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# 东秦岭东段五垛山花岗伟晶岩锆石U-Pb年代学和微量元素特征及地质意义

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**摘要:**东秦岭东段五垛山大型花岗岩基中花岗伟晶岩丰富,关于它的形成时代、岩石成因和地球动力学背景仍不清楚.LA-ICP-MS锆石U-Pb同位素定年结果显示五垛山花岗伟晶岩的年龄可分为3组:417.4±2.5 Ma,这组为花岗伟晶岩的结晶年龄,与东秦岭造山带花岗伟晶岩的形成时代相一致;429.5±2.1 Ma和450.9±3.3 Ma,这两组与五垛山花岗岩基的年龄相一致,为花岗伟晶岩脉捕获围岩锆石的年龄.花岗伟晶岩中417.4 Ma、429.5 Ma和450.9 Ma这3组锆石的 $\epsilon_{\text{Hf}}(t)$ 值分别为-5.6~-1.9、-8.7~-1.3和-5.3~-3.4,与秦岭岩群部分熔融形成岩浆岩的Hf同位素值近似.以上显示,五垛山花岗伟晶岩可能来自于秦岭岩群的部分熔融.早泥盆世,东秦岭处于原特提斯后碰撞阶段,后碰撞阶段的拉张作用使地幔减压部分熔融形成镁铁质岩浆,这些镁铁质岩浆底侵下地壳变质基底,使其部分熔融形成花岗伟晶岩的原生岩浆,这些岩浆沿着后碰撞拉张作用形成的通道上侵形成了五垛山花岗伟晶岩脉.

**关键词:**东秦岭;花岗伟晶岩;锆石LA-ICP-MS定年;微量元素;岩石学.

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## Zircon U-Pb Geochronology and Trace Element Characteristics of Wuduoshan Granitic Pegmatite in Eastern Part of East Qinling and Its Geological Significance

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**Abstract:** The granitic pegmatite exposed in Wuduoshan granitic pluton occurs extensively in volume. However, its formation time, petrogenesis and geodynamic background are still unclear. LA-ICP-MS zircon U-Pb dating shows that the zircon U-Pb ages from the granitic pegmatite are  $417.4 \pm 2.5$ ,  $429.5 \pm 2.1$  and  $450.9 \pm 3.3$  Ma, respectively, the first of which represents the crystallization age of granitic pegmatite and the other is consistent with the age of Wuduoshan granite batholith, representing the captured zircons from the surrounding rocks of granitic pegmatite veins. The  $\epsilon_{\text{Hf}}(t)$  values of granitic pegmatite are  $-5.6$  to  $-1.9$ ,  $-8.7$  to  $-1.3$ , and  $-5.3$  to  $-3.4$ , respectively, which are similar to the Hf isotopic values of magmatic rocks derived from partial melting of metasedimentary rocks of the Qinling Group. Together with the regional data, it is suggested that the East Qinling was in the post-collision stage relevant to the proto-Tethys Ocean in the Early Devonian, and it underwent extensional setting and resulting the decompression melting of mantle and generation of mafic magma. The rising high-temperature magma further underplated and heated the lower crust and induced the partial melting of metamorphic basement of the lower crust, ultimately generating the granitic pegmatites along the magmatic conduits which formed in a postcollision-related extensional setting.

**Key words:** East Qinling; granitic pegmatite; zircon LA-ICP-MS dating; trace elements; petrology.

稀有金属由于其独特的材料性能,在新兴产业具有广泛用途。据预测,随着科技和新兴产业的发展,未来几十年全球对关键金属的需求将迅速增加,供给矛盾日益突出(毛景文等,2019;翟明国等,2019)。伟晶岩是赋存稀有金属矿产的重要岩石类型之一,花岗伟晶岩提供了全世界四分之一的Li,十分之一的Be,大量的Ta和几乎全部的Cs(Bradley *et al.*, 2017)。因此,花岗伟晶岩一直是研究的热点(Černý *et al.*, 2012; Linnen *et al.*, 2012; London, 2018)。

东秦岭造山带花岗伟晶岩丰富,是我国三大伟晶岩分布区之一,其中以峦庄、官坡、龙泉坪和商南地区最为密集(卢欣祥等,2010;秦克章等,2019)。这些伟晶岩脉多与三稀矿产关系密切,特别是铀矿最为富集(Yuan *et al.*, 2020; Zhou *et al.*, 2021)。东秦岭中段花岗伟晶岩脉由于其富矿性,研究程度较高。结果显示,东秦岭中段花岗伟晶岩形成的峰值年龄为413 Ma,成矿元素的富集多与花岗伟晶岩母岩浆的分离结晶和围岩同化混染相关(Yuan *et al.*, 2018a, 2018b; Chen *et al.*, 2019)。笔者近年通过对东秦岭造山带东段南阳北部五垛山花岗岩基进行研究发现,在这一带也出露有大量花岗伟晶岩脉。与东秦岭造山带中段花岗伟晶岩主体侵位于基底变质岩系不同,这些花岗伟晶岩脉多侵位于五垛山花岗岩基。五垛山花岗岩基为一大型复式花岗岩基,岩石类型丰富。早期学者主要对五垛山花岗岩基进行了年代学和岩石地球化学研究。结果显示,

五垛山花岗岩基形成时代跨度较大,主体介于415~451 Ma(赖亚等,2017;易志强等,2017;李开文等,2019)。由于岩基形成时代的长期性,其构造环境也较为复杂,有俯冲、洋陆转换和后碰撞不同观点(雷敏,2010;刘丙祥,2013;李开文等,2019)。岩基中不同类型岩石具弧岩浆岩特征,其成因也较为复杂,主要包括古老地壳的部分熔融(刘丙祥,2013;李开文等,2019)和加厚下地壳物质部分熔融(周澍等,2019)两种观点。五垛山花岗岩基中的伟晶岩脉还处于初级研究阶段,主要为花岗伟晶岩的矿物组成研究,对伟晶岩脉的形成时代和岩石成因还未有涉及;特别是花岗伟晶岩侵位于花岗岩基,花岗伟晶岩与岩基的成因联系还未有研究。因此,五垛山花岗伟晶岩的研究对于扩展东秦岭早古生代花岗伟晶岩带的东延以及揭示伟晶岩与其伴生花岗岩的联系具有重要意义。

锆石作为副矿物广泛存在于岩浆岩,因其抗风化能力强,高U、Th含量及U-Th-Pb体系封闭温度高等特征而被广泛用于放射性同位素定年(吴元保和郑永飞等,2004;杨亚楠等,2014)。近年来,随着研究的深入,锆石中的微量元素被用来研究岩浆形成的物理化学环境(Watson *et al.*, 2006; Trail *et al.*, 2012)、岩浆演化过程(Yan *et al.*, 2018, 2020)和岩石成因(赵志丹等,2018;邹心宇等,2021),锆石的Hf-O同位素也可以示踪岩浆源区特征与地壳再循环等地质过程(Kemp *et al.*, 2006)。

因此,本文通过对东秦岭造山带东段五垛山花

对五垛山花岗伟晶岩脉进行锆石U-Pb年代学和微量元素的分析，并结合前人研究资料，拟限定五垛山花岗伟晶岩脉形成时代，揭示伟晶岩的岩石成因及其与花岗岩的联系，进而探讨东秦岭造山带早古生代花岗伟晶岩脉形成的地球动力学背景。

## 1 地质背景

秦岭造山带是经历长期多次不同造山作用形成的复合型大陆造山带，位于华北板块南缘，华南板块北部（图1），是我国中央造山系的重要组成部分（张国伟等，1995；Dong *et al.*, 2017；任纪舜等，2019；赵利刚等，2019）。以商南—丹凤断裂和勉略—巴山—襄广断裂为界，从北到南秦岭造山带可以划分为北秦岭构造带、南秦岭构造带和扬子板块北缘

