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二连—贺根山缝合带晚石炭世埃达克岩的发现及古亚洲洋洋内俯冲作用

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提要:内蒙古二连—贺根山缝合带额很傲包图英云闪长岩体,出露于西乌旗梅劳特乌拉SSZ型蛇绿岩带北侧。为了确定该岩体的岩石成因类型,探讨其构造环境及古亚洲洋俯冲消亡过程,对该岩体进行了岩石学、地球化学和LA-ICP-MS锆石U-Pb年代学研究。额很傲包图英云闪长岩高硅富铝,富钠贫钾,高锶低钇,富集Rb、Ba、Sr等大离子亲石元素和LREE,亏损Nb、Ta、Ti、P等高场强元素和HREE,无明显Eu异常。岩石学和岩石地球化学特征表明,该英云闪长岩体为高Si埃达克岩(HSA),形成于岛弧环境,具有洋内俯冲洋壳+俯冲深积物部分熔融并与上覆地幔楔橄榄岩反应成因特征。锆石LA-ICP-MS U-Pb测年表明,额很傲包图英云闪长岩体的侵位年龄为(305.6±1.5)Ma,形成时代为晚石炭世。结合二连—贺根山缝合带石炭纪蛇绿岩、石炭纪—二叠纪岛弧型岩浆岩的时空分布与演化特征,认为古亚洲洋二连—贺根山洋盆在石炭纪—早二叠世处于以洋内俯冲为特征的大洋俯冲消亡过程中。

关 键 词:英云闪长岩;埃达克岩;洋内俯冲作用;晚石炭世;二连—贺根山缝合带;地质调查工程

中图分类号:P588.12+2;P597+.3;P595 **文献标志码**:A **文章编号**:1000-3657(2021)02-0520-16

Discovery of the Late Carboniferous adakite in the Erenhot- Hegenshan suture zone and intra-oceanic subduction of the Paleo-Asian Ocean

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Abstract: The Ehenaobaotu tonalite is outcropped in the northern part of the Meilaotewula SSZ-type ophiolite of the Erenhot-Hegenshan suture zone in Xi Ujimqin Banner of Inner Mongolia. Based on the study of petrology, geochemistry and zircon LA-ICP-MS U-Pb geochronology, the genetic type and tectonic setting of the tonalite were determined, and the final closure time and subduction process of the Erenhot-Hegenshan ocean basin of the Paleo-Asian Ocean were discussed. The tonalite is characterized by high SiO_2, Al_2O_3, Na_2O, Sr and low K_2O, Y contents, enrichment of Rb, Ba, Sr large ion lithophile elements and LREE, and depletion of Nb, Ta, Ti, P high field strength elements and HREE. There is no pronounced Eu anomaly. The lithological and

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geochemical characteristics show that the Ehenaobaotu pluton is a high Si adakite (HSA)formed in island arc, and was derived from patial melting of the intra-oceanic subductingd oceanic crust and sediment and subsequently reaction with overlying mantle wedge peridotite. Its U-Pb LA-ICP-MS dating yields (305.6±1.5) Ma and suggests that the Ehenaobaotu pluton was formed during Late Carboniferous. Combined with the study of spatio-temporal evloution of the Carboniferous ophiolites and Carboniferous-Permian island arc magmatic rocks in the Erenhot-Hegenshan suture, it is assumed that the Erenhot-Hegenshan oceanic basin of the Paleo-Asian Ocean was in the process of oceanic subduction characterized by intra-oceanic subduction during the Carboniferous-Early Permian.

Key words: tonalite; adakite; intra-oceanic subduction; Late Carboniferous; Erenhot-Hegenshan suture zone; geological survey engineering

About the first author: WANG Jinfang, female, born in 1983, associate professor, engaged in the study of petrology and geochemistry.

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1　引　言

中亚造山带东段二连—贺根山缝合带是华北板块与西伯利亚板块的重要缝合界线之一,蕴涵着古亚洲洋二连—贺根山洋盆的俯冲消亡过程与信息(Xiao et al.,2003;Windley et al.,2007;Zhang et al.,2015;邓晋福等,2015;李钢柱等,2017)。内蒙古中部西乌旗地区为二连—贺根山缝合带古生代蛇绿岩和岛弧岩浆岩的典型发育地区之一,识别与研究这些古生代岛弧岩浆岩与蛇绿岩之间的时空分布关系和内在成因联系,对了解古亚洲洋二连—贺根山洋盆闭合时间和大洋俯冲消亡过程具有重要意义(陈斌等,2001;Miao et al.,2008;刘建峰等,2009;李英杰等,2012,2018b;Liu et al.,2013;董培培等,2020)。然而,二连—贺根山洋盆闭合时间仍存在着"晚泥盆世"与"晚二叠世"较大分歧(Shang,2004;Miao et al.,2008;Xiao et al.,2009;邵济安,2015;田树刚等,2016),与该区晚古生代石炭纪蛇绿岩密切伴生的晚石炭世岛弧型埃达克岩体也尚未见有报道,二连—贺根山洋盆"晚二叠世"闭合时间仍需要进一步的岩石学证据与年代学约束。笔者近年在内蒙古1∶5万高力罕牧场三连等四幅区域地质矿产调查中,新识别出额很傲包图英云闪长岩体。1∶20万罕乌拉幅区域地质矿产调查将该岩体划归为华力西晚期石英闪长岩,缺少地球化学和年代学等资料。因此,本文在1∶5万区域地质调查的基础上,选择西乌旗梅劳特乌拉SSZ型蛇绿岩北侧出露的额很傲包图英云闪长岩(图1)进行岩石学、地球化学和年代学研究,探讨其岩石成因类型及形成的构造环境,以期为古亚洲洋二连—贺根山洋盆俯冲消亡时间与过程提供一些岩石学、地球化学和年代学证据和约束。

2　区域地质背景和岩石学特征

研究区位于内蒙古西乌旗东北部,大地构造位置处于华北板块北缘增生带与西伯利亚板块南缘增生带的碰撞缝合部位,属于中亚造山带东段的二连—贺根山缝合带(图1a)。额很傲包图英云闪长岩体出露于梅劳特乌拉SSZ型蛇绿岩北侧(图1b)(李英杰等,2015;王金芳等,2017a,2018c),侵入于晚石炭世花岗岩之中,被早白垩世正长花岗岩所侵入(王金芳等,2017b),出露面积约27 km^2(图1b,c)。额很傲包图英云闪长岩呈浅灰色、浅灰绿色和灰白色,中粒—粗中粒半自形粒状结构,块状构造(图1d,e),矿物成分主要为斜长石(45%~55%)、石英(30%~35%)、黑云母(8%~10%)和角闪石(3%~5%),少量钾长石(2%±)。斜长石自形—半自形板状,可见卡钠复合双晶,双晶纹中细,部分颗粒具环带构造,偶见净边结构,均已不同程度绢云母化;石英它形粒状,部分颗粒可见波状消光;黑云母多为自形片状,可见绿泥石化;角闪石呈半自形柱状,可见黝帘石化和绿泥石化。

