# 阴山及邻区三叠纪富碱侵入岩的成因意义*

汤艳杰[1] 张宏福[1,2] 英基丰[2]
TANG YanJie[1], ZHANG HongFu[1,2] and YING JiFeng[2]

1. 中国科学院地质与地球物理研究所,岩石圈演化国家重点实验室,北京 100029
2. 西北大学地质学系,大陆动力学国家重点实验室,西安 710069
1. *State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing* 100029, *China*
2. *State Key Laboratory of Continental Dynamics, Department of Geology, Northwest University, Xi'an* 710069, *China*
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**Abstract** Alkali-rich intrusive rocks mainly include alkaline rocks and alkaline granites as well as alkali-feldspar granites. The total alkali contents of these rocks are generally more than 8%. Alkaline rocks mainly include syenite, nepheline syenite, pyroxene syenite, aegirine-augite syenite and amphibole syenite. The most striking feature of their chemical composition is relatively poor in silica, but rich in aluminum and total alkali. Alkaline granites refer to the alkaline amphibole and alkaline pyroxene-bearing granites. They are relatively rich in silica and total alkali but poor in aluminum. Alkali-rich intrusive only account for a very small proportion of total intrusive rocks. Their outcrop area approximately occupies 2% of the total area of all kinds of intrusive rocks. However, alkali-rich intrusive rocks have very important mineral and geological significance. As a result, the investigations of alkali-rich intrusive rocks not only are of important significance to reveal the characteristics of lithospheric mantle, the processes of crust-mantle interaction and their associated geodynamic background, but also can provide scientific basis for the research of lithospheric evolution, mineral exploration and resource evaluation. Based on the comprehensive summary of available information, there are lots of Triassic alkali-rich intrusions occurred in the Yanshan-Liaoning-Yinshan regions in the northern margin of the North China Craton. These alkali-rich intrusions start at the Baotou City in the Inner Mongolia in the west and end at the central part of Jilin Province and even the north part of North Korea in the east. They are generally located between north latitude 40° and north latitude 42° with width of about 100km and constitute a nearly east-west-direction and 1500-kilometer-long alkaline rock belt. The Triassic alkali-rich intrusive rocks in the Yinshan and its neighboring areas are mainly located in the territories of Baotou, Liangcheng, Siziwangqi, Chahar Right Back Banner and Chahar Right Middle Banner cities in the Inner Mongolia. The adjacent alkaline intrusive rocks to the east mainly occurred in the regions of the Tianzhen City in the Shanxi Province, Yangyuan and Fanshan cities in the Hebei Province. Base on early published data of whole-rock and mineral Rb-Sr isochron ages, these alkali-rich intrusions formed during 268 ~ 190Ma (these data have large errors of about 5 ~ 11Ma). Compared to those in the Siziwangqi and Chahar regions, the Liangcheng and Baotou alkali-rich intrusions are relatively younger (about 197 ~ 190Ma). The geochemical compositions of these alkali-rich intrusive rocks are highly variable, with $SiO_2$ contents ranging from 35% to 70%. In contrast, the syenites in the Siziwangqi and Chahar areas have higher contents of $SiO_2$ and $Al_2O_3$, but lower contents of $TiO_2$, $Fe_2O_3$ and MgO than those in other areas, which possibly reflect that these intrusive rocks are the products of higher-degree partial melting of mantle source and greater degree of fractional crystallization of pyroxene, olivine and amphibole. It should be noted that most of the syenites are very low in MgO contents, which are plotted in the field for the melt derived from plate in the experiments of 1 ~ 4GPa. Some of them have relatively high MgO contents and $Mg^\#$ values and drop in the field for the adakites generated by the melting of oceanic slab. These signatures suggest that the formation of those alkali-rich intrusive rocks could be related to the melting of recycled subducted slab. In the meanwhile, these alkali-rich intrusive rocks are characterized by enrichment in light rare earth elements (LREE), large-ion lithophile elements (LILE, such as Ba, K and Sr) and depletion in high field strength elements (HFSE, such as Nb, Ta and Ti), Th, U and P. Their $\varepsilon_{Nd}(t)$ and initial $^{87}Sr/^{86}Sr$ values vary from －17 to －3 and from 0.7054 to 0.7092, respectively. Most of the samples drop in the filed of marine sediments and show the contributions of type-2

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**第一作者简介**: 汤艳杰,男,1973年生,研究员,岩石地球化学专业,E-mail: tangyanjie@mail.igcas.ac.cn

enriched mantle (EM2) material to the mantle source of these rocks, indicating that the primary magmas of these syenites were mainly derived from enriched lithospheric mantle. The Siziwangqi syenite has the extremely low value of $\varepsilon_{Nd}(t)$ (-17), suggesting a greater contribution of lower crustal material. This reference is well consistent with the result of Pb isotopic compositions of potassium feldspar. The currently available Pb isotopic data also suggest the involvement of oceanic material during the magma generation of the alkali-rich intrusive rocks in the study area. The correlation between the $\varepsilon_{Nd}(t)$ values and formation ages of the alkali-rich intrusive rocks indicates that the involvement of lower crustal material increased with the decrease of formation ages of these rocks. To sum up, the above observations imply that the Triassic alkali-rich intrusive rocks in the Yinshan and its neighboring areas were mainly derived from partial melting of enriched lithospheric mantle with different-degree contributions of lower crustal material. The enriched mantle could be produced by mantle metasomatism of melts/fluids derived from the subducted oceanic plate, which was closely related with the closure of Paleo-Asian Ocean and the collision between the North China Craton and Mongolia block. The formation of these alkali-rich intrusive rocks could mark the complete closure of the Paleo-Asian Ocean and the end of North China Craton-Mongolia collision because alkali-rich intrusive rocks generally formed in an extensional tectonic setting. These events of subduction of Paleo-Asian Oceanic plate and collision between the North China Craton and Mongolia block have caused the considerable change in chemical compositions and geophysical property of the lithospheric mantle beneath the northern margin of the North China Craton as evidenced in many previous studies. The spatial and temporal distribution of magmatic activities and associated geodynamic background of these alkali-rich intrusive rocks will be further constrained by precise dating and detailed geochemical investigation in the near future.