构造带（许志琴等，2015；Li *et al.*, 2018）。北秦岭构造带由于受到多期次造山旋回作用，岩浆、沉积和构造复杂。从北向南，北秦岭构造带依次出露宽坪群、二郎坪群、秦岭群和丹凤群。宽坪群为一套中—低级变质岩系，主要由广东坪岩组斜长角闪岩、四岔口岩组云母石英片岩及谢湾岩组的大理岩组成，近年来经过碎屑锆石研究显示，宽坪群的碎屑锆石年龄为400~3 598 Ma，显示其由不同时代的地层和岩片构成（李承东等，2018）。二郎坪群为一套弧后火山—沉积岩系，主体形成于早古生代，自北向南可以划分为柿树园组、火神庙组、大庙组、二进沟组、小寨组和抱树坪组（杨士杰等，2015；李振强等，2021）。古元古代秦岭群作为秦岭造山带古老结晶基底，为一套多期变质变形改造的麻粒岩相一角闪岩

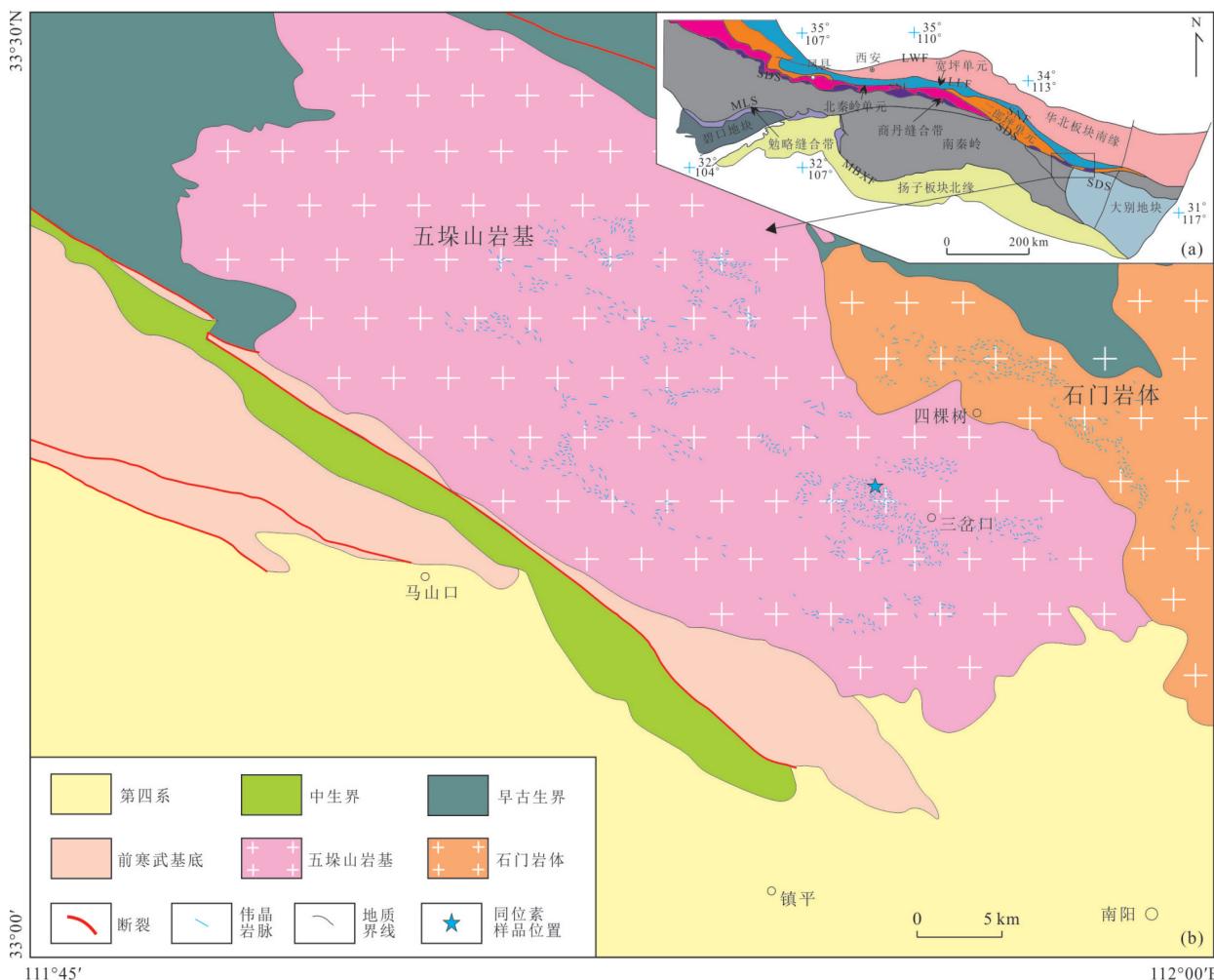


图1 秦岭造山带大地构造背景图(a),东秦岭东段五垛山一带地质简图(b)

Fig. 1 Simplified tectonic map of the Qinling orogenic belt showing the tectonic divisions (a), simplified geological map of Wuduoshan area in eastern section of the East Qinling (b)

图a修改自 Dong *et al.* (2011). LWF. 灵宝—鲁山—舞阳断裂; LLF. 洛南—栾川断裂; SNF. 商州—南召断裂; SDS. 商丹缝合带; MLS. 勉略缝合带; MBXF. 勉略—巴山—襄广逆冲断裂; TLF. 郑庐断裂

相变质岩系,上部主要由陆源碎屑岩夹杂基性火山岩组成,下部为石英片岩、片麻岩、斜长角闪岩和钙硅酸岩为主的中深变质杂岩系(张宗清等,1996; Cao *et al.*, 2017).丹凤群呈狭长透镜状断续续沿着商丹断裂带北侧展布,以斜长角闪岩和变钙碱性火山岩为主的一套绿片岩相至低角闪岩相的变质火山—沉积岩系(张国伟等,2001).

东秦岭造山带岩浆活动丰富,从新元古代—三叠纪皆有分布,主要集中在加里东期和印支期,岩石类型主要包括花岗岩类和镁铁质侵入岩(张成立等,2013;王晓霞等,2015;吴元保,2019).东秦岭大量出露的花岗伟晶岩脉多属于加里东期岩浆活动(卢欣祥等,2010).

五垛山大型花岗岩基是东秦岭造山带的重要组成部分,位于北秦岭构造带东部的内乡—南召—镇平—南阳一带,总体呈北西—南东向展布,与区域构造线方向一致,由牧虎顶、摸云垛、五垛山、黄龙庙、四棵树及寺庄等岩体组成的复式岩体,出露面积约 $1420\text{ km}^2$ (图1b).岩基北部侵入下古生界二郎坪群和早古生代板山坪岩体,南部侵入古元古界秦岭岩群,西部侵入下古生界二郎坪群,东侧侵入

石门岩体,主要由花岗闪长岩和黑云母二长花岗岩组成(李开文等,2019).东秦岭造山带东段花岗伟晶岩脉丰富,主要侵位于五垛山大型花岗岩基和石门花岗岩体(图2a~2b),少量侵入变质地层(图2c).花岗伟晶岩脉宽度主体为 $0.2\sim2.0\text{ m}$ ,主要包括黑云母花岗伟晶岩和白云母花岗伟晶岩,不同区域花岗伟晶岩中黑云母和白云母含量有所不同.花岗伟晶岩与围岩接触部位,未见冷凝边;花岗伟晶岩成分较为均匀,从边部到核部未见成分分异.