3　锆石U-Pb年代学

本文在额很傲包图采集了1件新鲜的英云闪长岩年龄样品(PS1-10),采样点地理位置:45°02′25.6″N、118°27′42.0″E(图1b、c)。

样品PS1-10的锆石挑选由河北省区域地质矿产调查研究所实验室完成。将岩石样品破碎成粉

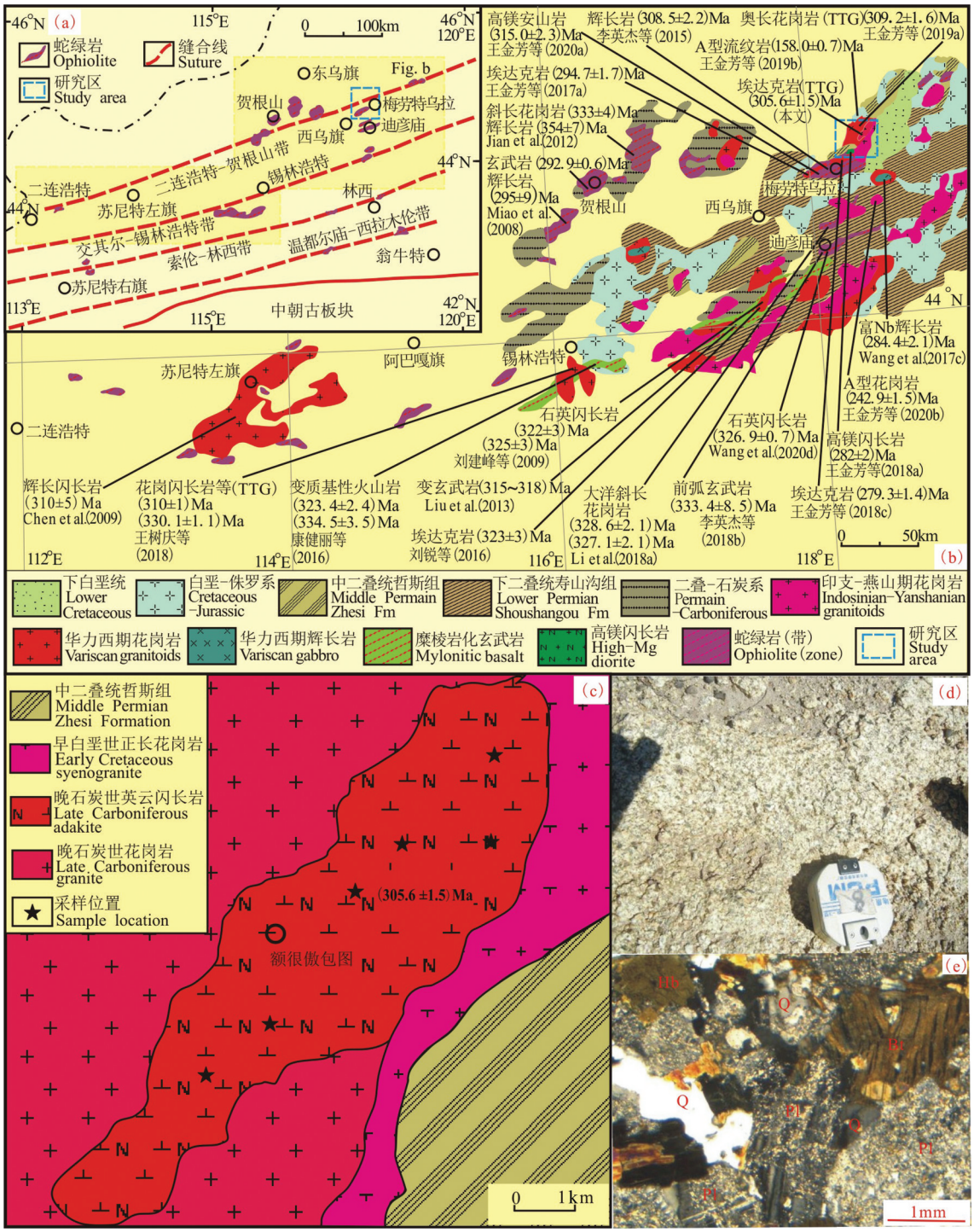

图1 额很傲包图英云闪长岩大地构造单元图(a)(修改自 Miao et al.,2008),区域地质图(b), 地质图(c),野外照片(d)和显微照片(e)

Fig.1 Tectonic unit map (a)(modified from Miao et al.,2008), regional geological map (b), geological map(c), field photograph (d) and photomicrograph (e) of the Ehenaobaotu tonalite

末,利用重液和磁选法分离技术分选。此后,在双目镜下根据晶形的完好程度、颜色的有无、透明度的高低以及包裹体和裂纹的有无等挑选出测试的锆石,然后用环氧树脂在玻璃板上固定挑选好的锆石与标样抛光至锆石中心(制靶)。通过双目镜和阴极发光(CL)图像研究锆石的晶形和内部结构,选择原位同位素分析的最佳点。制靶和阴极发光实验在北京锆年领航科技有限公司完成,锆石原位

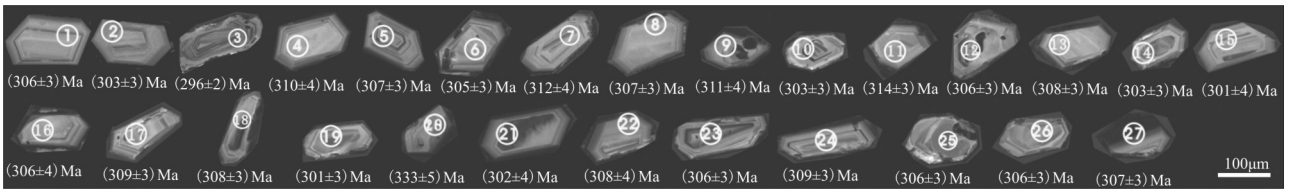

图2 额很傲包图英云闪长岩(PS1−10)锆石阴极发光图像及其LA−ICP−MS U−Pb年龄

Fig.2 Cathodoluminescent images and LA−ICP−MS U−Pb ages of zircons from the Ehenaobaotu tonalite

U−Pb同位素年龄在天津地质调查中心激光剥蚀等离子体质谱仪(LA−ICP−MS)上测定。进行了锆石样品测试数据的普通铅校正处理、U−Pb年龄谐和图的绘制和年龄权重平均计算(Ludwig,2003)。

测试样品锆石无色透明,呈自形柱状或双锥状,长短轴之比为1∶1~2∶1,几乎所有27颗锆石均显示较为典型的岩浆韵律振荡环带(图2),表明这些锆石为酸性岩浆成因。测试结果Th、U含量和Th/U比值分别为59×10^{-6}~331×10^{-6}、3×10^{-6}~18×10^{-6}和0.0628~0.8842,反映了岩浆成因的特征(Corfu et al.,2003;Wu et al.,2004)。27粒锆石的测定年龄值均落在谐和线上或附近,其$^{206}Pb/^{238}U$年龄加权平均值为(305.6 ±1.5)Ma(MSWD=1),代表该英云闪长岩的侵位结晶年龄(表1,图3)。

