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南秦岭铧厂沟碧口群玄武岩LA-ICP-MS锆石U-Pb年龄及岩石成因研究

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提要:铧厂沟地区碧口群玄武岩呈带状和透镜状分布于凝灰岩和凝灰质千枚岩中。在详细野外观察基础上, 利用显微镜观察、主微量元素及放射性同位素分析等综合分析技术对玄武岩的岩石学、地球化学以及年代学特征进行了研究。结果表明: 碧口群玄武岩普遍经历了绿片岩相的变质作用, 主要矿物为斜长石、绿泥石和绿帘石; SiO_2(44.67%~49.76%)、TiO_2(1.14%~1.34%)含量较低, TFe_2O_3(12.03%~15.47%)、MgO(7.57%~9.3%)、CaO(7.29%~10.54%)含量较高。稀土总量较低, 轻稀土亏损, 重稀土富集。岩石微量元素和锆石Hf同位素特征显示玄武岩形成环境可能类似N-MORB, 起源于软流圈, 并在上升过程中混入了古老的地壳物质。LA-ICP-MS锆石测年结果显示玄武岩的形成年龄为(316.3±6.0) Ma (MSWD=0.78; n=7), 表明碧口群火山岩系至少是两期(新元古代时期和晚古生代时期)火山作用的产物。其大规模形成时期为新元古代, 后经晚古生代火山作用的叠加改造而成。

关 键 词: 碧口群; 玄武岩; 锆石U-Pb定年; Hf同位素; 岩石成因; 铧厂沟
中图分类号: P588.14$^+$5 ;P597$^+$.3 **文献标志码**: A **文章编号**: 1000-3657(2014)04 -1341-15

位于扬子板块北缘的碧口群火山岩系是南秦岭造山带的主要结构组成单元之一[1],前人虽进行了大量研究,但对其形成构造环境和时代等关键问题,尚未形成统一的认识。关于其形成构造环境的主要认识有岛弧[1-9]、弧内裂谷环境[10-14]以及洋中脊和大洋板内环境[15-17]等。对其形成时代的认识有新元古代[4,7,17-24]、泥盆纪[9,25]以及志留—泥盆纪[26]。因此,继续深入研究碧口群火山岩的成因具有重大意义。本文通过对碧口群北部铧厂沟地区出露的玄武岩进行岩石学、地球化学、锆石U-Pb定年和Hf同位素研究,确定该套火山岩为一套形成于石炭纪中期的洋中脊玄武岩,这为碧口群火山岩系的成因提供了新的证据,同时也为该区古大地构造的重建提供了重要依据。

1 地质背景及岩相学特征

碧口群火山岩系分布于陕西、甘肃、四川3省交界区。研究区位于碧口群北段,秦岭微板块(南秦

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岭)和扬子陆块之间的勉略缝合带南缘[27],隶属摩天岭加里东褶皱带,出露的地层主要为碧口群和中下泥盆统三河口群(图1)。碧口群中亚群二岩性组上段($Pt_{2-3}bk_2^{2-3}$)按岩性组合可细分为3个岩性层:第一岩性层($Pt_{2-3}bk_2^{2-3a}$)岩性为灰白色、浅灰色、酸性凝灰岩、凝灰熔岩,局部夹基性熔岩条带;第二岩性层($Pt_{2-3}bk_2^{2-3b}$)岩性为浅灰色酸性灰岩、凝灰熔岩夹基性角砾凝灰岩、凝灰岩及酸性凝灰岩透镜体或条带;第三岩性层($Pt_{2-3}bk_2^{2-3c}$)岩性为浅灰绿色,灰白色中酸性凝灰岩,夹基性及中基性凝灰岩、凝灰熔岩透镜体,中上部夹凝灰质板岩及凝灰质千枚岩,局部夹石英岩透镜体。研究区北部的中下泥盆统三河口群地层($D_{1-2}sh$)与碧口群呈断层接触,其岩性主要为千枚岩和灰岩,其中断续分布细碧岩条带或透镜体。

区内出露的玄武岩呈带状或透镜状分布于碧口群中亚群二岩性组上段第二和第三岩性层凝灰岩和凝灰质千枚岩中(图1),延长最高达2 km,宽20~70 m。玄武岩普遍经历了绿片岩相变质作用,为灰绿-绿色,块状构造,斑状结构,斑晶主要为斜长石,基质主要由斜长石、绿泥石、绿帘石组成,副矿物为含铁暗色矿物(图2)。呈斑晶产出的斜长石为长条状,不发育双晶,粒径大小为0.1 mm×0.2 mm~0.2 mm×0.5 mm。绿帘石多呈规则六边形,粒度为0.1 mm×0.1 mm ~0.25 mm×0.3 mm。绿泥石呈片状和鳞片状,产于斜长石边缘或内部。

2 分析方法

对野外采集的样品进行详细的岩相学观察后,选择新鲜且没有脉体贯入的样品进行主量元素、微量元素分析。主量和微量元素分析均在核工业北京地质研究院分析测试研究中心完成,分析结果见表1。主量元素采用X-射线荧光光谱法(XRF)分析,微量元素和稀土元素采用等离子质谱法(ICP-MS)分析。测试方法和依据参照GB/T14506.14-2010《硅酸盐岩石化学分析方法》第14部分:氧化亚铁量测定,GB/T14506.28-2010《硅酸盐岩石化学分