## 2 岩相学特征

五垛山花岗伟晶岩呈浅肉红色,矿物颗粒粗大,具花岗伟晶结构,块状构造(图2d).主要造岩矿物由石英( $30\%\sim35\%$ )、钾长石( $30\%\sim35\%$ )、微斜条纹长石( $10\%\sim15\%$ )、奥长石( $5\%\sim10\%$ )和黑云母( $2\%\sim5\%$ )组成.石英分为两类,一类呈巨晶他形粒状(图3a),粒径 $0.5\sim2.0\text{ cm}$ ,另一类呈细粒分布在巨晶矿物的缝隙中(图3b).钾长石呈半自形—他形板状柱状,粒径为 $1\sim5\text{ cm}$ (图3b).微斜条纹长石粒径约 $0.5\sim4.0\text{ cm}$ (图3c),奥长石具钠长双晶,部分奥长

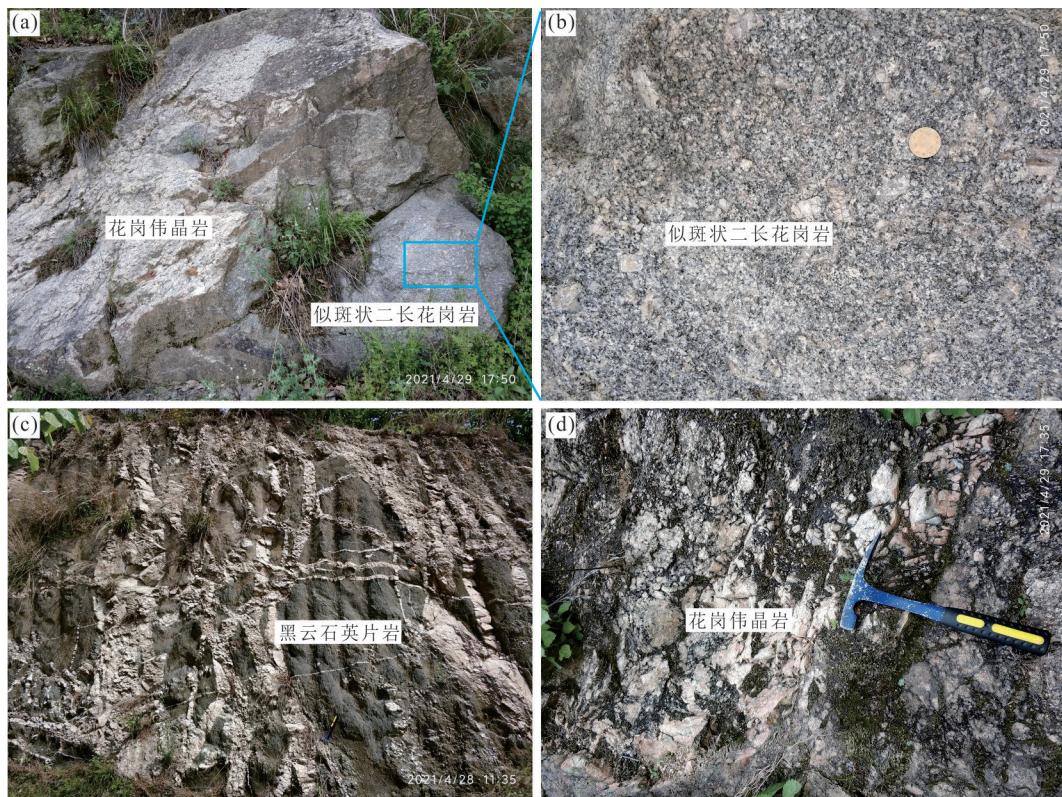


图2 东秦岭东段五垛山花岗伟晶岩野外地质特征

Fig. 2 Outcrop photos for granitic pegmatites in the Wuduoshan area in eastern section of the East Qinling

a. 花岗伟晶岩脉侵入似斑状二长花岗岩;b. 似斑状二长花岗岩;c. 花岗伟晶岩脉侵入黑云石英片岩;d. 花岗伟晶岩

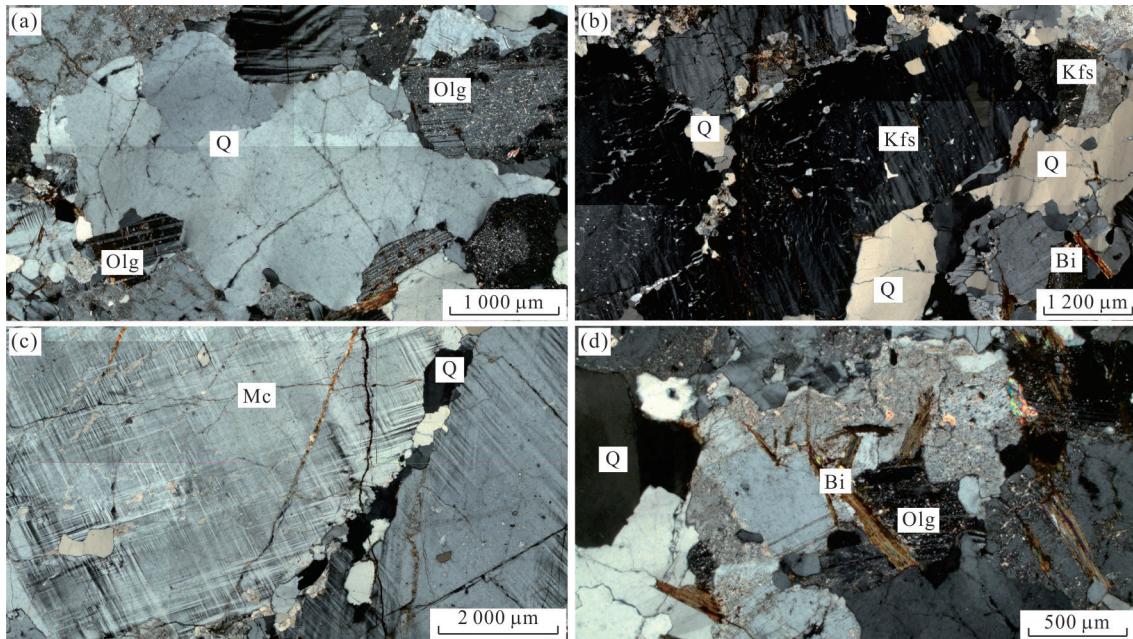


图3 东秦岭东段五垛山伟晶岩显微照片

Fig. 3 Microphotographs for granitic pegmatites in the Wuduoshan area in eastern section of the East Qinling  
Q. 石英; Mc. 微斜条纹长石; Olg. 奥长石; Kfs. 钾长石; Bi. 黑云母

石具有一定绢云母化(图3a,3d).黑云母呈片状分布于其他矿物间隙(图3d),部分黑云母可达2 cm.

### 3 样品采集及分析方法

样品采集于五垛山花岗岩基三岔口西部,样品编号为WDS007,采样坐标为N 33°11'15.29", E 112°16'36.43",具体采集位置见(图1b).

#### 3.1 锆石 U-Pb 定年

样品粉碎、锆石的反射光和透射光显微照相及阴极发光(CL)显微照相由西安瑞石地质科技有限公司进行.样品粉碎采用常规方法进行粉碎,并用常规浮选方法进行分选出锆石后,再用双目镜挑选出晶形和透明度较好的锆石颗粒作为测定对象.将锆石颗粒粘在双面胶上,经环氧树脂固定—环氧树脂固化—表面抛光工序后,进行锆石显微照相和阴极发光照相.

锆石 U-Pb 同位素组成分析在西北大学大陆动力学国家重点实验室激光剥蚀电感耦合等离子体质谱(LA-ICP-MS)仪上完成.分析仪器为配备有193nm A Rf-excimer 激光器的Geo-Las200M型(Microlas Gottingen Germany)激光剥蚀系统和Elan6100 DRC型四极杆质谱仪.分析采用激光剥蚀孔径30 μm,剥蚀深度20~40 μm,激光脉冲为10 Hz,能量为32~36 mJ.测试中用人工合成的硅酸

盐玻璃标准参考物质NIST610进行仪器最佳化.锆石年龄计算采用国际标准锆石SRM610作为外标校正.在所测锆石样品分析前后各测一次SRM610,同时以<sup>29</sup>Si作为内标测定锆石的U、Th、Pb含量.详细分析步骤和数据处理方法见袁洪林等(2003).样品的同位素比值和元素含量数据处理采用GLITTER(ver4.0, Macquarie University)程序,并采用Andersen软件对测试数据进行普通铅校正,年龄计算及谐和图绘制采用ISOPLOT(2.49版)软件完成.所有数据点年龄值的误差均为1σ,采用<sup>206</sup>Pb/<sup>238</sup>U年龄,其加权平均值具95%的置信度(Andersen, 2002; Ludwig, 2003),分析结果见附表1和附表2.