4 地球化学特征

4.1 主量元素特征

研究区6件地球化学样品的主量和微量元素测

表1 额很傲包图英云闪长岩(PS1−10)LA−ICP−MS 锆石U−Pb测试结果

Table 1 LA−ICP−MS U−Pb dating of zircons from the Ehenaobaotu tonalite

点号	含量/10^{-6}		Th/U	同位素比值						表面年龄/Ma	
	Pb	U		$^{207}Pb^{*}/^{206}Pb^{*}$	±%	$^{207}Pb^{*}/^{235}U$	±%	$^{206}Pb^{*}/^{238}U$	±%	$^{206}Pb/^{238}U$	
1	6	122	0.3858	0.0663	7.01	0.4445	7.08	0.0486	0.93	306	±3
2	15	286	0.6116	0.0555	5.71	0.3686	5.79	0.0482	0.89	303	±3
3	11	215	0.5546	0.0551	5.10	0.3574	5.16	0.0470	0.83	296	±2
4	6	108	0.4663	0.0547	18.78	0.3709	18.0	0.0492	1.15	310	±4
5	11	206	0.5115	0.0528	5.30	0.3553	5.39	0.0488	0.83	307	±3
6	6	124	0.3639	0.0561	8.31	0.3752	8.15	0.0485	1.01	305	±3
7	4	83	0.4065	0.0616	11.43	0.4217	10.9	0.0496	1.13	312	±4
8	13	259	0.3904	0.0601	5.82	0.4045	5.83	0.0488	0.87	307	±3
9	6	110	0.2835	0.0517	25.98	0.3524	25.1	0.0495	1.43	311	±4
10	12	225	0.5785	0.0550	5.42	0.3644	5.59	0.0481	0.86	303	±3
11	7	136	0.4376	0.0523	9.64	0.3591	9.70	0.0498	1.03	314	±3
12	9	176	0.4280	0.0519	6.35	0.3471	6.41	0.0485	0.85	306	±3
13	6	122	0.3991	0.0560	9.18	0.3780	9.18	0.0489	0.97	308	±3
14	11	218	0.4720	0.0541	5.48	0.3589	5.61	0.0481	0.84	303	±3
15	4	84	0.4081	0.0536	19.13	0.3530	17.5	0.0478	1.37	301	±4
16	3	59	0.4794	0.0868	13.64	0.5807	12.5	0.0485	1.40	306	±4
17	4	87	0.4436	0.0749	9.16	0.5073	9.01	0.0491	1.11	309	±3
18	18	331	0.8842	0.0512	3.68	0.3439	3.83	0.0487	0.89	307	±3
19	9	206	0.0628	0.0537	5.83	0.3538	5.94	0.0478	0.85	301	±3
20	3	60	0.5249	0.0492	43.97	0.3598	30.0	0.0530	1.40	333	±5
21	4	84	0.4270	0.0612	15.19	0.4051	14.8	0.0480	1.33	302	±4
22	4	82	0.4161	0.0819	9.56	0.5519	9.65	0.0489	1.34	308	±4
23	10	193	0.6232	0.0518	5.80	0.3471	5.85	0.0486	0.85	306	±3
24	7	127	0.4639	0.0754	5.94	0.5106	6.09	0.0491	0.97	309	±3
25	5	104	0.2562	0.0528	14.44	0.3538	14.0	0.0486	1.09	306	±3
26	5	94	0.3005	0.0617	9.65	0.4142	9.45	0.0487	1.07	306	±3
27	7	133	0.3657	0.0581	7.40	0.3913	7.41	0.0488	0.89	307	±3

注:误差为1σ;Pb^{*}指示放射成因铅;实验测试在天津地质矿产研究所完成。

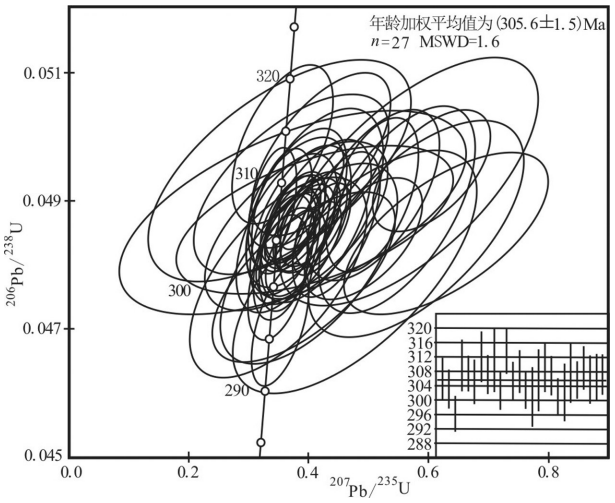

图3 额很傲包图英云闪长岩(PS1-10)锆石LA-ICP-MS U-Pb年龄谐和图和直方图

Fig.3 U-Pb concordia diagram and histograms of zircons from the Ehenaobaotu tonalite

试分析均在河北省区域地质矿产调查研究所实验室完成,主量元素分析采用Axios^{max} X射线荧光光谱仪测定,精度在1%以内,微量元素和稀土元素采用X Series 2等离子体质谱仪测定,测试精度在5%以内。主量、微量和稀土元素测试分析数据列于表2。

从表2可知,额很傲包图英云闪长岩SiO_2含量为65.97%~67.92%,平均值66.55%;Al_2O_3含量15.57%~16.36%,平均值16.04%,总体表现出高硅富铝特征;岩石Na_2O含量为4.25%~5.22%,K_2O含量为1.67%~1.95%,Na_2O/K_2O比值为2.23~2.98,显示富钠贫钾;全碱(Na_2O+K_2O)含量为6.10%~6.97%,平均值6.36%;里特曼指数σ为1.59~1.94,平均值1.72,为钙碱性岩;MgO含量1.19%~1.98%,$Mg^{\#}$42~51,平均值47;相对贫TiO_2(0.46%~0.51%)和P_2O_5(0.149%~0.161%)。该岩石的铝饱和指数A/CNK值介于1.02~1.18,A/NK为1.56~1.80,属弱过铝质—强过铝质(图4)。在SiO_2-(Na_2O+K_2O)(TAS)分类图解中,样品落入亚碱性花岗闪长岩区域(图5)。在An-Ab-Or图解中除1件样品落入奥长花岗岩区外,其余5件样品均落入英云闪长岩区(图6)。

4.2 稀土元素特征

额很傲包图英云闪长岩的稀土元素含量如表2所示,∑REE变化范围为53.01×10^{-6}~80.93×10^{-6},平均值62.68×10^{-6},相对较低;Yb含量0.82×10^{-6}~$1.33\times$

表2 额很傲包图英云闪长岩主量(%)、微量和稀土(10^{-6})元素分析结果

Table 2 Major element(%), trace element and REE analyses (10^{-6}) of the Ehenaobaotu tonalite