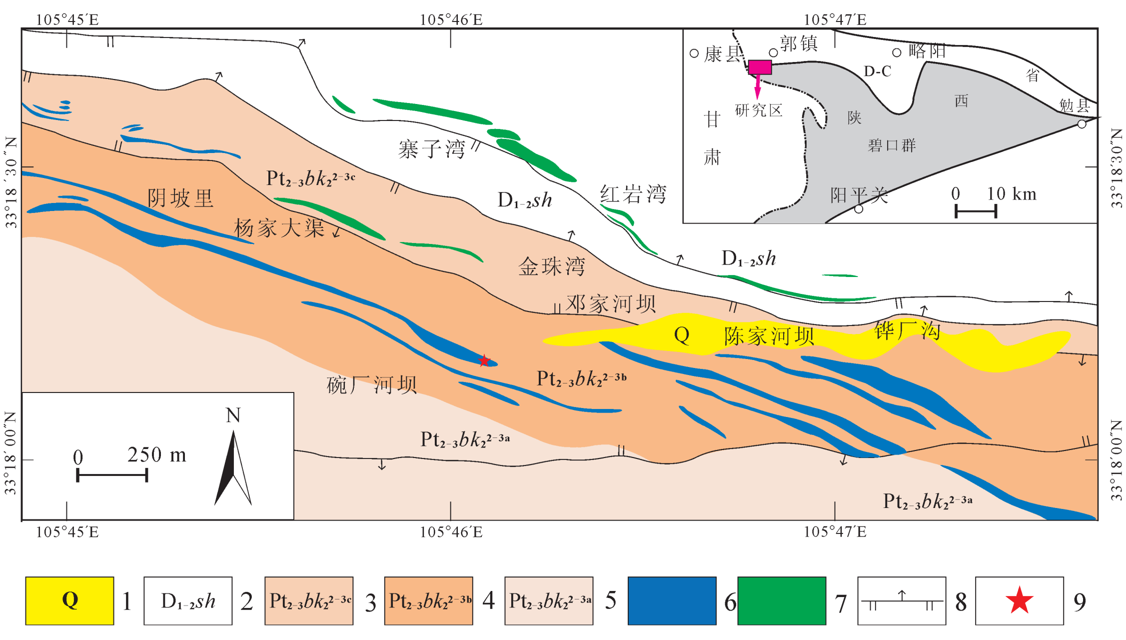

图1 铧厂沟地区碧口群玄武岩分布简图(据资料❶修改)

1—第四系覆盖物;2—中下泥盆统三河口群;3—碧口群中亚群二岩性组上段第三岩性层;4—碧口群中亚群二岩性组上段第二岩性层;5—碧口群中亚群二岩性组上段第一岩性层;6—玄武岩;7—细碧岩;8—逆断层;9—采样点

Fig. Schematic geological map showing the distribution of the Bikou Group basalt in Huachanggou area (after reference❶)

1-Quaternary overburden; 2-Middle-Lower Devonian Sanhekou Group; 3-3rd lithologic layer of 2nd member in middle subgroup of the Bikou Group; 4-2nd lithologic layer of 2nd member in middle subgroup of the Bikou Group; 5-1st lithologic layer of 2nd member in middle subgroup of the Bikou Group; 6-Basalt; 7-Spilite; 8-Thrust fault; 9-Sampling site

❶陕西省地质矿产勘查开发局汉中地质大队. 陕西省略阳县铧厂沟金矿地质图. 2010.

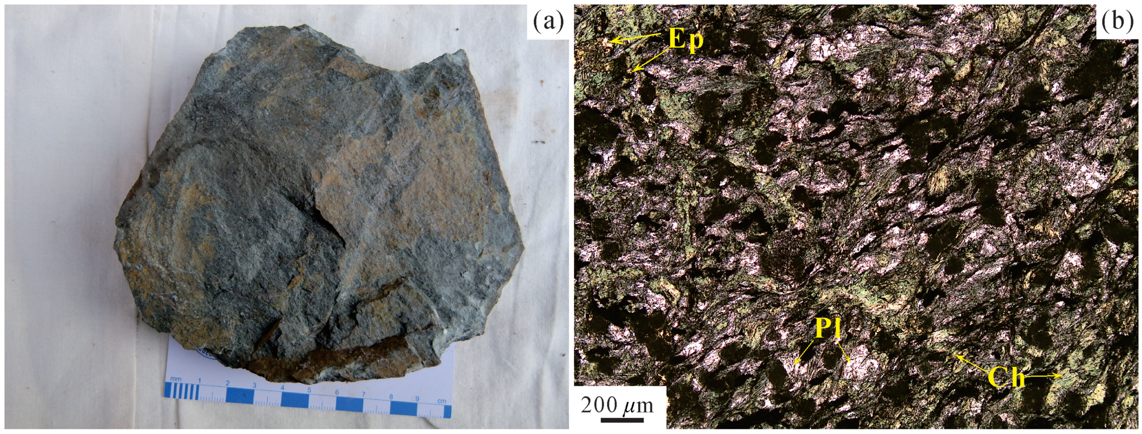

图2 碧口群玄武岩岩相学特征
a—块状构造玄武岩; b—斜长石呈板条状, 绿帘石呈片状, 绿帘石呈自形粒状产出, 单偏光;
Pl—斜长石; Ch—绿泥石; Ep—绿帘石
Fig.2 Petrographic characteristics of the Bikou Group basalt
a-Massive structure of basalt; b-Lath-shaped plagioclase, sheet chlorite and idiomorphic granular epidote, plainlight
Pl-Plagioclase; Ch-Chlorite; Ep-Epidote

析方法》第28部分: 16个主次成分量测定,实验过程中温度20℃,相对湿度30%。微量和稀土测试仪器型号为FinniganMAT制造,HR-ICP-MS(Element),测试方法和依据参照DZ/T0223-2001《电感耦合等离子体质谱(ICP-MS)方法通则》,实验过程中温度20℃,相对湿度30%。

锆石按常规重力和磁选方法分选,将样品人工破碎后,按常规重力和磁选方法分选出锆石,然后在双目镜下挑选。将分选出纯净的锆石颗粒和标样一同置于环氧树脂中制成靶,并打磨抛光至锆石中心部位暴露出来。然后对样品靶上的锆石进行透射光、反射光照相,据此选出晶体特征良好的锆石拍摄阴极发光(CL)图像,以查明锆石内部生长层的分布和结构,最后对选择的锆石进行LA-ICP-MS测年分析。锆石的CL图像在北京大学电子探针分析室完成。锆石LA-ICP-MS分析在中国地质大学(北京)科学研究院LA-ICP-MS实验室完成。分析使用的激光仪器型号为美国New Wave公司UP193SS型激光器,激光波长为193 nm。束斑直径为30 μm,激光频率为10 Hz; 预剥蚀时间和剥蚀时间分别为5 s和45 s。实验过程使用He作为载气,流速为0.8 L/min。等离子质谱(ICP-MS)型号为美国Agilent公司生产的7500a型质谱仪;元素积分时间U、Th、Pb为20 ms,Si、Zr为6 ms,其他元素为10 ms。数据处理软件使用Glitter4.4.1。年龄计算时以标准锆石TEM为外标进行同位素比值校正,标准锆石91500和Qinghu为监控盲样。元素含量以国际标样NIST610为外标,Si为内标计算,NIST612和NIST614做监控盲样,^{204}Pb方法同Anderson (2002)[28]。

