

孙晶,蒋蕾茵,侯文.渤海湾盆地新生代玄武岩成因:地球化学和Sr-Nd-Hf-Pb同位素证据.吉林大学学报(地球科学版), 2024,54(2):531-545. doi:10.13278/j.cnki.jjuese.20230173.

Sun Jing, Jiang Lei Yin, Hou Wen. Petrogenesis of Cenozoic Basalts in Bohai Bay Basin: Geochemical and Sr-Nd-Hf-Pb Isotopic Evidences. Journal of Jilin University(Earth Science Edition), 2024,54(2):531-545. doi:10.13278/j.cnki.jjuese.20230173.

渤海湾盆地新生代玄武岩成因 ——地球化学和Sr-Nd-Hf-Pb同位素证据

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摘要:渤海湾盆地新生代玄武岩是华北克拉通东北部新生代玄武岩的重要组成部分,由于该地区的玄武岩在地表出露较少,之前的研究程度一直很低。本次研究在辽河油田选取了钻孔岩心样品,通过岩石学、地球化学、Sr-Nd-Hf-Pb同位素方法进行分析,探讨了新生代玄武岩的成因。结果表明:渤海湾盆地新生代玄武岩主要为玄武岩和粗面玄武岩,玄武岩的 $w(\text{SiO}_2)$ 为49.08%~50.70%, $w(\text{MgO})$ 为2.63%~5.80%,具有明显的轻重稀土元素分馏, $(\text{La}/\text{Yb})_{\text{N}}$ 和 $(\text{Dy}/\text{Yb})_{\text{N}}$ 值分别为7.96~11.61和1.71~1.84, Eu和Ce没有明显的负异常,高场强元素(HFSE)和大离子亲石元素(LILE)富集,具有明显的Nb、Ta和Sr正异常;全岩的Sr、Nd、Hf同位素比值($^{87}\text{Sr}/^{86}\text{Sr}$)_i值为0.704 622~0.706 581, $\epsilon_{\text{Nd}}(t)$ 值为1.1~1.9和 $\epsilon_{\text{Hf}}(t)$ 值为1.6~4.6, $(^{206}\text{Pb}/^{204}\text{Pb})_{\text{i}}$ 、 $(^{207}\text{Pb}/^{204}\text{Pb})_{\text{i}}$ 和 $(^{208}\text{Pb}/^{204}\text{Pb})_{\text{i}}$ 值分别为17.257 7~17.409 9、15.201 5~15.335 4和37.185 8~37.912 9,显示渤海湾盆地新生代玄武岩具有洋岛玄武岩(OIB)的地球化学特征和同位素组成。综合本文研究,表明渤海湾盆地新生代玄武岩是软流圈地幔低程度部分熔融的结果,且源区中地壳混染和分离结晶作用不显著。

关键词: 新生代;玄武岩;地球化学;地幔;渤海湾盆地

doi:10.13278/j.cnki.jjuese.20230173

中图分类号:P588.1;P597

文献标志码:A

Petrogenesis of Cenozoic Basalts in Bohai Bay Basin: Geochemical and Sr-Nd-Hf-Pb Isotopic Evidences

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Abstract: The Cenozoic basalts in the Bohai Bay basin are an important part of the Cenozoic basalts

收稿日期:2023-07-23

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基金项目:国家自然科学基金青年基金项目(41602045)

Supported by the National Natural Science Foundation of China (41602045)

in the northeast of the North China craton. However, the limited exposure of basalt on the surface in the region hinders research of this place. In this study, we selected drill core samples from Liaohe oil field and analyzed their major and trace elements, and Sr - Nd - Hf - Pb isotopic compositions. The Cenozoic basalts from the Bohai Bay basin in this study are mainly tholeiite and trachybasalt. Their SiO_2 and MgO contents are ranging from 49.08% to 50.70%, and 2.63% to 5.80%, respectively. Moreover, they are enriched in LREEs with highly fractionated LREEs and HREEs ($(\text{La}/\text{Yb})_{\text{N}} = 7.96 - 11.61$ and $(\text{Dy}/\text{Yb})_{\text{N}} = 1.71 - 1.84$). These samples are enriched in high field strength elements (HFSE) and large ion lithophile elements (LILE), with evidently positive Nb, Ta and Sr and without Eu and Ce anomalies. The Sr, Nd and Hf isotope ratios of the whole rock are $(^{87}\text{Sr}/^{86}\text{Sr})_{\text{i}} = 0.704622 - 0.706581$, $\epsilon_{\text{Nd}}(t) = 1.1 - 1.9$, $\epsilon_{\text{Hf}}(t) = 1.6 - 4.6$, respectively. The ratios of $(^{206}\text{Pb}/^{204}\text{Pb})_{\text{i}}$, $(^{207}\text{Pb}/^{204}\text{Pb})_{\text{i}}$ and $(^{208}\text{Pb}/^{204}\text{Pb})_{\text{i}}$ are 17.257 7 - 17.409 9, 15.201 5 - 15.335 4 and 37.185 8 - 37.912 9, respectively. All these characteristics are similar to those of the oceanic island basalts (OIBs). The geochemical features, combined with petrographic observations and Sr - Nd - Hf - Pb isotopic compositions, suggest weak crustal contamination and fractional crystallization in their origin. In conclusion, the Bohai Bay Cenozoic basalts were derived from slight partial melting of asthenospheric mantle.

