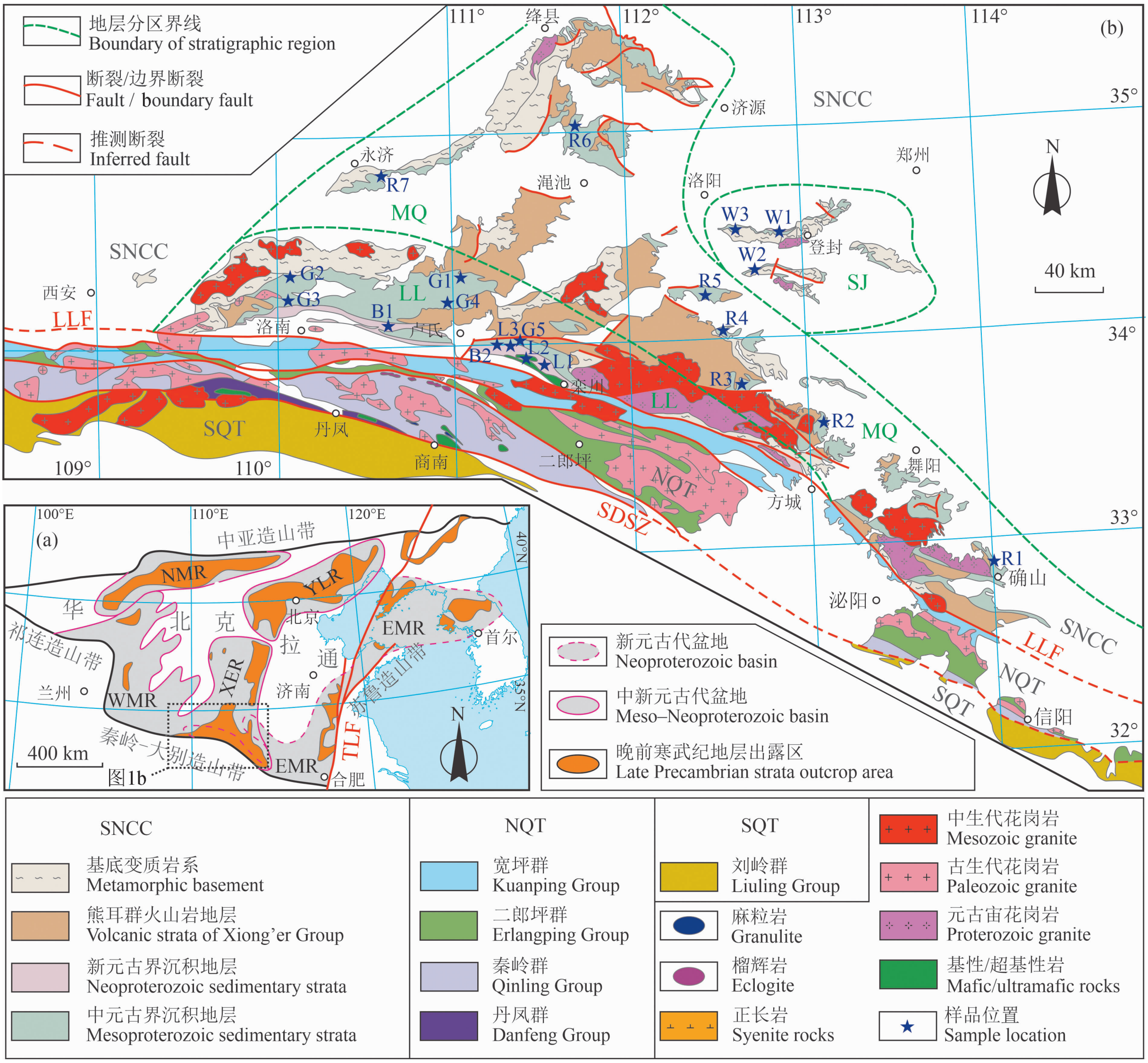


图 1　华北克拉通晚前寒武纪盆地略图(a,据 Peng Peng, 2015a 和 Guan Shuwei et al., 2017 修改)和南华北克拉通及秦岭造山带地质简图(b)

Fig. 1　Distribution of the late Precambrain basins in the North China Carton (a, modified after Peng Peng, 2015a and Guan Shuwei et al., 2017), and geological map of the southern North China Carton and Qinling orogenic belt (b)

NMR—北缘盆地;EMR—东缘盆地;YLR—燕辽盆地;XER—熊耳盆地;WMR—西缘盆地;SNCC—华北克拉通南部;NQT—北秦岭地体;SQT—南秦岭地体;TLF—郯庐断裂;LLF—洛南—栾川断裂;SDSZ—商丹缝合带;SJ—嵩箕地层分区;MQ—渑池—确山地层分区;LL—卢氏—栾川地层分区

NMR—Northern marginal basin; EMR—eastern marginal basin; YLR—Yan-Liao basin; XER—Xiong'er basin; WMR—western marginal basin; SNCC—southern North China Carton; NQT—North Qinling Terrane; SQT—South Qinling Terrane; TLF—Tancheng-Lujiang Fault; LLF—Luonan-Luanchuan Fault; SDSZ—Shangdan suture zone; SJ—Song-Ji stratigraphic area; MQ—Mianchi-Queshan stratigraphic area; LL—Lushi-Luanchuan stratigraphic area

第斯型火山岛弧环境(Jia Chengzao, 1987; Hu Shouxi et al., 1988; Zhao Guochun et al., 2003a, 2009; He Yanhong et al., 2009, 2010)、同造山弧后裂陷/拉张盆地环境(Hu Dexiang et al., 1987; Wang Miao et al., 2020a, 2020b)、造山后伸展/裂谷环境(Zhao Taiping et al., 2009; Deng Xiaoqin et al., 2016a, 2019)、非造山大陆边缘裂谷/坳拉槽环境(Zhang Guowei et al., 2001; Cui Minli et al., 2011; Zhai Mingguo et al., 2015; Zhao Taiping et al., 2016; Wang Changming et al., 2019)以及活动大陆边缘弧和被动裂谷并存(Chen Yanjing et al., 1992)等不同认识;对于熊耳群上覆沉积岩系,

依据组分 QFL 分析、元素地球化学分析等判断其沉积构造背景为被动大陆边缘(Guan Baode et al., 1993; Zhou Hongrui et al., 1999),但部分学者强调了顶部层位形成于被动大陆边缘向活动大陆边缘转化的背景下(Jiang Ganqing et al., 1994; Zhou Hongrui et al., 1999; Hu Guohui et al., 2012b; Li Zhensheng et al., 2020)。

熊耳盆地发育华北克拉通最齐全的晚前寒武纪地层,岩浆事件记录较丰富,多层位赋存遗迹化石、微古植物及宏观藻类化石等,为华北克拉通晚前寒武纪相关研究的热点地区之一(Guan Baode et al., 1988; Zhou Hongrui et al., 1999; Zhao Guochun et al., 2009; Zhao Taiping et al., 2016; Wang Changming et al., 2019),也是探讨华北克拉通与超大陆演化关系和早期生命演化进程的重要地区(Xiao Shuhai et al., 1997; Zhao Taiping et al., 2002; Peng Peng et al., 2008; Wang Xiaolei et al., 2011; Liu Xuefei et al., 2019; Zhang Heng et al., 2019)。近期依靠火山岩或凝灰质沉积夹层的确认和高精度年代学测试,陆续获得不少标定熊耳盆地晚前寒武纪年代地层格架的"锚点"(Su Wenbo, 2016; Zhang Heng et al., 2019; Li Zhensheng et al., 2020; Zhu Xiyan et al., 2020),同时相应的物源分析证实熊耳盆地中、新元古代古地理格局明显不同(Hu Guohui et al., 2012b; Liu Xuefei et al., 2019; Zuo Pengfei et al., 2019a, 2019b; Li Zhensheng et al., 2020),导致需要重新认识华北南部地区晚前寒武纪沉积和构造演化(Zuo Pengfei et al., 2019a; Wang Miao et al., 2020a)。然而,由于缺少可靠的同位素测年对象,一些关键层位至今没有获得新的突破(Zhu Xiyan et al., 2020)。本次工作全面收集和自测了熊耳盆地晚前寒武纪碎屑岩和相关岩浆岩的锆石年代学数据,依据岩相区域对比、碎屑锆石年龄谱对比和沉积古地理格局继承关系等完善年代地层格架,对缺乏可靠年龄约束的黄连垛组、董家组和五佛山群等层位归属进行讨论;利用碎屑锆石年代学数据统计分析盆地构造属性,结合区域的沉积和岩浆事件,重塑区域构造演化历史及沉积古地理格局等。

1 区域地质背景

华北克拉通是中国规模最大的克拉通,由早前寒武纪变质基底和晚前寒武纪—显生宙沉积盖层组成。华北克拉通的早前寒武纪构造格架由东部陆块、中部造山带和西部陆块三个主要构造单元所组成,东、西陆块在古元古代末期发生汇聚碰撞,并在~1.85 Ga 沿中部造山带最终拼贴形成统一的克拉通基底(Zhao Guochun et al., 2003b, 2012);自 1.8 Ga 进入地台演化阶段,晚前寒武纪经历了多期裂谷事件,并伴随有周期性陆内岩浆活动(Lu Songnian et al., 2008; Zhai Mingguo et al., 2015; Zhang Shuanhong et al., 2016a)。燕辽、熊耳和北缘盆地主要由中元古界长城系、蓟县系、待建系和新元古界青白口系组成(Zhai Mingguo et al., 2015; Hu Jianmin et al., 2016; Su Wenbo, 2016; Zhang Heng et al., 2019; Zhong Yan et al., 2019)。其中,熊耳盆地形成最早,起始以~1.78 Ga 熊耳群火山岩系为代表。西缘盆地由中元古界长城系、蓟县系及待建系组成(Li Zhenhong et al., 2019),起始以甘肃省华亭县马峡镇高山河组(群)下部 1759±17 Ma 凝灰岩夹层(Tan Cong et al., 2019)为代表。东缘盆地形成最晚,主体由新元古界青白口系和少量的南华系—震旦系组成(Yang Debin et al., 2012; Su Wenbo, 2016)。