锆石Hf同位素测试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Nepture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,实验过程中采用He作为剥蚀物质载体,剥蚀直径采用55 μm,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侯可军等[29]。

3 分析结果

3.1 地球化学特征

碧口群玄武岩的主微量及稀土元素分析数据见表1。Nb/Y-Zr/P_2O_5和Nb/Y-Zr/TiO_2火山岩分类命名及系列划分图是划分蚀变、变质火山岩系列的有效图解[30-31]。从图3-a、b可以看到,本区所有玄武岩样品均落入亚碱性拉斑系列玄武岩区,属于拉斑玄武岩系列。玄武岩的SiO_2含量较低(44.67%~49.76%),具有低TiO_2含量特征(1.14%~1.34%,平均

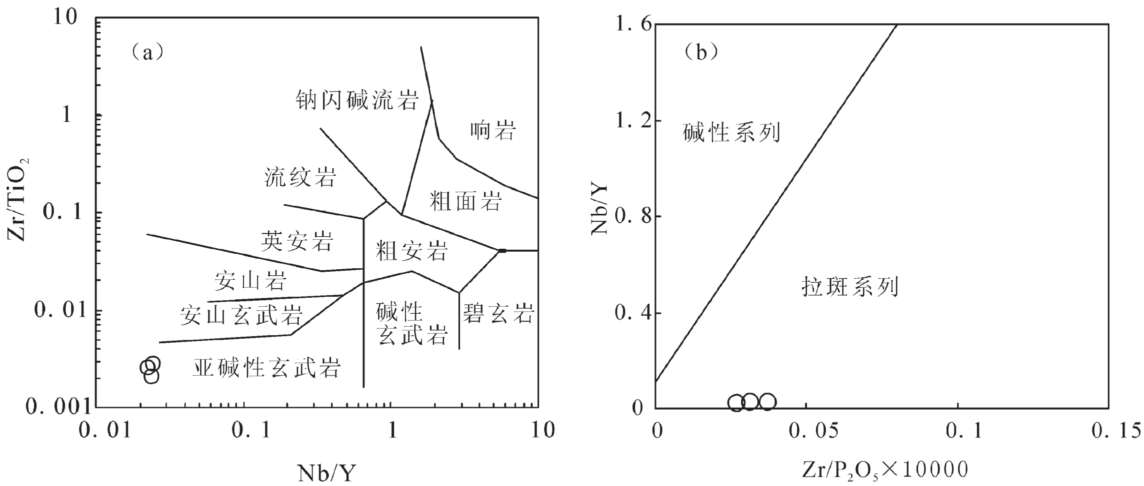

图3 碧口群玄武岩Nb/Y－Zr/TiO$_2$图解(a)和Zr/P$_2$O$_5$–Nb/Y图解(b)

Fig.3 Zr/TiO$_2$ versus Nb/Y diagram (a) and Nb/Y versus Zr/P$_2$O$_5$ diagram (b) of the Bikou Group basalt

为1.25%)，TFe$_2$O$_3$(12.03%~15.47%)、MgO(7.57%~9.3%)、CaO(7.29%~10.54%)含量较高，全碱含量较低(Na$_2$O+K$_2$O介于2.75%~3.16%，平均2.96%)，Na$_2$O>K$_2$O，其中K$_2$O含量极低(仅为0.13%~0.39%)。

本区玄武岩稀土总量较低，∑REE介于(34.88~40.24)×10^{-6}，平均为37.43×10^{-6}；轻重稀土分异不明显，∑LREE/∑HREE比较稳定，在1~1.28变化，平均为1.12；岩石具有明显的Eu正异常，δEu介于1.36~1.45，平均为1.39；(La/Yb)$_N$介于0.26~0.45，平均为0.34。在球粒陨石标准化配分图上(图4)，曲线总体显示为轻稀土亏损型。在原始地幔标准化微量元素蛛网图(图5)总体显示为左倾正斜率轻微富集型，Th、Nb、Sr、Zr呈现出不同程度的亏损。大离子亲石元素Rb、Ba、K显示出不同程度的富集。

3.2 锆石U–Pb年龄

碧口群玄武岩中锆石的CL图像如图6所示，锆石颗粒多呈无色透明，少数为浅棕色和浅玫瑰色，自形程度较高，形态复杂，多为柱状晶体，长度介于20~165 μm，长宽比介于1∶1~2.4∶1，多数可见震荡环带，部分锆石内部可见细小的包裹体和裂纹。采

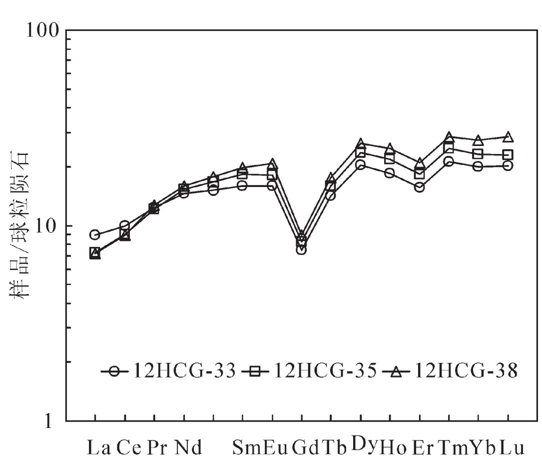

图4 碧口群玄武岩稀土元素球粒陨石标准化图
（标准化数据来自文献[32]）
Fig.4 Chondrite-normalized REE patterns of the Bikou Group basalt
（chondrite values after Reference [32]）

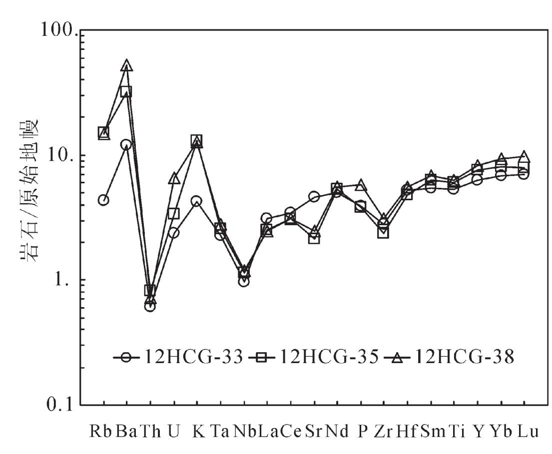

图5 碧口群玄武岩的微量元素蛛网图
（标准化数据来自文献[32]）
Fig.5 Incompatible element spider diagram of the Bikou Group basalt
（primitive mantle values after Reference [32]）