样号	PS1-08	PS1-09	PS1-10	PS1-11	PS1-12	PS1-13	高Si埃达克岩
SiO_2	66.58	66.45	66.03	67.92	66.37	65.97	64.8
TiO_2	0.50	0.49	0.48	0.48	0.46	0.51	0.56
Al_2O_3	15.57	16.14	15.84	16.33	16.36	15.98	16.64
Fe_2O_3	2.05	1.99	1.84	1.87	1.90	1.94	4.75
FeO	1.63	1.55	1.75	1.27	1.60	1.83	
MnO	0.071	0.071	0.072	0.053	0.064	0.066	0.081
MgO	1.64	1.94	1.68	1.19	1.49	1.98	2.18
CaO	3.39	2.90	3.33	1.84	3.55	2.98	4.63
Na_2O	4.25	4.45	4.46	5.22	4.43	4.46	4.19
K_2O	1.91	1.81	1.95	1.75	1.67	1.82	1.97
P_2O_5	0.151	0.157	0.152	0.161	0.151	0.149	0.2
LOI	2.11	1.95	2.28	1.78	1.81	2.12	
Total	99.86	99.88	99.86	99.86	99.86	99.81	
$Mg^{\#}$	46	51	47	42	45	50	48
La	10.89	12.67	10.51	14.57	10.70	12.10	19.2
Ce	21.62	27.35	20.93	32.89	21.4	26.23	37.3
Pr	2.73	3.13	2.66	4.25	2.61	3.39	
Nd	10.90	13.58	10.66	16.66	10.30	13.69	18.2
Sm	2.16	2.35	2.10	3.19	1.90	2.73	3.4
Eu	0.74	0.83	0.75	0.90	0.74	0.86	0.9
Gd	1.83	1.99	1.78	2.54	1.58	2.11	2.8
Tb	0.3	0.32	0.29	0.39	0.24	0.35	
Dy	1.71	1.82	1.66	2.18	1.44	2.14	1.9
Ho	0.31	0.35	0.30	0.41	0.26	0.33	
Er	0.89	1.12	0.85	1.22	0.78	0.98	0.96
Tm	0.14	0.18	0.14	0.21	0.13	0.14	
Yb	0.91	1.05	0.89	1.33	0.82	0.93	0.88
Lu	0.13	0.18	0.12	0.19	0.12	0.16	0.17
ΣREE	55.26	66.89	53.64	80.93	53.01	66.35	
Y	7.86	8.84	7.67	10.95	6.77	9.89	10
Ba	528.2	413.2	482.8	392.8	458.8	439.6	721
Rb	39.8	25.7	31.9	26.3	25.9	31.2	52
Sr	458.6	421.2	453.5	462.2	475.3	445.1	565
Zr	113.2	99.4	105.5	98.3	99.5	105.9	108
Nb	2.78	2.93	2.52	3.32	2.50	2.33	6
Th	4.29	3.73	3.56	4.43	3.24	4.35	
Ni	6.20	5.90	5.40	6.40	5.20	6.32	20
V	90.50	67.50	83.50	62.20	74.80	79.43	95
Cr	11.5	12.3	9.3	13.9	9.0	12.4	41
Hf	7.00	7.52	9.02	8.76	6.85	8.64	
Sc	7.88	6.12	7.45	6.17	5.96	7.13	
Ta	0.20	0.23	0.23	0.29	0.20	0.19	
Co	10.60	9.30	10.10	7.60	9.00	9.89	
Li	27.12	21.4.	28.93	19.45	19.44	25.31	
U	1.04	0.95	0.19	0.86	0.99	0.73	

注:氧化物含量%;稀土、微量元素含量10^{-6};高Si埃达克岩为267个样品平均值(Martin et al.,2005)。

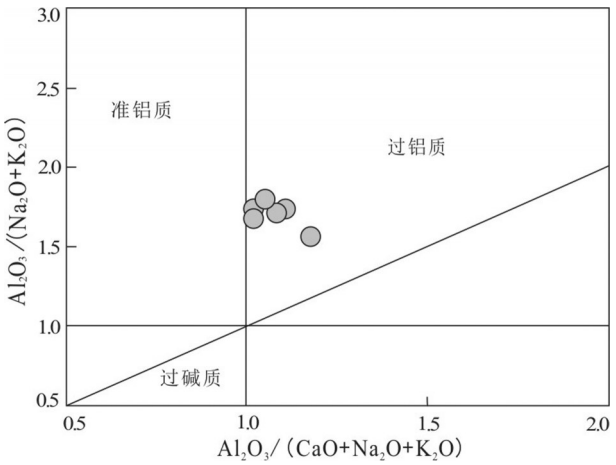

图4 额很傲包图英云闪长岩铝饱和指数(A/NK−A/CNK)图解(据Maniar and Piccoli, 1989

Fig.4 Shand's index of the Ehenaobaotu tonalite (after Maniar and Piccoli, 1989)

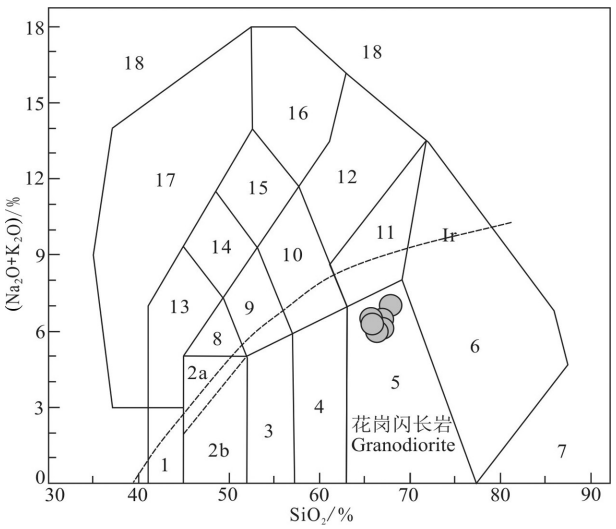

图5 额很傲包图英云闪长岩TAS分类图(据Middlemost,1994)

Fig.5 Total alkalis vs. silica(TAS) classification diagram of the Ehenaobaotu tonalite (after Middlemost,1994)

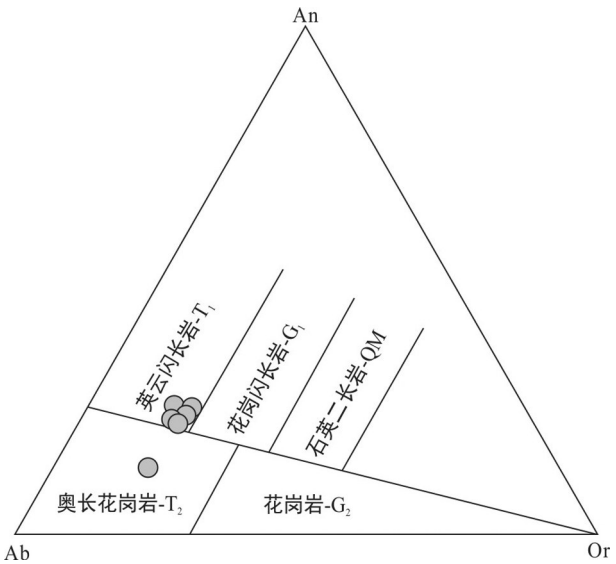

图6 额很傲包图英云闪长岩An−Ab−Or分类图解(据O'Connor,1965)

Fig.6 An−Ab−Or classification diagram of the Ehenaobaotu tonalite (after O'Connor,1965)

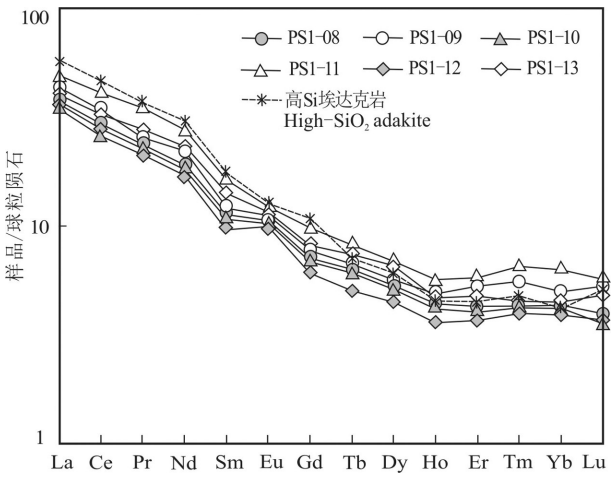

图7 额很傲包图英云闪长岩稀土元素球粒陨石标准化配分模式(球粒陨石标准化数值据Boynton, 1984;高Si埃达克岩据Martin et al.,2005)

Fig.7 Chondrite−normalized REE distribution patterns of the Ehenaobaotu tonalite (normalizing values after Boynton, 1984;High−SiO_2 adakite after Martin et al.,2005)