**Key words** Alkali-rich intrusive; Petrogenesis; Yinshan; Triassic; Paleo-Asian Ocean; North China Craton

**摘 要** 富碱侵入岩主要包括碱性岩和碱性花岗岩以及碱长花岗岩,其全碱含量($K_2O+Na_2O$)一般>8%。碱性岩主要包括正长岩、霞石正长岩、辉石正长岩、霓霞正长岩、闪石正长岩等,在岩石化学上相对贫硅富铝高碱。碱性花岗岩是指含碱性角闪石、碱性辉石的花岗岩,相对富硅贫铝高碱。在各类侵入岩中,富碱侵入岩所占比例很小,其出露面积约占各类侵入岩出露总面积的2%。但是,富碱侵入岩却有重要的矿产和地质意义。富碱侵入岩的研究不仅对于揭示岩石圈地幔的组成特征、壳幔相互作用及其地球动力学背景具有重要的意义,而且,能为有关岩石圈演化、找矿勘查和资源评价工作提供科学依据。根据对现有资料的总结,燕辽-阴山地区目前已发现很多三叠纪的富碱侵入岩体,它们西起内蒙古包头市,东到吉林省的中部,向东一直延伸到朝鲜的北部,大体分布于北纬40°~42°之间(宽度约100km),构成一条近EW向、长达1500km的碱性岩带。阴山及邻区的三叠纪富碱侵入岩分布在包头、凉城、四子王旗、察哈尔右后旗和察哈尔右中旗地区,东边与之相邻的碱性侵入岩主要分布在天镇、阳原和矾山,它们形成于268~190Ma,其中凉城和包头富碱侵入岩的形成年龄较小(197~190Ma)。这些杂岩体的岩石学和地球化学组成变化较大,其$SiO_2$含量变化可从35%到70%。相比之下,四子王旗和察哈尔地区的正长岩具有较高的$SiO_2$和$Al_2O_3$含量,较低的$TiO_2$、$Fe_2O_3$和MgO,这可能反映了它们是地幔源区物质较高程度部分熔融的产物,而且经历了相对较大程度的辉石、橄榄岩和角闪石的分离结晶作用。绝大多数正长岩具有很低的MgO含量,落在了板片熔融实验(1~4GPa)所产生的熔体范围之内,部分样品具有相对较高的MgO含量和$Mg^{\#}$,落在了来源于大洋板片熔融所产生的埃达克岩范围内,说明这些岩石的形成可能与再循环的俯冲板片熔融有关。这些侵入岩普遍富集轻稀土元素和大离子亲石元素(如Ba、K和Sr)富集、亏损高场强元素(Nb、Ta、Ti)、Th、U和P,其$\varepsilon_{Nd}(t)$和$(^{87}Sr/^{86}Sr)_i$值的变化范围分别为$-17\sim-3$和0.7054~0.7092。多数数据点落在了大洋沉积物的范围内,显示出II型富集地幔参与的特征,即这些正长岩的原始岩浆主要来源于富集的岩石圈地幔。四子王旗正长岩具有最低的$\varepsilon_{Nd}(t)$值(-17),表明下地壳物质的贡献较大,这与其钾长石的Pb同位素组成特征相一致。现有的Pb同位素数据也表明在研究区富碱侵入岩的岩浆形成过程中有大洋物质的参与。从$\varepsilon_{Nd}(t)$值与侵入岩形成年龄的相关性变化可以看出,随着形成年龄的减小,下地壳物质的贡献在增加。总之,上述特征表明它们主要来源于富集的岩石圈地幔,并有不同程度的下地壳物质的参与。该富集地幔的形成与古亚洲洋的俯冲作用有关。由于富碱侵入岩通常形成于拉张的构造背景下,因此研究区富碱侵入岩的形成标志着古亚洲洋的闭合以及华北-蒙古陆块碰撞的结束。这些俯冲和碰撞事件造成了华北北缘岩石圈地幔组成和性质的明显改变。该区富碱侵入岩的岩浆活动时空分布规律及其动力学背景尚需精确的年代学和详细的地球化学研究来进一步制约。

**关键词** 富碱侵入岩;岩石成因;阴山;三叠纪;古亚洲洋;华北克拉通

**中图法分类号** P588.121; P588.15

富碱侵入岩的概念是涂光炽先生于1982年在南京大学召开的国际花岗岩学术会议上首先提出来的(涂光炽等,1984;涂光炽,1989)。富碱侵入岩主要包括碱性岩和碱性花岗岩、以及和这两类岩石共生的碱含量很高的碱长花岗岩,其全碱含量($K_2O+Na_2O$)一般>8%。碱性岩主要包括正长岩、霞石正长岩、辉石正长岩、霓霞正长岩、闪石正长岩等,在岩石化学上相对贫硅富铝高碱。碱性花岗岩是指含碱性角闪石、碱性辉石的花岗岩,相对富硅贫铝高碱。在各类侵入岩中,富碱侵入岩所占比例很小,其出露面积约占各类侵入岩出露总面积的2%。但是,富碱侵入岩却有重要的矿产和地质意义(涂光炽,1989;任康绪,2003)。通过对碱性岩及其相关金属矿床的研究,可以获得有关壳幔物质组成、地球动力学状态和成岩成矿的物理化学条件等方面的重要信息,进而为有关岩石圈演化、找矿勘查和资源评价工作提

供科学依据(赵振华等, 2002; 任康绪, 2003; 聂凤军等, 2010; 及其参考文献)。

富碱侵入岩一般具有如下特征:(1)常呈线型(带状)展布,很难见到孤立的单个岩体产出、或者呈面状展布的富碱侵入岩群。(2)线型展布的富碱侵入岩带都受区域性大断裂的控制,常出现于裂谷或地堑等拉张环境;在板块碰撞后的一定时期,沿着缝合线发生拉张,在拉张环境中也可以形成富碱侵入岩。因此,富碱侵入岩的出现可能意味着某个时期板块俯冲和碰撞作用的结束。(3)无论是碱性岩还是碱性花岗岩,它们的岩体形态在地表常呈环状。(4)富碱侵入岩的同位素组成特征说明其成岩物质主要来自上地幔(也可能有少部分来自下地壳物质熔融产生的岩浆结晶分异的结果),还有不同程度的壳源物质的混染。考虑到富碱侵入岩的产出背景及其富含大离子亲石元素的特征,一般认为富碱岩浆的部分初始物质来源于富集型地幔(涂光炽, 1989; 赵振华和周玲棣, 1994)。

