# 榴辉岩相峰期流体活动:来自东昆仑榴辉岩石英脉的证据*

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**Abstract** This paper reports a quartz vein in eclogite from Wenquan area in the East Kunlun, and through a comprehensive research in U-Pb age and Lu-Hf isotope, which provides some evidence about fluid activity in peak eclogite-facies metamorphic stage. The zircon grains in Wenquan quartz vein have perfect euhedral habit and show sector or weak zoning, which precludes the possibility that the zircon crystals were physically introduced into the quartz vein from the country rock. Zircon grains from quartz vein and eclogite yield weighted mean $^{206}Pb/^{238}U$ date of 450 ± 2Ma and 451 ± 2Ma, respectively, which describes that the forming age of zircon in quartz vein and the peak eclogite-facies metamorphic stage are consistent. The similarity of Hf isotope composition in the two styles of zircon proves the aqueous fluid/melt that formed veins is internal source, which may be derived from the fused quartz in eclogite, but we can not preclude the exsolution of structural hydroxyl in omphacite and garnet. Quartz vein formed more likely in aqueous fluid rather than melt because of the low U, Th contents and Th/U ratios in zircons.
**Key words** Zircon; Quartz vein; Eclogite; U-Pb; Lu-Hf; East Kunlun

**摘 要** 本文通过对东昆仑温泉地区榴辉岩中石英脉的锆石U-Pb定年和Lu-Hf同位素的综合研究,为榴辉岩相峰期变质阶段的流体活动提供了一定的证据。石英脉中的锆石晶型较好,具有振荡环带或弱分带,排除了从寄主榴辉岩中捕获锆石的可能性。石英脉和寄主榴辉岩中锆石U-Pb年龄的加权平均值分别为450±2Ma和451±2Ma,说明石英脉中锆石的形成年龄与榴辉岩相的峰期变质阶段一致。两种锆石Hf同位素组成的相似性说明形成石英脉的流体/熔体为内部来源,推测可能为榴辉岩中石英发生溶解以及绿辉石和石榴石分子结构中羟基的出溶作用形成。锆石较低的U、Th含量以及Th/U比值说明石英脉更可能是流体活动形成而非熔体。
**关键词** 锆石;石英脉;榴辉岩;U-Pb;Lu-Hf;东昆仑
**中图法分类号** P588.348; P597.3

## 1 引言

在与俯冲和碰撞相关的变质作用中,流体扮演了非常重要的角色,它对认识碰撞造山中的变质作用、岩浆作用及高压-超高压岩石的形成和保存等有重要的意义(Miller *et al.*, 2002; Li *et al.*, 2004; Hermann *et al.*, 2006; Wu *et al.*, 2006, 2008, 2009; Sun *et al.*, 2007; Zhang *et al.*, 2008;

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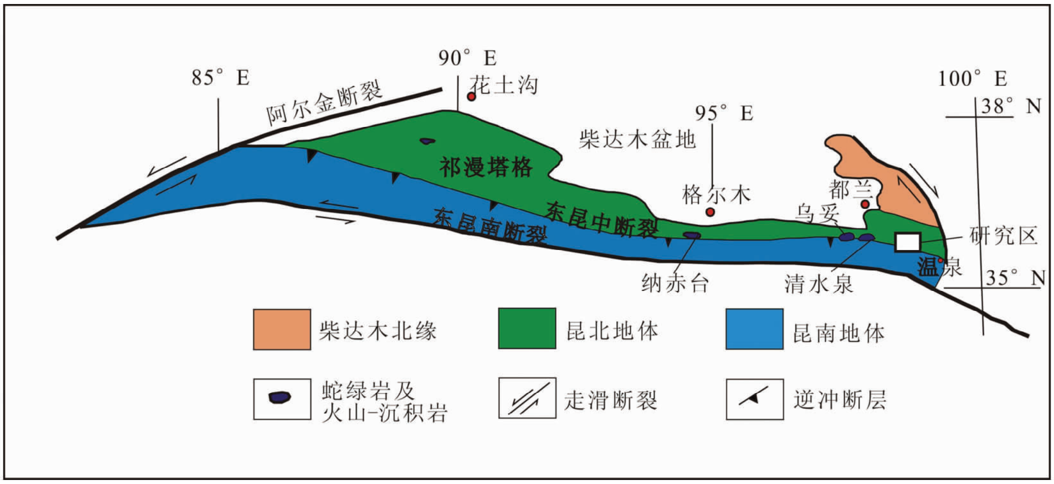


图1 东昆仑地区构造单元划分图(据姜春发等, 1992; Meng *et al.*, 2013 修改)

Fig. 1 Geological map of the East Kunlun orogen and its tectonic division (after Jiang *et al.*, 1992; Meng *et al.*, 2013)

Zhang *et al.*, 2009; Zheng *et al.*, 2003, 2007, 2011)。流体作用的产物在超高压岩石中常以浅色矿物为主的岩脉产出,尤其以石英脉最为明显(Wu *et al.*, 2009; 刘小驰等, 2009; Zheng *et al.*, 2007, 2011; Cao *et al.*, 2013)。石英脉经常出现在榴辉岩相变质岩石中,是流体与岩石反应的产物,为俯冲带流体活动的机制提供至关重要的信息(Liati and Gebauer, 1999; Rubatto *et al.*, 1999; Philippot and Rumble, 2000; Franz *et al.*, 2001; Widmer and Thompson, 2001; Rubatto and Hermann, 2003; Spandler and Hermann, 2006; 刘小驰等, 2009; Wu *et al.*, 2006, 2008, 2009; Zheng *et al.*, 2003, 2007, 2011; Sheng *et al.*, 2012)。

详细的岩石学和流体包裹体研究表明,在高压-超高压岩石中,形成岩脉的流体有两种来源:来自大规模迁移的外部流体和局部活动的内部流体(Henry *et al.*, 1996; Cartwright and Barnicoat, 1999; Scambelluri *et al.*, 1998; Zheng *et al.*, 2003, 2007; John *et al.*, 2008; Jamtveit *et al.*, 2000; Chen *et al.*, 2012)。在造山带形成过程中,石英脉可形成于不同的阶段:进变质阶段(Liati and Gebauer, 1999; Rubatto *et al.*, 1999; Molina *et al.*, 2004; Wu *et al.*, 2009)、峰期变质阶段(Rubatto and Hermann, 2003)和退变质阶段(Franz *et al.*, 2001; Rubatto and Hermann, 2003; Li *et al.*, 2004; Spandler and Hermann, 2006; Wu *et al.*, 2009; Zheng *et al.*, 2007, 2011)。在碰撞造山的过程中,特别是在压力的降低或温度的升高时会分别发生降压脱水作用和升温脱水作用,使得超高压岩石中的含水矿物发生分解或者名义上不含水矿物的羟基发生出溶作用形成流体(Li *et al.*, 2001; Li *et al.*, 2004)。