10^{-6},平均值0.99×10^{-6};Y含量6.77×10^{-6}~10.95×10^{-6},平均值8.66×10^{-6}。该英云闪长岩的铕异常不明显,δEu为0.94~1.27,平均值1.11,$(La/Yb)_N$7.39~8.80,轻重稀土分离明显,球粒陨石标准化的REE曲线呈LREE富集HREE亏损的右倾模式(图7)。

4.3 微量元素特征

如表2所示,该英云闪长岩具有高Sr和高Sr/Y比值的特征,Sr含量421.2×10^{-6}~475.30×10^{-6},平均值452.65×10^{-6};Sr/Y比值为42.21~70.21,平均值53.76。在原始地幔标准化的微量元素比值蛛网图中(图8),具有明显的Rb、Ba、Sr、K正异常和Nb、Ti、P负异常,与岛弧型岩浆岩微量元素分布型式相似。

5 讨　论

5.1 岩石成因类型与构造环境

如前所述,额很傲包图英云闪长岩体的SiO_2>

表3 额很傲包图英云闪长岩和高Si埃达克岩平均成分

Table 3 Average compositions of the Ehenaobaotu tonalite and high−SiO_2 adakites

岩石名称	SiO_2	Al_2O_3	MgO	Na_2O/K_2O	Sr	Yb	Y	Sr/Y
额很傲包图英云闪长岩	66.55	16.04	1.65	2.50	452.65	0.99	8.66	53.76
高Si埃达克岩	64.80	16.64	2.18	2.13	565.00	0.88	10.00	56.50

注:氧化物含量%,稀土、微量元素含量10^{-6}。额很傲包图英云闪长岩为研究区6个样品平均值,高Si埃达克岩为267个样品平均值(Martin et al.,2005)。

56%,Al_2O_3>15%,MgO<3%,Na_2O/K_2O比值>2,Sr>400×10^{-6},Yb<1.9×10^{-6},Y<18×10^{-6},Sr/Y比值>40,可与标准高Si埃达克岩相对比(表3);LREE相对HREE强烈富集,无明显的Eu异常,并与高Si埃达克岩(267个样品平均值)的稀土配分曲线基本吻合(图7);该岩石Rb、Ba、K和Sr等大离子亲石元素相对富集,Nb、P和Ti等高场强元素相对亏损,与高Si埃达克岩(267个样品平均值)蛛网图曲线相吻合(图8)。这些地球化学特征与国内、外典型岛弧型埃达克岩的特征相一致(Defant et al.,1990;刘敦一等,2003;王强等,2003;Martin et al.,2005;王金芳等,2017a,2018c)。因此,通过岩石学特征和主量、稀土、微量元素与标准高Si埃达克岩的对比(表3),并参考稀土元素配分图和微量元素蛛网图等(图7,8),额很傲包图英云闪长岩应归属为埃达克岩。

埃达克岩的岩浆成因和构造环境一直存在较大争议与分歧,可概括为以下2种主要观点:(1)俯冲洋壳部分熔融上升与上覆地幔楔橄榄岩反应成因的岛弧型埃达克岩(O型)(Defant et al.,1990;Kelemen,1995;Yogodzinski et al.,2001;Martin et al.,2005;Viruete et al.,2007;邓晋福等,2010,2015);(2)与加厚或拆沉玄武质下地壳熔融有关的埃达克岩(C型)(Sheppard et al.,2001;Hou et al.,2004;Wang et al.,2005;Xu et al.,2008)。一般认为,两种埃达克岩的主要区别在于岛弧型埃达克岩相对富钠(邓晋福等,2015),而C型埃达克岩则相对富钾。研究表明,由大洋俯冲带俯冲洋壳部分熔融形成的埃达克岩为一种特殊的岛弧型岩浆岩,即岛弧型中酸性富钠岩浆岩,主要为钙碱性系列,Na_2O/K_2O比值相对较大,一般认为多大于2(Defant et al.,1990;Stern et al.,1996;张旗等,2001;Samaniego et al.,2002;Bourdon et al.,2003;邓晋福等,2015)。加厚或拆沉的玄武质下地壳部分熔融产生的埃达克岩,则主要为高钾钙碱性系列,Na_2O/K_2O比值相对较小,一般认为多在1~2,甚至于$Na_2O/K_2O\leq1$,而且主要与造山带碰撞造山后"去根"作用或大陆板内古

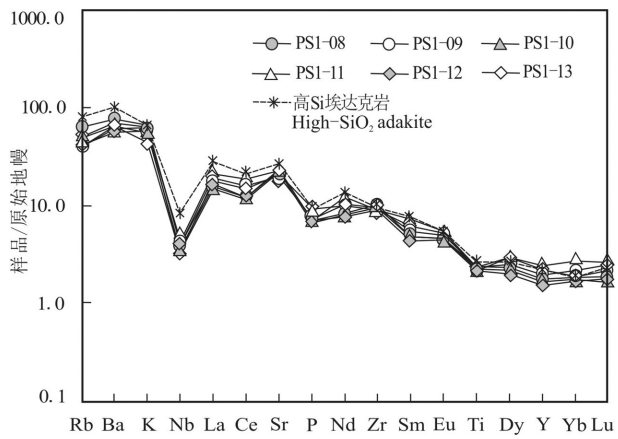

图8 额很傲包图英云闪长岩微量元素原始地幔标准化蛛网图 (原始地幔标准化数值据 Sun and McDonough, 1989;高Si埃达克岩据Martin et al.,2005)

Fig.8 Primitive mantle−normalized trace element spider diagram of the Ehenaobaotu tonalite(normalizing values after Sun and McDonough, 1989;High−SiO_2 adakite after Martin et al.,2005)

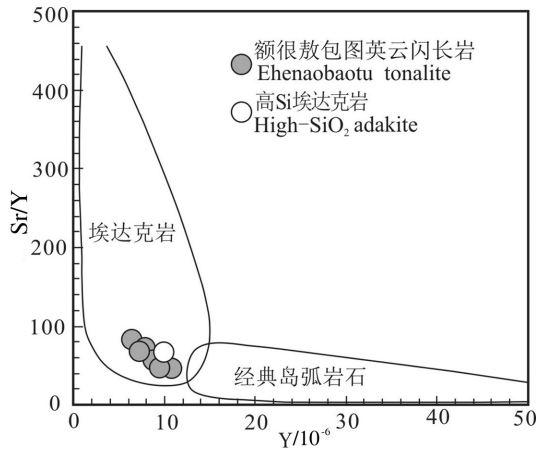

图9 额很傲包图英云闪长岩Y−Sr/Y构造判别图解(据Defant and Drummond,1990; Martin, 1999;高Si埃达克岩据Martin et al.,2005)

Fig.9 Y−Sr/Y tectonic discriminant diagram of the Ehenaobaotu tonalite (after Defant and Drummond,1990; Martin,1999;High−SiO_2 adakite after Martin et al.,2005)