用束斑直径为30 μm的激光剥蚀对样品进行了LA-ICP-MS定年分析,共完成21个锆石22个点的测试,分析结果见表2。

碧口群玄武岩中锆石年龄数据投点均位于谐和曲线附近,虽然锆石年龄变化范围较大,但数据主要集中在两个区间(图7),第一组区间为306~325 Ma,这类锆石均具有很好的震荡环带,$^{232}Th/^{238}U$=0.46~0.94(除23号锆石为0.09),属于岩浆成因锆石,测点均位于其生长环带,$^{206}Pb/^{238}U$年龄加权平均值为(316.3±6.0) Ma(MSWD=0.78,n=7),代表岩浆结晶年龄;另外一组区间为843~867 Ma,这类锆石不发育生长环带,$^{232}Th/^{238}U$=0.59~0.94,属于继承锆石,$^{206}Pb/^{238}U$年龄加权平均值为(854±17.0) Ma(MSWD=0.25,n=5),属于形成于新元古代的继承锆石。此外还测试到6颗锆石记录古元古代甚至更老年代信息,其年龄范围为1805~2672 Ma,其包括继承锆石和岩浆锆石内核。

3.3 锆石Hf同位素组成

在U-Pb年代学研究的基础上,对其中16颗锆石进行了Hf同位素测定。从表3可以看出,记录了古生代石炭纪年龄信息的锆石$^{176}Hf/^{177}Hf$比值介于0.282407~0.282773,对应的$\varepsilon_{Hf}(t)$值为6.2~6.7(除点号HCG-07的$\varepsilon_{Hf}(t)$值为-6.3),二阶段亏损地幔模式年龄(T_{DM2})主要集中在906~929 Ma,为典型的幔源岩浆锆石;记录新元古代年龄信息的锆石$^{176}Hf/^{177}Hf$比值介于0.281891~0.282678,对应的$\varepsilon_{Hf}(t)$值为-13.2~13.1,二阶段亏损地幔模式年龄(T_{DM2})为907~2424 Ma;记录古元古代及更早年龄信息的锆石$^{176}Hf/^{177}Hf$比值介于0.280903~0.281505,对应的$\varepsilon_{Hf}(t)$值为-11.2~-0.2,二阶段亏损地幔模式年龄(T_{DM2})为2816~3650 Ma。

4 讨　论

4.1 岩石成因

4.1.1 形成环境

一般来说,岛弧玄武岩和部分N-MORB的Ta,Nb丰度分别不大于0.7×10^{-6}和12×10^{-6},Nb/La<1,Hf/Ta>5,La/Ta>15,Ti/Y<350;而WPB和E-MORB却与之相反[33]。本区玄武岩中Ta和Nb丰度变化范围分别为0.09×10^{-6}~0.12×10^{-6}和0.69×10^{-6}~0.85×10^{-6},Nb/La变化在0.33~0.49,Hf/Ta变化在13.87~17.61,La/Ta变化在14.87~23.04,Ti/Y比值为216.88~

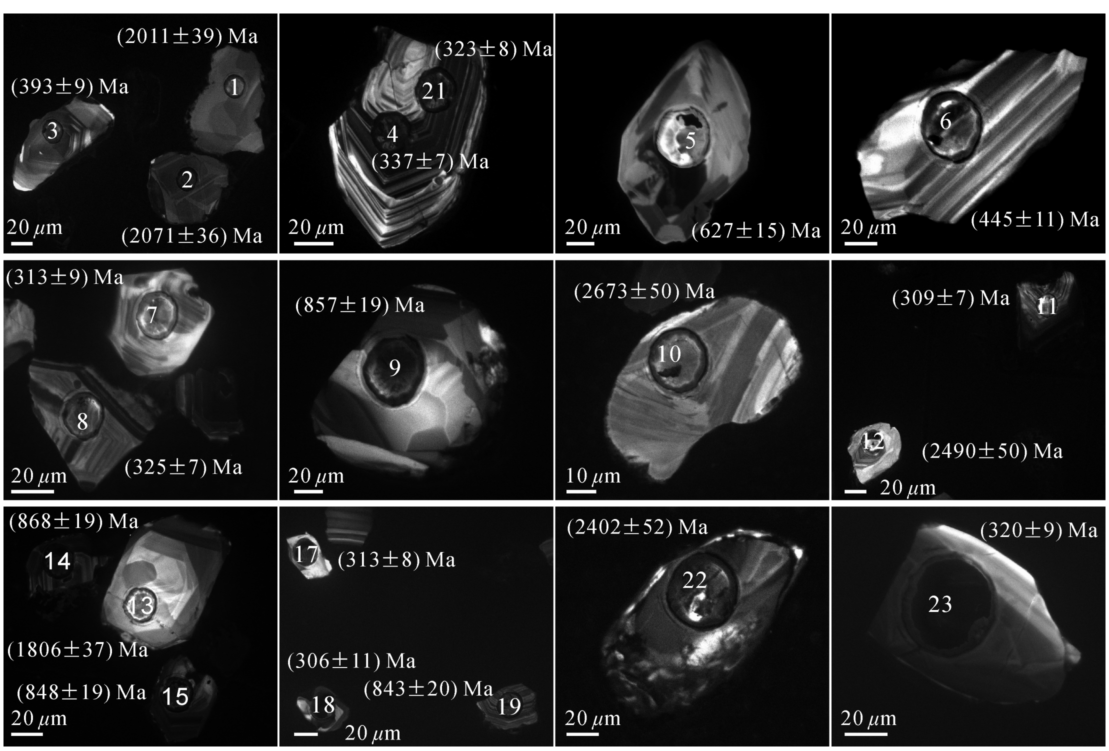

图6 碧口群玄武岩锆石阴极发光(CL)图像及测试位置
Fig. 6 Cathodoluminescence (CL) images and testing positions of representative zircons from the Bikou Group basalt

