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北秦岭西段凤县地区草滩沟群龙王沟组酸性凝灰岩年代学、岩石地球化学特征及其构造意义

陈国超[1,3)]，张亚峰[2)]，裴先治[3)]，李佐臣[3)]，季宪军[1)]，魏均启[4)]，莫嵘桓[1)]，王超[1)]

1）南阳理工学院土木工程学院，河南南阳，473000；2）陕西省矿产地质调查中心，西安，710068；
3）长安大学地球科学与资源学院，西安，710054；4）国土资源部稀土稀有稀散矿产重点实验室，武汉，430034

内容提要：草滩沟群龙王沟组在北秦岭西段广泛出露，对研究秦岭早古生代构造演化具有重要意义。LA-ICP-MS锆石U-Pb同位素定年结果显示草滩沟群龙王沟组酸性凝灰岩的结晶年龄为457.4±3.8Ma。草滩沟群龙王沟组酸性凝灰岩富硅（SiO_2＝64.55％～73.07％）和碱（Na_2O+K_2O＝5.35％～8.11％），低铝（Al_2O_3＝13.91％～16.07％）；轻稀土元素富集，重稀土元素亏损，具Eu负异常（δEu＝0.34～0.86）；富集Rb、Th等大离子亲石元素（LILE），亏损Nb、Ta、Ti等高场强元素（HFSE），具有较低的Nb/Ta比值和$Mg^{\#}$值。以上显示，草滩沟群龙王沟组酸性凝灰岩具壳源特征，为地壳部分熔融结果。北秦岭造山带草滩沟群龙王沟组酸性凝灰岩和晚奥陶世—早志留世岩浆岩具弧岩浆岩特征，显示它们形成于俯冲环境。结合北秦岭造山带早古生代超高压变质带、岩浆岩分布以及草滩沟群沉积特征显示，早奥陶世北秦岭造山带还处于商丹洋的俯冲阶段。

关键词：北秦岭西段；草滩沟群；龙王沟组；锆石U-Pb年龄；岩石地球化学；构造环境

秦岭造山带位于青藏高原东北缘（图1），是中国南、北板块拼合形成的构造结合带，也是古亚洲构造域与特提斯构造域的交汇部位（Zhang Guowei et al.，1995，2001；Xu Zhiqin et al.，2015；Domeier，2018；Li Sanzhong et al.，2018；Mu Dunling et al.，2018）。秦岭造山带是至少经历了新元古代、早古生代和晚古生代—早中生代构造岩浆热事件和造山作用的复合型造山带（Lu Songnian et al.，2006；Pei Xianzhi et al.，2009；Yan Zhen et al.，2009，2012；Dong Yunpeng et al.，2011，2016；Wang Xiaoxia et al.，2013，2015；Wu Yuanbao et al.，2013），地质构造复杂多样，特别是早古生代在秦岭地区构造演化过程中具有重要地位。草滩沟群在北秦岭西段广泛出露，其研究对于揭示秦岭造山带的构造演化具有重要意义。

草滩沟群为从秦岭群中解体出来的早古生代地层，Yang Zichao et al.（1984）根据岩石组合特征把草滩沟群由下到上划分为红花铺组和张家庄组；红花铺组岩石组合以沉积岩夹火山岩为特征，张家庄组岩石组合以火山熔岩夹沉积岩为特征。Sun Minsheng et al.（1995）依据原岩建造、沉积组合、沉积示顶构造及所含古生物化石，对草滩沟群中的张家庄组又进行二分，划分为张家庄组和龙王沟组，其中张家庄组与原划分方案一致，岩石组合为火山熔岩夹沉积岩，龙王沟组岩石组合为浅变质碎屑岩、沉凝灰质碎屑岩夹中性火山岩。早期研究者根据古生物化石，把红花铺组的形成时代限定为早奥陶世，张家庄组的形成时代为晚奥陶世（Yang Zichao et al.，1984）；Wang Hongliang et al.（2007）用锆石U-Pb法对两当张家庄一带的张家庄组的中—基性火山岩进行定年，精确测得其形成年龄为456.4±1.8Ma。而龙王沟组未发现生物化石，根据龙王沟组与张家庄组呈整合接触，其形成时代可能为晚奥陶世。Sun Minsheng（1998）和Wang Deyao（2002）通过对

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作者简介：陈国超，男，1979年生。博士，讲师，构造地质学专业，主要从事造山带构造岩浆作用研究。Email：chaoschen@126.com。通讯作者：张亚峰，男，1984年生。硕士，高级工程师，构造地质学专业，主要从事区域地质调查工作。Email：aimom84@163.com。
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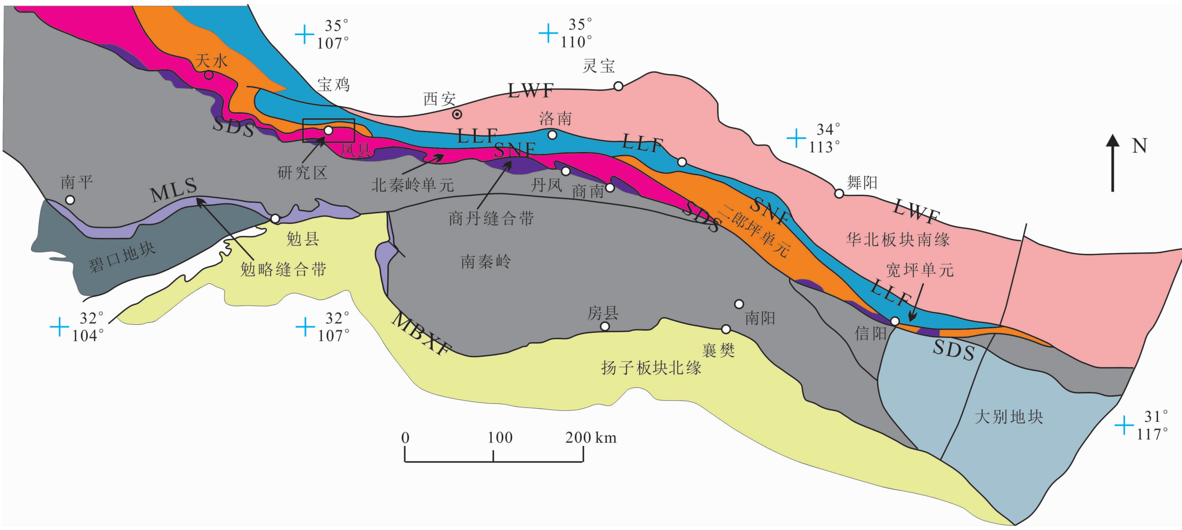

图 1　秦岭造山带大地构造背景图(修改自 Dong Yunpeng et al. ,2011)

Fig. 1　Simplified tectonic maps of the Qinling Orogenic Belt showing the tectonic divisions (modified after Dong Yunpeng 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—郯庐断裂

LWF—Lingbao-Lushan-Wuyang fault;LLF—the Luonan-Luanchuan fault;SNF—the Shangzhou-Nanzhao fault;SDS—Shangdan suture;MLS—the Mianlue suture;MBXF—the Mianlue-Bashan-Xiangguang fault;TLF—the Tanlu fault

凤县地区草滩沟群研究,其属钙性—钙碱性、中—酸性岩组合,具弧后盆地拉张裂谷的构造环境;Yan Quanren et al. (2007)、Zhu Tao et al. (2008)和 Xu Xiaochu et al. (2014)分别对凤县张家庄、太白县魏家湾和北秦岭天水阴崖沟一带草滩沟群火山岩进行岩石地球化学研究,显示草滩沟群火山岩具有岛弧火山岩特征。

以上显示,对草滩沟群龙王沟组的形成时代还未有精确限定,其形成构造背景也存在一定争议。所以,本文通过对北秦岭西段凤县地区草滩沟群龙王沟组酸性凝灰岩进行岩石学、锆石 U-Pb 年代学和岩石地球化学的分析,并结合前人研究资料,拟对草滩沟群龙王沟组中的酸性凝灰岩形成时代和岩石成因进行研究,进而探讨秦岭造山带早古生代地球动力学背景。