熊耳盆地位于华北克拉通南部豫-陕-晋交界地区,前寒武纪岩石序列发育完整,是我国记录前寒武纪地质的典型地区之一。其早前寒武纪结晶基底属于中部造山带中南段;晚前寒武纪沉积盖层由熊耳群陆相—海相火山-沉积岩系和上覆的小沟背组、汝阳群、洛峪群、高山河群、官道口群、五佛山群等河流—滨浅海相陆源碎屑岩-碳酸盐岩沉积岩系以及罗圈组陆相—海陆过渡相冰碛岩系组成(Guan Baode et al., 1988; DGMRHP, 1997; BGMRSP, 1998; Hu Guohui et al., 2013),自东北向西南划分为嵩山—箕山(嵩箕,SJ)、渑池—确山(MQ)和卢氏—栾川(LL)三个地层分区(图 1b),地层划分及接触关系如表 1 所示。

熊耳盆地南缘与秦岭造山带以洛南-栾川-方城断裂带为界(图 1b),秦岭造山带以商丹-勉略缝合带为界划分为北秦岭和南秦岭构造带(地体)。其中北秦岭构造带是秦岭造山带中变形变质、岩浆活动最为强烈的地带,以多条断裂为界自北向南依次划分为宽坪群中元古代—新元古代早期火山岩系和(新元古代晚期—)早古生代沉积岩系、二郎坪群早古生代火山-沉积岩系、秦岭群(古元古代—)中元古代末期—新元古代早期火山-沉积岩系和丹凤群早古生代火山-沉积岩系(Shi Yu et al., 2013; Zhang Zhen et al., 2015; Diwu Chunrong et al., 2019)。

表 1　熊耳盆地各地层分区及燕辽盆地晚前寒武纪地层对比表

Table 1　The Late Precambrian stratigraphic correlation table of Xiong'er and Yan-Liao basin

地层系统			年龄 (Ma)	燕辽盆地	控制年龄 (Ma)	熊耳盆地 卢氏—栾川小区		控制年龄 (Ma)	熊耳盆地 渑池—确山小区		控制年龄 (Ma)	熊耳盆地 嵩箕小区		控制年龄 (Ma)
下古生界			541	府君山组		陶湾群	东坡组		东坡组			东坡组		
新元古界	震旦系		635	西井峪组			罗圈组		罗圈组			罗圈组		
	南华系		780											
	青白口系			景儿峪组		栾川群	鱼库组	>844~830						
							大红口组	854~860						
							煤窑沟组	<884				红岭组		
				骆驼岭组			南泥湖组					五佛山群	何家寨组	<981
			1000				三川组	<983					骆驼畔组	<1766
中元古界	待建系		1200 1300	下马岭组	>1323⑨ 1366~1392⑧	白术沟组		1330~1332	董家组					
	蓟县系		1400	铁岭组	~1440⑦			<1550						
				洪水庄组		官道口群	冯家湾组	>1469	黄连垛组					
				雾迷山组	~1485⑥		杜关组							
				杨庄组			巡检司组							
				高于庄组	1559~1577⑤		龙家园组	1541~1549			<1498			
	长城系	上统	1600	大红峪组	1620~1624③	高山河群	陈家涧组		洛峪群	洛峪口组	1596~1639			
										三教堂组				
				团山子组	~1637④					崔庄组			葡峪组	
				串岭沟组	>1620③ 1621~1635②		二道河组		汝阳群	北大尖组			上马鞍山组	
							鳖盖子组	<1685		白草坪组			下马鞍山组	<1655
				常州沟组						云梦山组	<1644			
			1700						小沟背组		<1676	兵马沟组		<1792
		下统			密云环斑花岗岩① 1673~1685	熊耳群	马家河组	1776~1778⑩	熊耳群	马家河组				
							鸡蛋坪组	1751~1785⑩		鸡蛋坪组				
							许山组	1763~1783⑩		许山组				
							大古石组			大古石组				
			1800	密云群		太华群			太华群	涑水群—中条群		登封群—嵩山群		

角度不整合 Angular unconformity；平行不整合 Parallel unconformity；断层接触 Faulted contact；注：年代柱无比例尺 Note: no scale in the age column

<1655 砂岩YSG年龄 YSG age of sandstone；~1780 火山岩锆石年龄 Zircon age of volcanic rock；>1750 侵入岩锆石年龄 Zircon age of intrusive rock

注:燕辽盆地控制年龄来源:①—Gao Wei et al., 2008; Li Huaikun et al., 2011;②—Sun Huiyi et al., 2013; Liu dianbo et al., 2019;③—Zhang Jian et al., 2015;④—Zhang Shuanhong et al., 2013;⑤—Tian Hui et al., 2015;⑥—Li Huaikun et al., 2014;⑦—Su Wenbo et al., 2010; Li Huaikun et al., 2014; Guo Wenlin et al., 2019;⑧—Gao Linzhi et al., 2007, 2008; Su Wenbo et al., 2008, 2010;⑨—Li Huaikun et al., 2009; Zhang Shuanhong et al., 2009, 2012, 2017;⑩—Wang Changming et al., 2019。熊耳盆地控制年龄来源详见表 2。

2　董家组和黄连垛组碎屑锆石年代学分析

在渑池—确山地层分区,最新的锆石 U-Pb 年龄资料限定熊耳群—汝阳群—洛峪群归属于长城系(Su Wenbo, 2016; Zhang Heng et al., 2019);上覆的黄连垛组和董家组的时代归属是约束区域沉积-构造演化的关键因素之一,但尚缺少可靠的同位素年龄约束。黄连垛组和董家组曾划归震旦系(Guan Baode et al., 1988; DGMRHP, 1997; Hu Guohui et al., 2013)或分属蓟县系和青白口系(Su Wenbo, 2016)等。本次工作补充了黄连垛组和董家组的碎屑锆石年代学分析,探讨其沉积时代和物质来源,为区域沉积-构造演化提供新的约束。

2.1　岩石学特征

本次黄连垛组和董家组样品采自鲁山县下汤镇九女洞剖面(图 2a; Guan Baode et al., 1988)。董家组样品采自石盘地村北(33°45′41.8″N,111°40′43.5″E),YX69 样品为中下部黄色中薄层中粒长石石英砂岩(图 2b),YX70 样品为下部灰白色中厚层粗粒长石石英砂岩(图 2c),分选和磨圆均较好,颗粒成分为石英、微斜长石和白云母,填隙物为绢云母化黏土杂基。黄连垛组 YX192 样品采自庙前沟村黄连垛西坡(33°45′33.3″N,111°40′14.4″E),为下部

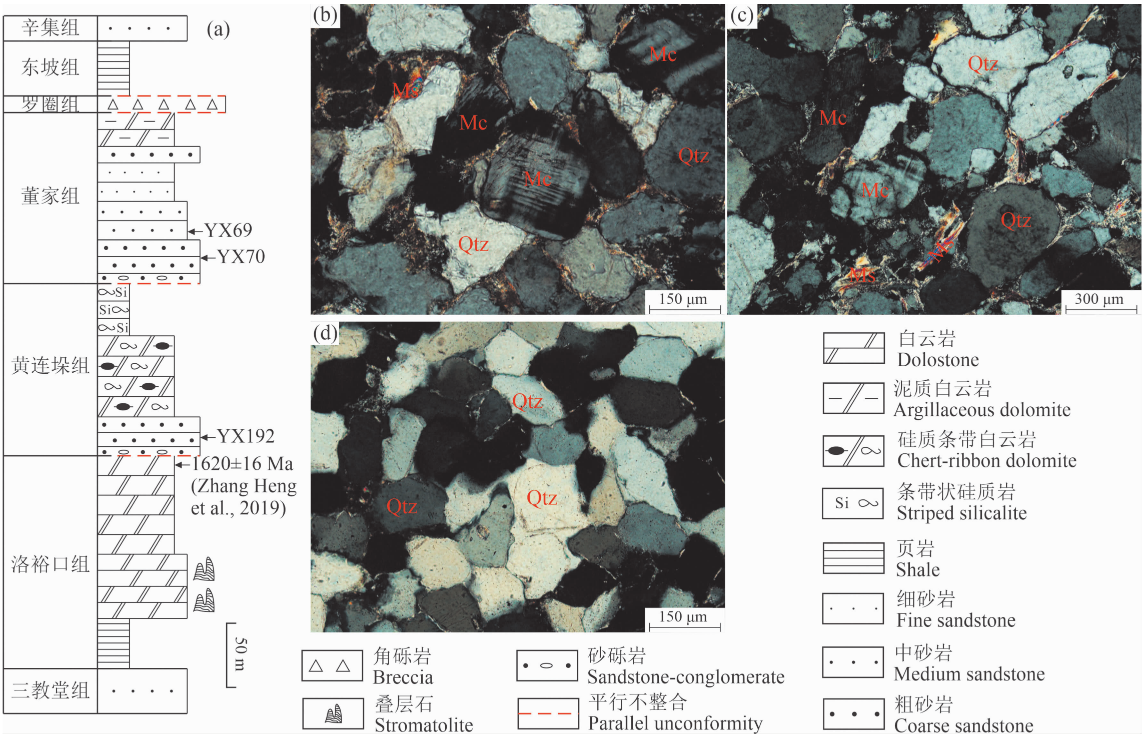


图 2 鲁山县下汤镇九女洞剖面柱状图(a)和董家组、黄连垛组砂岩的镜下显微照片(b～d)

Fig. 2 Column diagram of Jiunüdong section in Xiatang Town, Lushan County (a), and microscopic photos of sandstones from the Dongjia and Huanglianduo formations (b～d)

Ms—白云母;Mc—微斜长石;Qtz—石英

Ms—Muscovite; Mc—microcline; Qtz—quartz

浅肉红色厚层细粒石英砂岩(图 2d),分选和磨圆好,颗粒成分为石英和极少量微斜长石,填隙物为自生加大石英胶结物和少量绢云母化黏土杂基。

2.2 分析方法

单矿物锆石分选、锆石制靶、CL 照片和锆石 U-Pb 年代学测试分别在廊坊市峰泽源岩矿检测技术有限公司、北京锆年领航科技有限公司和合肥工业大学资源与环境工程学院 LA-ICPMS 实验室完成,详细的预处理、测试流程和条件见 Li Zhensheng et al. (2020)。

