

# 大别-苏鲁造山带南北两侧晚中生代富钾火山岩的成因:微量元素及 Sr-Nd-Pb 同位素制约

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**摘要** 大别-苏鲁造山带南、北两侧广泛发育晚中生代富钾火山岩,主要岩石组合为粗面玄武岩-玄武粗安岩-粗安岩-安粗岩-粗面岩,这套岩石总体具有富碱、富钾、富轻稀土和大离子亲石元素(如 Rb、Th 等),贫高场强元素(如 Nb、Ti 等), ( $^{87}\text{Sr}/^{86}\text{Sr}$ )<sub>i</sub> 值偏高,  $\epsilon_{\text{Nd}}(t)$  值偏低等特点,但南、北两侧富钾火山岩的地球化学特征存在较显著的差异,主要表现在造山带北侧富钾火山岩稀土总量更高,轻、重稀土分异更明显,且 ( $^{87}\text{Sr}/^{86}\text{Sr}$ )<sub>i</sub> 值更高,  $\epsilon_{\text{Nd}}(t)$  值和  $^{206}\text{Pb}/^{204}\text{Pb}$  值显著偏低。元素-同位素综合示踪显示,区内富钾火山岩均起源于富集地幔的部分熔融,但南、北两侧源区地幔的富集机制存在差异,南侧富集地幔的形成主要与俯冲洋壳析出流体的交代作用有关,而北侧富集地幔的形成除受到俯冲洋壳析出流体的交代作用外,在更大程度上主要起因于俯冲的扬子陆壳析出流体的交代作用,即其源区遭受了多次富集事件的影响,后者是导致南、北两侧富钾火山岩地球化学特征差异的主要原因。

**关键词** 富钾火山岩 地球化学 源区富集 岩石成因 大别-苏鲁造山带

## Petrogenesis of K-rich Volcanic Rocks on the Northern and Southern Sides of the Dabie-Sulu Orogenic Belt, Eastern China: Constraints from Trace Elements and Sr-Nd-Pb Isotopes

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**Abstract** Late Mesozoic K-rich volcanic rocks, mainly of the trachybasalt-basaltic trachyandesite-trachyandesite-latitude-trachyte association, are widely developed on the northern and southern sides of the Dabie-Sulu Orogenic Belt (DSCB). These rocks generally have abundant alkali- and potassium-rich LILE and LREE like Rb and Th, and are depleted in HFSE such as Nb and Ti. They also have high ( $^{87}\text{Sr}/^{86}\text{Sr}$ )<sub>i</sub> ratios and low  $\epsilon_{\text{Nd}}(t)$  values. Compared with those on the southern side of DSCB, the K-rich volcanic rocks on the northern side of DSCB have higher total REE contents and higher LREE/HREE and ( $^{87}\text{Sr}/^{86}\text{Sr}$ )<sub>i</sub> ratios but much lower  $\epsilon_{\text{Nd}}(t)$  and  $^{206}\text{Pb}/^{204}\text{Pb}$  values. Combined element-isotope tracing demonstrates that the studied K-rich volcanic rocks all originated from partial melting of the enriched mantle. However, the mantle source on the northern side of DSCB may be quite different from that on the southern side in the enrichment process. The formation of the enriched mantle on the southern side of DSCB is mainly related to metasomatism by fluids from dehydration of subducted oceanic crust materials, whereas the mantle source on the northern side of DSCB was subjected to the involvement of subducted Yangtze continental crust materials besides the influence of subducted oceanic crust materials. The involvement of continental crust materials in the mantle source is considered to be the main factor responsible for the geochemical differences of the K-rich volcanic rocks between the northern side and the southern side of DSCB.

**Key words** K-rich volcanic rocks geochemistry source enrichment petrogenesis Dabie-Sulu orogenic belt

大别-苏鲁造山带南、北两侧是中国晚中生代富钾火山岩的典型产地,南侧以下扬子断陷带庐枞、宁芜和溧水盆地的火山岩为代表,北侧包括大别山北

麓金寨-霍山-舒城盆地(北淮阳火山岩带)和山东沂沭断裂带及其两侧盆地的火山岩。这套岩石的主体均可归为钾玄武岩系,主要岩石组合为粗面玄武岩-

本文由国家自然科学基金项目(编号:40272035)和国家创新研究群体科学基金项目(编号:40221301)资助。

责任编辑:宫月萱。

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玄武粗安岩-粗安岩-安粗岩-粗面岩。前人对区内富钾火山岩进行过不同程度的研究(Zhou等,1994;Wang等,1996;邱检生等,1997;Fan等,2001;王元龙等,2001;刘洪等,2002),但对南、北两侧富钾火山岩地球化学特征(尤其是Sr-Nd-Pb同位素组成)的显著差异未以足够的重视。本文在综合已有资料的基础上,着重对比南、北两侧富钾火山岩地球化学特征的差异,并探讨了产生这一差异的深部机理及动力学过程。