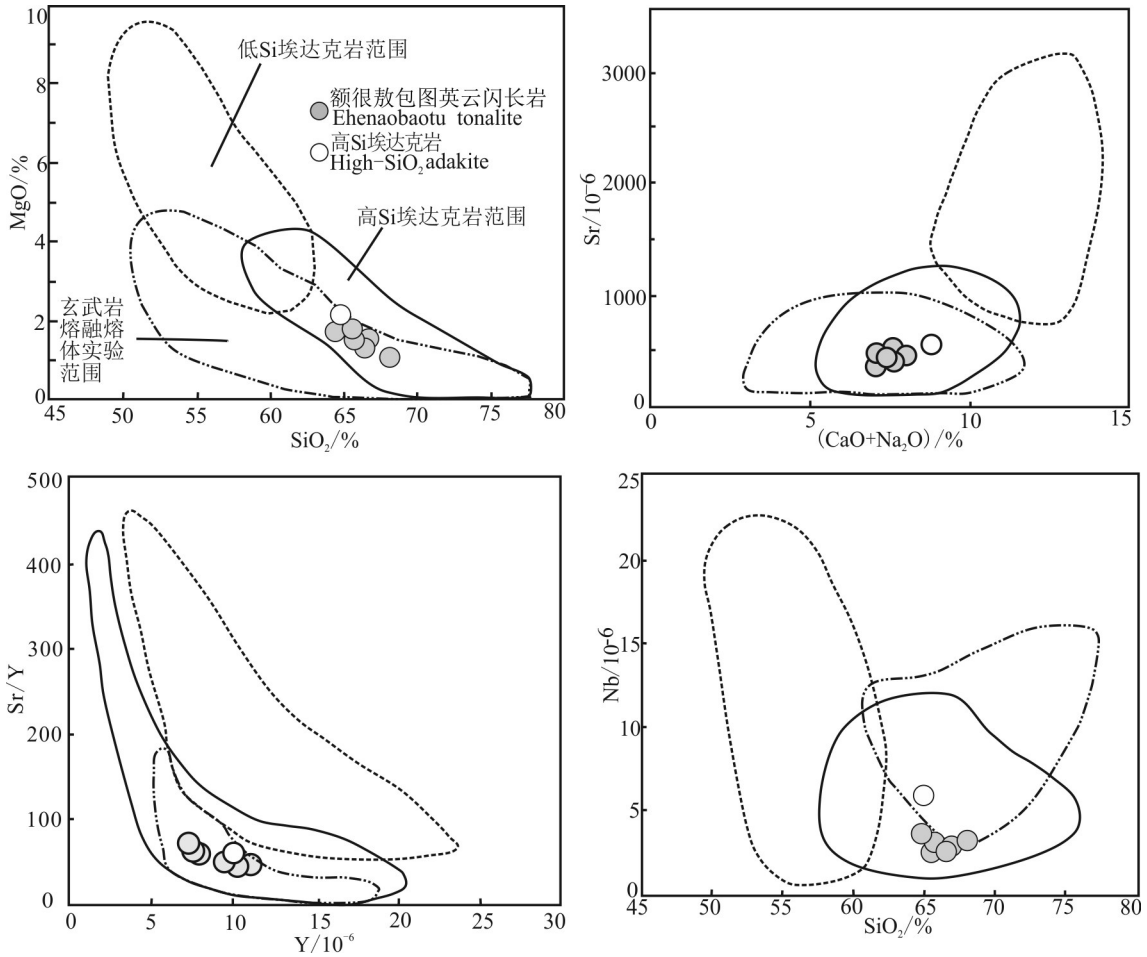

图10 额很傲包图英云闪长岩SiO_2-MgO、$(CaO+NaO_2)$-Sr、Y-Sr/Y和SiO_2-Nb图解(据Martin et al.,2005)

Fig.10 SiO_2-MgO,$(CaO+NaO_2)$-Sr,Y-Sr/Y and SiO_2-Nb diagrams of the Ehenaobaotu tonalite(after Martin et al.,2005)

老克拉通的"减薄"作用有关(张旗等,2001;王强等,2003)。

本区英云闪长岩属于中钾钙碱性系列,岩石富钠贫钾,Na_2O/K_2O为2.23~2.98 ,平均值2.5(表3),明显为富钠质岩石,具有岛弧型埃达克岩相对富钠的特征。在Y-Sr/Y图解中(图9),额很傲包图英云闪长岩均落入埃达克岩范围内,并与岛弧型高Si埃达克岩(267个样品的平均值)投点相吻合。在SiO_2-MgO、$(CaO+NaO_2)$-Sr、Y-Sr/Y和SiO_2-Nb图解中(图10),该岩石均落入高Si埃达克岩范围内,而且总体位于玄武岩熔融熔体范围内。这些地球化学图解,反映该英云闪长岩的物质来源或源区与俯冲洋壳玄武岩部分熔融物质的亲缘性和与岛弧型高Si埃达克岩源区的相似性,表明该英云闪长岩可能为岛弧型高Si埃达克岩。

在Rb-(Y+Nb)和Rb-(Yb+Ta)构造环境判别图解上(图11),额很傲包图英云闪长岩落在火山岛弧范围内,反映其为岛弧环境产物(Thorkelson et al.,2005;Viruete et al.,2007)。在识别TTG岩类(英云闪长岩-奥长花岗岩-花岗闪长岩)的An-Ab-Or分类图解中(图6),额很傲包图英云闪长岩体有4个样品投在英云闪长岩T_1(tonalite)区,1个样品投在奥长花岗岩T_2(trondhjemite)区,1个样品投在英云闪长岩T_1与奥长花岗岩T_2过渡区,反映该岩体具有$T_1T_2G_1$岩类的T_1T_2岩石组合特征(英云闪长岩-奥长花岗岩),进一步佐证其形成于大洋岛弧环境(邓晋福等,2015)。

综上所述,本区英云闪长岩的形成与大洋俯冲带环境形成的岛弧型高Si埃达克岩相类似,可能为俯冲洋壳部分熔融上升与上覆地幔楔橄榄岩反应成因(Rapp et al.,1999;邓晋福等,2015;肖庆辉等,2016)。然而,与高Si埃达克岩相类比,本区埃达克

岩相对富硅和明显高于MORB的Th含量(平均值3.93×10^{-6}),以及较高的Th/La(0.29~0.39)、Th/Sm(1.39~1.99)、Th/Yb(3.33~4.71)和Th/Ce(0.13~0.20)比值,又反映本区埃达克岩的岩浆源区除俯冲洋壳玄武岩部分熔融产生的熔体之外,尚有大洋俯冲沉积物组分参与部分熔融产生的(富Si)熔体。而且,额很傲包图埃达克岩的$Mg^{\#}$平均值为47,大于玄武岩部分熔融实验熔体的$Mg^{\#}$值(45),表明富Si熔体等板片熔体沿俯冲带向上运移过程中与上覆地幔楔橄榄岩之间发生反应,导致初始埃达克质岩浆的$Mg^{\#}$升高 (Sajona et al.,1993;Martin et al.,2005)。因此,大洋俯冲洋壳+俯冲深积物部分熔融产生的初始埃达克质熔体上升与上覆地幔楔橄榄岩反应,可能为额很傲包图埃达克岩的成因机制(图12)(Defant et al.,1993;Samaniego et al.,2002;Ishizuka et al.,2014;邓晋福等,2015;肖庆辉等,2016;Safonova,2017)。

5.2 古亚洲洋洋内俯冲作用

中亚造山带东段二连—贺根山缝合带区域地质调查研究工作取得重要进展,区内获得大量石炭纪蛇绿岩、石炭纪—二叠纪岛弧岩浆岩和三叠纪—早白垩世后造山A_2型花岗岩类的岩石学和年代学成果(图1b)(Miao et al.,2008;Xiao et al.,2009;Chen et al.,2009;Jian et al.,2012;Liu et al.,2013;邵济安,2015;Zhang et al.,2015;邓晋福等,2015;李英杰等,2015,2018b;田树刚等,2016;李钢柱等,2017;王金芳等,2017a,2018b;王树庆等,2018),为古亚洲洋二连—贺根山洋盆在石炭纪—中二叠世早期仍然存在和"晚二叠世"闭合提供了重要岩石学与年代学证据与约束。