1　研究区地质背景

秦岭造山带位于东昆仑造山带、祁连造山带、扬子板块和华北板块等地体的交接部位,由商丹缝合带和勉略缝合带从北到南划分为北秦岭、南秦岭和扬子板块北缘 3 个构造单元(图 1)(Meng Qingren et al. , 1999, 2000; Zhang Guowei et al. , 2001; Wang Zongqi et al. ,2009)。北秦岭造山带从北向南,可以分为宽坪单元、二郎坪单元和北秦岭单元,本文研究的草滩沟群位于北秦岭单元。研究区位于北秦岭造山带西段凤县地区(1)。研究区构造发育,断裂主体呈近东西向展布,有少量北西向断裂切穿研究区地层和岩体(图 2)。该区出露大面积变质岩,结晶基底主要为古元古界秦岭岩群(Pt_1Q),为一套经历多期变质变形改造的中高级变质岩石组合体。古生代地层包括下古生界丹凤岩群(Pz_1D)、寒武系—奥陶系罗汉寺岩组((∈-O)l)、奥陶系草滩沟群(OC)、上泥盆统大草滩组(D_3d)和上石炭统草凉驿组(C_2c)。除草滩沟群中的张家庄组和龙王沟组为整合接触,其余地层之间为断层接触。下古生界丹凤岩群(Pz_1D)为一套低绿片岩相变质的中基性火山岩系,且发育少量变质中—酸性火山岩、含碳硅质岩、浅灰色变英安质熔岩、凝灰岩和薄层硅质岩(Yan Zhen et al. ,2009)。寒武系—奥陶系罗汉寺组((∈-O)l)为浅变质、强变形有层无序的火山—沉积岩系,是一套含火山碎屑的弧前盆地沉积楔形体,其中的英安质晶屑凝灰岩形成时代为 491±5Ma (Cui Jiantang et al. ,2011)。奥陶系草滩沟群(OC)分布在研究区中部(图 2),呈近东西向展布,自下而上划分为红花铺组(O_1h)、张家庄组(O_3zh)和龙王沟组(O_3lw)(Song Zhigao et al. , 1991; Sun Minsheng,1998)。红花铺组南部和北部分别与上覆张家庄组和上石炭统草凉驿组断层相隔;张家庄

组北与上石炭统草凉驿组断层相隔，南与下伏红花铺组亦为断层相接；龙王沟组北与下伏地层张家庄组为整合接触，南与秦岭岩群以韧性断层相隔。张家庄组和红花铺组中的火山岩以中—酸性火山岩为主，呈夹层产出，而龙王沟组以凝灰质碎屑岩夹安山岩为主(图 3)，并具火山喷发韵律(Xu Xiaochun et al.，2014)。上泥盆统大草滩组(D_3d)主体为一套以紫红色、灰绿色为特征的陆相杂色碎屑岩(Wu Shukuan et al.，2012)。上石炭统草凉驿组(C_2c)形成于河流—沼泽相沉积环境，主体为砾岩和泥岩，夹不稳定煤层、煤线，产植物化石(Wu Xiuyuan et al.，2004)。研究区出露不同期次的侵入体，北部为中生代岩浆岩，中部和南部主体为早古生代岩浆岩(Chen Junlu et al.，2008a；Yao Zheng et al.，2017)。岩石类型主要包括奥长花岗岩，石英闪长岩和二长花岗岩，部分岩体具埃达克质岩浆岩特征(Ren Long et al.，2018)。红花铺岩体侵入草滩沟群张家庄组中，年代学研究显示，岩体的形成时代为450.5±1.8Ma(Wang Hongliang et al.，2006)，间接证明张家庄组的形成时代早于晚奥陶世早期。

2 岩石学特征

龙王沟组酸性凝灰岩呈深灰色，凝灰结构，块状构造(图 4a,b)，主要由火山灰组成，含有少量晶屑。火山灰全部重结晶形成纤维状、霏细状长英质，局部发生绿泥石化，同时有铁质析出。晶屑主要由石英和长石组成，石英晶屑呈棱角状、表面干净，见波状消光；长石晶屑主要为斜长石，呈棱角状、不规则的锯齿状，阶梯状，见聚片双晶和卡钠复合双晶(图 4c,d)。

3 样品采集及分析方法

3.1 样品采集

本文研究的样品采集于凤县草凉驿龙王沟的龙王沟组中(图 3)，为酸性凝灰岩。其中锆石 U-Pb 同位素年龄样品地理坐标为 N 36°04.172′，E 106°44.710′，样品编号为 PM10/7。

3.2 锆石 U-Pb 定年

样品破碎和锆石挑选由陕西省地勘局区域地质矿产研究院完成。常规方法将同位素测年样品粉碎至 100 目，并用常规浮选方法进行分选出锆石后，再

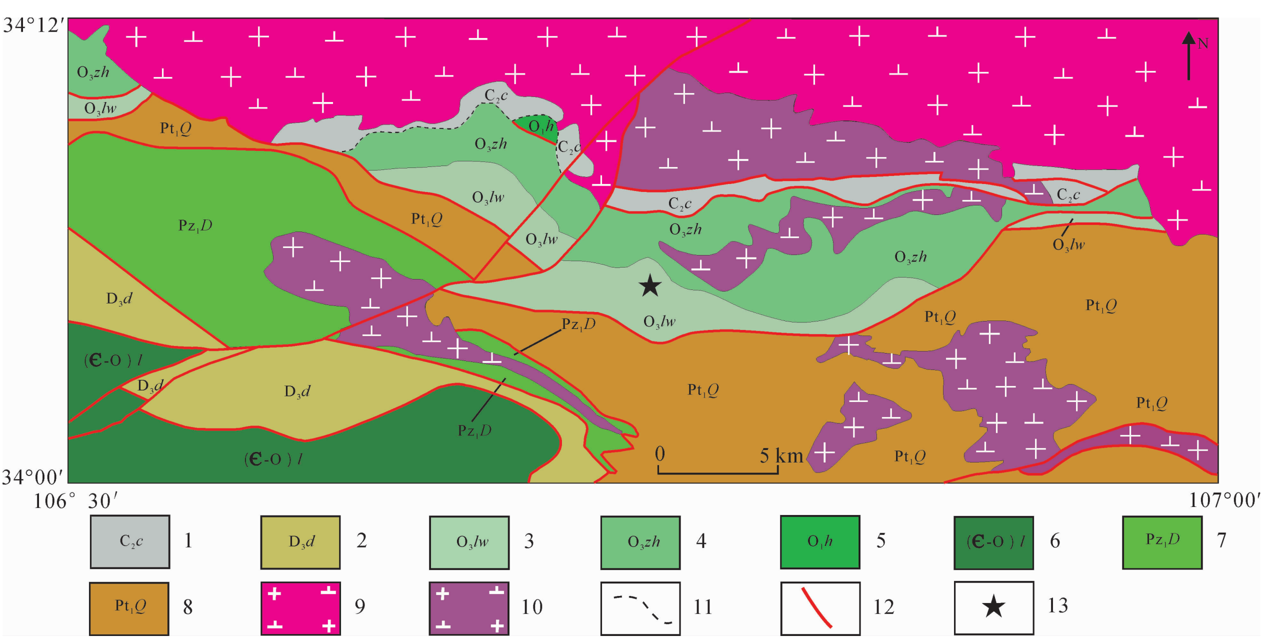

图 2 西秦岭凤县地区地质简图

Fig. 2 Simplified geological of Fengxian area in the West Qinling

1—上石炭统草凉驿组；2—上泥盆统大草滩组；3—上奥陶统龙王沟组；4—上奥陶统张家庄；5—上奥陶统红花铺组；6—寒武系—奥陶系罗汉寺岩组；7—下古生界丹凤岩群；8—古元古界秦岭岩群；9—早中生代岩浆岩；10—早古生代岩浆岩；11—角度不整合；12—断层；13—同位素年龄样品采样点

1—Upper Carboniferous Caoliangyi Fromation；2—Upper Devonian Dacaotan Formation；3—Upper Ordovician Longwanggou Formation；4—Upper Ordovician Zhangjiazhuang Formation；5—Lower Ordovician Honghuapu Formation；6—Cambrian-Ordovician Luohansi Formation；7—Lower Paleozoic Danfeng Group；8—Paleoproterozoic Qinling Group；9—Early-Mesozoic granites；10—Early-Palaeozoic granites；11—angular unconformity；12—fault；13—isotope age sample sampling point

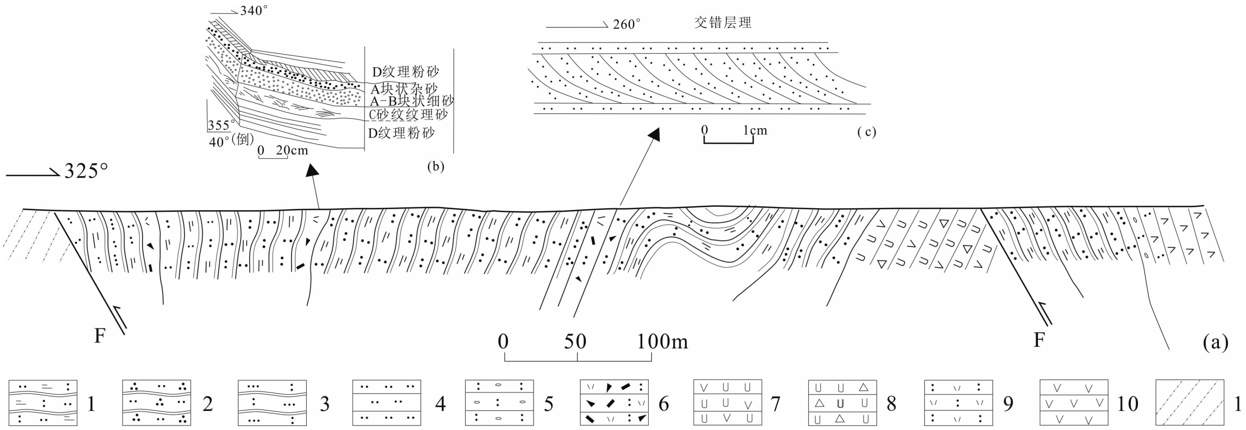

图 3　北秦岭西段凤县地区上奥陶统草滩沟群龙王沟组实测剖面图(修改自 Sun Minsheng et al.,1995)