### 1 火山岩地质

大别-苏鲁造山带南、北两侧富钾火山岩在空间上多邻近郯庐断裂带分布,火山岩的展布明显地受到基底深断裂的控制(图1)。造山带南、北两侧火

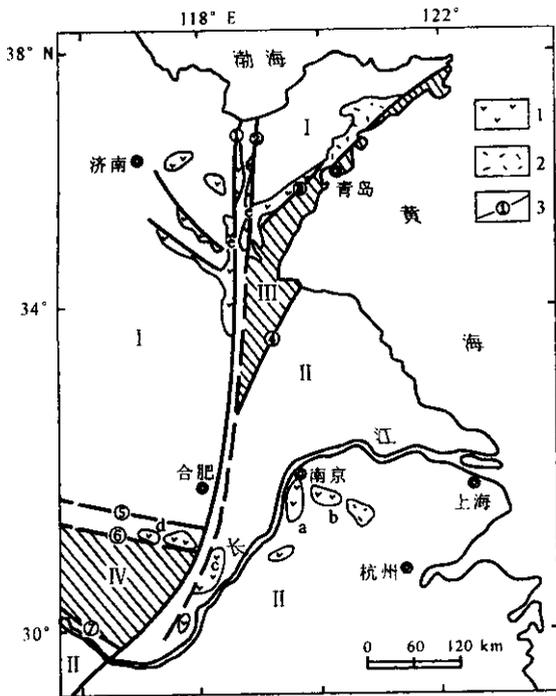


图1 大别-苏鲁造山带南北两侧富钾火山岩分布略图

Fig.1 Sketch geological map showing the distribution of K-rich volcanic rocks along the north and south sides of the Dabie-Sulu Orogenic Belt

- 1-富钾火山岩;2-酸性火山岩;3-深大断裂;①-郯庐西界断裂;②-郯庐东界断裂;③-五莲-荣城断裂;④-嘉山-响水断裂;⑤-信阳-舒城断裂;⑥-磨子潭-晓天断裂;⑦-襄樊-广济断裂;I-华北板块;II-扬子板块;III-苏鲁造山带;IV-大别造山带;a-宁芜盆地;b-溧水盆地;c-庐枞盆地;d-北淮阳火山岩带;e-沂沭断裂及两侧火山岩带
- 1-K-rich volcanic rocks;2-acidic volcanic rocks;3-deep fault;①-the western boundary fault of the Tanlu deep fault zone;②-the eastern boundary fault of the Tanlu deep fault zone;③-Wulian-Rongcheng fault;④-Jiashan-Xiangshui fault;⑤-Xinyang-Shucheng fault;⑥-Mozitan-Xiaotian fault;⑦-Xiangfan-Guangji fault;I-the north China plate;II-the Yangtze plate;III-Sulu Orogenic Belt;IV-Dabie Orogenic Belt;a-Ningwu basin;b-Lishui basin;c-Luzong basin;d-Beihuaiyang volcanic rock zone;e-volcanic rock zone along the Yishu deep fault and its both sides

山岩赋存盆地的类型存在显著差别,北侧火山岩多产于“上叠式”或“基底隆起型”火山盆地中,火山岩与基底地层存在不同程度的沉积间断,而南侧火山岩均发育于“继承式”或“基底拗陷型”火山盆地中,火山岩系的直接基底主要由古生代—中生代碎屑岩和碳酸盐岩系组成,火山岩与基底地层缺乏长期大范围的沉积间断。在地层层序上,沂沭断裂带及其两侧富钾火山岩地层为青山组,大别造山带北麓主要为毛坦厂组,晚期为响洪甸组(或白大畈组、望母山组等);下扬子断陷带各盆地火山岩依次可区分为不同旋回,如自早至晚,庐枞盆地区分为龙门院、砖桥、双庙和浮山旋回,宁芜盆地区分为龙王山、大王山、姑山和娘娘山旋回,溧水盆地区分为龙王山、云台山、大王山、观山和甲山旋回等。

对区内富钾火山岩的形成时代,前人已有较多的资料积累,但早期多为K-Ar年龄。由于K-Ar体系的抗扰动性差,使得K-Ar年龄常偏离地质体的实际年龄,加之精度较低,因而定年结果存在某些不确定性。近年来,随着多种高精度定年技术的广泛运用,区内富钾火山岩陆续积累了一批高质量的年龄数据,表1列出了近年来发表的<sup>40</sup>Ar-<sup>39</sup>Ar和锆石SHRIMP定年结果,可以看出,区内富钾火山岩的年龄多介于100~135 Ma之间,表明它们主要为早白垩世岩浆活动的产物。

### 2 地球化学

区内富钾火山岩主要为一套中基性岩石组合,尤以中性的安粗质-粗安质-粗面质岩石为主体。火山岩总体具有富碱、富钾特征,里特曼指数多介于3.3~9.0之间,主要属碱钙性岩石。在SiO<sub>2</sub>-K<sub>2</sub>O关系图上,样品点主要投影在钾玄岩系区,少部分落在高钾钙碱性岩系区(图2)。火山岩显著贫钛,TiO<sub>2</sub>含量一般均低于1.30%,且聚合带南北两侧富钾火山岩的TiO<sub>2</sub>含量存在较明显的差别,北侧富钾火山岩的TiO<sub>2</sub>含量多变化于0.80%~1.30%,较之南侧富钾火山岩的TiO<sub>2</sub>含量(主要变化于0.60%~0.80%)略偏高。

