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内蒙古西乌旗地区晚石炭世石英闪长岩的岩石成因及构造意义

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提要:内蒙古西乌旗地区出露一些石英闪长岩,其LA−ICP−MS锆石U−Pb年龄为(304.64±0.82)Ma和(309.84±0.86)Ma,表明这套岩石形成于晚石炭世。地球化学分析表明,西乌旗地区石英闪长岩属于低TiO_2和高Al_2O_3钙碱性玄武岩系列;富集Rb、Ba、K大离子亲石元素(LILE),亏损Nb、Ta、Ti、P等高场强元素(HFSE),具有典型弧岩浆岩的特征,显示岩浆源区曾经历过俯冲带流体的交代作用;稀土元素丰度偏低,呈LREE富集HREE亏损的右倾模式;强不相容元素比值(La/Nb、La/Ta等)及判别图解表明晚石炭世石英闪长岩类似大陆边缘弧玄武岩,岩浆来源于浅部岩石圈地幔,系石榴石+尖晶石二辉橄榄岩源区中等程度(10%~20%)部分熔融的结果。综合研究区样品的地球化学特征,结合区域地质资料及对比分析前人成果,认为早石炭世末期西乌旗地区在强烈拉张的裂谷环境下形成了有限洋盆,由于洋盆发育不成熟或边伸展边向两侧俯冲—消减,形成了西乌旗地区类似大陆边缘弧玄武岩特征的晚石炭世石英闪长岩。

关 键 词:石英闪长岩;锆石年龄;地球化学;拉张环境,晚石炭世;西乌旗

中图分类号:P588.12+2 **文献标志码**:A **文章编号**:1000−3657(2016)06−1932−15

Petrogenesis and tectonic significance of Late Carboniferous quartz diorite in Xi Ujimqin Banner, Inner Mongolia

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Abstract: Late Carboniferous quartz diorites are distributed in the Xi Ujimqin Banner of Inner Mongolia. The results of LA-ICP-MS zircon U-Pb dating of the quartz diorite samples indicate ages of 304.64±0.82 Ma and 309.84±0.86 Ma. In addition, new geochemical data from six quartz diorite samples are presented. All six samples show high Al_2O_3 values but low TiO_2 values, and are thus classified as calc-alkali basalt series. These samples are characterized by low REE abundance and slight LREE enrichment. They also show LILE enrichment, HFSE depletion and distinctly negative Nb and Ta anomalies. All of these characteristics resemble those of arc magmatic rocks. Furthermore, as shown in the correlation plots of La/Ba versus La/Nb, Ba/La versus Ce/Pb, and Nb/Y versus La/Yb, the magma source has experienced contamination and metasomatism from the subduction fluid. According to the Zr/Nb, La/Nb, La/Ta ratios and the diagram of Sm/Yb versus La/Sm, the magma was derived from the shallow lithospheric mantle and formed by moderate (10% - 20%) partial melting of spinel- garnet lherzolites. Based on geochemical characteristics of these samples in this study, combined with regional geological data and previous research results, the authors hold that, in the late Early-Carboniferous, there was a new limited ocean basin under an intensely extensional rift setting. Consequently, as the newly formed ocean basin was still immature or experienced subduction- related contamination and metasomatism, the Late Carboniferous quartz diorites of Xi Ujimqin Banner exhibited the continental margin-arc-like enriched signatures.

Key words: quartz diorite; zircon U-Pb dating; geochemistry; extensional setting; late Carboniferous; Xi Ujimqin Banner

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中亚造山带是全球显生宙地壳增生与改造最显著的地区,其构造演化一直备受国内外学者的关注与研究,详细的增生过程仍然是国际学术界争议的前沿课题[1-10]。中国内蒙古地区位于中亚造山带中东部,华北板块与西伯利亚板块之间,区内岩浆活动频繁,岩浆弧和增生楔中散布着众多前寒武纪微地块和条带状蛇绿岩,正确认识各地质体间的时空关系对解决中亚造山带的构造演化具有重要意义[11]。长期以来,在内蒙古地区晚古生代构造演化的问题上一值存在争议,焦点之一就是该地区古亚洲洋的最终闭合时间。关于古亚洲洋的闭合时间,存在多种不同的观点:泥盆纪[7-8,12]、石炭纪早期[9,13]、二叠纪[1,3-4,14-18]。