锆石是榴辉岩和石英脉中常见的副矿物(吴元保郑永飞, 2004; Wu *et al.*, 2006; Zheng *et al.*, 2007; 刘小驰等, 2009),利用锆石的U-Pb体系可以精确地确定流体活动的年代。锆石中Lu-Hf体系非常的稳定(Cherniak and Watson, 2003),可以示踪寄主岩石来源和演化过程(Zheng *et al.*, 2006),根据锆石的Lu/Hf比值,确定锆石是否与石榴石共生,以进一步限定锆石的形成条件(Zheng *et al.*, 2005; Wu *et al.*, 2006; 刘小驰等, 2009)。综合石英脉中锆石的U-Pb定年、Lu-Hf同位素信息,可以为高级变质岩石中流体的来源、活动的时间以及形成条件等方面提供重要的制约。本文对东昆仑温泉地区榴辉岩中石英脉的锆石的形态特征、U-Pb定年、Lu-Hf同位素综合研究,不但为东昆仑榴辉岩峰期变质过程中流体的活动提供证据,同时也确定了流体的性质和来源,对理解流体活动在造山过程中的作用有重要意义。

## 2 区域地质概况及样品特征

昆仑造山带是中国中央造山带的重要组成部分之一,位于青藏高原北部,以阿尔金断裂为界分为东昆仑造山带和西昆仑造山带,其中东昆仑造山带以北为柴达木盆地,以南为巴颜喀拉-松藩甘孜地体(Bian *et al.*, 2004; 陈能松等, 2006)。东昆仑中央断裂带(东昆中断裂)是东昆仑造山带中一条非常重要的构造界线,从北至南可把东昆仑分为昆北地体和昆南地体两部分(图1)(李怀坤等, 2006; 许志琴等, 2006; Meng *et al.*, 2013)。

昆北地体由元古代金水口群、早古生代纳赤台群和晚泥盆世契盖苏群组成(陈能松等,2006)。金水口群被认为是本区最古老的变质岩系,原岩主要为杂砂岩、泥质岩,其次为碳酸盐岩,含少量中基性到基性火山岩,形成于古-中元古代,该群遭受早古生代角闪岩相至麻粒岩相的区域变质作用(陈能松等,1999,2006,2007;张建新等,2003;李怀坤等,2006;刘彬等,2012)和区域混合岩化作用,形成一些条痕状、条带状、眼球状混合岩及少量混合花岗岩;纳赤台群为一套绿片岩相变质的火山岩、碎屑岩和碳酸盐岩(姜春发等,1992),被大量志留纪-泥盆纪的花岗闪长岩和花岗岩侵入(莫宣学等,

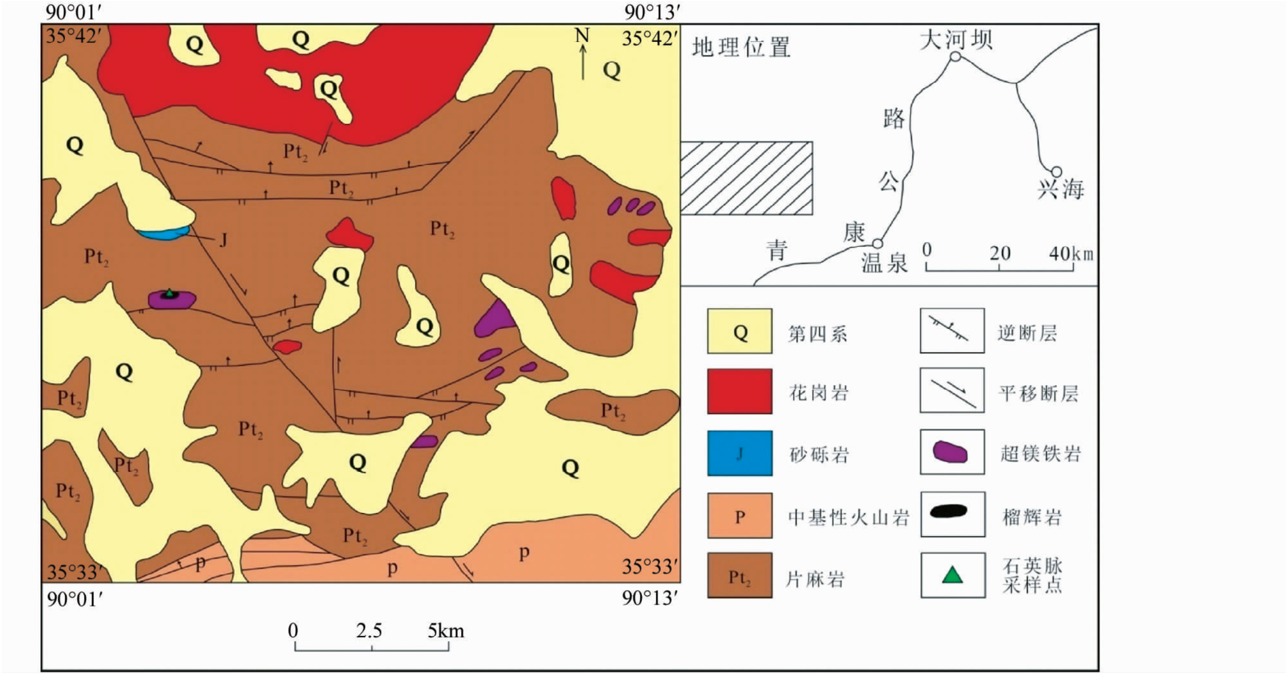


图 2　东昆仑温泉地区地质简图(据王秉璋等, 2001 修改)

Fig. 2　Geological sketch map of Wenquan area in East Kunlun (after Wang *et al.*, 2001)

2007;许志琴等,2007;刘彬等,2012),存在零星分布的早古生代蛇绿岩,如祁漫塔格地区的鸭子泉蛇绿岩(姜春发等,1992;崔美慧等,2011);晚泥盆世契盖苏群由碎屑岩和陆相火山岩组成(姜春发等,1992),代表了造山后期的磨拉石建造。

昆南地体由元古代的苦海群、万宝沟群、早古生代的纳赤台群以及志留-泥盆纪的牦牛山组红色磨拉石建造组成。苦海群主要为角闪岩、长英质片麻岩和大理岩,其原岩为碎屑岩、中-基性火山岩和碳酸盐岩,经历了早古生代的角闪岩相变质作用(王国灿等, 2004; Liu *et al.*, 2005);万宝沟群从下而上可分为五个组,依次为下碎屑岩组、火山岩组、绿色片岩组、碳酸盐岩组和上碎屑岩组,经历了绿片岩相变质作用(姜春发等,1992;潘裕生等,1996);纳赤台群主要为灰黑色、灰绿色变砂岩夹千枚岩以及大透镜状灰岩,经历了低级变质作用(姜春发等,1992),还有少量的石英岩和石英片岩(陈有炘等,2011),存在部分早古生代蛇绿岩残片,比如清水泉和乌妥地区的蛇绿岩(高延林等, 1988; Yang *et al.*, 1996; 朱云海等, 1999; 冯建赟等, 2010);晚泥盆世牦牛山组红色磨拉石建造标志着早古生代造山作用的结束(潘裕生等,1996;李荣社等,2007;许志琴等,2007;张耀玲等,2010)。

研究区位于东昆仑山最东端,距都兰东南方向约100km,温泉乡西北方向40km(图2),在东昆中断裂与温泉断裂交汇处的北西侧(王秉璋等,2001)。区内发育不同类型的高级变质岩,主要为元古代片麻岩,超镁铁岩和榴辉岩相邻产出于片麻岩之中(解玉月, 1998; 王秉璋等, 2001; Meng *et al.*, 2013);在片麻岩的北部和南部分别为泥盆纪花岗岩和石炭纪-二叠纪的沉积岩(Meng *et al.*, 2013)。