在微量元素组成上,区内富钾火山岩均具有富轻稀土和大离子亲石元素、贫高场强元素的特点。火山岩的Rb、Ba、Th含量相当于原始地幔的数十倍至数百倍,稀土分布模式均呈右倾型,缺乏显著的铈负异常,表明成岩过程中斜长石的分离结晶作用不强。在相对于原始地幔(Sun等,1989)标准化的蛛网图上均表现出显著的Nb、Ti负异常(图3),这一

表 1 大别-苏鲁造山带南北两侧富钾火山岩同位素年龄

Table 1 Isotopic ages of K-rich volcanic rocks along the north and the south sides of the Dabie-Sulu orogenic belt

采样点	序号	岩性	产地	层位	年龄/Ma	测试方法	资料来源
大别-苏鲁造山带 北侧	1	钾玄岩	蒙阴	青山组	114.8±0.6	全岩 <sup>40</sup> Ar- <sup>39</sup> Ar 年龄	邱检生等,2001a
	2	钾玄岩	蒙阴	青山组	117.8±0.6	全岩 <sup>40</sup> Ar- <sup>39</sup> Ar 年龄	邱检生等,2001a
	3	安粗岩	蒙阴	青山组	124.3±0.6	全岩 <sup>40</sup> Ar- <sup>39</sup> Ar 年龄	邱检生等,2001a
	4	钾玄岩	蒙阴	青山组	117.0±0.6	全岩 <sup>40</sup> Ar- <sup>39</sup> Ar 年龄	邱检生等,2001a
	5	钾玄岩	蒙阴	青山组	118.2±0.6	全岩 <sup>40</sup> Ar- <sup>39</sup> Ar 年龄	邱检生等,2001a
	6	安粗岩	胶莱	青山组	109.9±0.6	全岩 <sup>40</sup> Ar- <sup>39</sup> Ar 年龄	邱检生等,2001b
	7	粗面岩	胶莱	青山组	108.2±0.6	全岩 <sup>40</sup> Ar- <sup>39</sup> Ar 年龄	邱检生等,2001b
	8	粗面质凝灰熔岩	北淮阳	响洪甸组	94.0±2.6	全岩 <sup>40</sup> Ar- <sup>39</sup> Ar 年龄	邱检生等,2002b
	9	假白榴石响岩	北淮阳	响洪甸组	101.3±2.8	全岩 <sup>40</sup> Ar- <sup>39</sup> Ar 年龄	邱检生等,2002b
	10	粗面质响岩	北淮阳	响洪甸组	103.7±2.8	全岩 <sup>40</sup> Ar- <sup>39</sup> Ar 年龄	邱检生等,2002b
	11	安粗质火山岩	北淮阳	毛坦厂组	127.1±3.5	全岩 <sup>40</sup> Ar- <sup>39</sup> Ar 年龄	邱检生等,2002b
	12	黑云母粗面岩	北淮阳	毛坦厂组	124.1±0.7	黑云母 <sup>40</sup> Ar- <sup>39</sup> Ar 年龄	周泰禧等,1992
大别-苏鲁造山带 南侧	1	安粗岩	庐枞	砖桥组	140.1±0.8	全岩 <sup>40</sup> Ar- <sup>39</sup> Ar 年龄	刘洪等,2002
	2	钾玄岩	庐枞	双庙组	125.5±0.8	全岩 <sup>40</sup> Ar- <sup>39</sup> Ar 年龄	刘洪等,2002
	3	粗面斑岩	庐枞	浮山组	126.0±3.4	全岩 <sup>40</sup> Ar- <sup>39</sup> Ar 年龄	刘洪等,2002
	4	安粗岩	宁芜	龙王山组	131.0±4.0	锆石 SHRIMP 年龄	张旗等,2003
	5	安粗岩	宁芜	大王山组	127.0±3.0	锆石 SHRIMP 年龄	张旗等,2003

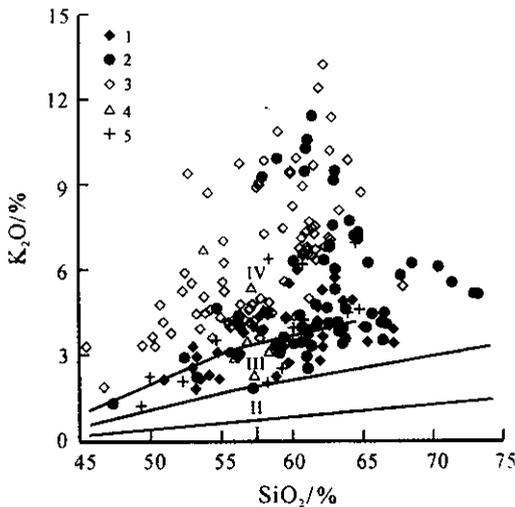


图 2 大别-苏鲁造山带南北两侧富钾火山岩 SiO<sub>2</sub>-K<sub>2</sub>O 关系图

Fig. 2 SiO<sub>2</sub> versus K<sub>2</sub>O diagram of K-rich volcanic rocks along

the north and south sides of the Dabie-Sulu Orogenic Belt

1-沂沭断裂带及两侧;2-大别山北缘;3-庐枞;4-宁芜;5-溧水;I-岛弧拉斑玄武岩系;II-钙碱性岩系;III-高钾钙碱性岩系;IV-橄辉安粗岩系.资料引自 Zhou 等,1994;邱检生等,1997,2002a;Fan 等,2001;汪元龙等,2001;底图据 Peccerillo 等,1976.

