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东亚原特提斯洋(Ⅲ):北秦岭韧性剪切带构造特征*

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Abstract　The North Qinling orogenic belt, located in the junction zone between the North China Block and the South Qinling micro-continental block, is a key area to study the tectonic evolution of the Proto-Tethys Ocean. The North Qinling orogenic belt mainly developed four ductile shear zones, including the Luonan-Luanchuan and the Shangdan shear zones which bound the orogenic belt, and the Guanpo-Qiaoduan and the Zhuyangguan-Xiaguan shear zones in the interior of the orogenic belt. Based on detailed analysis of filed and microscopic observations and EBSD fabric analysis for quartz, structures of the four shear zones could be obtained: (1) after the collision between the North China Block and the North Qinling micro-continental block in the Early Paleozoic, the Luonan-Luanchuan, Guanpo-Qiaoduan and Zhuyangguan-Xiaguan shear zones started their activities during the exhumation process; (2) after ~380Ma, the relationship between the North China and the South China blocks was changed from a generally east-west trend to a generally north-south trend due to their northward drifting, resulting in the dextral shearing of the Luonan-Luanchuan and the Shangdan shear zones; (3) ~320Ma, the scissors-type closure between the North China Block and the South Qinling micro-continental block led to the dextral shearing of the Luonan-Luanchuan shear zone and the sinistral shearing of the Shangdan shear zone. However, the Guanpo-Qiaoduan and the Zhuyangguan-Xiaguan shear zones performed as sinistral and dextral shearing, respectively, due to the adjustment among different lithotectonic units in the North Qinling orogenic belt.

Key words　Proto-Tethys Ocean; North Qinling; Shear zone; EBSD

摘　要　北秦岭造山带位于华北陆块与南秦岭微陆块的衔接部位,是研究原特提斯洋构造演化的关键区域之一。北秦岭造山带内主要发育四条韧性剪切带,包括位于边界处的洛南-栾川剪切带和商丹剪切带,及其内部的官坡-乔端剪切带和朱阳关-夏馆剪切带。通过详细的野外构造解析、显微构造分析和石英 EBSD 组构分析,获得了四条主要剪切带的活动特征,认为(1)在早古生代华北陆块与北秦岭微陆块拼合后的折返过程中,洛南-栾川、官坡-乔端和朱阳关-夏馆剪切带开始了初始的剪切活动;(2)~380Ma 之后,华北、华南陆块在向北漂移过程中逐渐由近东西向展布转换为近南北向展布,导致洛南-栾川和商丹剪切带表现为明显的右行剪切;(3)~320Ma 时,华北陆块和南秦岭微陆块之间的剪刀式拼合导致洛南-栾川剪切带表现为右行剪切,商丹剪切带表现为左行剪切,而官坡-乔端和朱阳关-夏馆剪切带在陆块内部不同构造单元的协调作用下分别表现为左行剪切和右行剪切。

关键词　原特提斯洋;北秦岭;剪切带; EBSD

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1 引言

北秦岭造山带位于连接华北陆块和华南陆块的关键位置,其北部以洛南-栾川断裂带为界与华北陆块相连,南部以商丹断裂带为界与南秦岭微陆块相接(张国伟等, 1996, 2001; Dong *et al.*, 2011a; Liu *et al.*, 2011a)。最新的研究成果认为北秦岭造山带是研究东亚原特提斯洋北界的关键位置之一,其变形特征及演化过程对限制原特提斯洋的存在时间、俯冲极性及华北与华南陆块的界线有着重要意义(Liu *et al.*, 2013; Dong *et al.*, 2014, 2015; Yu *et al.*, 2015; Zhao *et al.*, 2015)。北秦岭造山带内主要韧性剪切带的发育指示了各陆块/微陆块之间的相互作用关系,因而可进一步约束东亚原特提斯洋的演化过程。

前人针对北秦岭造山带在岩石学、年代学、地球化学和构造学等方面都已经取得了重大进展(张国伟等, 1996, 2001; Zheng *et al.*, 2005; Cheng *et al.*, 2012; Diwu *et al.*, 2012; Liu *et al.*, 2013; Wang *et al.*, 2013a, 2014; Wu and Zheng, 2013; Dong *et al.*, 2014; Zhao *et al.*, 2015),但对造山带内主要韧性剪切带的研究还不够深入。位于北秦岭造山带边界处的洛南-栾川和商丹断裂带,及划分造山带内部次级岩石构造单元的官坡-乔端和朱阳关-夏馆断裂带均具有韧性剪切变形特征(李亚林等, 1998;王涛等, 2009; Song *et al.*, 2009;张欢等, 2012;Liu *et al.*, 2012),但前期研究除了关注商丹剪切带(Mattauer *et al.*, 1985; Ratschbacher *et al.*, 2003; Wang *et al.*, 2005; Liu *et al.*, 2012),对其他三条剪切带则缺乏详细的研究。近年来随着对北秦岭造山带的深入研究,宽坪洋被认为是一个长期存在的大洋(Dong *et al.*, 2014; Zhao *et al.*, 2015),它闭合的缝合带——洛南-栾川剪切带也是一条重要的边界断裂,且有可能是划分华北与华南的真正界线(第五春荣等, 2010; Liu *et al.*, 2013; Zhao *et al.*, 2015)。官坡-乔端和朱阳关-夏馆剪切带也形成于华北陆块与北秦岭微陆块的拼合过程中(张欢等,2012)。因此,详细研究北秦岭造山带内四条主要韧性剪切带的构造特征,对阐明华北陆块与华南陆块之间的拼贴关系及原特提斯洋的演化过程具有重要意义。

本文针对北秦岭造山带内的四条主要韧性剪切带,开展野外构造解析和显微构造分析,并综合石英 EBSD(电子背散射衍射)组构分析,详细研究各剪切带的变形特征和形成环境,进一步探讨原特提斯洋的构造演化过程。