表1 碧口群玄武岩的主量(%)和微量(10^{-6})元素分析结果

Table 1 Major (%) and trace elements composition (10^{-6}) of the Bikou Group basalt

样品编号	岩性	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	MnO	TiO_2	P_2O_5	LOI	总量	Li	Be	Sc	V	Cr	Co
12HCG-33	玄武岩	49.76	12.89	5.70	5.70	7.57	10.54	2.62	0.13	0.23	1.14	0.08	2.74	99.11	22.7	0.25	50.0	344	104	64.1
12HCG-35	玄武岩	45.17	15.01	4.36	8.43	9.30	7.29	2.78	0.39	0.27	1.28	0.08	4.42	98.78	51.3	0.25	55.8	432	120	61.1
12HCG-38	玄武岩	44.67	15.35	6.11	8.43	7.91	8.31	2.57	0.38	0.24	1.34	0.13	3.31	98.75	43.2	0.26	62.7	408	103	71.7

样品编号	岩性	Ni	Cu	Zn	Ga	Rb	Sr	Y	Nb	Mo	Cd	In	Sb	Cs	Ba	La	Ce	Pr	Nd	Sm
12HCG-33	玄武岩	63.9	131.0	119	18.2	2.73	96.9	28.3	0.69	1.47	0.12	0.08	0.44	0.20	83.8	2.12	6.09	1.17	6.82	2.43
12HCG-35	玄武岩	71.9	104.0	119	21.0	9.49	45.3	34.2	0.82	2.36	0.07	0.09	0.36	0.74	224.0	1.72	5.53	1.15	7.19	2.80
12HCG-38	玄武岩	70.8	75.4	124	22.0	9.32	52.5	37.5	0.85	1.25	0.15	0.11	0.39	0.75	370.0	1.71	5.47	1.21	7.47	3.04

样品编号	岩性	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Ta	W	Re	Tl	Pb	Bi	Th	U	Zr	Hf
12HCG-33	玄武岩	0.93	1.54	0.53	5.17	1.05	2.58	0.54	3.40	0.51	0.09	0.44	0.02	0.01	3.48	0.03	0.05	0.05	31.5	1.62
12HCG-35	玄武岩	1.05	1.70	0.60	6.01	1.24	3.03	0.63	3.95	0.58	0.11	0.43	0.02	0.04	1.33	0.02	0.07	0.07	26.2	1.47
12HCG-38	玄武岩	1.21	1.83	0.66	6.70	1.40	3.46	0.73	4.64	0.72	0.12	0.43	0.02	0.04	0.95	0.01	0.06	0.14	34.5	1.71

244.5。这表明其成因与环境类似岛弧玄武岩或N-MORB的形成环境。然而，由于玄武岩中TiO_2含量(1.14%~1.34%)明显高于岛弧火山岩TiO_2含量(0.17%~0.70%)[34]，同时，结合玄武岩样品中Nb、Ta无明显负异常，Th未呈现富集特征以及稀土元素配分曲线显示正常洋中脊玄武岩的特点，排除了其形成于岛弧环境的可能性。

不活动微量元素协变关系是岩石源区及形成构造环境判别的有效方法。在Th/Yb-Ta/Yb图解(图8-a)中，样品均落入MORB区，进一步使用Hf/Th/Ta图解(图8-b)判断，发现本区玄武岩样品均落入N-MORB区内，故推断其与N-MORB具有类似的形成环境。

4.1.2 源区性质

地壳岩石及其部分熔融体中一般具有很低的TiO_2含量和较低的Nb、Ta含量[37]，因此地壳混染作用会降低地幔源玄武岩中原始Ti、Nb、Ta含量[38]。一般来说，低Nb/La比值(<1)是受到地壳混染玄武岩最鲜明的特点[39-40]。碧口群玄武岩具有低Nb/La比值(0.33~0.49)，这表明其在形成过程中受到了一定程度的地壳混染(图9)。此外，该区岩石中存在大量继承性或捕获的老锆石，指示玄武岩浆在上升过程中与地壳物质发生了较为强烈的混染作用。为了消除地壳混染以及蚀变作用的影响，运用Condie[41]建立的高场强(HFSE)评价体系来判断碧口群玄武岩原岩的幔源性质。图10显示有3个玄武岩样品投影点相对靠近N-MORB区，表明其岩浆源区性质为正常洋中脊玄武岩源区。对软流圈来源的玄武岩来说，其La/Ta<22，岩石圈地幔来源的玄武岩则与之相反[42]，3件玄武岩样品中除1件由于地壳混染使得La/Ta值略大于22，其他2件均明显小于22(La/Ta值分别为23.04、16.23和14.87)，暗示其来源于软流圈地幔。

锆石Hf同位素作为有力的示踪工具已广泛应用于地球化学储库(如亏损地幔、球粒陨石和地壳等)的源区判别[43]。碧口群玄武岩中锆石Hf同位素数据表明，记录晚古生代年龄信息的锆石$\varepsilon_{Hf}(t)$较高，表明其来源于地幔物质部分熔融；记录新元古代年龄信息的锆石的$\varepsilon_{Hf}(t)$值变化范围较广，T_{DM2}为907~2424 Ma，表明其来源于元古代基底和地幔物质的混合；而记录古元古代及更早年龄信息的锆石的