1-K-rich volcanic rocks along the Yishu deep fault zone and its both sides;2-K-rich volcanic rocks in the northern margin of Dabie mountain;3-K-rich volcanic rocks in the Luzong basin;4-K-rich volcanic rocks in the Ningwu basin;5-K-rich volcanic rocks in the Lishui basin;I-island arc tholeiite series;II-calc-alkaline rock series;III-high potassium calc-alkaline rock series;IV-shoshonite series data are quoted from Zhou et al., 1994;Qiu et al., 1997;Fan et al., 2001;Wang et al., 2001;Qiu et al., 2002a. The base map is after Peccerillo et al., 1976.

特征通常出现在俯冲带火山岩中(Briqueu 等, 1984),并可能和岩石圈地幔的交代作用有关(Arndt 等,1992)。造山带南北两侧富钾火山岩的微量元素组成也存在一定差异,主要体现在北侧火山岩的 Rb、Th 含量更低,而 Ba 的含量更高(图 3),此外,北侧火山岩的稀土总量和轻重稀土比值较之南侧火山岩均明显偏高,表明南、北两侧富钾火山岩的源区组成或成岩过程存在差异。

富钾火山岩的 Sr、Nd 同位素组成明显有别于原始或亏损地幔派生的岩浆(<sup>87</sup>Sr/<sup>86</sup>Sr)<sub>i</sub> 值偏高,ε<sub>Nd</sub>(*t*)均为负值,在(<sup>87</sup>Sr/<sup>86</sup>Sr)<sub>i</sub>-ε<sub>Nd</sub>(*t*)关系图上均投影在第四象限(图 4),表现出类似壳源或壳幔混源岩石的 Sr、Nd 同位素组成特征,说明成岩过程中有壳源物质的参与。造山带南、北两侧富钾火山岩的 Sr、Nd 同位素(尤其是 Nd 同位素)组成存在显著差异,北侧富钾火山岩的 ε<sub>Nd</sub>(*t*)值多低于 -15,而南侧富钾火山岩的 ε<sub>Nd</sub>(*t*)值均大于 -8(图 4),这一特征同样说明南、北两侧富钾火山岩的源区组成或成岩过程存在差异。北大别后碰撞镁铁-超镁铁侵入岩[时间为 120~130 Ma,ε<sub>Nd</sub>(*t*)为 -15~-20;Jahn 等,1999]及山东淄博一带碳酸岩[时间为 123~125 Ma,ε<sub>Nd</sub>(*t*)为 -12.3~-14.6;刘建明等,2003]均具有与富钾火山岩类似的显著偏低的 Nd 同位素组成,充分说明聚合带北侧源区地幔的特殊性。

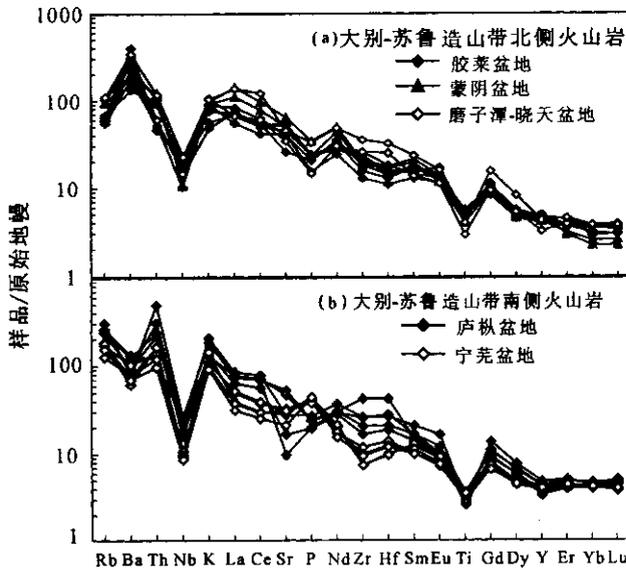


图3 大别-苏鲁造山带南北两侧富钾火山岩微量元素相对于原始地幔标准化蛛网图(资料来源同图2)

Fig.3 Primitive mantle-normalized spidergrams of trace elements for K-rich volcanic rocks along the north and south sides of the Dabie-Sulu Orogenic Belt (Data sources are the same as those in Fig.2)

