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太行山北段木吉村髫髻山组安山岩锆石 U-Pb 年龄和 Hf 同位素特征及其对区域成岩成矿规律的指示

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内容提要：太行山北段是中国东部中生代重要的成矿区带，髫髻山组火山岩记录了该地区中生代大规模成岩成矿事件发生的时代和有关岩浆作用源区的信息。髫髻山组安山岩中锆石大多具有明显的核幔结构，LA-MC-ICP-MS 测试得出，锆石幔部年龄为 144～145Ma 左右，核部年龄为 2.08～2.65Ga。两组锆石年龄中，前者代表了髫髻山组火山岩的形成时代，两件样品加权平均年龄分别为 145.28±0.44Ma 和 144.61±0.76Ma；后者年龄与华北克拉通在前寒武纪增生变质等演化时代一致，揭示出火山岩形成过程中华北克拉通古老地壳的参与。对应两组年龄，锆石 Hf 同位素特征也明显的分为两组，中生代 $\varepsilon Hf_{(t)}$ 值集中于－25～－10 之间，表现为壳幔混合源区特征；新太古代—古元古代 $\varepsilon Hf_{(t)}$ 值集中于 0～10 之间，表现为地壳增生的特征，与华北克拉通前寒武纪的演化时代相一致。结合已有岩石地球化学研究，髫髻山组火山岩的形成源于富集地幔部分熔融，在岩浆上侵过程中同化混染（或混合）了华北克拉通的古老地壳，在经历了分离结晶作用后侵位产出。髫髻山组火山岩是晚中生代华北克拉通构造背景转换的代表，在其形成后发育有大量与之相关的斑岩型铜钼矿床，通过总结对比中生代中国东部成岩成矿规律，我们推测太行山地区在中生代可能形成有两期重要的成矿事件，一期以斑岩型铜—钼矿床的形成为特征，另一期由金矿床的产出为代表。

关键词：太行山北段；木吉村；髫髻山组火山岩；锆石 U-Pb 年龄

太行山北段成矿带位于中国东部华北克拉通中部造山带北端，受克拉通构造演化及中生代板块活动影响的控制。中生代古太平洋板块的俯冲诱发了华北克拉通东部整体的裂解，形成了大规模的岩浆活动和伸展盆地，同时发育有大量的斑岩型铜钼矿化及金矿化，是中国东部重要的成矿单元组成（Zhu Rixiang et al.，2001；Mao Jingwen et al.，2003，2005，2014）。发育于中生代的髫髻山组和土城子组火山岩及不整合覆盖之上的张家口组和义县组火山岩，记录了白垩纪和侏罗纪之间的动力学调整的信息（Ren Jishun et al.，1998），是燕山运动的重要标志（Wong Wenhao，1929）。髫髻山组火山岩的分布较广，在北京西山、冀北和辽西等地均有出露，前人对其进行了大量的研究，揭示了华北克拉通及中国东部地区的构造演化，标志着大规模成岩成矿事件的开始（Zhao Yue et al.，2004）。近年来，太行山北段斑岩型铜钼矿床的发现、勘探和成因研究受到较高的关注，研究多认为成矿作用与高 Sr 低 Y 性质岩浆的喷发（髫髻山组火山岩）及其后期发育的次火山岩侵入活动有关，并同属于中生代中国东部成岩成矿大事件（Ma Guoxi，1997；Ma Guoxi et al.，2009；Zhang Qing et al.，2009；Gao Yongxing et al.，2011）。木吉村斑岩型铜钼矿床（图 1）是太行山北段多金属成矿带最重要的代表之一，对该地区髫髻山组火山岩年代学和地球化学的研究取得了诸多的成果，但以下问题仍存在争议：对火山岩的年代学研究得到成岩阈值为 150.5～131Ma，其跨越了 20Ma，同时横跨晚侏罗纪和早白垩纪，时代约束较松散，这与紧随髫髻山组火山岩发育的闪长玢岩以及伴随形成的斑岩型铜钼矿床（141～144Ma）在形成时代上相矛盾（Gao Yongfeng et al.，2011；Zhao Yue et al.，2004；Yuan et al.，2006；Li Wuping et

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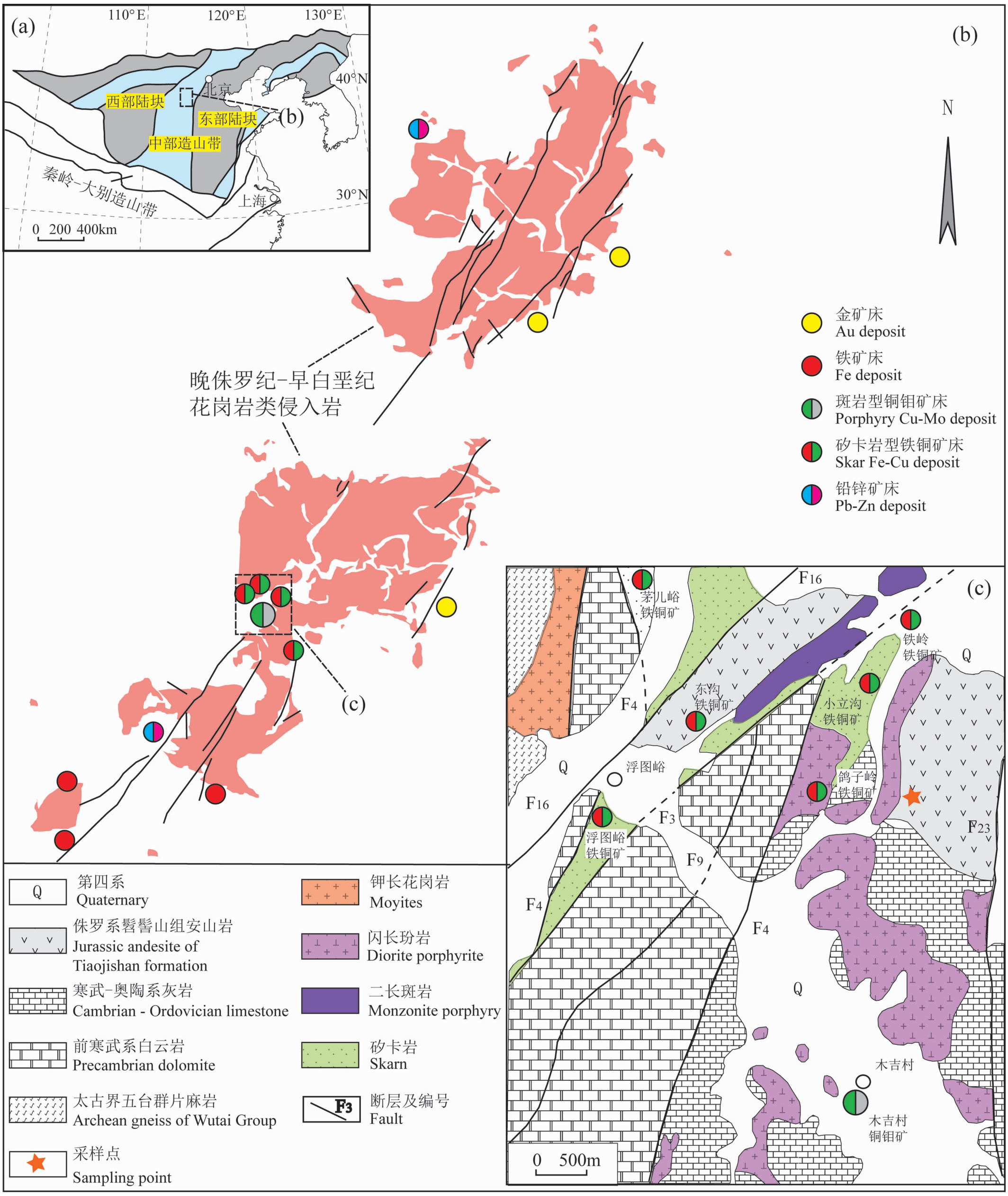

图 1 (a)华北克拉通构造略图;(b)太行山北段岩浆与矿产分布图;(c)木吉村矿田地质图(据 Dong Guochen et al.,2013 修改)