Fig. 3　Stratigraphic section of the Upper Ordovician Longwanggou Formation in the Caotangou Group in Fengxian area in western section of the North Qinling(modified after Sun Minsheng,1995)

1—凝灰质粉砂质绢云母板岩;2—变质石英粉砂岩;3—变凝灰质细砂岩;4—粉砂岩;5—凝灰质砾岩;6—岩屑晶屑凝灰岩;7—蚀变中性熔岩;8—蚀变安山质角砾熔岩;9—凝灰岩;10—安山岩;11—糜棱岩

1—tuffaceous silty sericite slate; 2—metamorphic quartz siltstone; 3—meta-tuffaceous fine-grained sandstone; 4—siltstone; 5—tuffaceouse conglomerate;6—crystal-lithic tuff;7—altered medium lava;8—altered andesitic breccias lava;9—tuff;10—andesite;11—mylolite

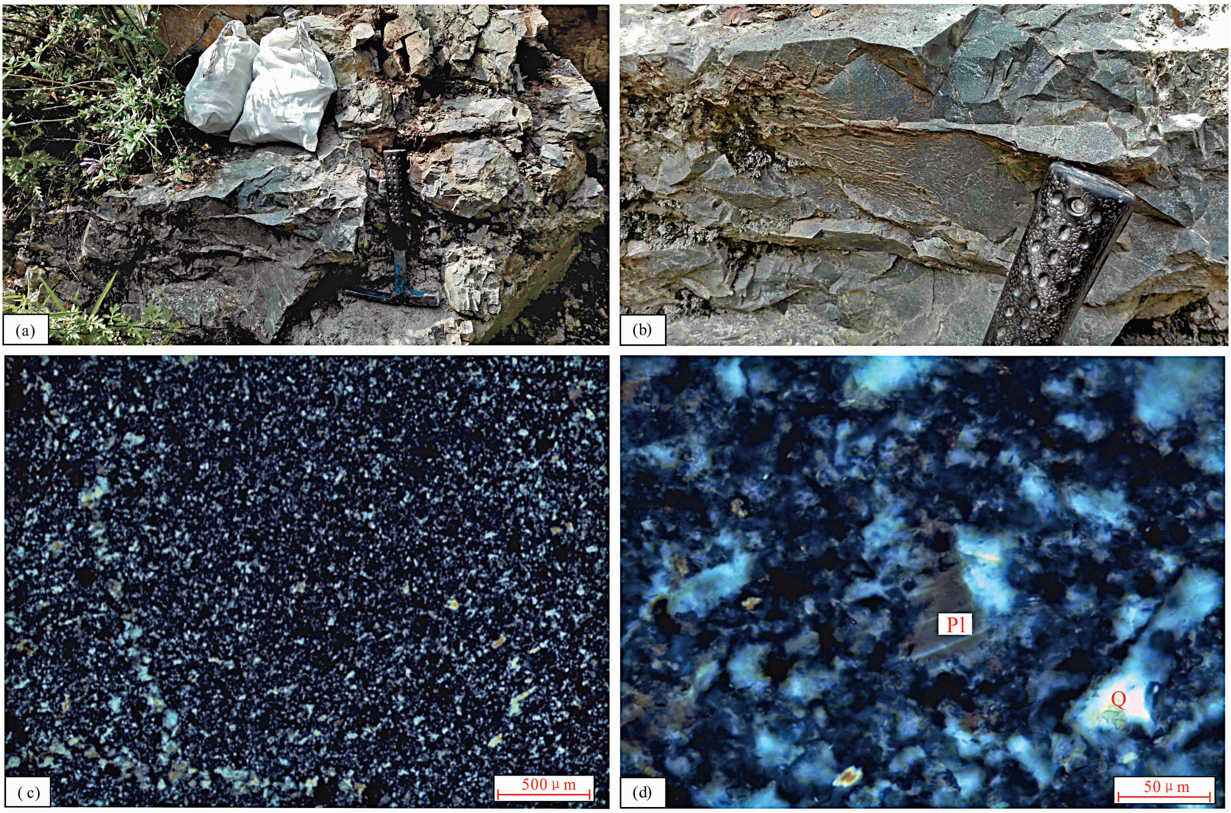

图 4　北秦岭西段凤县地区草滩沟群龙王沟组酸性凝灰岩野外地质特征(a,b)和显微照片(c,d)

Fig. 4　Outcrop photos (a,b) and microphotographs (c,d) for acidic tuff in the Longwanggou Formation of Caotangou Group in Fengxian area in western section of the North Qinling

Pl—斜长石;Q—石英 (a)—酸性凝灰岩中火山灰全部重结晶形成霏细状长英质;(b)—酸性凝灰岩中斜长石晶屑呈阶梯状

Pl—plagioclase;Q—quartz (a)—recrystallization of volcanic ash to form felsites in acidic tuff;(b)—plagioclase crystal is staircase in acidic tuff

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。锆石的反射光和透射光

显微照相及阴极发光(CL)显微照相在西北大学大陆动力学国家重点实验室扫描电镜加载阴极发光仪上完成。

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193nmA 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 91500 作为外标校正。在所测锆石样品分析前后各测一次 NIST610,同时以 ^{29}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 Yuan Honglin et al.(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 $^{206}Pb/^{238}U$ 年龄,其加权平均值具 95%的置信度(Anderson,2002;Ludwig,2003),分析结果见表 1、表 2。

表 1　北秦岭草滩沟群龙王沟组酸性凝灰岩(PM10/7)LA-ICP-MS 锆石 U-Pb 同位素分析结果

Table 1　LA-ICP-MS zircon U-Pb isotope analysis results for acidic tuff in the Longwanggou Formation of Caotangou Group in North Qinling

测点号	元素含量($\times10^{-6}$)及比值			同位素比值						表面年龄(Ma)					
	Th	U	Th/U	$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ	$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ
01	145	400	0.36	0.0582	0.0022	0.5855	0.0257	0.0731	0.0007	539	81	468	16	455	4
02	542	728	0.74	0.3684	0.0371	66.6656	10.1954	0.6205	0.0790	3785	153	4279	154	3112	314
03	314	528	0.59	0.0581	0.0020	0.5857	0.0220	0.0732	0.0006	600	72	468	14	456	4
04	116	743	0.16	0.0567	0.0009	0.5917	0.0080	0.0757	0.0005	480	36	472	5	470	3
05	145	400	0.36	0.0556	0.0013	0.5592	0.0116	0.0729	0.0005	438	49	451	8	453	3
06	691	935	0.74	0.0553	0.0011	0.5433	0.0094	0.0713	0.0005	424	43	441	6	444	3
07	589	2050	0.29	0.0645	0.0007	0.9331	0.0069	0.1050	0.0006	757	24	669	4	643	3
08	152	1095	0.14	0.0558	0.0008	0.5800	0.0066	0.0754	0.0004	443	31	465	4	469	3
09	345	1120	0.31	0.0560	0.0010	0.5669	0.0197	0.0733	0.0008	454	41	456	13	456	5
10	102	616	0.17	0.0537	0.0010	0.5519	0.0089	0.0745	0.0005	359	41	446	6	463	3
11	314	528	0.59	0.0564	0.0012	0.5769	0.0109	0.0741	0.0005	468	46	463	7	461	3
12	613	1154	0.53	0.0637	0.0010	0.9000	0.0114	0.1024	0.0006	732	32	652	6	629	4
13	370	1663	0.22	0.0597	0.0009	0.7737	0.0094	0.0940	0.0006	591	32	582	5	579	3
14	152	1095	0.14	0.0568	0.0011	0.5753	0.0157	0.0734	0.0008	483	44	461	10	457	5
15	1723	1496	1.15	0.0602	0.0013	0.6104	0.0113	0.0735	0.0005	611	44	484	7	457	3
16	184	1984	0.09	0.1132	0.0012	3.0357	0.0181	0.1944	0.0010	1851	19	1417	5	1145	5
17	538	1263	0.43	0.0611	0.0013	0.6309	0.0119	0.0749	0.0005	642	45	497	7	466	3
18	501	1406	0.36	0.0572	0.0014	0.5724	0.0210	0.0733	0.0010	502	49	460	14	456	6
19	345	1120	0.31	0.0565	0.0009	0.5636	0.0073	0.0724	0.0004	470	35	454	5	451	3
20	289	1143	0.25	0.0813	0.0012	2.1928	0.0241	0.1955	0.0012	1229	27	1179	8	1151	6
21	239	563	0.42	0.0620	0.0011	0.7203	0.0114	0.0842	0.0005	675	39	551	7	521	3
22	213	1294	0.16	0.0566	0.0011	0.5531	0.0164	0.0706	0.0006	480	43	447	11	440	4
23	241	933	0.26	0.0674	0.0013	0.9855	0.0297	0.1055	0.0013	850	45	696	15	647	8
24	350	474	0.74	0.1234	0.0018	1.2644	0.0147	0.0743	0.0005	2006	26	830	7	462	3
25	381	864	0.44	0.0635	0.0010	0.9571	0.0115	0.1093	0.0006	724	31	682	6	669	4