2 区域构造背景

北秦岭造山带与其北侧的华北陆块和南侧的南秦岭微陆块分别以洛南-栾川剪切带和商丹剪切带为界,造山带内部又被官坡-乔端剪切带和朱阳关-夏馆剪切带进一步划分为宽坪群、二郎坪群和秦岭群三个次级构造单元(Ratschbacher *et al.*, 2003; Hacker *et al.*, 2004; Dong *et al.*, 2011b; Wang

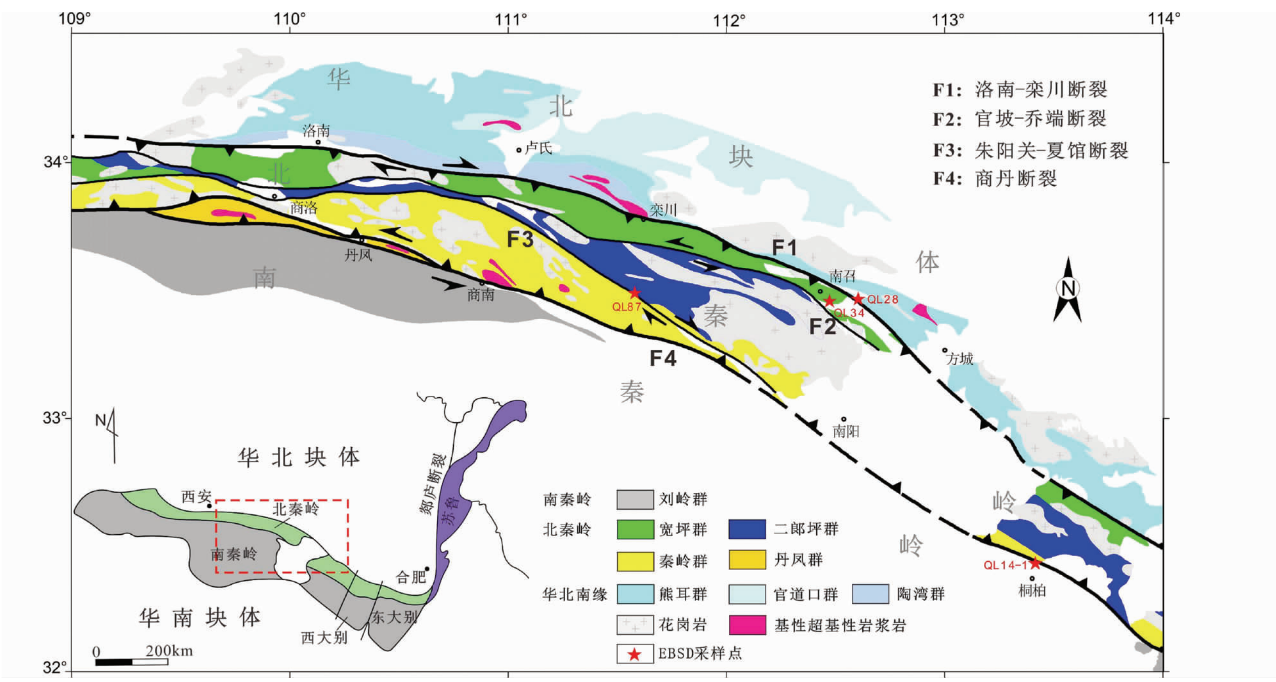

图1 北秦岭造山带及其邻区岩石-构造单元划分简图,插图指示了研究区在秦岭-桐柏-大别-苏鲁造山带中的位置(据 Wang *et al.*, 2011b 修改)

Fig. 1 Division of lithotectonic units in the North Qinling orogenic belt and its neighbors with inset showing its location in the Qinling-Tongbai-Dabie-Sulu orogenic system (revised after Wang *et al.*, 2011b) *et al.*, 2011a, b; Wu and Zheng, 2013; 图1)。这三个次级构造单元在平面上主体表现为北西西至北西向带状展布,并被大量的古生代和中生代花岗岩体侵入(Kröner *et al.*, 1993; 杨力等, 2010; Wang *et al.*, 2013a; Li *et al.*, 2015a)。

宽坪群是北秦岭造山带内最北部的构造单元,其主要岩性为变质的基性火山岩、陆源碎屑岩和大理岩(杨经绥等, 2003; Dong *et al.*, 2008; Liu *et al.*, 2013; Li *et al.*, 2015b)。其中碎屑岩的物源主要来自于秦岭群,其次来源于华北陆块(陆松年等, 2009; Zhu *et al.*, 2011; Shi *et al.*, 2013; Zhao *et al.*, 2015)。前人对于宽坪群的属性尚存在不同认识,认为其(1)属于华北陆块南部的被动陆缘沉积(Meng and Zhang, 2000; Dong *et al.*, 2011b; Wang *et al.*, 2013b; Wu and Zheng, 2013);(2)形成于秦岭群北部的弧后盆地(张宗清和张旗, 1995; Dong *et al.*, 2008; 陆松年等, 2009);(3)并非是一个单一的地层单元,而是由多个构造岩片拼贴而成,应解体为沉积地层和大洋洋壳两个构造单元(张寿广等, 1991; 第五春荣等, 2010);(4)是新元古代-早古生代期间形成的一个俯冲-增生杂岩或增生楔(Zheng *et al.*, 2005; Liu *et al.*, 2013)。此外,宽坪群内获得了442~415Ma的锆石U-Pb变质年龄和角闪石$^{40}Ar/^{39}Ar$变质年龄(Zhai *et al.*, 1998; Liu *et al.*, 2011b)及348~319Ma的云母$^{40}Ar/^{39}Ar$变质年龄(Mattauer *et al.*, 1985;闫全人等,2008),说明宽坪群在志留纪和石炭纪期间都经历了重要的变质事件。