表2 碧口群玄武岩锆石U-Pb年龄分析结果

Table 2 Zircon U-Pb dating results of the Bikou Group basalt

测点号	$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ	$^{238}U/^{232}Th$	1σ	年龄/Ma					
									$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ
HCG–1	0.12397	0.00943	6.24793	0.46482	0.36601	0.00828	0.62	0.01	2014	100	2011	65	2011	39
HCG–2	0.12880	0.00828	6.71900	0.42169	0.37881	0.00774	1.29	0.01	2082	82	2075	55	2071	36
HCG–3	0.05456	0.00571	0.47249	0.04876	0.06288	0.00142	1.01	0.01	394	192	393	34	393	9
HCG–4	0.05393	0.00415	0.39892	0.03012	0.05371	0.00114	1.35	0.01	368	132	341	22	337	7
HCG–5	0.06063	0.00547	0.85354	0.07531	0.10220	0.00253	1.13	0.01	626	148	627	41	627	15
HCG–6	0.05581	0.00707	0.54943	0.06858	0.07146	0.00190	0.88	0.01	445	232	445	45	445	11
HCG–7	0.05270	0.01084	0.36088	0.07366	0.04970	0.00151	1.87	0.02	316	362	313	55	313	9
HCG–8	0.05293	0.00450	0.37759	0.03140	0.05178	0.00122	1.56	0.02	326	146	325	23	325	7
HCG–9	0.06763	0.00537	1.32582	0.10287	0.14224	0.00329	1.71	0.02	857	123	857	45	857	19
HCG–10	0.18212	0.01318	12.89632	0.91254	0.51381	0.01169	1.31	0.01	2672	87	2672	67	2673	50
HCG–11	0.05256	0.00473	0.35599	0.03147	0.04914	0.00115	1.16	0.01	310	158	309	24	309	7
HCG–12	0.16422	0.01262	10.67353	0.80148	0.47153	0.01136	0.77	0.01	2500	94	2495	70	2490	50
HCG–13	0.11030	0.00867	4.91543	0.37787	0.32325	0.00768	1.24	0.01	1804	105	1805	65	1806	37
HCG–14	0.06795	0.00539	1.35029	0.10489	0.14413	0.00336	1.19	0.01	867	123	868	45	868	19
HCG–15	0.06735	0.00555	1.30521	0.10526	0.14056	0.00337	1.17	0.01	849	128	848	46	848	19
HCG–17	0.05264	0.00502	0.36142	0.03377	0.04979	0.00130	1.61	0.02	313	164	313	25	313	8
HCG–18	0.05286	0.01578	0.35429	0.10510	0.04860	0.00185	2.19	0.02	323	484	308	79	306	11
HCG–19	0.06716	0.00592	1.29324	0.11183	0.13963	0.00354	1.35	0.01	843	138	843	50	843	20
HCG–20	0.06758	0.00876	1.31371	0.16778	0.14095	0.00417	1.06	0.01	856	220	852	74	850	24
HCG–21	0.05284	0.00501	0.37417	0.03482	0.05134	0.00135	1.06	0.01	322	163	323	26	323	8
HCG–22	0.15515	0.01401	9.66286	0.85599	0.45153	0.01170	23.47	0.23	2403	116	2403	82	2402	52
HCG–23	0.05278	0.00545	0.37082	0.03759	0.05093	0.00140	10.87	0.11	319	178	320	28	320	9

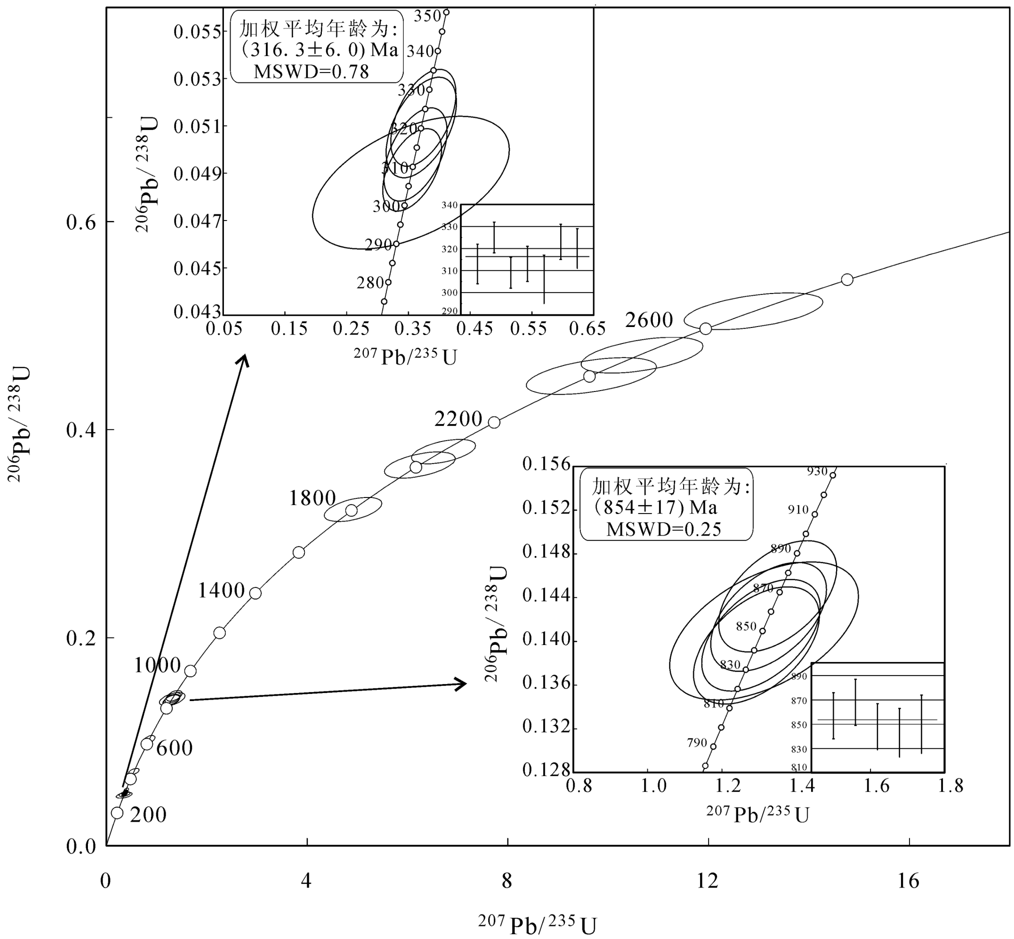

图7 碧口群玄武岩锆石U-Pb谐和图
Fig.7 Concordia diagram of zircon U-Pb dating for the Bikou Group basalt

$\varepsilon_{Hf}(t)$值较低，T_{DM2}介于2816~3650 Ma，表明其来源于太古宙基底[44-48]。综上所述，碧口群玄武岩来源于软流圈地幔，岩浆上升运移过程中混入了古老的地壳物质，使得岩石中锆石年龄显示多样性。

4.2 碧口群火山岩系形成时代认识

锌厂沟地区碧口群玄武岩的微量元素特征表明其形成于海盆环境，而从早古生代到晚古生代，秦岭地区曾先后出现过两个古洋盆，即位于北秦岭的商丹古洋盆和位于南秦岭的勉略古洋盆，前者于早古生代后期消失[50-51]，天水地区出露的关子镇亏损型洋中脊蛇绿岩形成时代为(471±1.4) Ma[52]，代表了商丹古洋盆高度演化的稳定时期; 后者打开阶段为D_{2-3}-C_1，扩张发育时期为C_1-P_1，俯冲消亡时间为P_2-T_2[53-60]。锌厂沟玄武岩锆石年代学研究结果表明，其形成时间为(316.3±6.0) Ma，对应于勉略古洋盆扩张发育时期，这与其具有N-MORB玄武岩特征是一致的。

