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大兴安岭北段中一新生代玄武岩成分变异：对地幔热演化过程意义

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摘要：近年来，东北地区地幔热演化过程的相关研究相对较少，而揭示东北地区地幔热演化过程的有效手段就是研究东北地区玄武岩的成分变异特征.系统总结并对比了大兴安岭北段早白垩世玄武质岩石和新生代玄武质岩石的化学成分变异，以便揭示研究区中生代晚期－新生代的地幔热演化过程.大兴安岭北段早白垩世玄武岩在化学上属于拉斑玄武岩系列，以亏损Nb、Ta、Ti等高场强元素为特征，它们的La/Nb和La/Ta比值分别介于1.8～5.6和30～87，暗示岩浆起源于岩石圈地幔；它们的初始$^{87}Sr/^{86}Sr$值、$\varepsilon_{Nd}(t)$和$\varepsilon_{Hf}(t)$值分别介于0.704 5～0.706 9、－1.52～＋3.60和＋1.74～＋7.77，表明岩浆源区属于弱亏损－弱富集的岩石圈地幔；早白垩世玄武质岩石的Sr-Nd-Pb同位素成分指示岩浆源区是由DM和EMII型地幔端元混合而成，并经历了俯冲流体的交代.表明大兴安岭北段早白垩世玄武质岩浆源区为受早期俯冲流体交代的岩石圈地幔.新生代超钾质和钾质玄武岩具有Nb-Ta的弱负异常，$^{87}Sr/^{86}Sr$值为0.704 7～0.705 7、$\varepsilon_{Nd}(t)$值为－6.3～－0.8，而地幔捕掳体具有Sr-Nd同位素亏损特征；钠质玄武岩具有Nb-Ta的正异常，较超钾质和钾质玄武岩具有低的$^{87}Sr/^{86}Sr$(0.703 5～0.704 2)以及高的$\varepsilon_{Nd}(t)$值(＋3.4～＋6.6)，类似MORB的同位素组成，这些特征说明大兴安岭北段新生代玄武质岩石起源于软流圈地幔.综上所述，大兴安岭北段早白垩世和新生代玄武质岩石成分的差异不仅指示其岩浆源区从岩石圈地幔转变为软流圈地幔，更为重要的是它揭示了研究区地幔的热演化过程——从早白垩世高的地温梯度到新生代低的地温梯度的转变.这一过程也是岩石圈从中生代晚期到新生代逐渐增厚的过程.结合区域构造演化，可以得出大兴安岭北段早白垩世的玄武质岩浆作用与岩石圈伸展、减薄形成的裂陷作用相关，而新生代玄武质岩浆作用则与陆内裂谷作用相关.

关键词：大兴安岭北段；早白垩世；新生代；玄武质岩石；地幔热演化；岩石学.
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Composition Variations of Mesozoic and Cenozoic Basalts in Northern Great Xing'an Range: Implications for Thermal Evolution of Mantle

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Abstract: Recently, few researches have been made on the thermal evolution of the mantle in Northeast China. An effective means to solve this issue is to study the variation characteristics in composition of basalts in Northeast China. In this paper, it summarizes and discusses the composition variations of the Mesozoic and Cenozoic basalts in the northern Great Xing'an Range, with the aim of revealing the thermal evolution of the mantle within the study area. The Early Cretaceous basalts in the north-

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ern Great Xing'an Range geochemically belong to tholeiitic series, which are characterized by depletion in high field strength elements (e.g., Nb, Ta and Ti). Their La/Nb and La/Ta ratios range from 1.8 to 5.6 and from 30 to 87, respectively, implying the basaltic magmas originated from the partial melting of the lithospheric mantle. Their initial $^{87}Sr/^{86}Sr$ ratios of 0.704 5－0.706 9, $\varepsilon_{Nd}(t)$ values of －1.52－＋3.60 and $\varepsilon_{Hf}(t)$ values of ＋1.74－＋7.77 further indicate that the magma source is weakly depleted-weakly enriched lithospheric mantle. Additionally, the Sr-Nd-Pb isotope compositions of the Early Cretaceous basalts suggest that their magmatic sources are characterized by mixing between DM and EMII modified by subduction-derived fluids. Taking the above-mentioned into consideration, it is suggested that the Early Cretaceous basaltic magma was derived from partial melting of a lithospheric mantle metasomated by subduction-related fluids. The Cenozoic ultrapotassic and potassic basalts have weakly negative Nb-Ta anomalies, $^{87}Sr/^{86}Sr$ ratios of 0.704 7－0.705 7 and $\varepsilon_{Nd}(t)$ values of －6.3 to －0.8 whereas the mantle xenoliths entrained by Cenozoic ultrapotassic and potassic basalts show the depleted Sr-Nd isotopic characteristics. The Cenozoic sodium basalts have positive Nb-Ta anomalies, and lower $^{87}Sr/^{86}Sr$ ratios of 0.703 5－0.704 2 and higher $\varepsilon_{Nd}(t)$ values of ＋3.4－＋6.6 than those of the ultrapotassic and potassic basalts, similar to those of MORB. These geochemical features suggest that the Cenozoic basaltic magmas in the northern Great Xing'an Range were primarily produced by melting of asthenospheric mantle. The composition variations of the Early Cretaceous and Cenozoic basalts in the northern Great Xing'an Range not only indicate that the basaltic magma sources had changed from lithospheric to asthenospheric mantle, but also reveal the thermal evolution of the mantle in the study area, i.e., high geothermal gradient in the late Early Cretaceous changed to low geothermal gradient in the Cenozoic. Combined with the regional tectonic evolution, it is concluded that the Early Cretaceous basaltic magmatism in the northern Great Xing'an Range is related to the taphrogeny caused by the lithospheric extension and thinning, while the Cenozoic basaltic magmatism is related to the intracontinental rifting.

Key words: northern Great Xing'an Range; Early Cretaceous; Cenozoic; basalts; thermal evolution of the mantle; petrology.

0 引言

我国东北地区属于中亚造山带的东段，由一系列微陆块和其间的构造带组成，自西北向东南这些微陆块包括额尔古纳地块、兴安地块、松嫩－张广才岭地块、佳木斯地块以及兴凯地块（李锦轶等，1999；Wilde *et al*.，2003；Wu *et al*.，2011）.该区古生代期间经历了古亚洲洋构造体系的演化（Sengör and Natalin，1996；Li，2006），以多个微陆块之间的碰撞－拼合和古亚洲洋的最终闭合为特征（Li，2006；Windley *et al*.，2007）.中生代期间，东北地区经历了环太平洋构造体系和蒙古－鄂霍茨克构造体系的双重叠加和改造（Xu *et al*.，2009，2013；Wu *et al*.，2011；孟恩等，2011）.近年来，对东北基础地质的研究主要集中在对微陆块基底属性的研究、对古生代微陆块拼贴历史及古亚洲洋演化历史的研究、以及对中生代蒙古－鄂霍茨克构造体系和环太平洋构造体系演化与影响的时空范围的研究，而对东北地区地幔热演化过程的研究相对较少.玄武质岩浆是地幔物质部分熔融的产物，其形成过程及化学组成受控于地幔源区特征、部分熔融程度、地幔潜能温度和岩石圈厚度等多个因素（McKenzie and Bickle，1988；Langmuir *et al*.，1992）.如能区分这些因素对玄武岩组成变化的相对贡献，那么玄武岩组成就可用以反演深部地幔的演化历史（DePaolo and Daley，2000；Wang *et al*.，2002；徐义刚，2006）.因此，揭示东北地区地幔热演化过程的有效手段就是研究东北地区玄武岩的成分变异特征.