二郎坪群夹于宽坪群和秦岭群之间,北部以官坡-乔端剪切带与宽坪群相隔,南部以朱阳关-夏馆剪切带与秦岭群相连(Liu *et al.*, 2013; Wang *et al.*, 2013b;图1)。二郎坪群主要包括超基性岩、基性-中性火山岩(如辉长岩、块状或枕状玄武岩、层状岩墙)、高级变质杂岩、放射虫燧石、大理岩和细粒碎屑岩(变沉积岩组合)等(Xue *et al.*, 1996; Meng and Zhang, 2000; Dong *et al.*, 2008; Wang *et al.*, 2013a; Li *et al.*, 2015b)。先前的研究认为二郎坪群形成于洋内岛弧环境(Xue *et al.*, 1996; Ratschbacher *et al.*, 2003, 2006),或弧后盆地环境(Kröner *et al.*, 1993; Meng and Zhang, 2000; 张国伟等, 2001; Dong *et al.*, 2011b),最近的研究则认为二郎坪群是早古生代期间商丹洋向北俯冲形成的岛弧-弧后盆地体系(Liu *et al.*, 2011b, 2013)。二郎坪群变质岩的原岩主要形成于早古生代(490~470Ma)(Xue *et al.*, 1996; Chen *et al.*, 2006; Liu *et al.*, 2013),变质年龄主要为440~359Ma的锆石U-Pb年龄、角闪石$^{40}Ar/^{39}Ar$年龄及Rb-Sr全岩等时线年龄(孙卫东等, 1996; Zhai *et al.*, 1998; Sun *et al.*, 2002; Liu *et al.*, 2011b),说明二郎坪群在志留纪-泥盆纪之间也发生了变质事件。

秦岭群位于北秦岭造山带的最南部,主要由花岗质片麻岩、榴辉岩、麻粒岩、角闪岩、大理岩及变泥质岩等组成(Kröner *et al.*, 1993; Zhai *et al.*, 1998; Dong *et al.*, 2008; Wang *et al.*, 2013a; Li *et al.*, 2015b)。目前秦岭群的属性还存在争论,认为其(1)是从扬子克拉通上裂离出来的前寒武纪微陆块(Liu *et al.*, 2013; Zhang *et al.*, 2015);(2)新元古代-早古生代期间属于华北陆块的南缘(Meng and Zhang, 1999, 2000);(3)是位于华北陆块南缘大洋内岛弧基础上形成的独立微陆块(Dong *et al.*, 2011a;Yu *et al.*, 2015; Zhao *et al.*, 2015)。秦岭群被早古生代的变形和变质作用强烈改造(Yang *et al.*, 2003; Chen *et al.*, 2004; 刘良等, 2009),目前已经获得了榴辉岩、麻粒岩、片麻岩、角闪岩及岩石内部脉体等多种类型的变质岩年龄,且变质年龄跨度较大,大致位于520~310Ma之间(Zhai *et al.*, 1998; Yang *et al.*, 2003; Dong *et al.*, 2011b; Liu *et al.*, 2011b; Wang *et al.*, 2011a; 刘良等, 2013)。这说明秦岭群自寒武纪开始经历了强烈的变质作用,并在志留纪-石炭纪期间发生了多期变质事件。

3 早古生代变形特征

前人根据详细的野外构造解析和显微构造分析,在北秦岭造山带及其邻区识别出三幕褶皱变形,其中前两幕变形(D_1-D_2)均形成于早古生代(约440~400Ma),是区域性的构造事件,在北秦岭造山带内的宽坪群、二郎坪群、秦岭群以及华北陆块南缘均有广泛的出露(Zhao *et al.*, 2015)。尽管前期变形受到了后期变形的强烈改造,但由于这三幕变形都是在相同方向的挤压应力下形成的,前期变形的整体构造样式并没有太大变化(Zhao *et al.*, 2015),因此,第一幕变形仍可反映华北陆块与北秦岭微陆块碰撞后的初始折返过程。大量的野外观测数据表明,第一幕变形形成了区域性的透入性片理、片麻理及糜棱面理(S_1),产状分布指示其主体倾向北北东和南南西两个方向(图2),指示了近北北东-南南西方向的俯冲。

从横跨整个北秦岭造山带及其邻区的地质剖面图(图2)中可以看出,除了三幕褶皱变形,研究区还存在大量断裂带。北秦岭造山带内的四条主要断裂带中,除了商丹断裂倾向北东,洛南-栾川、官坡-乔端和朱阳关-夏馆断裂均主体倾向南西,结合S_1面理产状的分布情况,可能指示了华北陆块向南俯冲到北秦岭微陆块之下(Zhao *et al.*, 2015)。

4 主要韧性剪切带特征

作为北秦岭造山带的重要构造边界,洛南-栾川、官坡-乔端、朱阳关-夏馆及商丹断裂带除了具有逆断层性质,还具有明显的走滑分量(图2、图3、图4)。然而其详细的运动学特征仍不清楚,其构造-热演化历史还没有得到很好的约束。