富碱侵入岩的研究越来越受到学者们的重视。例如,20世纪90年代以来,前人对我国北方显生宙富碱侵入岩的年代学、岩石学和地球化学等方面做了大量研究工作,取得了许多重要进展(如阎国翰等, 1988, 2000, 2001a, b, 2002, 2008; 牟保磊和阎国翰, 1992; 赵振华和周玲棣, 1994; Zhou and Zhao, 1996; 牟保磊等, 2001; 韩宝福等, 2004; 任荣等, 2009)。但是,仍然有许多问题有待于深入研究,例如,富碱侵入岩的成因问题仍然没有很好地解决(原始岩浆起源于富集的岩石圈地幔、还是亏损的软流圈? 岩浆上升过程中地壳物质混染的贡献如何? 壳幔相互作用过程中岩浆是如何演化的? 岩浆活动与成矿作用事件是否有确定的因果关系? 岩石圈的富集是否与板块的俯冲消减作用有关?),碱性岩浆的形成机制、演化过程及其深部动力学背景(形成于板内裂谷环境、板块俯冲挤压之后的拉张环境、还是与热点地幔柱有关系? 阴山地区三叠纪岩浆活动事件能否为华北地块与西伯利亚南缘蒙古褶皱带最终碰撞拼合时代提供进一步的约束?)等重要的科学问题也都要求对其开展进一步的研究工作。本文旨在总结阴山及邻区三叠纪富碱侵入岩的年代学、岩石学和地球化学资料,在前人研究的基础上,进一步探讨其成因和指示意义,并为该区富碱侵入岩的下一步研究提供借鉴。

## 1　阴山及邻区三叠纪富碱侵入岩的分布和形成年龄

燕辽-阴山地区目前已发现很多三叠纪的富碱侵入岩体,它们西起内蒙古包头市,东到吉林省的中部,向东一直延伸到朝鲜的北部,大体分布于北纬40°～42°之间(宽度约100km),构成一条近EW向、长达1500km的碱性岩带(阎国翰等, 2000; 任荣等, 2009; 张拴宏等, 2010)。阴山地区位于华北克拉通的北缘,该区的三叠纪碱性侵入岩分布在包头、凉城、四子王旗、察哈尔右后旗和察哈尔右中旗地区,东边与之相邻的碱性侵入岩主要分布在天镇、阳原和矾山(图1)。阎国翰等(2001b)将阴山地区的富碱侵入岩分为南、北两个带:南带由凉城霓辉正长岩体和包头东霓辉正长岩构成,东边与之相邻的天镇、阳原和矾山碱性杂岩体与前者处于同一纬度;北带由四子王旗黄合少碱性正长岩体、察哈尔右后旗古城碱性正长岩体和察哈尔右中旗义发泉正长岩体组成。

南带:凉城霓辉正长岩体和包头东霓辉正长岩体的Rb-Sr等时线年龄分别为190.3±5.6Ma和197.7±5.6Ma(阎国翰等, 2000)。阳原的东城和姚家庄正长岩体的Rb-Sr等时线年龄分别为268.1±11Ma和235.9±5Ma(阎国翰等, 2000),阳原响水沟霞石正长岩体和天镇罗家沟霓辉正长岩的K-Ar同位素年龄分布为248Ma和246～219Ma(牟保磊和阎国翰, 1992)。河北矾山杂岩体的Rb-Sr等时线年龄为218±8Ma(牟保磊和阎国翰, 1992),SHRIMP锆石U-Pb年龄为218±2Ma(任荣等, 2009),二者在误差范围内相一致。

北带:四子王旗黄合少岩体的全岩Rb-Sr等时线年龄为203±4Ma(阎国翰等, 2000);察哈尔右后旗古城和察哈尔右中旗义发泉正长岩体尚未年龄数据。根据现有的数据,阴山三叠纪富碱侵入岩的年龄为南带较年轻(197～190±5.6Ma),北带较老(203±4Ma)。而与之相邻的东边阳原和矾山岩体的年龄则更老(大约268～220Ma)。

前人早期获得的同位素年龄确定了上述岩体主要形成于三叠纪,表明阴山地区在三叠纪曾经存在碱性拉张型岩浆-构造活动(阎国翰等, 2000)。然而,不同测年方法所得到的结果还存在较大的差别(和误差)。例如,利用K-Ar法测定的矾山岩体的形成年龄在248～203Ma之间,Rb-Sr等时线年龄为218±8Ma(牟保磊和阎国翰, 1992及其参考文献),Sm-Nd等时线年龄则为243±9.7Ma(牟保磊等, 2001),而锆石SHRIMP U-Pb年龄则为218±2Ma(任荣等, 2009)。这些数据说明上述岩体(除了矾山岩体)还需要开展进一步的定

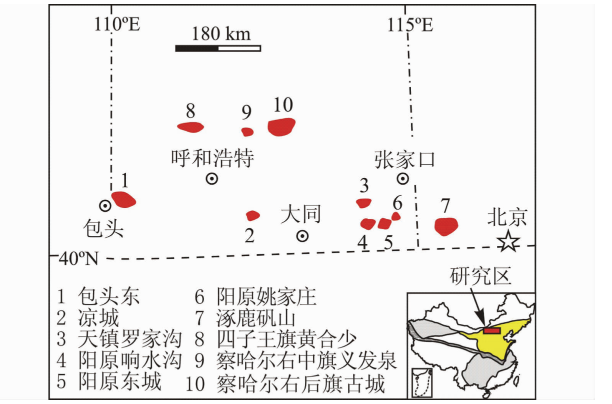


图1　阴山及邻区三叠纪富碱侵入体的分布(据阎国翰等, 2000)