Key words: Cenozoic; basalt; geochemistry; mantle; Bohai Bay basin

0 引言

玄武岩的化学成分和同位素组成可以用来反演地幔源区特征,探索地幔岩浆演化过程和地球深部特征^[1-2]。中、新生代时期,华北克拉通发育有大量的玄武质岩浆,为研究华北克拉通岩石圈地幔演化提供了样品^[3-9]。然而对于这些玄武岩的成因仍然存在较大的争议,其争论的焦点在于软流圈地幔^[10-11]与何种物质发生了反应,是与岩石圈地幔相互作用^[12-13],单纯的地幔柱成因^[14],还是地壳物质^[15-16]或俯冲洋壳物质^[17-20]加入。

前人^[3-9]对于华北克拉通新生代玄武岩的研究主要集中在出露地表的样品,而对于盆地中没有出露的样品则研究程度较低。本文选取了辽河油田的岩心样品——渤海湾盆地新生代玄武岩,通过对其进行岩石学、地球化学和 Sr - Nd - Hf - Pb 同位素的分析,讨论渤海湾盆地新生代玄武岩的地幔源区特征和岩石成因,以期研究华北克拉通东部玄武质岩浆的成因与演化提供重要的数据资料补充。

1 地质背景与岩石学特征

华北克拉通是世界上最经典的古老克拉通之一(3.8~2.5 Ga^[21-22]),也是中国东部最为重要的地质构造单元。其南北分别以苏鲁一大别造山带和中亚造山带为界,东西分别临太平洋板块和青藏高原东北部,由南北重力梯度带划分为东部和西部地块,并

在 1.85 Ga 时碰撞拼合^[23]。渤海湾盆地位于华北克拉通东北部,具有中国东部最薄的地壳和最高的地温梯度。辽河盆地位于渤海湾盆地的东北部(图 1a),郯庐断裂带的北段,是我国东部大型含油气裂谷盆地。辽河盆地的次级负向构造单元西部凹陷呈北东向展布^[24-25],发育大量中、新生代火山岩,具体采样位置见图 1b。

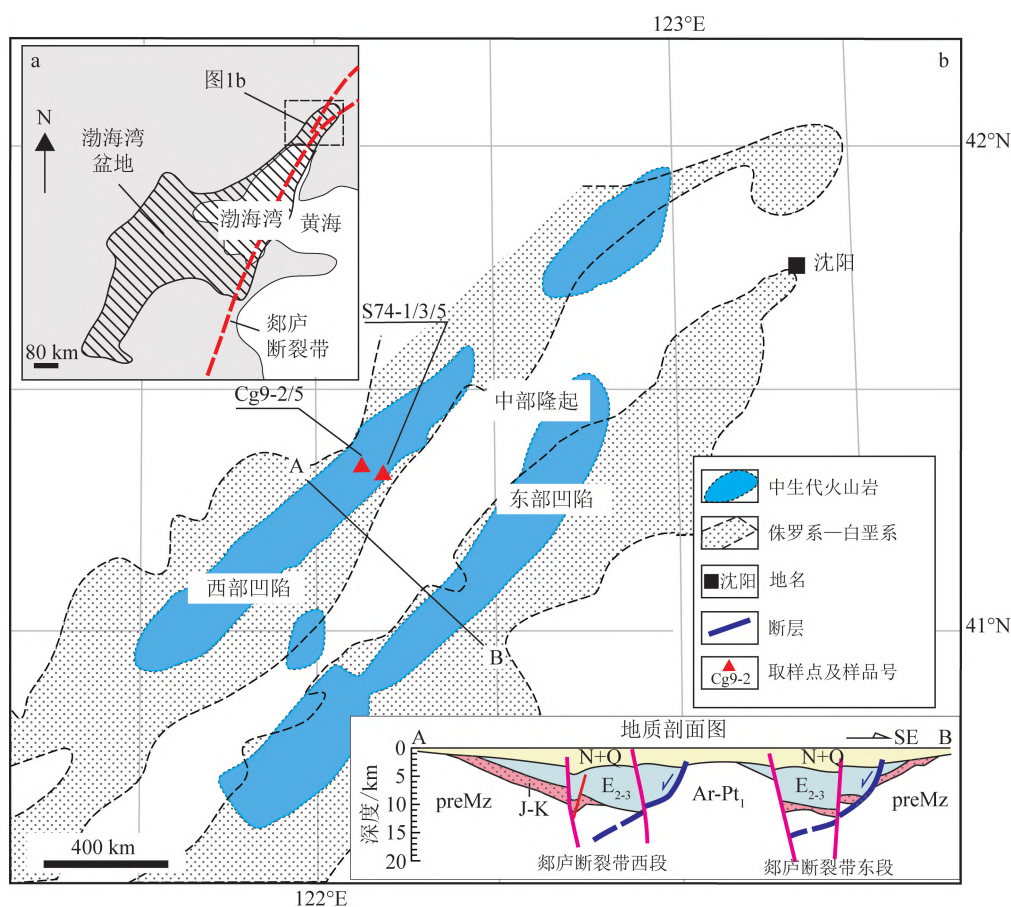
本文样品来自辽河西部凹陷北部的长古 9 号井(Cg9)和曙 74 号井(S74)共 5 件玄武岩岩心样品,所在地层为古近纪房身泡组(约 60 Ma),上覆地层为沙河街组四段。通过岩石学的观察(图 2),发现这些样品均具有气孔构造,斑状结构,斑晶主要为辉石、橄榄石和少量长石;基质为间粒结构、间隐结构,主要由斜长石、辉石、橄榄石和不透明矿物组成。

2 分析方法

对样品进行全岩的地球化学和 Sr - Nd - Hf - Pb 同位素分析,本文所有的测试分析都在南京聚谱检测科技有限公司完成。

2.1 全岩的主微量元素分析

玄武岩样品的全岩主量元素分析利用 X 荧光光谱(XRF)玻璃熔片分析法,用 AXIOS XRF 仪器(PANalytical 公司,顺序式 X-射线荧光光谱仪)进行测试。元素质量分数的不同分析精度不同,分析精度在 1% ~ 5% 之间。全岩的微量元素分析采用混合酸溶样法,测试用的仪器为 Agilent



Ar-Pt₁. 太古宇—古元古界;preMz. 前中生界;J-K. 侏罗系—白垩系;E₂₋₃. 始新统一渐新统;N+Q. 新近系—第四系。

图1 渤海湾盆地分布图(a)与辽河盆地新生代玄武岩和次级负向构造单元图(b)

Fig.1 Map of Bohai Bay basin (a) and Cenozoic basalts and secondary negative structural units in Liaohe basin (b)