4.1 主要韧性剪切带的构造特征

洛南-栾川剪切带是北秦岭微陆块和华北陆块南缘的分界线,西起洛南,向东经卢氏、栾川、南召、方城一带,被南阳盆地覆盖,在桐柏造山带地区再次出露(称为油房庄韧性剪

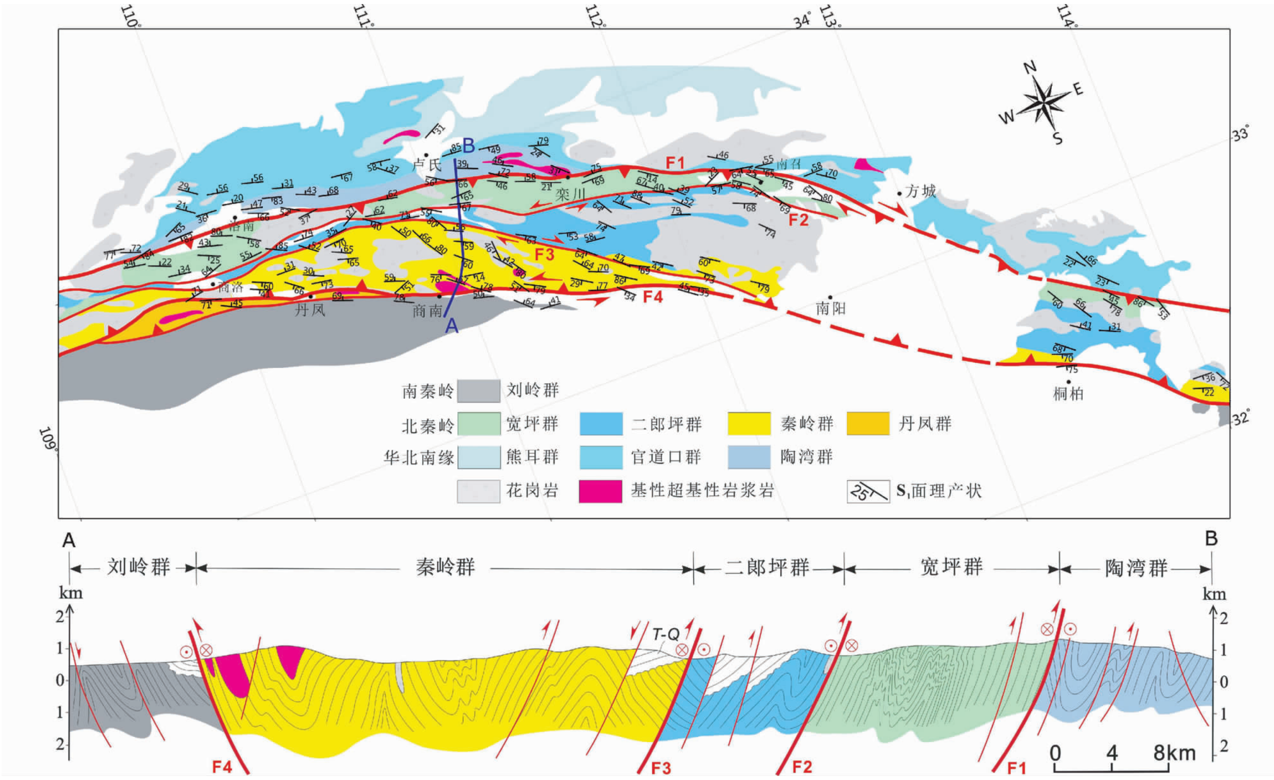

图2 北秦岭造山带及其邻区 S_1 面理分布图及地质剖面图(A-B)

Fig. 2 Distribution of S_1 foliations and a geological cross-section (A-B) of the North Qinling orogenic belt and its neighbors

切带)(刘鑫等, 2010)。该剪切带整体上呈北西西-南东东走向,带内主要发育有韧性剪切和逆冲推覆两种变形,逆冲推覆的发育时间晚较,切穿了早期的韧性剪切带(宋传中等, 2009a, b; 任升莲等, 2010),野外露头上发育的书斜式构造指示该剪切带具有明显的右行走滑特征(图3a;Zhao *et al.*, 2015)。断裂晚期主要表现为自南向北的逆冲推覆,且产状陡立(图3b)。此外,采自断裂带内的黑云长英质糜棱岩构造定向样品(QL28)的镜下切片可见石英和云母定向排列,石英呈矩形、带状分布,且波状消光明显,局部石英发生亚颗粒化,边界呈缝合带状,这些特征均指示了韧性变形的存在(图4a)。其中石英颗粒组成的S-C组构,也指示了明显的右行剪切变形特征(图4a)。

官坡-乔端剪切带也称为瓦穴子-乔端-方城断裂(涂文传等, 2013),是宽坪群和二郎坪群的分界线。该剪切带主体上也呈北西西-南东东走向延伸,向西延伸至陕西省商州市,向东延伸被南阳盆地覆盖,在桐柏造山带地区的对应断裂称为小董庄韧性剪切带(刘鑫等, 2010)。先前的研究认为该剪切带是一条具有俯冲带特征的大型糜棱岩带(李亚林等, 1998)。野外的面理特征表现为Q/M带,说明主面理为完全置换的 S_2 面理,而不是早期的 S_1 片理,其中的S-C组构指示了该剪切带的左行走滑特征(图3c),说明该幕走滑变形发生在区域性第二幕褶皱作用之后。在剪切带北部的宽坪群内采集了斜长角闪质糜棱岩构造定向样品(QL34),该点野外露头可见长石"σ"型残斑(图3d),指示自南向北的逆冲推覆。镜下切片显示石英和云母强烈定向,石英波状消光明显,局部S-C组构指示宽坪群内部局部也表现为左行剪切运动特征(图4b)。

朱阳关-夏馆剪切带位于北秦岭造山带中部,是二郎坪群和秦岭群的分界线,其产状变化较大,在西部为近东西走向,在东部则为北西走向,其在桐柏造山带地区的对应断裂称为好汉坡韧性剪切带(刘鑫等, 2010)。朱阳关-夏馆剪切带是一条由韧性、韧-脆性、脆性变形共同组成并伴随走滑性质的大型构造带(张欢等, 2012),前人认为该剪切带主要表现为右行走滑特征(Wang *et al.*, 2005)。野外露头上的斜长角闪质糜棱岩中的"σ"型长石残斑指示自南向北的逆冲推覆(图3e)。同点采集的花岗质糜棱岩构造定向样品(QL87)在正交偏光镜下韧性变形非常明显,呈条带状定向分布的石英显示出明显的波状消光特征,局部亚颗粒化明显(图4c),总体上Q/M带显著,且长石主要呈碎斑状和眼球状,大多为"σ"型,部分斜长石发生破裂,形成书斜构造(图4c),指示该剪切带于区域第二幕变形之后经历了右行剪切作用。

商丹剪切带整体上呈北西西-南东东向展布,经过丹凤、商南、西峡、商州等地区,向东跨过南阳盆地,在桐柏造山带地区的延伸为松扒韧性剪切带(刘鑫等, 2010)。商丹断裂带主体表现为自北向南的逆冲作用,同时兼有左行走滑分量(Wang *et al.*, 2005; 涂文传等, 2012)。野外露头上具Q/M