Jian et al.(2012)在贺根山蛇绿岩的辉长岩墙和斜长花岗岩脉中分别获得354 Ma和333 Ma SHRIMP锆石U-Pb年龄,提出贺根山蛇绿岩形成于早石炭世。Zhang et al.(2015)在二连浩特东蛇绿岩中获得辉长岩锆石U-Pb年龄为354 Ma和353 Ma,斜长花岗岩年龄为345 Ma,指出该蛇绿岩形成于早石炭世。李英杰等(2016)在迪彦庙孬来可吐SSZ型蛇绿岩中获得层状辉长岩LA-ICP-MS锆石U-Pb年龄为330 Ma,蛇绿岩形成时代为早石炭世。李英杰等(2015)在梅劳特乌拉SSZ型蛇绿岩中获得辉长岩的LA-ICP-MS锆石U-Pb年龄为(308.5±2.2)Ma,提出该蛇绿岩形成于晚石炭世。Miao et al.(2008)在贺根山蛇绿岩带朝克山蛇绿岩中获得辉绿岩(墙)SHRIMP锆石U-Pb年龄为(295±9)Ma,认为朝克山蛇绿岩形成于晚石炭世。李刚柱等(2017)在内蒙古索伦山蛇绿岩带硅质岩中发现早二叠世放射虫化石,提出索伦山蛇绿岩形成时间持续到早二叠世,并提出古亚洲洋闭合时间在早二叠世之后。王惠等(2005)在内蒙古中部达茂旗巴彦敖包地区硅质岩中发现早二叠世晚期—中二叠世早期的放射虫化石,认为索伦山蛇绿岩带形成时间为中二叠世早期。越来越多的蛇绿岩年代学研究成果表

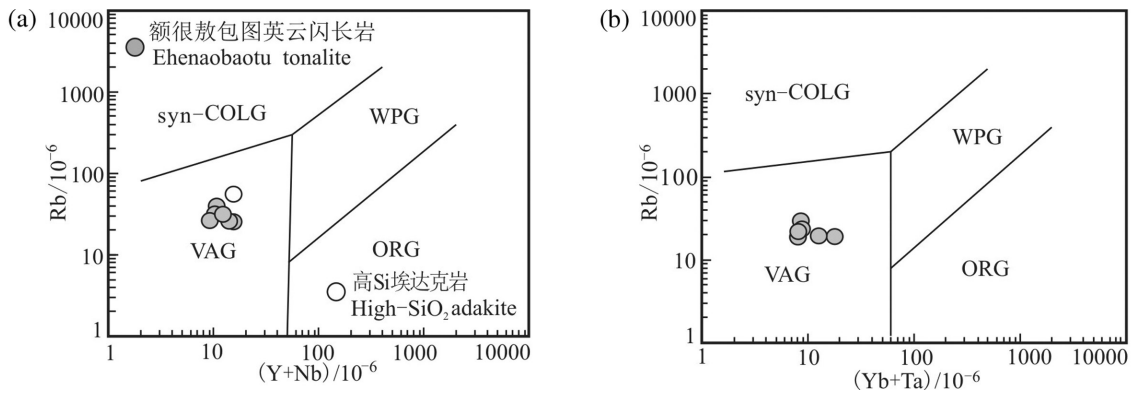

图11 额很傲包图英云闪长岩(Y+Nb)-Rb(a)及(Yb+Ta)-Rb(b)构造判别图解(据Pearce,1984;高Si埃达克岩据Martin et al.,2005)

Fig.11 (Y+Nb)-Rb (a) and (Yb+Ta)-Rb (b) tectonic discriminant diagrams of the Ehenaobaotu tonalite(after Pearce,1984;High-SiO_2 adakite after Martin et al.,2005)

syn-collision granites(syn-COLG), volcanic arc granites(VAG), within plate (WPG) and normal and anomalous ocean ridge (ORG) granites

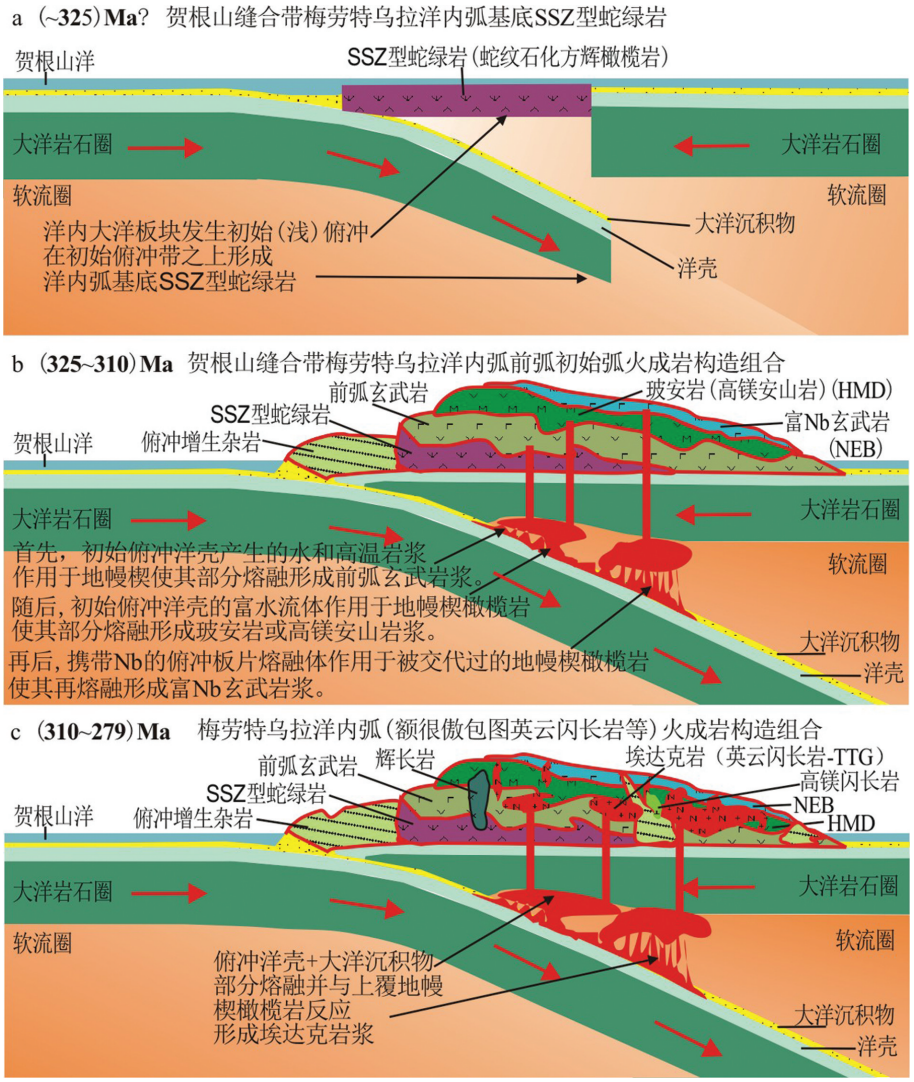

图12 额很傲包图英云闪长岩和梅劳特乌拉洋内弧火成岩构造组合成因与演化模式图

Fig.12 Genetic and evolution model of the Ehenaobaotu tonalite and igneous petrotectonic assemblage of the Meilaotewula intra-oceanic arc