对于锆石^{206}Pb/^{238}U 表面年龄<1500 Ma 的样品,采用^{206}Pb/^{238}U 表面年龄(Spencer et al., 2016),有效年龄统计时剔除^{206}Pb/^{238}U-^{207}Pb/^{235}U 谐和度(Con1)<90%的数据点。对于锆石^{206}Pb/^{238}U表面年龄>1500 Ma 的样品,采用^{207}Pb/^{206}Pb 表面年龄,有效年龄统计时剔除^{206}Pb/^{238}U-^{207}Pb/^{206}Pb年龄谐和度(Con2)<90%的数据点。对收集的碎屑锆石年代学数据采取相同的方法重新统计。谐和度计算公式:

$$\mathrm{Con1}=\{1-\mathrm{abs}[1-(^{206}\mathrm{Pb}/^{238}\mathrm{U\ age})/(^{207}\mathrm{Pb}/^{235}\mathrm{U\ age})]\}\times 100\%$$

$$\mathrm{Con2}=\{1-\mathrm{abs}[1-(^{206}\mathrm{Pb}/^{238}\mathrm{U\ age})/(^{207}\mathrm{Pb}/^{206}\mathrm{Pb\ age})]\}\times 100\%$$

2.3 分析结果

董家组长石石英砂岩 YX69 和 YX70 中锆石粒径多为 50～200 μm,黄连垛组石英砂岩 YX192 中锆石粒径为 30～140 μm。CL 图像显示锆石颗粒内部结构清晰(图 3),大部分具有清晰的振荡环带,部分弱分带或无分带(如 YX69-78,YX70-41,YX192-35,YX192-79);Th/U 比值为 0.14～3.83,绝大部分>0.4(图 4a、b),表明绝大部分为岩浆成因锆石,部分为岩浆锆石但可能受变质作用及再旋回影响(Wu Yuanbao et al., 2004)。

董家组长石石英砂岩 YX69 和 YX70 均测试 80 颗锆石的年龄数据点,分别获得了 67 个和 71 个有效年龄(附表 1,http://www.geojournals.cn/dzxb/ch/reader/view_abstract.aspx?file_no=202111099)。碎屑锆石 U-Pb 年龄值介于 3448±35 Ma 和 1621±59 Ma 之间,可分为 3448 Ma(n=1,0.7%)、3072～1950 Ma(n=133,96.4%)和 1876～1621 Ma(n=4,

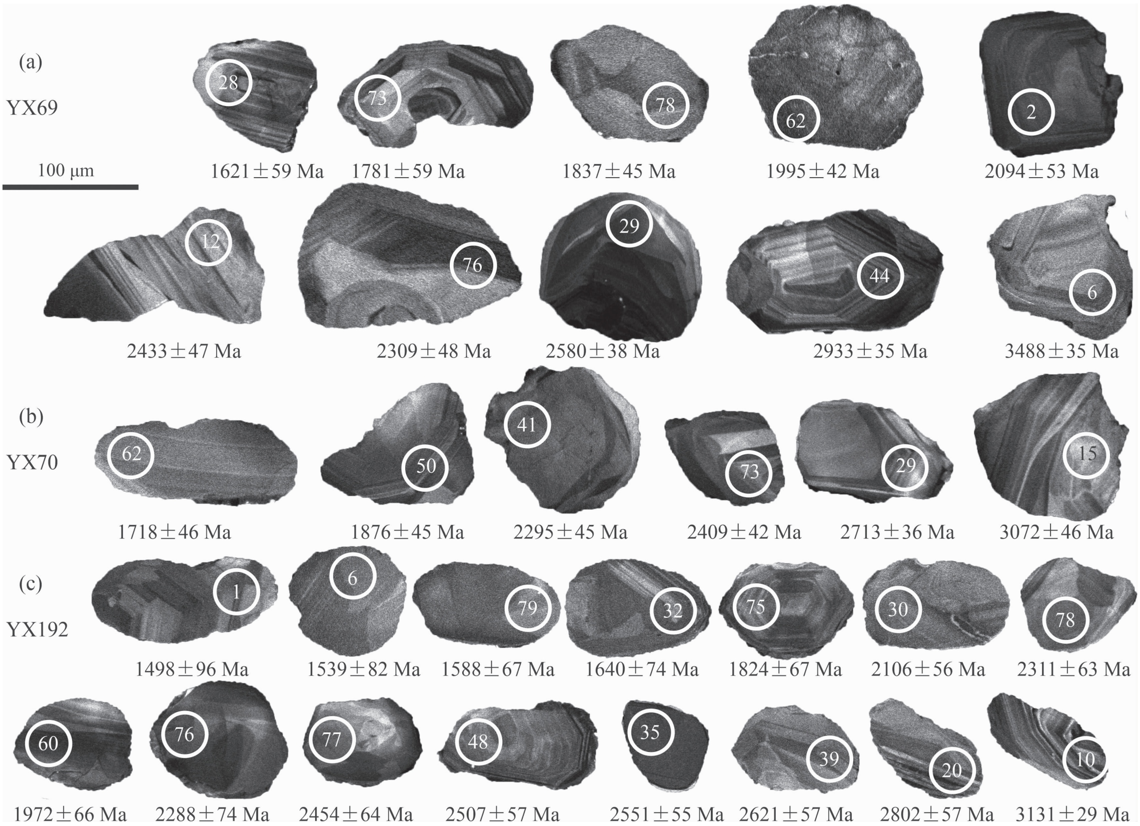


图 3　董家组(a、b)和黄连垛组(c)代表性碎屑锆石 CL 图像

Fig. 3　Representative CL images of detrital zircons from Dongjia (a, b) and Huanglianduo (c) formations

2.9%),峰值为 2.96～2.69 Ga、～2.44 Ga、～2.30 Ga、～2.12 Ga 和～1.74 Ga(图 4c)。与已报道的长石石英砂岩样品 17DJ-02 和 MLA-04-2(Zuo Pengfei et al., 2019a)相比,本次的 YX69 和 YX70 两个样品中～1.80 Ga 或～1.90 Ga 年龄的碎屑锆石所占比例极低。所有样品碎屑锆石 U-Pb 年龄值明显老于下伏的洛峪口组凝灰岩结晶年龄(1.65～1.60 Ga;表 2),未能有效地限定董家组的沉积时代。

黄连垛组石英砂岩 YX192 测试 80 颗锆石的年龄数据点,获得了 62 个有效年龄(附表 1,http://www.geojournals.cn/dzxb/ch/reader/view_abstract.aspx?file_no=202111099)。碎屑锆石 U-Pb 年龄值介于 3482±58 Ma 和 1498±96 Ma 之间,可以分为 3482～3131 Ma(n=2,3.2%)、2854～2443 Ma(n=3,4.8%)、2621～2443 Ma(n=17,27.4%)、2311～1709 Ma(n=30,48.4%)和 1643～1498 Ma(n=10,16.1%),峰值为～2.75 Ga、～2.54 Ga、～2.15 Ga、～1.85 Ga 和～1.61 Ga(图 4d)。与已报道的长石石英砂岩样品 17HLD-04(Zuo Pengfei et al., 2019a)和石英砂岩样品 0724-4(Wang Miao et al., 2020a)相比,仅本次的 YX192 样品识别出～1.61 Ga 次要年龄峰,相应的最年轻单颗粒锆石年龄(YSG)和峰值年龄(YPP)分别为 1498±96 Ma 和 1568±61 Ma (MSWD= 0.18, n=6),限定黄连垛组沉积时代不早于 1568 Ma。

综合来看,董家组和黄连垛组砂岩汇总的碎屑锆石年龄谱图相似,集中在 3.00～1.70 Ga,董家组碎屑锆石的年龄峰值为 2.95～2.69 Ga、～2.43 Ga 和～1.85 Ga(图 4e),黄连垛组碎屑锆石的年龄峰值为～2.88 Ga、～2.52 Ga、～2.18 Ga 和～1.85 Ga(图 4f),与华北克拉通 2.9～2.7 Ga 陆壳巨量生长事件(Huang Xiaolong et al., 2013; Zhao Guochun et al., 2013; Diwu Chunrong et al., 2016, 2018)、～2.5 Ga 陆壳生长和再造及变质事件(Huang Xiaolong et al., 2013; Zhao Guochun et al., 2013; Xiao Lingling et al., 2015; Diwu Chunrong et al., 2016, 2018)、～2.31 Ga 和～2.10 Ga 古元古代活动带岩浆事件(Huang Xiaolong et al., 2013; Zhao Guochun et al., 2013; Diwu Chunrong et al., 2016, 2018; Zhou Yanyan et al., 2016)、～1.97 Ga 和～1.85 Ga 两期变质作用和伴生的混合岩化和花岗质岩浆事件(Zhao Guochun et al.,

