

# 华北陆块北部燕山地区中元古代辉绿岩 地球化学特征及成因意义

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**摘要:**华北陆块北部燕山地区广泛发育侵位于下马岭组的一套辉绿岩岩床。其岩石地球化学特征表明,燕山地区辉绿岩以高 $TiO_2$ (1.70%~4.29%),低 $Al_2O_3$ (11.33%~14.98%)和低 $MgO$ (4.17%~5.86%),以及 $Na_2O > K_2O$ 为特征,属大陆拉斑玄武岩系列。稀土元素特征显示, $\Sigma REE$ 总量较高,LREE明显富集,轻重稀土分馏不明显;配分曲线右倾,无明显Eu异常。结合Zr-Y、Zr-Nd、Zr/Y-Zr、Ti/100-Zr-Y $\times 3$ 、Ta/Hf-Th/Hf及Nb/Zr-Th/Zr等图解综合分析认为:该辉绿岩岩浆源自过渡性地幔,形成于华北陆块北部中元古代晚期的板内伸展构造背景。

**关键词:**辉绿岩;地球化学;中元古代;华北陆块;燕山地区

**中图分类号:**P584;P595 **文献标志码:**A **文章编号:**1000-3657(2014)02-0351-10

华北陆块北部的燕辽拗拉槽内发育有全球范围内最为连续的中元古代地层剖面,该剖面不仅是中国中元古代地层的标准剖面,也是世界上罕见的晚前寒武纪完整地层剖面。近年来,基于中新元古代地层中侵入体的一系列高精度锆石U-Pb定年数据<sup>[1-5]</sup>,使华北陆块中新元古代几次关键热-构造事件得以深入探讨,尤其是中元古代晚期侵入燕山地区下马岭组中的基性岩床(辉绿岩床),引起了地学界的广泛关注。前人获取了该辉绿岩及下马岭组凝灰岩的锆石U-Pb年龄<sup>[1-4]</sup>,缺少利用地球化学特征探究岩浆起源及构造背景方面的研究。本文拟通过主微量元素地球化学特征来探讨该基性岩床的岩浆起源及其构造背景,以期对中元古代末—新元古代初华北陆块是否参与了Columbia超大陆裂解至Rodinia超大陆汇聚提供线索。

## 1 区域地质背景与样品描述

研究区位于华北陆块北部燕辽拗拉槽中段,地理位置为河北省承德县大范杖子一带。区内广泛

出露中—新元古代长城系、蓟县系、青白口系,岩性主要为一套厚度巨大的碎屑岩和海相富镁碳酸盐岩夹少量碱性玄武岩和粗安岩,地层序列清楚且基本未受变质作用影响,古生物化石丰富<sup>[6-8]</sup>。古生界寒武系、奥陶系分布较为局限,主要分布于宋营一带,岩性主要为一套浅海—潮坪相的海相碳酸盐岩地层。中生界侏罗系南大岭组、下花园组、髫髻山组、九龙山组分布于研究区中部,主要为一套成分复杂的陆相火山沉积地层。侵入岩主要有侵入下马岭组的辉绿岩(床)和侵入中生代地层的石英正长斑岩。

辉绿岩样品采自河北省承德县石灰窑乡大范杖子—东梁一带,位于承德市东偏南28 km(图1),地理坐标:N40°51'13",E118°19'20"。辉绿岩(床)顺层侵入下马岭组灰黑色页岩、粉砂质页岩,共发育3层,其产状和围岩完全一致,界线平直,厚度15~100 m,延伸8 km左右。李怀坤等<sup>[4]</sup>曾获取该基性岩锆石SHRIMP U-Pb年龄为(1320±6) Ma,陆松年等<sup>[9]</sup>将其侵位年龄置于1320~1350 Ma,说明该基性

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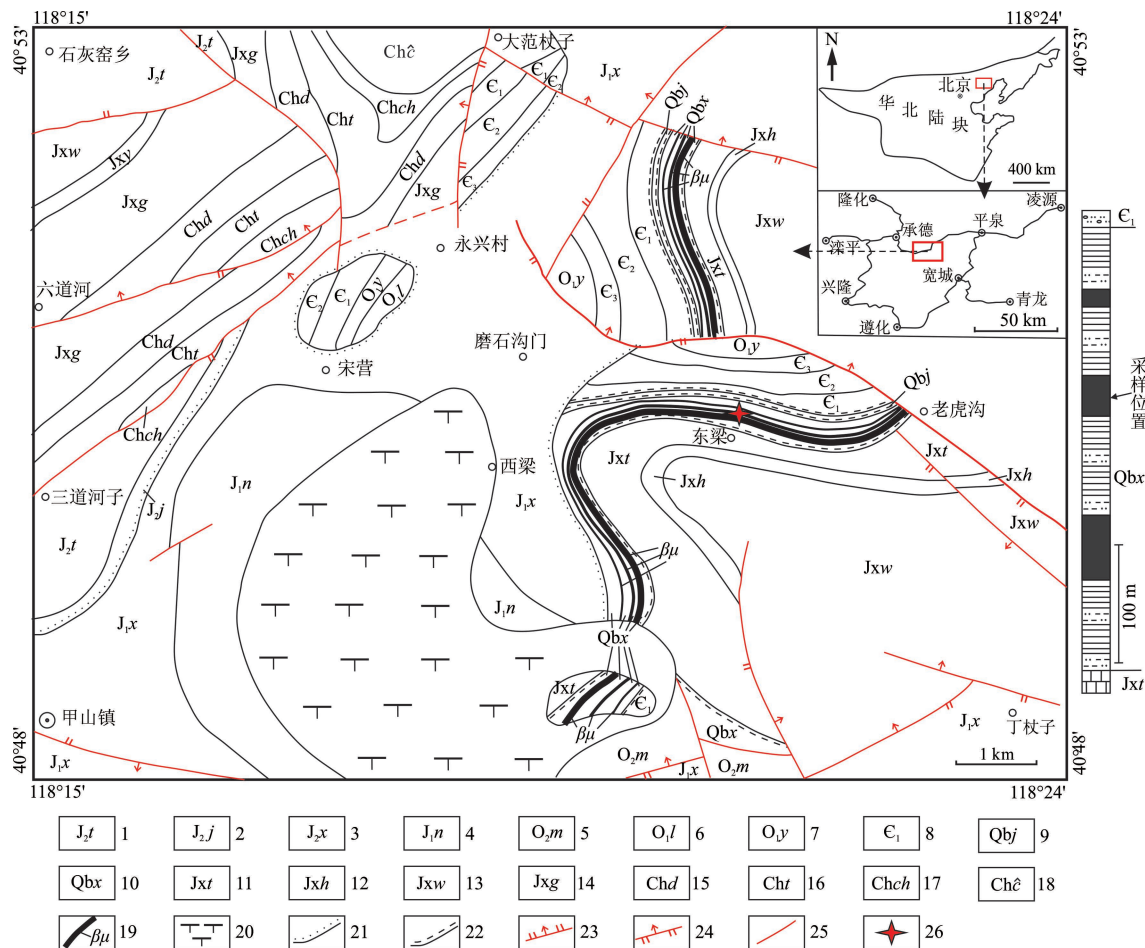