Fig. 1　The distribution of Triassic alkali-rich intrusions in the Yinshan and neighboring areas (after Yan *et al.*, 2000)

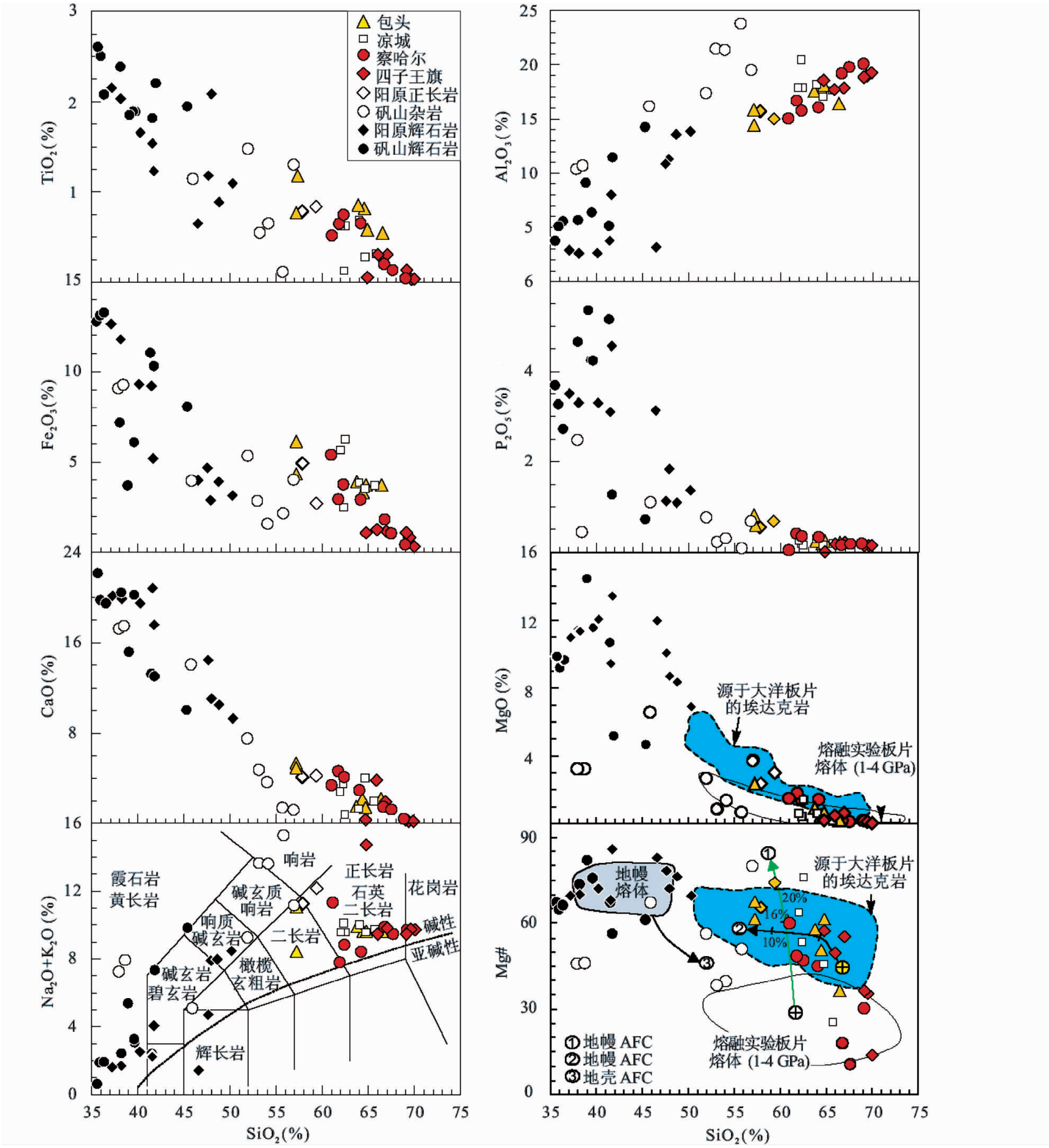


图 2 富碱侵入体的主量元素组成(底图据 Tang *et al.*, 2013 及其参考文献)

杂岩体数据据牟保磊和阎国翰, 1992; 侯增谦, 1992; 阎国翰等, 2001b. 图 3、图 4、图 5、图 7 数据来源同此图

Fig. 2 Major-oxide variations of the alkali-rich intrusive rocks (base map after Tang *et al.*, 2013, and references therein)

年工作,从而获得不同岩体精确的形成年龄,为探讨其成因和时空分布特征提供精确的年龄依据。

## 2 富碱侵入岩的岩石学特征

南带的凉城和包头东岩体均为霓辉正长岩体,其主要造岩矿物为正长石和霓辉石;阳原的东城和姚家庄正长岩体分别为霞霓正长岩体和环状次透辉岩-正长岩体。河北矾山杂岩体为层状超镁铁质岩-正长岩体,平面上呈环状,内环为正长岩系,外环为辉石岩系。北带则以碱性正长岩体为主,古城碱性正长岩的主要造岩矿物为条纹长石、微斜条纹长石,次要矿物为辉石、角闪石、钠长石和少量霞石;黄合少正长岩