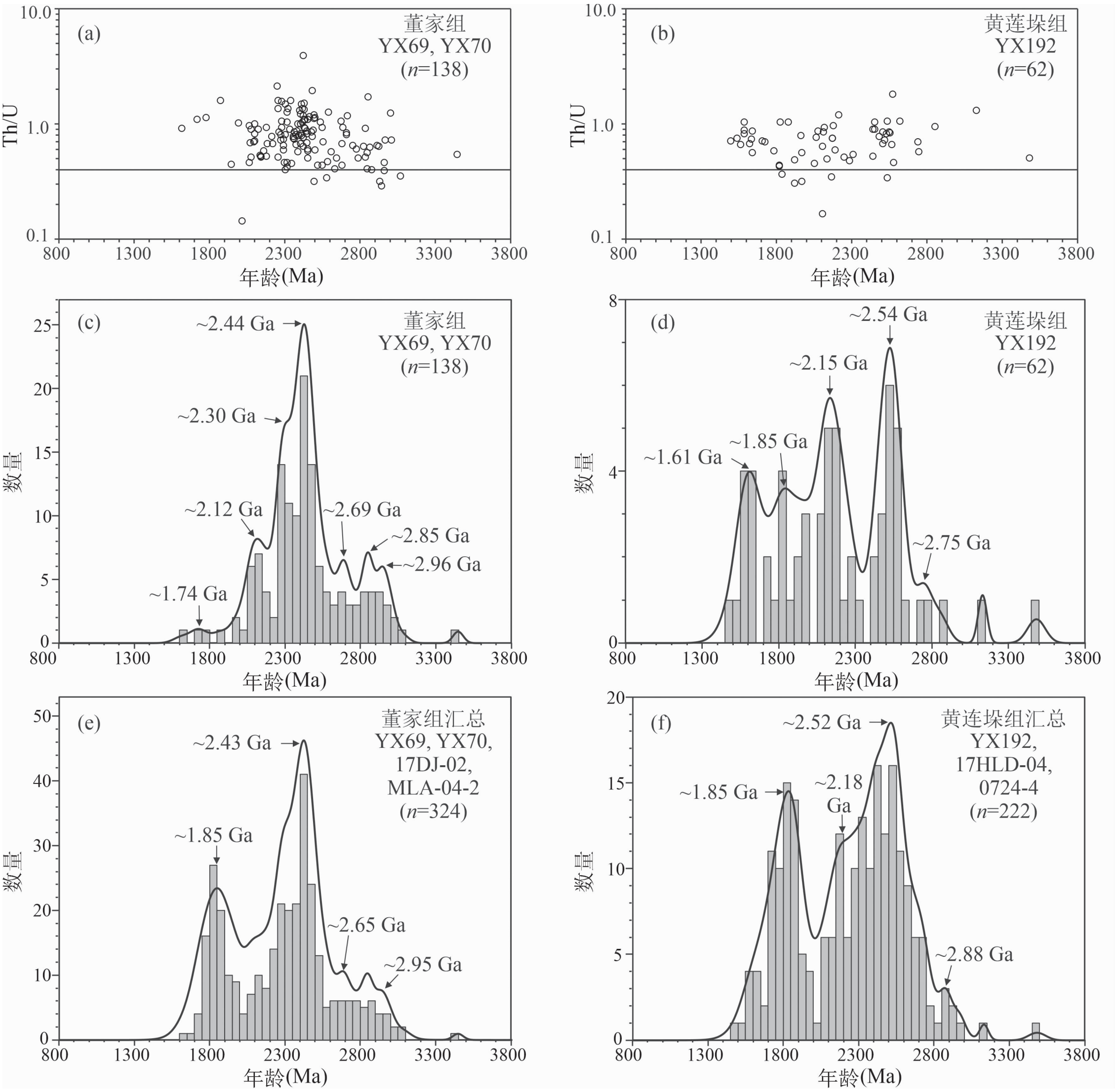


图 4 董家组(a、c、e)和黄连垛组(b、d、f)碎屑锆石 Th/U 比值和年龄统计谱图(数据来源见表 2)

Fig. 4 Th/U ratio and U-Pb age statistical histogram of detrital zircons from Dongjia (a, c, e) and Huanglianduo (b, d, f) Formations (the source information of the original data are detailed in Table 2)

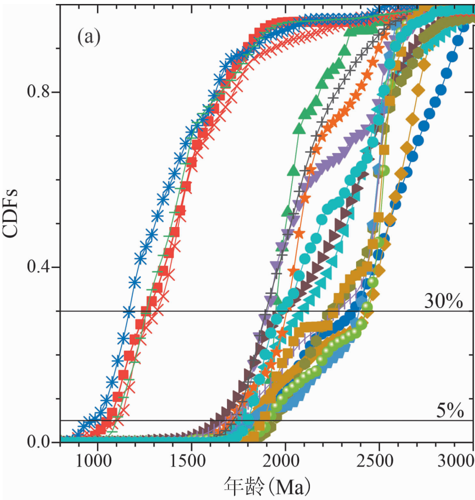
2013; Xiao Lingling et al., 2015; Diwu Chunrong et al., 2016, 2018)及 1.84～1.53 Ga 造山后或非造山岩浆事件(Zhai Mingguo et al., 2015; Deng Xiaoqin et al., 2016b, 2019; Zhao Taiping et al., 2016)具有极好的对应性,因此推断华北克拉通为黄连垛组和董家组的物源区。

3 年代地层格架分析

碎屑锆石年代学统计结果已被广泛应用于限定沉积地层的最大沉积年龄,最年轻单颗粒年龄(YSG)、最年轻碎屑锆石年龄(YDZ)及最年轻峰值年龄(YPP)是最可信的(Dickinson et al., 2009; Tucker et al., 2013; Coutts et al., 2019)。其中,YSG 是在全体数据中挑选出单个最年轻的碎屑锆石颗粒,并且在 1σ 之内需要覆盖次年轻的锆石年龄;YPP 是在直方图上记录的最年轻的碎屑锆石年龄峰值,通过沿着一个年龄概率曲线图或者年龄分布曲线识别第一个最大年龄峰值(几个颗粒或者颗粒簇,即碎屑锆石数≥3);YDZ 是使用蒙特卡罗分析分析产生的最年轻年龄值。本文收集和自测熊耳盆地 39 个碎屑岩样品的碎屑锆石年代学数据,统计的 YSG、YPP 和 YDZ 年龄和相关的 23 个岩浆岩结晶年龄及数据来源情况详见表 2 及图 1b。

3.1 年代地层基础框架

熊耳群沉积-火山岩系的形成时代为 1.78～1.75 Ga(Zhao Taiping et al., 2004; He Yanhong et al., 2009, 2010; Cui Minli et al., 2011; Wang



(b)

层位	Qb*h*	Qb*l*	Ch_2sm	Ch_2xm	Ch_2b	Dj_1d	Jx*h*	Ch_2s
DA (Ma)	947	947	1644	1644	1676	1498	1498	1639
$CA_{5\%}$ (Ma)	1042	1830	1862	1763	1818	1741	1645	1942
$CA_{30\%}$ (Ma)	1260	2357	1948	1908	2435	2090	1980	2244
$CA_{5\%}$–DA (Ma)	95	883	218	119	142	243	147	303
$CA_{30\%}$–DA (Ma)	313	1410	304	264	759	592	482	605
盆地属性	碰撞型	伸展型	伸展型	碰撞型	碰撞型	伸展型	伸展型	伸展型
层位	Ch_2bc	Ch_2y	Qb*y*	Qb*m*	Qb*s*	Dj_1b	Ch_2cj	Ch_2bg
DA (Ma)	1644	1644	860	860	947	1330	1639	1676
$CA_{5\%}$ (Ma)	1910	1720	1104	974	1095	1686	1875	1796
$CA_{30\%}$ (Ma)	2428	1895	1314	1168	1260	2279	2257	1975
$CA_{5\%}$–DA (Ma)	266	76	244	114	148	356	236	120
$CA_{30\%}$–DA (Ma)	784	251	454	308	313	949	618	399
盆地属性	伸展型	碰撞型	伸展型	碰撞型	碰撞型	伸展型	伸展型	碰撞型

图 5　熊耳盆地按组统计的碎屑锆石年龄累计分布函数(a)和构造背景判别参数(b)

Fig. 5　The cumulative distribution function (a) and discriminant parameters of tectonic setting (b) based on detrital zircon age of each group in Xiong'er basin

原始数据来源及地层符号见表 2;CDFs—累计分布函数,采用美国亚利桑那大学 LaserChron Centers 设计的 Excel 表格(http://www.laserchron.org)计算;DA—假定的地层沉积年龄;$CA_{5\%}$—累计概率 5%对应的年龄值;$CA_{30\%}$—累计概率 30%对应的年龄值

The information of the original data and stratum symbol are shown in Table 2; CDFs—cumulative distribution functions, which are calculated by Excel spreadsheet designed by LaserChron Centers, University of Arizona, America (http://www.laserchron.org); DA—deposition age; $CA_{5\%}$—crystallization age in the youngest 5% of the zircons; $CA_{30\%}$—crystallization age in the youngest 30% of the zircons

Changming et al., 2019),归属于中元古界下长城统。依据近年获得的最年轻碎屑锆石年龄和相关岩浆岩的结晶年龄资料(表 2),将卢氏—栾川地区高山河群、官道口群、白术沟组和栾川群分别归属为上长城统、蓟县系、待建系下部和青白口系,渑池—确山地区的汝阳群—洛峪群归属为上长城统(表 1)。

熊耳盆地三个地层分区晚前寒武纪沉积岩系的碎屑锆石年龄谱图自下而上变化规律相似(图 5a),表明整个盆地的晚前寒武纪沉积序列及其演化可以进行对比。物源分析证实中元古代长城纪和新元古代青白口纪两期盆地的古地理格局明显不同:上长城统兵马沟组、高山河群和汝阳群以华北克拉通内部物源区为主(Zhu Xiyan et al., 2011, 2019; Li Meng et al., 2013; Hu Guohui et al., 2014; Yue Liang et al., 2017; Zuo Pengfei et al., 2019b; Wang Miao et al., 2020a, 2020b),而青白口系栾川群以华北克拉通南缘北秦岭物源区为主(Jia Chao, 2018; Liu Xuefei et al., 2019; Li Zhensheng et al., 2020)。本次从沉积古地理格局继承的角度出发,综合前人区域地层对比成果,讨论缺乏可靠年龄约束的黄连垛组、董家组和五佛山群的年代归属,最终厘定的熊耳盆地晚前寒武纪地层对比方案见表 1。

3.2　白术沟组时代探讨

熊耳盆地西南缘的洛南—卢氏(小秦岭)地区在蓟县系官道口群碳酸盐岩和震旦系罗圈组冰碛砾岩之间的一套碎屑岩系曾称为石北沟组或大庄组,区域地层对比认为向东与栾川地区白术沟组相当(DGMRHP, 1997; BGMRSP, 1998),向西可延伸到鄂尔多斯西缘的岐山和陇山地区(Li Zhenhong et al., 2019)。目前白术沟组归属有两种观点:一种观点将白术沟组划为官道口群顶部地层(Wang Xiaolei et al., 2011; Li Zhenhong et al., 2019; Liu Xuefei et al., 2019),与燕辽地区待建系下马岭组同期(Su Wenbo, 2016; Li Zhenhong et al., 2019; Lü Qiqi et al., 2020);另一种观点将其划为栾川群底部地层(Guan Baode et al., 1988; DGMRHP, 1997),属于青白口系(Li Zhensheng et al., 2020)。最近在栾川地区祖师庙、东沟脑、抱犊寨等剖面的白术沟组上段识别出~1330 Ma 层凝灰岩(Zhu Xiyan et al., 2020);并依据最新区调资料(2019 年评审验收的三川幅 1∶5 万区域地质调查