图1 燕山地区大范杖子一带地质略图(据1:20万平泉幅<sup>①</sup>修编)

- 1—侏罗系髫髻山组;2—侏罗系九龙山组;3—侏罗系下花园组;4—侏罗系南大岭组;5—奥陶系马家沟组;
- 6—奥陶系亮甲山组;7—奥陶系冶里组;8—寒武系(含C<sub>1</sub>、C<sub>2</sub>、C<sub>3</sub>);9—青白口系景儿峪组;10—青白口系下马岭组;
- 11—蓟县系铁岭组;12—蓟县系洪水庄组;13—蓟县系雾迷山组;14—蓟县系高于庄组;15—长城系大红峪组;
- 16—长城系团山子组;17—长城系申岭沟组;18—长城系常州沟组;19—辉绿(玢)岩;20—石英正长斑岩;
- 21—角度不整合界线;22—平行不整合界线;23—正断层;24—逆断层;25—性质不明断层;26—取样位置

Fig.1 Geological sketch map of diabase in Dafanzhangzi, Yanshan Mountain area(modified after reference ①)

- 1—Jurassic Tiaojishan Formation; 2—Jurassic Jiulongshan Formation; 3—Jurassic Xiahuayuan Formation; 4—Jurassic Nandaling Formation; 5—Ordovician Majiagou Formation; 6—Ordovician Liangjiashan Formation; 7—Ordovician Yeli Formation;
- 8—Cambrian; 9—Qingbaikouan Jingeryu Formation; 10—Qingbaikouan Xiamaling Formation; 11—Jixianian Tieling Formation; 12—Jixianian Hongshuizhuang Formation; 13—Jixianian Wumishan Formation; 14—Jixianian Gaoyuzhuang Formation;
- 15—Changchengian Dahongyu Formation; 16—Changchengian Tuanshanzi Formation; 17—Changchengian Chuanlinggou Formation; 18—Changchengian Changzhougou Formation; 19—Diabase; 20—Quartz orthophyre; 21—Angular unconformity;
- 22—parallel unconformity; 23—Normal fault; 24—Reverse fault; 25—Undefined fault; 26—Sampling location

岩形成时代为中元古代晚期。

辉绿岩(床)表面风化强烈,球形风化较发育(图2-a),呈酱黄色,新鲜面为黑色或黑绿色,岩性主要为辉绿(玢)岩,辉绿结构,斑状结构,块状构造。矿物成分为钛普通辉石、斜长石和少量钾长石、石英,副矿物有磷灰石、钛磁铁矿。主要矿物

粒径一般0.5~1.5 mm,斜长石 An=50~55 为拉长石,半自形板状-板条状,具绢云母化、绿帘石化、皂化等。辉石,半自形-他形柱粒状,具次闪石化、绿泥石化等,他形粒状辉石充填于斜长石板条状晶粒构成的三角形格架空隙中,构成辉绿结构(图2-b,2-c)。

①河北省地矿局. 区域地调查报告(1:20万平泉幅). 1976.