东北地区是中国中－新生代火山岩最主要的分布区（图1），火山岩主要是沿着松辽盆地的东侧、西侧和北侧分布，向西北可延伸至蒙古和俄罗斯境内，是东亚大陆边缘巨型火山岩带的重要组成部分.中国东北中生代玄武岩主要为拉斑玄武岩，而新生代玄武岩则以碱性玄武岩为主.随着多元同位素体系和非传统同位素在新生代玄武岩研究中的应用，近年来的研究表明新生代玄武岩并不是直接来自交代岩石圈地幔物质的部分熔融，钾质和超钾质碱性玄武岩主要来自软流圈地幔（Choi *et al*.，2006；张辉煌等，2006；Kuritani *et al*.，2013；Liu *et al*.，2017），而钠质碱性玄武岩可能是受俯冲的太平洋板块的影响，起源于地幔过渡带（Kuritani *et al*.，2011；Xu *et al*.，2012；Chen *et al*.，2017；Wang *et al*.，2017）.相对新生代玄武岩来说，东北地区中生代玄武岩的研究明显薄弱，并且对其成因存在不同的认识：(1)有的学者认为大兴安岭中生代玄武岩的形成与地幔柱有关，并且地幔柱源区的形成与古亚洲洋的闭合作用相关（葛文春等，1999）；(2)有的学者认为东北中生代玄武岩是软流圈熔体和岩石圈地幔相互反应的结果（张辉煌等，2006；张连昌等，2008）；(3)有的

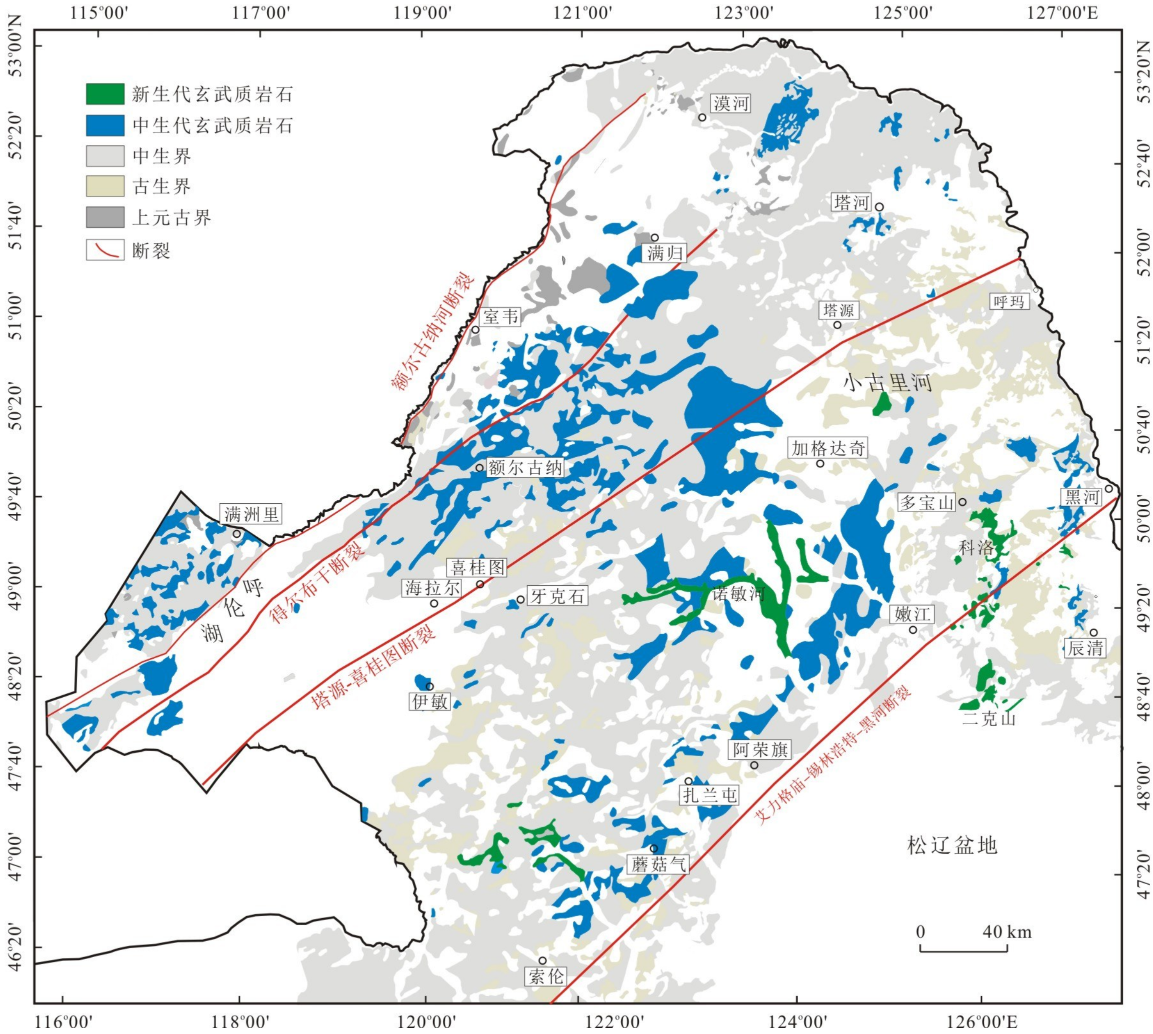

图1　大兴安岭北段中－新生代玄武质岩石分布

Fig.1　Distribution of the Mesozoic-Cenozoic basalts in the northern Great Xing'an Range

据 Wu *et al*.(2011);Xu *et al*.(2013)

学者认为中生代玄武岩起源于受俯冲流体交代的岩石圈地幔的部分熔融，东北地区东部的俯冲流体可能与俯冲的古太平洋板块有关，西部的俯冲流体与古亚洲洋板块和蒙古－鄂霍次克大洋板块相关(Zhang *et al*.,2008;张吉衡,2009;Wang *et al*.,2015).那么，东北地区中生代玄武岩的岩浆源区究竟是岩石圈地幔还是软流圈地幔？中－新生代玄武岩成分存在怎样的差异？它们反映了怎样的地幔热演化过程？

我国东北大兴安岭北段(满洲里－牙克石－额尔古纳－满归地区)存在大面积的中－新生代玄武质岩石(图1)，这为研究地幔热演化过程提供了重要窗口.因此，本文总结了大兴安岭北段中生代玄武质岩石的主、微量元素以及Sr-Nd-Pb-Hf同位素组成，并与研究区新生代玄武岩进行了系统对比，以便查明大兴安岭北段中－新生代玄武岩的成分变异，进而揭示中－新生代地幔的热演化过程.

1　区域地质与中－新生代玄武岩特征

大地构造上，大兴安岭北段位于额尔古纳地块和兴安地块范围内，额尔古纳地块东南部以塔源－喜桂图缝合带为界与兴安地块在早古生代早期(约490 Ma)完成碰撞拼合(Wu *et al*.,2011);额尔古纳地块西南部与中蒙古地块于早古生代发生碰撞拼合成为一个整体，即中蒙古－额尔古纳地块(李锦轶，1998;Wu *et al*.,2012);兴安地块东南部以艾力格庙－锡林浩特－黑河缝合带为界与松嫩－张广才岭地块相邻(徐备等,2014;Li *et al*.,2017)，并在晚古生代期间(～320 Ma)完成了碰撞拼合(赵芝等,

2010；Li *et al*.，2014）.额尔古纳地块和兴安地块上除了塔源－喜桂图和艾力格庙－锡林浩特－黑河缝合带外，还有额尔古纳河断裂、得尔布干断裂和黑河－贺根山断裂.

大兴安岭北段前寒武纪基底主要为兴华渡口群（苗来成等，2007；Wu *et al*.，2012）、佳疙瘩组（Zhao *et al*.，2016）和额尔古纳河组（Zhang *et al*.，2014b）的变质火山岩和变质沉积岩，以及古元古代和新元古代的花岗质岩石（Gou *et al*.，2013；Tang *et al*.，2013；孙立新等，2013）.研究区内侵入岩主要形成于中生代，少量形成于古生代，岩性以花岗质岩石为主，伴随少量的中基性侵入岩.研究区内出露少量古生代地层（赵英利等，2018），主要由砂岩、粉砂岩、板岩、灰岩等组成；中生代地层则以火山岩为主，基性－酸性火山岩均有大面积出露，包括塔木兰沟组玄武岩、玄武安山岩、安山岩，吉祥峰组流纹岩，上库力组流纹质、英安质熔岩，伊列克得组玄武岩、粗安岩、粗面岩.