内蒙古西乌旗位于内蒙古中部即兴蒙造山带范围内,西乌旗地区广泛出露晚石炭世石英闪长岩,储存了大量晚古生代构造演化信息,但对该地区石炭纪的构造环境仍存在争议。鲍庆中等[19]对西乌旗白音高勒地区的石炭纪石英闪长岩进行了SHRIMP锆石U-Pb年代学测定,所获年龄为(313±5)Ma~(323±4)Ma,认为其形成于华北板块与亲西伯利亚板块碰撞之后的张性构造环境。刘建峰等[11]通过分析西乌旗南部的石炭纪石英闪长岩的地球化学特征,认为其形成于与俯冲有关的活动陆缘的构造环境,并且获得了(325±3)Ma和(323±3)Ma两个LA-ICP-MS锆石U-Pb年龄。因此本文在1∶5万区域地质调查的基础上,选择西乌旗南部猴头庙出露的石英闪长岩(图1-a)进行岩石学、年代学和地球化学研究,探讨其形成的构造环境,以期为该地区的晚古生代构造演化提供新的依据。

1　地质概况及岩石特征

研究区位于内蒙古西乌旗南部,大地构造位置上处于西伯利亚板块南缘增生带与华北板块北缘增生带的碰撞接壤部位,同时也位于贺根山蛇绿岩带和温都尔庙—西拉木伦河缝合带之间(图1-b)。区内晚古生代岩浆活动强烈,研究区石英闪长岩以岩滴和小岩基形式产出,其侵入到早元古代宝音图群、奥陶纪布龙山组、石炭系本巴图组和早石炭世闪长岩,部分岩体还带有片岩捕掳体,并且石英闪长岩被二叠纪花岗岩侵入,出露面积约20 km^2。少数岩石发生韧性变形,局部岩石见有闪长质暗色包体(图2-a、b)。岩石呈浅灰色、灰白色、浅灰绿色,中细粒半自形柱状结构,块状构造。主要由斜长石、角闪石和石英组成。镜下特征为:斜长石1~3

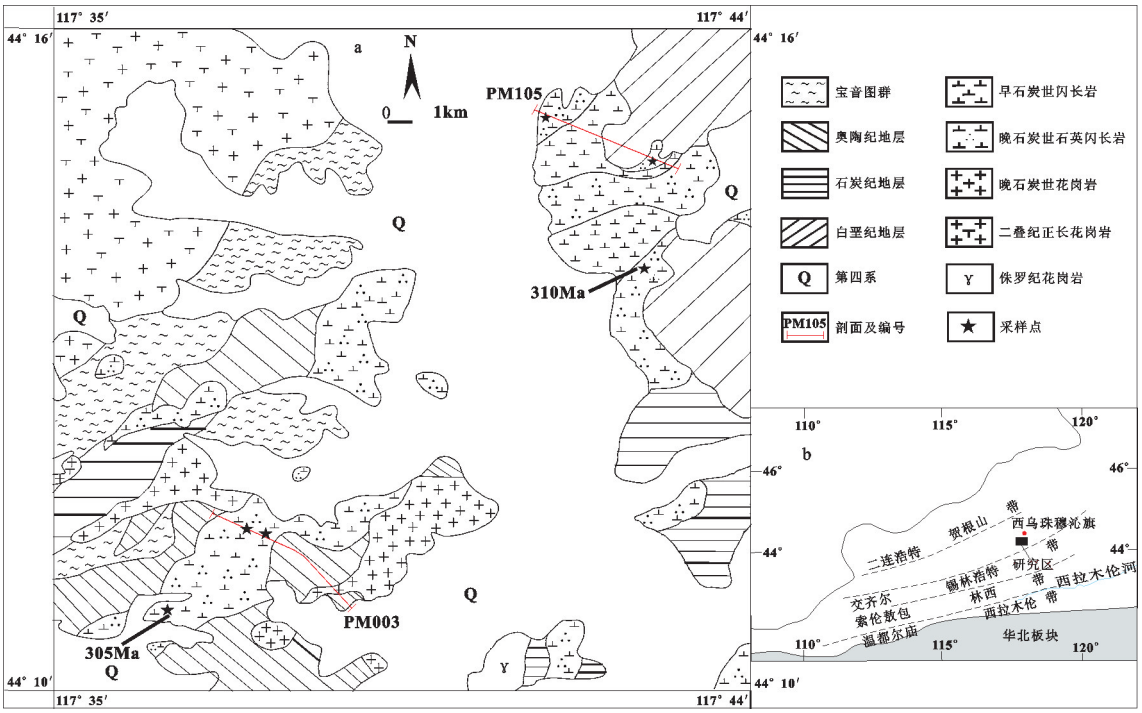

图1研究区地质简图和大地构造位置简图

a—研究区地质简图,据资料❶修改;b—大地构造位置简图,据[4]和[17]修改

Fig. 1 Geological sketch map and simplified tectonic geological map

a–Geological sketch map (modified after reference❶);

b–Simplified tectonic geological map (modified after references [4] and [17])

mm,半自形板状,发育聚片双晶,绢云母化、黝帘石化,含量约45%~55%;浅黄—褐色角闪石1~2 mm,长柱状,部分绿泥石化、次闪石化,与斜长石相间分布,韧性变形的岩石角闪石被挤压呈透镜状长轴定向排列,含量约30%~35%;石英他形细粒状,分布在斜长石和角闪石之间,含量约10%~15%;黑云母少量;岩石中见有磁铁矿、榍石、磷灰石等副矿物(图2-c、d)。本文采集了6个比较新鲜的地球化学样品和2个比较新鲜的年龄样品,采样位置见图1-a。