#### 3.2 锆石 Lu-Hf 同位素分析

原位锆石Lu-Hf同位素分析在西北大学大陆动力学国家重点实验室完成,所用仪器为Nu plasma型MC-ICP-MS,激光为193-nm ArF准分子激光,激光束斑直径为44 μm,所用激光脉冲速率为10 Hz.详细分析方法与参数同Yuan *et al.*(2008).分析结果见附表3.

## 4 分析结果

### 4.1 锆石 U-Pb 测年

五垛山花岗伟晶岩中的锆石多为不规则粒状

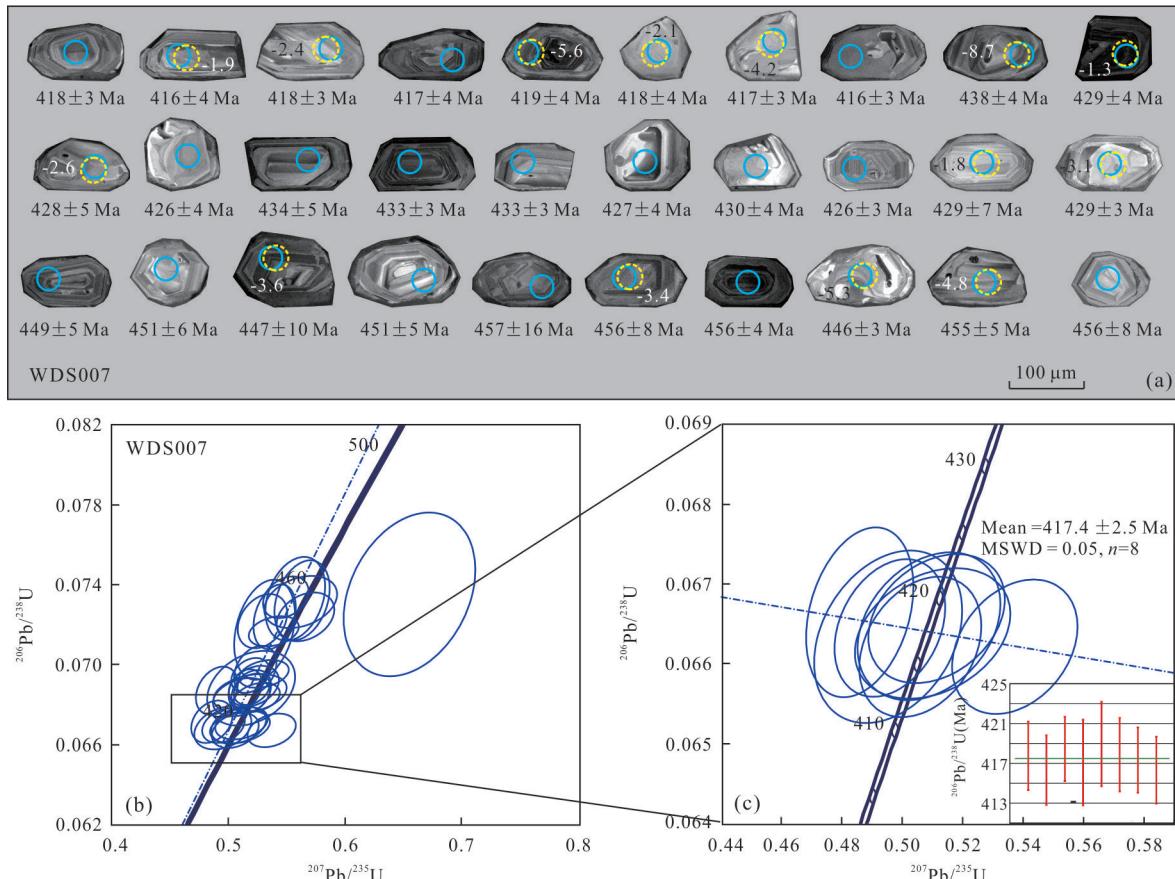


图4 东秦岭东段五垛山花岗伟晶岩锆石的阴极发光(CL)图像及U-Pb年龄(实线圆圈)及锆石Hf分析结果(虚线圆圈)(a)和LA-ICP-MS锆石U-Pb年龄谐图及其锆石 $^{206}\text{Pb}/^{238}\text{U}$ 加权平均年龄图(b~c)

Fig. 4 Cathodoluminescence photos (CL) of zircons, with marked U-Pb ages and Hf isotopic compositions (a) and LA-ICP-MS zircon U-Pb concordant age diagram,  $^{206}\text{Pb}/^{238}\text{U}$  weighted mean ages of zircons (b~c) for granitic pegmatites in the Wuduoshan area in eastern section of the East Qinling

或柱状,长轴方向长约70~120 μm,长宽比在1:1~1.5:1。阴极发光(CL)图像显示测试锆石颗粒发育振荡环带(图4a),锆石整体较为均匀,部分锆石有微小的核部和包裹体。CL图像未显示锆石结晶过程中和后期有流体作用的痕迹(Hoskin and Schaltegger, 2003)。样品(WDS007)共测试了30个点,测点的 $^{206}\text{Pb}/^{238}\text{U}$ 和 $^{207}\text{Pb}/^{235}\text{U}$ 谐和性较好(图4c),其 $^{206}\text{Pb}/^{238}\text{U}$ 年龄可分为3组。第1组有10个测点, $^{206}\text{Pb}/^{238}\text{U}$ 年龄介于(446±3)~(457±16) Ma(附表1), $^{206}\text{Pb}/^{238}\text{U}$ 加权平均年龄为450.9±3.3 Ma(MSWD=0.66)。第2组有12个测点, $^{206}\text{Pb}/^{238}\text{U}$ 年龄介于(426±4)~(434±5) Ma(附表1), $^{206}\text{Pb}/^{238}\text{U}$ 加权平均年龄为429.5±2.1 Ma(MSWD=0.58)。第3组有8个测点, $^{206}\text{Pb}/^{238}\text{U}$ 年龄介于(416±3)~(419±4) Ma(附表1), $^{206}\text{Pb}/^{238}\text{U}$ 加权平均年龄为417.4±2.5 Ma(MSWD=0.05)(图4b~4c)。

## 4.2 锆石微量元素

五垛山花岗伟晶岩锆石微量元素变化范围较大,Th/U比值都大于0.1(附表2);稀土元素呈现LREE亏损,HREE富集的左倾特征(图5),显示明显的Eu负异常和Ce正异常,具岩浆锆石特征(Corfu and Hoskin, 2003;吴元保和郑永飞, 2004;赵志丹等, 2018)。在锆石类型判别图中,花岗伟晶岩中的锆石也落入岩浆锆石区域(图6)。花岗伟晶岩417.4 Ma组锆石的Th含量为 $78 \times 10^{-6}$ ~ $521 \times 10^{-6}$ , U含量为 $394 \times 10^{-6}$ ~ $886 \times 10^{-6}$ , Th/U比值为0.17~0.90; $\Sigma$ REE为 $189.08 \times 10^{-6}$ ~ $1331.43 \times 10^{-6}$ , Eu/ $\text{Eu}^*$ 为0.25~0.79,Ce/ $\text{Ce}^*$ 为2.52~217.10;Ti含量较低,为 $2.38 \times 10^{-6}$ ~ $14.98 \times 10^{-6}$ 。429.5 Ma组锆石的Th和U含量稍微高于417.4 Ma组锆石,分别为 $92 \times 10^{-6}$ ~ $954 \times 10^{-6}$ 和 $280 \times 10^{-6}$ ~ $1110 \times 10^{-6}$ , Th/U比值为0.20~1.30; $\Sigma$ REE含量为 $189.60 \times 10^{-6}$ ~ $591.49 \times 10^{-6}$ , Eu/ $\text{Eu}^*$ 和Ce/ $\text{Ce}^*$ 低于