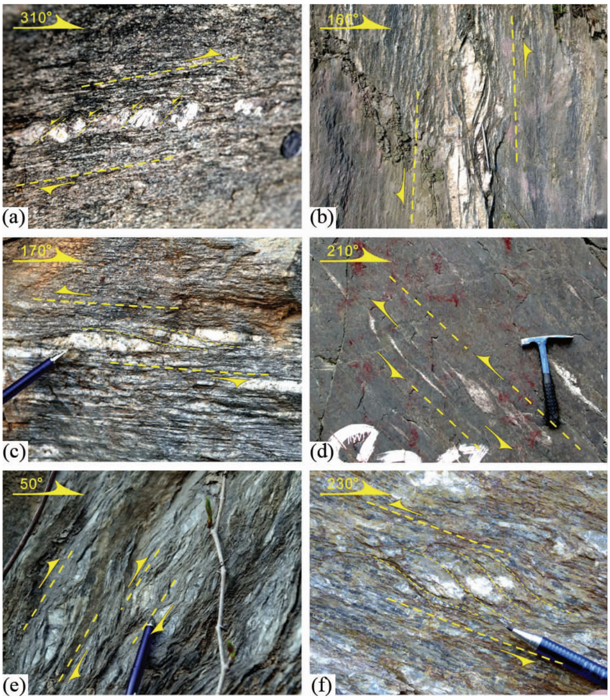

图3 北秦岭造山带主要剪切带宏观韧性变形特征

(a)发育在洛南-栾川断裂中的书斜构造,GPS: 33°33.001′N, 112°28.211′E;(b)发育在洛南-栾川剪切带中的S-C组构,GPS: 34°04.499′N, 109°39.542′E;(c)发育在官坡-乔端剪切带中的S-C组构,GPS: 33°37.473′N, 111°58.913′E;(d)发育在宽坪群内的S-C组构,GPS: 33°27.573′N, 112°28.334′E;(e)发育在朱阳关-夏馆剪切带中的σ型碎斑,GPS: 33°29.506′N, 111°34.818′E;(f)发育在商丹剪切带中的S-C组构,GPS: 33°32.051′N, 111°04.633′E. 铅笔长14cm,地质锤长31cm

Fig. 3 Ductile deformation and macrostructures of the main shear zones in the North Qinling orogenic belt

(a) bookshelf structure in the Luonan-Luanchuan shear zone; (b) S-C fabric in the Luonan-Luanchuan shear zone; (c) S-C fabric in the Guanpo-Qiaoduan shear zone; (d) S-C fabric in the Kuanping Group; (e) sigmoidal fabric in the Zhuyangguan-Xiaguan shear zone; (f) S-C fabric in the Shangdan shear zone. Pencil is 14cm long, the length of the geological hammer is 31cm

带特征的 S_2 面理被彻底置换,平行Q/M带可见"σ"型长石残斑及S-C组构,指示了区域性第二幕变形之后的左行剪切运动(图3f)。采自断裂带内的斜长角闪质糜棱岩构造定向样品(QL14)在正交偏光镜下表现为明显的石英波状消光,同时可见斜长石和角闪石变斑晶呈"σ"型(图4d),这些镜下特征均指示左行剪切运动。

4.2 主要韧性剪切带的石英EBSD组构特征

本研究在中国地质大学(北京)岩石组构实验室,对4个构造定向样品,进行了石英的EBSD组构测试分析,获得了糜棱岩中石英晶体的结晶学信息(刘俊来等,2008),可根据石英组构特征与滑移系和变形温度之间的对应关系(许志琴等,2006, 2009)推测各韧性剪切带的形成环境。

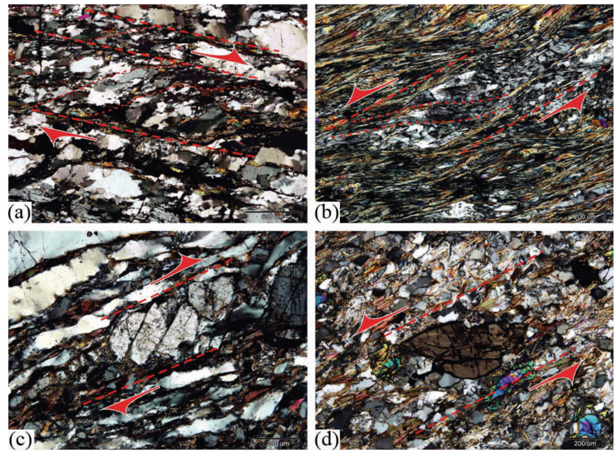

图4 北秦岭造山带主要剪切带显微韧性变形特征

(a)洛南-栾川剪切带中的S-C组构,GPS: 33°28.086′N, 112°36.199′E;(b)宽坪群内的S-C组构,GPS: 33°27.573′N, 112°28.334′E;(c)朱阳关-夏馆剪切带中的书斜构造,GPS: 33°29.504′N, 111°34.791′E;(d)商丹剪切带中的σ型残斑系,GPS: 32°25.684′N, 113°24.965′E

Fig. 4 Ductile deformations and microstructures of the main shear zones in the North Qinling orogenic belt

(a) S-C fabric in the Luonan-Luanchuan shear zone; (b) S-C fabric in the Kuanping Group; (c) plagioclase with bookshelf structure in the Zhuyangguan-Xiaguan shear zone; (d) sigmoidal type porphyroclast system in the Shangdan shear zone

洛南-栾川剪切带内的QL28样品,在薄片内均匀标定了146个石英晶体颗粒。分析结果(图5a)表明,石英c轴优选方位主要包括两个主极密和两个次极密,为底面<a>滑移系,指示该样品形成于低温环境下(小于400℃)。这说明洛南—栾川剪切带在该点处变形温度较低,这与前人的研究结果一致(任升莲等, 2013)。

官坡-乔端剪切带北部的宽坪群内采集的QL34样品,在薄片内均匀标定了209个石英晶体颗粒,该点处的石英c轴优选方位非常复杂,包括四个主极密和两个次极密(图5b)。位于大圆环上的两个主极密和两个次极密与 Z_0 轴和 X_0 轴之间的两个主极密共同组成了不完整的交叉环带,代表了底面<a>滑移系,指示该点处的韧性变形发生于较低温度下(小于400℃)。

朱阳关-夏馆剪切带内的QL87样品,在薄片内均匀标定了206个石英晶体颗粒,该点处的石英c轴优选方位仅包括一个简单的主极密,该主极密位于 Z_0 轴和 X_0 轴之间(图5c),代表了菱面<a>滑移系,表明其形成于中温的条件下(约400~550℃)。这与张欢等(2012)获得的该断裂形成于中温-中低压条件下的结果吻合。