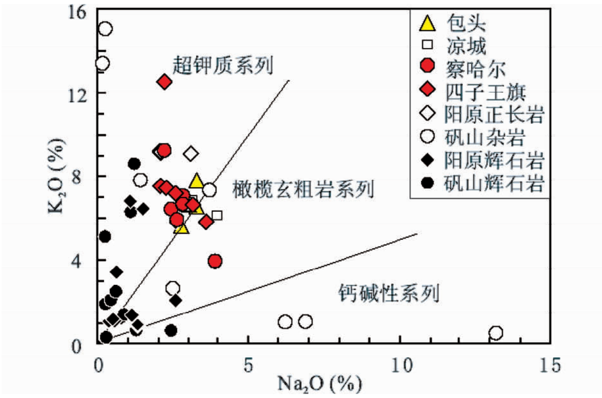


图 3 富碱侵入体的 $K_2O$ 和 $Na_2O$ 组成变化

Fig. 3 $K_2O$-$Na_2O$ variations of the alkali-rich intrusive rocks

的造岩矿物以微斜长石为主,有少量霞石和霓石(阎国翰等,2000,2001b;牟保磊等,2001;任荣等,2009)。

阴山地区碱性岩中的浅色矿物碱性长石为钾长石和钠长石。钾长石广泛出现在各个岩体中,含量可达80%。而钠长石仅出现在北带岩体中,含量可达15%(阎国翰等,2001b)。在显微镜下,南带包头东和凉城岩体中的钾长石为卡氏双晶发育的正长石,北带黄合少和古城岩体则以格子双晶发育的微斜长石为主,有少量条纹长石。根据X光粉晶衍射数据,计算出南带岩体的钾长石有序度为0.01~0.06,明显低于北带岩体钾长石的有序度(0.26~0.89),可能反映出南带的碱性岩比北带有较高的结晶温度(阎国翰等,2001b)。最新的研究在矾山杂岩体中发现了含钡和锶的钾长石(钡冰长石和锶钡冰长石),指示岩浆晚期锶、钡含量的明显提高,推测早中生代作为岩浆源区的岩石圈地幔有不断富集的趋势(牟保磊等,2013)。

在岩石化学组成上,阴山及邻区的三叠纪富碱侵入岩几乎全部落入碱性系列的范围内,但其组成变化范围很大(图2),从辉石岩-碱玄岩-二长岩-正长岩到花岗岩呈连续变化($SiO_2$ 含量从35%增加到70%),主要组成元素之间显示出规律性的变化:$TiO_2$、$Fe_2O_3$、CaO、$P_2O_5$ 和 MgO 与 $SiO_2$ 之间呈负相关性,$Al_2O_3$ 与 $SiO_2$ 呈正相关性。大多数正长岩位于超钾质系列和橄榄玄粗岩系列,矾山杂岩的 $K_2O$ 和 $Na_2O$ 变化范围非常大,少数位于钙碱性系列范围内(图3)。相比之

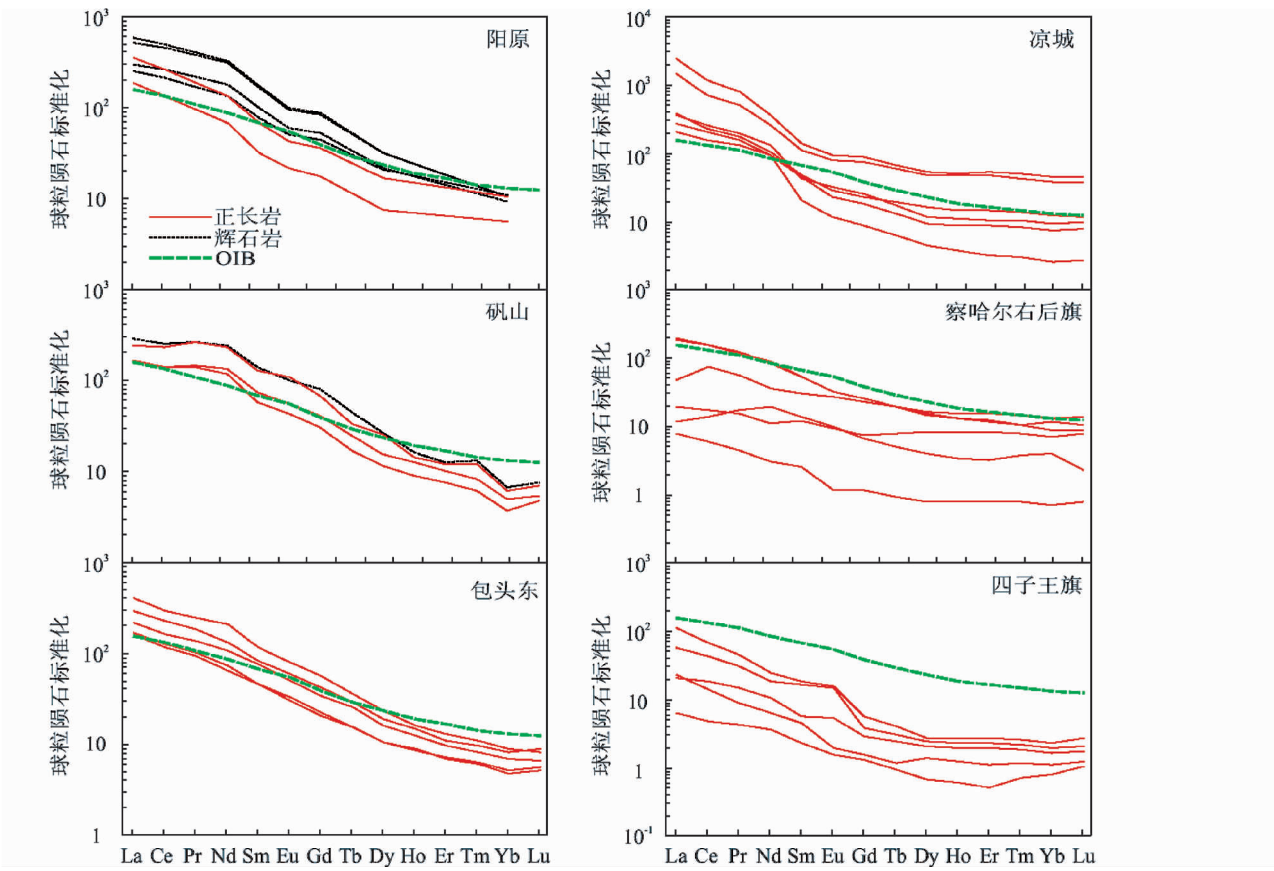


图4 富碱侵入体的稀土元素球粒陨石标准化配分形式(球粒陨石值据 Anders and Grevesse, 1989;OIB 据 Sun and McDonough, 1989)

Fig. 4 Chondrite-normalized REE patterns of the alkali-rich intrusive rocks (chondrite values after Anders and Grevesse, 1989; OIB after Sun and McDonough, 1989)