Fig. 1 (a)Tectonic geological map of the North China Craton; (b)sketch of magmatic intrusion and deposits distribution in north Taihang Mt. area; (c)geological map of the Mujicun ore cluster. (Modified by Dong Guochen et al., 2013)

al., 2001; Shen Zhichao et al., 2015);对火山岩形成的源区亦存在不同的认知,其可能源于玄武质下地壳熔融或富集的岩石圈地幔上侵过程中与古老地壳的混染(或混合)(Li Wuping et al., 2001a, 2001b, 2007; Ge Xiaoyue et al., 2002; Zhao Yue et al., 2004; Chen Bin et al., 2005, 2013; Wang Rui et al., 2007; Gao Yongfeng et al., 2011, 2012, 2013)。在对木吉村髫髻山组安山岩的研究中,我们发现了大量的核幔构造锆石,对捕获锆石的研究可以更为直接的揭示岩浆岩的起源和演化等信息。因而,对木吉村髫髻山组安山岩锆石新生幔和捕获锆石(位于锆石核部)的 U-Pb 年代学与 Hf 同位素地球化学特征的研究,将会更为精细的约束火山岩的形成时代揭示火山岩演化信息,同时为太行山地区成岩成矿作用过程的理解提供新的佐证。

1 区域地质背景

太行山北段中生代岩浆岩带在构造上处于华北克拉通中部造山带。华北克拉通是全球最古老的克拉通之一,经历了多阶段的构造演化和强烈的变质

改造，多数研究认为克拉通的东西板块沿中部造山带拼合于 1.85Ga 左右，完成克拉通化（Zhao Guochun et al.，2001，2012；Wilde et al.，2002；Kröner et al.，2006；Wilde et al.，2005）。在 1.85～1.7Ga 期间进入伸展构造体制，内部及边部发生了拉张，抬升等地质事件，对应于古元古代末—中元古代初 Columbia 全球性的非造山岩浆活动，是一次超大陆裂解事件（Zhai Mingguo，2004，2012；Zhai Mingguo et al.，2003；Peng Peng et al.，2007；Windley，1995；Yu Jianhua et al.，1996；Rämö et al.，1995；Zhao Taiping et al.，2004；Lu Songnian et al.，2008）。此后华北克拉通进入盖层沉积阶段，大部分地区一直稳定到早中生代（Xu Yigang，2001；Gao Shan et al.，2002；Yang Jinhui et al.，2003；Zhu Rixiang et al.，2011）。晚中生代以来，大规模的伸展作用使华北克拉通中部造山带发生强烈的构造岩浆活动，形成了 NNE 向展布的太行山构造岩浆岩带。

太行山北段的中生代岩浆岩带主要由中生代火山岩及其之后发育的次火山岩、王安镇岩体、大河南岩体和涞源岩体组成，其展布受东、西两侧分布的 NNE 向紫荆关断裂和乌龙沟断裂带控制（Cai Jianhui et al.，2003；Gao Yongfeng et al.，2011）。其中，涞源杂岩体是中生代岩浆岩带太行山北段最大的复式岩基，主要以中酸性侵入岩为主，含有少量同期基性侵入体及早阶段火山岩，发育有以木吉村斑岩型铜钼矿床为代表的一系列铜、钼、铁、铅锌等矿床。木吉村斑岩铜矿体赋存在髫髻山火山岩绵胡坨古火山机构西南侧的闪长玢岩岩体中，火山机构底部火山集块岩和火山角砾岩呈环带分布，其被火山凝灰岩和溢流熔岩覆盖。对火山岩—次火山岩野外研究工作证实，与成矿密切相关的闪长玢岩即为髫髻山火山旋回晚阶段次火山岩相的产物（Ma Guoxi，1997；Ma Guoxi et al.，2010；Gao Yongfeng et al.，2011；Peng Yuxuan，2011）。含矿岩体发育有典型斑岩型矿床分带蚀变特征，从中心向外可划分出 4 个蚀变带：强硅化带（石英核）、钾化带、绢英岩化带、青磐岩化带，铜钼矿化主要出现在钾化带中。

2 样品采集与测试

2.1 样品采集及锆石特征

木吉村髫髻山组火山岩主要由火山碎屑岩、安山岩和英安岩组成，它们不整合覆盖在古生代寒武纪—奥陶纪地层上，后又被东岭台组火山岩不整合覆盖。本文两件火山岩样品采自绵胡坨火山机构喷发中心西南约 0.5km（N114°51′0.4″；E39°22′2.4″）。安山岩呈灰色、紫红色，具有斑状结构，气孔杏仁构造发育（图 2a，b）。斑晶（30%～40%）主要为斜长

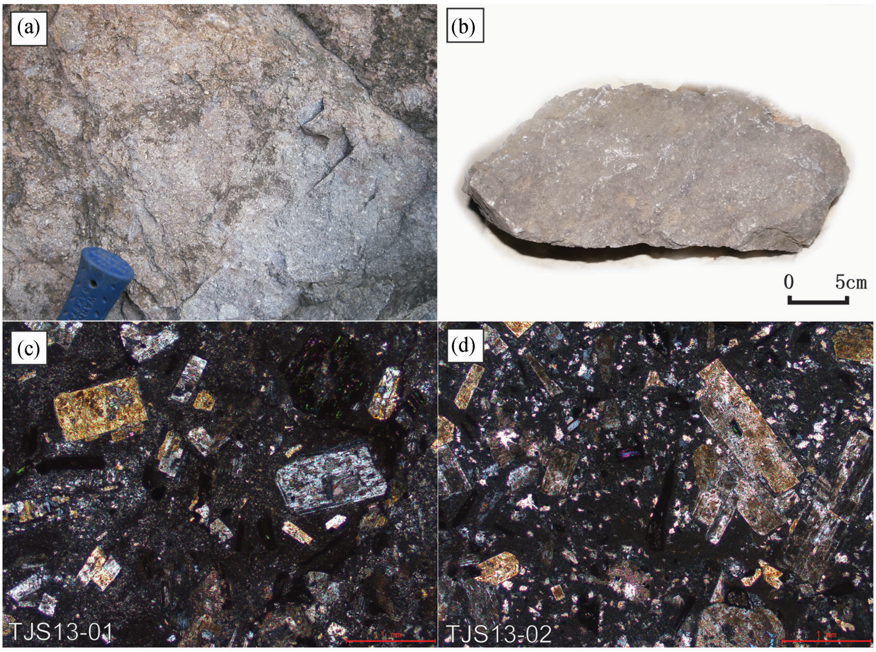

图 2 太行山北段木吉村髫髻山组安山岩照片

Fig. 2 Photos of the andesite from Tiaojishan in north Taihang Mountain

(a)—野外照片；(b)—手边本照片；(c、d)—正交偏关显微镜下照片

(a)—Photo of the outcrop; (b)—photo of the sample; (c) and (d)—micrographs

石,辉石、角闪石少量发育;基质(60%~70%)主要为斜长石微晶和隐晶质组成(图 2c,d)。由于该地区火山作用后期岩浆侵入作用强烈,且近木吉村,鸽子岭等矿床,受部分热液影响,可见少量钾长石化发育,后期发育绿泥石化、泥化。火山岩样品 TJS13-01 和 TJS13-02 中锆石特征相似,为无色透明或浅黄色,以板状—短柱状为主,粒度 100~200μm。阴极发光图像显示,锆石内部结构主要分为两类(图 3):①锆石具有明显的核幔构造,幔部具有清晰明显的震荡环带,锆石核部分具有震荡环带,部分则表现为变质成因特征;②锆石颗粒核幔构造不明显,但具有良好的震荡环带结构特征;此外,少量锆石颗粒受后期热液及变质作用影响,环带不发育。

2.2　测试方法

测试样品经破碎后,通过常规重力和磁选方法分选出锆石,在双目镜下挑选。将待测锆石颗粒置于环氧树脂中制靶,然后磨至一半用于后期测试。锆石阴极发光在中国地质科学院地质研究所离子探针室 HITACHI S3000-N 型扫描电子显微镜上完成。在透反射显微镜观察及阴极发光研究的基础上选择合适锆石颗粒进行锆石 U-Pb 定年和 Hf 同位素测试。