2 样品分析方法

样品主量元素和微量元素在河北省区域地质矿产调查研究所实验室分别采用XRF和ICP-MS仪器完成,主量元素相对标准偏差(RSD)小于5%,微量元素的RSD小于10%。

锆石的挑选由河北省区域地质矿产调查研究所实验室完成,制靶和阴极发光实验在北京锆年领航科技有限公司制备,锆石U-Pb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,具体实验原理和数据处理方法详见参考文献[20]。

3 年代学特征

本文对研究区出露的石英闪长岩进行了LA-ICP-MS锆石U-Pb年代学研究。所选样品阴极发光图像(CL)如图3所示,U-Pb谐合图见图4,LA-ICP-MS锆石U-Pb年龄结果见表1。

样品D3014-TW1采样位置为东经117°35′58″,北纬44°10′46″,D3021-TW1采样位置为东经117°41′53″,北纬44°14′02″。锆石浅褐色到黑色,晶形复杂,短柱状和粒状,少数长柱状。从阴极发光图像(图3)中可以看出,大部分锆石韵律环带比较发育,

❶中国地质大学(北京)地质调查研究院.内蒙古1:5万巴拉格尔农业分场幅(L50E022015)、阿拉腾格勒公社幅(L50E022016)、猴头庙幅(L50E023015)、阿拉腾敖包大队幅(L50E023016)区域地质调查报告[R]. 2012.