榴辉岩中有石英脉产出(图3a),脉宽约为3~8cm,主要有以下三个特征:(1)石英脉与寄主榴辉岩有明显的边界(图3a, c);(2)在石英脉中没有发现超高压变质的指示性矿物(图3d);(3)石英脉主要由石英组成,含量约为98%,含有少量方解石(图3d),进一步说明该石英脉为流体形成。这些特征说明石英脉并非形成于俯冲阶段,有可能形成于峰期变质阶段或早期折返阶段。寄主榴辉岩为黑绿色,块状构造,半自形柱状、粒状结构,主要由石榴石(40%)、绿辉石(10%)、后成合晶(20%)、石英(15%~20%)和金红石(5%~10%)组成。石榴石,粒状,半自形结构,颗粒大小为0.5~3mm,内部含有金红石和石英包体;绿辉石,粒状,半自形-他形结构,可见两组解理,粒径为0.03~0.50mm;后成合晶分散在石榴石和绿辉石之间(图3b),主要由单斜辉石和斜长石组成,粒径为5~10μm。榴辉岩的原岩为中基性侵入岩,其形成年龄为934Ma(Meng *et al.*, 2013),榴辉岩相峰期变质年龄为451Ma。

## 3　分析方法

锆石的分选由河北廊坊区调院完成,岩石样品经过破碎、淘洗并用重液分选出锆石,在双目镜下挑选出晶形和透明度较好的锆石颗粒作为测定对象,将待测锆石粘在双面胶上,用无色透明的环氧树脂固定,待环氧树脂充分固化后,对其表面进行抛光至锆石内部结构暴露,再进行锆石反射光和透射光照相、阴极发光(CL)显微图像研究以及LA-ICP-

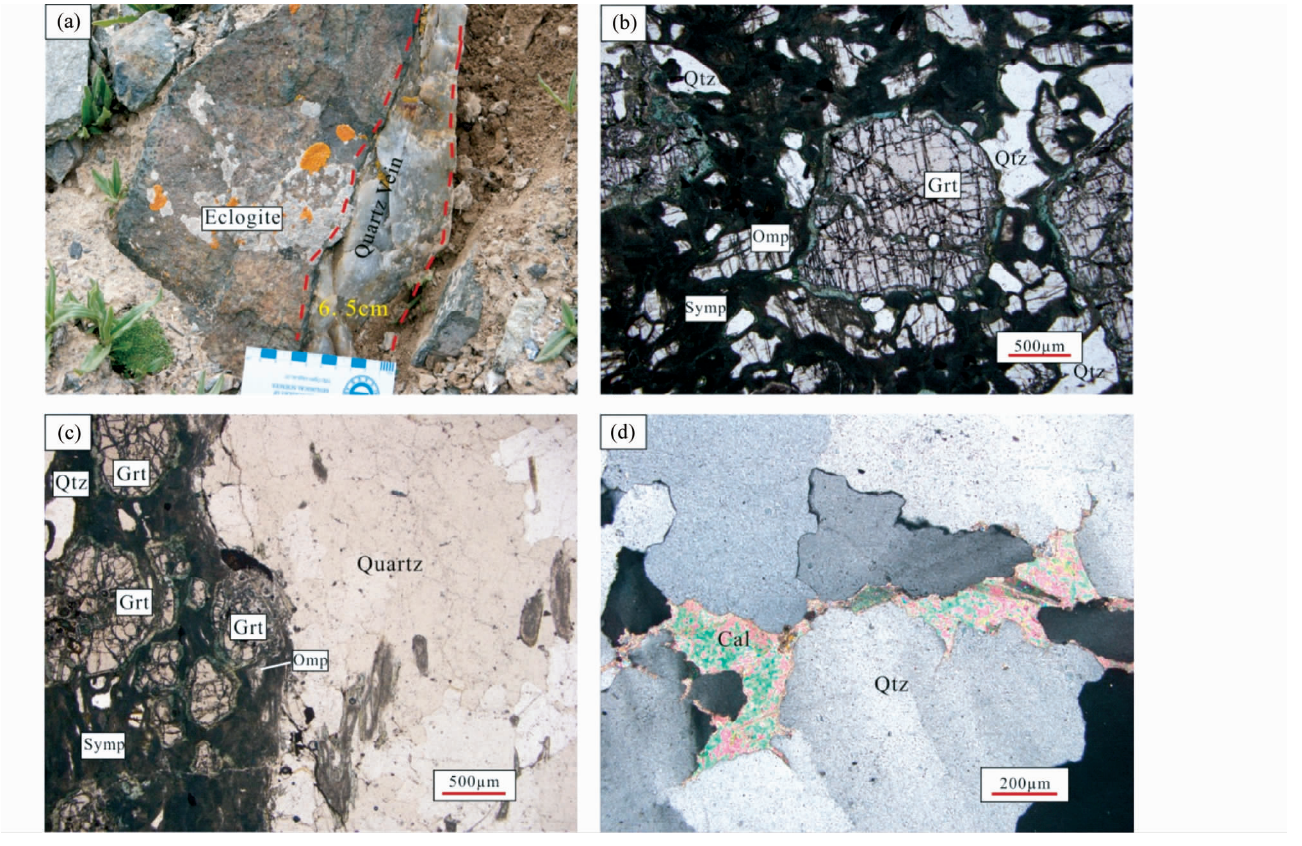


图3 东昆仑温泉地区榴辉岩中石英脉

(a)-榴辉岩和石英脉接触关系,脉宽约6.5cm;(b)-单偏光下榴辉岩;(c)-单偏光下榴辉岩和石英脉;(d)-正交光下石英脉,主要由石英(95%)组成,方解石充填在石英颗粒的间隙,含量约为5%. 矿物名称缩写:Qtz-石英;Omp-绿辉石;Symp-后成合晶;Grt-石榴石;Cal-方解石

Fig. 3 Quartz vein in eclogite from Wenquan area in East Kunlun

(a)-contact relationship between eclogite and quartz vein, quartz vein width of about 6.5cm; (b)-eclogite (-); (c)-eclogite and quartz vein (-); (d)-quartz vein (+) mainly composed of quartz (95%) and calcite (5%) fills in the gap. Abbreviations: Qtz-quartz; Omp-omphacite; Symp-symplectite; Grt-garnet; Cal-calcite

MS分析。测试点的选取首先根据锆石反射光和透射光显微照片进行初选,再与CL照片进行对比,尽量避开内部裂隙、包裹体以及不同成因的区域,以获得相对精确的年龄信息。

锆石的LA-ICP-MS测试由天津地质矿产研究所同位素实验室完成:利用193nm激光器对锆石进行剥蚀,通常采用的激光剥蚀的斑束直径为35或50μm,激光能量密度为13~14J/cm$^2$,频率为8~10Hz,激光剥蚀物质以He为载气送入Neptune,利用动态变焦扩大色散可以同时接受质量数相差很大的U-Pb同位素从而进行锆石U-Pb同位素原位测定。利用TEMORA作为外部锆石年龄标准。采用中国地质大学刘勇胜博士研发的ICPMSDataCal和Kenneth R. Ludwig的Isoplot程序进行数据处理,采用$^{208}$Pb校正法对普通铅进行校正。采用NIST612玻璃标样作为外标计算锆石样品的Pb、U、Th含量(李怀坤等,2009)。