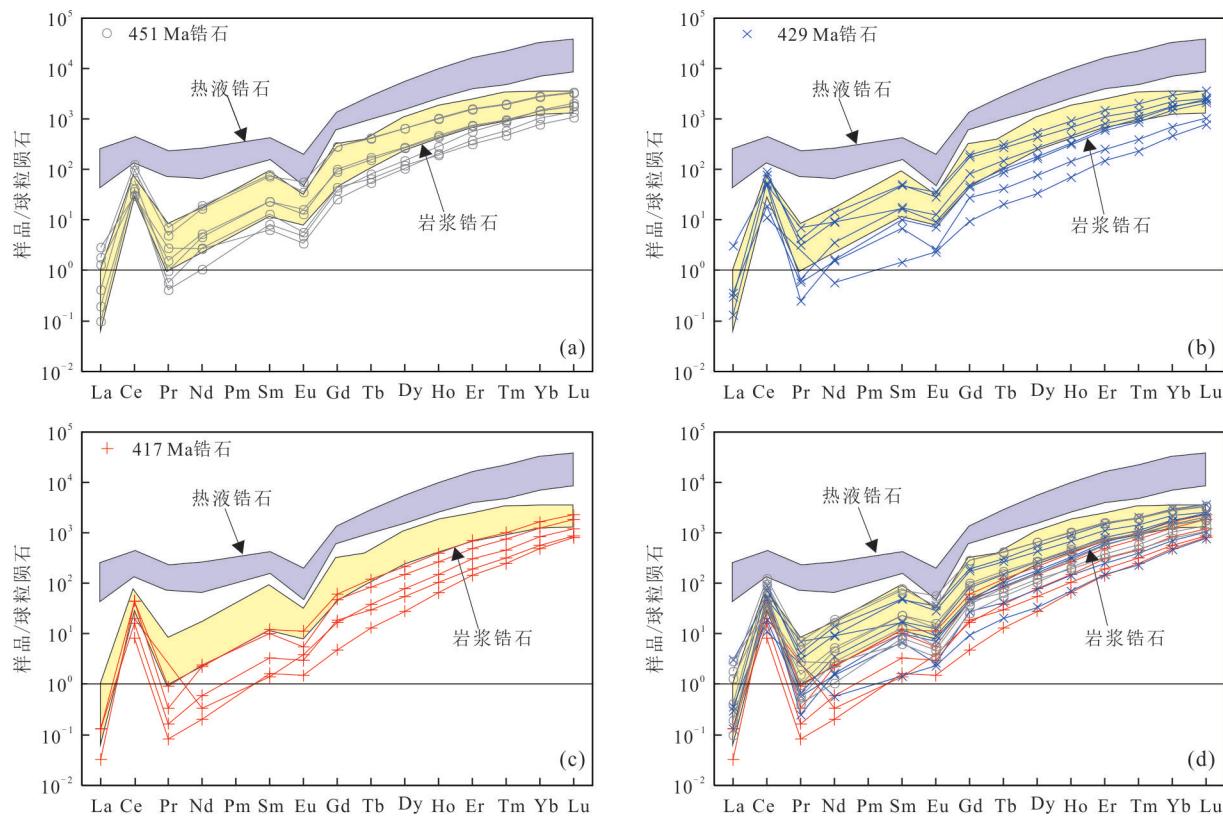


图5 东秦岭东段五垛山花岗伟晶岩锆石球粒陨石标准化稀土元素配分图(标准化值据Boynton, 1984)

Fig. 5 REE chondrite-normalized distribution pattern for granitic pegmatites in the Wuduoshan area in eastern section of the East Qinling(normalized values after Boynton, 1984)

岩浆锆石和热液锆石区域据Hoskin(2005)

417.4 Ma 组锆石, 分别为 0.19~0.64 和 0~196.31; Ti 含量最高, 为 0~296.08×10<sup>-6</sup>. 450.9 Ma 组锆石具有最高 Th、U 和 ΣREE 的含量, 分别为 189×10<sup>-6</sup>~1 760×10<sup>-6</sup>、349×10<sup>-6</sup>~1 289×10<sup>-6</sup> 和 387.86×10<sup>-6</sup>~11 205.52×10<sup>-6</sup>, Th/U 比值为 0.31~1.53, Eu/Eu\* 为 0.24~0.42, Ce/Ce\* 为 0~207.12; Ti 含量稍微高于 417.4 Ma 组锆石, 为 0.96×10<sup>-6</sup>~32.08×10<sup>-6</sup>.

#### 4.3 锆石 Lu-Hf 同位素

对五垛山花岗伟晶岩的锆石进行了 Lu-Hf 同位素组成测定, 测定结果及计算的相关参数见附表 3. 花岗伟晶岩中锆石的  $^{176}\text{Yb}/^{177}\text{Hf}$  和  $^{176}\text{Lu}/^{177}\text{Hf}$  比值范围分别在 0.010 014~0.089 224 和 0.000 401~0.002 908, 表明锆石在形成后具极少的放射成因 Hf 的累积, 测定的  $^{176}\text{Hf}/^{177}\text{Hf}$  比值可以代表其形成时体系的 Hf 同位素组成(吴福元等, 2007). 花岗伟晶岩共测定 14 个测点(图 7), 其中 417.4 Ma 组 5 个测点,  $\epsilon_{\text{Hf}}(t)$  为 -5.6~-1.9, 平均为 -3.2, 二阶段 Hf 模式年龄( $t_{\text{MD2}}$ )为 1 354~1 166 Ma; 429.5 Ma 组 5 个测

点,  $\epsilon_{\text{Hf}}(t)$  为 -8.7~-1.3, 平均为 -3.5, 二阶段 Hf 模式年龄( $t_{\text{MD2}}$ )为 1 516~1 139 Ma; 450.9 Ma 组 4 个测点,  $\epsilon_{\text{Hf}}(t)$  为 -5.3~-3.4, 平均为 -4.3, 二阶段 Hf 模式年龄( $t_{\text{MD2}}$ )为 1 335~1 244 Ma.

## 5 讨论

### 5.1 五垛山花岗岩基及伟晶岩脉的形成时代

东秦岭东段岩浆活动丰富, 五垛山大型花岗岩基是其重要组成部分. 五垛山花岗岩为一复式花岗岩基, 由不同期次和不同类型的花岗质岩浆岩组成. 五垛山花岗岩基的形成时代为 400~451 Ma, 具 3 个峰值年龄, 分别为 449 Ma、432 Ma 和 416 Ma(图 8a). 五垛山花岗岩基岩石类型主要包括中细粒花岗闪长岩、中细粒黑云母二长花岗岩、中粗粒黑云母二长花岗岩、中粗粒似斑状黑云母二长花岗岩和中粗粒二云母花岗岩(李开文等, 2019). 中细粒花岗闪长岩和中粗粒黑云母二长花岗岩的形成时代稍早, 似斑状黑云母二长花岗岩的形成时代稍晚.