表 2　熊耳盆地晚前寒武纪碎屑岩的最年轻碎屑锆石年龄及相关岩浆岩的结晶年龄汇总表

Table 2　The youngest detrital zircon ages of the Late Precambrian detrital rocks and the crystallization ages of related magmatic rocks in the Xiong'er basin

采样层位	岩性	样品编号	位置编号	方法	YSG 年龄（Ma）	YPP 年龄（Ma）	YDZ 年龄（Ma）	来源
何家寨组（Qbh）	石英砂岩	YX41	W1	LA-ICP-MS	947±21	976±20（n=4）	947.92 +31/−48	Jia Chao，2018
	石英砂岩	W150730-3	W1	LA-ICP-MS	991±20			Jia Chao，2018
骆驼畔组（Qbl）	石英砂砾岩	YX25	W1	LA-ICP-MS	1776±51	1748±89（n=5）	1608.3 +120/−140	自测；未发表
	石英砂砾岩	W150730-2	W1	LA-ICP-MS	1606±62			自测；未发表
上马鞍山组（Ch_2sm）	石英砂岩	WFS-1	W1	LA-ICP-MS	1787±8	1856±56（n=5）	1790 +15/−34	Hu Guohui et al.，2012a
下马鞍山组（Ch_2xm）	紫色砂岩	B065	W3	LA-ICP-MS	1717±42	1713±17（n=11）	1643.3 +37/−58	Meng Yao et al.，2018
	砂岩	WFS13-01	W1	SIMS	1793±6			Zhang Hongfu et al.，2016
	砂岩	AGQ13-08	W2	SIMS	1788±14			Zhang Hongfu et al.，2016
	石英砂岩	WFS11	W1	LA-ICP-MS	1655±22			Hu Guohui et al.，2012a
兵马沟组 小沟背组（Ch_2b）	紫色砂岩	B063	W3	LA-ICP-MS	1792±147	1740±70（n=4）	1637.5 +82/−210	Meng Yao et al.，2018
	砂岩	B001	W3	LA-ICP-MS	2137±37			Meng Yao et al.，2018
	砂岩	MC-1	R3	LA-ICP-MS	1676±90			Zuo Pengfei et al.，2019b
董家组（Xsd）	长石石英砂岩	MLA-04-2	R2	LA-ICP-MS	1813±101	1685±61（n=5）	1562.5 +67/−340	Zuo Pengfei et al.，2019a
	长石石英砂岩	17DJ-02	R3	LA-ICP-MS	1661±129			Zuo Pengfei et al.，2019a
	长石石英砂岩	YX69，70	R3	LA-ICP-MS	1621±59			本文
黄连垛组（Jxh）	长石石英砂岩	YX192	R3	LA-ICP-MS	1498±96	1568±61（n=6）	1450 +93/−290	本文
	长石石英砂岩	17HLD-04	R3	LA-ICP-MS	1687±107			Zuo Pengfei et al.，2019a
	石英砂岩	0724-4	R3	LA-ICP-MS	1690±66			Wang Miao et al.，2020a
三教堂组（Ch_2s）	砂岩	LLS02	R1	SIMS	1938±12	1869±55（n=4）	1806.2 +73/−120	Lan Zhongwu et al.，2014
	石英砂岩	ZTS13	R5	LA-ICP-MS	1824±58			Li Xiyao et al.，2020
	石英砂岩	ZTS14	R5	LA-ICP-MS	1898±54			Li Xiyao et al.，2020
崔庄组（Ch_2c）	砂岩	ZTS01	R7	LA-ICP-MS	1651±61	1708±64（n=5）	1608.3 +100/−150	Li Xiyao et al.，2020
北大尖组（Ch_2bd）	长石石英砂岩	ZTS02	R7	LA-ICP-MS	1743±72	1790±89（n=2）	1741.7 +120/−160	Li Xiyao et al.，2020
白草坪组（Ch_2bc）	石英砂岩	110504-1	R6	LA-ICP-MS	1817±22	1828±27（n=3）	1807.5 +37/−48	Li Meng et al.，2013
	石英砂岩	110505-2	R7	LA-ICP-MS	1829±28			Li Meng et al.，2013
	石英砂岩	110504-2	R6	LA-ICP-MS	1838±23			Li Meng et al.，2013
	石英砂岩	110505-1	R7	LA-ICP-MS	1924±17			Li Meng et al.，2013
云梦山组（Ch_2y）	砂岩	Hu-28	R3	LA-ICP-MS	1682±56	1664±55（n=5）	1581.3 +68/−110	Hu Guohui et al.，2014
	砂岩	Hu-26	R3	LA-ICP-MS	1711±57			Hu Guohui et al.，2014
	岩屑石英砂岩	Hu-2	R3	LA-ICP-MS	1717±53			Hu Guohui et al.，2014
	石英砂岩	0723-5	R3	LA-ICP-MS	1644±60			Wang Miao et al.，2020a
	石英砂岩	ZTS18	R5	LA-ICP-MS	1722±69			Li Xiyao et al.，2020
	石英砂岩	ZTS19	R5	LA-ICP-MS	1776±53			Li Xiyao et al.，2020
鱼库组（Qby）	石英岩	YX120	L1	LA-ICP-MS	882±18	946±150（n=3）	882.5 +39/−41	Jia Chao，2018
煤窑沟组（Qbm）	石英阳起片岩	YX140	L1	LA-ICP-MS	884±20	898±26（n=3）	876.67 +37/−50	Jia Chao，2018
三川组①（Qbs）	石英岩	YX115	L3	LA-ICP-MS	1065±21	1050±35（n=4）	1016.7 +31/−110	Jia Chao，2018
	石英岩	BSGSC1	L3	LA-ICP-MS	1027±14			Zuo Pengfei，2016
白术沟组（Xsb）	炭质片岩	YSXSX1	B1	LA-ICP-MS	1494±23	1523±79（n=4）	1493.7 +42/−100	Zuo Pengfei，2016
	炭质片岩	YSXSX2	B1	LA-ICP-MS	1594±44			Zuo Pengfei，2016
陈家涧组（Ch_2cj）	石英砂岩	GSH21	G2	LA-ICP-MS	1816±29	1873±40（n=5）	1832.5 +17/−81	Zhu Xiyan et al.，2019
鳖盖子组（Ch_2bg）	石英砂岩	17GS04	G1	LA-ICP-MS	1764±13	1720±50（n=3）	1679.2 +55/−88	Zhu Xiyan et al.，2019
	石英砂岩	17GS02	G1	LA-ICP-MS	1769±43			Zhu Xiyan et al.，2019
	砂岩	GSH0806	G1	LA-ICP-MS	1785±15			Zhu Xiyan et al.，2011
	砂岩	GSH0808	G1	LA-ICP-MS	1830±27			Zhu Xiyan et al.，2011
	岩屑石英砂岩	0730−2	G1	LA-ICP-MS	1685±39			Wang Miao et al.，2020b

续表 2

相关岩浆岩部分							
采样层位	岩性	样品编号	位置编号	方法	结晶年龄(Ma)	备注	来源
栾川辉长岩体	辉长岩	07CTD-08	L1	LA-ICP-MS	855±19	最高侵位于栾川群大红口组-鱼库组	Wang Xiaolei et al., 2011
	辉长岩	07CTD-09	L1	LA-ICP-MS	830±7		Wang Xiaolei et al., 2011
	辉长岩	07CTD-18	L1	SHRIMP	826±34		Wang Xiaolei et al., 2011
大红口组	碱性粗面岩	08-4-1		SHRIMP	860±8		Yan Guohan et al., 2010
	碱性粗面岩	17Y05-2	L2	LA-ICP-MS	840±4		Hu Guohui et al., 2019
	碱性粗面岩	18Y015	L2	LA-ICP-MS	845±5		Hu Guohui et al., 2019
	碱性粗面岩	18Y017	L3	LA-ICP-MS	846±6		Hu Guohui et al., 2019
	碱性粗面岩	YX130	L1	LA-ICP-MS	854±8		Jia Chao, 2018
白术沟组上段	凝灰岩	1904BS02	B2	LA-MC-ICPMS	1330±10		Zhu Xiyan et al., 2020
	凝灰岩	1904BS08	B2	LA-MC-ICPMS	1332±10		Zhu Xiyan et al., 2020
潘河岩体	黑云母正长岩	LSB-118	G4	LA-ICP-MS	1469±8	最高侵位于官道口群杜关组底	Zeng Lingjun et al., 2013
龙家园组	层凝灰岩	20180726-1	G5	SHRIMP	1594±8		Zhang Heng et al., 2019
	晶屑凝灰岩	20180726-7	G5	SHRIMP	1541±8		Zhang Heng et al., 2019
麻坪岩体	花岗斑岩	13MP-6	G3	LA-ICP-MS	1600±24	最高侵位于官道口群龙家园组	Deng Xiaoqin et al., 2015
	花岗斑岩	13MP-9	G3	LA-ICP-MS	1583±28		Deng Xiaoqin et al., 2015
洛峪口组	层凝灰岩	YP12292	R4	LA-MC-ICPMS	1611±8		Su Wenbo et al., 2012
	流纹质凝灰岩	13YX212	R5	LA-MC-ICPMS	1638±9		Li Chengdong et al., 2017
	流纹质凝灰岩	13YX206	R4	LA-MC-ICPMS	1634±10		Li Chengdong et al., 2017
	流纹质凝灰岩	170325-3	R4	SHRIMP	1639±13		Peng Nan et al., 2018
	凝灰岩	20161121-3	R5	SHRIMP	1608±17		Zhang Heng et al., 2019
	凝灰岩	20161120-4	R4	SHRIMP	1597±7		Zhang Heng et al., 2019
	凝灰岩	20161120-1	R4	SHRIMP	1596±15		Zhang Heng et al., 2019
	层凝灰岩	20180723-8	R3	SHRIMP	1620±16		Zhang Heng et al., 2019

注：① 原文为白术沟组中上段，据最新区调资料修订为三川组(Zhu Xiyan et al., 2020)；YSG—最年轻单颗粒年龄；YPP—最年轻峰值年龄；YDZ—最年轻碎屑锆石年龄；YPP 和 YDZ 年龄由 Isoplot 软件(Ludwig K R, 2003)计算。