锆石Lu-Hf同位素在中国地质科学院测定,用$^{176}$Lu/$^{175}$Lu=0.02669(DeBievre and Taylor, 1993)和$^{176}$Yb/$^{172}$Yb=0.5886(Chu *et al.*, 2002)进行同量异位干扰校正计算测试样品的$^{176}$Lu/$^{177}$Hf和$^{176}$Hf/$^{177}$Hf比值。$\varepsilon_{Hf}$的计算采用$^{176}$Lu衰变常数为$1.867\times10^{-11}y^{-1}$(Söderlund *et al.*, 2004),球粒陨石现今的$^{176}$Hf/$^{177}$Hf=0.282772,$^{176}$Lu/$^{177}$Hf=0.0332(Blichert-Toft and Albarède, 1997);Hf亏损地幔单阶段模式年龄$t_{DM1}$的计算采用现今的亏损地幔$^{176}$Hf/$^{177}$Hf=0.2835和$^{176}$Lu/$^{177}$Hf=0.0384(Griffin *et al.*, 2000),两阶段模式年龄$t_{DM2}$依据大陆上地壳平均组成$f_{Lu/Hf}=-0.55$(Griffin *et al.*, 2000)。

## 4 结果

### 4.1 锆石特征

石英脉(K12-2-4.2)中的锆石为自形-半自形,无色透明,长柱状,长度介于50~200μm,长宽比为2:1~3:1,核边结构不明显,具有较好的振荡环带或弱分带(图4a),晶型较好,明显与变质锆石不同,与热液成因的锆石特征类似(Rubatto *et al.*, 1999; Rubatto and Hermann, 2003; Zheng

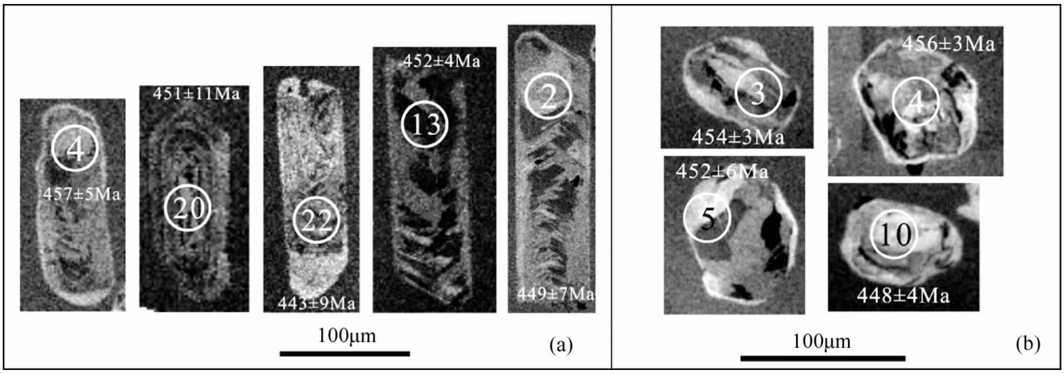


图4 东昆仑温泉地区石英脉(a)及榴辉岩(b)中代表性锆石阴极发光图像

Fig. 4 Representative CL images of analyzed zircon for quartz vein (a) and eclogite (b) from Wenquan area in East Kunlun

*et al.*, 2007; 吴元保和郑永飞, 2004)。

榴辉岩(K11-17-4.7)中的锆石为他形，无色透明，粒状-短柱状，长度介于 50～100μm，长宽比为 1∶1～2∶1(图4b)。CL 图像显示锆石具有弱的扇形分带结构，部分具有核边结构，边部较窄，这些特征表明锆石可能形成于变质作用的过程中。

### 4.2 锆石 U-Pb 同位素

对石英脉中的锆石测试了 30 个点(表 1)，所有的锆石点都具有较低的 Pb 含量($5\times10^{-6}\sim23\times10^{-6}$)和 U 含量($50\times10^{-6}\sim353\times10^{-6}$)，Th/U 比值也较低(0.0003～0.053)(除一点为 0.1126)，为典型的热液锆石(Rubatto, 2002)。大部分锆石的 $^{206}U/^{238}Pb$ 年龄集中在 441～459Ma(除一点为 363Ma)(图 5a, b)，其加权平均年龄为 449.9±1.9Ma($2\sigma$, n=29, MSWD=1.07)，这组年龄代表石英脉的形成年龄。

榴辉岩中的锆石共测试了 19 粒(表 1)，所有的锆石点都具有较低的 Pb 含量($5\times10^{-6}\sim42\times10^{-6}$)，其 U 含量为 $71\times10^{-6}\sim627\times10^{-6}$，Th/U 比值为 0.003～0.317，一致低的 Th/U 说明在榴辉岩相变质作用中存在含水流体。所有锆石的 $^{206}U/^{238}Pb$ 年龄集中在 446～459Ma(除一点为 431Ma)(图 5c, d)，其加权平均年龄为 451±2Ma($2\sigma$, n=18, MSWD=1.9)，这组年龄可能代表榴辉岩的峰期变质年龄。

### 4.3 锆石 Lu-Hf 同位素

石英脉中的锆石共分析了 15 颗 Lu-Hf 同位素数据(表 2)，$^{176}Lu/^{177}Hf$ 比值为 0.000006～0.000029，平均值为 0.000012，$^{176}Hf/^{177}Hf$ 比值为 0.2828450～0.2830796，平均值为 0.2829592。利用 LA-ICP-MS 测得各个相对锆石的 U-Pb 年龄，计算其 $\varepsilon_{Hf}(t)$ 值为 12.66～20.93，平均值为 16.5(图 6a)。寄主榴辉岩中共测试了 15 个锆石 Lu-Hf 同位素数据(有一点数据异常除外)，$^{176}Lu/^{177}Hf$ 比值为 0.000004～0.000120，平均值为 0.000027，$^{176}Hf/^{177}Hf$ 比值为 0.2828361～0.2830221，平均值为 0.2829286。利用 LA-ICP-MS 测得各个相对锆石的 U-Pb 年龄，计算其 $\varepsilon_{Hf}(t)$ 值为 12.19～18.85，平均值为 15.5(图 6b)。

## 5 讨论

### 5.1 流体活动的时间

目前大别地区超高压榴辉岩中石英脉的研究程度较高，大量研究认为在超高压峰期变质阶段流体活动受到限制(Rumble *et al.*, 2000; Fu *et al.*, 2001; Zheng *et al.*, 2003; Wu *et al.*, 2006)，其超高压峰期变质时间达 5～10Myr (Zheng *et al.*, 1998; Wu *et al.*, 2006)。温泉地区的榴辉岩中并未发现柯石英或金刚石等超高压的代表性矿物，属于高压榴辉岩(Meng *et al.*, 2013)。由于在进变质、峰期变质和退变质作用过程中矿物都存在结构水，因此不能排除流体活动发生在峰期变质阶段，尽管流体的流量是很小的。本文测得榴辉岩中锆石的加权平均年龄为 451±2Ma(图 5c, d)，即榴辉岩相峰期变质的年龄。Meng *et al.* (2013)利用 LA-ICP-MS 测得榴辉岩的峰期变质年龄为 430Ma，这两组数据在实验误差范围内(5%)一致，因此推测温泉地区榴辉岩相峰期变质年龄在 430～451Ma，石英脉中锆石的加权平均年龄为 450±2Ma(图 5a, b)。