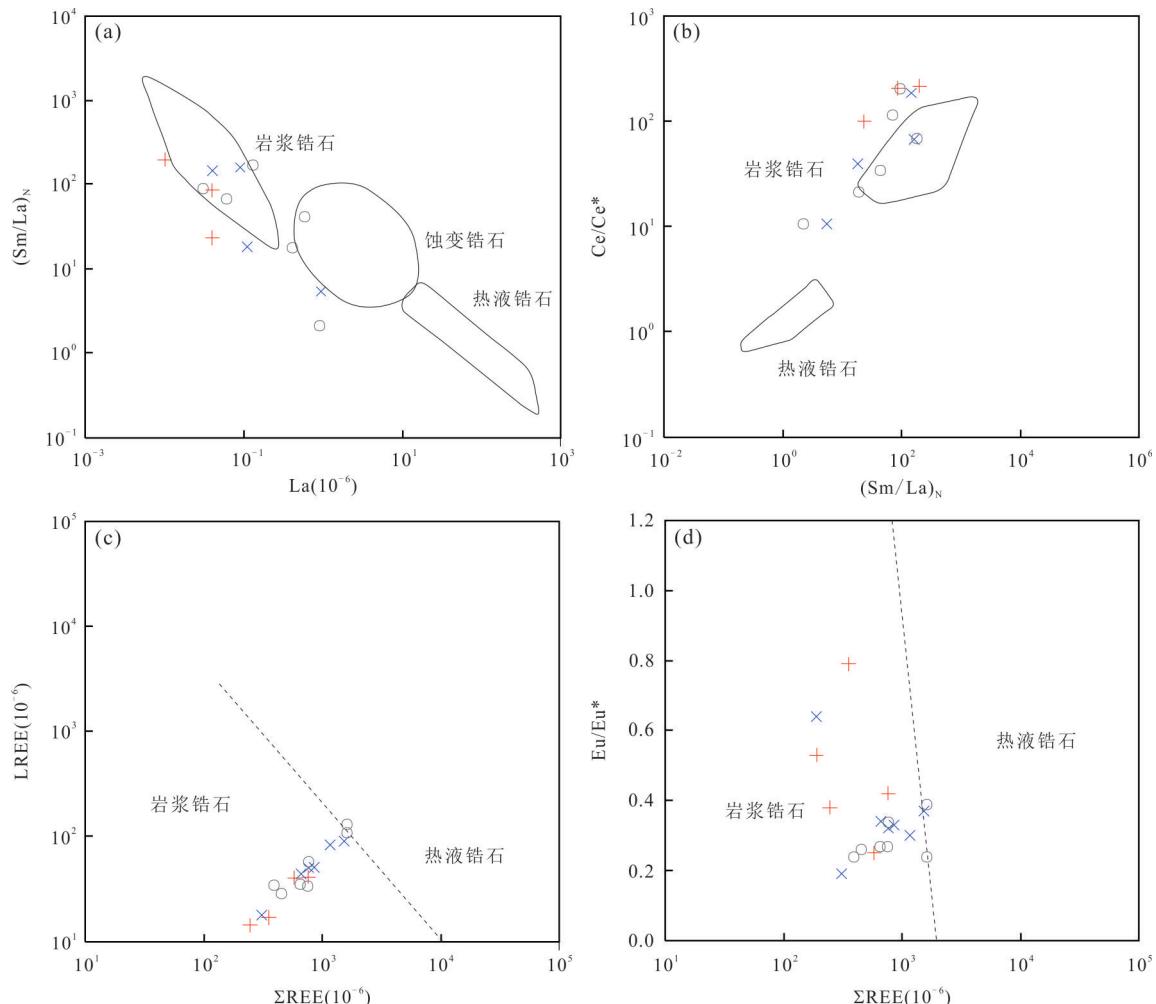


图 6 东秦岭东段五垛山花岗伟晶岩锆石成因判别图解

Fig. 6 Discriminant diagrams of zircons for granitic pegmatites in the Wuduoshan area in eastern section of the East Qinling

图 a~b 底图据 Hoskin(2005); 图 c~d 底图据 Li *et al.*(2018). 图例同图 5

五垛山花岗伟晶岩脉中锆石的 U-Pb 年龄分布较宽, 为 416~457 Ma, 可以分为 3 组, 分别为 450.9 Ma、429.5 Ma 和 417.4 Ma(图 8b). 这 3 组年龄与五垛山花岗岩基的 3 个峰值年龄相对应(图 8a). 研究显示, 同期岩浆活动的演化时间小于 10 Ma (Glazner *et al.*, 2004). 五垛山花岗伟晶岩中 3 组锆石的年龄差值大于 10 Ma, 因此五垛山花岗伟晶岩 3 期锆石不是同一次岩浆作用的产物, 同东秦岭中部灰池子岩体相似, 为不同期次岩浆叠加的结果(Yuan *et al.*, 2020). 450.9 Ma 和 429.5 Ma 两组锆石可能为花岗伟晶岩在上侵过程中捕获五垛山花岗岩基的围岩锆石. 最年轻的 417.4 Ma 这组锆石应为花岗伟晶岩脉的结晶年龄. 这组年龄与五垛山花岗岩基中 416 Ma 这组年龄相近似, 说明花岗伟晶岩与这组年龄相关的花岗岩可能具有成因联系或者形成于同一构造背景.

## 5.2 锆石微量元素数据选取

随着 LA-ICP-MS 分析技术的发展, 锆石中微量元素含量可以迅速准确测定(Yuan *et al.*, 2008; 周伶俐等, 2019), 这些锆石微量元素数据被广泛应用于指示岩浆形成的物理环境、岩浆演化过程、源区物质和锆石成因(赵振华, 2010; 赵志丹等, 2018). 但是, 锆石中的微量元素含量受熔体成分(Burnham, 2020)、脱晶化作用(李秋立, 2016)、后期蚀变(Hoskin, 2005)和矿物包裹体(Zou *et al.*, 2019)等因素的影响. 因此, 在利用锆石微量元素讨论岩浆形成物理环境、岩浆成因和源区属性时要排除这部分锆石.

由于轻稀土元素在锆石中的丰度远低于其他地壳物质和其他稀土元素, 轻稀土配分模式的干扰最有可能是锆石微量元素含量被破坏的重要因素. 因此, 可以用 LREE-I 值( $=\text{Dy}/\text{Nd} + \text{Dy}/\text{Sm}$ )来识

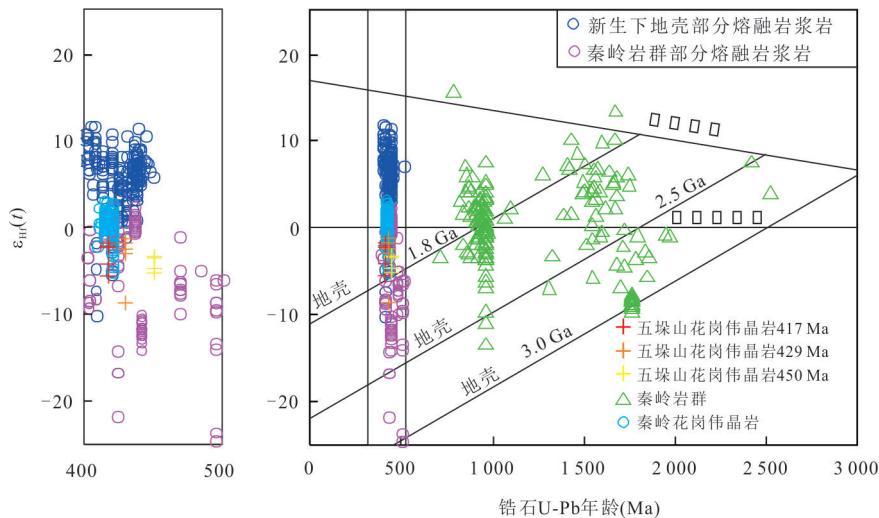
图7 东秦岭东段五垛山花岗伟晶岩锆石 $\epsilon_{\text{Hf}}(t)$ —U-Pb年龄

Fig. 7 Diagram of zircons  $\epsilon_{\text{Hf}}(t)$ —U-Pb ages for granitic pegmatites in the Wuduoshan area in eastern section of the East Qinling  
 图中数据来源:新生下地壳部分熔融岩浆岩数据 Wang et al., 2009; 秦拯纬, 2016; Chen et al., 2019; Qin et al., 2020; Yuan et al., 2020; Ren et al., 2021; 秦岭岩群部分熔融岩浆岩数据 Wang et al., 2009; 王浩, 2014; 秦拯纬, 2016; Qin et al., 2020; Wang et al., 2020; Yuan et al., 2020; Ren et al., 2021; 秦岭岩群数据 Shi et al., 2013; Diwu et al., 2014; 王浩, 2014; 杨阳, 2017; Yuan et al., 2020; 东秦岭伟晶岩数据 Yuan et al., 2018a, 2020; Chen et al., 2019