7500a 型四级杆电感耦合等离子体质谱仪(ICPMS),其分析精度优于 $\pm 10\%$ 。

2.2 全岩的 Sr-Nd-Hf-Pb 同位素分析

岩石样品的 Sr-Nd-Hf-Pb 同位素分析前处理的详细步骤参照文献[26],元素质量分数和同位素比值分别在 Agilent 7700x 四极杆型 ICP-MS 和 Nu Plasma II MC-ICP-MS 上测定。同位素比值测试时分别选取 NIST SRM 987、JNdi-1、NIST SRM 981 和 Alfa Hf 作为 Sr、Nd、Pb、Hf 的外标来校正仪器的漂移。仪器质量分馏校正采用 $^{86}\text{Sr}/^{88}\text{Sr}=0.1194$, $^{146}\text{Nd}/^{144}\text{Nd}=0.7219$, $^{205}\text{Tl}/^{203}\text{Tl}=2.3885$, $^{179}\text{Hf}/^{177}\text{Hf}=0.7325$ 。玄武岩 BCR-2、玄武岩 BHVO-2、安山岩 AGV-2 是整个化学和分析测试流程中的监测标样,在化学前处理和质谱测定中都有跟踪测试。在本次实验中,这些标样的 Sr-Nd-Hf-Pb 同位素比值实测值与文献[27]报道值在误差范围内一致,说明本次实验样品的测试

结果是准确的。

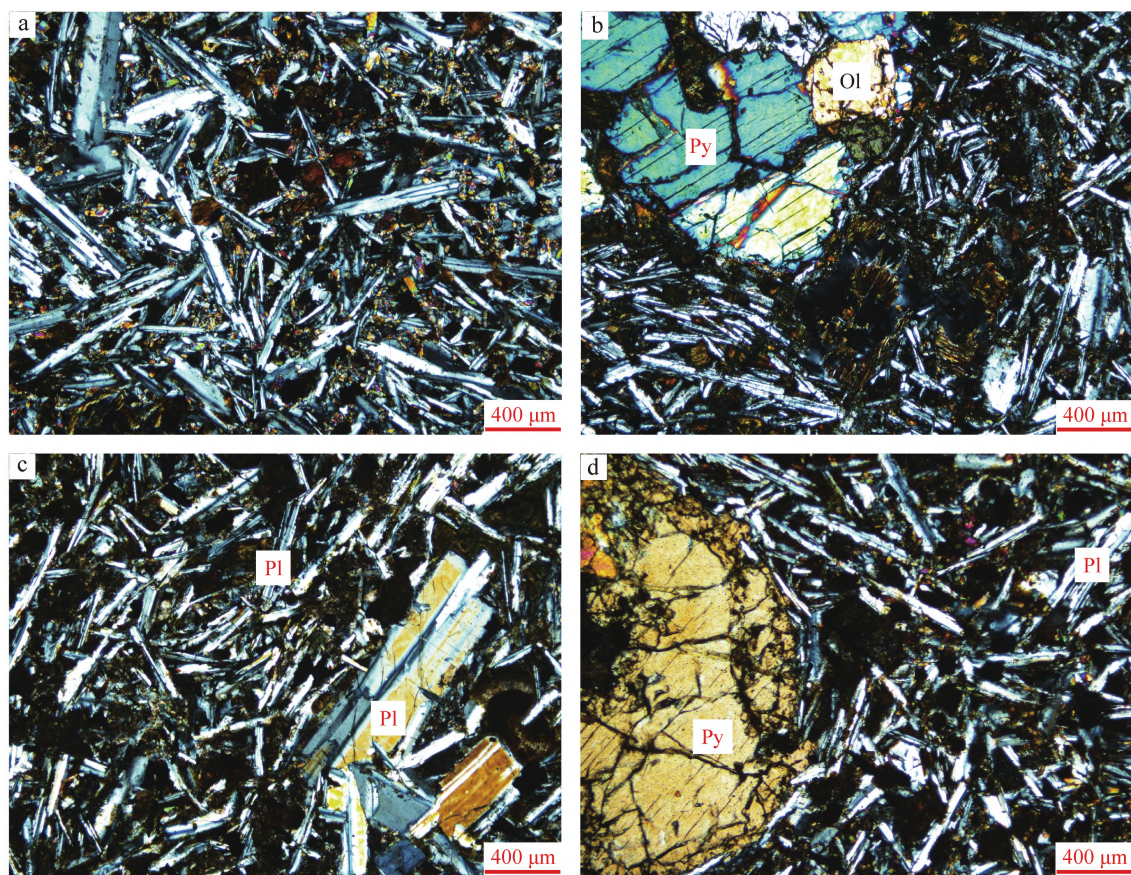
3 分析结果

3.1 全岩的主量元素特征

渤海湾盆地新生代玄武岩全岩的主量元素分析结果见表1。从 TAS(图3)图解中可以看出渤海湾盆地新生代玄武岩落在了粗面玄武岩和玄武岩区域,且 $w(\text{Na}_2\text{O})$ 大于 $w(\text{K}_2\text{O})$ (表1)。通过 CIPW 标准矿物计算,岩石中含有石英、钙长石、正长石和透辉石而无橄榄石和霞石。全岩 $w(\text{SiO}_2)$ 为 $49.08\%\sim 50.70\%$, $w(\text{TiO}_2)$ 为 $1.42\%\sim 2.14\%$, $w(\text{K}_2\text{O}+\text{Na}_2\text{O})$ 为 $4.51\%\sim 5.16\%$, $\text{Na}_2\text{O}/\text{K}_2\text{O}$ 值为 $1.46\sim 2.05$,全铁(TFe_2O_3)为 $7.55\%\sim 12.04\%$, $\text{Mg}^\#$ 为 $54.96\sim 69.63$ 。

3.2 全岩的微量元素特征

渤海湾盆地新生代玄武岩全岩的微量元素分析结果见表1,稀土元素球粒陨石标准化配分曲线和



Py. 辉石; Ol. 橄榄石; Pl. 斜长石。

图2 渤海湾盆地新生代玄武岩显微照片

Fig.2 Microphotographs of Cenozoic basalt in Bohai Bay basin

微量元素原始地幔标准化蛛网图解见图4。渤海湾盆地新生代玄武岩全岩的稀土总量为 $87.35 \times 10^{-6} \sim 134.07 \times 10^{-6}$, 具有轻稀土元素富集、重稀土元素亏损的右倾稀土元素球粒陨石标准化配分曲线(图4a)特征, 且轻、重稀土元素分馏强烈, $(La/Yb)_N$ 和 $(Dy/Yb)_N$ 的比值分别为 $7.96 \sim 11.61$ 和 $1.71 \sim 1.78$, 无明显的 Eu 和 Ce 负异常。在微量元素原始地幔标准化蛛网图(图4b)中可以看出, 渤海湾盆地新生代玄武岩富集高场强元素(HFSE, 如 Ti、Zr、Hf 等)和大离子亲石元素(LILE, 如 Rb、Sr、Ba、Th、U 等), 具有明显的 Sr、Nb 和 Ta 正异常, Hf 显示出弱的负异常, 其中 $Nb/U = 27.76 \sim 49.87$, $La/Nb = 0.66 \sim 0.73$, $Ba/Nb = 9.22 \sim 21.55$ 。