结合前人对锆石学的研究，榴辉岩相变质条件下形成的锆石一般呈他形到半自形，无分带、弱分带到扇形分带，部分锆石具有残留岩浆核(Corfu *et al.*, 2003; Hoskin and Schaltegger, 2003; 吴元保和郑永飞, 2004)。本文榴辉岩中的锆石为他形，粒状-短柱状，具有弱的扇形分带结构，部分具有核边结构，边部较窄，这些特征表明锆石可能形成于变质作用的过程中。变质流体活动过程中形成的岩脉中的锆石一般为规则的外形，无分带到明显的面状分带或者振荡环带(Corfu *et al.*, 2003; Hoskin and Schaltegger, 2003; 吴元保和郑永飞, 2004)。本文石英脉中的锆石为自形-半自形，长柱状，核边结构不明显，具有较好的振荡环带或弱分带(图4)，晶型较好，明显与变质锆石不同，与热液成因的锆石特征类似。石英脉的寄主岩石为榴辉岩，石英脉中的锆石和榴辉岩中的锆石明显不同，这排除了在流体活动的过程中从榴辉

表 1 锆石 U-Pb 同位素定年测试数据结果

Table 1 U-Pb isotope data of zircons

| 序号 | Pb (×10⁻⁶) | U (×10⁻⁶) | $\frac{^{207}Pb}{^{206}Pb}$ | 1σ | $\frac{^{207}Pb}{^{235}U}$ | 1σ | $\frac{^{206}Pb}{^{238}U}$ | 1σ | $\frac{^{207}Pb}{^{206}Pb}$ (Ma) | 1σ | $\frac{^{207}Pb}{^{235}U}$ (Ma) | 1σ | $\frac{^{206}Pb}{^{238}U}$ (Ma) | 1σ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| K12-2-4.2 石英脉 | | | | | | | | | | | | | | |
| 1 | 5 | 72 | 0.0568 | 0.0039 | 0.5527 | 0.0384 | 0.0706 | 0.0016 | | | 447 | 31 | 443 | 10 |
| 2 | 6 | 77 | 0.0574 | 0.0030 | 0.5704 | 0.0315 | 0.0721 | 0.0012 | | | 458 | 25 | 449 | 7 |
| 3 | 7 | 103 | 0.0557 | 0.0023 | 0.5639 | 0.0252 | 0.0735 | 0.0012 | | | 454 | 20 | 457 | 7 |
| 4 | 11 | 160 | 0.0541 | 0.0019 | 0.5483 | 0.0195 | 0.0735 | 0.0009 | | | 444 | 16 | 457 | 5 |
| 5 | 16 | 235 | 0.0566 | 0.0011 | 0.5668 | 0.0126 | 0.0726 | 0.0010 | | | 456 | 10 | 452 | 6 |
| 6 | 6 | 78 | 0.0569 | 0.0037 | 0.5701 | 0.0372 | 0.0727 | 0.0013 | | | 458 | 30 | 452 | 8 |
| 7 | 6 | 94 | 0.0563 | 0.0029 | 0.5684 | 0.0323 | 0.0733 | 0.0010 | | | 457 | 26 | 456 | 6 |
| 8 | 8 | 109 | 0.0577 | 0.0027 | 0.5815 | 0.0287 | 0.0731 | 0.0012 | | | 465 | 23 | 455 | 7 |
| 9 | 6 | 50 | 0.0539 | 0.0035 | 0.5479 | 0.0391 | 0.0738 | 0.0026 | | | 444 | 32 | 459 | 16 |
| 10 | 15 | 219 | 0.0575 | 0.0012 | 0.5850 | 0.0134 | 0.0738 | 0.0007 | | | 468 | 11 | 459 | 5 |
| 11 | 8 | 83 | 0.0547 | 0.0038 | 0.5530 | 0.0420 | 0.0733 | 0.0014 | | | 447 | 34 | 456 | 9 |
| 12 | 14 | 208 | 0.0557 | 0.0013 | 0.5651 | 0.0137 | 0.0736 | 0.0006 | | | 455 | 11 | 458 | 4 |
| 13 | 11 | 166 | 0.0571 | 0.0018 | 0.5709 | 0.0194 | 0.0726 | 0.0007 | | | 459 | 16 | 452 | 4 |
| 14 | 14 | 212 | 0.0566 | 0.0013 | 0.5588 | 0.0138 | 0.0715 | 0.0007 | | | 451 | 11 | 445 | 4 |
| 15 | 11 | 168 | 0.0579 | 0.0013 | 0.5773 | 0.0132 | 0.0724 | 0.0009 | | | 463 | 11 | 451 | 6 |
| 16 | 9 | 173 | 0.0635 | 0.0016 | 0.5066 | 0.0151 | 0.0578 | 0.0007 | | | 416 | 12 | 363 | 4 |
| 17 | 14 | 200 | 0.0561 | 0.0012 | 0.5718 | 0.0126 | 0.0740 | 0.0010 | | | 459 | 10 | 460 | 6 |
| 18 | 11 | 166 | 0.0563 | 0.0014 | 0.5590 | 0.0147 | 0.0721 | 0.0007 | | | 451 | 12 | 449 | 4 |
| 19 | 11 | 163 | 0.0556 | 0.0013 | 0.5576 | 0.0136 | 0.0727 | 0.0009 | | | 450 | 11 | 452 | 6 |
| 20 | 13 | 189 | 0.0562 | 0.0013 | 0.5585 | 0.0131 | 0.0721 | 0.0006 | | | 451 | 11 | 449 | 4 |
| 21 | 12 | 177 | 0.0563 | 0.0012 | 0.5510 | 0.0116 | 0.0710 | 0.0012 | | | 446 | 9 | 442 | 7 |
| 22 | 11 | 176 | 0.0534 | 0.0012 | 0.5243 | 0.0115 | 0.0712 | 0.0012 | | | 428 | 9 | 443 | 7 |
| 23 | 13 | 199 | 0.0543 | 0.0011 | 0.5324 | 0.0106 | 0.0711 | 0.0009 | | | 433 | 9 | 443 | 6 |
| 24 | 23 | 353 | 0.0549 | 0.0006 | 0.5405 | 0.0065 | 0.0714 | 0.0008 | | | 439 | 5 | 444 | 5 |
| 25 | 14 | 201 | 0.0545 | 0.0014 | 0.5536 | 0.0244 | 0.0737 | 0.0012 | | | 447 | 20 | 459 | 8 |
| 26 | 14 | 220 | 0.0579 | 0.0009 | 0.5644 | 0.0090 | 0.0708 | 0.0006 | | | 454 | 7 | 441 | 4 |
| 27 | 12 | 173 | 0.0564 | 0.0011 | 0.5681 | 0.0120 | 0.0731 | 0.0009 | | | 457 | 10 | 455 | 6 |
| 28 | 19 | 293 | 0.0558 | 0.0008 | 0.5526 | 0.0078 | 0.0719 | 0.0006 | | | 447 | 6 | 448 | 4 |
| 29 | 15 | 235 | 0.0532 | 0.0010 | 0.5273 | 0.0102 | 0.0719 | 0.0007 | | | 430 | 8 | 448 | 4 |
| 30 | 15 | 232 | 0.0551 | 0.0010 | 0.5479 | 0.0103 | 0.0722 | 0.0006 | | | 444 | 8 | 449 | 4 |
| K11-17-4.7 榴辉岩 | | | | | | | | | | | | | | |
| 1 | 7 | 102 | 0.0667 | 0.0025 | 0.6770 | 0.0261 | 0.0736 | 0.0005 | 829 | 79 | 525 | 20 | 458 | 3 |
| 2 | 7 | 109 | 0.0567 | 0.0023 | 0.5682 | 0.0233 | 0.0727 | 0.0005 | 480 | 90 | 457 | 19 | 452 | 3 |
| 3 | 24 | 351 | 0.0574 | 0.0010 | 0.5770 | 0.0106 | 0.0730 | 0.0005 | 506 | 37 | 463 | 8 | 454 | 3 |
| 4 | 26 | 377 | 0.0572 | 0.0010 | 0.5774 | 0.0105 | 0.0733 | 0.0005 | 498 | 38 | 463 | 8 | 456 | 3 |
| 5 | 22 | 322 | 0.0597 | 0.0008 | 0.5994 | 0.0092 | 0.0728 | 0.0005 | 593 | 31 | 477 | 7 | 453 | 3 |
| 6 | 42 | 627 | 0.0568 | 0.0006 | 0.5650 | 0.0059 | 0.0721 | 0.0004 | 485 | 22 | 455 | 5 | 449 | 3 |
| 7 | 10 | 142 | 0.0598 | 0.0018 | 0.6081 | 0.0190 | 0.0738 | 0.0004 | 596 | 67 | 482 | 15 | 459 | 3 |
| 8 | 7 | 99 | 0.0646 | 0.0038 | 0.6546 | 0.0391 | 0.0735 | 0.0006 | 760 | 125 | 511 | 31 | 457 | 4 |
| 9 | 16 | 241 | 0.0598 | 0.0019 | 0.5903 | 0.0196 | 0.0716 | 0.0004 | 596 | 70 | 471 | 16 | 446 | 3 |
| 10 | 13 | 187 | 0.0702 | 0.0029 | 0.6966 | 0.0302 | 0.0720 | 0.0006 | 933 | 84 | 537 | 23 | 448 | 4 |
| 11 | 5 | 71 | 0.0565 | 0.0042 | 0.5667 | 0.0420 | 0.0728 | 0.0006 | 472 | 165 | 456 | 34 | 453 | 4 |
| 12 | 17 | 259 | 0.0577 | 0.0022 | 0.5502 | 0.0213 | 0.0692 | 0.0005 | 519 | 83 | 445 | 17 | 431 | 3 |
| 13 | 11 | 162 | 0.0564 | 0.0014 | 0.5652 | 0.0138 | 0.0727 | 0.0004 | 467 | 53 | 455 | 11 | 453 | 3 |
| 14 | 8 | 115 | 0.0571 | 0.0018 | 0.5692 | 0.0183 | 0.0723 | 0.0005 | 495 | 69 | 457 | 15 | 450 | 3 |
| 15 | 24 | 357 | 0.0575 | 0.0010 | 0.5746 | 0.0101 | 0.0725 | 0.0006 | 510 | 37 | 461 | 8 | 451 | 4 |
| 16 | 12 | 176 | 0.0602 | 0.0026 | 0.5948 | 0.0255 | 0.0716 | 0.0004 | 612 | 92 | 474 | 20 | 446 | 3 |
| 17 | 11 | 162 | 0.0566 | 0.0015 | 0.5627 | 0.0157 | 0.0721 | 0.0004 | 475 | 60 | 453 | 13 | 449 | 3 |
| 18 | 8 | 120 | 0.0683 | 0.0025 | 0.6763 | 0.0254 | 0.0718 | 0.0004 | 878 | 76 | 525 | 20 | 447 | 3 |
| 19 | 11 | 95 | 0.0565 | 0.0019 | 0.5642 | 0.0216 | 0.0724 | 0.0005 | 473 | 72 | 454 | 17 | 451 | 3 |