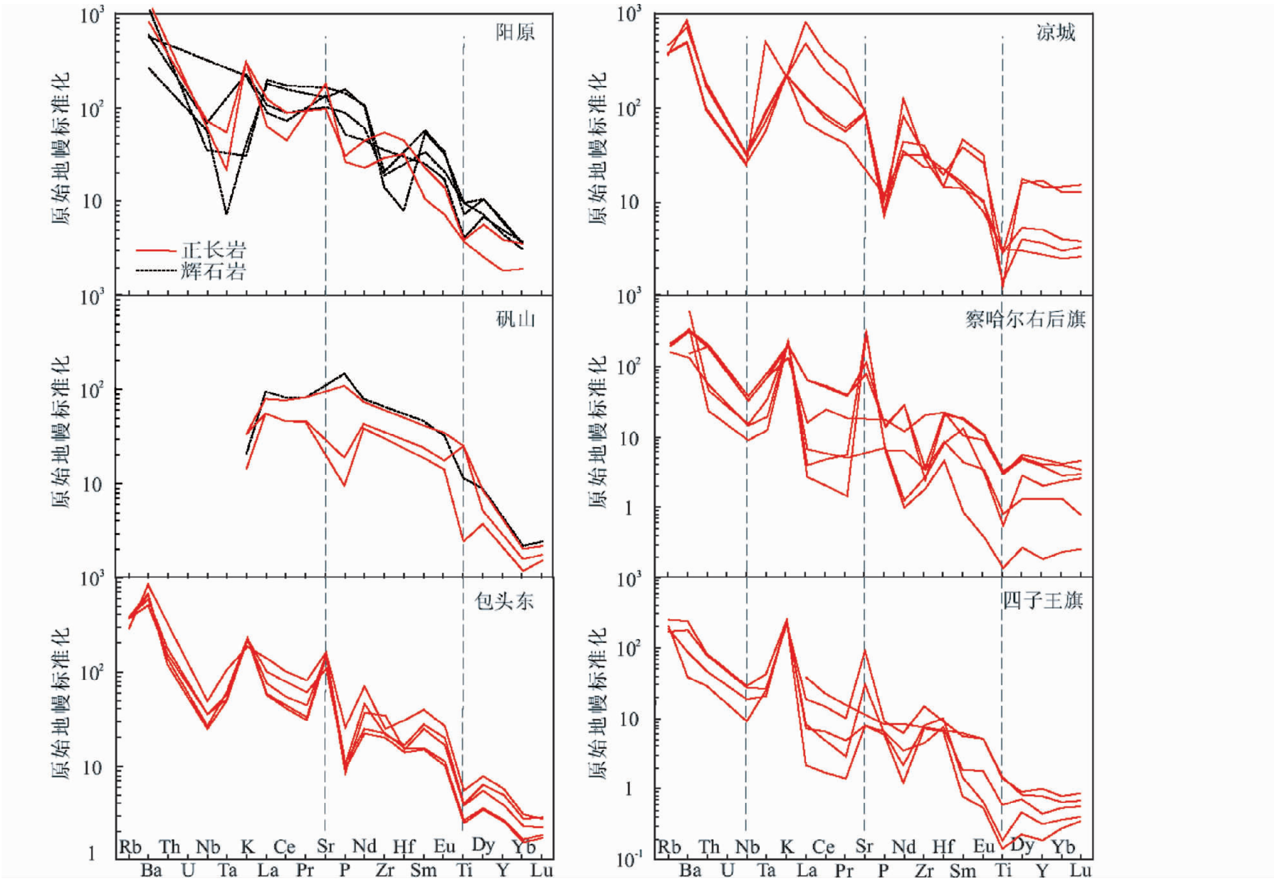


图5 富碱侵入体的微量元素原始地幔标准化图解(标准化值据 McDonough and Sun, 1995)

Fig. 5 Primitive mantle-normalized trace-element diagrams for the alkali-rich intrusives (normalization values after McDonough and Sun, 1995)

下,四子王旗和察哈尔地区的正长岩具有较高的 $SiO_2$ 和 $Al_2O_3$ 含量,较低的 $TiO_2$、$Fe_2O_3$ 和 MgO,这可能反映了它们是地幔源区物质较高程度部分熔融的产物(Tang *et al.*, 2006),而且经历了相对较大程度的辉石、橄榄岩和角闪石的分离结晶作用(见下文)。绝大多数正长岩具有很低的 MgO 含量,落在了板片熔融实验(1~4GPa)所产生的熔体范围之内(图2),部分样品具有相对较高的 MgO 含量和 $Mg^{\#}$,落在了来源于大洋板片熔融所产生的埃达克岩范围内,说明这些岩石的形成可能与再循环的俯冲板片熔融有关(Tang *et al.*, 2013)。辉石岩的母岩浆则主要来源于地幔物质的部分熔融。

研究区所有样品均显示出轻稀土元素富集的特征(图4),与 OIB 的稀土元素配分形式相似,但是,北带四子王旗和察哈尔地区正长岩的稀土元素含量明显偏低(位于 OIB 配分曲线之下)。个别样品显示轻微的 Eu 异常,尽管同一岩体中不同岩石的稀土元素含量不同,但其配分模式大致平行,这些特征暗示它们为同源岩浆演化的产物(阎国翰等, 2001b)。在微量元素蛛网图上(图5),绝大多数样品显示出明显的大离子亲石元素(如 Ba、K 和 Sr)富集、高场强元素(Nb、Ta、Ti)、Th、U 和 P 的亏损。这些特征暗示富碱侵入岩的地幔源区曾经历了再循环的地壳物质的改造作用(阎国翰等, 2001b; Tang *et al.*, 2013),这与其 MgO 和 $SiO_2$ 含量变化所反映的地幔源区特征相一致(图2)。