商丹剪切带内的QL14样品,在薄片内均匀标定了210个石英晶体颗粒,该点处的石英c轴优选方位包括一个主极密和四个次极密(图5d)。其中位于大圆环上的四个次极密

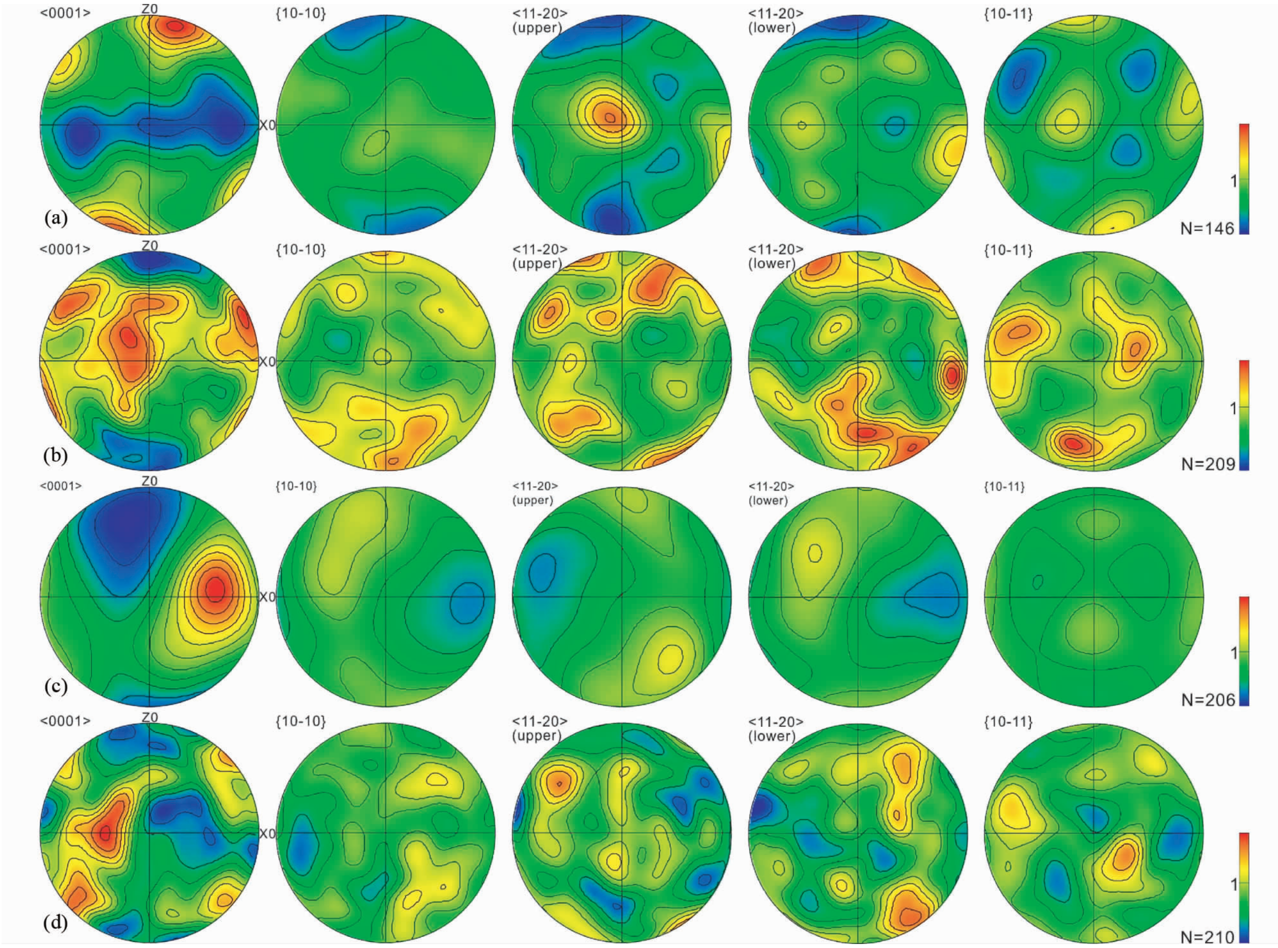

图 5 北秦岭造山带主要韧性剪切带变形岩石石英 EBSD 组构图(样品位置见图 1)

(a)样品 QL28 采自洛南-栾川剪切带;(b)样品 QL34 采自宽坪群;(c)样品 QL87 采自朱阳关-夏馆剪切带;(d)样品 QL14 采自商丹剪切带中

Fig. 5 Stereographic projections (lower hemisphere equal area) of quartz crystal preferred orientations of deformed rocks from the main ductile shear zones in the North Qinling orogenic belt determined by EBSD (locations of these samples are shown in Fig. 1)

(a) Sample QL28 from the Luonan-Luanchuan shear zone; (b) Sample QL34 from the Kuanping Group; (c) Sample QL87 from the Zhuyangguan-Xiaguan shear zone; (d) Sample QL14 from the Shangdan shear zone

和 Z_0 轴与 X_0 轴之间的一个主极密共同组成了不完整的交叉环带,代表了底面 < a > 滑移系,表明其形成于低温条件下(小于 400℃)。这说明商丹剪切带的左行走滑也发生于低温环境下。