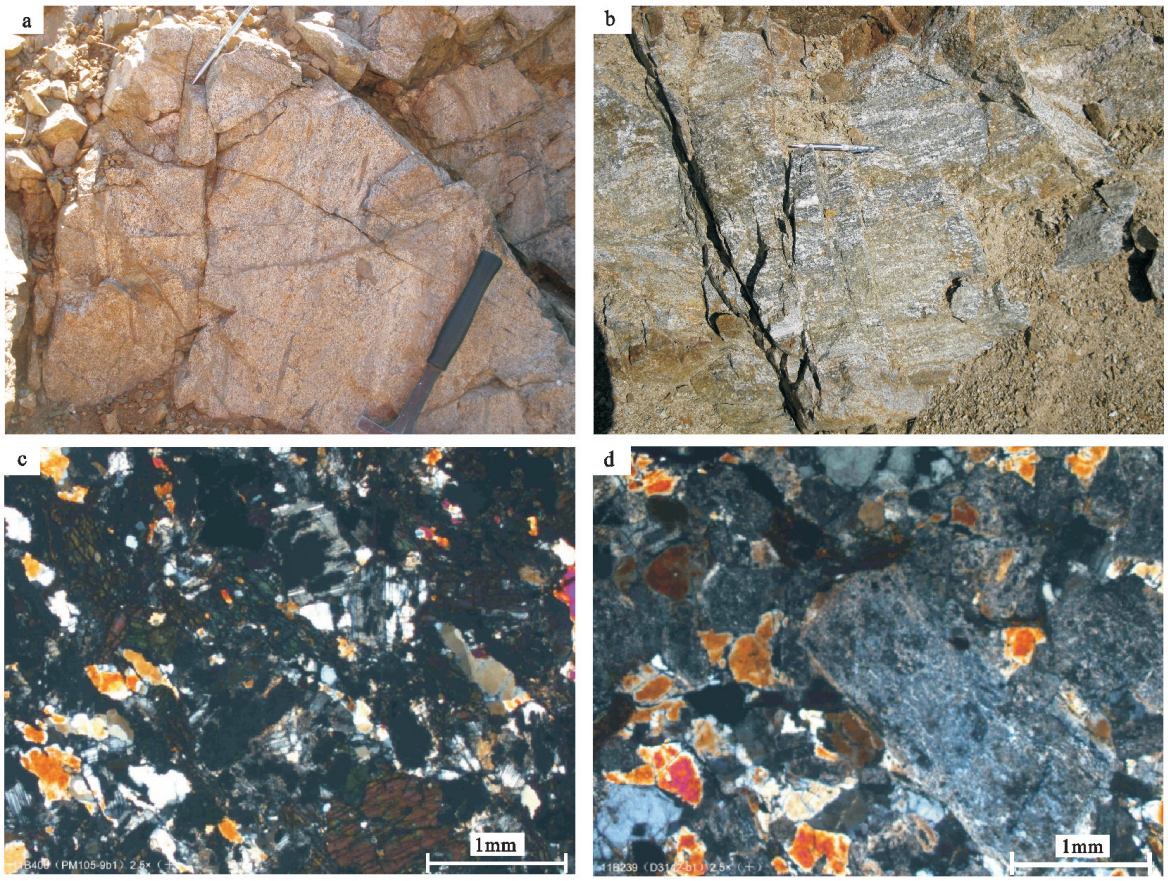

图2 石英闪长岩野外与显微照片

Fig.2 Representative field photos and photomicrographs of quartz diorites

显示了岩浆成因的特征[21]。样品D3014−TW1的25个点的测试结果U含量和Th/U比值分别为104×10^{-6}~572×10^{-6}和0.31×10^{-6}~0.73×10^{-6};样品D3021−TW1的23个点的测试结果U含量和Th/U比值分别为65×10^{-6}~246×10^{-6}和0.34×10^{-6}~0.68×10^{-6};均反映了岩浆成因的特征。D3014−TW1和D3021−TW1的$^{206}Pb/^{238}U$年龄加权平均值分别为(304.64±0.82)Ma(MSWD =0.71)和(309.84±0.86)Ma(MSWD =0.40)(图4),代表了石英闪长岩的侵位结晶年龄。

4 地球化学特征

石英闪长岩的主量元素和微量元素分析结果见表2。

4.1 主量元素

石英闪长岩的SiO_2质量分数为58.22%~62.68%;Al_2O_3含量较高(15.69%~17.27%),平均16.21%;MgO含量偏低(2.76%~4.08%),$Mg^{\#}$为47.1~52.56;TiO_2质量分数比较低(0.59%~0.80%),平均0.69%;Na_2O和K_2O含量分别为2.85%~3.86%、1.24%~2.01%,Na_2O/K_2O比值1.58~3.10,为钠质岩石;铝饱和指数A/CNK值介于0.88~1.08,平均0.98,属于准铝质及弱的过铝质。在TAS图解中(图5−a)所有样品均分布在亚碱性闪长岩区域,并且里特曼指数σ为1.23~1.68,属钙性岩石,与TAS图解结果相符。AFM图解中(图5−b)样品落入钙碱性玄武岩系列范围。

4.2 微量元素

安第斯活动大陆边缘弧玄武岩Nb含量为5.3×10^{-6},Ta为0.25×10^{-6}~0.5×10^{-6},Ni为38.6×10^{-6},Cr为48.4×10^{-6};而岛弧钙碱性玄武岩Nb含量为0.7×10^{-6},Ta为0.1×10^{-6},Ni为50×10^{-6},Cr为160×10^{-6}[22]。研究区石英闪长岩Nb的含量为3.05×10^{-6}~4.33×10^{-6},Ta为0.28×10^{-6}~0.42×10^{-6}(除样品D3014异常1.55×10^{-6}),Ni为9.03×10^{-6}~18.4×10^{-6},Cr为18.4×10^{-6}~