3.3　岩石地球化学分析

岩石地球化学分析在咸阳核工业二零三研究所分析测试中心完成。常量元素用常规湿法、容量法分析,其中烧失量用重量法分析,微量元素用电感耦合等离子体发射光谱法(ICP-AES)分析,稀土元素用电感耦合等离子体质谱法。常量元素的分析精度(相对标准差)一般小于 1%,微量元素和稀土元素分析精度优于 5%。

4　分析结果

4.1　锆石 U-Pb 年龄

草滩沟群龙王沟组酸性凝灰岩的锆石为浅黄

表 2　北秦岭草滩沟群龙王沟组酸性凝灰岩(PM10/7)中锆石微量及稀土元素($\times 10^{-6}$)分析结果

Table 2　Zircon trace and REE ($\times 10^{-6}$) analysis results for acidic tuff in the Longwanggou Formation of Caotangou Group in North Qinling

测点号	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Y	Nb	Ta	Ti
01	0.58	6.03	0.29	2.36	5.06	0.32	31.45	12.26	151.28	58.41	260.23	53.62	510.89	93.06	8603.58	1760.71	1.05	0.36	44.16
02	0.81	9.61	0.49	4.17	8.43	1.01	40.74	14.59	220.34	65.05	277.79	54.75	508.92	93.28	4501.23	1908.60	1.03	0.36	22.81
03	0.02	1.76	0.030	0.33	1.73	0.15	15.96	7.78	113.92	48.48	235.49	51.10	502.43	89.80	11237.21	1510.38	0.73	0.32	6.83
04	0.04	1.80	0.05	0.59	2.62	0.16	23.94	11.63	161.21	66.03	305.28	65.59	625.20	113.13	10655.74	2030.62	0.80	0.47	6.31
05	0.02	2.42	0.05	1.39	3.17	0.17	20.97	8.42	110.38	43.52	197.67	41.44	397.03	72.83	10076.35	1308.83	0.65	0.35	9.47
06	0.01	5.74	0.10	1.05	3.69	0.86	24.38	9.81	124.98	50.40	240.55	53.38	545.95	107.58	10689.30	1502.05	1.27	0.68	4.12
07	0.09	5.87	0.04	0.69	1.53	0.13	13.26	6.39	88.90	37.39	186.03	44.27	460.80	86.98	12537.21	1168.60	7.28	3.18	3.94
08	0.08	3.20	0.07	0.91	2.28	0.22	19.75	9.39	131.91	54.31	258.19	57.38	564.10	104.52	11278.56	1677.62	2.43	0.95	4.55
09	0.05	6.70	0.064	0.76	3.29	0.62	24.20	10.57	143.89	59.07	277.24	58.62	564.35	103.61	9185.23	1749.73	0.91	0.44	5.09
10	0.04	13.26	0.04	0.74	2.89	1.10	18.62	7.98	111.61	44.70	212.46	47.58	470.82	88.25	9997.26	1366.67	1.67	0.73	5.10
11	0.02	10.50	0.07	1.46	3.93	0.79	21.90	8.94	113.58	45.89	213.58	45.67	442.00	84.52	9086.87	1341.42	1.46	0.50	10.45
12	7.57	38.08	2.60	14.82	8.37	1.74	39.18	14.01	166.86	65.06	291.89	62.18	615.66	114.76	8300.60	1872.34	4.34	0.90	5.33
13	0.03	6.66	0.04	0.79	2.88	0.26	19.82	10.11	141.15	59.92	292.45	63.66	625.76	118.06	11251.77	1861.38	2.15	0.59	4.93
14	9.10	9.68	3.16	11.63	5.69	0.47	22.48	10.42	161.60	71.13	368.70	88.20	884.48	163.54	11409.81	2214.86	2.07	1.35	6.14
15	0.02	21.96	0.11	1.67	4.39	0.97	30.61	11.54	145.61	58.37	254.54	53.65	507.86	94.48	9150.58	1652.85	3.18	1.04	6.06
16	0.04	3.23	0.03	0.70	1.92	0.20	13.92	7.07	102.37	44.33	223.98	52.09	543.71	103.20	10913.80	1366.01	1.80	1.58	7.32
17	0.94	14.90	0.30	1.91	2.87	0.43	14.46	5.20	71.23	29.22	136.90	30.59	304.10	59.70	10274.44	856.32	2.00	1.07	3.78
18	1.16	7.98	0.45	3.90	9.33	0.52	57.23	24.47	308.72	119.11	532.77	110.17	1016.98	179.30	8546.97	3610.20	2.17	0.83	55.87
19	0.10	4.24	0.07	1.67	4.48	0.18	34.44	15.38	210.75	86.75	399.73	86.25	818.92	146.07	10910.56	2665.29	8.80	1.28	2622.41
20	0.06	13.40	0.08	1.37	1.79	0.63	10.02	3.49	40.89	15.87	74.59	17.53	194.82	41.93	8694.86	498.36	1.15	0.35	5.49
21	0.03	8.16	0.06	1.00	2.86	0.49	20.19	7.69	99.16	40.00	181.09	38.98	381.72	72.72	9348.85	1153.32	1.21	0.61	6.55
22	0.03	17.79	0.12	2.34	6.16	1.45	32.81	12.68	167.04	67.23	316.28	67.84	671.03	126.18	9523.55	2062.34	4.20	1.35	2.19
23	0.04	3.75	0.25	3.30	4.57	0.11	19.34	7.06	84.46	32.76	148.71	31.79	310.47	57.34	10650.47	956.31	1.26	0.59	7.45
24	0.16	8.13	0.30	3.83	7.79	1.54	41.45	14.77	171.67	64.60	280.84	56.77	530.53	97.55	8320.58	1870.38	1.09	0.38	12.51
25	0.03	14.48	0.13	3.09	7.48	1.21	36.59	13.22	162.55	62.85	283.46	60.79	594.96	110.94	8624.60	1838.47	2.76	0.68	6.68

注:$\delta Eu = Eu_N/(Sm_N + Gd_N)^{1/2}$。

色—无色透明，锆石环带发育(图 5a)，大部分锆石 Th/U 比值大于 0.1(表 1)，轻、重稀土元素分馏明显，具 Ce 的正异常和 Eu 的负异常，整体为向左倾斜的轻稀土亏损型模式(图 5b)，以上显示这些锆石具岩浆锆石特征(Jian Ping et al.，2001；Corfu et al.，2003；Wu Yuanbao et al.，2004)。样品共测试了 25 个点，其中 16 个测点$^{206}Pb/^{238}U$ 年龄值介于 440～470Ma 之间，有 1 个测点年龄不谐和，剩余 15 个测点$^{206}Pb/^{238}U$ 和$^{207}Pb/^{235}U$ 谐和性较好(图 5c)，$^{206}Pb/^{238}U$ 年龄的加权平均值为 457.4±3.8Ma(MSWD=1.5)(图 5)，为晚奥陶世早期，代表了酸性凝灰岩的结晶年龄。剩余 9 个测点的年龄值较老(小于 1000Ma 的年龄采用$^{206}Pb/^{238}U$ 值，大于 1000Ma 的用$^{207}Pb/^{206}Pb$ 值)，为 521～3785Ma，代表捕获锆石的年龄，表明可能有老的物质参与(后述)。