LA-MC-ICP-MS 锆石 U-Pb 定年测试分析在中国地质科学院矿产资源研究所 MC-ICP-MS 实验室完成,锆石定年分析所用仪器为 Finnigan Neptune 型 MC-ICP-MS 及与之配套的 Newwave UP 213 激光剥蚀系统。所用激光剥蚀斑束直径为 25μm,频率为 10Hz,能量密度约为 2.5J/cm^2,以 He 为载气。信号较小的^{207}Pb,^{206}Pb,^{204}Pb(+^{204}Hg),^{202}Hg 用离子计数器(multi-ion-counters)接收,^{208}Pb,^{232}Th,^{238}U 信号用法拉第杯接收,实现了所有目标同位素信号的同时接收并且不同质量数的峰基本上都是平坦的,进而可以获得高精度的数据。均匀锆石颗粒^{207}Pb/^{206}Pb,^{206}Pb/^{238}U,^{207}Pb/^{235}U 的测试精度(2σ)均为 2%左右,对锆石标准的定年精度和准确度在 1%(2σ)左右。LA-MC-ICP-MS 激光剥蚀采样采用单点剥蚀的方式,数据分析前用锆石 GJ-1 进行调试仪器,使之达到最优状态,锆石 U-Pb 定年以锆石 GJ-1 为外标,U、Th 含量以锆石 M257(U:923×10^{-6};Th:439

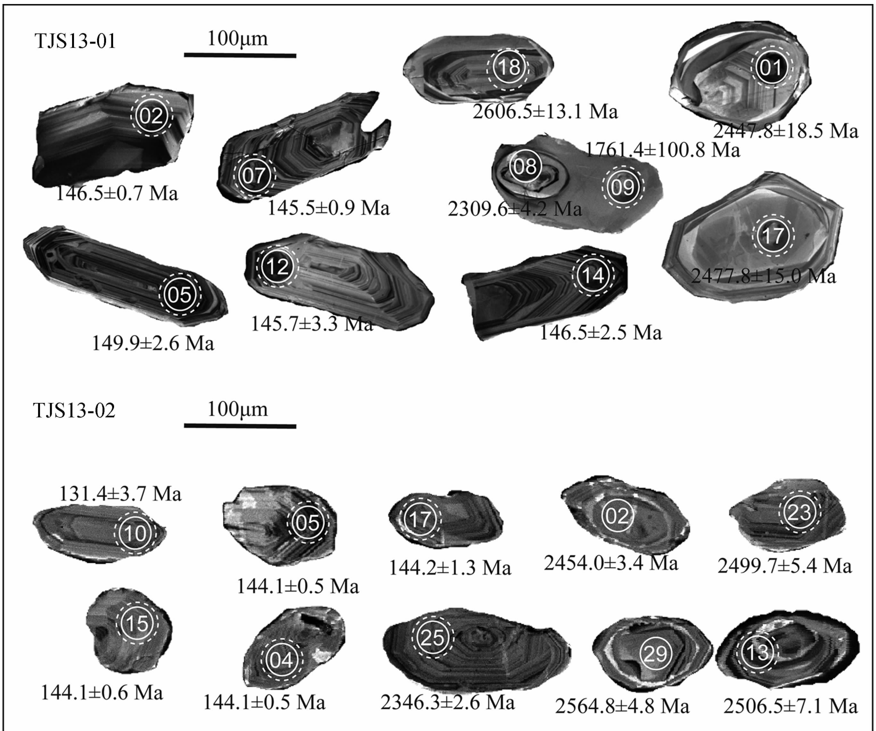

图 3　太行山北段木吉村髫髻山组安山岩典型锆石阴极发光照片及年代学测试数据
(实线圈为 U-Pb 年龄测试位置,虚线圈为 Hf 同位素测试位置)

Fig. 3　The data of ages and Cathodoluminescence images of zircons from andesites of Tiaojishan Formation in Mujicun in north Taihang Mountain (the full line cycles are the positions for the age dating and the dashed line cycles are the positions for the Hf isotopes dating)

$\times10^{-6}$；Th/U：0.475，Nasdala et al，2008)为外标进行校正。测试过程中在每测定 10 个样品前后重复测定两个锆石标准，对样品进行校正，并测量一个锆石标准 Plesovice，观察仪器的状态以保证测试的精确度。数据处理采用 ICPMSDataCal 程序(Liu Yongsheng et al.，2010)，测量过程中绝大多数分析点$^{206}Pb/^{204}Pb$＞1000，未进行普通铅校正，^{204}Pb由离子计数器检测，^{204}Pb 含量异常高的分析点可能受包体等普通 Pb 的影响，对^{204}Pb 含量异常高的分析点在计算时剔除，锆石年龄谐和图用 Isoplot 3.0 程序获得。详细实验测试过程可参见 Hou Kejun et al.(2009)文章。样品分析过程中，Plesovice 标样作为未知样品的分析结果为 337.3±1.1Ma(n＝5，2σ)，对应的年龄推荐值为 337.13±0.37(2σ)(Sláma et al.，2008)，两者在误差范围内完全一致，测试数据精度良好。

锆石 Hf 同位素测试是在中国地质科学院矿产资源研究所国土资源部成矿作用与资源评价重点实验室 Neptune 多接收等离子质谱和 Newwave UP213 紫外激光剥蚀系统(LA-MC-ICP-MS)上进行的，实验过程中采用 He 作为剥蚀物质载气，剥蚀直径采用 55μm，测定时使用锆石国际标样 GJ1 作为参考物质，分析点与 U-Pb 定年分析点为同一位置。相关仪器运行条件及详细分析流程见 Hou Kejun et al.(2007)。分析过程中锆石标准 GJ1 和 PL 的$^{176}Hf/^{177}Hf$ 测试加权平均值分别为 0.282016±1(2σ，n＝5)和 0.282907±4(2σ，n＝10)，与文献报道值(Hou Kejun et al.，2007；Li Xianhua et al.，2010)在误差范围内完全一致，测试数据精度良好。

2.3 测试结果

2.3.1 年代学数据

TJS13-01 样品中 20 颗锆石及 TJS13-02 样品中 30 颗锆石进行年代学测试得到 48 个谐和度均大于 90％的年代学数据，测试结果集中于两个峰值，一组锆石幔部年龄为 145Ma 左右，测试的两件样品锆石幔部加权平均年龄分别为 145.28±0.44Ma(n＝11，MSWD＝0.87)(图 4a)和 144.61±0.76Ma(n＝9，MSWD＝1.9)(图 4b)，代表了髫髻山组安山岩的形成时代；另一组锆石核部年龄为 2.08～2.65Ga(图 4c，d)，代表捕获锆石形成时代，具体测试结果见表 1。此外，测试过程中获得了 4 颗差异较大的锆石年龄：TJS13-02 样品中 03、10、26 和 28 点，$^{206}Pb/^{238}U$ 模式年龄分别为 128.6Ma、131.4Ma、88.5Ma 和 131.4Ma，尽管这四颗锆石具有较高的 Th/U 比值(＞0.4)，但他们的阴极发光照片中具有蚀变或变质特征(Wu Yuanbao et al.，2004)(图 3)，极有可能受到了来自后期岩浆活动或成矿热事件的影响，因而未被记入火山岩成岩年龄的拟合中；在捕获锆石中点 TJS13-01 中 09 测试点获得年龄为 1761±101Ma，该颗粒锆石为变质锆石(图 3)，其年代学在误差范围内与华北克拉通 1.85Ga 发生的区域变质作用及 1.8～1.6Ga 发育的基性岩脉的时代相一致，但测试误差较大，因而未记入核部年龄的统计中。

表 1 太行山北段木吉村矿田髫髻山组火山岩锆石 U-Pb 年代学测试结果

Table 1 U-Pb isotope compositions of zircons from Tiaojishan volcanic rocks in Mujicun ore district in north Taihang Mountain