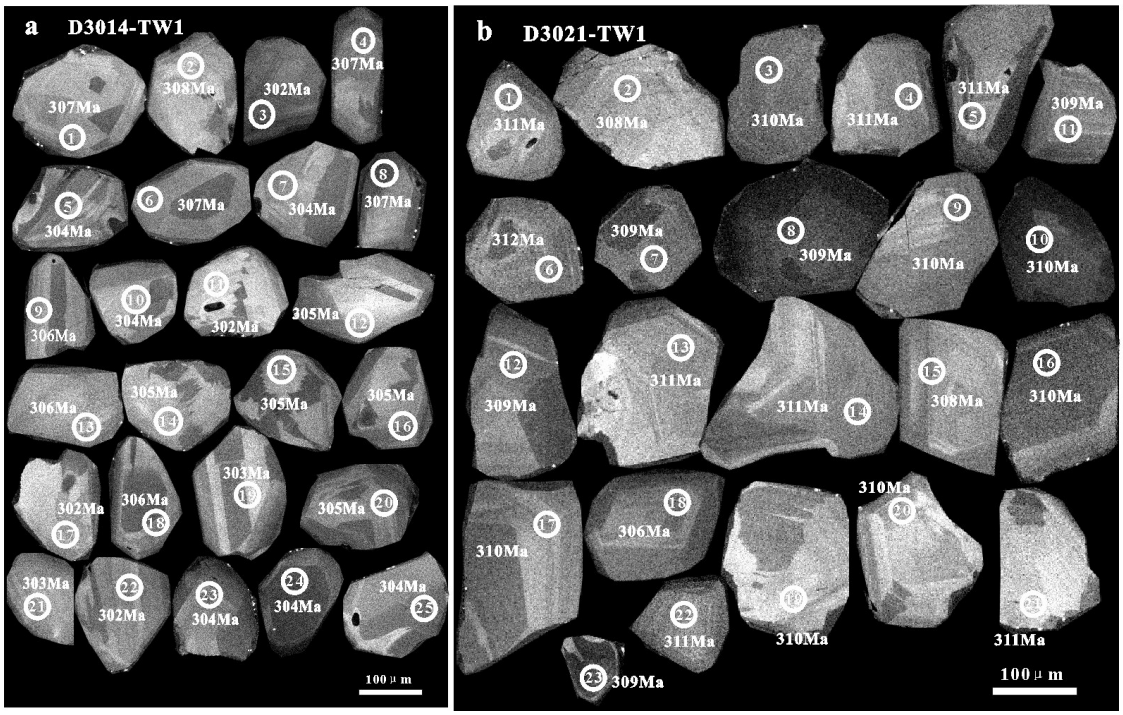

图3 石英闪长岩锆石阴极发光图像

Fig. 3 CL images for analyzed zircon grains from quartz diorites

51.4×10^{-6}，总体与安第斯活动大陆边缘弧玄武岩接近。在原始地幔标准化的微量元素比值蛛网图中（图6−a），同样显示LILE和Th富集和Nb、Ta、Ti、P等高场强元素的亏损，与弧岩浆岩微量元素分布型式相似[23]，同样具有与俯冲作用有关岩浆岩的特征[24]。

4.3 稀土元素

石英闪长岩稀土总量为82.27×10^{-6}~100.68×10^{-6}，$(La/Yb)_N$为2.79~3.92（LREE/HREE=1.46~1.85），具有弱的负Eu异常，δEu为0.74~0.94。轻稀土元素内部存在明显的分馏作用（$(La/Sm)_N$=1.57~2.16），而重稀土元素内部存在较弱的分馏作用（$(Gd/Yb)_N$=1.07~1.46）。球粒陨石标准化的REE曲线（图6−b）呈LREE富集HREE亏损的右倾模式。

5 讨 论

5.1 岩石成因

高场强元素如Nb、Ta、Ti等在蚀变和变质作用过程中具有良好稳定性，是岩石成因和源区性质的良好示踪剂。源于软流圈地幔的玄武岩La/Nb < 1.5，La/Ta < 22，岩石圈地幔玄武岩则与之相反[25]。研究区石英闪长岩的La/Nb为2.45~3.40，La/Ta为25.44~37.10（样品D3014比较低，为6.96），说明本区岩石来源于岩石圈地幔。一般地壳岩石的TiO_2含量很低（平均0.72%[26]），来自软流圈的岩浆TiO_2含量在1.27%左右[23]，而与深部地幔物质活动有关的岩浆，TiO_2含量往往大于2.0%[27]。测区晚石炭世石英闪长岩TiO_2质量分数为0.59%~0.80%，平均值为0.69%，TiO_2含量较低，显示岩浆源区主要与浅部的地幔有关。

一般地，当尖晶石二辉橄榄岩发生部分熔融时，地幔残留体和熔体具有相似的Sm/Yb比值，而La/Sm比值将随着部分熔融程度的增高而降低，因此，尖晶石二辉橄榄岩源区的部分熔融将产生相对水平的熔融趋势（接近或靠近地幔排列）；而石榴石二辉橄榄岩源区（源区残留有石榴石）中低程度部分熔融产生的熔体具有显著增高的Sm/Yb比值，导致石榴石二辉橄榄岩的熔融趋势明显偏离地幔排列[27−28]。在Sm/Yb−La/Sm图（图7−a）上，研究区石英闪长岩投点与石榴石+尖晶石二辉橄榄岩熔融趋势为代表的地幔排列趋势一致，暗示岩浆主要来源于石榴石+尖晶石二辉橄榄岩源区中等程度（10%~20%）的部分熔融。Dy/Yb也是判断源区性质的重

表1 西乌旗地区石英闪长岩LA-ICP-MS锆石U-Pb测年结果

Table 1 LA-ICP-MS zircon U-Pb isotopic data of quartz diorites from Xi Ujimqin Banner