4.2 岩石地球化学特征

研究区草滩沟群龙王沟组酸性凝灰岩的主量元素和微量元素含量见表 3。其中一件岩石地球化学样品成分变化较大，可能与喷发过程中地壳物质的混入有关。草滩沟群龙王沟组酸性凝灰岩富硅(SiO_2=64.55%～73.07%)和碱(Na_2O+K_2O=5.35%～8.11%)，低铝(Al_2O_3=13.91%～16.07%)，在 TAS 图解中落入流纹岩和英安岩区域(图 6)。凝灰岩稀土总量较高，为 107.00×10^{-6}～219.22×10^{-6}；$(La/Yb)_N$比值为 3.52～9.80，富集

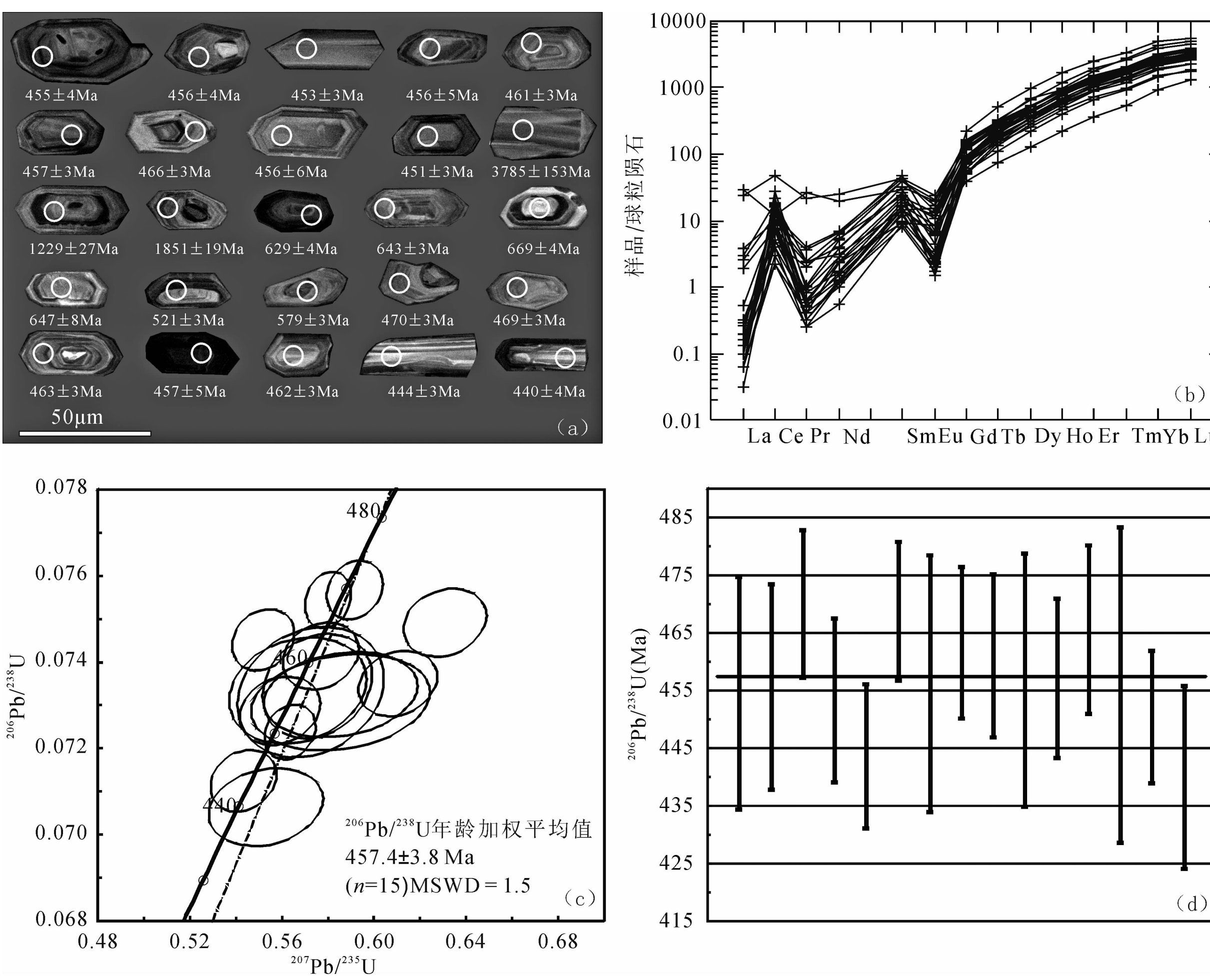

图 5 北秦岭西段凤县地区草滩沟群龙王沟组酸性凝灰岩锆石的阴极发光(CL)图像及 U-Pb 年龄(a)、锆石球粒陨石标准化稀土元素配分图(b)(标准化值据 Boynton，1984)、LA-ICP-MS 锆石 U-Pb 年龄谐和图(c)和锆石$^{206}Pb/^{238}U$ 加权平均年龄图(d)

Fig. 5 Cathodoluminescence photos(CL) of zircons，with marked U-Pb ages(a)，REE chondrite-normalized distribution pattern(b)(normalized values after Boynton，1984)，LA-ICP-MS zircon U-Pb concordant age diagram (c)and $^{206}Pb/^{238}U$ weighted mean ages of zircons(d)for acidic tuff in the Longwanggou Formation of Caotangou Group in Fengxian area in western section of the North Qinling

表 3 北秦岭草滩沟群火山碎屑岩和熔岩主量元素(%)和微量元素($\times10^{-6}$)分析结果

Table 3 Major(%) and trace element ($\times10^{-6}$) analysis results for the pyroclastic rocks and volcanic rocks of Caotangou Group in North Qinling

样品号	PM10/5	PM10/7	PM10/8	D08-1	D10-1	D10-2	D10-3	D10-4
岩性	酸性凝灰岩			流纹岩	流纹岩	流纹岩	流纹岩	流纹岩
数据来源	龙王沟组,本文数据			张家庄组,Yan Quanren et al.,2007				
SiO_2	64.55	71.48	73.07	83.04	66.56	63.19	71.48	72.25
TiO_2	0.57	0.25	0.43	0.32	0.69	0.63	0.45	0.44
Al_2O_3	13.91	14.88	16.07	5.54	10.39	14.88	11.94	11.96
FeO^T	5.36	2.96	2.42	2.00	5.74	2.94	1.22	2.79
MnO	0.10	0.06	0.02	1.70	3.20	1.66	1.20	1.27
MgO	2.28	0.57	0.22	0.04	0.07	0.16	0.12	0.06
CaO	3.21	0.68	0.11	3.12	5.37	2.79	2.26	2.10
Na_2O	3.78	7.59	0.10	0.09	0.16	0.08	0.05	0.07
K_2O	2.28	0.52	5.25	1.32	2.86	4.09	2.16	3.19
P_2O_5	0.13	0.15	0.03	0.69	1.60	6.43	5.57	2.15
LOI	3.81	0.81	2.57	1.47	3.31	3.22	1.93	3.40
Total	99.98	99.95	100.19	99.55	100.28	100.20	99.52	99.75
Sc	14.1	6.40	7.60	38.1	9.60	9.73		
V	113	27.5	24.5					
Cr	83.0	12.2	6.60					
Co	10.9	3.78	4.48	30.3	1.53	1.58		
Ni	21.3	8.88	4.70					
Cu	22.1	12.9	15.1					
Zn	71.9	60.2	21.5					
Ga	13.2	12.4	14.7	20.0	17.5	17.6		
Rb	70.2	40.5	160.1	3.97	75.7	77.8		
Sr	263	307	17.4	512	99.4	106		
Y	25.2	51.1	34.9	14.4	76.7	52.3	48.2	49.5
Nb	4.89	16.9	6.94	2.64	7.78	7.95		
Cs								
Ba	491	191	378	108	860	865		
La	20.10	26.20	49.40	20.11	49.93	45.38	36.38	39.23
Ce	42.60	60.70	92.80	40.10	106.49	93.15	75.49	80.89
Pr	5.06	6.76	9.31	4.36	12.74	11.79	9.75	10.42
Nd	19.30	26.10	39.30	16.28	52.34	47.21	39.65	42.26
Sm	4.29	6.42	6.13	3.29	12.12	0.58	8.59	8.82
Eu	1.19	0.69	1.42	0.74	2.81	2.47	2.43	2.53
Gd	4.13	5.86	6.38	3.04	11.40	9.65	8.65	9.08
Tb	0.71	1.19	0.92	0.49	2.11	1.47	1.38	1.49
Dy	3.68	7.60	4.91	2.62	13.07	8.70	8.11	8.33
Ho	0.85	1.54	1.09	0.52	2.79	1.91	1.75	1.79
Er	2.18	4.39	3.15	1.45	7.76	5.61	5.01	4.96
Tm	0.34	0.68	0.47	0.23	1.21	0.85	0.78	0.80
Yb	2.24	5.02	3.40	1.44	7.84	5.70	5.09	4.95
Lu	0.33	0.69	0.54	0.20	1.22	0.93	0.80	0.82
Hf	4.04	5.62	9.02	2.31	6.25	6.24		
Ta	1.30	2.06	1.01	0.13	0.42	0.44		
Pb	22.4	83.8	9.10	6.70	13.5	10.2		
Th	8.13	15.0	16.9	1.99	7.51	7.22		
U	1.92	5.92	2.27	0.63	1.47	1.45		
Zr	138	132	268	78.8	245	250		
$Mg^{\#}$	43	26	14	3	2	9	15	4
δEu	0.86	0.34	0.69	0.72	0.78	0.86	0.86	0.68
Nb/Ta	3.76	8.20	6.87	20.31	18.52	18.07		
$(La/Yb)_N$	6.05	3.52	9.80	9.42	5.37	4.82	5.34	9.39