5 讨论

5.1 剪切带活动时间

目前对于洛南-栾川剪切带的具体形成时间仍存在较大争议。部分学者认为该剪切带形成于新元古代北秦岭微陆块与华北陆块南缘的碰撞过程中(Dong *et al.*, 2014),另有学者则认为该碰撞事件发生在早古生代(Liu *et al.*, 2013; Zhao *et al.*, 2015)。前人在洛南-栾川剪切带中的糜棱岩和糜棱状片麻岩中获得的白云母和黑云母的 $^{40}Ar/^{39}Ar$ 年龄,说明该剪切带在 ~372Ma 时发生了强烈的变形变质作用(Song *et al.*, 2009)。由于洛南-栾川剪切带是伴随着华北陆块向北秦岭微陆块下俯冲而形成的,云母的 $^{40}Ar/^{39}Ar$ 年龄则可能记录的是俯冲板片折返至较浅深度时的冷却年龄(Dong *et al.*, 2011c),因而洛南-栾川剪切带在更深位置的起始活动时间应早于 ~372Ma。考虑到华北陆块与北秦岭微陆块在约 440 ~ 400Ma 的碰撞-折返过程(Zhao *et al.*, 2015),该剪切带走滑活动的起始时间可能为早古生代。官坡-乔端和朱阳关-夏馆剪切带目前还没有获得准确的韧性剪切活动时间,由于这两条剪切带都是伴随着华北陆块与北秦岭微陆块拼合过程中二郎坪弧后盆地的闭合而形成的(张欢等, 2012),其很可能与洛南-栾川剪切带是同时活动的。前人认为商丹剪切带的左行走滑运动大致发生于 323 ~ 314Ma(裴先治等, 1995),石英 EBSD 组构结果表明该期运动形成于低温条件下(图 5d)。而在 QL14 附近采集的另一个糜棱岩样品则指示商丹剪切带在中温条件下(约 400 ~ 550℃)表现为右行剪

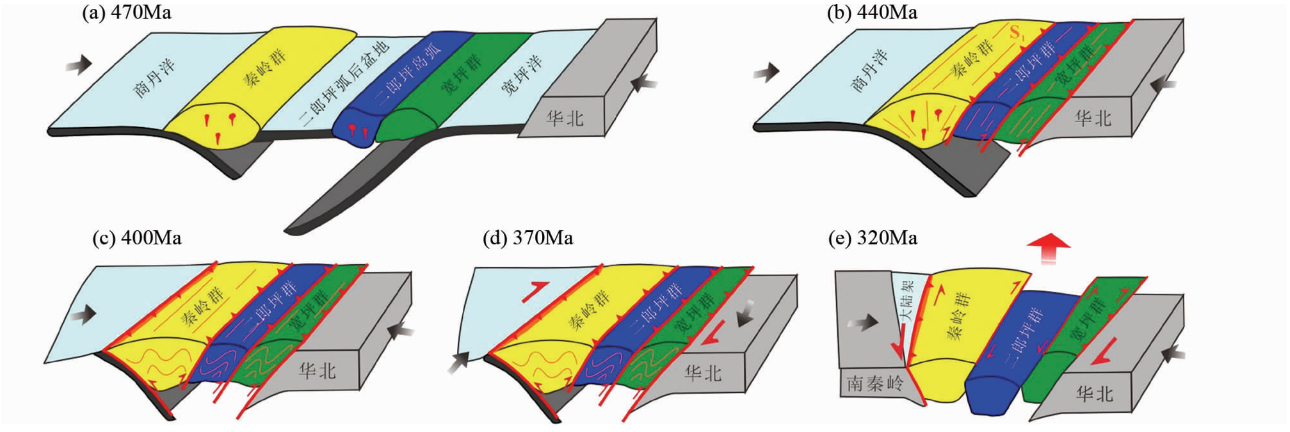

图 6 北秦岭造山带古生代构造演化模式图(详情请见正文描述)

Fig. 6 Schematic cartoons demonstrating the tectonic evolution of the North Qinling orogenic belt during the Paleozoic (see text for details)

切活动(Liu *et al.*, 2012)。因此,本文推断商丹剪切带至少具有两期活动,早期在较深部表现为右行剪切,晚期折返至较浅深度时转换为左行剪切。

5.2 原特提斯洋及其后续演化过程

原特提斯洋是新元古代-早古生代期间存在于冈瓦纳大陆北缘的一个横贯东西的大洋(Chang *et al.*, 1989; Mattern and Schneider, 2000; Stampfli, 2000),其构造演化过程与 Rodinia 超大陆的裂解和 Pangea 超大陆最终聚合前的演化历史密切相关(von Raumer and Stampfli, 2008)。其中,原特提斯洋北部边界的东段(又称为宽坪洋)涉及到华北与华南两个主要陆块的拼合过程。宽坪洋至少自 ~510Ma 已经开始向北秦岭微陆块下俯冲,在俯冲过程中形成了二郎坪弧后盆地(图 6a),该持续俯冲导致华北陆块与北秦岭微陆块最终在 ~440Ma 拼合(图 6b),并在华北陆块与北秦岭微陆块之间的俯冲-碰撞-折返过程中形成了第一幕和第二幕褶皱变形(图 6b, c)。宽坪洋闭合后的主缝合线为洛南-栾川剪切带,该事件也指示了原特提斯洋北界东段在早古生代的闭合(Liu *et al.*, 2013; Zhao *et al.*, 2015)。同时,全球陆块/微陆块在约 420 ~400Ma 聚合,东亚各陆块/微陆块拼贴至冈瓦纳北缘,在全球新形成一个超大陆,称为 Carolina 超大陆(李三忠等, 2016a, b, c, d)。

古地磁数据表明,寒武纪-奥陶纪期间,华北陆块与华南陆块均位于南半球中低纬度(黄宝春等, 2000),二者在纬向上呈近东西向展布(图 7a)。之后,华北陆块越过赤道持续向北漂移,华南陆块则相对向南漂移,到石炭纪时,华北陆块东、西部古纬度分别为 9.5°N 和 10.6°N,而华南陆块东、西部古纬度分别为 8.2°S 和 13.4°S(翟永建和周姚秀, 1989),二者在纬向上呈南北向展布(图 7b)。

~380Ma 之后,勉略洋和古特提斯洋开始打开,华北、华南、印支等陆块裂离冈瓦纳北缘,沿转换断层向北方的劳俄大陆南缘聚合(李三忠等, 2016e)。在此过程中,华北陆块与大华南陆块逐渐由近东西向展布向近南北向展布转换(图 7a),同时,由于各陆块间存在相对位移,在华北陆块与南秦岭微陆块间形成右行剪切活动,导致洛南-栾川缝合带和商丹缝合带在此时表现为明显的右行走滑运动(图 6d、图 7a)。北祁连和柴达木地块早古生代褶皱带形成晚泥盆世磨拉石沉积,并与下伏地层呈角度不整合接触(许志琴等, 2007),标志着弯山构造此时已经形成(李三忠等,2016c)。