报告)认为白术沟组建组剖面地点及其附近的白术沟组中段“石英岩”非原始层位，实为上覆栾川群三川组下部被断层切割形成的断块(Zhu Xiyan et al., 2020)。基于最新的地质资料，本文将白术沟组置于待建系下部(对应于国际年代表的延展系)，并将原“白术沟组中上段石英岩”的层位修订为三川组。

3.3　黄连垛组和董家组时代探讨

早期依据岩性组合、叠层石、碳同位素负偏等特征以及区域内存在的不整合接触关系认为黄连垛组可能与官道口群龙家园组或巡检司组同期(Xiao Shuhai et al., 1997; Su Wenbo, 2016)。本次研究结果表明，黄连垛组石英砂岩(YX192)中少量蓟县纪碎屑锆石的 YSG 和 YPP 年龄分别为 1498±96 Ma 和 1568±62 Ma (MSWD＝0.18, n＝6)，并与龙家园组下部 1.59～1.54 Ga 凝灰岩年龄(Zhang Heng et al., 2019)相近。进一步表明黄连垛组可与蓟县系官道口群对比，为碳酸盐台地的边缘相沉积(Gao Linzhi et al., 2002; Zuo Pengfei et al., 2019a)。

前人一般认为董家组岩性组成与燕辽地区长龙山组—景儿峪组等完全相仿，沉积于新元古代早期(Su Wenbo, 2016)；然而董家组与下伏黄连垛组、白草坪和云梦山组具有相似的碎屑锆石年龄谱(图 5a)，海侵方向均为自西向东和自(西)南向北(Guan Baode et al., 1988; Zuo Pengfei et al., 2019a, 2019b)，表明董家组继承了下伏中元古代地层的沉积古地理格局。同时，董家组和邻区的白术沟组与上下地层关系均为平行不整合接触；碎屑锆石年龄谱图相似且均缺失与沉积时代相近的碎屑锆石；白术沟组形成于相对缺氧及沉积源区供给缺乏的水体环境(Zhu Xiyan et al., 2020)，而董家组可能构成了沉积时期盆地的边缘相(Zuo Pengfei et al., 2019a)。因此，基于区域岩相变化、上下地层关系和碎屑锆石年龄谱图对比等认为董家组大体可与白术沟组对比，归属于待建系下部(延展系)。

3.4　五佛山群时代探讨

下马鞍山组与汝阳群和高山河群位于熊耳群上覆沉积岩系底部；它们的碎屑锆石年龄谱图相似，以 2.2～1.8 Ga 和/或～2.5 Ga 为主(图 5a)，以华北克拉通内部物源区为主(Zhu Xiyan et al., 2011, 2019; Hu Guohui et al., 2012a, 2014; Li Meng et al., 2013; Zhang Hongfu et al., 2016; Meng Yao et al., 2018; Wang Miao et al., 2020a, 2020b),应是同一盆地的同期地层单元。同时,葡峪组常与洛峪群崔庄组对比(DGMRHP, 1997; Su Wenbo, 2016),与上覆的骆驼畔组断层或微不整合接触(Suo Shutian et al., 2004; Zuo Pengfei et al., 2019a, 2019b),因此将下马鞍山组、上马鞍组和葡峪组归属于上长城统,分别与云梦山组—白草坪组、北大尖组和崔庄组对应。

何家寨组和青白口系栾川群位于熊耳群上覆沉积岩系顶部;它们的碎屑锆石年龄谱图相似,以1.8～1.0 Ga为主(图5a),物源区转变为以华北克拉通南缘北秦岭地体为主(Jia Chao, 2018; Liu Xuefei et al., 2019; Li Zhensheng et al., 2020),应是同一盆地的同期地层单元。我们的物源分析揭示骆驼畔组含有较高的2.95～2.70 Ga碎屑锆石年龄记录,其碎屑物质来源于南侧的登封-鲁山地区,因此,骆驼畔组与上覆何家寨组的沉积古地理格局类似,明显不同于下伏的下马鞍山组和上马鞍组。同时,骆驼畔组高成熟度砂砾岩可解释为底砾岩,将骆驼畔组置于青白口系底部是合理的。考虑红岭组和煤窑沟组具有相似的叠层石组合(Guan Baode et al., 1988),约束骆驼畔组、何家寨组及红岭组应归属于青白口系,分别与卢氏—栾川地区三川组、南泥湖和煤窑沟组相当。

4 沉积构造背景分析

4.1 沉积构造背景判别方法

通过盆内或盆缘岩浆作用类型及其活动频率、新成物质保存潜力和蚀源区地域范围的综合对比,Cawood et al. (2012)提出了一种利用碎屑锆石年龄累积函数判别盆地构造属性的统计方法。该方法给出了两个重要的统计学判别指标:累计概率5%和30%所对应的年龄与地层沉积年龄的差值,$CA_{5\%}-DA$和$CA_{30\%}-DA$;被动大陆边缘盆地、裂谷盆地和内克拉通盆地等伸展型盆地中$CA_{5\%}-DA>150$ Ma和$CA_{30\%}-DA>100$ Ma,前陆盆地等碰撞型盆地中$CA_{5\%}-DA<150$ Ma和$CA_{30\%}-DA>100$ Ma,海沟盆地、弧前盆地和弧后盆地等汇聚型盆地中$CA_{5\%}-DA<150$ Ma和$CA_{30\%}-DA<100$ Ma。

4.2 沉积构造背景判别结果

假设相当地层中最小的YSG年龄或相邻的火山岩年龄作为地层沉积年龄(DA),鱼库组和煤窑沟组采用大红口组碱性粗面岩的结晶年龄最大值(860 Ma),白术沟组采用上部凝灰岩夹层的结晶年龄(1330 Ma),陈家涧组及三教堂组采用相当地层中洛峪口组凝灰岩层的结晶年龄最大值(1639 Ma),其他层位采用相当地层中最小的YSG年龄(图5b)。

在熊耳盆地晚前寒武纪所有层系中,与沉积时代相近的碎屑锆石含量极低或缺失,$CA_{30\%}-DA>100$ Ma;$CA_{5\%}-DA<150$ Ma的层位有:上长城统下部(兵马沟组/小沟背组、下马鞍山组、云梦山组及鳖盖子组)和青白口系下部(栾川群煤窑沟组、三川组及五佛山群何家寨组),盆地属性判断为碰撞型;$CA_{5\%}-DA>150$ Ma的层位有:上长城统中—上部(上马鞍山组、白草坪组、三教堂组及陈家涧组)、蓟县系(黄连垛组)、待建系(白术沟组及董家组)、青白口系底部(骆驼畔组)和青白口系上部(鱼库组),盆地属性判断为伸展型。此外,依据碎屑锆石年龄统计判断北缘盆地长城纪地层单元普遍为碰撞型构造属性(Zhong Yan et al., 2019)。基于碎屑锆石年龄统计的物源分析和构造属性判别表明,熊耳盆地存在晚长城世和青白口纪两期碰撞型—伸展型的属性转换,支持北秦岭块体与华北克拉通拼贴—裂解的演化模式(Zhang Guowei et al., 2001; Dong Yunpeng et al., 2003, 2014, 2016)。

5 沉积构造演化

依据最新的区域地层对比方案、沉积构造属性分析及区域岩浆活动,熊耳盆地晚前寒武纪演化阶段可划分为六期:早长城世裂陷、晚长城世断陷、蓟县纪坳陷、待建纪早期坳陷、青白口纪坳陷及晚震旦世冰期坳陷,并发育早长城世末期、待建纪中晚期和南华纪—早震旦世三期重要的沉积间断。

北秦岭地体的构造属性和宽坪群变基性火山岩所对应洋盆(宽坪洋)的闭合时间是反演熊耳盆地演化的关键因素,北秦岭地体的构造属性主要有隶属于华北陆块(Zhang Guowei et al., 2001)、扬子陆块(Zhang Zhen et al., 2015)和独立于华北陆块和扬子陆块的微陆块属性(Dong Yunpeng et al., 2003; Zhang Guowei et al., 2019; Diwu Chunrong et al., 2019)等观点;宽坪洋是有限小洋盆或广阔大洋盆地,在新元古代初期(Dong Yunpeng et al., 2014, 2016; Zhang Guowei et al., 2019)或早古生代(Liu Xiaochun et al., 2013; Diwu Chunrong et al., 2019)闭合等观点。首先,物源分析揭示北秦岭地体是栾川群最可能的物源区(Jia Chao, 2018; Liu Xuefei et al., 2019; Li Zhensheng et al., 2020),支持宽坪洋新元古代初期闭合(Dong

Yunpeng et al.，2014，2016）；其次，熊耳、东缘和北缘盆地青白口系碎屑岩的碎屑锆石 U-Pb 年龄和 Hf 同位素特征相似（Hu Bo et al.，2012；Yang Debin et al.，2012；Liu Chaohui et al.，2017；Jia Chao，2018；Liu Xuefei et al.，2019；Li Zhensheng et al.，2020），表明在整个克拉通的南缘和北缘都发育与北秦岭类似的构造带；第三，华北克拉通周缘保存了克拉通内部不发育或难于保存的中元古代热构造事件记录（Zhao Guochun et al.，2006；Li Zhong et al.，2016；Park et al.，2016），暗示了华北克拉通周缘地区中元古代构造演化可能比较复杂，推测至少华北克拉通周缘曾强烈卷入了 Columbia 超大陆裂解和 Rodinia 超大陆聚合过程，只是由于超大陆破裂后的多次热构造事件的叠加改造或海平面升降影响，导致曾经存在过的超大陆汇聚的地质记录多数已不复存在（Lu Songnian et al.，2012）；第四，华北克拉通南缘、北秦岭地体与栾川群源区具有相同的地壳增生阶段且显示出地壳由北到南的逐渐增生发展过程（Jia Chao，2018；Liu Xuefei et al.，2019；Li Zhensheng et al.，2020）。因此，我们倾向于传统观点认为北秦岭块体隶属于华北陆块（Zhang Guowei et al.，2001）或独立微陆块（Dong Yunpeng et al.，2003；Zhang Guowei et al.，2019），其构造演化类似董云鹏等提出的模式（Dong Yunpeng et al.，2014 中图 14）：1.78～1.45 Ga 熊耳裂谷和 1.45～0.95 Ga 宽坪洋的伸展阶段、1000～900 Ma 宽坪洋向南俯冲—碰撞造山阶段和 889～844 Ma 碰撞后伸展阶段，分别对应于 Columbia 超大陆裂解、Rondina 超大陆聚合和 Rondina 超大陆裂解过程。依据本次盆地属性分析结果及北秦岭松树沟镁铁质岩石等最新年龄资料（Sun Shengsi et al.，2019；Diwu Chunrong et al.，2019），将熊耳盆地及北秦岭地体的演化模式修订如下（图 6）。