测点号	含量($\times10^{-6}$)		Th/U	同位素比值						年龄(Ma)						谐和度
	Th	Th		$^{207}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$	1sigma	$^{207}Pb/^{206}Pb$	1sigma	$^{207}Pb/^{235}U$	1sigma	$^{206}Pb/^{238}U$	1sigma	
TJS13-01-01	28	36	0.79	0.1593	0.0018	10.0313	0.2308	0.4563	0.0071	2447.8	18.5	2437.7	21.2	2423.3	31.5	99%
TJS13-01-02	135	127	1.06	0.0496	0.0005	0.1570	0.0017	0.0230	0.0001	176.0	22.2	148.1	1.5	146.5	0.7	98%
TJS13-01-03	176	263	0.67	0.0491	0.0007	0.1541	0.0029	0.0228	0.0004	150.1	30.6	145.6	2.6	145.4	2.3	99%
TJS13-01-04	88	179	0.49	0.0493	0.0051	0.1546	0.0162	0.0228	0.0000	161.2	225.9	146.0	14.2	145.1	0.3	99%
TJS13-01-05	253	267	0.95	0.0491	0.0008	0.1597	0.0052	0.0235	0.0004	150.1	40.7	150.5	4.5	149.9	2.6	99%
TJS13-01-06	251	112	2.24	0.0493	0.0016	0.1508	0.0043	0.0222	0.0005	164.9	77.8	142.6	3.8	141.7	3.0	99%
TJS13-01-07	163	189	0.86	0.0490	0.0007	0.1544	0.0029	0.0228	0.0001	150.1	36.1	145.8	2.5	145.5	0.9	99%
TJS13-01-08	26	60	0.44	0.1468	0.0004	8.6313	0.0395	0.4264	0.0016	2309.6	4.2	2299.9	4.2	2289.3	7.4	99%
TJS13-01-09	21	27	0.77	0.1077	0.0060	4.6611	0.2734	0.3138	0.0012	1761.4	100.8	1760.3	49.1	1759.2	6.0	99%
TJS13-01-10	84	102	0.82	0.1619	0.0006	9.9400	0.1048	0.4452	0.0043	2475.6	6.6	2429.2	9.7	2373.8	19.3	97%
TJS13-01-11	114	100	1.14	0.0502	0.0011	0.1592	0.0046	0.0230	0.0004	211.2	53.7	150.0	4.0	146.6	2.5	97%
TJS13-01-12	49	86	0.57	0.0498	0.0015	0.1568	0.0056	0.0229	0.0005	187.1	68.5	147.9	5.0	145.7	3.3	98%
TJS13-01-13	31	54	0.57	0.0503	0.0022	0.1583	0.0087	0.0228	0.0010	209.3	100.0	149.2	7.6	145.6	6.3	97%
TJS13-01-14	82	163	0.50	0.0500	0.0017	0.1581	0.0048	0.0230	0.0004	194.5	81.5	149.1	4.2	146.5	2.5	98%
TJS13-01-15	239	112	2.14	0.1715	0.0006	11.0164	0.2255	0.4656	0.0085	2571.9	11.6	2524.5	19.1	2464.2	37.6	97%
TJS13-01-16	35	38	0.92	0.1763	0.0027	11.6371	1.1596	0.4778	0.0463	2618.2	25.9	2575.7	93.4	2517.8	201.9	97%

续表 1

测点号	含量(×10⁻⁶)		Th/U	同位素比值						年龄(Ma)						谐和度
	Th	Th		$^{207}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$	1sigma	$^{207}Pb/^{206}Pb$	1sigma	$^{207}Pb/^{235}U$	1sigma	$^{206}Pb/^{238}U$	1sigma	
TJS13-01-17	35	43	0.82	0.1611	0.0014	9.6231	1.0250	0.4327	0.0459	2477.8	15.0	2399.4	98.3	2317.7	206.5	96%
TJS13-01-18	33	144	0.23	0.1751	0.0013	10.0599	0.2971	0.4159	0.0095	2606.5	13.1	2440.3	27.3	2241.7	43.5	91%
TJS13-01-19	35	100	0.35	0.1500	0.0006	8.4334	0.1658	0.4076	0.0075	2346.0	6.9	2278.8	17.9	2203.8	34.5	96%
TJS13-01-20	165	113	1.47	0.0498	0.0010	0.1556	0.0031	0.0227	0.0003	183.4	44.4	146.9	2.7	144.7	1.7	98%
TJS13-02-01	194	96	2.02	0.0500	0.0045	0.1584	0.0138	0.0230	0.0003	194.5	200.0	149.3	12.1	146.6	1.8	98%
TJS13-02-02	119	65	1.84	0.1599	0.0003	9.6453	0.0384	0.4375	0.0014	2454.0	3.4	2401.5	3.7	2339.6	6.3	97%
TJS13-02-03	216	83	2.60	0.0488	0.0010	0.1359	0.0035	0.0201	0.0002	200.1	50.0	129.4	3.2	128.6	1.3	99%
TJS13-02-04	154	87	1.77	0.0493	0.0004	0.1534	0.0012	0.0226	0.0001	161.2	23.1	145.0	1.0	144.1	0.5	99%
TJS13-02-05	711	461	1.54	0.0491	0.0002	0.1531	0.0008	0.0226	0.0001	153.8	7.4	144.7	0.7	144.1	0.5	99%
TJS13-02-06	75	132	0.57	0.0492	0.0022	0.1544	0.0070	0.0228	0.0002	166.8	100.9	145.8	6.2	145.1	1.0	99%
TJS13-02-07	174	145	1.20	0.0490	0.0008	0.1563	0.0024	0.0231	0.0002	150.1	38.9	147.5	2.1	147.5	1.0	99%
TJS13-02-08	191	125	1.52	0.1643	0.0003	10.5311	0.0504	0.4649	0.0021	2501.9	2.5	2482.7	4.4	2461.1	9.3	99%
TJS13-02-09	40	69	0.57	0.1461	0.0003	8.4011	0.0382	0.4172	0.0018	2301.9	3.7	2275.3	4.1	2247.6	8.3	98%
TJS13-02-10	262	92	2.86	0.0504	0.0031	0.1431	0.0100	0.0206	0.0006	213.0	142.6	135.8	8.8	131.4	3.7	96%
TJS13-02-11	198	132	1.50	0.1434	0.0004	7.3450	0.0674	0.3715	0.0038	2268.8	4.6	2154.3	8.2	2036.5	18.1	94%
TJS13-02-12	260	199	1.30	0.1681	0.0008	9.9874	0.1633	0.4306	0.0054	2539.2	7.7	2433.6	15.1	2308.5	24.2	94%
TJS13-02-13	70	189	0.37	0.1649	0.0007	9.1615	0.0874	0.4029	0.0029	2506.5	7.1	2354.3	8.7	2182.4	13.5	92%
TJS13-02-15	102	78	1.30	0.0502	0.0004	0.1564	0.0013	0.0226	0.0001	205.6	23.1	147.6	1.1	144.1	0.6	97%
TJS13-02-16	34	50	0.68	0.1277	0.0003	6.2254	0.0400	0.3533	0.0018	2077.8	4.6	2008.0	5.6	1950.3	8.4	97%
TJS13-02-17	119	135	0.88	0.0489	0.0010	0.1526	0.0030	0.0226	0.0002	146.4	46.3	144.2	2.7	144.2	1.3	99%
TJS13-02-19	2	208	0.01	0.1296	0.0003	5.5716	0.0441	0.3117	0.0022	2094.4	4.8	1911.7	6.8	1749.0	10.8	91%
TJS13-02-20	148	110	1.34	0.1527	0.0004	9.1283	0.0543	0.4334	0.0020	2376.9	4.3	2350.9	5.4	2320.9	9.0	98%
TJS13-02-21	236	170	1.39	0.0506	0.0036	0.1590	0.0108	0.0228	0.0001	233.4	166.6	149.9	9.4	145.3	0.6	96%
TJS13-02-22	33	40	0.81	0.0491	0.0013	0.1526	0.0039	0.0226	0.0002	150.1	63.0	144.2	3.5	144.0	1.4	99%
TJS13-02-23	122	101	1.21	0.1642	0.0004	9.3584	0.0450	0.4133	0.0014	2499.7	5.4	2373.8	4.4	2230.1	6.5	93%
TJS13-02-24	243	235	1.03	0.1798	0.0009	10.4748	0.1211	0.4223	0.0033	2650.9	8.3	2477.7	10.7	2271.1	14.7	91%
TJS13-02-25	170	130	1.31	0.1499	0.0003	8.3129	0.0365	0.4022	0.0016	2346.3	2.6	2265.7	4.0	2179.2	7.2	96%
TJS13-02-26	50	55	0.90	0.0491	0.0049	0.0912	0.0070	0.0138	0.0007	150.1	222.2	88.6	6.5	88.5	4.1	99%
TJS13-02-27	47	138	0.34	0.1604	0.0008	9.0809	0.0890	0.4108	0.0047	2461.1	8.6	2346.2	9.0	2218.6	21.3	94%
TJS13-02-28	757	320	2.36	0.0485	0.0008	0.1376	0.0027	0.0206	0.0003	124.2	42.6	130.9	2.4	131.4	1.7	99%
TJS13-02-29	180	140	1.29	0.1706	0.0004	10.8187	0.0930	0.4600	0.0037	2564.8	4.8	2507.7	8.0	2439.4	16.4	97%
TJS13-02-30	58	87	0.67	0.1387	0.0004	7.0493	0.0543	0.3682	0.0022	2213.0	5.6	2117.7	6.8	2021.0	10.5	95%