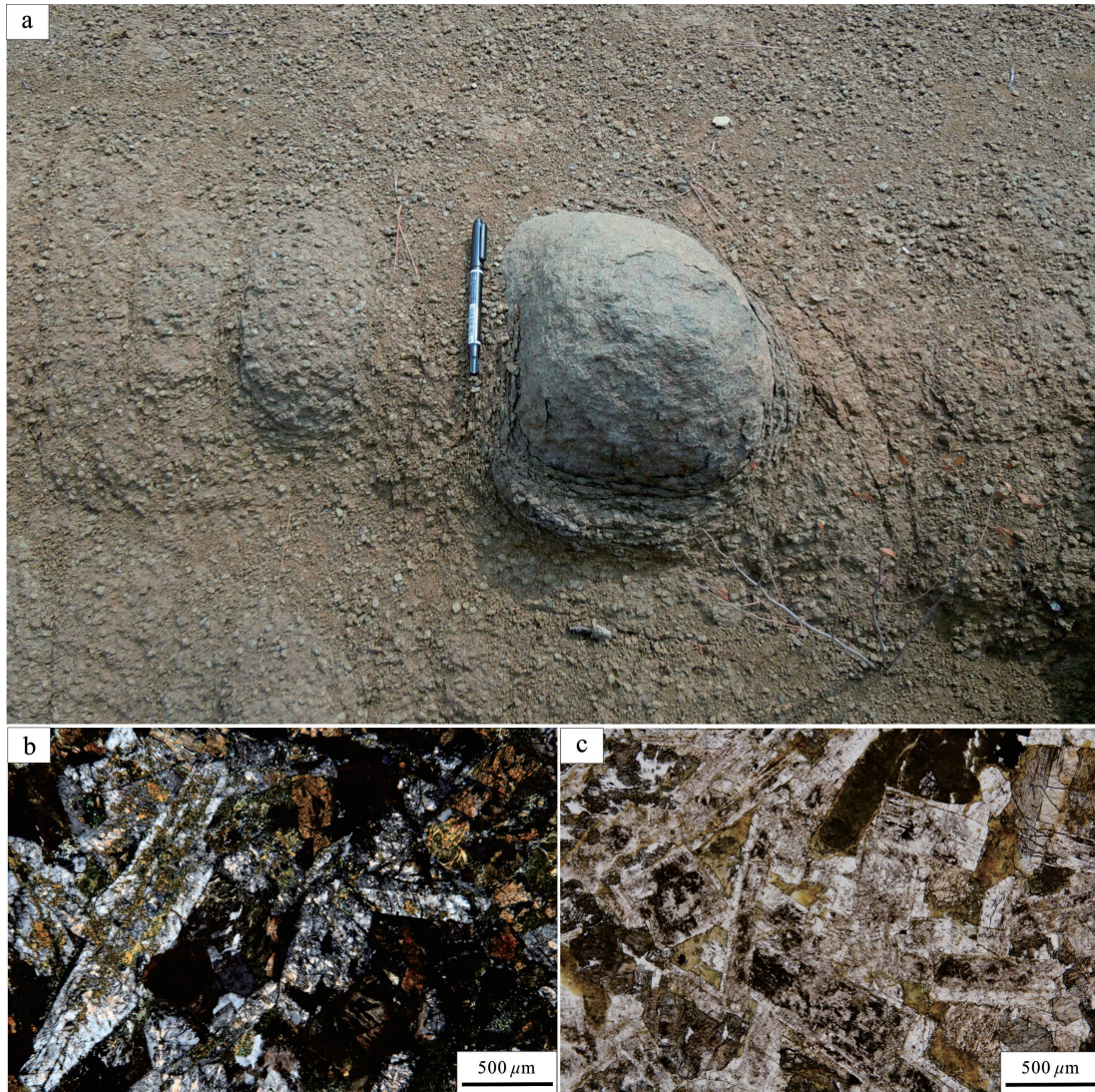


图2 下马岭组辉绿岩野外特征(a)及薄片显微特征(b,c)

Fig.2 Diabase of the Xiamaling Formation(a) and its features in thin section(b, c)

5件辉绿岩样品主微量元素分析在河北省地矿局廊坊实验室完成。主量元素采用XRF法在荷兰帕纳科公司研制的Axios X射线荧光光谱仪上测定,分析精度一般优于2%,稀土和微量元素采用美国赛默飞世尔科技公司(Thermo Fisher Scientific)研制的X Series II型等离子体光谱仪(ICP-MS)测定,并以GSD9标准样做分析样品元素浓度的校正标准,分析精度一般优于1%~5%。

## 2 分析结果

### 2.1 主量元素特征

研究区5件辉绿岩样品地球化学组成分析结果(表1)表明, $\text{SiO}_2$ 含量变化在43.89%~48.56%,平均

为47.34%; $\text{Al}_2\text{O}_3$ 含量较低,变化在11.33%~14.98%,平均13.17%; $\text{MgO}$ 含量较低,变化在4.17%~5.86%,平均5.07%; $\text{Na}_2\text{O}+\text{K}_2\text{O}$ 含量范围为2.28%~4.87%,平均3.82%,且 $\text{Na}_2\text{O} > \text{K}_2\text{O}$ ;  $\text{TiO}_2$ 含量较高,变化于1.70%~4.29%,平均2.71%,明显区别于岛弧钙碱性玄武岩(0.98%),相近于板内拉斑玄武岩(2.23%)<sup>[10]</sup>。综上,大范杖子辉绿岩总体以低 $\text{Al}_2\text{O}_3$ 、 $\text{MgO}$ ,高 $\text{TiO}_2$ 为特征,与板内拉斑玄武岩相似。

$\text{SiO}_2-(\text{Na}_2\text{O}+\text{K}_2\text{O})$ (TAS)图解<sup>[11]</sup>显示,辉绿岩样品点全部落入玄武岩范围内。 $\text{Nb}/\text{Y}-\text{Zr}/\text{TiO}_2$ 图解<sup>[12]</sup>中,辉绿岩投点于拉斑玄武岩区(图3~4)。 $\text{K}_2\text{O}-\text{TiO}_2-\text{P}_2\text{O}_5$ 图解<sup>[13-14]</sup>(KTP三角图)上除DL-5样品外均投点于大陆拉斑玄武岩区(II'区)(图5),表明燕

表1 燕山地区大范杖子辉绿岩主量(%)和微量元素( $10^{-6}$ )组成

Table 1 Analytical results for Mesoproterozoic diabase in Dafanzhangzi of Yanshan Mountain area