明,二连浩特-贺根山缝合带发育早石炭世—晚石炭世蛇绿岩,而且存在着早二叠世(—中二叠世早期)蛇绿岩,表明古亚洲洋二连—贺根山洋盆在石炭纪—早二叠世(—中二叠世早期)仍然存在。本文额很傲包图晚石炭世((305.6±1.5)Ma)岛弧型高Si埃达克岩或TTG岩类的识别,更进一步揭示古亚洲洋二连—贺根山洋盆在晚石炭世并没有消失,而是正处于洋壳俯冲消减阶段,晚石炭世之后的一段时间可能为古亚洲洋二连—贺根山洋盆的洋壳俯冲期。

上述蛇绿岩的形成时代与该区石炭纪—二叠纪岛弧岩浆岩的形成时代相吻合。康健丽等(2016)在锡林浩特一带早石炭世岛弧型变质基性火山岩中获得(323~334)Ma的LA-ICP-MS锆石U-Pb年龄,提出古亚洲洋在早石炭世并没有关闭,而是正处于大洋俯冲消减阶段。刘建峰等(2009)在西乌旗南部晚石炭世早期岛弧型石英闪长岩中获得锆石LA-ICP-MS U-Pb年龄为322~325 Ma,认为形成于古亚洲洋俯冲岛弧环境。王树庆等(2018)在锡林浩特跃进地区获得一套岛弧型花岗闪长岩、英云闪长岩、石英闪长岩锆石LA-ICP-MS U-Pb年龄为310~330 Ma, 提出古亚洲洋在早石炭世—晚石炭世仍然存在并处于大洋俯冲状态。刘锐等(2016)在西乌旗达青牧场和苏勒陶勒盖花岗岩中分别获得锆石LA-ICP-MS U-Pb年龄为323 Ma和

(318)Ma,提出了晚石炭世大洋俯冲带岛弧型埃达克岩。Liu et al.(2013)在西乌旗达青牧场玄武岩中获得315~318 Ma的LA-ICP-MS锆石U-Pb年龄,认为玄武岩是晚石炭世古亚洲洋俯冲作用形成的岛弧岩浆岩。Chen et al.(2009)在白音宝力道晚石炭世岛弧型辉长闪长岩中获得SHRIMP锆石U-Pb年龄为310 Ma。张树栋等(2017)在二连浩特包饶勒敖包岛弧型石英闪长岩体中获得(302)Ma的LA-ICP-MS锆石U-Pb年龄,提出了晚石炭世末洋壳俯冲消减事件。Jian et al.(2010)在索伦山SSZ型蛇绿岩中获得洋内弧辉长岩和斜长花岗岩SHRIMP锆石U-Pb年龄分别为284 Ma和288 Ma,提出该区古亚洲洋初始俯冲时间为294~280 Ma(早二叠世)。王金芳等(2017a,2018a)在西乌旗梅劳特乌拉晚石炭世SSZ型蛇绿岩中识别出晚石炭世—早二叠世洋内弧玻安岩、埃达克岩(花岗闪长岩—英云闪长岩)和高镁闪长岩,分别获得(315.0±6.2)Ma、(294.7±1.7)Ma和(282±2)Ma的LA-ICP-MS锆石U-Pb年龄。Wang et al.(2017c)在西乌旗巴彦花识别出早二叠世岛弧型富Nb辉长岩,获得284 Ma的锆石LA-ICP-MS U-Pb年龄。总之,越来越多的岛弧岩浆岩年代学研究成果表明,二连—贺根山缝合带发育早石炭世—晚石炭世岛弧岩浆岩,存在着早二叠世岛弧岩浆岩,表明古亚洲洋二连—贺根山洋盆在石炭纪—早二叠世仍然存在。额很傲包图晚石炭世大洋俯冲带岛弧型高Si埃达克岩的确认,更进一步揭示古亚洲洋二连—贺根山洋盆在晚石炭世正处于洋壳俯冲消减过程中,而且表现出洋内俯冲作用或洋内弧(IOA intraoceanic arc)的TTG岩浆作用特征。这与该区梅劳特乌拉晚石炭世SSZ型蛇绿岩中的晚石炭世—早二叠世(315~279 Ma)洋内弧和迪彦庙SSZ型蛇绿岩中的早石炭世((333.4±8.5)Ma)达哈特洋内弧洋内俯冲与岩浆作用相一致(王金芳等,2017a,2018c,2021;李英杰等,2018b),可能反映古亚洲洋二连—贺根山洋盆在石炭纪—早二叠世存在着广泛而强烈的洋内俯冲作用,或该时期主要表现为洋内俯冲作用与洋内弧岩浆作用。

这些石炭纪—中二叠世早期蛇绿岩和岛弧岩浆岩的岩石学和年代学证据,与二连—贺根山缝合带区域内下二叠统寿山沟组半深海—深海复理石建造和中二叠统哲斯组泥岩中放射虫化石所反映的古洋盆环境相吻合(Shang,2004;公繁浩等,2013),也与该区石炭纪—早二叠世(古亚洲洋阶段)—中二叠世(兴蒙海槽阶段)构造古地理环境及演变阶段相对应(田树刚等,2016),表明古亚洲洋二连—贺根山洋盆在晚石炭世—中二叠世并没有关闭,而是正处于大洋俯冲消减阶段,大洋最终闭合应在中二叠世之后。结合二连—贺根山缝合带三叠纪—早白垩世后山造A_2型花岗岩类时空分布(张晓晖等,2006;石玉若等,2007;程天赦等,2014;王金芳等,2017b,2018b,2019b,2020b,c,e),二连—贺根山缝合带碰撞造山缝合时间应为二叠纪末期。因此,本文额很傲包图晚石炭世大洋俯冲带岛弧型高Si埃达克岩的识别与确认,可能更进一步揭示了古亚洲洋二连—贺根山洋盆在石炭纪—早二叠世正处于以洋内俯冲作用为特征的大洋俯冲消亡过程,也更进一步反映了中亚造山带东段二连—贺根山缝合带在石炭纪—早二叠世可能主要通过洋内俯冲作用形成洋内弧(IOA intraoceanic arc)与大洋板块地层(OPS ocean plate stratigraphy)或俯冲增生杂岩(SAC subduction accretional complex)的洋陆转换过程与信息(李英杰等,2012,2018b;李刚柱等,2017;Li et al.,2018a;王金芳等,2019a,2020a,d,2021)。

6 结 论

(1)通过岩石学和岩石地球化学研究,证明了额很傲包图英云闪长岩体是岛弧型埃达克岩,其形成于大洋俯冲带岛弧环境,俯冲洋壳+俯冲深积物部分熔融产生的初始埃达克质熔体上升与上覆地幔楔橄榄岩反应可能是其成因机制。

(2)额很傲包图岛弧型埃达克岩的形成年龄为(305.6±1.5)Ma,时代为晚石炭世,表明二连—贺根山缝合带在晚石炭世存在着大洋俯冲、岛弧岩浆作用。

(3)额很傲包图晚石炭世岛弧型埃达克岩的识别与确定,及其与梅劳特乌拉晚石炭世SSZ型蛇绿岩以及区域二连—贺根山缝合带石炭纪蛇绿岩、石炭世—二叠纪岛弧型岩浆岩的时空分布与演化关系,反映古亚洲洋二连—贺根山洋盆在晚石炭世—中二叠世仍然存在,而且可能主要表现为洋内俯冲与洋内弧岩浆作用。

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