## 3 同位素地球化学特征

目前的同位素数据较少,根据现有的数据可知,阴山及邻区三叠纪富碱侵入岩具有富集的 Sr-Nd 同位素组成特征,其 $\varepsilon_{Nd}(t)$ 值从大约-17 变化到大约-3(图6a),$(^{87}Sr/^{86}Sr)_i$ 比值从 0.7054 变化到 0.7092,多数数据点落在了大洋沉积物的范围内,显示出 II 型富集地幔参与的特征,即这些正长岩的原始岩浆主要来源于富集的岩石圈地幔(阎国翰等, 2000; 牟保磊等, 2001)。四子王旗正长岩具有最低的 $\varepsilon_{Nd}(t)$ 值(-17),表明下地壳物质的贡献较大,这与其钾长石的 Pb 同位素组成特征相一致(阎国翰等, 2001b)。

现有的 Pb 同位素数据也表明在研究区富碱侵入岩的岩浆形成过程中有大洋物质的参与(图6c, d)。从 $\varepsilon_{Nd}(t)$ 值与侵入岩形成年龄的相关性变化(图6b)可以看出,随着形成

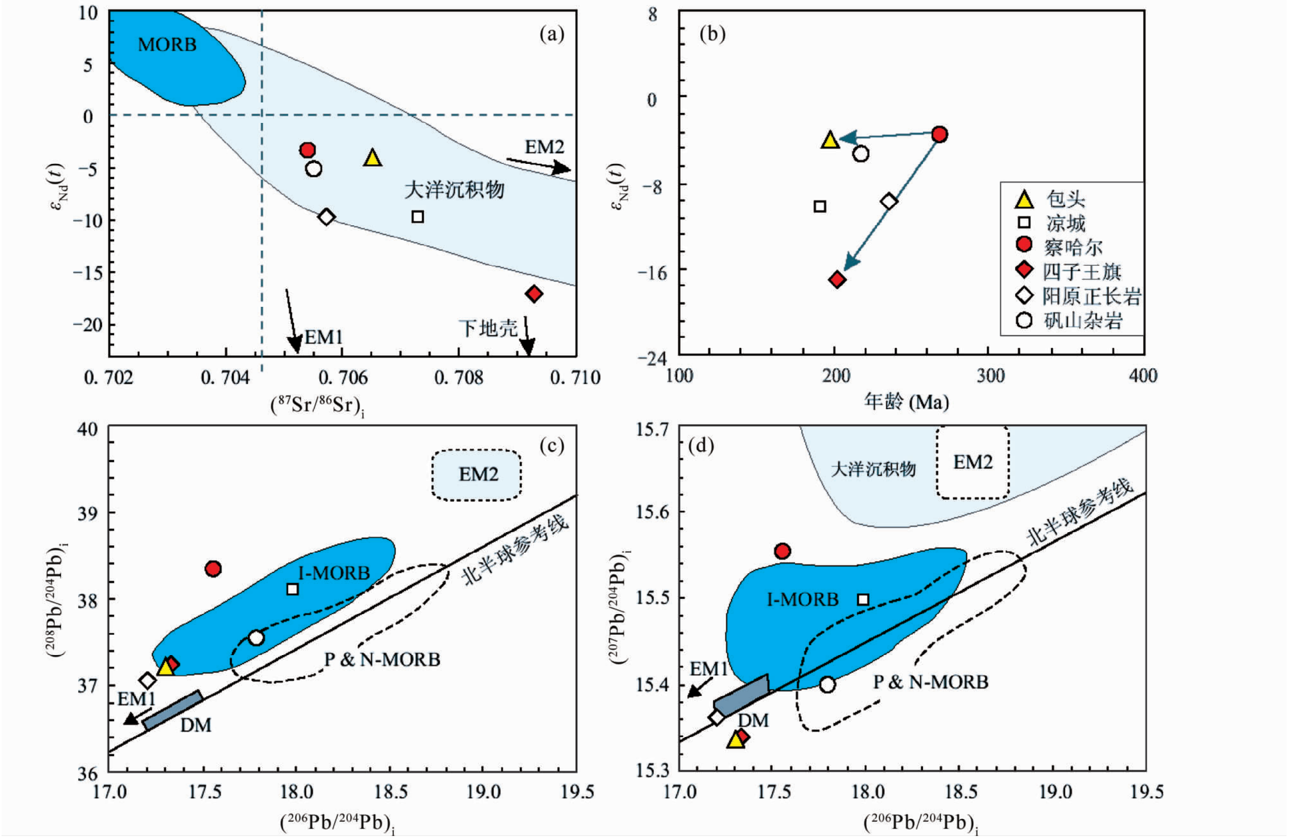


图 6 富碱侵入体的 Sr-Nd-Pb 同位素变化特征

MORB 和大洋沉积物据 Hofmann, 2003;其他数据据牟保磊和阎国翰, 1992; 阎国翰等, 2000; 牟保磊等, 2001; Pb 同位素底图据 Tang *et al.*, 2006

Fig. 6 The diagrams showing the variations of Sr-Nd isotopes (a), $\varepsilon_{Nd}(t)$-age (Ma) (b), Pb isotopes (c) and (d) for the alkali-rich intrusive rocks

年龄的减小,下地壳物质的贡献在增加。由于数据较少,目前只能获得非常初步的认识,因此,相应的年代学和同位素地球化学工作有待加强,以便获得较为准确的信息,进而为揭示碱性岩浆的形成机制、岩浆活动的时空分布规律和岩石圈演化过程提供依据。

## 4 岩石成因意义

根据上述总结可知,阴山及邻区的三叠纪富碱侵入岩主要来源于富集的岩石圈地幔,并有或多或少的下地壳物质的贡献。根据微量元素 Ba 和 Nb 的判别图(图 7a),该区富碱侵入岩的母岩浆在上升过程中经历了小程度的地壳物质同化混染作用;根据岩石中相容元素 Cr 和 Ni 含量的变化关系(图 7b)可以看出,在岩浆演化的过程中有大量的单斜辉石、角闪石和橄榄石的分离结晶。不相容元素 La 和 Yb 的相关性变化(图 7c)表明,四子王旗和察哈尔地区的富碱侵入岩可能是地幔源区物质经历较高程度部分熔融的产物,而且经历了较大程度的单斜辉石和角闪石的分离结晶作用(图 7b),相比之下,凉城、包头、矾山和阳原富碱侵入岩则为源区物质较低程度部分熔融的产物,在 La/Nb 和 Ba/Nb 判别图上,后者明显具有岛弧熔岩的特征(图 7d),这与其主量元素(图 2)和同位素组成特征相一致(图 6),即在岩浆形成过程中有来源于俯冲的大洋板片物质的贡献。