**表 2 锆石 Lu-Hf 同位素数据结果**

Table 2 Lu-Hf isotope data of zircons

| 序号 | $^{176}Yb/^{177}Hf$ | $^{176}Lu/^{177}Hf$ | $^{176}Hf/^{177}Hf$ | $2\sigma$ | Age (Ma) | $\varepsilon_{Hf}(0)$ | $\varepsilon_{Hf}(t)$ | $t_{DM1}$ (Ma) | $f_{Lu/Hf}$ |
|---|---|---|---|---|---|---|---|---|---|
| K12-2-4.2 石英脉 | | | | | | | | | |
| 1 | 0.0002812 | 0.0000060 | 0.2829794 | 0.0000205 | 443 | 7.34 | 17.10 | 376 | -0.9998 |
| 2 | 0.0003267 | 0.0000078 | 0.2829653 | 0.0000186 | 449 | 6.84 | 16.73 | 396 | -0.9998 |
| 3 | 0.0006192 | 0.0000139 | 0.2828452 | 0.0000237 | 457 | 2.59 | 12.66 | 562 | -0.9996 |
| 4 | 0.0003864 | 0.0000088 | 0.2830429 | 0.0000231 | 459 | 9.58 | 19.70 | 288 | -0.9997 |
| 5 | 0.0004314 | 0.0000098 | 0.2830009 | 0.0000218 | 459 | 8.10 | 18.22 | 346 | -0.9997 |
| 6 | 0.0004108 | 0.0000112 | 0.2830796 | 0.0000289 | 456 | 10.88 | 20.93 | 237 | -0.9997 |
| 7 | 0.0003701 | 0.0000084 | 0.2830114 | 0.0000215 | 452 | 8.47 | 18.43 | 332 | -0.9997 |
| 8 | 0.0005671 | 0.0000120 | 0.2829503 | 0.0000218 | 458 | 6.30 | 16.40 | 417 | -0.9996 |
| 9 | 0.0004852 | 0.0000118 | 0.2829836 | 0.0000267 | 445 | 7.48 | 17.29 | 370 | -0.9996 |
| 10 | 0.0005507 | 0.0000136 | 0.2829238 | 0.0000271 | 449 | 5.37 | 15.26 | 453 | -0.9996 |
| 11 | 0.0004257 | 0.0000087 | 0.2829000 | 0.0000241 | 443 | 4.53 | 14.29 | 486 | -0.9997 |
| 12 | 0.0010389 | 0.0000292 | 0.2829294 | 0.0000369 | 441 | 5.57 | 15.28 | 446 | -0.9991 |
| 13 | 0.0007572 | 0.0000163 | 0.2829054 | 0.0000276 | 449 | 4.72 | 14.61 | 479 | -0.9995 |
| 14 | 0.0006034 | 0.0000137 | 0.2829568 | 0.0000206 | 455 | 6.53 | 16.56 | 408 | -0.9996 |
| 15 | 0.0006780 | 0.0000145 | 0.2829133 | 0.0000239 | 449 | 5.00 | 14.89 | 468 | -0.9996 |
| K11-17-4.7 榴辉岩 | | | | | | | | | |
| 16 | 0.0031595 | 0.0001196 | 0.2828564 | 0.0000203 | 458 | 2.98 | 13.04 | 548 | -0.9964 |
| 17 | 0.0004145 | 0.0000100 | 0.2830221 | 0.0000281 | 454 | 8.84 | 18.85 | 317 | -0.9997 |
| 18 | 0.0002684 | 0.0000072 | 0.2829946 | 0.0000197 | 456 | 7.87 | 17.92 | 355 | -0.9998 |
| 19 | 0.0002827 | 0.0000066 | 0.2829698 | 0.0000278 | 453 | 7.00 | 16.98 | 389 | -0.9998 |
| 20 | 0.0003999 | 0.0000090 | 0.2829841 | 0.0000288 | 449 | 7.50 | 17.40 | 370 | -0.9997 |
| 21 | 0.0002244 | 0.0000055 | 0.2829482 | 0.0000180 | 459 | 6.23 | 16.35 | 419 | -0.9998 |
| 22 | 0.0001519 | 0.0000038 | 0.2829216 | 0.0000212 | 446 | 5.29 | 15.12 | 456 | -0.9999 |
| 23 | 0.0018034 | 0.0000680 | 0.2828785 | 0.0000336 | 451 | 3.77 | 13.69 | 517 | -0.9980 |
| 24 | 0.0002809 | 0.0000116 | 0.2832328 | 0.0000445 | 431 | 16.30 | 25.80 | 24 | -0.9997 |
| 25 | 0.0011847 | 0.0000334 | 0.2829114 | 0.0000262 | 451 | 4.93 | 14.86 | 471 | -0.9990 |
| 26 | 0.0006769 | 0.0000247 | 0.2829078 | 0.0000309 | 451 | 4.80 | 14.74 | 476 | -0.9993 |
| 27 | 0.0010353 | 0.0000302 | 0.2829491 | 0.0000198 | 451 | 6.26 | 15.90 | 418 | -0.9991 |
| 28 | 0.0008116 | 0.0000190 | 0.2828642 | 0.0000243 | 451 | 3.26 | 13.19 | 536 | -0.9994 |
| 29 | 0.0003594 | 0.0000078 | 0.2829565 | 0.0000224 | 451 | 6.52 | 16.46 | 408 | -0.9998 |
| 30 | 0.0011337 | 0.0000384 | 0.2828361 | 0.0000235 | 451 | 2.27 | 12.19 | 575 | -0.9988 |