本文所研究的中生代中基性火山岩主要来自塔木兰沟组和伊列克得组，时代集中在 132～106 Ma 之间（表 1），即早白垩世晚期，它们在大兴安岭北段广泛出露，呈面状展布（Wang *et al*.，2006；Zhang *et al*.，2008；孟恩等，2011；徐美君等，2011；张丽等，2017）.塔木兰沟组是大兴安岭北段层位最低的火山岩地层，岩石类型有玄武岩、玄武安山岩、玄武粗安岩、粗安岩和安山岩.岩石气孔杏仁发育，少斑－斑状结构（局部多斑或无斑），基质为间粒、间隐或交织结构，斑晶由斜长石、橄榄石、单斜辉石组成，橄榄石暗化边发育，单斜辉石新鲜.基质主要为斜长石，少量橄榄石，其间充填辉石和不透明矿物，局部析出石英（张昱等，2005）.伊列克得组为区内层位最高的火山岩地层，其分布范围比较广泛，主要由玄武岩和玄武安山岩组成.这些岩石通常为辉绿结构和玻基斑状结构.斑晶矿物组合为橄榄石、单斜辉石、斜长石，个别橄榄石具有单斜辉石反应边，基质由斜长石微晶、伊丁石化橄榄石、单斜辉石和磁铁矿组成.气孔杏仁构造发育（张吉衡，2009）.

大兴安岭北段新生代玄武质岩石主要分布在 5 个地区，分别是小古里河、诺敏河、科洛、二克山和哈拉哈－柴河，它们呈近南北向带状分布于松辽盆地

表 1　大兴安岭北段早白垩世玄武质岩石定年结果

Table 1　Geochronological data for the Early Cretaceous basalts in the northern Great Xing'an Range

样品号	采样位置		岩性	年龄（Ma）	测年方法	文献
12ER21	50°09′40″N	120°11′58″E	玄武安山岩	119±1	^{40}Ar-^{39}Ar	未发表数据
ER1	49°59′57″N	120°06′50″E	粗安岩	128±2	LA-ICPMS	徐美君等，2011
ER3	50°19′57″N	120°15′01″E	玄武粗安岩	125±3	LA-ICPMS	徐美君等，2011
ER5-1	50°26′01″N	120°00′54″E	安山岩	114±3	LA-ICPMS	徐美君等，2011
ER19-1	50°42′37″N	120°12′52″E	玄武安山岩	127±1	LA-ICPMS	徐美君等，2011
MZ10-1	49°23′56″N	117°25′21″E	辉石安山岩	125±2	LA-ICPMS	孟恩等，2011
MZ21-1	49°26′42″N	117°02′31″E	橄榄玄武岩	129±2	LA-ICPMS	孟恩等，2011
14ER19-1	51°43′05″N	120°44′43″E	玄武安山岩	132±2	SIMS	Zhao *et al*.，2016
14ER20-1	51°43′05″N	120°44′43″E	玄武安山岩	126±2	SIMS	Zhao *et al*.，2016
FW04-420	48°16′31″N	123°38′12″E	玄武安山岩	123±2	LA-ICPMS	Zhang *et al*.，2008
GW04257	48°09′13″N	121°14′44″E	玄武岩	128±8	LA-ICPMS	Zhang *et al*.，2008
GW04027	48°51′11″N	121°37′27″E	玄武岩	112±2	^{40}Ar-^{39}Ar	Zhang *et al*.，2008
GW04032	49°07′01″N	120°55′43″E	玄武岩	118±1	^{40}Ar-^{39}Ar	Zhang *et al*.，2008
ELC04-1	50°40′04″N	122°35′57″E	玄武岩	125±1	^{40}Ar-^{39}Ar	Wang *et al*.，2006
TH08	52°19′30″N	124°40′40″E	玄武岩	124±1	^{40}Ar-^{39}Ar	Wang *et al*.，2006
TH24	52°39′38″N	124°19′38″E	玄武安山岩	126±1	^{40}Ar-^{39}Ar	Wang *et al*.，2006
TH22	52°39′39″N	124°19′42″E	玄武岩	122±1	^{40}Ar-^{39}Ar	Wang *et al*.，2006
GH07	50°19′54″N	120°14′53″E	玄武岩	123±1	^{40}Ar-^{39}Ar	Wang *et al*.，2006
GH10	50°26′23″N	120°48′13″E	玄武岩	121±1	^{40}Ar-^{39}Ar	Wang *et al*.，2006
YKSNQ04-4	49°12′22″N	120°36′50″E	玄武岩	116±1	^{40}Ar-^{39}Ar	Wang *et al*.，2006
YKSNQ04-1	49°12′47″N	120°36′50″E	玄武安山岩	114±1	^{40}Ar-^{39}Ar	Wang *et al*.，2006
ZLT04-8	48°00′18″N	122°48′23″E	玄武安山岩	122±1	^{40}Ar-^{39}Ar	Wang *et al*.，2006
YKS04-3	48°50′47″N	121°34′58″E	玄武粗安岩	106±1	^{40}Ar-^{39}Ar	Wang *et al*.，2006
GH04-1	50°21′32″N	120°26′49″E	粗玄岩	124±1	^{40}Ar-^{39}Ar	Wang *et al*.，2006
GH04-4	50°59′17″N	121°19′16″E	玄武粗安岩	115±1	^{40}Ar-^{39}Ar	Wang *et al*.，2006
JGD04-4	49°56′53″N	124°22′48″E	玄武岩	115±1	^{40}Ar-^{39}Ar	Wang *et al*.，2006

和大兴安岭隆起之间的狭长地带.岩石类型有碧玄岩、粗玄岩、玄武粗安岩、玄武安山岩、粗安岩,岩石具有玻基斑状结构、斑状结构,斑晶有橄榄石、单斜辉石和少量斜方辉石,较自形,偶有熔蚀现象,有的岩石基质中以基质玻璃和针状长石为主,有的岩石基质由细粒橄榄石、辉石、斜长石、磁铁矿等铁钛氧化物和玻璃质组成(赵勇伟和樊祺诚,2012;Sun *et al*.,2014;Zhao *et al*.,2014).玄武岩中可见尖晶石相橄榄岩和石榴石相橄榄岩捕掳体(Zhang *et al*.,2011;Zhao *et al*.,2014;隋建立等,2014).

2　大兴安岭北段早白垩世玄武质岩石成因

早白垩世中－基性火山岩的 SiO_2 含量介于 47.34%～60.00%,K_2O 含量介于 1.04%～3.79%,Na_2O 含量介于 2.70%～6.13%,在 TAS 图解(图 2a)中落入玄武岩、玄武安山岩、玄武粗安岩、粗安岩和安山岩中,在 SiO_2-K_2O 图解中(图 2b)主要落入高钾钙碱性系列中,少量落入钙碱性和钾玄岩系列中.大兴安岭北段大面积产出的早白垩世玄武质岩石的成因如何?岩浆演化过程中是否受到了陆壳物质的混染,是否经历了矿物的分离结晶作用,岩浆源区是起源于岩石圈还是软流圈呢?这些问题将从中生代玄武质岩石的地球化学特征中得到回答.