注:$Mg^{\#}=100\times(Mg^{2+}(Mg^{2+}+Fe^{2+}))$;$\delta Eu=Eu_N/(Sm_N\times Gd_N)^{1/2}$

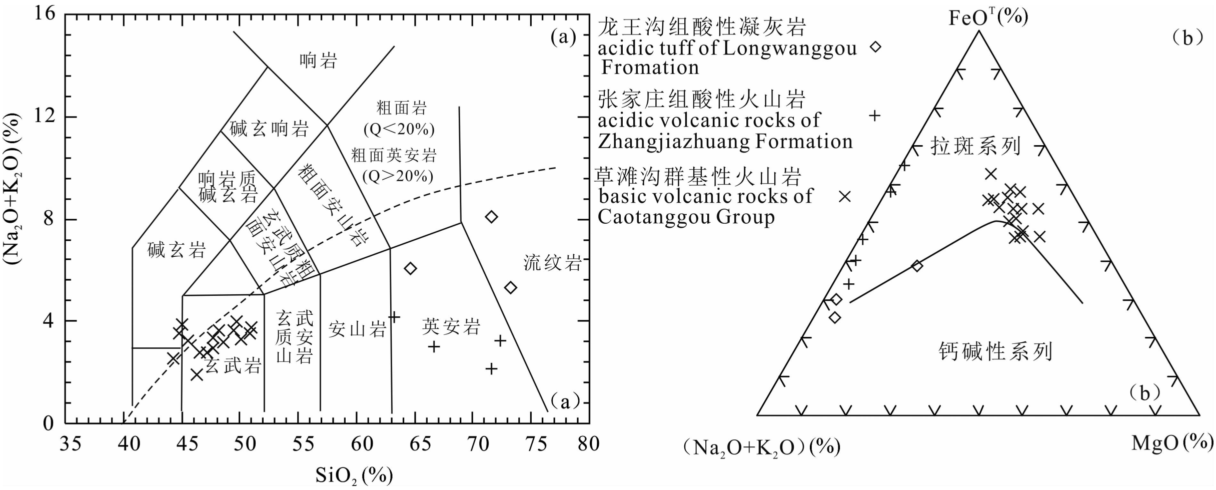

图 6 北秦岭草滩沟群火山岩和酸性凝灰岩 SiO_2-ALK 分类图解

(a,据 Le Maitre et al.,2002)和 AFM 图解(b,据 Irvine et al.,1971)

Fig. 6 SiO_2 vs. ALK classifying diagrams (a)(agter Le Maitre et al.,2002)and AFM diagrams (b)(after Irvine et al.,1971) for volcanic rocks and acidic tuff of Caotangou Group of the North Qinling

数据来源:龙王沟组酸性凝灰岩(本文数据);张家庄组酸性火山岩据 Yan Quanren et al.,2007;草滩沟群基性火山岩据 Zhu Tao et al.,2008 和 Xu Xiaochun et al.,2014

Data from:acidic tuff of Longwanggou Fromation(this study);acidic volcanic rocks of Zhangjiazhuang Formation after Yan Quanren et al.,2007;basic volcanic rocks of Caotanggou Group after Zhu Tao et al.,2008 and Xu Xiaochun et al.,2014

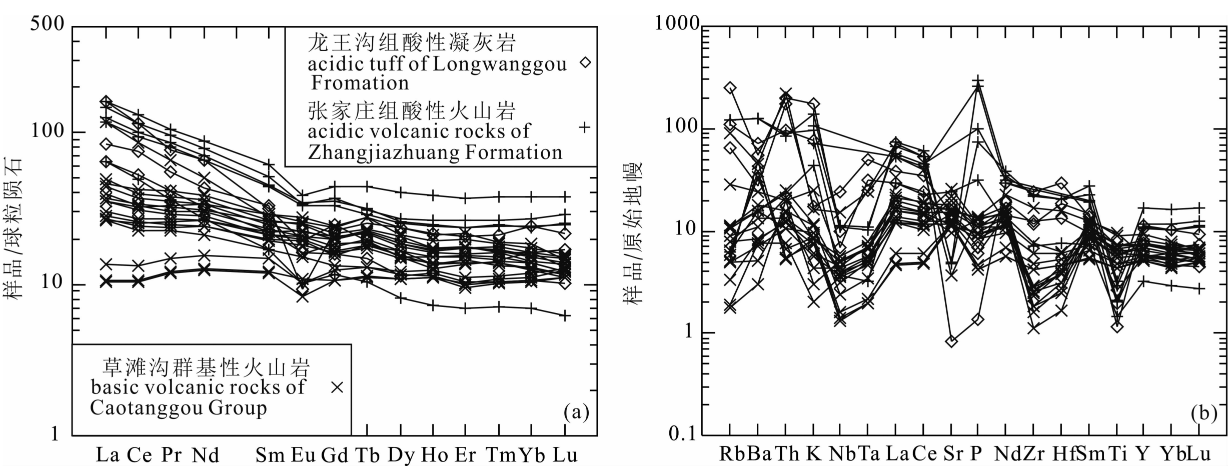

图 7 北秦岭草滩沟群火山岩和酸性凝灰岩的球粒陨石标准化稀土元素配分图(a,标准化值据 Boynton,1984)和微量元素原始地幔标准化蛛网图(b,标准化值据 Sun et al.,1989)

Fig. 7 Chondrite-normalized REE distribution patterns(a)(normalized after Boynton,1984)and primitive mantle-normalized trace element spider diagrams(b)(normalized after Sun et al.,1989) for volcanic rocks and acidic tuff of Caotangou Group of the North Qinling

轻稀土元素,亏损重稀土元素(图 7a),具 Eu 的负异常(δEu=0.34~0.86)。在原始地幔标准化微量元素蛛网图中,富集 Rb、Th、K 等大离子亲石元素(LILE),亏损 Nb、Ta 和 Ti 等高场强元素(HFSE)(图 7b)。

5 讨论

5.1 龙王沟组酸性凝灰岩形成时代

草滩沟群作为北秦岭西段重要的地层单元,主要分布于天水党川、两当张家庄、凤县草凉驿至唐藏一带(Yan Quanren et al.,2009)。古生物研究显示,草滩沟群红花铺组含有腕足类、三叶虫和腹足类等化石,而张家庄组含珊瑚、腹足类、层孔虫、竹节石和海百合茎等化石,其形成时代分别确定为早奥陶世和晚奥陶世(Yang Zichao et al.,1984)。Wang Hongliang et al.(2007)在两当张家庄地区用锆石 U-Pb 法测得草滩沟群张家庄组的中—基性火山岩

形成年龄为 456.4±1.8Ma。本文研究的草滩沟群龙王沟组酸性凝灰岩的形成时代为 457.4±3.8Ma，同中—基性火山岩形成年龄近似。并且，侵入于草滩沟群张家庄组的红花铺岩体的形成时代为 450.5±1.8Ma(Wang Hongliang et al.，2006)，也间接限定草滩沟群张家庄组的形成时代早于晚奥陶世中期。以上研究结果说明，草滩沟群的形成时代为晚奥陶世早期之前。