综述所述,阴山及邻区的三叠纪富碱侵入岩主要来源于富集的岩石圈地幔的部分熔融,该富集的岩石圈地幔是由于俯冲的大洋板片熔融所释放的熔体/流体交代而形成的。这说明华北北缘(阴山及东边邻区)的岩石圈地幔经历了俯冲的大洋板片物质的交代作用,该事件可能与古生代以来古亚洲洋的闭合密切相关。前人关于华北北缘中生代高镁安山岩和侵入岩的成因(Zhang *et al.*, 2003, 2004)、新生代玄武岩携带的辉石岩捕虏体(Xu, 2002)和地幔橄榄岩捕虏体(Tang *et al.*, 2007; Liu *et al.*, 2010; Zhang *et al.*, 2012)的研究均表明再循环的俯冲洋壳对华北北缘岩石圈地幔的改造作用。研究区三叠纪富碱侵入岩的形成所指示的拉张环境则意味着古亚洲洋的最终闭合以及华北与蒙古陆块俯冲/碰撞作用的结束。

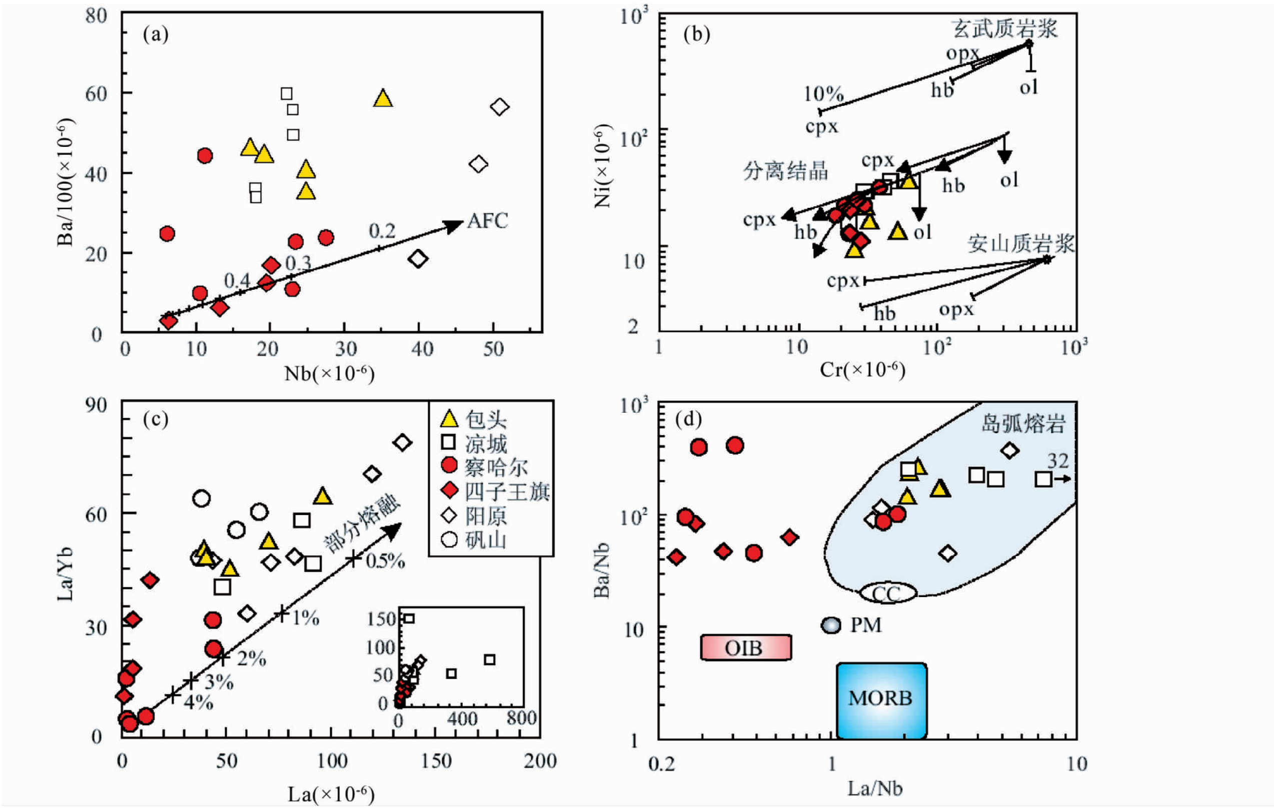


图7 富碱侵入体的微量元素变化特征(底图据 Yang *et al.*, 2005; Tang *et al.*, 2013)

Fig. 7 The variations of selected trace elements for the alkali-rich intrusive rocks (base map after Yang *et al.*, 2005; Tang *et al.*, 2013)

## 5 结束语

目前对阴山及其邻区三叠纪富碱侵入岩的年代学和岩石地球化学的研究程度不高。现有的数据表明,该区三叠纪富碱侵入岩的形成年龄为 268 ~ 190Ma,由于绝大多数年龄数据为 Rb-Sr 等时线、Sm-Nd 等时线或 K-Ar 同位素年龄,年龄数据偏少,而且存在同一岩体的测定结果不一致的现象,还有一些岩体至今尚无年龄制约。由于精确的年龄测定对于探讨岩石成因、岩浆活动的时空分布规律和岩石圈演化过程都具有至关重要的作用,因此有必要对该区的富碱侵入岩开展进一步的定年工作。

该区三叠纪富碱侵入岩的地球化学特征表明,它们主要起源于经过俯冲的大洋板片熔融所释放的熔体/流体交代的富集型岩石圈地幔,并有不同程度的下地壳物质的参与。这些侵入岩的形成很可能标志着古亚洲洋的闭合和华北-蒙古陆块碰撞作用的结束。但不同岩体的形成年龄、岩石学和地球化学特征上的差异及其深部动力学背景仍需要进一步的研究。

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