3.3 全岩的 Sr - Nd - Hf - Pb 同位素特征

玄武岩样品的全岩 Sr - Nd - Hf - Pb 同位素结果见表2。渤海湾盆地新生代玄武岩的 Nd 同位素组成具有较小的变化范围($\epsilon_{Nd}(t) = 1.1 \sim 1.9$); 相比之下, Sr 和 Hf 同位素比值变化范围较大, ($^{87}Sr/$

^{86}Sr)_i = $0.704622 \sim 0.706581$, $\epsilon_{Hf}(t) = 1.6 \sim 4.6$ 。在同位素二元相关图(图5)中, 渤海湾盆地新生代玄武岩的 Sr、Nd 和 Hf 同位素都落在了 OIB(洋岛玄武岩)内, 且 $\epsilon_{Hf}(t)$ 与 $\epsilon_{Nd}(t)$ 呈弱的正相关并与地幔演化趋势线重合。

渤海湾盆地新生代玄武岩5个样品的 $(^{206}Pb/^{204}Pb)_i$ 、 $(^{207}Pb/^{204}Pb)_i$ 和 $(^{208}Pb/^{204}Pb)_i$ 值分别为 $17.2577 \sim 17.4099$, $15.2015 \sim 15.3354$ 和 $37.1858 \sim 37.9129$ 。从 $(^{208}Pb/^{204}Pb)_i - (^{206}Pb/^{204}Pb)_i$ 图(图6)可见, 这些样品基本落在汉诺坝范围内, 且均落在 NHRL(北半球参考线)附近。

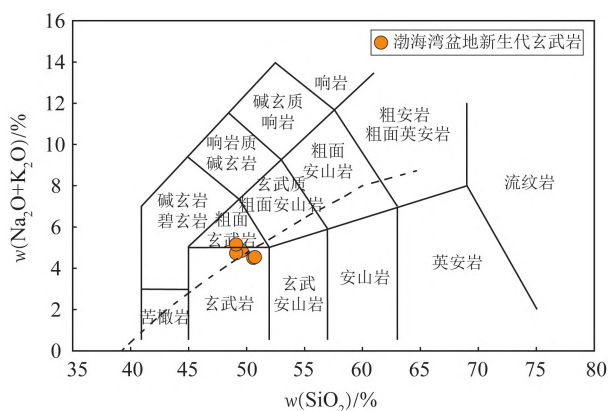
4 讨论

大陆玄武岩可能是部分熔融、分离结晶、地壳混染或它们共同作用的结果^[7,43]。本文将根据渤海湾盆地新生代玄武岩的地球化学特征和 Sr - Nd - Hf - Pb 同位素组成, 讨论渤海湾盆地新生代玄武岩的岩浆源区特征以及其经历的熔融程度。

表 1 渤海湾盆地新生代玄武岩主、微量元素质量分数组成^[28]
Table 1 Major and trace element compositions of Cenozoic basalt from Bohai Bay basin^[28]

样品号	岩石类型	SiO ₂	TiO ₂	Al ₂ O ₃	TF _{e2} O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	烧失量	总和	Mg [#]	
S74-1	玄武岩	49.57	2.14	16.27	7.55	0.09	2.63	11.64	2.88	1.97	0.46	4.71	99.91	58.24	
S74-3	玄武岩	50.70	2.10	15.40	9.55	0.10	5.44	8.49	2.92	1.62	0.45	3.22	99.98	69.51	
S74-5	玄武岩	49.09	2.04	15.21	11.20	0.07	5.56	5.74	2.82	1.92	0.40	5.86	99.91	66.51	
Cg9-2	玄武岩	50.56	2.13	14.82	10.11	0.09	5.80	7.57	2.80	1.71	0.46	3.82	99.87	69.63	
Cg9-5	泥化玄武岩	49.08	1.42	15.17	12.04	0.11	3.67	7.15	3.47	1.69	0.23	5.83	99.86	54.96	
样品号	岩石类型	V	Co	Ni	Ga	Rb	Ba	Th	U	Nb	Ta	La	Ce	Sr	Nd
S74-1	玄武岩	222.20	48.52	86.82	21.09	26.42	504.37	2.81	0.73	36.52	2.08	25.20	50.19	747.63	25.16
S74-3	玄武岩	221.57	44.33	91.46	20.37	21.72	366.28	2.76	0.84	35.88	2.09	25.49	50.61	642.73	25.49
S74-5	玄武岩	218.88	40.58	84.48	21.01	29.26	400.55	2.78	1.02	36.51	2.08	24.04	47.25	673.62	23.09
Cg9-2	玄武岩	226.95	44.63	85.68	20.61	21.95	353.55	2.83	0.84	38.33	2.18	26.20	52.48	602.71	26.54
Cg9-5	泥化玄武岩	176.40	53.33	170.88	19.40	32.49	498.43	1.71	0.83	23.13	1.20	16.84	32.89	463.79	16.83
样品号	岩石类型	Zr	Hf	Sm	Eu	Ti	Gd	Tb	Ho	Er	Y	Yb	Lu	(La _a /Yb) _N	(Dy/Yb) _N
S74-1	玄武岩	188.32	3.90	5.38	1.82	13 624.11	5.06	0.76	0.82	2.08	23.05	1.71	0.23	3.45	134.07
S74-3	玄武岩	185.13	4.00	5.50	1.83	13 505.38	5.33	0.78	0.88	2.19	24.49	1.82	0.26	3.12	127.39
S74-5	玄武岩	198.67	4.03	4.87	1.66	13 557.18	4.55	0.66	0.72	1.77	20.12	1.43	0.20	3.64	129.38
Cg9-2	玄武岩	194.06	4.15	5.71	1.92	14 157.76	5.55	0.81	0.90	2.26	25.11	1.86	0.27	3.19	118.49
Cg9-5	泥化玄武岩	146.31	3.02	3.90	1.39	9 319.14	4.14	0.62	0.73	1.78	20.79	1.46	0.20	3.46	87.35