测点号	含量/10^{-6}		$^{232}Th/^{238}U$	同位素比值						表面年龄/Ma			
	Pb	U		$^{206}Pb/^{238}U$	1σ	$^{207}Pb/^{235}U$	1σ	$^{207}Pb/^{206}Pb$	1σ	$^{206}Pb/^{238}U$	1σ	$^{207}Pb/^{235}U$	1σ
D3014-1	9	165	0.52	0.0488	0.0004	0.3558	0.0158	0.0529	0.0024	307	2	309	14
D3014-2	7	132	0.50	0.049	0.0004	0.3554	0.0224	0.0526	0.0033	308	3	309	19
D3014-3	5	104	0.45	0.048	0.0004	0.3518	0.0175	0.0532	0.0026	302	3	306	15
D3014-4	6	112	0.31	0.0488	0.0004	0.3541	0.0081	0.0527	0.0012	307	2	308	7
D3014-5	14	266	0.44	0.0483	0.0003	0.3576	0.0117	0.0536	0.0017	304	2	310	10
D3014-6	10	174	0.69	0.0488	0.0003	0.356	0.0099	0.0529	0.0015	307	2	309	9
D3014-7	20	376	0.62	0.0482	0.0003	0.3574	0.0099	0.0538	0.0015	304	2	310	9
D3014-8	10	192	0.45	0.0488	0.0003	0.3559	0.0109	0.0529	0.0016	307	2	309	9
D3014-9	11	195	0.71	0.0486	0.0003	0.3525	0.0105	0.0526	0.0016	306	2	307	9
D3014-10	9	160	0.73	0.0483	0.0003	0.3519	0.0101	0.0528	0.0015	304	2	306	9
D3014-11	13	250	0.60	0.048	0.0003	0.3507	0.0161	0.053	0.0024	302	2	305	14
D3014-12	11	206	0.45	0.0485	0.0003	0.3542	0.0136	0.053	0.002	305	2	308	12
D3014-13	29	572	0.41	0.0485	0.0003	0.358	0.0126	0.0535	0.0018	306	2	311	11
D3014-14	6	123	0.48	0.0485	0.0003	0.358	0.0115	0.0535	0.0017	305	2	311	10
D3014-15	12	240	0.37	0.0484	0.0003	0.3514	0.0116	0.0527	0.0017	305	2	306	10
D3014-16	11	196	0.59	0.0485	0.0003	0.3499	0.013	0.0523	0.0019	305	2	305	11
D3014-17	14	258	0.57	0.048	0.0003	0.3514	0.0115	0.0532	0.0017	302	2	306	10
D3014-18	10	180	0.52	0.0487	0.0003	0.3526	0.0153	0.0525	0.0023	306	2	307	13
D3014-19	11	209	0.63	0.0481	0.0003	0.3504	0.0133	0.0528	0.002	303	2	305	12
D3014-20	9	154	0.67	0.0485	0.0003	0.3547	0.0149	0.0531	0.0021	305	2	308	13
D3014-21	8	157	0.36	0.0482	0.0003	0.357	0.0127	0.0537	0.0019	303	2	310	11
D3014-22	8	156	0.43	0.0479	0.0003	0.347	0.01	0.0525	0.0015	302	2	302	9
D3014-23	10	191	0.47	0.0483	0.0003	0.3571	0.01	0.0536	0.0015	304	2	310	9
D3014-24	18	354	0.45	0.0483	0.0003	0.3589	0.0071	0.0539	0.0011	304	2	311	6
D3014-25	11	204	0.64	0.0483	0.0003	0.3497	0.0114	0.0525	0.0017	304	2	305	10
D3021-1	6	107	0.4164	0.0494	0.0003	0.3694	0.0116	0.0543	0.0017	311	2	319	10
D3021-2	6	102	0.5494	0.0489	0.0003	0.522	0.0116	0.0774	0.0016	308	2	426	9
D3021-3	8	151	0.4027	0.0493	0.0003	0.3686	0.0075	0.0542	0.0011	310	2	319	7
D3021-4	5	101	0.3445	0.0495	0.0003	0.3584	0.0121	0.0525	0.0017	311	2	311	10
D3021-5	7	124	0.4208	0.0494	0.0003	0.3652	0.0098	0.0536	0.0014	311	2	316	9
D3021-6	6	107	0.4277	0.0496	0.0003	0.3635	0.0117	0.0532	0.0017	312	2	315	10
D3021-7	5	106	0.4043	0.0491	0.0003	0.372	0.0105	0.0549	0.0015	309	2	321	9
D3021-8	7	130	0.4711	0.0491	0.0003	0.3556	0.0089	0.0525	0.0013	309	2	309	8
D3021-9	12	246	0.3402	0.0492	0.0003	0.3615	0.0049	0.0532	0.0007	310	2	313	4
D3021-10	5	102	0.4167	0.0493	0.0003	0.3684	0.0113	0.0542	0.0016	310	2	318	10
D3021-11	11	224	0.3416	0.0491	0.0003	0.3653	0.0062	0.054	0.0009	309	2	316	5
D3021-12	5	91	0.4193	0.0491	0.0003	0.3635	0.0127	0.0537	0.0018	309	2	315	11
D3021-13	7	135	0.5738	0.0494	0.0003	0.3815	0.0089	0.056	0.0013	311	2	328	8
D3021-14	5	84	0.4655	0.0494	0.0003	0.3746	0.0123	0.055	0.0018	311	2	323	11
D3021-15	6	109	0.4122	0.049	0.0004	0.3596	0.0138	0.0532	0.0017	308	2	312	12
D3021-16	6	117	0.4262	0.0493	0.0003	0.3836	0.0095	0.0564	0.0014	310	2	330	8
D3021-17	9	171	0.5827	0.0493	0.0003	0.3855	0.0076	0.0567	0.0011	310	2	331	6
D3021-18	3	54	0.3689	0.0486	0.0004	0.3559	0.0189	0.0531	0.0028	306	2	309	16
D3021-19	4	77	0.4988	0.0493	0.0003	0.3787	0.0183	0.0557	0.0026	310	2	326	16
D3021-20	6	104	0.6805	0.0492	0.0003	0.3707	0.0146	0.0546	0.0021	310	2	320	13
D3021-21	4	81	0.571	0.0494	0.0003	0.3645	0.0133	0.0535	0.0019	311	2	316	11
D3021-22	3	65	0.5273	0.0495	0.0003	0.3725	0.0177	0.0546	0.0026	311	2	322	15
D3021-23	4	75	0.5036	0.049	0.0004	0.3691	0.0153	0.0546	0.0023	309	2	319	13