2.3.2 Hf 同位素特征

在锆石 U-Pb 年代学测试的基础上对已获得年代数据的 48 颗锆石进行原位 Hf 同位素测试。其中 TJS13-01 样中 08 点以及 TJS13-02 样中 02、29 和 30 点在测试中受激光半径和剥蚀程度的影响出现了测试样成分混合的情况,数据信号具有较大波动,因而去除,具体数据见表 2。除少数点外,锆石颗粒的 $^{176}Lu/^{177}Hf$ 比值均小于 0.002,表明锆石在形成之后放射性成因 Hf 的积累极其有限。对应两组锆石 U-Pb 年龄,锆石 Hf 同位素特征也明显的分为两组(图 5):一组 $\varepsilon Hf_{(t)}$ 值集中于 −25～−10 之间,对应于中生代年龄,表现为壳幔混源特征;另一组 $\varepsilon Hf_{(t)}$ 值集中于 0～10 之间,对应于中晚元古代年龄,具有新生地壳特征。两阶段模式年龄阈值为 1.8～3.0Ga 集中于 2.3～2.7Ga。

3 讨论

3.1 髫髻山组火山岩年龄

髫髻山组火山岩主要分布于北京西山、冀北和辽西等地,以北京西山髫髻山和百花山一带向斜核部中基性火山岩最为发育,是此组火山岩地层的命名地(Li Wuping et al., 2001a)。随着精确年代学测试技术的发展,近十几年来对髫髻山组火山岩年代学研究取得了一些新的研究结果:①对北京西山髫髻山组粗安岩进行的斜长石 Ar-Ar 测年,得到成岩年龄 148.91±2.98Ma 和 146.60±2.93Ma(Li Wuping et al., 2001a);对北京西山盆地髫髻山组底部安山岩的锆石 SHRIMP U-Pb 测试获得年龄为 157±3Ma(Zhao Yue et al., 2004),上部英安岩锆石 SHRIMP U-Pb 年龄为 137.1±4.5Ma(Yuan

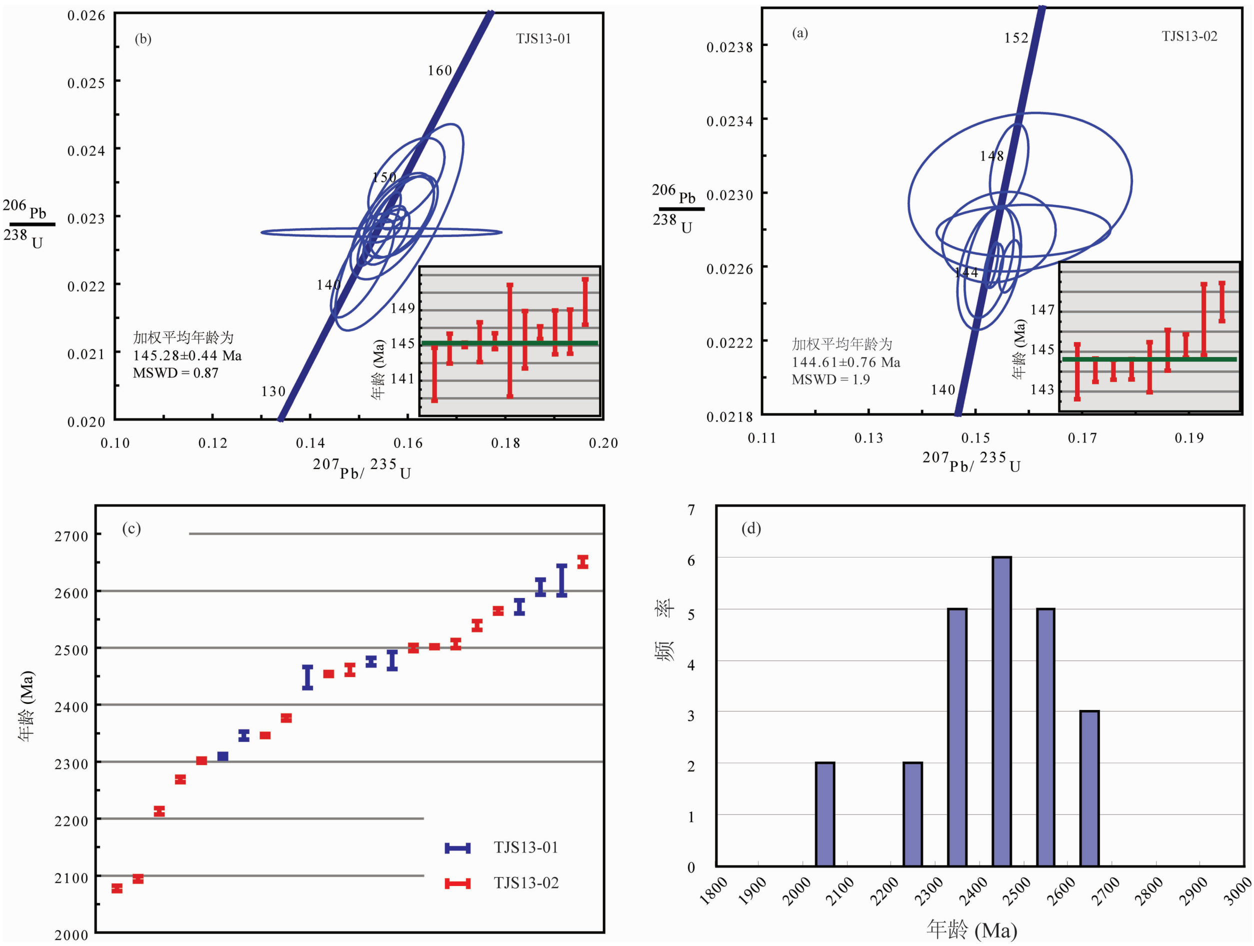

图 4 太行山北段木吉村髫髻山组安山岩锆石 U-Pb 年龄

Fig. 4 The U-Pb ages of andesites from Tiaojishan Formation in Mujicun in north Taihang Mountain

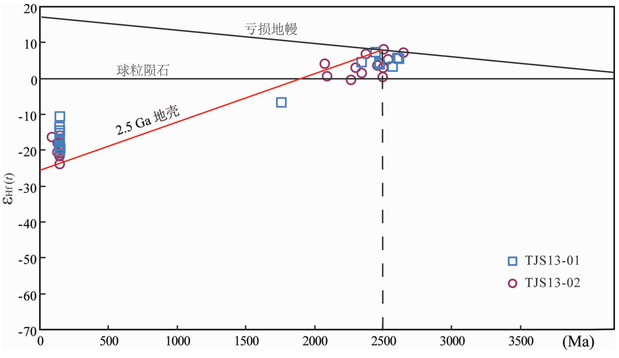

图 5 太行山北段木吉村髫髻山组安山岩锆石 Hf 同位素特征

Fig. 5 Hf isotope characteristics of zircons from andesites of Tiaojishan Formation in Mujicun in north Taihang Mountain