5.1　早长城世裂陷盆地

华北克拉通早长城世沉积仅分布在熊耳盆地和北缘盆地（Zhai Mingguo et al.，2015；Zhong Yan et al.，2019），～1.78 Ga 熊耳群火山岩和基性岩墙群收敛位置指示整个华北克拉通裂谷活动中心位于南缘栾川—熊耳地区（Hou Guiting et al.，2008；Peng Peng，2015a，2015b；Guan Shuwei et al.，2017）。

华北克拉通在古元古代末期汇聚碰撞（吕梁运动，或称中条运动）成为 Columbia 超大陆的一部分

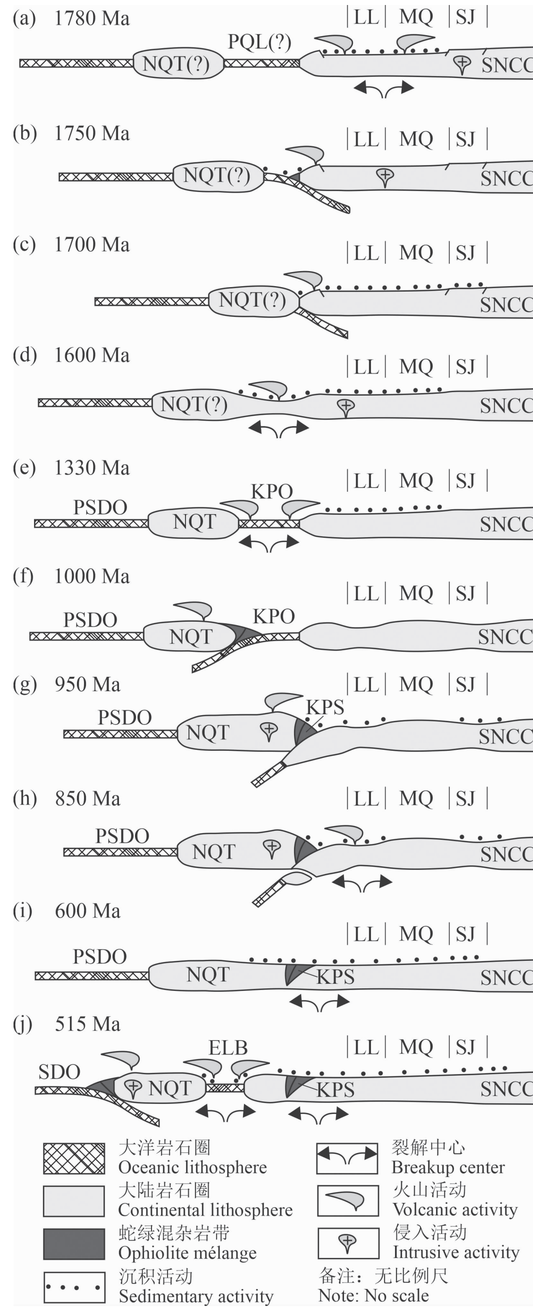


图 6　熊耳盆地晚前寒武纪演化示意图（据 Dong Yunpeng et al.，2014，2016 和 Liu Liang et al.，2016 修改）

Fig. 6　Schematic cartoons showing the Late Precambrian tectonic evolution of the Xiong'er basin (modified after Dong Yunpeng et al.，2014，2016 and Liu Liang et al.，2016)

SNCC—华北克拉通南部；SJ—嵩箕地区；MQ—渑池—确山地区；LL—卢氏—栾川地区；NQT—北秦岭地体；PSDO—古商丹洋；PQL—古北秦岭洋；KPO—宽坪洋；KPS—宽坪缝合线；SDO—商丹洋；ELB—二郎坪弧后洋盆

SNCC—Southern North China Carton；SJ—Song-Ji area；MQ—Mianchi-Queshan area；LL—Lushi-Luanchuan area；NQT—North Qinling Terrane；PSDO—Proto-Shangdan ocean；PQL—Proto-North Qingling ocean；KPO——Kuanping ocean；KPS——Kuanping sutures；SDO—Shangdan ocean；ELB—Erlangping back-arc oceanic basin

(Zhao Guochun et al., 2012),克拉通南部在～1.84 Ga由碰撞挤压转变为造山后伸展环境(Zhao Taiping et al., 2009, 2016; Deng Xiaoqin et al., 2016a, 2019);至少自～1.78 Ga开始发育早长城世裂陷盆地(图6a):熊耳(豫陕—吕梁)三岔裂谷,两支基本与华北南缘边界一致,另一支从中条山地区一直延续到华北中部吕梁山地区(Zhao Taiping et al., 2004; Qiao Xiufu et al., 2014; Zhai Mingguo et al., 2015);相应的地质记录包括1.78～1.75 Ga熊耳群及小两岭组火山-沉积岩系和基性岩墙群(Qiao Xiufu et al., 2014; Zhai Mingguo et al., 2015)、嵩箕地区1.78～1.74 Ga钾长花岗岩(Zhao Taiping et al., 2009; Wan Yusheng et al., 2009; Zhang Juan et al., 2013)以及北秦岭西部地区1.81～1.74 Ga片麻状花岗岩(Gao Sheng et al., 2015)。该时期盆地形成于大陆边缘裂谷/坳拉槽环境(Zhai Mingguo et al., 2015; Zhao Taiping et al., 2002, 2016),熊耳群火山岩与同时期的基性岩墙群共同表征了华北克拉通在中元古代早期的初始裂解(Hou Guiting et al., 2008; Lu Songnian et al., 2008; Zhao Taiping et al., 2002, 2016),属于Columbia超大陆裂解相关的热-构造事件(Zhao Taiping et al., 2002; Peng Peng et al., 2008; Zhai Mingguo et al., 2015)。

早长城世末期熊耳裂陷盆地闭合(熊耳运动,或称王屋山运动和垣曲运动),相应的地质响应包括熊耳群与上覆沉积岩系之间的不整合面、沉积岩系底部鳖盖子组—云梦山组—下马鞍山组及小沟背组/兵马沟组对应的碰撞型盆地。对其成因推测与北秦岭古洋盆向华北克拉通俯冲消减致使北秦岭地体首次拼接到于华北南缘有关(Dong Yunpeng et al., 2003;图6b、c),并建议将首次最终拼接时间由1800 Ma(Zhang Guowei et al., 2001)或1600 Ma(Dong Yunpeng et al., 2003)修订为早长城世末期;其中秦岭群杂岩中1870 Ma和宽坪群杂岩中1974～1681 Ma变火山岩(Zhang Zhen et al., 2015)可能是北秦岭古洋盆的残留。但是也不能完全排除宽坪洋是广阔大洋,华北克拉通在长城纪期间未与北秦岭相邻,而是处于汇聚碰撞环境向伸展体系转变的构造反转期(Zhong Yan et al., 2019)或与未知块体汇聚闭合。

5.2 晚长城世断陷盆地

晚长城世—蓟县纪是华北克拉通晚前寒武纪盆地范围最大的时期,熊耳、燕辽、北缘和西缘盆地可能相互贯通(Li Zhenhong et al., 2019; Du Jinhu et al., 2019; Lü Qiqi et al., 2020),1.74～1.60 Ga非造山岩浆事件和1.37～1.32 Ga基性岩席或大火成岩省指示裂谷活动中心移位至中北部燕辽地区直至待建纪早期(Peng Peng, 2015a, 2015b; Guan Shuwei et al., 2017)。

熊耳盆地晚长城世转变被动大陆边缘(图6c),大规模的海侵形成陆相—滨浅海相的陆源碎屑沉积(Jiang Ganqing et al., 1994; Hu Guohui et al., 2013; Wang Miao et al., 2020a, 2020b)。该碎屑岩系超覆于熊耳群火山-沉积岩系和变质基底之上,整体呈北北东向展布,仍受三岔裂谷边界断裂的断陷作用限制,沉降中心位于河南渑池和陕西洛南一带,最大厚度分别达1883 m和3707 m(DGMRHP, 1997),向东或西厚度减薄;以无障壁海岸—浅海陆棚沉积和障壁型海岸沉积为主(Lü Qiqi et al., 2020),仅在底部兵马沟组和小沟背组包含陆相冲积扇—扇三角洲沉积(Guan Baode et al., 1988; Yue Liang et al., 2017; Meng Yao et al., 2018)。同期的热事件记录包括～1.64 Ga庙岭霓辉正长岩脉(Ren Fugen et al., 2000)、～1.62 Ga龙王𡉼花岗岩(Lu Songnian et al., 2003; Bao Zhiwei et al., 2009; Wang Xiaolei et al., 2013)等非造山岩浆侵位,以及洛峪群顶部洛峪口组1.64～1.60 Ga凝灰岩沉积(Su Wenbo et al., 2012; Li Chengdong et al., 2017; Peng Nan et al., 2018; Zhang Heng et al., 2019)。

5.3 蓟县纪坳陷(陆表海)盆地

裂谷盆地的巨厚碎屑岩沉积往往是碳酸盐岩台地形成的必要条件和垫板,而碳酸盐岩台地的出现代表该盆地填充的最后阶段(Gao Linzhi et al., 2002)。蓟县纪熊耳盆地转变为陆表海盆地,可能存在一期构造抬升导致盆地范围较长城纪缩小(图6d),沉降中心迁移至卢氏—栾川地区(DGMRHP, 1997)。蓟县纪盆地沉降中心的官道口群以碳酸盐岩局限台地的潮坪相沉积为主体(DGMRHP, 1997; Li Zhenhong et al., 2019; Lü Qiqi et al., 2020),厚达1300～2400 m;盆地边缘为黄连垛组三角洲—滨浅海相或滨海—潮坪沉积(Zuo Pengfei et al., 2019a),厚度变化较大,在叶县、方城地区最厚达457 m,向西北、东南两侧变薄(DGMRHP, 1997)。同期的岩浆事件包括～1.60 Ga麻坪花岗斑岩(Deng Xiaoqin et al., 2015)、～1.53 Ga张家坪花岗岩(Deng Xiaoqin et al., 2016b)及～1.47