岩中捕获锆石的可能性，因此有充分的证据可以说明石英脉中的锆石是从流体活动过程中形成的。

通常情况下 U 较 Th 在流体中有更高的溶解度，其活动性强于 Th，石英脉中形成的锆石比寄主榴辉岩中的锆石具有更低的 Th/U 比值（吴元保和郑永飞，2004；Wu *et al.*，2006，2009；刘小驰等，2009）。本文榴辉岩中变质锆石的 Th/U 比值的变化范围是 0.003 ~ 0.053，石英脉中结晶的锆石的 Th/U 比值的变化范围为 0.003 ~ 0.317（表 1），石英脉中锆石的 Th/U 比值整体比榴辉岩中的略小或者两者几乎一致，表明其形成条件的相似性。

锆石一般有较高的 Hf 含量，其 Lu/Hf 比值较低，相反，一些诸如石榴石、褐帘石、独居石等富集 REE 的矿物通常具有较高的 Lu/Hf 比值（Zheng *et al.*，2005；Wu *et al.*，2006）。若锆石与石榴石同时形成，则锆石的 Lu/Hf 比值将会更低，但如果锆石在石榴石分解之后形成，则其 Lu/Hf 比值会相应的增大。本文中锆石的 Lu/Hf 比值都相对较低（表 2），故从这一角度说明该石英脉并非形成于折返阶段。

结合以上对温泉地区榴辉岩和石英脉中锆石的 U-Pb 定年、Th/U 比值以及 Lu/Hf 比值的综合研究，推测此次流体活动发生在榴辉岩相峰期变质阶段。

## 5.2 流体的来源和特征

在大别-苏鲁地区，普遍认为在当陆壳俯冲到地幔深度时的峰期变质阶段中很难有流体活动（Rumble *et al.*，2000；Fu *et al.*，2001；Zheng *et al.*，2003，2007；Frezzotti *et al.*，2007）。但是，在减压的过程中会有大量流体从含水矿物的分解（Li *et al.*，2004；Wu *et al.*，2006）以及名义上无水矿物（绿辉石、石榴石和金红石）羟基的出溶作用中产生（Zheng *et al.*，2003，2007；Chen *et al.*，2007；Frezzotti *et al.*，2007；Sheng *et al.*，2007）。经实验研究，榴辉岩中辉石、石榴石和

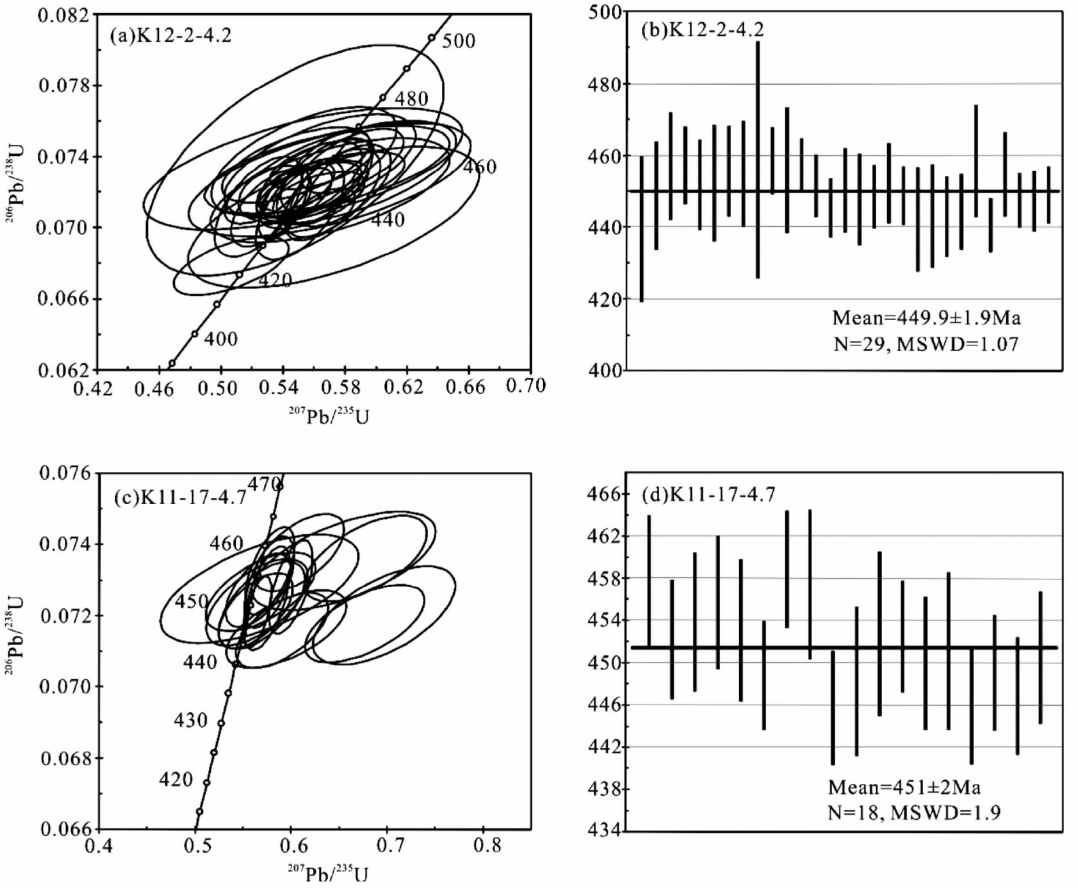


图5 东昆仑温泉地区石英脉(a、b)及榴辉岩(c、d)中锆石 U-Pb 年龄谐和曲线图

Fig. 5 Zircon U-Pb age concordia diagram for quartz vein (a, b) and eclogite (c, d) from Wenquan area in East Kunlun