分析项目	DL-1	DL-2	DL-3	DL-4	DL-5
SiO <sub>2</sub>	47.60	48.56	48.22	48.41	43.89
Al <sub>2</sub> O <sub>3</sub>	11.33	14.98	14.70	12.95	11.89
TiO <sub>2</sub>	3.71	1.93	1.70	1.94	4.29
Fe <sub>2</sub> O <sub>3</sub>	11.99	6.68	5.18	4.17	12.52
FeO	5.34	6.06	7.09	11.11	7.42
CaO	7.27	6.90	9.30	8.44	9.33
MgO	4.17	5.12	5.86	5.63	4.57
K <sub>2</sub> O	1.69	1.71	1.20	1.07	0.36
Na <sub>2</sub> O	2.68	3.16	2.93	2.39	1.92
MnO	0.18	0.18	0.18	0.21	0.24
P <sub>2</sub> O <sub>5</sub>	0.22	0.17	0.14	0.20	0.14
H <sub>2</sub> O <sup>+</sup>	3.44	4.05	3.16	3.20	2.91
H <sub>2</sub> O	1.57	1.74	1.10	0.62	1.62
烧减量	3.69	4.42	3.40	3.26	3.22
总量	99.89	99.87	99.89	99.77	99.79
Y	40.45	25.92	25.94	39.86	32.08
La	18.87	14.77	12.58	22.10	13.70
Ce	43.14	33.00	28.34	44.23	29.12
Pr	6.53	4.92	4.31	6.97	4.34
Nd	26.73	19.30	17.66	30.06	19.35
Sm	7.03	4.86	4.73	7.27	4.86
Eu	2.42	1.69	1.63	2.26	1.90
Gd	6.25	4.26	4.19	6.09	4.91
Tb	1.33	0.88	0.90	1.36	0.95
Dy	7.90	5.16	5.37	8.21	6.36
Ho	1.63	1.04	1.10	1.63	1.25
Er	4.47	2.79	2.97	4.66	3.58
Tm	0.76	0.49	0.51	0.76	0.59
Yb	4.66	2.93	3.11	4.70	3.81
Lu	0.80	0.51	0.52	0.76	0.61
∑REE	132.52	96.6	87.92	141.06	95.33
∑LREE	104.72	78.54	69.25	112.89	73.27
∑HREE	27.8	18.06	18.67	28.17	22.06
∑L/∑H	3.7669	4.3488	3.7092	4.0075	3.3214
δEu	1.0928	1.1101	1.0956	1.0101	1.1771
δCe	0.9503	0.9451	0.9407	0.8675	0.9195
(La/Yb) <sub>N</sub>	2.905	3.616	2.902	3.373	2.579
Rb	62.90	62.90	45.80	38.12	11.20
Sr	179.00	360.00	288.00	186.10	182.30
Ba	457.00	533.00	234.00	298.00	110.90
Cr	7.30	93.20	308.90	80.51	11.30
V	236.90	443.10	470.60	323.20	1364.60
Nb	22.00	12.30	11.40	14.93	12.00
Ta	1.75	1.10	1.05	0.85	0.78
Zr	192.00	116.00	109.00	154.30	109.50
Hf	6.60	4.10	3.90	3.44	2.75
Th	4.54	3.86	2.62	2.47	9.90
U	1.05	0.86	0.56	0.78	0.66
Cs	3.31	1.84	2.54	2.06	0.69
Li	38.90	43.60	19.20	23.71	16.80
Zr/TiO <sub>2</sub>	51.752	60.104	64.118	79.536	25.524
Nb/Y	0.544	0.475	0.439	0.375	0.374
Zr/Y	4.747	4.475	4.202	3.871	3.413
Ta/Hf	0.265	0.268	0.269	0.247	0.284
Th/Hf	0.688	0.941	0.672	0.718	3.600
Th/Zr	0.024	0.033	0.024	0.016	0.090
Nd/Zr	0.139	0.166	0.162	0.195	0.177

注:数据由河北省地矿局廊坊实验室于2011年测试。

山地区辉绿岩属于大陆拉斑玄武岩系列岩石,形成于华北陆块北部的板内环境。

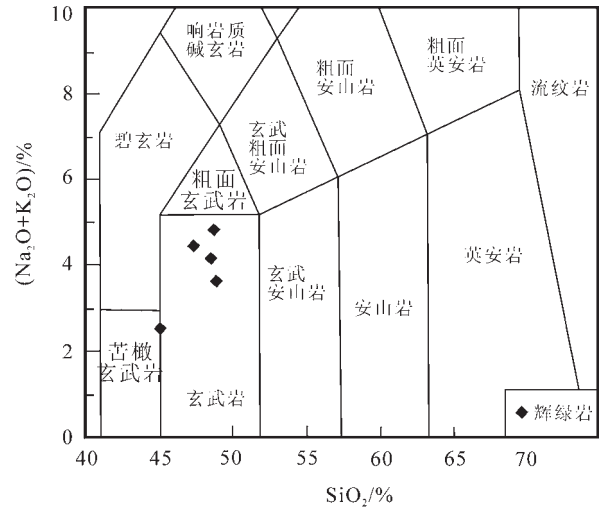


图3 辉绿岩TAS图解 (底图据文献[11])

Fig.3 TAS classification diagram for Mesoproterozoic diabase from Yanshan Mountain area (base diagram after reference [11])