本文研究的凤县草滩沟群龙王沟组酸性凝灰岩锆石 U-Pb 年龄与其西部张家庄一带张家庄组具有相似的特征，含有大量捕虏锆石，并且其捕虏锆石的年龄分布特征也近似(Wang Hongliang et al.，2007)。捕虏锆石年龄可以分为两组，第一组有 3 颗锆石，其 $^{207}Pb/^{206}Pb$ 年龄大于 1000Ma，分别为 3785Ma、1851Ma 和 1229Ma；第二组有 6 颗锆石，其 $^{206}Pb/^{238}U$ 年龄为 521～669Ma，为新元古代—早古生代早期。龙王沟组和张家庄组都含有大于 3.0Ga 的老锆石，表明北秦岭造山带可能存在太古代—冥古宙地壳物质(Hu Jian et al.，2013)。通过全球古元古代末期构造一热事件特征对比，一般认为 2.0Ga～1.85Ga 期间 Columbia 超大陆基本形成(Rogers et al.，2000；Ernst et al.，2016)，聚合开始于 2.1Ga，主要形成时期为 1.9～1.8Ga，在 1.4～1.2Ga 期间 Columbia 超大陆裂解(Li Sanzhogn et al.，2016；Zhao Guochun et al.，2018)。龙王沟组酸性凝灰岩中 1851Ma 和 1229Ma 捕获锆石可能为 Columbia 超大陆不同构造演化阶段的产物。Rodinia 是一个 1.0Ga 前由大陆碰撞形成的全球性的超大陆(Zhang Ruiying et al.，2016；Zhang Juan et al.，2018)，主要以 Grenvillian(1.3～1.0Ga)造山带为缝合标志(Chaves et al.，2013；Dong Yunpeng et al.，2014，2017)。在新元古代中期(～730Ma)，秦岭造山带 Rodnia 超级大陆随之开始解体，商丹地区重新拉开，发育一套裂谷型火山—沉积岩系(Bader et al.，2013；Liu Hang et al.，2018；Zhao Guochun et al.，2018)。龙王沟组酸性凝灰岩中 521～669Ma 年龄为 Rodnia 超级大陆伸展裂解阶段的记录。龙王沟组不同期次的锆石分别代表了北秦岭造山带不同地质时期的构造—岩浆事件的时代信息。

5.2　岩石成因

草滩沟群龙王沟组酸性凝灰岩具有较低的 Nb/Ta 比值和 Mg$^{\#}$ 值(表 3)，相对富集轻稀土元素，亏损重稀土元素，大部分样品 LILE 富集，而 Sr 和 HFSE 亏损(图 7)，具壳源特征(Rudnike et al.，2003)，显示其为地壳部分熔融的产物(Sun et al.，1989)。凤县地区出露的岩浆岩包括红花铺岩体、唐藏岩体、黄牛埔岩体、闫家店岩体、张家庄中基性火山岩和本文研究的龙王沟酸性凝灰岩。其中唐藏岩体、黄牛埔岩体和闫家店岩体具有埃达克质岩浆岩特征，其具有较低的($^{87}Sr/^{86}Sr)_i$(0.7032～0.7059)以及较高的 $\varepsilon_{Nd}(t)$ 值(－2.79～－0.65)，为受俯冲流体交代的地幔部分熔融形成的岩浆再经过分离结晶形成(Ren Long et al.，2018)。张家庄组的中—基性火山岩具有更高的 $\varepsilon_{Nd}(t)$ 值(＋9.3～＋10.2，Yuan Quanren et al.，2007)，也为受到混染的富集地幔部分熔融形成。具埃达克质特征岩浆岩和张家庄中基性火山岩都具有高 Nb/Ta(平均为 13.14)、Sr/Y 比值(平均为 54.54)和 Mg$^{\#}$ 值(平均为 48)。但龙王沟组酸性凝灰岩和红花铺岩体明显不同，其 Nb/Ta(龙王沟组酸性凝灰岩 6.28；红花铺岩体 8.21)、Sr/Y 比值(龙王沟组酸性凝灰岩 5.65；红花铺岩体 10.49)和 Mg$^{\#}$ 值(龙王沟组酸性凝灰岩 28；红花铺岩体 33)较低，体现壳源特征。所以龙王沟组酸性凝灰岩成因可能与红花铺花岗闪长岩相似，为地壳部分熔融形成(Dong Zengchan et al.，2009)。龙王沟组酸性凝灰岩稀土元素配分曲线呈右倾斜型，反映岩石成岩过程中 LREE 发生过分馏；负 Eu 异常反映成岩过程中可能经历了斜长石结晶分离(图 7a)。

5.3　构造意义

对于秦岭造山带晚奥陶世岩浆活动，多数研究者认为是商丹洋向北俯冲或者为二郎坪弧后小洋盆向南俯冲的结果(Dong Yunpeng et al.，2011，2016；Qin Zhengwei et al.，2014；Dai Liming et al.，2018)。但是研究显示，秦岭造山带在 480～500Ma 期间广泛发育超高压变质事件，并且在后期经历了～450Ma 中压麻粒岩相和～420Ma 角闪岩相退变质作用，北秦岭造山带晚奥陶世的岩浆活动可能为大陆深俯冲及其后期折返的动力学反映(Zhang Jianxin et al.，2011；Liu Liang et al.，2013，2016；Zhang Chengli et al.，2013；Chen Danling et al.，2015)。还有研究者根据秦岭造山带岩浆岩时空分布和岩石地球化学特征，认为在晚奥陶世为同碰撞环境(Wang Xiaoxia et al.，2015；Wang Jiangbo et al.，2018)。以上显示，秦岭造山带晚奥陶世构造环境还存在较大争议。

北秦岭榴辉岩与华南陆块和南秦岭造山带内同

期大陆玄武岩类似，其大地构造属性总体上与华南陆块北缘岩石相似(Wang Hao et al.,2013a;Tang Huan et al.,2017)。而且，同位素地球化学研究表明，秦岭造山带内部各地质单元的地球化学组成有很大的差异，可能存在更多的微板块(Zhang Hongfu et al.,2015;Dai Liming et al.,2018)。因此，485～500Ma 期间北秦岭超高压变质带可能是秦岭微陆块俯冲的响应(Xiang Hua et al.,2014)。450Ma 和 420Ma 左右的变质作用具有巴罗式变质作用特征，可能与商丹洋的向北俯冲相关(Xiang Hua et al.,2014;Mao Xiaohong et al.,2017;Ren Liudong et al.,2018)。

草滩沟群火山岩和火山碎屑岩富集大离子亲石元素，亏损高场强元素，在原始地幔标准化微量元素蛛网图中具有 Nb、Ta 和 Ti 的负异常(图 7b)，显示弧岩浆岩特征(Zheng Yongfei el al.,2011)。而且在北秦岭造山带，早古生代长英质岩浆岩和镁铁质岩浆岩也都呈现弧岩浆岩特征。特别是与草滩沟群位于同一地区(凤县)的唐藏岩体(Chen Junlu et al.,2008b;Ren Long et al.,2018)、红花铺岩体(Dong Zengchan et al.,2009;Ren Long et al.,2018)、黄牛埔岩体(Yao Zheng et al.,2017)和闫家庄岩体(Ren Long et al.,2018)都具有俯冲岩浆岩特征。镁铁质岩浆岩中富水岩体(Wang Hao et al.,2013b,2014;Zhang Hongfu et al.,2015)、百花岩体(Pei Xianzhi et al.,2007)和流水沟岩体(Gao Jingmin et al.,2012)呈现出富集地幔特征，例如，富集大离子亲石元素、亏损高场强元素、高的 Sr 同位素以及低的 Nd 和 Hf 同位素特征。在构造判别图中，草滩沟群火山岩及其同时代的岩浆岩主体投入火山弧岩浆岩区域(图 8)，说明在早古生代秦岭造山带还处于俯冲阶段。而且，李子园群火山岩具玻安岩特征，形成于俯冲带之上的岛弧/弧前构造环境，进一步证明商丹洋在早古生代早期的俯冲作用(Ding Saping et al.,2004;Pei Xianzhi et al.,2006)。

研究显示，北秦岭造山带的北秦岭单元和二郎坪单元中都出露埃达克质岩浆岩，但二者具有一定区别。北秦岭单元的埃达克质岩浆岩主体晚于460Ma，大部分具 C 型埃达克质岩浆岩特征(Wang Hongliang et al.,2006;Chen Junlu et al.,2008a,2008b;Wang Jing et al.,2008;Wang Tao et al.,2009;Qin Zhengwei et al.,2015;Meng Xiangshu et al.,2017;Yuan Feng et al.,2017;Ren Long et al.,