最新的锆石测年结果显示，碧口群火山岩的形成时代主要为新元古代，如碧口群中段碧口地区的火山岩年龄840~776 Ma[24]、平头山地区闪长岩年龄884 Ma[61]以及碧口群西段董家河辉绿岩年龄839.2 Ma[17]。而锌厂沟地区碧口群玄武岩的形成时间为(316.3±6.0) Ma，属于石炭纪中期。这表明锌厂沟地区的碧口群玄武岩和碧口群中、西段等地出露的火山岩为不同地质历史时期的产物，因此推断碧口群火山岩系至少是两期(新元古代时期和晚古生代时期)火山作用的产物。根据碧口群大规模出露新元古代火山岩这一野外地质事实判断碧口群火山岩的主形成时期为新元古代。值得注意的是，另外有5颗记录新元古代的锆石(加权平均年龄为(854±17.0) Ma)，与碧口群中、西段大范围出露的火山岩年龄一致，这可能是由于玄武岩岩浆在上升过程中

表3 碧口群玄武岩锆石Hf同位素分析结果

Table 3 Analytical data of Hf isotope in zircons of the Bikou Group basalt

测点号	年龄/Ma	$^{176}Yb/^{177}Hf$	2σ	$^{176}Lu/^{177}Hf$	2σ	$^{176}Hf/^{177}Hf$	2σ	$\varepsilon_{Hf}(t)$	$\varepsilon_{Hf}(0)$	T_{DM1}	T_{DM2}	$f_{Lu/Hf}$
HCG–1	2011	0.006656	0.000046	0.000224	0.000002	0.281338	0.000048	−6.1	−50.7	2618	3035	−0.99
HCG–2	2071	0.012809	0.000039	0.000461	0.000002	0.281167	0.000046	−11.2	−56.8	2864	3400	−0.99
HCG–3	393	0.068792	0.000700	0.002374	0.000024	0.282862	0.000054	11.2	3.2	573	672	−0.93
HCG–5	627	0.027515	0.000263	0.000904	0.000003	0.282231	0.000112	−5.7	−19.1	1436	1933	−0.97
HCG–6	445	0.030787	0.000564	0.001105	0.000021	0.282809	0.000080	10.8	1.3	629	740	−0.97
HCG–7	313	0.031570	0.000313	0.001148	0.000014	0.282407	0.000059	−6.3	−12.9	1198	1723	−0.97
HCG–8	325	0.038772	0.000104	0.001544	0.000004	0.282770	0.000052	6.7	−0.1	694	908	−0.95
HCG–9	857	0.011809	0.000231	0.000431	0.000010	0.281943	0.000037	−10.7	−29.3	1813	2424	−0.99
HCG–10	2673	0.025913	0.000462	0.000956	0.000017	0.280903	0.000042	−7.8	−66.1	3256	3650	−0.97
HCG–11	309	0.039050	0.000359	0.001723	0.000017	0.282765	0.000029	6.2	−0.2	703	929	−0.95
HCG–13	1806	0.017092	0.000138	0.000524	0.000005	0.281505	0.000027	−5.2	−44.8	2412	2816	−0.98
HCG–14	868	0.094355	0.002104	0.003427	0.000087	0.282358	0.000057	2.6	−14.6	1349	1597	−0.90
HCG–15	848	0.113223	0.000612	0.004188	0.000023	0.282678	0.000131	13.1	−3.3	888	907	−0.87
HCG–19	843	0.028151	0.000181	0.001148	0.000007	0.281891	0.000061	−13.2	−31.1	1919	2572	−0.97
HCG–21	323	0.044259	0.000275	0.001796	0.000014	0.282773	0.000044	6.7	0.0	694	906	−0.95
HCG–22	2402	0.018551	0.000215	0.000658	0.000010	0.281274	0.000023	−0.2	−53.0	2734	2960	−0.98

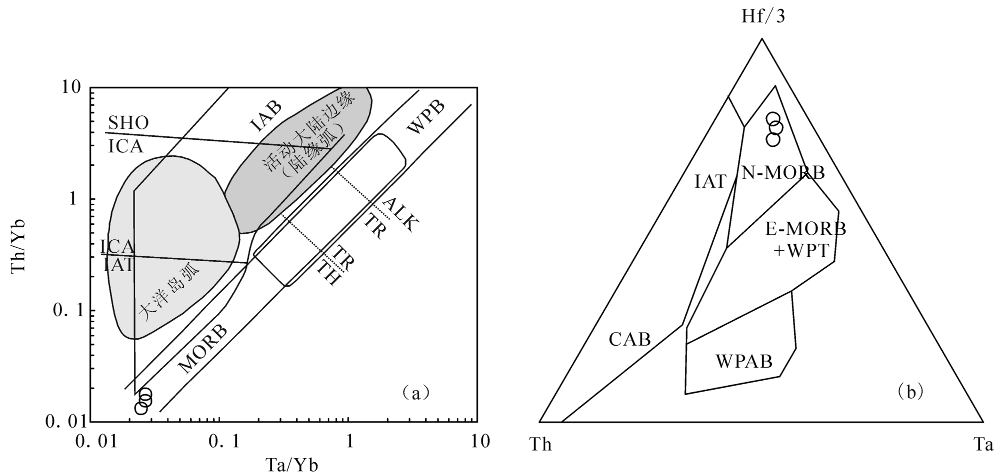

图8 碧口群玄武岩构造环境判别图解
a—Th/Yb-Ta/Yb图解(底图据文献[35]修改); b—Hf/Th/Ta图解(底图据文献[36]修改)
IAB—岛弧玄武岩; IAT—岛弧拉斑系列; ICA—岛弧钙碱性系列; SHO—岛弧橄榄玄粗岩系列; WPB—板内玄武岩; WPT—板内拉斑玄武岩; WPAB—板内碱性玄武岩; MORB—洋中脊玄武岩; N-MORB—正常洋中脊玄武岩; E-MORB—富集型洋中脊玄武岩; TH—拉斑玄武岩; CAB—岛弧钙碱性玄武岩; TR—过渡玄武岩; ALK—碱性玄武岩