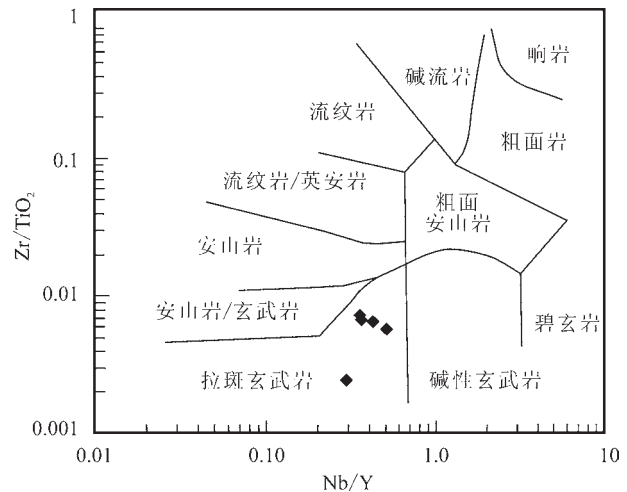


图4 辉绿岩Nb/Y—Zr/TiO<sub>2</sub>图解 (底图据文献[12])

Fig.4 Nb/Y—Zr/TiO<sub>2</sub> plot for Mesoproterozoic diabase from Yanshan Mountain area (base diagram after reference [12])

2.2 微量元素特征

微量元素组成特征与其形成的地质、物理化学环境有关,其含量与比值对确定成岩成矿物质来源具有十分重要的指示意义<sup>[15]</sup>。研究区辉绿岩样品稀土元素地球化学分析结果(表1)显示,稀土总量∑REE较高(87.92×10<sup>-6</sup>~141.06×10<sup>-6</sup>);∑LREE/∑HREE变化不大,为3.321~4.349;在球粒陨石标准化图解上(图

6), 样品表现出比较一致的右倾型配分模式, 轻稀土富集, 轻重稀土分馏不明显,  $(La/Sm)_N = 1.717 \sim 1.962$ ,  $(Gd/Yb)_N = 1.066 \sim 1.203$ ; 无明显 Ce 负异常,  $\delta Ce = 0.868 \sim 0.950$ ; Eu 正异常亦不明显,  $\delta Eu = 1.010 \sim 1.177$ 。REE-La/Yb 图解上<sup>[16]</sup>样品点绝大多数落于大陆拉斑玄武岩区域内(图7)。

高场强元素 Zr、Hf、Nb、Ta 在蚀变和变质作用过程中具有良好的稳定性, 是岩石成因和源区性质的良好示踪剂。研究区辉绿岩 Zr、Hf 丰度变化分别为  $109 \times 10^{-6} \sim 192 \times 10^{-6}$  (平均  $136.16 \times 10^{-6}$ ) 和  $2.75 \times 10^{-6} \sim 6.6 \times 10^{-6}$  (平均  $4.16 \times 10^{-6}$ ), 相当于板内拉斑玄武岩和碱性玄武岩的 Zr ( $149 \times 10^{-6} \sim 213 \times 10^{-6}$ )、Hf

( $3.44 \times 10^{-6} \sim 6.36 \times 10^{-6}$ ), 高于 MORB 玄武岩的 Zr ( $90 \times 10^{-6} \sim 96 \times 10^{-6}$ )、Hf ( $2.4 \times 10^{-6} \sim 2.93 \times 10^{-6}$ ), 明显高于火山弧拉斑玄武岩、钙碱性玄武岩和钾玄武岩的 Zr ( $40 \times 10^{-6}$ 、 $71 \times 10^{-6}$  和  $87 \times 10^{-6}$ )、Hf ( $1.17 \times 10^{-6}$ 、 $2.23 \times 10^{-6}$  和  $2.24 \times 10^{-6}$ )<sup>[36]</sup>。本区辉绿岩 Nb ( $11.4 \times 10^{-6} \sim 22 \times 10^{-6}$ , 平均  $14.53 \times 10^{-6}$ )、Ta ( $0.78 \times 10^{-6} \sim 1.75 \times 10^{-6}$ , 平均  $1.11 \times 10^{-6}$ ) 的丰度值接近于板内拉斑玄武岩和碱性玄武岩的 Nb、Ta 丰度 (分别变化在  $13 \times 10^{-6} \sim 84 \times 10^{-6}$  和  $0.73 \times 10^{-6} \sim 5.9 \times 10^{-6}$ )<sup>[36]</sup>。原始地幔标准化图解(图8)显示高场强元素和稀土元素的丰度都高于 N-MORB。

### 3 讨论

#### 3.1 辉绿岩成因

基性岩墙(床)群作为深源岩浆浅侵位的构造岩浆活动, 是基性岩浆快速侵位到先存裂隙内的产物。其所含受后期蚀变影响较小的高场强元素(HFSE) Ti、Zr、Y、Nb、Ta、Hf、Th 和稀土元素(REE) 等不活泼元素的地球化学特征基本上反映了岩浆源区性质。

综上所述, 华北陆块北部燕山地区辉绿岩  $\Sigma$  REE 总量较高, LREE 明显富集, 轻重稀土分馏不明显。配分曲线右倾, 无明显 Eu 异常, 其特征反映辉绿岩岩浆起源相对比较深, 可能源自幔源岩浆(图