注:主量元素质量分数单位为%;微量元素质量分数单位为10⁻⁶。



虚线为碱性及亚碱性系列分界线。

图3 渤海湾盆地新生代玄武岩 $w(\text{Na}_2\text{O} + \text{K}_2\text{O}) - w(\text{SiO}_2)$ 图

Fig.3 Plots of $w(\text{Na}_2\text{O} + \text{K}_2\text{O})$ vs. $w(\text{SiO}_2)$ diagram for Cenozoic basalts in Bohai Bay basin

4.1 地壳混染作用

从深部地幔上升至地表的过程中,玄武质岩浆会穿过大陆地壳,这一过程可能会遭受到地壳混染作用的影响^[47]。因此,在利用地球化学和同位素数据讨论源区特征之前,需要确定样品受到地壳混染作用影响的程度。

前人^[48]的研究结果显示, Th/La 和 La/Nb 值可以有效地确定玄武岩是否受到了地壳混染作用的影响。大陆地壳的 Th/La 平均值为 0.15,渤海湾盆地新生代玄武岩的 Th/La 值为 0.10~0.12,明显低于大陆地壳的平均值。它们的 La/Nb 值为 0.66~0.73,也明显低于中国东部大陆地壳的 La/Nb 值 1.7。同时,大陆地壳以 Nb、Ta 和 Ti 亏损为特征^[29],

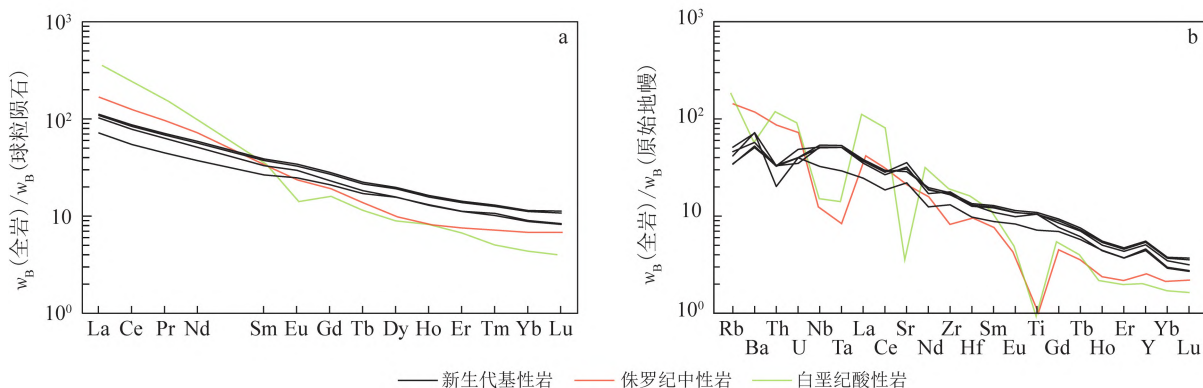
且具有较低的 Nb 和 Ta 质量分数,而渤海湾新生代玄武岩具有富集的 Nb、Ta,在微量元素原始地幔标准化蛛网图中呈现出正异常,与大陆地壳的特征不一致。这些地球化学特征都说明渤海湾新生代玄武岩所受到的地壳混染作用的影响程度较小。

4.2 分离结晶作用

从岩相学观察可以看出,玄武岩样品斑晶中含有橄榄石和辉石,这暗示着渤海湾盆地的玄武岩岩浆曾经历过橄榄石和辉石的分离结晶作用^[7]。从图7中也可以看出样品的强不相容元素与 Th 之间呈现较好的线性相关性,加上全岩的 $\text{Mg}^\#$ 为 54.96~69.63,说明岩浆在演化过程中经历了一定程度的分离结晶作用。但是,渤海湾盆地新生代玄武岩并没有明显的 Eu 负异常(图4),这说明斜长石没有大量晶出^[49]。同时,渤海湾盆地新生代玄武岩全岩的 $w(\text{MgO})$ 较低,且 $w(\text{Ni})$ 不随 $w(\text{MgO})$ 变化,暗示着橄榄石的分离结晶作用较弱。虽然我们没有进行 Cr 元素的分析,无法判断辉石的分离结晶作用程度,但是从岩相学和全岩的地球化学组成上分析,渤海湾盆地新生代玄武岩并没有经历非常强烈的分离结晶作用。

4.3 岩浆源区特征

通过前文的讨论,可以看出渤海湾盆地新生代玄武岩在形成过程中经历过较弱的地壳混染作用和分离结晶作用,这说明该地区新生代玄武岩样品的地球化学和同位素特征可以代表其原始岩浆的成分,可以用来反映该地区岩浆的源区特征和部分熔融条件。渤海湾盆地新生代玄武岩具较高的 $w(\text{TiO}_2)$ (1.42%~2.14%) 和 $w(\text{TFe}_2\text{O}_3)$ (7.55%~



球粒陨石、原始地幔数据来源于文献^[29];渤海湾盆地侏罗纪和白垩纪岩石数据来源于文献^[30]。

图4 渤海湾盆地新生代玄武岩稀土元素球粒陨石标准化配分曲线(a)和微量元素原始地幔标准化蛛网图(b)

Fig.4 Rare earth element (REE) patterns (a) and spider diagrams (b) for Cenozoic basalts in Bohai Bay basin

表 2 渤海湾盆地新生代玄武岩 Sr - Nd - Hf - Pb 同位素组成

Table 2 Sr - Nd - Hf - Pb isotopic compositions of Cenozoic basalt from Bohai Bay basin