首先,地幔起源的熔体 Nb/U 和 Ce/Pb 比值高(Hofmann *et al*.,1986),而地壳岩石熔出的熔体 Nb/U 和 Ce/Pb 低(Rudnick and Gao,2003),因此,它们通常被用来约束地壳混染的程度.大兴安岭北段早白垩世玄武质岩石具有低的 Nb/U(3.75～33.0)和 Ce/Pb 值(2.67～11.5),低于与 MORB 和 OIB 的 Nb/U 和 Ce/Pb 值(Nb/U＝47±10;Ce/Pb＝25±5),而与大陆地壳组分接近(Nb/U≈10;Ce/Pb≈4).因此,早白垩世玄武质岩石可能受到了地壳的混染作用.然而,除了大兴安岭北端塔河地区的玄武岩外,早白垩世玄武质岩石具有较一致的 Sr-Nd 同位素特征($(^{87}Sr/^{86}Sr)_i$＝0.704 5～0.706 9,$\varepsilon_{Nd}(t)$＝－1.52～＋3.60),与 SiO_2 含量之间不存在线性关系,说明地壳混染的程度较低.此外,由于地壳物质具有低的 Sm/Nd 比值和 $\varepsilon_{Nd}(t)$ 值,因此,当岩浆受地壳混染时,$\varepsilon_{Nd}(t)$ 和 Sm/Nd 比值将呈线性关系,而大兴安岭北段早白垩世玄武质岩石并没有出现上述相关关系(图 3),进一步说明它们受到的地壳物质混染程度不高,其 Sr-Nd-Pb-Hf 同位素仍可反映岩浆源区特征.

其次,除塔河玄武质岩石外,早白垩世玄武质岩石具有相近的 $\varepsilon_{Nd}(t)$ 值,指示它们可能为同源岩浆演化的产物.在 Harker 图解中(图 4),早白垩世玄武质岩石的 SiO_2 与大多数常量元素具有较好的相关性,SiO_2 与 CaO、MgO、FeO^T 具有负相关性,与 Na_2O 和 K_2O 具有正相关性,与 TiO_2 和 P_2O_5 没有明显的相关性(图 2b,图 4),反映岩浆分离结晶演化趋势.在 La－La/Sm 图解中(图 5),同样表明分离结晶作用在大兴安岭北段早白垩世玄武质岩浆演化

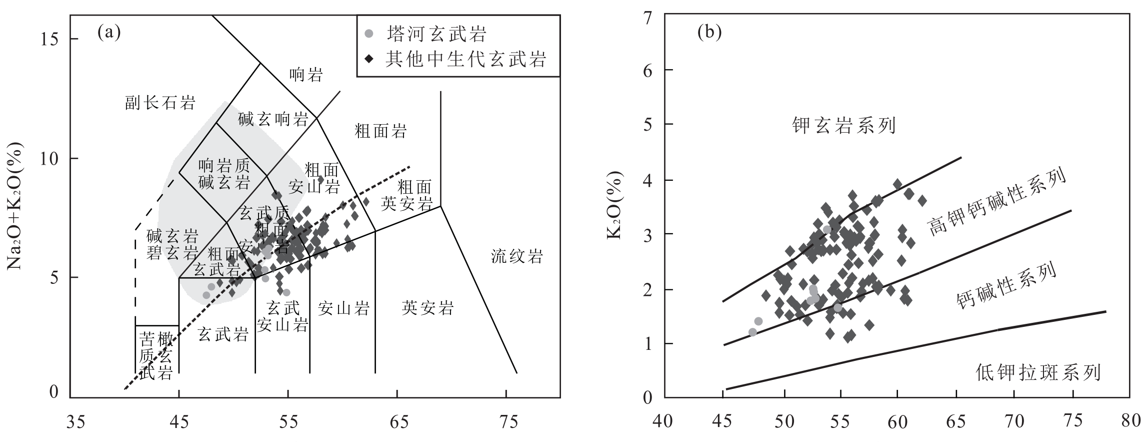

图 2　大兴安岭北段中生代玄武质岩石的 TAS 图解(a)和 SiO_2-K_2O 图解(b)

Fig.2　Plots of TAS (a) and SiO_2 versus K_2O (b) for the Mesozoic basalts in the northern Great Xing'an Range

图 a 据 Le Bas *et al*.(1986);图 b 据 Peccerillo and Taylor,1976;数据来源:未发表数据;Fan *et al*.(2003);Zhang *et al*.(2008);葛文春等(1999,2000);林强等(2003);孟恩等(2011);徐美君等(2011);阴影区代表大兴安岭北段新生代玄武质岩石,引自 Zhang *et al*.(1995);Chen *et al*.(2007);Ho *et al*.(2013);Kuritani *et al*.(2013);Sun *et al*.(2014);Zhao *et al*.(2014);Li *et al*.(2018)

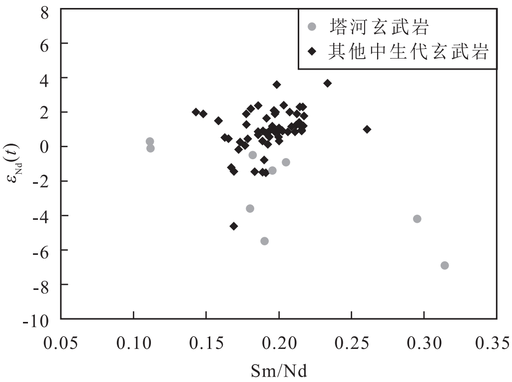

图 3　大兴安岭北段中生代玄武质岩石的 Sm/Nd－$\varepsilon_{Hf}(t)$图解

Fig.3　Plot of Sm/Nd－$\varepsilon_{Hf}(t)$ for the Mesozoic basalts in the northern Great Xing'an Range

数据来源见图 2

过程中占主导因素.随着 SiO_2 的升高，MgO、FeO^T、Ni 和其他相容元素含量降低，表明岩浆在喷发过程

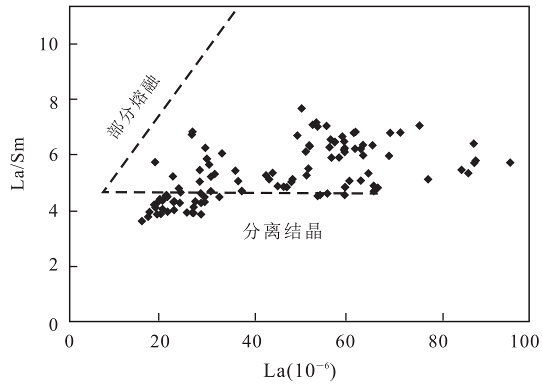

图 5　大兴安岭北段中生代玄武质岩石的 La－La/Sm 图解

Fig.5　Plot of La－La/Sm for the Mesozoic basalts in the northern Great Xing'an Range

数据来源见图 2，不包括塔河玄武岩

中发生了橄榄石、辉石等镁铁质矿物的分离结晶.