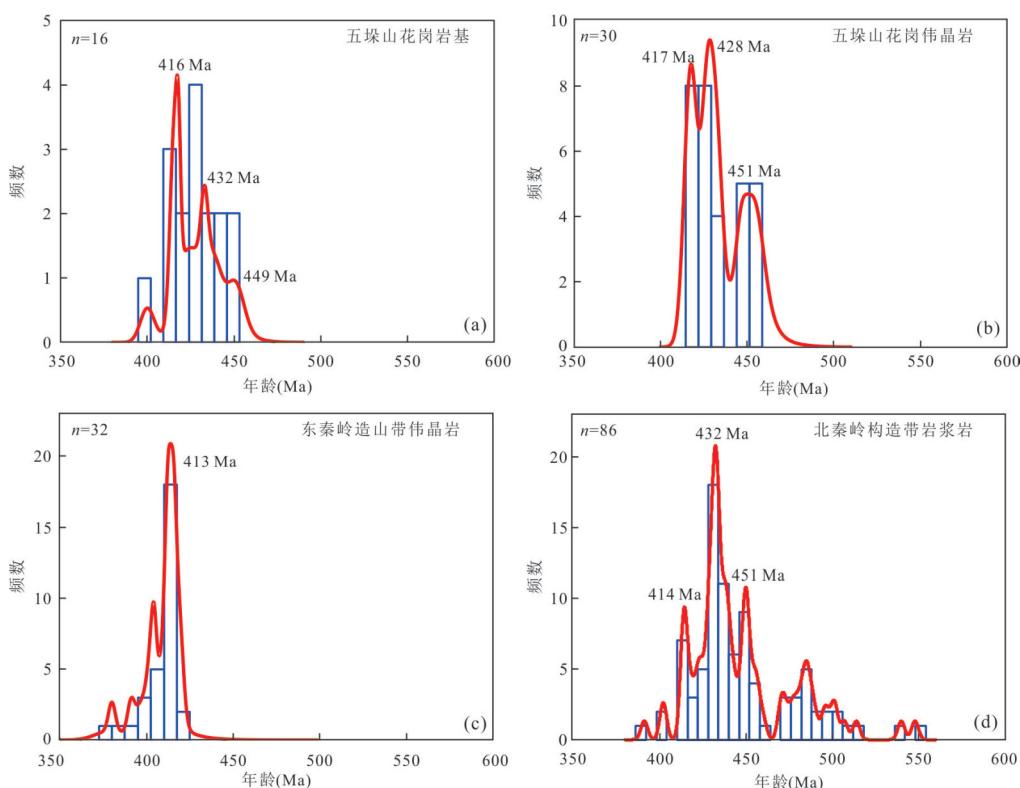


图8 东秦岭东段五垛山花岗伟晶岩年龄频谱直方图的区域对比特征

Fig. 8 Regional contrast features of the age spectra histograms for granitic pegmatites in the Wuduoshan area in eastern section of the East Qinling

五垛山花岗岩基数据 刘丙祥, 2013; 赖亚等, 2017; 易志强等, 2017; 李开文等, 2019; 周澍等, 2019. 东秦岭造山带伟晶岩数据 刘刚等, 2017; Wu et al., 2018; 袁峰等, 2017; Yuan et al., 2018a, 2018b, 2020; Chen et al., 2019; Guo et al., 2021; 北秦岭构造带岩浆岩数据 Wang et al., 2009; 张成立等, 2013; 王晓霞等, 2015; Dong and Santosh, 2016 及参考文献

别锆石与外部流体交代或后期成矿作用造成的污染,当LREE-I<30时指示锆石经历了一定蚀变作用(Bell *et al.*, 2016)。锆石具有非常低的La含量,锆石中即使混入极少量的矿物包裹体,都可能导致La含量增高。因此,La含量( $<1.0 \times 10^{-6}$ )指标可以简洁地指示锆石微量元素有没有受到外来因素的影响(Zou *et al.*, 2019; 邹心宇等, 2021)。本文对锆石类型、成因和结晶物理化学条件论述的锆石满足LREE-I>30和La< $1.0 \times 10^{-6}$ 。

### 5.3 锆石结晶物理化学条件

**5.3.1 结晶温度** 锆石晶体中Ti可以与Zr<sup>4+</sup>和Si<sup>4+</sup>类质同象的形式存在,锆石中的Ti含量是温度的函数,随着岩浆温度的上升,锆石中Ti的含量逐步增加(Watson *et al.*, 2006)。因此,锆石Ti温度计已被广泛应用于火成岩结晶温度的计算(Ferry and Watson, 2007)。五垛山花岗伟晶岩锆石Ti温度计计算结果见附表2。数据显示,五垛山花岗伟晶岩的锆石Ti温度为627~738 °C,平均为692 °C;450.9 Ma这组捕获锆石的温度为674~847 °C,平均为767 °C;429.5 Ma这组捕获锆石的温度为641~849 °C,平均为776 °C。结果显示,五垛山花岗伟晶岩的形成温度低于两组捕获锆石,两组捕获锆石的形成温度较为近似。

**5.3.2 氧逸度** 近年来,研究者根据锆石中微量元素的含量,建立了不同的锆石氧逸度计算方法。但是,这些方法由于受矿物分离结晶和岩浆水含量的影响,都难以计算出可靠的氧逸度。最近,Loucks *et al.*(2020)根据锆石中的4价元素Ce<sup>4+</sup>、U<sup>4+</sup>和Ti<sup>4+</sup>提出了全新的锆石氧逸度计算方法,该计算方法标准误差为0.6个对数单位,适用于从金伯利岩到流纹岩、拉斑玄武岩、埃达克岩、闪长岩以及几乎所有准铝质、过铝质和过碱性的岩浆(罗雕等,2020)。数据显示,五垛山花岗伟晶岩锆石结晶时的氧逸度为QFM-0.5~QFM+1.0;450.9 Ma这组捕获锆石结晶时的氧逸度为QFM+0~QFM+1.7;429.5 Ma这组捕获锆石结晶时的氧逸度为QFM-1.0~QFM+2.8。以上显示,整体上450.9 Ma这组捕获锆石的氧逸度最高,429.5 Ma这组捕获锆石的氧逸度次之,五垛山花岗伟晶岩锆石的氧逸度最低(图9)。

### 5.4 花岗伟晶岩脉的源区和成因

五垛山花岗伟晶岩主体侵入到花岗岩基中,因此,这些花岗伟晶岩可能与花岗岩基有着成因联系。锆石U-Pb年代学研究显示,花岗伟晶岩与五垛山花岗岩基其中一期岩浆作用具有近似的形成年龄

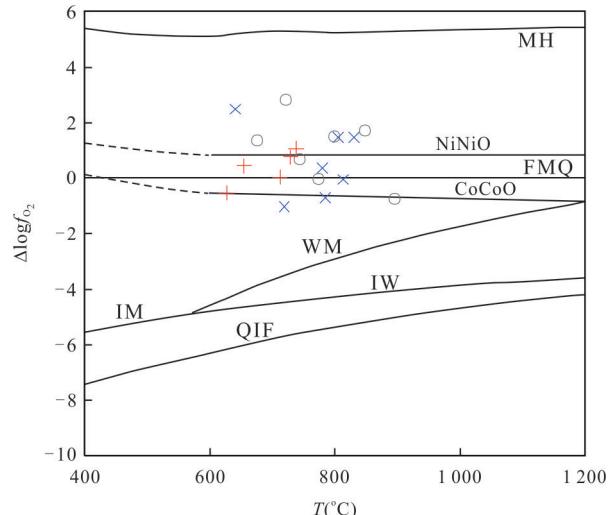


图9 东秦岭东段五垛山花岗伟晶岩的T- $\Delta\log f_{O_2}$ 图

Fig. 9 Diagram of  $T-\Delta\log f_{O_2}$  for granitic pegmatites in the Wuduoshan area in eastern section of the East Qinling