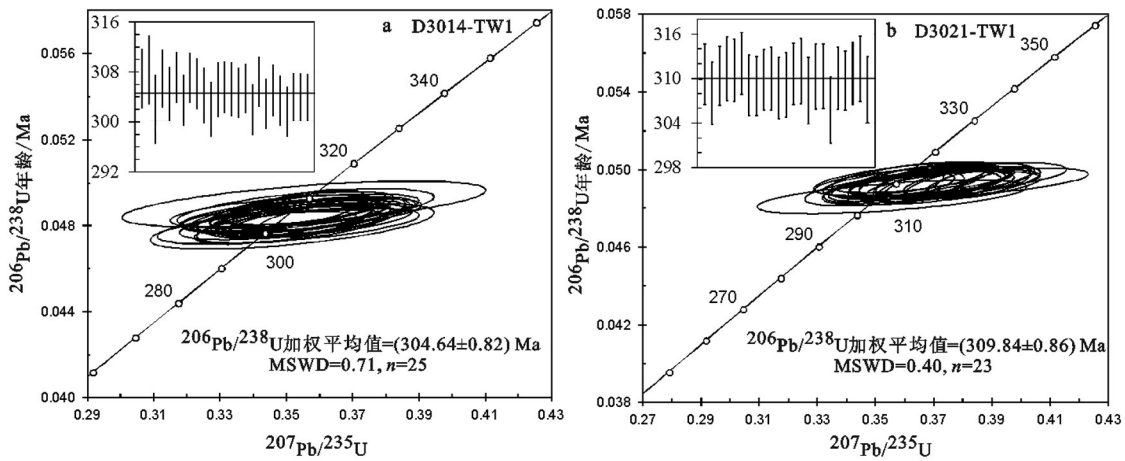

图4 石英闪长岩LA-ICP-MS锆石U-Pb年龄协和图

Fig. 4 LA-ICP-MS U-Pb concordia diagrams for analyzed zircon grains from quartz diorites

要指标;如果源区是石榴石稳定区域,其熔体的Dy/Yb > 2.5;如果熔融作用在尖晶石稳定区域,则熔体的Dy/Yb < 1.5[29]。研究区石英闪长岩Dy/Yb为1.72~2.06,比值介于石榴石稳定区与尖晶石稳定区之间,也说明其岩浆为石榴石+尖晶石二辉橄榄岩部分熔融的产物。

岩石明显富集LILE(K、Rb、Ba)、LREE和强不相容元素Th,亏损Nb、Ta、P、Ti等高场强元素,具有岛弧或活动大陆边缘弧岩浆岩的特点。岩石具有明显的"TNT"(Ta、Nb、Ti)异常,Sun and Mcdonough[23]认为其主要为俯冲带幔源岩石的特点。在图La/Nb-La/Ba中(图7-b),所有样品位于俯冲改造的大陆岩石圈区域,再次证明源区主要受到消减带流体交代作用的影响。在Ba/La-Ce/Pb图解(图8-a)中,样品分布在沉积岩与俯冲带岩浆区域内,暗示源区在部分熔融之前可能经历了沉积物质的影响[31]。Nb/Y和La/Nb比值图解(图8-b)更进一步说明源区主要受俯冲板块流体交代作用控制[32]。