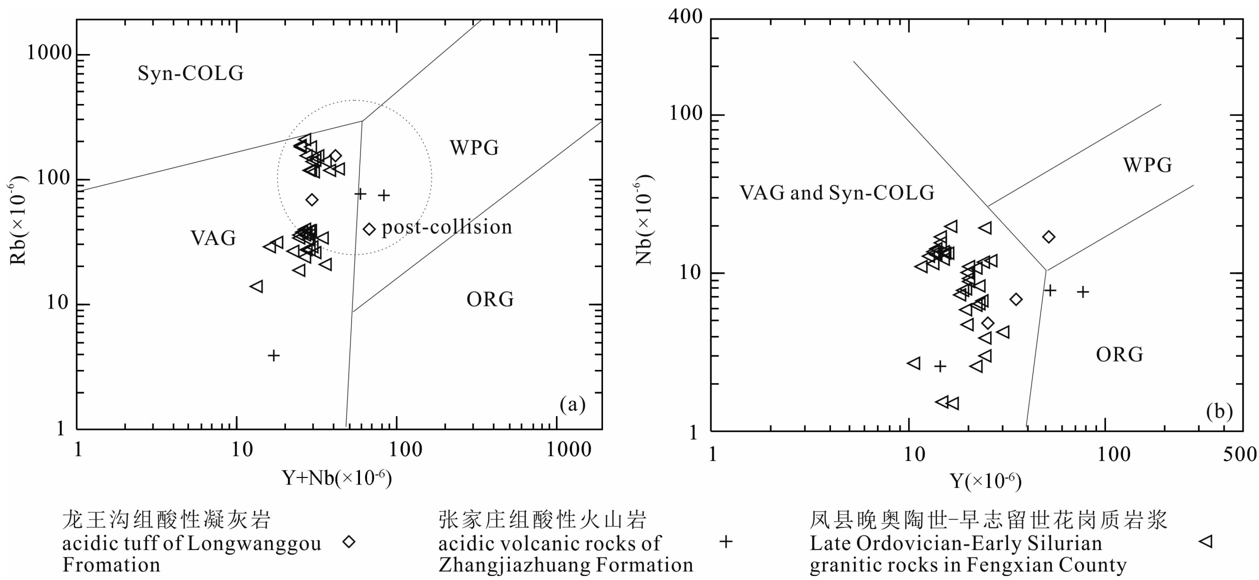

图 8 北秦岭草滩沟群酸性火山岩和酸性凝灰岩构造环境判别图解(据 Pearce et al.,1984)

Fig. 8 Tectonic discrimination diagrams for volcanic rocks and acidic tuff of Caotangou Group of the North Qinling(after Pearce et al.,1984)

凤县晚奥陶世—早志留世花岗质岩浆岩数据据:Chen Junlu et al.,2008b;Dong Zengchan et al.,2009;Yao Zheng et al.,2017;Ren Long et al.,2018;Syn-COLG—同碰撞花岗岩;WPG—板内花岗岩;VAG—火山弧花岗岩;ORG—洋脊花岗岩

Data ofLate Ordovician-Early Silurian granitic rocks in Fengxian County after:Chen Junlu et al.,2008b;Dong Zengchan et al.,2009;Yao Zheng et al.,2017;Ren Long et al.,2018;Syn-COLG—collisionalgranites;WPG—within plate granites;VAG—volcanicarc granites;ORG—Oceanic ridge granites

2018);而二郎坪单元的埃达克质岩浆岩主体早于460Ma,主体具O型埃达克质岩浆岩特征(Tian Wei et al.,2005;Wang Tao et al.,2009;Guo Cailian et al.,2011;Li Mingze et al.,2014)。结合超高压变质带的分布,说明二郎坪弧后洋盆在496Ma左右已经闭合,如果存在二郎坪洋盆的俯冲,这些埃达克质岩浆岩应该分布在俯冲带上盘的北秦岭单元中,但这与事实相反。所以,北秦岭造山带岩浆岩应该与商丹洋的向北俯冲相关(Zhang Hongfu et al.,2015)。

本文研究的草滩沟群龙王沟组中含有鲍马序列(图3),张家庄组基性火山岩具有枕状构造(Song Zhigao et al.,1991),在草滩沟群红花铺组和张家庄组中发现海相古生物化石(Wu Xiuyuan et al.,2004;Yan Quanren et al.,2007),草滩沟群具有海相碎屑岩—碳酸盐岩岩石组合,显示草滩沟群具海相沉积特征(表4)。年代学研究显示草滩沟群张家庄组和龙王沟组的形成时代分别为456±2Ma和457.4±3.8Ma,这些特征显示商丹洋在晚奥陶世还未闭合。北秦岭造山带晚奥陶世岩浆活动为商丹洋向北俯冲的结果。

表 4 草滩沟群岩石组合特征对比表

Table 4 The table of rock assemblages characteristics of Caotangou Group

	研究区域	岩石组合	火山岩特征	沉积变质特征	古生物特征	参考文献
龙王沟组	凤县草凉驿龙王沟	碎屑岩为主,夹少量火山岩	安山质火山岩	含凝灰质粉砂岩、凝灰质细砂岩,具鲍马序列		Yan Quanren et al.,2007
	辛家庄、红花铺	细粒碎屑岩夹火山岩	中性火山岩	含凝灰质粉砂质板岩,凝灰质细砂岩为主		Sun Minsheng,1998
张家庄组	凤县龙王沟及老厂	火山岩为主,夹少量板岩及灰岩薄层条带	中基性、中酸性火山熔岩、火山碎屑岩	板岩、灰岩	腕足类及海百合茎化石	Yan Quanren et al.,2007
	天水党川乡阴崖沟	变质岩为主,夹火山岩	变英安岩	变石英砂岩、粉砂质板岩		Xu Xiaochu et al.,2014
	辛家庄、红花铺	中—中酸性火山岩夹碳酸岩	变质中酸性凝灰质角砾岩、集块岩、晶屑岩屑凝灰岩、熔岩	灰岩		Sun Minsheng,1998
	两当张家庄	火山岩为主	玄武岩—安山岩—英安岩—流纹岩组合,基性火山岩具枕状构造			Song Zhigao et al.,1991
红花铺组	凤县红花铺杨家岭	一套碎屑岩夹细碧岩、中酸性火山岩	细碧岩、中酸性火山岩	下段粉砂质板岩、粉砂岩夹少量细碧岩、砂砾岩、灰岩薄层;上段粉砂质板岩,粉砂岩、石英砂岩和灰岩	下段腕足类、腹足类及海百合茎化石;上段腕足类及三叶虫化石	Yan Quanren et al.,2007
	天水党川乡阴崖沟	变质岩为主,夹火山岩	变玄武安山岩、变安山岩	黑云石英片岩、二云石英片岩、绢云母石英片岩、中基性火山碎屑岩		Xu Xiaochu et al.,2014
	辛家庄、红花铺	细粒碎屑岩为主夹碳酸盐岩及火山岩	英安岩、流纹岩为主,另有安山岩和少量玄武岩	灰绿色变质粉砂岩、粉砂质板岩		Sun Minsheng,1998
	红花铺	沉积岩夹火山岩				Song Zhigao et al.,1991

6 结论

(1)北秦岭构造带西段草滩沟群龙王沟组中的酸性凝灰岩锆石LA-ICP-MS U-Pb定年结果为457.4±3.8Ma,形成时代为晚奥陶世。

(2)草滩沟群龙王沟组酸性凝灰岩具弧岩浆岩特征,为地壳部分熔融的结果。

(3)北秦岭造山带在晚奥陶世商丹洋还未闭合,仍处于俯冲阶段。

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Age and geochemical characteristics of acidic tuff in the Longwanggou Fromation of Caotangou Group in the Fengxian area, western part of the North Qinling orogenic belt, and their tectonic implications

CHEN Guochao[1,3], ZHANG Yafeng[*2], PEI Xianzhi[3], LI Zuochen[3], JI Xianjun[1], WEI Junqi[4], MO Ronghuan[1], WANG Chao[1]

1) *School of Civil Engineeringy, Nanyang Institutte of Technolog, Nanyang*, 473000;

2) *Shaanxi Mineral Resources and Geological Survey, Xi'an*, 710068;

3) *Faculty of Earth Science and Resources Chang'an University, Xi'an*, 710054;

4) *Key Laboratory of Rare Mineral, Ministry of Land and Resources, Wuhan*, 430034

* *Corresponding author: aimom84@163.com*

Abstract

The Longwanggou Formation of Caotangou Group is widely exposed in the western part of northern Qinling Orogenic Belt, which is of great importance for understanding the early Paleozoic tectonic evolution of the Qinling Orogenic Belt. The acidic tuff in the Longwanggou Formation yields an LA-ICP-MS zircon age of 457.4±3.8 Ma. The acidic tuff samples in the Longwanggou Formation have SiO_2 (72.06%～74.49%) and Na_2O+K_2O (5.35%～8.11%), and low Al_2O_3 (13.91%～16.07%) contents. The rocks are geochemically featured by LILE enrichment and HFSE depletion, low $Mg^{\#}$ values and Nb/Ta ratios and obvious negative anomalies (δEu=0.34～0.86). The acidic tuff in the Longwanggou Formation has the characteristics of crustal source. The acidic tuff in the Longwanggou Formation and Late Ordovician-Early Silurian magmatic rocks have gecchemical characteristics of arc magmatic rocks, indicating that they were formed in a subduction environment. Combined with the early Paleozoic ultrahigh pressure metamorphic belt, the distribution of magmatic rocks and the sedimentary characteristics of Caotanggou Group, we suggest that the subduction of the Shangdan Ocean was still ongoing in the Early Ordovician.

Key words: Western part of the North Qinling Orogenic Belt; Caotangou Group; Longwanggou Formation; Zircon U-Pb age; geochemistry; tectonic evolution