造山带南、北两侧富钾火山岩的铅同位素组成也存在显著差异,北侧(尤其是大别山北缘)岩石的 $^{206}\text{Pb}/^{204}\text{Pb}$ 值明显偏低(图5),其铅同位素组成与该区后碰撞镁铁-超镁铁岩相似,均落在或靠近大别山中生代花岗岩长石铅同位素组成(张理刚,1995)范围内(图5)。大别山中生代花岗岩侵位于具中地壳特征的角闪岩相片麻岩中,其源区最可能为下地壳(黄方等,2002),富钾火山岩与花岗岩类似的铅同位素组成特征指示其成岩过程应有古老陆壳物质的参与。对鲁西南临沂方城中生代玄武岩Sr-Nd-Pb同位素的研究也认为(Zhang等,2002),其岩浆源区可能受到了因扬子板块向华北板块深俯冲而进入地幔的中-下地壳物质的混染。南侧庐枞、宁芜盆地富钾火山岩富放射成因铅, $^{206}\text{Pb}/^{204}\text{Pb}$ 、 $^{207}\text{Pb}/^{204}\text{Pb}$ 和 $^{208}\text{Pb}/^{204}\text{Pb}$ 值(尤其是 $^{206}\text{Pb}/^{204}\text{Pb}$ 和 $^{208}\text{Pb}/^{204}\text{Pb}$ 值)较之北侧岩石均偏高(图5),其铅同位素组成靠近洋脊玄武岩(White,1985)和现代深海沉积物(Ben Othman等,1989)的分布范围,这一特征暗示洋壳物质可能参与了成岩过程。

### 3 成因讨论

前述元素-同位素地球化学特征综合显示,区内富钾火山岩不可能由原始或亏损地幔所派生,其成

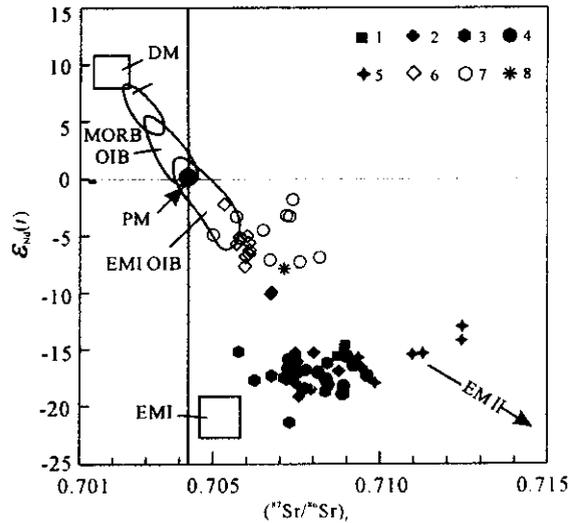


图4 大别-苏鲁造山带南北两侧富钾火山岩( $^{87}\text{Sr}/^{86}\text{Sr}$ )<sub>t</sub>- $\epsilon_{\text{Nd}}(t)$ 关系图

Fig.4 ( $^{87}\text{Sr}/^{86}\text{Sr}$ )<sub>t</sub> versus  $\epsilon_{\text{Nd}}(t)$  diagram for K-rich volcanic rocks along the north and south sides of the Dabie-Sulu Orogenic Belt

MORB-洋脊玄武岩;OIB-洋岛玄武岩;DM-亏损地幔;PM-原始地幔;EMI OIB-具EMI型富集地幔特征的洋岛玄武岩;EMI-I型富集地幔;EMI-II型富集地幔;1-大别造山带北缘后碰撞富钾火山岩;2-北大别后碰撞镁铁-超镁铁质侵入岩;3-大别山后碰撞二长质-正长质侵入岩;4-胶莱盆地后碰撞富钾火山-侵入岩;5-鲁西富钾火山岩;6-庐枞盆地富钾火山-侵入岩;7-宁芜盆地富钾火山-侵入岩;8-溧水盆地富钾火山岩;资料引自White等,1982;Hart,1988;邱检生等,2001a,2002a;Jahn等,1999;马昌前等,1999;Fan等,2001;邢凤鸣等,1999;刘洪等,2002;王元龙等,2001;Zhou等,1994。

MORB-Mid-ocean ridge basalt;OIB-ocean island basalt;DM-depleted mantle;PM-primitive mantle;EMI OIB-ocean island basalt with EMI signature;EMI-I-enriched mantle I;EMI-II-enriched mantle II;1-post-collisional K-rich volcanic rocks in the northern margin of Dabie Mountain;2-post-collisional mafic-ultramafic intrusions in northern Dabie Mountain;3-post-collisional monzonitic-syenitic intrusions in Dabie Mountain;4-post-collisional K-rich volcanic-intrusive rocks in Jiaolai basin;5-K-rich volcanic rocks in western Shandong province;6-K-rich volcanic-intrusive rocks in Luzong basin;7-K-rich volcanic-intrusive rocks in Ningwu basin;8-K-rich volcanic rocks in Lishui basin;Data are drawn after White et al.,1982;Hart,1988;Qiu et al.,2001a,2002a;Jahn et al.,1999;Ma et al.,1999;Fan et al.,2001;Xing et al.,1999;Liu et al.,2002;Wang et al.,2001;Zhou et al.,1994