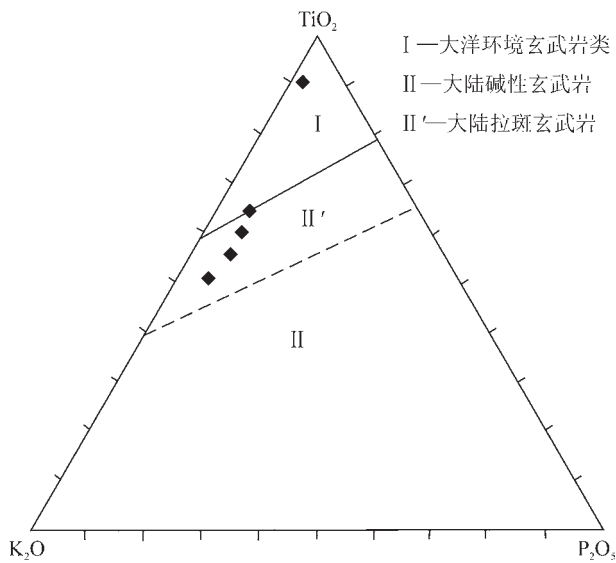


图5 辉绿岩KTP图解(底图据文献[13-14])  
Fig.5 KTP diagram for Mesoproterozoic diabase from Yanshan Mountain area (base diagram after reference [13-14])

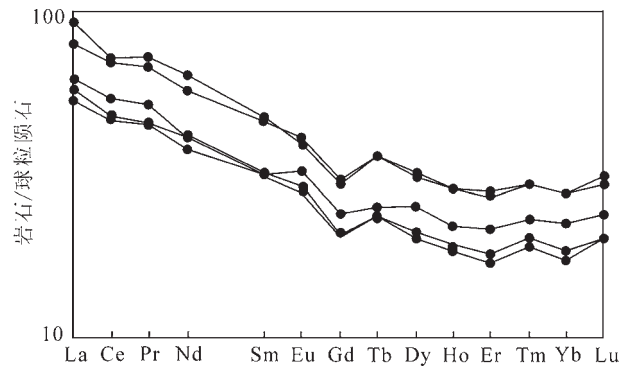


图6 辉绿岩REE配分模式图  
Fig.6 Chondrite-normalized REE patterns of Mesoproterozoic diabase

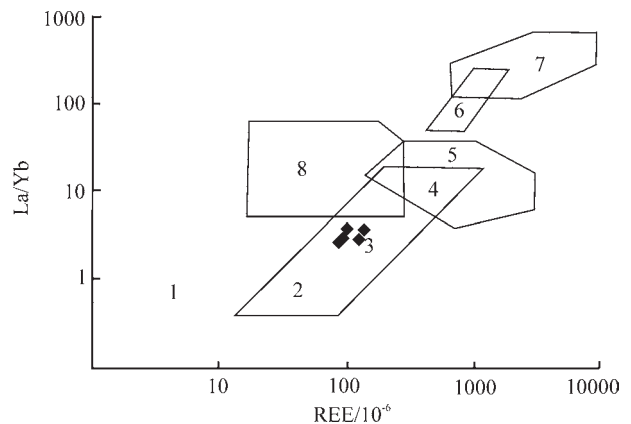


图7 辉绿岩La/Yb-REE关系图解(据文献[16])  
1-球粒陨石; 2-大洋拉斑玄武岩; 3-大陆拉斑玄武岩; 4-碱性玄武岩; 5-花岗岩; 6-金伯利岩; 7-碳酸盐岩; 8-沉积岩  
Fig.7 La/Yb-REE diagram of Mesoproterozoic diabase (after reference [16])  
1-Chondrite; 2-Oceanic tholeiite; 3-Continental tholeiite; 4-Alkali basalt; 5-Granite; 6-Kimberlite; 7-Carbonate rock; 8-Sedimentary rock

6)。高场强元素 Zr、Hf 明显高于火山弧拉斑玄武岩,相 近于板内拉斑玄武岩;Nb、Ta 明显高于岛弧拉斑玄武岩 Nb、Ta,相 似于板内拉斑玄武岩<sup>[10]</sup>。Zr-Y、Zr-Nb 图解<sup>[17]</sup>亦显示岩浆来源于过渡性地幔(图 9)。综合主微量元素特征,表明该辉绿岩的岩浆来自于大陆板内过渡性地幔区。

### 3.2 构造背景

元古宙基性辉绿岩墙(床)群作为一种特殊的构造-岩浆地质体,对全球超大陆的演化起到了很好的标志作用,承载了极为重要的热-构造事件信息,受到地学界广泛关注<sup>[18-26]</sup>。尤其是中元古代一系列火山岩夹层及侵入体高精度测年数据的获取,重新厘定了中新元古界年代地层柱<sup>[27]</sup>,为超大陆裂解汇聚演化进程的研究提供了重要的科学依据。陆松年等<sup>[9]</sup>总结华北陆块在中元古代出现了三幕热构造事

件群,这三幕与裂解有关的热-构造事件群间接指示了 Columbia 超大陆裂解过程中在华北陆块的响应。而发生于 1350~1320 Ma 的北陆块北部的基性岩墙侵入事件,与北美花岗岩-流纹岩地体晚期岩浆事件<sup>[28]</sup>时限上相当,稍早于北美西北部的 Mackenzie 基性岩墙群<sup>[24]</sup>的形成时代。因此研究该基性岩(床)形成时的构造背景,对进一步探讨华北陆块与其他古大陆之间的亲缘关系,以及重塑当时华北陆块在超大陆中所处位置都将起到积极作用。

燕山地区辉绿岩样品在微量元素 Zr/Y-Zr<sup>100</sup>和 Ti/100-Zr-Y×3 图解<sup>[29]</sup>中,基本上落于板内玄武岩区(图 10),主量元素 K<sub>2</sub>O-TiO<sub>2</sub>-P<sub>2</sub>O<sub>5</sub>图解亦显示该辉绿岩为形成于板内环境下的大陆拉斑玄武岩。应用 Ta/Hf-Th/Hf 及 Nb/Zr-Th/Zr 图解(图 11)样品投点基本上位于大陆板内拉张环境。综合主、微量元素特征,表明研究区辉绿岩形成中元古代晚期华北陆块内部的板内拉张背景。