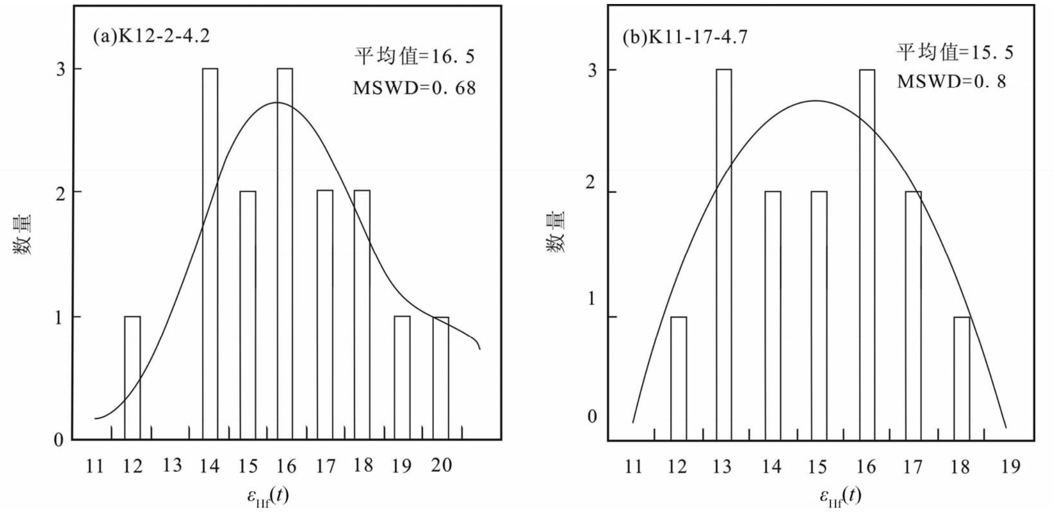


图6 东昆仑温泉地区石英脉(a)及榴辉岩(b)中锆石 Lu-Hf 同位素 $\varepsilon_{Hf}(t)$ 值频率分布图

Fig. 6 Histograms of zircon $\varepsilon_{Hf}(t)$ values of Lu-Hf isotope for quartz vein (a) and eclogite (b) from Wenquan area in East Kunlun

金红石在地幔压力下有大量的水储存在结构水的羟基中(Skogby *et al.*, 1990; Rossman, 1996; Sheng *et al.*, 2007),辉石的羟基含水量为 $600\times10^{-6}\sim1300\times10^{-6}$(Ingrin and Skogby, 2000),金红石的羟基中含水量为 $4300\times10^{-6}\sim9600\times10^{-6}$,石榴石的羟基含水量为 $92\times10^{-6}\sim1735\times10^{-6}$(Zhang *et al.*, 2001),使得绿辉石以及金红石等成为在俯冲

至地幔过程中最重要的再生水矿物(Zheng *et al.*, 2003),这种流体可以溶解围岩榴辉岩中的元素并且可以运输短暂的距离(Rubatto and Hermann, 2003)。

温泉地区榴辉岩与石英脉具有明显的边界,且接触界线较为平直(图3c),推测在榴辉岩相峰期变质阶段末发生流体活动之前,此处岩石破裂,裂隙处压力突然降低导致榴辉岩中绿辉石、石榴石等矿物结构中的羟基发生出溶作用,进而产生流体进入到裂隙形成石英脉。另外,在寄主榴辉岩中含有15% ~20%的石英(图3b),绿辉石和石榴石中也发现石英包体,在榴辉岩相峰期变质条件下,这部分石英也可能发生溶解,进入裂隙参与岩脉的形成。因此,温泉地区榴辉岩中的石英脉是榴辉岩中石英溶解以及绿辉石和石榴石结构中羟基发生出溶共同作用的结果。

高级变质作用中锆石的生长机制主要有3种:1)在深熔作用中从熔体中结晶的(Vavra *et al.*, 1999);2)矿物分解释放的Si和Zr进而形成锆石(Bingen *et al.*, 2004);3)在含水流体中结晶的(Vavra *et al.*, 1999; Rubatto and Hermann, 2003; Wu *et al.*, 2006)。绿辉石是榴辉岩相中的典型矿物,在高压榴辉岩中绿辉石和石榴石都是含锆的矿物(锆含量分别可达到$1.8 \times 10^{-6}$和$4.7 \times 10^{-6}$; Sassi *et al.*, 2000; Rubatto and Hermann, 2003),尽管这两种矿物分解可以促进在榴辉岩相变质作用下锆石的生长,但若缺少流体,这些都是无意义的,所有变质锆石的生长都只能发生在流体相中(Fraser *et al.*, 1997; Zheng *et al.*, 2004; Corfu *et al.*, 2003; Wu *et al.*, 2006)。

在流体中U比Th流动性更强,故极低的Th/U比值的锆石往往是在含水流体中结晶的。熔体中形成的长英质脉体一般包含石英和长石(Chen *et al.*, 2012),但此次研究的石英脉却没有发现长石,这些证据说明锆石形成于流体而并非熔体。至于形成方解石的Ca(图3d),可能来自绿辉石;流体中的$CO_2$,可能与其他热液流体蚀变有关(Rayner *et al.*, 2005)。

由于锆石富集Hf的能力比Lu强,通常利用Hf同位素的组成能够识别流体的来源。石英脉中的锆石的$\varepsilon_{Hf}(t)$值为12.66~20.93,寄主榴辉岩中$\varepsilon_{Hf}(t)$值为12.19~18.85(图6),$^{176}Lu/^{177}Hf$比值和$^{176}Hf/^{177}Hf$比值见表2。从数据中我们可以看出,石英脉中锆石的Hf同位素组成与寄主榴辉岩相似,但是有小的变化。这些相似性表明形成石英脉的流体为内部来源,并经历了短距离的运移。Zheng *et al.* (2007)在大别山东部的石英脉中通过氧同位素的研究也得出了相似的结论。榴辉岩中锆石的$\varepsilon_{Hf}(t)$平均值为15.5,如此高的$\varepsilon_{Hf}(t)$值表明榴辉岩的原岩(中-基性辉长岩)源于亏损的地幔(Wu *et al.*, 2006; Zheng *et al.*, 2005, 2006; 吴福元等, 2007)。

## 6 结论

本文综合了锆石的U-Pb定年和Lu-Hf同位素的研究,详细解释了高压条件下流体活动的时代、条件以及来源。通过对石英脉的野外接触关系、矿物组成、锆石内部结构、Th、U含量和Th/U比值以及Hf同位素的分析,得出以下认识:

(1)测得榴辉岩的峰期变质年龄为451±2Ma,石英脉中锆石的年龄为450±2Ma,两者在误差范围内一致的年龄说明在榴辉岩相峰期变质阶段可以出现内部流体活动。

(2)认为锆石更可能形成于含水流体而非熔体,对比寄主榴辉岩的锆石和石英脉中锆石的Hf同位素组成,其相似性说明形成石英脉的流体来自榴辉岩的内部,推测流体来源于寄主榴辉岩中石英的溶解以及绿辉石和石榴石分子结构中羟基的出溶作用。

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