岩过程必须有地壳物质的参与。地壳物质参与富钾火山岩的成岩过程既可以发生在岩浆上升喷出地表的过程中(浅部混染),也可以通过深俯冲作用将地壳物质带至地幔而在岩浆源区发生混合(源区富集)。大别-苏鲁造山带南、北两侧晚中生代富钾火山岩具壳源岩石的地球化学特征究竟是浅部混染形成,还是源区富集所致,抑或是两种作用的叠加,这

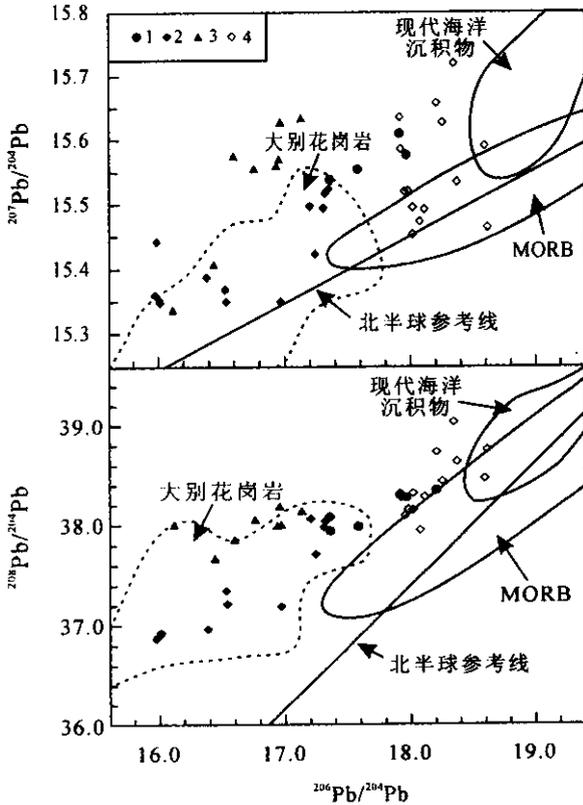


图 5 大别-苏鲁造山带南北两侧富钾火山岩

$^{207}\text{Pb}/^{204}\text{Pb}$ - $^{206}\text{Pb}/^{204}\text{Pb}$  和  $^{208}\text{Pb}/^{204}\text{Pb}$ - $^{206}\text{Pb}/^{204}\text{Pb}$  关系图

Fig. 5  $^{207}\text{Pb}/^{204}\text{Pb}$ - $^{206}\text{Pb}/^{204}\text{Pb}$  and  $^{208}\text{Pb}/^{204}\text{Pb}$ - $^{206}\text{Pb}/^{204}\text{Pb}$

diagrams for K-rich volcanic rocks along the north and south sides of the Dabie-Sulu Orogenic Belt

1-沂沭断裂带及两侧富钾火成岩 2-大别山北缘富钾火山-侵入岩 3-大别山后碰撞镁铁-超镁铁质侵入岩 4-庐枞、宁芜盆地富钾火山-侵入岩 资料引自张理刚,1995;杨祝良等,1999;黄方等,2002;于学元等,1981;邢凤鸣等,1999;大别花岗岩范围据张理刚,1995;MORB

和现代海洋沉积物范围据 White,1985;Othman等,1989

1-K-rich igneous rocks along the Yishu deep fault zone and its both sides 2-K-rich volcanic-intrusive rocks in northern Dabie Mountain; 3-post-collisional mafic-ultramafic intrusions in northern Dabie Mountain; 4-K-rich volcanic-intrusive rocks in Luzong and Ningwu basins. Data are quoted from Zhang,1995;Yang et al.,1999;Huang,2002;Yu et al.,1981;Xing et al.,1999;The field of Dabie granite is drawn from Zhang,1995; fields of MORB and modern marine sediments are drawn from

White,1985;Othman et al.,1989

是首先必须探讨的问题。

Fan 等(2001)根据苏鲁造山带北侧胶莱盆地玄武质火山岩 Nd、Sr 同位素组成相对均一,以及岩石的 La/Sm 比值和  $\text{K}_2\text{O}/\text{TiO}_2$ 、 $\text{K}_2\text{O}/\text{P}_2\text{O}_5$  比值变化较小等特点,认为岩浆上升过程中不大可能存在强烈的壳源物质的混染作用。鲁西蒙阴盆地富钾火山岩的 Sr、Nd、Pb 同位素组成与从岩石中分离出的单斜