燕山地区辉绿岩(床)作为中元古代晚期华北陆块北部板内裂解事件的产物,与华北陆块北缘白云鄂博-渣尔泰拗拉槽、陆块东南缘徐淮拗拉槽、陆块内部的晋北、鲁西地区以及全球其他古大陆同期热-构造事件<sup>[25,26,28,31-35]</sup>存在一定可比性,因此可能是中元古代晚期 Columbia 超大陆逐步裂解过程中在华北陆块上的响应。

## 4 结 论

(1)燕山地区中元古代辉绿岩主微量元素地球化学特征显示其属于大陆拉斑玄武岩系列。

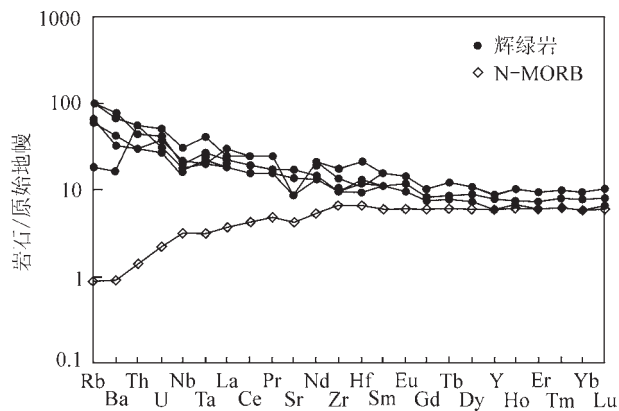


图8 辉绿岩原始地幔标准化的微量元素配分图  
Fig.8 Primitive mantle normalized incompatible element spidergram for diabase-dykes

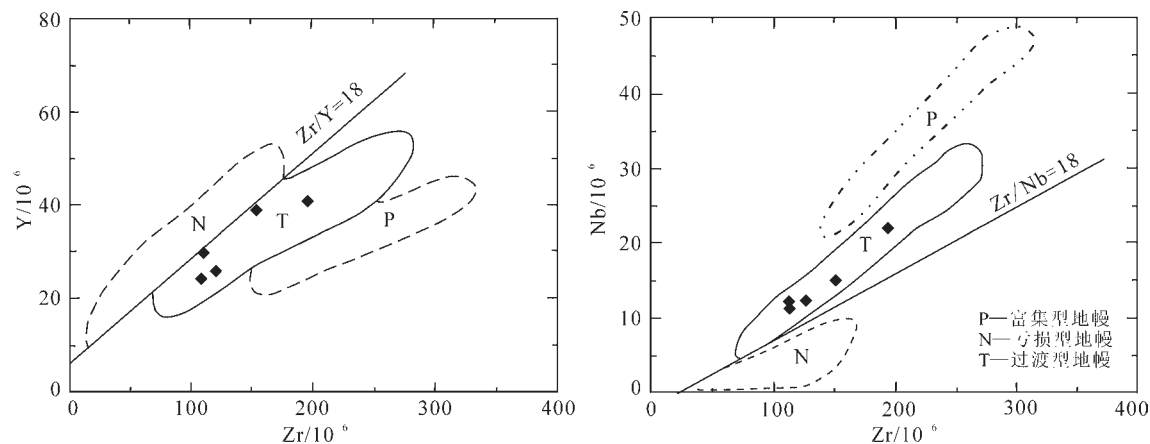


图9 辉绿岩的 Zr-Y 图解和 Zr-Nb 图解(底图据文献[17])  
Fig.9 Zr-Y and Zr-Nb classification diagram for Mesoproterozoic diabase from Yanshan Mountain area (base diagram after reference [17])

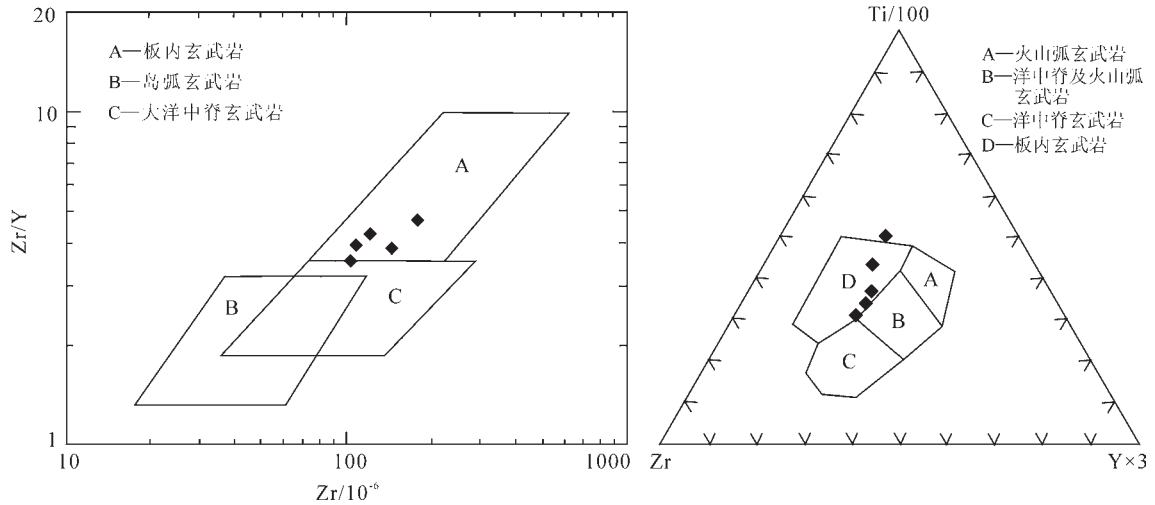


图10 辉绿岩的Zr/Y-Zr及Ti/100-Zr-Y×3图解(底图据文献[10,29])  
 Fig.10 Zr/Y-Zr and Ti/100-Zr-Y×3 classification diagram for Mesoproterozoic diabase (base diagram after reference [10,29])