第三，大兴安岭北段早白垩世玄武质岩石中未

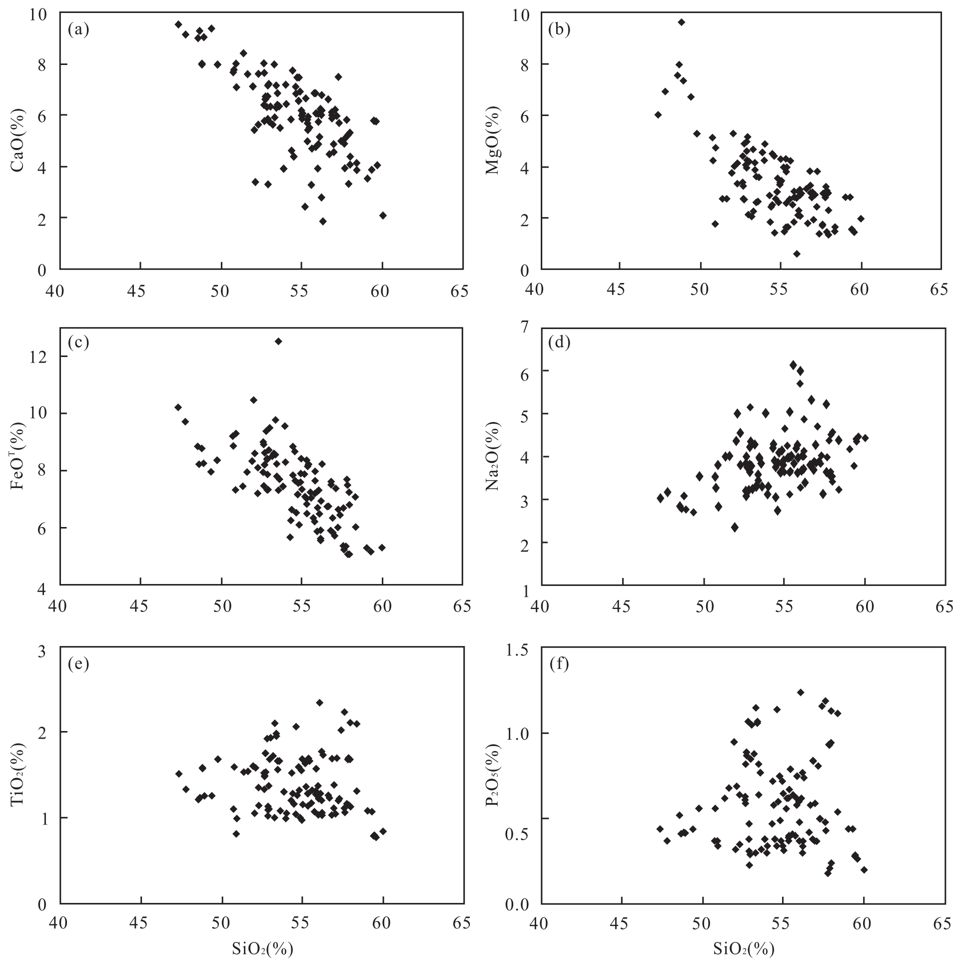

图 4　大兴安岭北段中生代玄武质岩石的 Hark 图解

Fig.4　Hark diagrams for the Mesozoic basalts in the northern Great Xing'an Range

数据来源见图 2，不包括塔河玄武岩

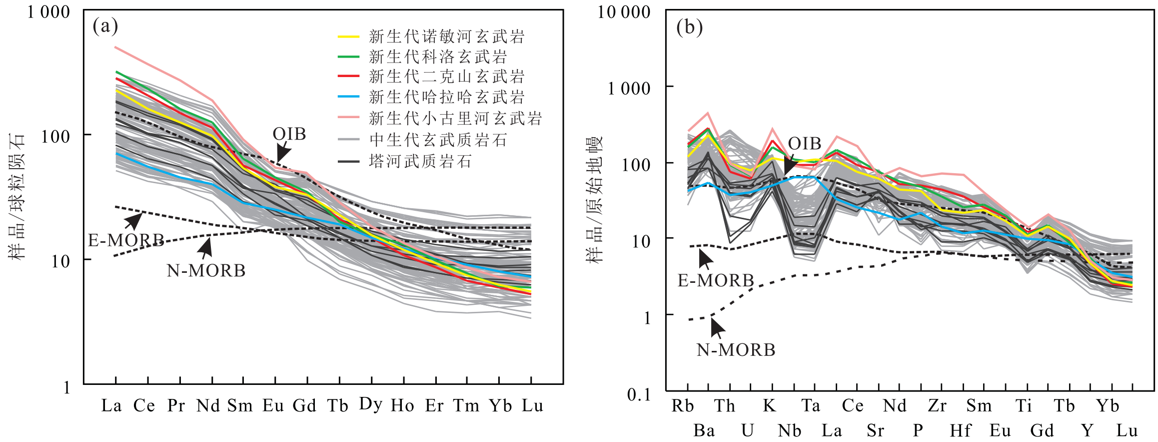

图 6 大兴安岭北段中-新生代玄武质岩石球粒陨石标准化稀土元素配分图(a);原始地幔标准化微量元素蛛网图(b)

Fig.6 Chondrite-normalized REE patterns (a) and primitive-mantle-normalized trace element spidergrams (b) for the Mesozoic-Cenozoic basalts in the northern Great Xing'an Range

图 a 中标准化数值据 Boynton (1984);图 b 中标准化数值据 Sun and McDonough (1989);中生代玄武质岩石数据来源见图 2;新生代玄武质岩石数据为平均值,来源:Zhang *et al*.(1995);Chen *et al*.(2007);Ho *et al*.(2013);Kuritani *et al*.(2013);Sun *et al*.(2014);Zhao *et al*.(2014);Liu *et al*.(2017)

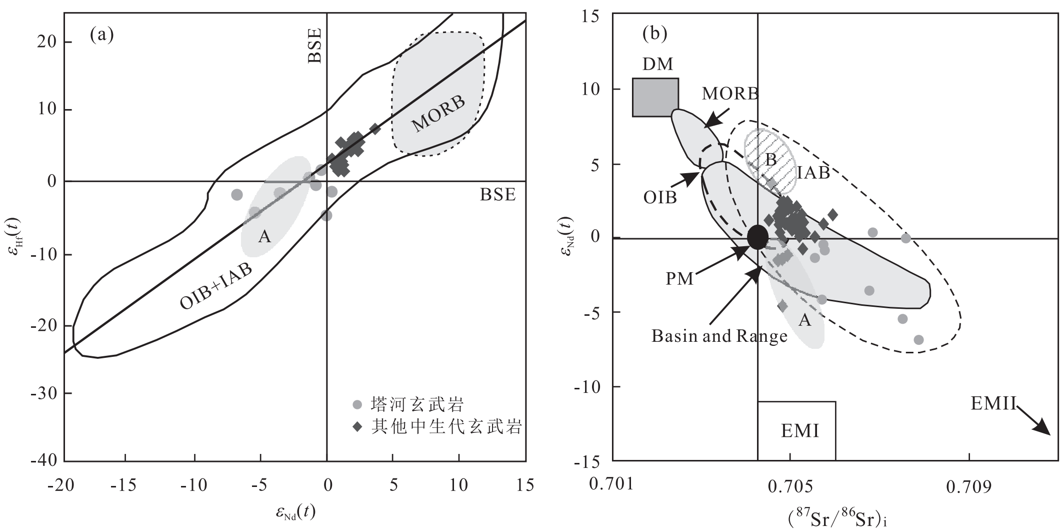

图 7 大兴安岭北段中-新生代玄武质岩石的 $\varepsilon_{Nd}(t)$-$\varepsilon_{Hf}(t)$(a)和$(^{87}Sr/^{86}Sr)_i$-$\varepsilon_{Nd}(t)$(b)图解

Fig.7 Plots of $\varepsilon_{Nd}(t)$-$\varepsilon_{Hf}(t)$ (a) and $(^{87}Sr/^{86}Sr)_i$-$\varepsilon_{Nd}(t)$(b) for the Mesozoic-Cenozoic basalts in the northern Great Xing'an Range

A.新生代超钾质-钾质玄武岩;B.新生代钠质玄武岩;BSE.全硅酸盐地球值;MORB.洋脊玄武岩;OIB.大洋岛屿玄武岩;IAB.岛弧玄武岩;全球阵列参考线 $\varepsilon_{Hf}(t)=1.36\varepsilon_{Nd}(t)+2.95$,引自 Vervoort and Blichert-Toft (1999);Basin and Range.美国盆岭地区新生代火山岩,引自 Hawkesworth *et al*.(1995)和 Rogers *et al*.(1995);PM.原始地幔;EMI.I 型富集地幔,EMII.II 型富集地幔,引自 Zindle and Hart (1986)