辉石单矿物十分接近(邱检生等,2001a),鲁西南方城中生代玄武岩的 Sr、Nd 同位素组成与淄博一带碳酸岩基本一致( $^{87}\text{Sr}/^{86}\text{Sr}$ )<sub>i</sub> 值为 0.70940~0.71009、0.70926~0.71029,  $\epsilon_{\text{Nd}}(t)$  值为 -12.8~-14.4、-12.3~-14.6(刘建明等,2003),且变化范围均较小,说明这些岩石的高( $^{87}\text{Sr}/^{86}\text{Sr}$ )<sub>i</sub> 和低  $\epsilon_{\text{Nd}}(t)$  值特征应非是岩浆上升过程中强烈的地壳物质混染所致。对大别造山带北缘磨子潭-晓天一带富钾火山岩 Nd、Sr 同位素组成的混合模拟计算表明,火山岩具壳源岩石的 Nd、Sr 同位素组成特征并非是岩浆上升过程中大别群变质基底强烈同化混染形成,而更可能是岩浆源区存在有因俯冲而进入地幔的扬子古老基底,即崆岭群混染和交代的结果(邱检生等,2002a)。Chen 等(2001)对下扬子地区火成岩 Nd、Sr 同位素组成的系统研究也认为,该区火成岩成岩过程中浅部地壳物质的混染作用不强。区内富钾火山岩的 Nd、Sr 同位素组成与相应样品的  $\text{SiO}_2$  含量和 Sr、Nd 含量之间均缺乏明显的线性或双曲线演化关系,这一特征同样不支持富钾火山岩的成岩过程存在强烈的浅部混染作用。因此,区内富钾火山岩具壳源岩石的地球化学特征应是其源区性质的反映,即岩浆源区存在有较强的因俯冲而进入地幔的地壳物质的混染和交代作用,富钾火山岩应起源于富集地幔的部分熔融。

从火山岩产出的构造背景来看,研究区位于亚洲大陆东缘,中生代处于古太平洋板块与欧亚板块强烈相互作用地带,这一动力学过程必然对火山岩的形成产生影响。而对于大别-苏鲁造山带北侧的富钾火山岩而言,岩石的形成除受到古太平洋板块与欧亚板块碰撞俯冲动力体系的影响外,还受到扬子板块与华北板块碰撞动力体系的制约。按已有的定年资料,多数学者均主张扬子板块与华北板块在三叠纪(221~228 Ma)完成碰撞对接(Li 等,1993;王清晨等,1998),此前于晚古生代时期经历了古大别洋的闭合,即发生了洋壳向华北陆块的俯冲(潘国强等,1997)。在三叠纪二大板块拼贴之后,又发生了进一步的陆内俯冲作用,即扬子陆块继续向北俯冲至华北陆块之下(王清晨等,1998),这些过程无疑会对造山带北侧幔源岩浆的源区性质产生重要的制约作用。

采用有关地球化学图解对区内富钾火山岩源区性质的判别表明,无论是造山带南侧还是北侧的火山岩,均有洋壳物质参与成岩过程的印记,如在 Othman 等(1989)提出的 Pb-Pb/Ce 关系图(图 6)和

( $La/Sm$ )<sub>N</sub>-( $Ba/La$ )<sub>N</sub> 关系图(图7)上,样品点均位于或靠近深海沉积物分布区。岩石的  $La/Yb$  比值一般均在 20 以上,具有高且变化范围大的  $Rb/Ba$  比值,这些特征也与俯冲带流体交代型富集地幔(李曙光等,1997)相似。但正如前述,造山带南、北两侧富钾火山岩的  $Sr$ 、 $Nd$ 、 $Pb$  同位素(特别是  $Nd$  同位素)组成存在较显著的差异,造山带南侧下扬子断陷带富钾火山岩的( $^{87}Sr/^{86}Sr$ )<sub>i</sub> 值相对较低,  $\epsilon_{Nd}(t)$  值较高,在( $^{87}Sr/^{86}Sr$ )<sub>i</sub>- $\epsilon_{Nd}(t)$  关系图上,样品点靠近 EM I 型洋岛玄武岩(刘丛强等,1995)的分布区(图4)。对于具 EM I 特征的洋岛玄武岩的成因,Weaver 等(1986)认为是板块俯冲将深海沉积物带入地幔并与正常洋岛玄武岩的源区物质混合而成, Tatsumoto 等(1991)也用与古板块俯冲带有关的地幔交代作用机制来解释中国东北、日本海及部分日本岛弧具 EM I 特征玄武岩的成因。因此,洋壳及深海沉积物因俯冲而进入地幔参与成岩过程可能是导致造山带南侧下扬子断陷带富钾火山岩具异常地球化学特征的主要原因,火山岩的  $Pb$  同位素组成也支持这一认识。

大别-苏鲁造山带北侧富钾火山岩的  $Nd$  同位素组成显著偏低,  $\epsilon_{Nd}(t)$  值多介于 -15 ~ -20 之间,而( $^{87}Sr/^{86}Sr$ )<sub>i</sub> 值则相对偏高,且变化范围也较大,在( $^{87}Sr/^{86}Sr$ )<sub>i</sub>- $\epsilon_{Nd}(t)$  值关系图上,样品点分布于