Honglin et al., 2006);②对承德兴隆髫髻山组安山岩的 Ar-Ar 的年龄测试获得 148±2Ma(Davies et al., 2001);对承德盆地髫髻山组顶部晶屑凝灰岩和底部粗安岩锆石 LA-ICP-MS U-Pb 测试研究获得年龄分别是 153±1Ma 和 156±3Ma(Liu Jian et al., 2006);③对辽西髫髻山组凝灰岩和安山质火山角砾岩锆石 SHRIMP U-Pb 年龄测试获得岩石形成时代为 158±1Ma(Zhao Yue et al., 2004);④对涞源神仙山髫髻山组安山质角砾凝灰岩的锆石 SHRIMP U-Pb 测试,获得年龄为 131±2Ma(Xu Bo et al., 2012);对涞源木吉村地区髫髻山组安山岩锆石 U-Pb LA-ICP-MS 年代学研究,获得 150.5～140.8Ma 形成年代阈值(Gao Yongfeng et al., 2011);应用 SHRIMP 对木吉村髫髻山组安山岩进行锆石 U-Pb 年代学测试获得加权平均年龄为 138.89±0.9Ma(Shen Zhichao et al., 2015)。综上研究成果,尽管在内陆形成的火山喷发喷溢旋回的形成时代可能会受到区域的影响而有所不同(Yuan Honglin et al., 2006),但目前对涞源地区髫髻山组火山岩形成时代的研究获得了一个近 20Ma 间距的时代阈值(131～150.5Ma),与火山旋回快速喷发形成的研究结果(Yuan Honglin et al., 2006; Liu Jian et al., 2006)形成了较大差异,并跨越了晚侏罗纪与早白垩纪的分界。

本次研究工作对木吉村髫髻山组火山岩两件安

表 2 太行山北段木吉村矿田髫髻山组火山岩锆石 Hf 同位素特征

Table 2 In situ zircon Hf isotope compositions of Tiaojishan volcanic rocks in Mujicun ore district in north Taihang Mountain

测试号	年龄(Ma)	$^{176}Yb/^{177}Hf$	$^{176}Lu/^{177}Hf$	$^{176}Hf/^{177}Hf$	2σ	$\varepsilon_{Hf}(0)$	$\varepsilon_{Hf(t)}$	T_{DM1}(Ma)	T_{DM2}(Ma)	$f_{Lu/Hf}$
TJS13-01-01	2447.8	0.039864	0.001232	0.281475	0.000017	−45.9	7.1	2497	2525	−0.96
TJS13-01-02	146.5	0.035032	0.001186	0.282269	0.000021	−17.8	−14.7	1394	2121	−0.96
TJS13-01-03	145.4	0.030759	0.001011	0.282205	0.000019	−20.1	−17.0	1476	2262	−0.97
TJS13-01-04	145.1	0.036465	0.001269	0.282251	0.000017	−18.4	−15.4	1421	2161	−0.96
TJS13-01-05	149.9	0.018768	0.000679	0.282123	0.000014	−23.0	−19.7	1576	2439	−0.98
TJS13-01-06	141.7	0.052450	0.001855	0.282159	0.000018	−21.7	−18.7	1575	2370	−0.94
TJS13-01-07	145.5	0.023964	0.000894	0.282191	0.000017	−20.5	−17.4	1490	2291	−0.97
TJS13-01-09	1761.4	0.007271	0.000277	0.281476	0.000014	−45.8	−6.9	2434	2853	−0.99
TJS13-01-10	2475.6	0.015791	0.000566	0.281347	0.000014	−50.4	4.2	2627	2719	−0.98
TJS13-01-11	146.6	0.083853	0.002992	0.282384	0.000019	−13.7	−10.8	1294	1876	−0.91
TJS13-01-12	145.7	0.019235	0.000753	0.282146	0.000015	−22.1	−19.0	1547	2390	−0.98
TJS13-01-13	145.6	0.041049	0.001710	0.282251	0.000017	−18.4	−15.4	1438	2164	−0.95
TJS13-01-14	146.5	0.019402	0.000833	0.282107	0.000014	−23.5	−20.4	1604	2477	−0.97
TJS13-01-15	2571.9	0.017109	0.000669	0.281260	0.000015	−53.5	3.1	2752	2861	−0.98
TJS13-01-16	2618.2	0.016996	0.000689	0.281291	0.000017	−52.4	5.3	2711	2768	−0.98
TJS13-01-17	2477.8	0.011947	0.000472	0.281327	0.000012	−51.1	3.7	2648	2752	−0.99
TJS13-01-18	2606.5	0.013830	0.000510	0.281295	0.000011	−52.2	5.5	2693	2746	−0.98
TJS13-01-19	2346.0	0.008699	0.000363	0.281422	0.000014	−47.7	4.3	2513	2616	−0.99
TJS13-01-20	144.7	0.083155	0.003005	0.282302	0.000019	−16.6	−13.7	1414	2057	−0.91
TJS13-02-01	146.6	0.065484	0.002655	0.282233	0.000021	−19.1	−16.1	1501	2208	−0.92
TJS13-02-03	128.6	0.019603	0.000821	0.282110	0.000022	−23.4	−20.7	1600	2481	−0.98
TJS13-02-04	144.1	0.028015	0.001156	0.282070	0.000020	−24.8	−21.8	1669	2561	−0.97
TJS13-02-05	144.1	0.012997	0.000598	0.282092	0.000017	−24.1	−21.0	1616	2511	−0.98
TJS13-02-06	145.1	0.024030	0.000811	0.282006	0.000018	−27.1	−24.0	1742	2700	−0.98
TJS13-02-07	147.5	0.021907	0.000915	0.282136	0.000019	−22.5	−19.4	1568	2413	−0.97
TJS13-02-08	2501.9	0.019209	0.000802	0.281301	0.000016	−52.0	2.8	2706	2828	−0.98
TJS13-02-09	2301.9	0.007877	0.000243	0.281403	0.000015	−48.4	2.8	2530	2672	−0.99
TJS13-02-10	131.4	0.020848	0.000837	0.282178	0.000022	−21.0	−18.2	1506	2329	−0.97
TJS13-02-11	2268.8	0.011404	0.000511	0.281341	0.000021	−50.6	−0.6	2632	2854	−0.98
TJS13-02-12	2539.2	0.018083	0.000772	0.281341	0.000019	−50.6	5.1	2649	2715	−0.98
TJS13-02-13	2506.5	0.018607	0.000833	0.281444	0.000015	−47.0	7.9	2514	2519	−0.97
TJS13-02-15	144.1	0.022658	0.000924	0.282073	0.000018	−24.7	−21.6	1655	2554	−0.97
TJS13-02-16	2077.8	0.006218	0.000265	0.281578	0.000019	−42.2	3.9	2297	2434	−0.99
TJS13-02-17	144.2	0.030995	0.001328	0.282126	0.000020	−22.8	−19.8	1599	2439	−0.96
TJS13-02-19	2094.4	0.002376	0.000107	0.281464	0.000017	−46.3	0.4	2441	2659	−1.00
TJS13-02-20	2376.9	0.013835	0.000614	0.281479	0.000017	−45.7	6.6	2452	2498	−0.98
TJS13-02-21	145.3	0.043578	0.001758	0.282121	0.000020	−23.0	−20.0	1624	2451	−0.95
TJS13-02-22	144.0	0.029769	0.001248	0.282155	0.000016	−21.8	−18.8	1555	2374	−0.96
TJS13-02-23	2499.7	0.012123	0.000552	0.281219	0.000017	−54.9	0.2	2799	2981	−0.98
TJS13-02-24	2650.9	0.018227	0.000806	0.281325	0.000016	−51.2	7.0	2673	2687	−0.98
TJS13-02-25	2346.3	0.012225	0.000487	0.281344	0.000017	−50.5	1.3	2626	2798	−0.99
TJS13-02-26	88.5	0.017522	0.000814	0.282252	0.000019	−18.4	−16.5	1403	2191	−0.98
TJS13-02-27	2461.1	0.010496	0.000475	0.281328	0.000016	−51.1	3.4	2647	2761	−0.99
TJS13-02-28	131.4	0.054799	0.002233	0.282184	0.000020	−20.8	−18.1	1555	2322	−0.93