见地幔包体,它们具有低的 SiO_2 含量,相似的微量元素组成——富集轻稀土元素,亏损重稀土元素,无明显 Eu 异常,富集 Rb、Ba、K 等大离子亲石元素(LILE),亏损 Nb、Ta、Ti 等高场强元素(HFSE),明显不同于 OIB 和 MORB 玄武岩(图 6),它们的 La/Nb(1.8~5.6)和 La/Ta(30~87)值明显高于软流圈地幔(La/Nb<1.5;La/Ta<22)、而与岩石圈地幔起源的玄武质岩石相似(La/Nb>1.5;La/Ta>22;Fitton *et al*., 1988; Thompson and Morrison, 1988),表明其岩浆起源于岩石圈地幔物质的部分熔融.对于早白垩世玄武质岩石的 Sr-Nd-Pb-Hf 同位素组成,大兴安岭北端的塔河玄武质岩石与其他地区早白垩世玄武质岩石具有较大差异:塔河玄武质岩石的 $^{87}Sr/^{86}Sr$ 比值为 0.705 5~0.707 9,$\varepsilon_{Hf}(t)$值为-4.58~+1.88,$\varepsilon_{Nd}(t)$值为-6.9~+0.3,$^{206}Pb/^{204}Pb$ 为 18.150~18.530,$^{207}Pb/^{204}Pb$ 为

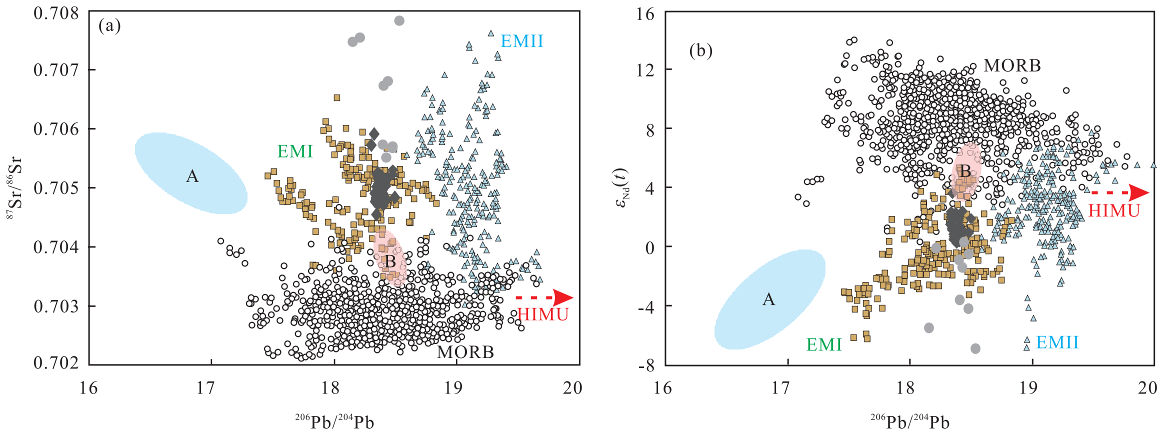

图 8　大兴安岭北段中—新生代玄武质岩石全岩 Sr-Nd-Pb 同位素协变图

Fig.8　Variations of Sr-Nd-Pb isotopic compositions for the Mesozoic-Cenozoic basalts in the northern Great Xing'an Range

图例见图 7;A.新生代超钾质—钾质玄武岩;B.新生代钠质玄武岩;HIMU.高 $^{238}U/^{204}Pb$ 值地幔;EMI、EMII、MORB 数据来自 GEOROC

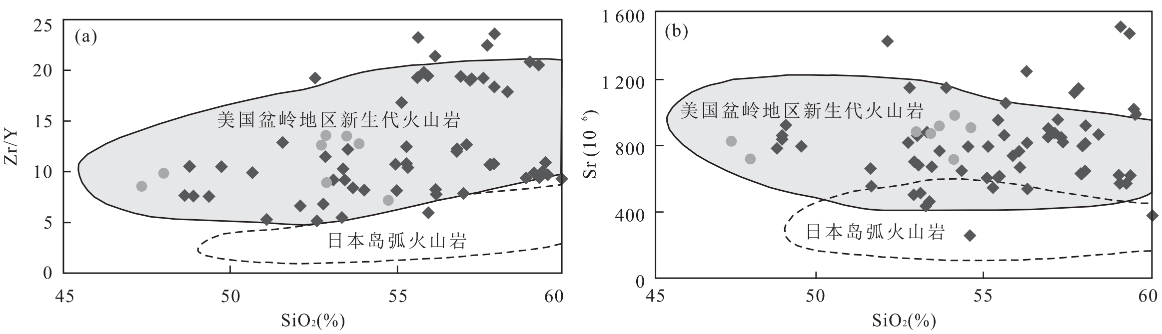

图 9　大兴安岭北段中生代玄武质岩石的 SiO_2—Zr/Y(a)和 SiO_2—Sr 图解(b)

Fig.9　Plots of SiO_2—Zr/Y (a) and SiO_2—Sr (b) for the Mesozoic basalts in the northern Great Xing'an Range

图例见图 7;美国盆岭地区新生代火山岩和日本岛弧火山岩引自 Hawkesworth *et al*.(1995)和 Rogers *et al*.(1995)

15.539～15.489,$^{208}Pb/^{204}Pb$ 为 37.761～38.344;其他早白垩世玄武质岩石的 $^{87}Sr/^{86}Sr$ 比值为 0.704 5～0.706 9,$\varepsilon_{Nd}(t)$ 值为 −1.52～+3.60,$\varepsilon_{Hf}(t)$ 值为 +1.74～+7.77,$^{206}Pb/^{204}Pb$ 为 18.301～18.531,$^{207}Pb/^{204}Pb$ 为 15.457～15.586,$^{208}Pb/^{204}Pb$ 为 37.940～38.440.这些同位素地球化学特征表明大兴安岭北段早白垩世玄武质岩石的岩浆源区是弱亏损—弱富集的岩石圈地幔,而不是软流圈地幔或地幔柱(Hawkesworth *et al*.,1995;Rogers *et al*.,1995;Fan *et al*.,2003).

第四,在 $\varepsilon_{Nd}(t)$—$\varepsilon_{Hf}(t)$ 图解中(图 7a),早白垩世玄武质岩石的 $\varepsilon_{Nd}(t)$ 与 $\varepsilon_{Hf}(t)$ 值呈正相关关系,未见 Nd—Hf 解耦的特征,它们落在全球阵列参考线附近,$\varepsilon_{Nd}(t)$ 与 $\varepsilon_{Hf}(t)$ 值明显低于 MORB 型亏损地幔($\varepsilon_{Nd}(t)\approx+8$;$\varepsilon_{Hf}(t)\approx+13$),而与 OIB+IAB 型地幔相似(Zhang *et al*.,2008).在 $(^{87}Sr/^{86}Sr)_i$-$\varepsilon_{Nd}(t)$ 图解中(图 7b),早白垩世玄武质岩石投在 DM 和 EMII 之间,其中塔河玄武质岩石具有向 EMII 演化趋势,在 $^{206}Pb/^{204}Pb$-$^{87}Sr/^{86}Sr$ 和 $^{206}Pb/^{204}Pb$-$\varepsilon_{Nd}(t)$ 图解中(图 8),早白垩世玄武质岩石落在 MORB、EMI 和 EMII 之间,表明早白垩世玄武质岩浆源区是由 DM 和 EMII 型地幔端元混合而成,并经历了俯冲流体的交代.大兴安岭北段早白垩世玄武质岩石亏损 Nb、Ta,Ba/Nb 比值(26.9～239.0)变化幅度大,而 Ce/Nb(3.82～12.7)比值变化幅度小,反映其源区特征与流体交代作用趋势相近,同时高场强元素相对轻稀土元素强烈亏损($(Nb/La)_N$ 远小于 1),这种特征进一步反映了岩浆源区受俯冲流体交代作用的影响(Pearce and Peate,1995).此外,由于大洋玄武质地壳具有亏损的 Nd 同位素特征,因此析出流体也相应具有相对亏损的 Nd 同位素组成,所以受到流体交代的地幔楔或亏损地幔发生部分熔融作用产生的玄武质岩浆也可能具 Nd 同位素弱亏损至弱富集的特征(郭锋等,2001),这也与大兴安岭北段早白垩世玄武质岩石的 Nd 同位素组成特征相一致.根据元素和同位