样品号	$^{87}\text{Rb}/^{86}\text{Sr}$	$(^{87}\text{Sr}/^{86}\text{Sr})_{\text{m}}$	σ	$(^{87}\text{Sr}/^{86}\text{Sr})_{\text{i}}$	$^{147}\text{Sm}/^{144}\text{Nd}$	$(^{143}\text{Nd}/^{144}\text{Nd})_{\text{m}}$	σ	$(^{143}\text{Nd}/^{144}\text{Nd})_{\text{i}}$	$\epsilon_{\text{Nd}}(t)$	T_{DM}/Ma
S74-1	0.102 21	0.705 944	0.000 003	0.705 857	0.129 3	0.512 666 1	0.000 000 3	0.512 615 4	1.1	877
S74-3	0.097 74	0.705 162	0.000 004	0.705 078	0.130 3	0.512 701 9	0.000 000 4	0.512 650 7	1.8	822
S74-5	0.125 65	0.706 069	0.000 002	0.705 962	0.127 4	0.512 697 6	0.000 000 2	0.512 647 6	1.7	802
Cg9-2	0.105 34	0.704 712	0.000 003	0.704 622	0.129 9	0.512 690 7	0.000 000 4	0.512 639 7	1.5	839
Cg9-5	0.202 61	0.706 754	0.000 003	0.706 581	0.140 1	0.512 713 8	0.000 000 5	0.512 658 8	1.9	906

样品号	$^{176}\text{Lu}/^{177}\text{Hf}$	$(^{176}\text{Hf}/^{177}\text{Hf})_{\text{m}}$	σ	$\epsilon_{\text{Hf}}(t)$	T_{DM}/Ma	$(^{206}\text{Pb}/^{204}\text{Pb})_{\text{i}}$	σ	$(^{207}\text{Pb}/^{204}\text{Pb})_{\text{i}}$	σ	$(^{208}\text{Pb}/^{204}\text{Pb})_{\text{i}}$	σ
S74-1	0.008 51	0.282 810	0.000 003	2.3	981	17.274 9	0.003 7	15.267 8	0.004 8	37.772 8	0.015 6
S74-3	0.009 29	0.282 857	0.000 002	3.9	879	17.257 7	0.003 7	15.201 5	0.004 9	37.493 0	0.016 2
S74-5	0.007 04	0.282 789	0.000 002	1.6	1 025	17.395 3	0.014 9	15.335 3	0.014 5	37.826 1	0.041 5
Cg9-2	0.009 39	0.282 852	0.000 002	3.8	889	17.409 9	0.003 9	15.335 4	0.005 1	37.912 9	0.016 8
Cg9-5	0.009 57	0.282 876	0.000 002	4.6	836	17.405 8	0.004 8	15.329 1	0.006 2	37.185 8	0.020 1

注:下标 m 表示测量值; $t=60\text{ Ma}$ 。

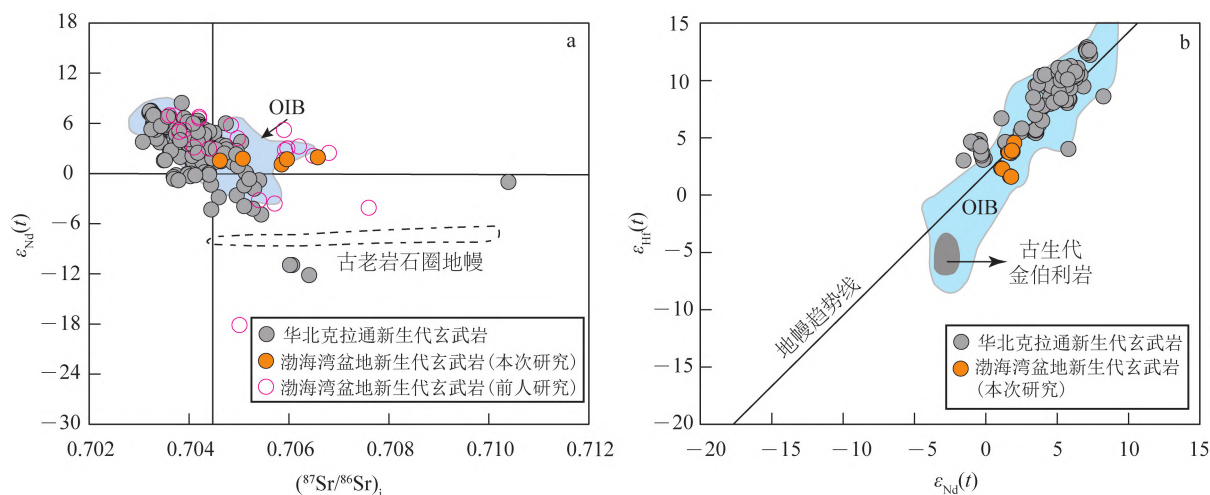
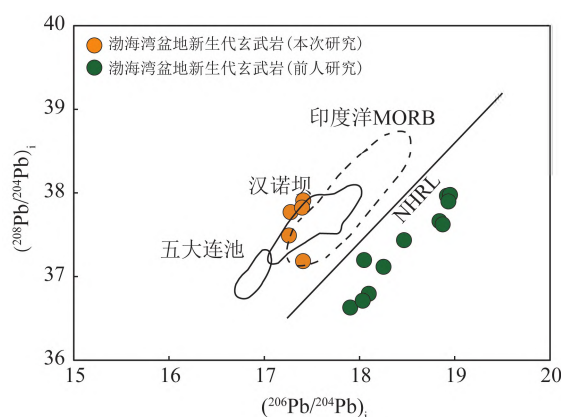


图5 渤海湾盆地新生代玄武岩 $\epsilon_{\text{Nd}}(t)$ -($^{87}\text{Sr}/^{86}\text{Sr}$)_i 相关图(a)和 $\epsilon_{\text{Hf}}(t)$ - $\epsilon_{\text{Nd}}(t)$ 相关图(b)

Fig.5 $\epsilon_{\text{Nd}}(t)$ vs. ($^{87}\text{Sr}/^{86}\text{Sr}$)_i (a) and $\epsilon_{\text{Hf}}(t)$ vs. $\epsilon_{\text{Nd}}(t)$ (b) diagrams of basalts from Bohai Bay basin



印度洋 MORB 数据文献[38-39];NHRL 数据文献[40];五大连池玄武岩数据文献[41-42];汉诺坝玄武岩数据文献[11, 43-46];渤海湾盆地新生代玄武岩数据文献[34-35]。

图6 渤海湾盆地新生代玄武岩 ($^{208}\text{Pb}/^{204}\text{Pb}$)_i-($^{206}\text{Pb}/^{204}\text{Pb}$)_i 图解