注:$\varepsilon_{Hf}(0)=((^{176}Hf/^{177}Hf)_S/(^{176}Hf/^{177}Hf)_{CHUR,0}-1)\times10000$,$\varepsilon_{Hf(t)}=((^{176}Hf/^{177}Hf)_S-(^{176}Lu/^{177}Hf)_S\times(e^{\lambda t}-1))/((^{176}Hf/^{177}Hf)_{CHUR,0}-(^{176}Lu/^{177}Hf)_{CHUR}\times(e^{\lambda t}-1))-1)\times10000$,$T_{DM1}=1/\lambda\times\ln\{1+[(^{176}Hf/^{177}Hf)_S-(^{176}Hf/^{177}Hf)_{DM}]/[(^{176}Lu^{177}Hf)_S-(^{176}Lu/^{177}Hf)_{DM}]\}$,$T_{DM2}=T_{DM1}-(T_{DM1}-t)\times((f_{CC}-f_S)/(f_{CC}-f_{DM}))$,$f_S=(^{176}Lu/^{177}Hf)_S/(^{176}Lu/^{177}Hf)_{CHUR}-1$,$f_{CC}=(^{176}Lu/^{177}Hf)_C/(^{176}Lu/^{177}Hf)_{CHUR}-1$,$f_{DM}=(^{176}Lu/^{177}Hf)_{DM}/(^{176}Lu/^{177}Hf)_{CHUR}-1$,$(^{176}Lu/^{177}Hf)_S$ 和 $(^{176}Hf/^{177}Hf)_S$ 为测试值,$(^{176}Lu/^{177}Hf)_{CHUR}=0.03321$,$(^{176}Hf/^{177}Hf)_{CHUR,0}=0.282772$,$(^{176}Lu/^{177}Hf)_{DM}=0.03842$,$(^{176}Hf^{177}Hf)_{DM}=0.28325$(Blichert-Toft and Albarede, 1997),$(^{176}Lu/^{177}Hf)_C=0.015$(Griffin et al., 2002),$t$ 为锆石原位 U-Pb 年代学数据,$\lambda_{Lu}=1.867\times10^{-11}$ year^{-1}(Soderlund et al., 2004)。

山岩样品中不同构造类型的锆石颗粒进行了详细的年代学分析测试工作。获得锆石具有震荡环带的幔部加权平均年龄分别为 145.28±0.44Ma 和 144.61±0.76Ma,两者在误差范围内一致,因而

145Ma 代表了髫髻山组中安山岩在中生代喷发喷溢就位时的形成时代。稍早于后期侵入髫髻山组火山碎屑岩和熔岩发育的含矿闪长玢岩岩体的形成时代(141.7～144.1Ma，Gao Yongfeng et al.，2011；Dong Guochen et al.，2013)以及与闪长玢岩具有密切成因联系的木吉村斑岩型铜钼矿的形成时代(140.3～143.8Ma，Gao Yongfeng et al.，2011；Chen Chao et al.，2013；Dong Guochen et al.，2013)，与地质现象的客观接触关系相耦合。在区域中，大量的斑岩型铜钼矿床也发育于一时期，例如：太行山北段木吉村斑岩铜钼矿床南侧大湾斑岩矿床(144.4±7.4Ma，Huang Dianhao et al.，1996)、北京大庄科角砾岩型钼矿床(147.1±6.6Ma，Huang Dianhao et al.，1996；137.6±3.7，Liu Shubo et al.，2012)、冀北寿王坟斑岩斑岩铜钼矿(148Ma±4，Huang Dianhao et al.，1996)，安妥岭钼矿床(146.9±1Ma，Zhe Meng et al.，2014；147.8±1Ma，Liang Tao et al.，2010)。晚侏罗世是髫髻山火山岩发育的重要时期，同时也是该地区与火山岩及其后期次火山岩有关的大量斑岩型铜钼矿床产出的集中时期。

3.2 髫髻山组火山岩源区

髫髻山组火山岩是太行山中生代的产物之一。对髫髻山组火山岩岩石地球化学的研究得出，火山岩具有高 Sr，Ba，亏损 HREE，Eu 异常不明显，大离子亲石元素相对富集，高场强元素相对亏损等特征。部分学者认为火山岩源于古老的玄武质下地壳部分熔融(Li Wuping et al.，2001a，2001b，2007；Ge Xiaoyue et al.，2002；Zhao Yue et al.，2004；Lu Fengxiang et al.，2006)。火山岩具有的高 Sr/Y 和 La/Yb 比值的特征，也使其被归类于陆源埃达克质岩石，在华北地区中生代发育的其他岩浆岩亦被认为是源于下地壳的部分熔融形成的埃达克岩(Zhang Qi et al.，2001a，2001b；Davis，2003；Li Wuping et al.，2007)。这类埃达克岩的重要演化过程是下地壳的部分熔融使得源区斜长石消失形成榴辉岩相残留，从而造成喷出或侵入地壳中的岩浆岩具有了高的 Sr/Y 和 La/Yb 比值和较低的 Y 和 Yb。但随着研究的深入，加厚地壳熔融的成因模式受到了质疑。首先，最早埃达克岩石的提出是用来描述源自年轻洋壳俯冲形成的一套中酸性岩石组合(Defant and Drummond，1990)，埃达克质特征(高 Sr/Y 和 La/Yb 比值)的形成可源于多种岩浆演化过程，不能以此作为源区指示(Moyen，2009；Richards and Kerrich，2007；Gao Yongfeng et al.，2012，2013；Chen Bin et al.，2013)。其次，在对北京西山地区髫髻山组火山岩样品的研究中，Wang Rui et al.(2007)得出火山岩在同等硅含量条件下具有比玄武岩熔融实验熔体(Rapp et al.，1995)明显高的含镁指数，而表明髫髻山组火山岩不大可能形成于基性下地壳的部分熔融过程，幔源岩浆的混合可能是必需的；此外，大部分火山岩样品具有比较低的硅(SiO_2<58%)，这样低硅的岩浆通常也不会是纯的地壳熔体(Montel et al.，1997)。对华北太行山、胶东和大别山岩浆岩的源区综合性研究也与此相一致(Chen Bin et al.，2005)。另一方面，对于拆沉作用使熔融下地壳具有高 $Mg^{\#}$ 的推测(Yuan Honglin et al.，2006)也未能得到榴辉岩包体大量出现、苏鲁大别造山带中榴辉岩存在部分熔融现象和同位素地球化学的证据支持(Zhang R Y et al.，1997；Chen Bin et al.，2005，2013)。Chen Bin et al.(2013)通过对这类具有高镁埃达克地球化学特征的岩石进行岩石学和 Nd-Sr-Os 同位素特征的研究，提出了交代地幔玄武质岩浆与重熔地壳混合成因模式。在对西山髫髻山组火山岩的 Nd 同位素的研究中也得到了壳幔混源的源区特征，较高的 Sr，Ba，高 Sr/Y 比值和亏损的 HREE，Y 等可能继承了富集地幔的基性岩浆特征，在上升过程中受到了下地壳物质的混染(或岩浆混合)，并经历了后期的结晶分异作用(Wang Rui et al.，2007)。这一成因模式也得到了众多太行山地区发育的大量中酸性杂岩体，基性岩脉以及基性包体的地球化学属性研究成果的相互应证(Chen Bin et al.，2003，2008，2009a，2009b；Wang Rui et al.，2007；Chen Zhichao et al.，2007；Shen Zhichao et al.，2015；Liu Ling et al.，2009)。Gao Yongfeng et al.(2012，2013)研究认为髫髻山组火山岩的形成可能经历了 MASH 模型(熔融—同化作用—储藏—均一化作用)的过程，富集地幔岩石圈熔融，铁镁质幔源熔体上侵，使得下地壳发生部分熔融，随后发生了岩浆的分离结晶与混合，并最终上升到地壳就位。

本次研究中，我们获得了具有核幔构造的火山岩锆石，年代学的测试得到了锆石核部年龄为 2.08～2.65Ga(图 4c)，集中于 2.3～2.6Ga，表明在髫髻山组火山岩形成过程中具有来自古老地壳物质的参与。在年代学测试相同位置进行的 Hf 同位素测试得到锆石幔部和核部 Hf 同位素特征具有较大的差异。对应于形成于 2.08～2.65Ga 的核部锆石，