底图据 Frost(1991). 图例同图5

(易志强等, 2017)。因此,两者可能为同一岩浆房或者为同一构造背景下岩浆活动。

五垛山花岗伟晶岩锆石的二阶段Hf模式年龄( $t_{MD2}$ )为1 139~1 516 Ma,显示五垛山花岗伟晶岩(417.4 Ma)和捕获锆石代表的岩浆岩(429.5 Ma和450.9 Ma)可能来自于古老下地壳的部分熔融。五垛山花岗伟晶岩锆石3组年龄的 $\epsilon_{Hf}(t)$ 平均值分别为-3.2(417.4 Ma)、-3.5(429.5 Ma)和-4.3(450.9 Ma),与东秦岭花岗伟晶岩近似(图7)。研究显示,东秦岭造山带早古生代花岗质岩浆岩源区主要分为两类,一类具有较高的 $\epsilon_{Hf}(t)$ 值,为新生下地壳部分熔融的结果(图7),例如灰池子岩体(Wang *et al.*, 2009; 秦拯纬, 2016; Chen *et al.*, 2019)、枣园岩体(秦拯纬, 2016)、两岔河岩体(Qin *et al.*, 2020)、铁峪铺岩体(Qin *et al.*, 2020)、窑沟岩体(Qin *et al.*, 2020)、张庄二云母花岗岩(Ren *et al.*, 2021)、北星沟岩体(Ren *et al.*, 2021)和小花沟黑云母花岗岩(Yuan *et al.*, 2020);另一类具有较低的 $\epsilon_{Hf}(t)$ 值,来自于基底变沉积岩的部分熔融(图7),例如四棵树岩体(王浩, 2014)、桐柏岩体(王浩, 2014)、漂池岩体(Wang *et al.*, 2009; 秦拯纬, 2016)、大房沟岩体(Wang *et al.*, 2009; Qin *et al.*, 2020)、张庄白云母花岗岩(Ren *et al.*, 2021)和小花沟二长花岗岩(Yuan *et al.*, 2020)等。这些岩体的 $\epsilon_{Hf}(t)$ 值与部分秦岭岩群近似(图7),显示这些岩体

可能来自于秦岭岩群的部分熔融(Wang *et al.*, 2009; 秦拯纬, 2016; Qin *et al.*, 2020). 五垛山花岗伟晶岩中3组锆石的 $\epsilon_{\text{Hf}}(t)$ 值与其近似.

研究显示, 五垛山花岗岩基中黑云母花岗岩和二长花岗岩的形成时代分别为438~441 Ma和431~433 Ma, 富集Rb、Ba、K和Pb, 亏损Nb、Ta、P、Ti,  $^{87}\text{Sr}/^{86}\text{Sr}(i)$ 为0.703 04~0.712 90,  $\epsilon_{\text{Nd}}(t)$ 值为-4.6~-1.9(周澍等, 2019), 其Sr-Nd同位素与 $\epsilon_{\text{Hf}}(t)$ 相似, 都体现壳源特征. 因此, 五垛山花岗伟晶岩, 以及捕获锆石所代表的两期岩浆岩都来自于秦岭岩群的部分熔融. 五垛山花岗岩基中部分黑云母二长花岗岩同花岗伟晶岩具有近似的形成时代(易志强等, 2017). 因此, 五垛山花岗伟晶岩可能与其具有成因联系, 为黑云母二长花岗岩分离结晶的结果. 早奥陶世—早泥盆世东秦岭造山带随着南秦岭地块和北秦岭地块的碰撞, 后碰撞阶段的拉张作用导致岩石圈地幔部分熔融形成镁铁质岩浆, 这些镁铁质岩浆底侵下地壳变质基底中的变沉积岩, 使其部分熔融形成了五垛山黑云母二长花岗岩, 这些黑云母二长花岗岩在上侵过程中结晶分异形成了五垛山花岗伟晶岩.

### 5.5 东秦岭花岗伟晶岩活动时限及地球动力学背景

东秦岭中段商洛—丹凤北部, 是我国重要的花岗伟晶岩成矿带(卢欣祥等, 2010), 发现了大量稀有金属矿床, 主要包括光石沟、小花岔、纸房沟和陈家庄(赵如意等, 2013; Yuan *et al.*, 2020)等铀矿床, 官坡锂、铍矿床(周起凤等, 2019). 东秦岭中段花岗伟晶岩形成时代较为集中, 为377~420 Ma, 峰值在413 Ma(图8c). 本文研究的五垛山花岗伟晶岩形成时代为早泥盆世(417.4 Ma), 与东秦岭中段花岗伟晶岩形成时代相一致(图8a, 8c). 东秦岭造山带从中段到东段短时间内形成大量花岗伟晶岩, 说明这些岩浆活动形成于统一的地球动力学背景.

东秦岭造山带原特提斯演化阶段, 随着商丹洋的俯冲、弧后拉张以及不同地块之间的碰撞, 东秦岭造山带岩浆活动丰富, 这些岩浆活动主体分布于400~500 Ma之间(图8d). 由于商丹洋的俯冲作用, 东秦岭在450~500 Ma期间形成大量具弧特征的岩浆岩, 这些岩浆岩 $\epsilon_{\text{Hf}}(t)$ 值变化范围较大, 主体呈正值, 表明这些岩浆主要来源于较早侵位于下地壳的镁铁质岩石的部分熔融, 并混入了不同数量的古老地壳成分(Qin *et al.*, 2014). 在450~485 Ma期间,

部分俯冲的年轻洋壳部分熔融, 在东秦岭造山带形成了一套具O型埃达克质特征的岩浆岩(郭彩莲和陈丹玲, 2011). 随着南秦岭地块和北秦岭地块的碰撞作用, 东秦岭造山带在晚奥陶世(440~450 Ma)处于挤压环境, 岩浆活动减弱(图8d). 进入早志留世(440 Ma), 由于板片的断离作用, 使秦岭造山带这一时期岩浆活动增强(Zhang *et al.*, 2015), 在430 Ma左右达到峰值. 板片的断离, 使地幔减压部分熔融形成镁铁质岩浆, 这些镁铁质岩浆底侵地壳, 使其部分熔融形成大量长英质岩浆岩. 东秦岭由于洋壳的俯冲和陆陆碰撞作用使地壳增厚, 加厚地壳部分熔融形成具C型埃达克质特征的岩浆岩(田伟和魏春景, 2005). 这些岩浆活动与秦岭造山带在古生代经历的变质事件相一致(~500 Ma、~450 Ma和~420 Ma)(刘良等, 2013; Dong and Santosh, 2016).

五垛山花岗岩基中449 Ma和432 Ma岩浆活动分别对应于东秦岭造山带原特提斯演化阶段的俯冲和碰撞阶段. 五垛山花岗伟晶岩和岩基416 Ma的岩浆活动同东秦岭造山带花岗伟晶岩带的形成相一致(413 Ma), 与秦岭造山带晚志留世—早泥盆世岩浆活动和角闪岩相退变质作用相对应. 五垛山花岗伟晶岩和岩基416 Ma岩浆活动具有近似的形成时代, 与灰池子岩体相似, 花岗伟晶岩为同时代花岗岩分离结晶的结果(Chen *et al.*, 2019; Yuan *et al.*, 2020). 由于这一时期东秦岭造山带的地壳的抬升和拉张作用, 在地壳内形成一系列岩浆通道, 为花岗伟晶岩的原生岩浆向上运移提供了空间, 使这一时期东秦岭造山带形成大量花岗伟晶岩脉.

## 6 结论

(1) 东秦岭东段五垛山花岗伟晶岩锆石LA-ICP-MS U-Pb定年结果为417.4±2.5 Ma, 形成时代为早泥盆世.

(2) 五垛山花岗伟晶岩为东秦岭变质基底秦岭岩群部分熔融的结果.

(3) 东秦岭造山带在早泥盆世处于原特提斯演化的后碰撞阶段, 后碰撞阶段的拉张作用为花岗伟晶岩的上侵提供了通道.

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附表见本刊官网(<http://www.earth-science.net>).

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