Fig.6 ($^{208}\text{Pb}/^{204}\text{Pb}$)_i vs. ($^{206}\text{Pb}/^{204}\text{Pb}$)_i diagrams for basalts from Bohai Bay basin

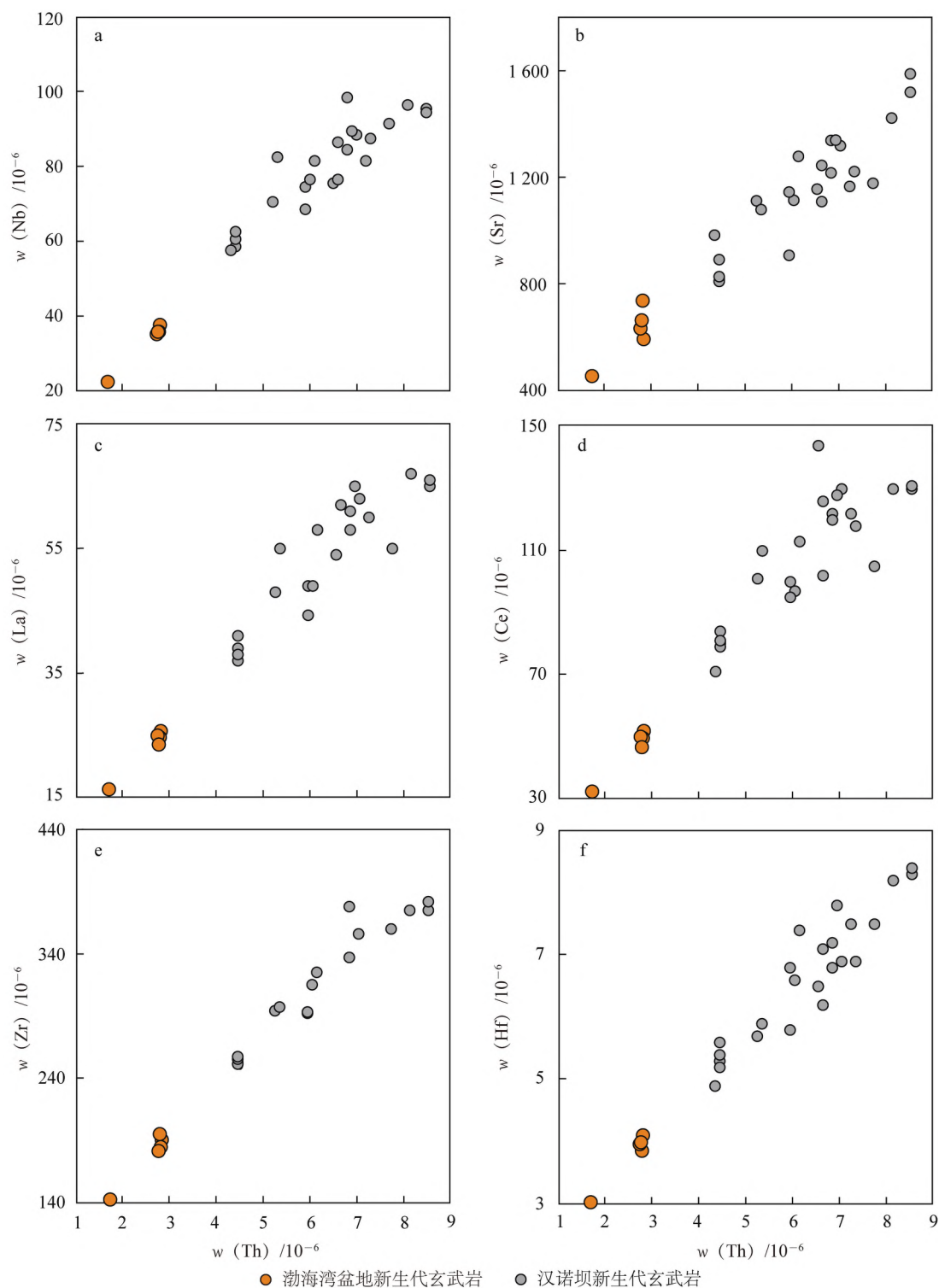
12.04‰), 暗示着它们的地幔源区相对饱满且未经经历大程度熔体的抽离^[50-51]。渤海湾盆地新生代玄武岩的 ($^{87}\text{Sr}/^{86}\text{Sr}$)_i 值、 $\epsilon_{\text{Nd}}(t)$ 和 $\epsilon_{\text{Hf}}(t)$ 值分别为 0.704 622~0.706 581, 1.1~1.9, 1.6~4.6, 呈现不均一的亏损同位素组成特征。在 $\epsilon_{\text{Nd}}(t)$ -($^{87}\text{Sr}/^{86}\text{Sr}$)_i (图 5a)、 $\epsilon_{\text{Hf}}(t)$ - $\epsilon_{\text{Nd}}(t)$ (图 5b) 和 ($^{208}\text{Pb}/^{204}\text{Pb}$)_i-($^{206}\text{Pb}/^{204}\text{Pb}$)_i 同位素图解(图 6)上, 渤海湾盆地新生代玄武岩与华北克拉通东部地区新生代玄武岩一

样都落在汉诺坝和 OIB 所在的区域内, 结合它们富集 Rb、Ba 等大离子亲石元素和 Nb、Ta、Ti 等高场强元素的特征, 显示了软流圈地幔的源区属性, 且没有受到地壳物质混染和俯冲带的影响, 暗示其形成于板内构造环境。

4.4 熔融程度与深度

玄武岩的硅饱和程度与岩浆的部分熔融深度有关^[52-53], 实验岩石学得出硅饱和的拉斑玄武岩浆产生的压力要低于硅不饱和的碱性岩浆^[52, 54-55]。前人^[56]的研究显示, 华北克拉通碱性玄武岩的源区深度 > 80 km, 而拉斑玄武岩的源区深度为 50~60 km。渤海湾盆地新生代玄武岩为粗面玄武岩和玄武岩, 介于碱性和亚碱性玄武岩之间, 说明这些玄武岩的熔融深度可能存在一定的差异, 这些差异可能暗示着地幔源区的不均一性。