素特征(图7,图9),大兴安岭北段早白垩世玄武质岩石较弧火山岩具有高Sr、Zr/Y比值,与美国盆岭地区新生代火山岩具有相似性(Hawkesworth *et al*.,1995),美国盆岭地区新生代火山岩形成于伸展环境,起源于受古俯冲(而不是同时期俯冲)流体交代的岩石圈地幔.因此,我们认为大兴安岭北段早白垩世玄武质岩石的源区为受早期俯冲流体交代的岩石圈地幔,交代作用不是发生在岩浆作用同时期(早白垩世),而是由于早期俯冲洋壳物质在深部发生脱水并交代了仰冲的地幔楔,导致该地幔源区相对富集LILE而亏损HFSE,在这种地幔源区岩浆产生的火山岩同样继承了相对富集LILE而亏损HFSE的性质.此外,大兴安岭北段塔河玄武质岩浆源区与其他同时代玄武质岩浆的源区存在差异,为弱富集的岩石圈地幔,其他早白垩世玄武质岩浆源区为弱亏损-弱富集的岩石圈地幔.

3 大兴安岭北段新生代玄武质岩石成因

通过对东北亚陆缘中-新生代火成岩定年结果的统计,发现大兴安岭北段存在较大范围的岩浆间歇期,缺失晚白垩世-古近纪的岩浆作用(Tang *et al*.,2018),新生代火山岩喷出时代主要为16~0.5 Ma.

大兴安岭北段新生代玄武质岩石为碱性玄武岩,根据K_2O/Na_2O比值,小古里河火山岩为超钾质玄武岩($K_2O/Na_2O>1$),诺敏河、科洛和二克山火山岩为钾质系列($1<K_2O/Na_2O<2$),哈拉哈-柴河火山岩为钠质系列($K_2O/Na_2O<1$)(Zhang *et al*.,1995;Chu *et al*.,2013;Ho *et al*.,2013;Sun *et al*.,2014).在稀土元素配分图解中(图6a),大兴安岭北段新生代玄武质岩石具有相似的重稀土元素含量,但它们的轻稀土元素含量从超钾质到钾质再到钠质玄武质岩石逐渐降低.新生代超钾质和钾质玄武岩具有相似的微量元素含量和同位素地球化学特征,而与钠质玄武岩具有较大差异(图6b).新生代超钾质和钾质玄武岩富集大离子亲石元素、亏损高场强元素,具有Th-U负异常和弱的Nb-Ta负异常,具有异常低的放射性成因$^{206}Pb/^{204}Pb$(16.44~17.23),中等的$^{87}Sr/^{86}Sr$(0.704 7~0.705 7),以及低的$\varepsilon_{Nd}(t)$值为-6.3~-0.8,类似EMI的地幔端元,而钾质玄武岩中携带的地幔捕掳体具有亏损的Sr-Nd-Hf同位素组成($\varepsilon_{Nd}(t)$值为-0.05~+7.58,$\varepsilon_{Hf}(t)$值为+2.4~+21.1,Zhang *et al*.,2011).综合上述特征,可以判定这些玄武质岩浆应起源于软流圈地幔,而非岩石圈地幔(Liu *et al*.,2016;2017).由于平均下地壳的K_2O含量大约只有0.61%(Rudnick and Gao,2003),因此,再循环下地壳的部分熔融不能产生这种具有极其高钾含量特征的岩浆(Sun *et al*.,2014),根据新生代超钾质-钾质玄武岩的微量元素特征和Pb同位素组成,再循环沉积物可作为这些玄武岩的源区组分的观点得到越来越多学者认可(Yaxley,2000;Kuritani *et al*.,2013;Sun *et al*.,2014,2015).此外,在熔体上涌过程中,岩石圈地幔不仅控制上涌地幔物质最终的熔融深度和压力(Humphreys and Niu,2009;Niu *et al*.,2011),还会通过熔体-岩石相互作用使得上升的熔体发生混染(Xu *et al*.,2005;Tang *et al*.,2006),新生代钾质玄武岩携带的橄榄岩捕掳体中可见脉状或粒间的金云母作为主要的交代矿物相出现,这为新生代钾质玄武质岩浆在上升过程中发生熔体-岩石相互作用提供了最直接的证据(Zhang *et al*.,2011;隋建立等,2014).

大兴安岭北段新生代钠质玄武岩(哈拉哈玄武岩)具有Nb-Ta正异常,与OIB具有相似的微量元素特征,较超钾质和钾质玄武岩具有低的$^{87}Sr/^{86}Sr$(0.703 5~0.704 2),以及高的$\varepsilon_{Nd}(t)$值为+3.4~+6.6,显示与MORB相似的亏损地幔同位素特征(图7b),表明钠质玄武岩起源于亏损的软流圈地幔(Ho *et al*.,2013).此外,大兴安岭北段新生代钠质玄武岩富集轻稀土元素,它们的La/Ce(0.43~0.51)和Ce/Sm(6.9~8.8)值高于原始地幔(La/Ce和Ce/Sm值分别为0.39和4.0,Sun and McDonough,1989),结合亏损的Sr-Nd同位素特征,表明源区的软流圈地幔发生过交代作用(Ho *et al*.,2013).根据火山岩中携带的石榴石二辉橄榄岩*P*-*T*平衡条件估算其形成深度大于70 km(樊祺诚等,2008),来自尖晶石二辉橄榄岩与石榴石二辉橄榄岩相转变带之下的石榴石橄榄岩稳定区.大兴安岭北段钠质玄武岩的$^{207}Pb/^{204}Pb$值为15.537~15.552,$^{206}Pb/^{204}Pb$值为18.388~18.552,它们不像典型的HIMU组分具有非常高的放射性成因Pb同位素成分,又比N-型洋中脊玄武岩(N-MORB)具有高的$^{206}Pb/^{204}Pb$值,位于北半球参考线之上(NHRL;Hart,1984;Ho *et al*.,2013),表明与短期内的再循环洋壳相关(<1.5 Ga;Thirlwall,1997;Xu *et al*.,2012).地震层析成像研究表明太平洋板块在中国东北地区的地幔过渡带中停滞不前,累积厚度达到150~200 km

(Zhao，2004)，滞留板块达到了大兴安岭的东缘，因此，大兴安岭北段新生代钠质玄武岩的形成可能与滞留的太平洋板块密切相关.

大兴安岭北段新生代玄武质岩石都起源于软流圈地幔，但超钾质－钾质玄武岩与钠质玄武岩的地球化学特征具有较大的差异，这可能是由于其源区性质存在差异.综合中生代玄武质岩浆源区性质，暗示大兴安岭北段由中生代岩石圈地幔起源向新生代软流圈地幔起源转变.