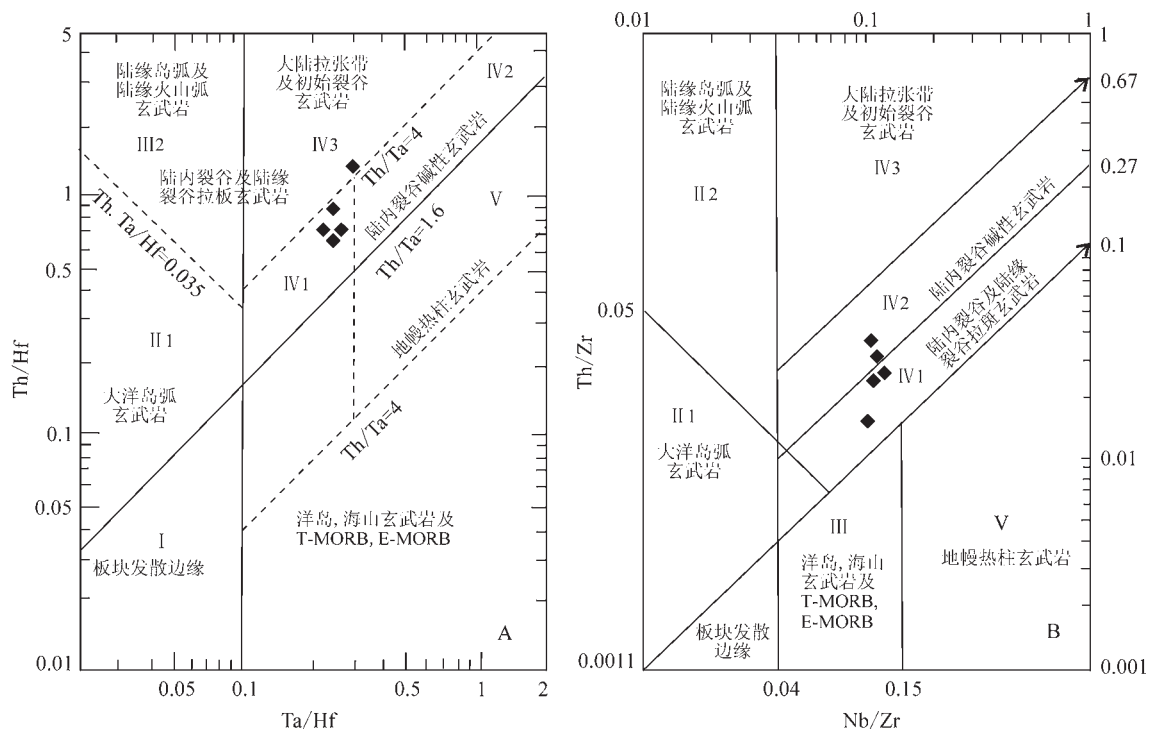


图11 辉绿岩的Ta/Hf—Th/Hf及Nb/Zr—Th/Zr图解(底图据文献[30,31])  
 Fig.11 Ta/Hf—Th/Hf and Nb/Zr—Th/Zr classification diagram for Mesoproterozoic diabase (base diagram after reference [30,31])

(2)辉绿岩稀土元素特征指示其可能来源于幔源岩浆。综合高场强元素特征分析认为该辉绿岩的岩浆来自于大陆板内过渡性地幔区。

(3)微量元素 Ta/Hf—Th/Hf及 Nb/Zr—Th/Zr 图解

及主量元素  $K_2O-TiO_2-P_2O_5$  图解显示该辉绿岩形成的构造背景为板内拉张环境。此次华北陆块北部板内裂解事件可能是中元古代末 Columbia 超大陆裂解过程在华北陆块上的响应。

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## Geochemistry of the Mesoproterozoic diabase sills from Yanshan Mountain area in the northern part of North China Plate

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**Abstract:** The intrusion of diabase sills in the shales of the Xiamaling Formation is extensively developed in Yanshan Mountain area of the northern part of North China Plate. Geochemistry of the diabase is characterized by high content of  $\text{TiO}_2$  (1.70%~4.29%), low content of  $\text{Al}_2\text{O}_3$  (11.33%~14.98%),  $\text{MgO}$  (4.17%~5.86%) and  $\text{Na}_2\text{O} > \text{K}_2\text{O}$ . In the  $\text{K}_2\text{O}-\text{TiO}_2-\text{P}_2\text{O}_5$  plot, all sample points almost fall into the field of continental tholeiite. REE study indicates that the diabase is enriched in light rare earth elements with abundant rare earth elements, and the fractionation between LREE and HREE is not pronounced. Meanwhile, the chondrite-normalized distribution curve is right-oblique without obvious depletion of Eu. All these characteristics in combination with the Zr-Y, Zr-Nd, Zr/Y-Zr,  $\text{Ti}/100-\text{Zr}-\text{Y} \times 3$ , Ta/Hf-Th/Hf and Nd/Zr-Th/Zr diagrams indicate that the magma was derived from the transitional mantle, and the diabase was formed in an intra-continent extension setting of North China Plate during the late Mesoproterozoic.

**Key words:** diabase; geochemistry; Mesoproterozoic; North China Plate; Yanshan Mountain area

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