Fig.8 Discrimination diagrams of the tectonic setting for the Bikou Group basalt
a-Th/Yb-Ta/Yb diagram (modified after Reference [35]); b-Hf/Th/Ta diagram (modified after Reference [36])
IAB-Island arc basalt; IAT-Island arc tholeiite series; ICA-Island arc calc-alkaline series; SHO-Island arc shoshonite series; WPB-Intraplate basalt; WPT-Intraplate tholeiite; WPAB-Intraplate alkaline basalt; MORB-Mid-ocean ridge basalt; N-MORB-Normal mid-ocean ridge basalt; E-MORB-enriched mid-ocean ridge basalt; TH-Tholeiite; CAB-Island arc calc-alkaline basalt; TR-Transitional basalt; ALK-Alkaline basalt

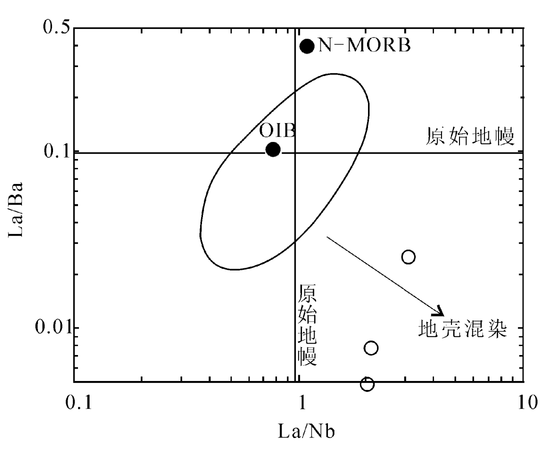

图9 碧口群玄武岩的La/Ba-La/Nb图解(据文献[49]修改)
Fig.9 La/Ba versus La/Nb diagram for the Bikou Group basalt (modified after Reference [49])

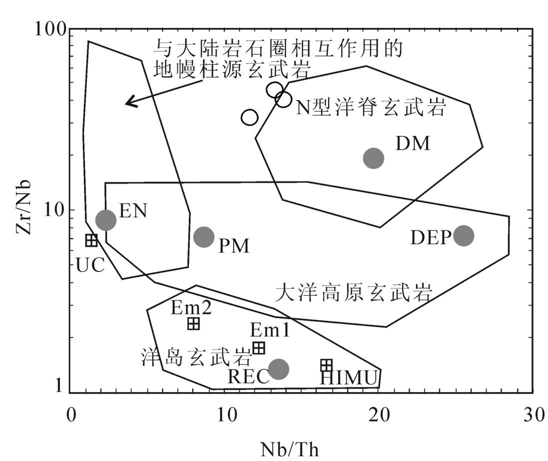

图10 碧口群玄武岩在Zr/Nb-Nb/Th图解中的分布(据文献[41]修改)
Fig.10 Distribution of the Bikou Group basalt in Zr/Nb-Nb/Th diagram (modified after Reference [41])

大量混入了新元古代时期碧口群火山岩物质。新元古代晚期,随着扬子板块北缘的裂解,大规模的火山喷发形成碧口群的主体火山岩系,晚古生代时期随着勉略洋盆的打开和扩张,碧口群北部出现海洋环境,伴随着洋盆的伸展扩张,起源于软流圈地幔的玄武质岩浆沿裂隙上升过程中先后捕获古元

古代以前的古老基底和新元古代喷发的碧口群火山物质,最后喷出海底,形成玄武岩,并在后期扬子板块和秦岭微板块碰撞过程中发生区域变质。

5 结 论

(1)锌厂沟地区碧口群玄武岩具有较低的SiO_2、TiO_2含量和较高的TFe_2O_3、MgO、CaO含量; 稀土元素配分曲线为轻稀土亏损型,微量元素蛛网图总体显示为左倾正斜率轻微富集型,Th、Nb、Sr、Zr呈现出不同程度的亏损。大离子亲石元素Rb、Ba、K显示出不同程度的富集。

(2)锌厂沟地区碧口群玄武岩的微量元素及锆石Hf同位素特征表明,其来源于软流圈地幔,岩浆上升运移过程中混入了古老的地壳物质,其形成环境类似正常洋中脊玄武岩。

(3)锌厂沟地区碧口群玄武岩形成年龄为(316.3±6.0) Ma,表明碧口群火山岩系至少是两期(新元古代时期和晚古生代时期)火山作用的产物。其大规模形成时期为新元古代,经过晚古生代火山作用的叠加改造而成。

致谢:室内工作得到中国地质大学(北京)代鸿章博士帮助,审稿专家及责任编辑杨艳博士对论文提出了宝贵修改意见,在此一并致以诚挚的谢意!

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LA-ICP-MS zircon U-Pb dating and petrogenesis of the Bikou Group basalt in Huachanggou area, South Qinling

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Abstract: The Bikou Group basalt lenticular or banded in form is distributed in tuffs and tuffaceous phyllites of Huachanggou area. Based on detailed field geological survey and systematic laboratory studies including microscope observation, major and trace element analysis and radioactive isotope analysis, the authors investigated the petrological, geochemical and chronological characteristics of the basalt. The result shows that the basalt in Bikou Group has been subjected to metamorphism of greenschist facies, and mainly consists of plagioclase, chlorite and epidote. The basalt exhibits low SiO_2 (44.67%-49.76%), TiO_2 (1.14%-1.34%) and REE, high TFe_2O_3 (12.03%-15.47%), MgO (7.57%-9.3%) and CaO (7.29%-10.54%), with LREE depletion and HREE enrichment. It originated from asthenosphere, occurred in N-MORB setting and was mixed with the old crust. The basalt sample yielded zircon LA-ICP-MS U-Pb age of (316.3±6.0) Ma (MSWD=0.78; n=7), which indicates that the Bikou Group volcanic rocks are products of at least two periods of volcanic activities, i.e., Neoproterozoic and late Paleozoic. They were formed massively in Neoproterozoic and reformed by the volcanic activity in late Paleozoic.

Key words: Bikou Group; basalt; zircon U-Pb dating; Hf isotope; petrogenesis; Huachanggou

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