4　大兴安岭北段中－新生代地幔热演化过程

4.1　大兴安岭北段中－新生代玄武质岩石起源深度

大兴安岭北段中生代玄武质岩石以拉斑玄武岩和亚碱质玄武岩为主，而新生代则以碱性－强碱性玄武岩为主(图 2a)，实验岩石学结果显示拉斑玄武岩起源于地幔较浅位置(15×10^8～25×10^8 Pa；50～60 km)经大程度部分熔融而形成的，而碱性玄武岩则由深部地幔(＞30×10^8 Pa；＞80 km)经小程度部分熔融而成(Falloon *et al*.，1988).因此，推测大兴安岭北段玄武质岩浆起源区由早白垩世浅的岩石圈地幔到新生代深的软流圈地幔.许文良等(2000)依据火山岩的岩石化学资料，推算伊列克得组(早白垩世玄武质岩石的主要来源)岩浆起源的压力为1.2～1.4 GPa，温度约为 1 300 ℃，起源深度约为46 km，大兴安岭北段不仅存在早白垩世玄武质岩石，还产出大面积同时代壳源流纹岩和花岗岩(Wu *et al*.，2011；Xu *et al*.，2013)，暗示早白垩世期间该区地温梯度较高，推测早白垩世玄武质岩石的岩浆起源深度与此时岩石圈厚度接近，当时的地温梯度可达 28 ℃/km.根据地球物理数据，大兴安岭北段新生代火山岩区下覆的岩石圈厚度约为 120～150 km(马杏垣，1987；Zhang *et al*.，2014a)，新生代玄武质岩浆起源于软流圈与岩石圈的交界部位，因此，推断大兴安岭北段新生代玄武质岩石的起源深度约为 120～150 km(Liu *et al*.，2016；2017).这与根据岩石碱度变化所获得的结论是一致的，即大兴安岭北段玄武质岩浆起源深度由中生代到新生代逐渐加深，根据软流圈中玄武质岩浆的温度(约 1 400 ℃)和岩浆起源深度(120～150 km)，推测该区新生代的地温梯度约为 9.3～11.7 ℃/km.此外，大兴安岭北段早白垩世－新生代岩石圈厚度相差较大，暗示从中生代晚期到新生代，大兴安岭北段岩石圈厚度逐渐增大(图 10)，这与该区从中生代晚期到新生代地温梯度显著降低的特征相吻合.

4.2　大兴安岭北段中－新生代地幔发生熔融的条件

地幔发生熔融的必要条件是地温线与地幔固相线相交，导致地温线与地幔固相线相交有 3 种方式(徐义刚，2006)：(1)降低上地幔的熔融温度，实验证

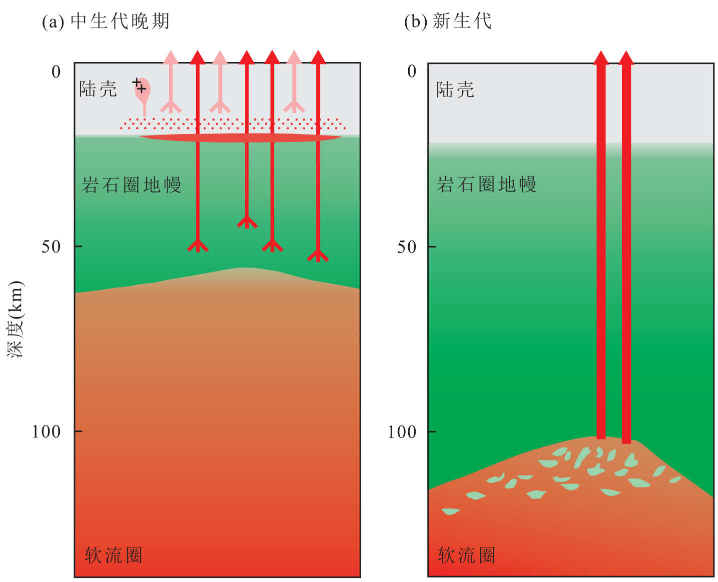

图 10　大兴安岭北段中－新生代玄武质岩石形成过程

Fig.10　Simplified carton describing formation process of the Mesozoic-Cenozoic basalts in the northern Great Xing'an Range

a.中生代晚期玄武质岩浆起源深度约为 46 km，源区为受早期俯冲流体交代的岩石圈地幔；b.新生代玄武质岩浆起源深度约为 120～150 km，源区为具有 EMI 特征的再循环地壳物质

实，上地幔体系中挥发分（如 H_2O、CO_2）的加入可以大大地降低特定压力条件下上地幔的熔融温度（Olafsson and Eggler，1983）；（2）提高地幔的温度；（3）岩石圈拉张引起软流圈绝热（减压）上升而发生熔融.那么大兴安岭北段中－新生代地幔熔融条件有哪些异同呢？

前文研究表明大兴安岭北段早白垩世玄武质岩石的岩浆源区为早期受俯冲流体交代的岩石圈地幔，这表明地幔中有挥发分的加入，降低了地幔的熔融温度.大兴安岭北段中生代玄武质岩石不仅包括大面积出露的早白垩世玄武质岩石，还包括零星出露的早侏罗世和晚侏罗世玄武质岩石（孟恩等，2011；Wang *et al.*，2015），那么，为什么交代的地幔是在早白垩世发生大范围的熔融，而不是侏罗纪或更早呢？这可能是因为挥发分的加入虽然降低了地幔的熔融温度，但还不足以使地温线与地幔固相线相交.从区域大地构造分析可知，在晚中生代大兴安岭地区发生了快速的岩石圈伸展、减薄和软流圈上隆作用（林强等，1998），进入了以裂陷作用为主的构造活动时期（郭锋等，2001），岩石圈的逐渐减薄和软流圈的上隆使得地幔的温度提高，早白垩世期间地温线与地幔固相线相交，被俯冲流体交代的岩石圈地幔发生了大范围的熔融，形成了早白垩世的玄武质岩石，这也说明早白垩世玄武质岩浆起源深度与此时岩石圈的厚度接近.对于俯冲流体的来源，本文认为其可能与蒙古－鄂霍茨克构造体系或古亚洲洋构造体系相关，而与古太平洋板块的俯冲作用无关，这是因为吉黑东部（东宁－汪清－珲春一线）存在早－中侏罗世（173～190 Ma）钙碱性火山岩组合（裴福萍等，2009；许文良等，2013），而小兴安岭－张广才岭地区存在同时代双峰式火成岩组合（唐杰等，2011；Yu *et al.*，2012；徐美君等，2013），推断早白垩世之前古太平洋板块俯冲影响的空间范围向西未达到大兴安岭地区，因此，排除了俯冲流体与其相关.

大兴安岭北段新生代玄武质岩石的起源深度约为120～150 km.然而，McKenzie and Bickle（1988）认为正常地温梯度下干的橄榄岩地幔熔融的前提条件是岩石圈厚度必须小于65～80 km，只有岩石圈减薄至该厚度时，对流软流圈绝热上升才能使地幔地热梯度和干固相线相交，导致亏损地幔来源的岩浆作用的产生（徐义刚，2006）.那么，大兴安岭北段新生代软流圈为什么会在如此厚的岩石圈下发生熔融呢？这可能与新生代玄武质岩浆的源区性质有关，新生代玄武质岩浆的源区为具有EMI特征的再循环地壳物质参与，属于易熔组分.地球物理资料显示地幔过渡带存在滞留的太平洋俯冲板片，再循环的地壳物质可能来自俯冲的太平洋板块（陈欢，2017）.此外，滞留的太平洋俯冲板片还可以造成玄武质岩浆源区水含量增加，降低熔融温度，从而使得软流圈成分发生熔融形成新生代碱性玄武岩.邵济安和张文兰（2008）将火山岩的地球化学填图和地震构造活动带结合，论证了NNW走向的小古里河－科洛－五大连池－二克山火山岩带是新生代初始的大陆裂谷，切穿了大兴安岭NNE向构造带，说明新生代玄武质岩浆的形成与陆内裂谷作用相关.

综上所述，大兴安岭北段早白垩世玄武质岩浆的形成与岩石圈伸展、减薄形成的裂陷作用相关，而新生代玄武质岩浆的形成则与陆内裂谷作用相关.

5 结论

（1）大兴安岭北段早白垩世玄武质岩浆起源于受早期俯冲流体交代的岩石圈地幔，新生代玄武质岩浆则起源于软流圈地幔.

（2）大兴安岭北段岩石圈厚度从中生代晚期到新生代逐渐增厚，这与该区地温梯度的显著降低相吻合.

（3）大兴安岭北段早白垩世玄武质岩浆的形成与岩石圈伸展、减薄形成的裂陷作用相关，而新生代玄武质岩浆的形成则与陆内裂谷作用相关.

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