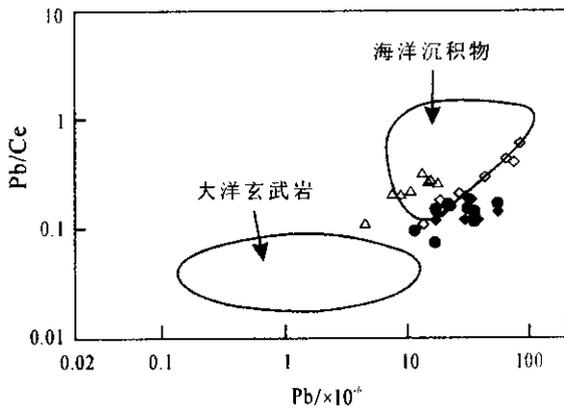


图6 大别-苏鲁造山带南北两侧晚中生代富钾火山岩 Pb-Pb/Ce 关系图

Fig. 6 Pb versus Pb/Ce diagram for late Mesozoic K-rich volcanic rocks along north and south sides of the Dabie-Sulu Orogenic Belt

海洋沉积物及大洋玄武岩范围据 Ben Othman 等, 1989 资料来源及图例同图 2

The fields of marine sediments and oceanic basalts are drawn after Othman et al., 1989; the data sources and legends are the same as those in Fig. 2

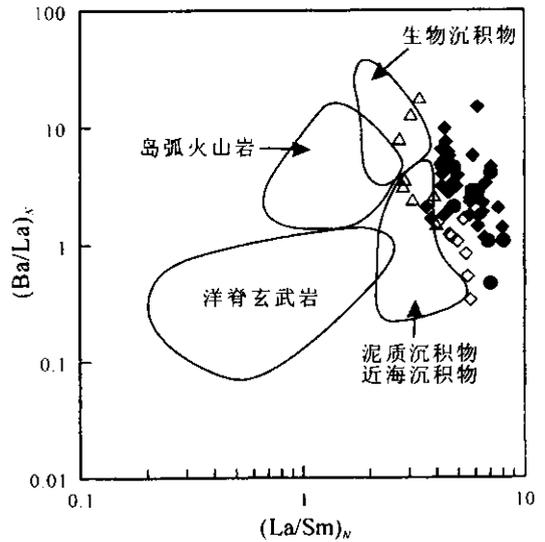


图7 大别-苏鲁造山带南北两侧晚中生代富钾火山岩 ( $La/Sm$ )<sub>N</sub>-( $Ba/La$ )<sub>N</sub> 关系图

Fig. 7 ( $La/Sm$ )<sub>N</sub> versus ( $Ba/La$ )<sub>N</sub> diagram

for Late Mesozoic K-rich volcanic rocks along the north and south sides of the Dabie-Sulu Orogenic Belt

图中各范围据 Othman, 1989 资料来源及图例同图 2

Fields drawn after Othman et al., 1989; the data sources and legends are the same as those in Fig. 2

EMI 和 EMII 之间(图3),反映其岩浆源区应包括 EMI 和 EMII 在内的多种富集组份,即除有俯冲洋壳组份外,还应有俯冲的陆壳组份,岩浆源区经历了多次富集事件的影响。刘建明等(2003)对鲁西早白垩世碳酸岩、方城玄武岩和胶东白垩世煌斑岩  $Sr$ 、 $Nd$  同位素的研究均显示岩浆源区具 EMII 型富集地幔的印记,暗示了再循环陆壳物质对地幔源区的改造。大别造山带中的后碰撞镁铁-超镁铁岩也具有与富钾火山岩相似的  $Sr$ 、 $Nd$  同位素组成, Jahn 等(1999)认为是俯冲陆壳析出流体的交代作用所致; Fan 等(2001)对苏鲁造山带北侧后碰撞富钾火山岩的研究也主张因俯冲而进入地幔的陆壳物质的再循环对岩石的形成有重要影响。因此,对大别-苏鲁造山带北侧的富钾火山岩而言,岩石的形成除有俯冲洋壳的贡献外,在更大程度上还受到了俯冲陆壳及其析出流体的混染和交代作用,后者应是导致岩石具显著偏低  $\epsilon_{Nd}(t)$  值的主要原因。

### 4 结论

(1)大别-苏鲁造山带南北两侧富钾火山岩主要形成于早白垩世,这套岩石总体具有富碱、富钾、富轻稀土和大离子亲石元素,贫高场强元素( $^{87}Sr/$

$^{86}\text{Sr}_i$  值偏高,  $\epsilon_{\text{Nd}}(t)$  值偏低等特点, 但造山带北侧富钾火山岩稀土总量更高, 轻、重稀土分异更明显, 且 ( $^{87}\text{Sr}/^{86}\text{Sr}$ ) $_i$  值更高,  $\epsilon_{\text{Nd}}(t)$  值和  $^{206}\text{Pb}/^{204}\text{Pb}$  值显著偏低。

(2) 元素-同位素综合示踪显示区内富钾火山岩均起源于富集地幔的部分熔融, 但南、北两侧源区地幔的富集机制存在差异, 南侧富集地幔的形成主要与俯冲洋壳析出流体的交代作用有关, 而北侧富集地幔的形成除受到俯冲洋壳析出流体的交代作用外, 在更大程度上主要起因于俯冲的扬子陆壳析出流体的交代作用, 即其源区遭受了多次富集事件的影响, 后者是导致南、北两侧富钾火山岩地球化学特征差异的主要原因。

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