随着东亚各陆块/微陆块整体向北漂移, ~320Ma 时华北陆块与大华南陆块已经逐渐调整为近南北向关系(图 7b)。大华南陆块向南秦岭微陆块下俯冲,导致勉略洋开始缩减-闭合。同时,华北陆块向东楔入到大华南陆块之下,导致华北与南秦岭微陆块呈东早西晚的剪刀式拼合,在此过程中,北秦岭微陆块向西挤出,导致主缝合带洛南-栾川剪切带和商丹剪切带分别表现为右行和左行走滑运动(图 3、图 4、图 6e、图 7b)。北秦岭微陆块内的次级断裂带——官坡-乔端和朱阳关-夏馆剪切带则在整体格局下进行调整,分别表现为左行和右行走滑特征(图 3、图 4、图 6e)。

6 结论

围绕 Pangea 聚合过程中原特提斯洋-陆格局与陆块/微陆块早古生代聚合这一核心科学问题,本文以北秦岭造山带内的四条主要韧性剪切带为重点研究对象,采用野外构造解析、显微构造分析和石英 EBSD 组构分析等手段,得出以下几点新认识:

(1)华北陆块与北秦岭微陆块在 ~440Ma 拼合,导致宽坪洋和二郎坪弧后盆地闭合,在此过程形成了洛南-栾川、官坡-乔端和朱阳关-夏馆剪切带,这些剪切带的初始活动时间可能为早古生代。

(2)洛南-栾川剪切带主体表现为较低温度环境下(小于 400℃)的右行走滑,官坡-乔端剪切带表现为较低温度环境

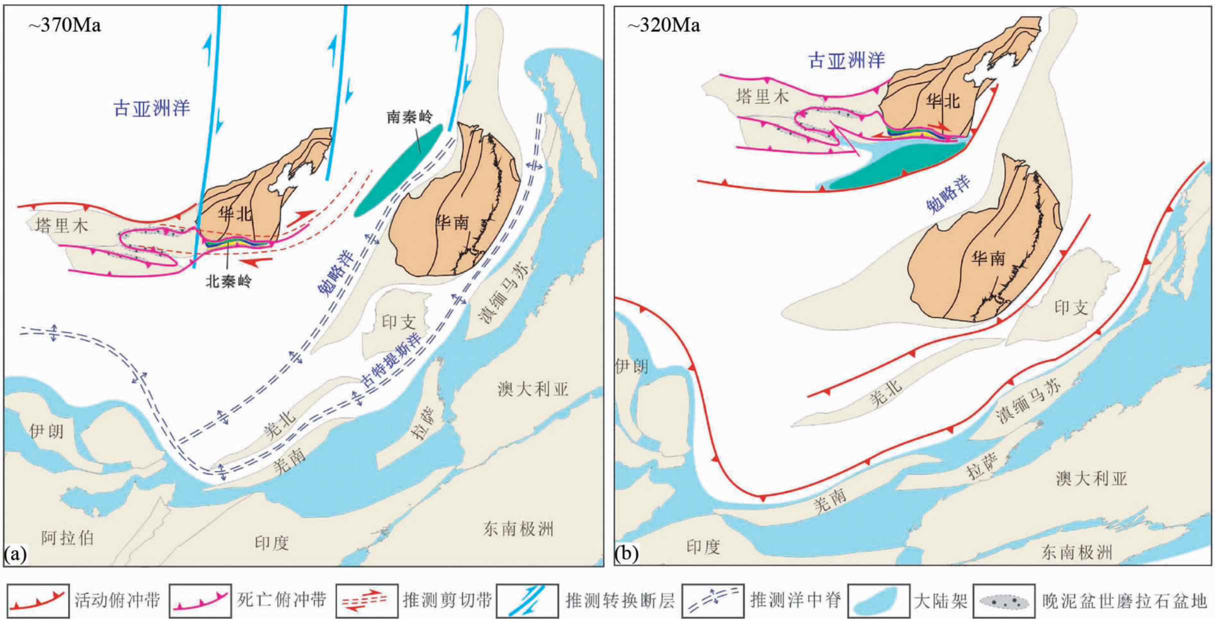

图7 东亚陆块/微陆块晚古生代拼合过程

(a)勉略洋和古特提斯洋打开,多陆块沿转换断层向北运动,在华北陆块与大华南陆块间形成右行剪切活动;(b)华北陆块与南秦岭微陆块呈东早西晚的剪刀式拼合,导致北秦岭微陆块向西挤出,洛南-栾川和商丹剪切带分别表现为右行和左行走滑运动

Fig. 7 Late Paleozoic assembly processes of continental/micro-continental blocks in East Asia

(a) the Mianlue Ocean and the Paleo-Tethys Ocean opened, and some blocks drifted northward along transform faults, which generated the dextral shearing between the North China and the Great South China blocks; (b) the scissors-type closure between the North China Block and the South Qinling micro-continental block led to the westward extrusion of the North Qinling micro-continental block, the dextral shearing of the Luonan-Luanchuan fault and the sinistral shearing of the Shangdan fault

下的左行走滑,朱阳关-夏馆剪切带表现为中温环境下(约400~550℃)的右行走滑,商丹剪切带早期表现为中温环境下的右行走滑,晚期表现为较低温度环境下的左行走滑。

(3)~380Ma之后,勉略洋和古特提斯洋打开,导致华北、华南陆块在向北漂移过程中逐渐由近东西向展布转换为近南北向展布,华北陆块与南秦岭微陆块在~320Ma时已经开始进行剪刀式拼合。

致谢 近5年来,我们主要集中研究原特提斯洋的演化,本文主要介绍了对北秦岭造山带内四条主要韧性剪切带初步认识,供专家批评指正。感谢刘永江教授和两位匿名审稿专家对本文提出的宝贵意见。同时,谨以此文祝贺杨振升教授85华诞。

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