$\varepsilon Hf_{(t)}$ 值大部分为正值,集中于 0～10 之间,具有新生地壳的特征(Kinny et al., 2003),而这一时期正是华北克拉通在漫长演化过程中最为重要的一个地壳增生阶段,经历了大规模的地壳形成及区域变质事件(Zhao Guochun et al., 2012;Geng Yuansheng et al.,2012)。因而,可以肯定华北克拉通古老地壳物质参与了髫髻山火山岩的形成演化过程。锆石幔部的 $\varepsilon Hf_{(t)}$ 值为－25～－10,在图 5 中处于平均地壳演化线与富集地幔 $\varepsilon Hf_{(t)}$ 值(－8～－10,Chen Bin et al.,2008)之间,呈大范围连续线性分布,并未出现向某个端元的集中,表明髫髻山组火山岩的形成不可能由单一的富集地幔或地壳重熔再循环演化而来,而是古老华北克拉通地壳与富集地幔相互作用演化的产物。

3.3 区域成岩成矿规律指示

大规模成矿或大爆发式成矿是在一定特殊地球动力学环境中的产物(Mao Jingwen et al., 1999, 2005; Hua Renmin et al., 1999),华北克拉通在中生代的裂解使得包括太行山地区在内的华北克拉通东部发育了区域性的构造伸展,大规模的岩浆活动和成矿作用(Mao Jingwen et al., 2014, 2011a, 2011b; Wu Fuyuan et al., 2005; Zhu Rixiang et al., 2011; Yang Jinhui et al., 2003)。大多数研究认为,太平洋板块向东亚大陆的持续俯冲所引发的非稳态地幔流动是华北克拉通东部整体破坏的重要诱因(Yang Jinhui et al., 2003; Zhao Yue et al., 2004; Chen Ling, 2010; Zhu Rixiang et al., 2011; Mao et al. 2014; Chen Bin et al., 2013; Guo Pu et al., 2013)。Chen Bin et al. (2005)研究提出古太平洋的俯冲最早在日本岛 Hide 带和朝鲜半岛形成钙碱性弧岩浆(220～200Ma),于 180Ma 作用于胶东半岛和辽东半岛,大约在 138Ma 左右弧岩浆岩带移至太行山和大别山并持续至 110Ma 左右。髫髻山组火山岩的形成则记录了古太平洋俯冲的开始(Zhao Yue et al., 2004),伸展构造体制在 125Ma 左右达到了最高峰期(Zhai Mingguo et al., 2003; Zhu Rixiang et al., 2011; Lin Wei et al., 2013)。

太行山北段在这一时期的岩浆活动形成了髫髻山组火山岩及其之后发育的次火山岩(闪长玢岩)(约 145Ma)、以中酸性岩为主的王安镇杂岩体和大河南杂岩体、小五台岩体、赤瓦屋岩体、麻棚岩体,以及少量中基性岩体等岩浆岩(138～126Ma,Chen Bin et al., 2005, 2009b; Chen Zhichao et al., 2007; Dong Guochen et al., 2013; Gao Yongfeng et al., 2013; Li shengrong et al., 2013; Shen Zhichao et al., 2015)。Zhang Qiang et al. (2009)认为以上岩浆活动可分为两期:一期是中—晚侏罗世形成的火山杂岩体,包括末期的超浅成次火山岩体;另一期是燕山晚期形成的大河南和王安镇杂岩体及一些出露面积较小的杂岩体。随着精确年代学数据的积累,太行山地区的成矿作用事件出现了两个时期的集中:如前述斑岩型铜钼矿床多形成于 145Ma 左右(140～148Ma);金矿床及与金矿床形成密切相关的岩浆岩则多形成于 130Ma 左右,例如:与金矿成矿相关的麻棚岩体及相邻的斑状岩墙形成于 124～130Ma (Yang Jinhui et al., 2003; Liu Yang et al., 2010; Li Linlin et al., 2012; Li Shengrong et al., 2013;Li Qing et al., 2015),赤瓦屋岩体形成于 126.4Ma(Li Linlin et al., 2012)。相对比于同时期相同大地构造背景的中国东部其他地区,长江中下游斑岩型铜金钼矿形成于 145Ma 左右、玢岩型铁矿及少量金矿床形成于 130～125Ma (Mao Jingwen et al., 2011b, 2012; Zhou Taofa et al., 2011);在胶东地区,134～120Ma 是金矿化和伸展构造体系背景下 A 型花岗岩,辉绿岩墙和变质核杂岩的一个主要的形成时期(Wu Fuyuan et al., 2005; Guo Pu et al., 2013; Yang Liqiang et al., 2014);在东秦岭—大别地区,侏罗纪到白垩纪,斑岩型钼矿床主要形成于 148～138Ma(Mao Jingwen et al., 2008, 2014),金钼矿床主要形成于 131～112Ma(Wang Yitian et al., 2001; Li Houmin et al., 2007; Mao Jingwen et al., 2014)。Mao Jingwen et al. (2005)在对华北、东北及长江中下游地区的成岩成矿作用规律的研究基础上,提出古太平洋俯冲及构造体制的转变(侏罗纪—白垩纪)使中国东部出现了两期重要的成矿事件:一期为与壳幔混源花岗质岩石有关的斑岩—矽卡岩型铜钼矿床的大量形成,另一期为岩石圈伸展环境中地幔流体积极参与的金铁等矿床的形成。从目前已获得的成岩成矿年代学数据相对集中的角度,我们推测太行山地区在中生代亦形成有两期重要的成矿事件,从属于中国东部在侏罗纪—白垩纪的这两期重要的成矿事件,一期以斑岩型铜—钼矿床的形成为特征,另一期由大量的金矿床的形成为代表。而这两期成矿作用的相互关系仍需要进一步的研究。

4 结论

太行山北段木吉村髫髻山组火山岩形成于

145Ma 左右，捕获锆石年龄为 2.08～2.65Ga，对应两组年龄，锆石 Hf 同位素特征 $\varepsilon Hf_{(t)}$ 值集中于－25～－10 和 0～10 之间，揭示出火山岩形成过程中华北克拉通古老地壳的参与。结合已有岩石地球化学研究，髫髻山火山岩在形成过程中，随着岩浆上侵同化混染（或混合）了华北克拉通的古老地壳。火山岩形成于晚侏罗纪，是晚侏罗世—早白垩世华北克拉通岩石圈构造背景转换的代表之一。推测太行山地区在中生代至少形成有两期重要的成矿事件，一期以斑岩型铜—钼矿床的形成为特征，另一期由金矿床的产出为代表。

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Zircon U-Pb Geochronological and Hf Isotope Study on Tiaojishan Volcanic Formation, Mujicun, North Taihang Mountain and Implications for Regional Metallogeny and Magmatism

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Abstract

The North Taihangshan Mountain area is one of the most important metallogenic belts in the East China. In this area, the Tiaojishan volcanic formation recorded the metallogenic-magmatism event times and resources in Mesozoic. The majority zircons from the andesite show the core-mantle texture. By LA-MC-ICP-MS U-Pb geochronology dating on the core and mantle of zircons, two group ages have been gained. One is younger, with two weighted average ages as 145.28±0.44Ma and 144.61±0.76Ma from two samples, which indicates the andesite forming time, and the other one is 2.08～2.65Ga from the core of zircons, which indicates the old crustal material being in the magma forming. LA-MC-ICP-MS in-situ Hf isotopic analysis of zircons gains two different $\varepsilon Hf_{(t)}$ values ranges corresponded to the two group U-Pb ages. For the younger group (～145Ma), the $\varepsilon Hf_{(t)}$ values are in the range of −25 to −10, which suggests the volcanic rocks originated from the interaction process (mixing or mingling) between the enrich mantle and the old crust; for the other group (2.08～2.65Ga), the $\varepsilon Hf_{(t)}$ values are in the range of 0 to 10, which indicate the core of zircon derived from juvenile crusts same with the major crustal growth of the North China Craton (NCC), and suggests the old crust material have been involved during this magmatism. Combined with the geochemistry studies, the Tiaojishan volcanic rocks might originate from partial melting of an enriched mantle, contaminated by the old NCC crustal component en route, then emplaced after fractional crystallization. This volcanic event was formed in Mesozoic metallogenic-magmatism event, and it implicates the NCC tectonic changing by lithosphere extension in Late Mesozoic. Based on the geochronology data, we infer that there might be two major metallogenic events, one is characterized by the forming of porphyry Cu-Mo deposits, and the other one is characterized by the forming of Au deposits.

Key words: North Taihang Mountain; Mujicun; Tiaojishan volcanic rocks; U-Pb dating; Hf isotope