Ga 潘河正长岩（Zeng Lingjun et al.，2013）等非造山岩浆侵位，以及官道口群底部龙家园组 1.59～1.54 Ga 凝灰岩沉积（Zhang Heng et al.，2019）。

5.4　待建纪早期坳陷盆地

待建纪早期沉积记录在燕辽、熊耳、北缘及西缘盆地局限分布（Li Zhenhong et al.，2019；Zhong Yan et al.，2019；Zhu Xiyan et al.，2020），其沉积背景及顶部长达 250 Ma 沉积间断（下汤运动）所代表的地质事件性质和意义究竟如何目前仍不明确（Zhu Xiyan et al.，2020）。部分学者倾向于将下马岭组归为与长城系、蓟县系一致的持续裂谷沉积（Zhai Mingguo et al.，2015），与 1.33～1.3 Ga 大火成岩省密切相关，即"岩浆活动前的穹窿状地壳抬升事件"（Zhang Shuanhong et al.，2017）；部分学者关注燕辽盆地下马岭组斑脱岩具有同碰撞岛弧火山岩的地球化学特征，将其视为响应于罗迪尼亚超大陆的汇聚过程（Su Wenbo et al.，2008；Meng Qingren et al.，2011），形成于弧后深水盆地（Qiao Xiufu et al.，2014）。

中元古代中期华北南缘和北秦岭地体间持续裂解分离，形成宽坪有限洋盆（图 6e），相应的地质记录为 1.45～0.95 Ga 宽坪群火山岩系（Diwu Chunrong et al.，2010；Dong Yunpeng et al.，2014）。熊耳盆地待建纪早期沉降中心的白术沟组以黑色页岩/板岩为主体，为浅海含碳泥砂坪沉积（DGMRHP，1997；Zuo Pengfei et al.，2019a），厚度变化较大，栾川地区最厚达 1011 m（DGMRHP，1997），反映了中元古代中期盆地迅速沉降、水体加深的沉积背景（Zhu Xiyan et al.，2020）；盆地边缘为董家组三角洲—滨浅海—海湾泻湖或滨浅海—潮坪沉积（Zuo Pengfei et al.，2019a），厚度变化较大，在叶县、方城地区最厚达 343 m，向西北、东南两侧变薄（DGMRHP，1997）。

5.5　青白口纪坳陷盆地

华北青白口纪盆地范围较大，在熊耳盆地、燕辽盆地、北缘盆地和东缘盆地广泛分布，～900 Ma 基性岩墙群的收敛位置指示整个华北克拉通裂谷活动中心移位至东南缘徐淮地区（Peng Peng，2015a，2015b；Guan Shuwei et al.，2017）。然而，熊耳青白口纪盆地范围较小，仅分布在南缘的卢氏—栾川地区和东北部的嵩箕地区，沉积厚度分别达 1700～3100 m 和 485 m，向东与东缘盆地相互连通（Peng Peng，2015a，2015b）。

熊耳盆地和北秦岭地体的青白口纪构造属性转换过程具有极好的对应关系，是华北克拉通参与全球 Rodinia 汇聚和裂解过程的地质记录（Dong Yunpeng et al.，2014，2016；Li Zhensheng et al.，2020）。1000～900 Ma 宽坪洋向南俯冲—碰撞造山（Dong Yunpeng et al.，2014，2016），北秦岭地体再度拼贴于华北南缘（图 6f、g），华北南缘由被动大陆边缘转变为同碰撞挤压盆地（Li Zhensheng et al.，2020），发育栾川群下部三川组—煤窑沟组无障壁海岸碎屑沉积（DGMRHP，1997；Lü Qiqi et al.，2020）；北秦岭发育秦岭群弧前碎屑沉积及～940 Ma 强烈变形 S 型同碰撞花岗岩，代表了 Rodinia 超大陆聚合的地质记录（Shi Yu et al.，2013；Wang Xiaoxia et al.，2013；Diwu Chunrong et al.，2014，2019）。自～889 Ma 碰撞造山过程结束转变为后碰撞伸展甚至裂谷环境（图 6h），华北南缘形成栾川群上部大红口组和鱼库组碳酸盐台地沉积（DGMRHP，1997；Lü Qiqi et al.，2020），并伴有～860Ma 大红口组碱性火山岩（Yan Guohan et al.，2010；Hu Guohui et al.，2019；Li Zhensheng et al.，2020）和～830 Ma 基性岩床群（Wang Xiaolei et al.，2011）等岩浆活动；北秦岭地区发育～880 Ma 后碰撞 I 型花岗岩（Wang Xiaoxia et al.，2013）和～844 Ma 板内 A 型花岗岩（方城碱性正长岩；Bao Zhiwei et al.，2008），代表了 Rodinia 超大陆裂解的地质记录（Yan Guohan et al.，2010；Wang Xiaolei et al.，2011；Wang Xiaoxia et al.，2013；Zhang Shuanhong et al.，2016a；Diwu Chunrong et al.，2019）。

5.6　晚震旦纪世冰期坳陷

南华纪—早震旦世华北克拉通整体上处于沉积间断状态（豫西运动或晋宁运动），然而世界各地超大陆裂解岩浆活动、裂谷盆地沉积及冰川事件发育（Zheng Yongfei，2003），其成因仍需深入研究。经过豫西运动后，华北克拉通所有裂谷系关闭，呈现出北高南低、西高东低的形态（Guan Shuwei et al.，2017），整体进入了一个新的沉积期（Du Jinhu et al.，2019），发育震旦纪至早古生代被动大陆边缘坳陷沉积（图 6i、j）；因商丹洋 600～534 Ma 洋盆形成和 524～500 Ma 向北俯冲的影响，北秦岭发育早古生代岛弧-弧后盆地沉积（Dong Yunpeng et al.，2015，2016；Liu Liang et al.，2016）。

罗圈组及相当地层在华北南缘和西缘广泛分布，主流观点认为时代为新元古代晚震旦世，属于新元古代最后一期（Gaskiers 冰期）冰川沉积记录

(Gao Linzhi et al., 2002; Shen Bing et al., 2007; Zhou Chuanming et al., 2019; Zhang Biyun et al., 2019)。罗圈组厚度变化较大(10～230 m),超覆在不同时代的地层之上(Lu Songnian et al., 1985; Gao Linzhi et al., 2002),最高层位为董家组,最低可直接与太古宙登封群接触;属于大陆冰川—冰海相沉积(Lu Songnian et al., 1985; Guan Baode et al., 1988; Zhang Biyun et al., 2019),由北向南依次发育大陆冰碛—冰海陆源碎屑滨岸—冰海陆棚相沉积(Lu Songnian et al., 1985; Lü Qiqi et al., 2020)。

6 结论

(1)黄连垛组砂岩中碎屑锆石的最年轻单颗粒年龄(YSG)和峰值年龄(YPP)分别为 1498±96 Ma 和 1568±62 Ma (MSWD=0.18, n=6);董家组和黄连垛组的碎屑锆石年龄范围相似,集中在 3.00～1.70 Ga,指示物源区为华北克拉通。

(2)依据碎屑锆石年龄谱区域对比、沉积古地理格局继承关系和岩相区域对比等建议将嵩箕地区下部的兵马沟组、马鞍山组和葡峪组归属于上长城统,上部的骆驼畔组、何家寨组及红岭组属于青白口系,分别与高山河群/汝阳群—洛峪群和栾川群相当;渑池—确山地区上部的黄连垛组和董家组分别属于蓟县系和待建系,与官道口群和白术沟组相当。

(3)熊耳盆地晚前寒武纪演化可划分为六个阶段:早长城世裂陷、晚长城世断陷、蓟县纪坳陷、待建纪早期坳陷、青白口纪坳陷及晚震旦世冰期坳陷,以及早长城世末期、待建纪中晚期和南华纪—早震旦世三期重要的沉积间断,支持北秦岭地体与华北克拉通拼贴—裂解的构造演化模式,并建议将北秦岭地体和华北南缘首次拼接时间修订为早长城世末期。

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Late Precambrian chronostratigraphic framework and tectonic evolution of the Xiong'er basin in southern North China Craton

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Abstract

The Xiong'er basin, with best preserved late Precambrian stratain the North China Craton, is an ideal site for reevaluating the sedimentary and tectonic evolution history of this period. Based on the collected and newly analyzed zircon chronology data of 38 clastic and 23 magmatic rocks, regional comparison of lithofacies and inheritance of sedimentary palaeogeographic patterns, the Late Precambrian chronostratigraphic framework, tectonic setting, evolution history as well as sedimentary paleogeography pattern are systematically studied. The readjusted chronostratigraphic framework divides the Late Precambrian evolution of the Xiong'er Basin into 6 basin stages, including aulacogen in the Early Changcheng Epoch, fault basin in the Late Changcheng Epoch, depression basin in the Jixian Period, depression basin in the early phase of the Unnamed period (Ectasian Period), depression basin in the Qingbaikou Period, as well as glacial depression basin in the Late Sinian Epoch, with three major sedimentary discontinuities in the end of Early Changcheng Epoch, middle-late phase of the Unnamed period, and Nanhua Period to Early Sinian Epoch. The collisional to extensional transition of tectonic setting in the Late Changcheng Epoch and Qingbaikou Period support the evolution model of multi-stage convergence and breakup between the North Qinling Terrane and the North China Craton. The volcanic-sedimentary rock series in the Early Changcheng Epoch to the early phase of the Unnamed period (Ectasian period) of the Mesoproterozoic Era and the 1. 64～1. 47 Ga anorogenic magmatic events are the geological responses to the breakup of the Columbia supercontinent. The sedimentary rock series of collisional setting and volcanic-sedimentary rock series of extensional setting in the early phase of the Qingbaikou Period are the geological response to convergence and breakup of the Rodinia supercontinent respectively.

Key words: Late Precambrian; basin tectonic setting; supercontinent evolution; Xiong'er basin; North Qinling