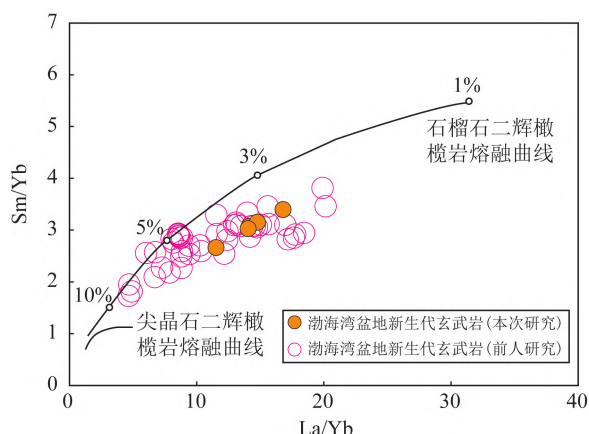
渤海湾盆地新生代玄武岩的轻、重稀土元素强烈分馏, (La/Yb)_N=7.96~11.61, (Dy/Yb)_N=1.71~1.84, 暗示着其源区有石榴石的残留。Yb 在石榴石中为相容元素, La、Sm 是不相容元素, 这也表明源区中石榴石相橄榄岩部分熔融程度越低, 对应的 La/Yb 和 Sm/Yb 值变化越大; 与之相反, 尖晶石相橄榄岩在部分熔融作用中表现出来的 La/Yb 值变化较小, Sm/Yb 值基本不变^[12, 57-58]。因此, Sm/Yb-La/Yb 图解(图 8)可以用于区分玄武岩是来自石榴石相橄榄岩源区还是尖晶石相橄榄岩源区的部分熔融^[12]。从图 8 中可以看出, 该地区的玄武岩落在



汉诺坝新生代玄武岩数据据文献[11]。

图7 渤海湾盆地新生代玄武岩不相容元素与 $w(\text{Th})$ 的关系图

Fig.7 Incompatible elements vs. $w(\text{Th})$ contents of Bohai Bay basin Cenozoic basalts



图中曲线上方数字为熔融比例;底图据文献[59];渤海湾盆地新生代玄武岩数据据文献[34-36,60];熔融比例据文献[61]。

图8 渤海湾盆地新生代玄武岩 Sm/Yb - La/Yb 图解

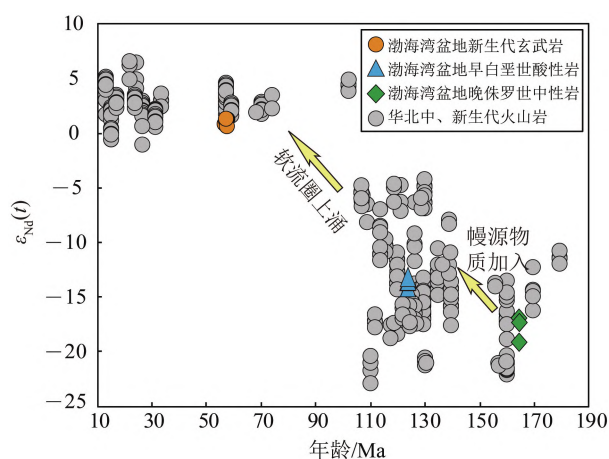
Fig.8 Sm/Yb vs. La/Yb for Bohai Bay basin Cenozoic basalts

了石榴石二辉橄榄岩熔融模拟曲线附近,且熔融的程度为3%~5%。因此,渤海湾盆地新生代玄武岩是石榴石相二辉橄榄岩经过3%~5%部分熔融的结果,且玄武岩来源深度存在一定的差异。

4.5 地球动力学

自中、新生代以来,渤海湾盆地共发育3期岩浆活动,分别为晚侏罗世(165 Ma)的中性火山岩、早白垩世(122 Ma)的长英质火山岩和新生代的玄武岩。从稀土元素球粒陨石标准化配分曲线(图4a)可以看出,侏罗纪中性火山岩亏损重稀土元素且没有明显的Eu负异常,说明岩浆源区有石榴石且没有斜长石的残留,意味着渤海湾盆地此时的地壳厚度在晚侏罗世大于50 km。早白垩世长英质火山岩亏损重稀土元素、具有明显的Eu负异常,暗示着石榴石和斜长石在其源区都有残留,意味着渤海湾盆地在此时地壳变薄,为30~50 km^[30]。到了新生代,玄武岩没有明显的Eu负异常,岩浆的形式逐渐转变为OIB型。同样,从同位素中也可以看出从侏罗纪到白垩纪再到新生代岩浆性质的变化。在Nd同位素与年龄的图解(图9)中可以看出,从侏罗纪到新生代, $\epsilon_{Nd}(t)$ 值显著增加,岩浆从富集型转变为亏损型,反映了地幔物质逐渐加入到了岩浆中的演化过程^[28]。渤海湾盆地3期火山岩的这些特征与华北克拉通东部地区中、新生代岩浆的特征基本一致,说明华北克拉通东部在白垩纪大规模减薄后,到了新生代,软流圈物质突破了岩石圈厚度的限制,不断上涌形成玄武岩。前人^[35]对中国东部及邻区大

地构造环境的研究也表明,在新生代中国濒太平洋区域的主要构造热事件是陆内伸展扩张作用,渤海湾盆地就是在这一事件中形成的伸展盆地^[75],渤海湾盆地新生代的玄武质岩浆就是在区域伸展构造体制下快速上升喷发形成的。



底图据文献[28];渤海湾盆地中生代数据据文献[30];华北中、新生代火山岩数据据文献[62-74]。

图9 渤海湾盆地中、新生代火山岩的Nd同位素组成

Fig.9 Nd isotopic compositions of Mesozoic-Cenozoic volcanic rocks from Bohai Bay basin

5 结论

1)渤海湾盆地新生代玄武岩为粗面玄武岩和玄武岩,具有类似于OIB的地球化学特征,表明它们可能起源于软流圈地幔源区。

2)渤海湾盆地新生代玄武岩未受到明显的地壳混染和分离结晶作用的影响。

3)渤海湾盆地新生代玄武岩全岩的地球化学和Sr-Nd-Hf-Pb同位素组成显示,该地区新生代的玄武岩是石榴石相橄榄岩经小程度(3%~5%)部分熔融而形成的。

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