5.2 构造环境

一些强不相容元素对在岩浆活动中由于其分配系数远小于部分熔融比例,并且在变质过程中具有较好的稳定性,其比值在部分熔融及分离结晶过程中保持不变,从而可以消除岩石后期变化及岩浆演化过程中的影响,反映原始岩浆及源区的性质[33-34],因此可以作为判断其形成的构造环境及源区性质的依据。表3列出了研究区不相容元素的元素对比值。严格按照Condie[33]提出的不同构造背景玄武岩的判别流程,发现本区石英闪长岩属于大陆边缘弧钙碱性玄武岩(CABC)。

在Nb×2-Zr/4-Y三角图解(图9-a)中,所有样品落入C和D区域,表明这些样品不是板内碱性玄武岩和富集洋中脊玄武岩,但是难以进一步区分这些样品是正常洋中脊玄武岩、板内拉斑玄武岩还是火山弧玄武岩。已有研究表明,Hf/3-Th-Nb/16构造环境判别图解可以识别出洋中脊玄武岩、板内碱性玄武岩以及火山弧拉斑玄武岩[35],Hf/3-Th-Nb/16图解(图9-b)表明这些样品为火山弧玄武岩。另外,Canbanis and Lecolle[36]提出的Y/15-La/10-Nb/8图解(图9-c)可以用来区分火山弧玄武岩、大陆玄武岩和大洋玄武岩,该图解判别结果表明,所有样品落入钙碱性大陆火山弧玄武岩及过渡区域。并且在区分大洋弧还是大陆边缘弧的Th/Yb-Ta/Yb图解(图9-d)中,样品基本投影在大陆边缘弧区域及附近,而未落入板内玄武岩和洋中脊玄武岩区域,进一步辅助Nb×2-Zr/4-Y三角图解证明样品为火山弧玄武岩。

因此,上述一系列玄武岩构造环境判别图解及微量元素比值均表明研究区石英闪长岩具有大陆边缘弧玄武岩的特征。

5.3 构造意义

西乌旗地区石英闪长岩的LA-ICP-MS锆石U-Pb年龄分别为(304.6±0.82)Ma和(309.8±0.86)

表2 西乌旗地区石英闪长岩主量元素分析结果(%)、微量元素分析结果(10^{-6})

Table 2 Major (%) and trace element (10^{-6}) analytical result of quartz diorites from Xi Ujimqin Banner

样号	PM105-1YQ1	PM105-15YQ1	D3021YQ1	PM003-25YQ1	PM003-26YQ1	D3014YQ1
SiO_2	58.78	58.71	59.78	58.49	62.68	58.22
Al_2O_3	16.06	15.92	16.09	17.27	15.69	16.21
TiO_2	0.72	0.70	0.64	0.67	0.59	0.80
Fe_2O_3	2.40	2.73	2.39	3.41	3.03	2.64
FeO	4.44	4.19	4.17	3.14	2.59	4.74
CaO	6.25	5.87	5.33	4.76	3.65	5.89
MgO	3.65	4.08	3.89	3.07	2.76	3.92
K_2O	1.89	1.73	1.39	1.24	2.01	1.39
Na_2O	2.98	2.85	3.28	3.86	3.49	2.95
MnO	0.13	0.12	0.13	0.11	0.11	0.13
P_2O_5	0.12	0.15	0.13	0.13	0.11	0.17
LOI	2.48	2.86	2.48	3.74	3.22	2.81
TOTAL	99.90	99.89	99.68	99.89	99.91	99.85
A/CNK	0.88	0.92	0.97	1.06	1.08	0.95
A/NK	2.31	2.43	2.33	2.25	1.98	2.55
σ	1.50	1.33	1.30	1.68	1.53	1.23
$Mg^{\#}$	49.87	52.46	52.56	47.10	48.30	49.76
V	152.28	167.20	147.20	150.93	143.37	132.70
Cr	34.87	51.40	26.44	23.95	27.67	18.40
Co	20.53	21.60	16.72	17.96	17.06	15.93
Ni	14.07	18.40	13.54	13.57	13.95	9.03
Cu	45.08	34.40	37.11	130.70	36.13	73.90
Zn	64.59	66.40	65.86	64.79	62.79	60.56
Ga	15.70	15.72	13.85	15.64	16.15	11.74
Rb	56.76	54.70	39.35	41.67	73.47	35.39
Sr	298.02	322.50	273.20	400.90	319.01	205.10
Zr	131.50	113.20	62.50	106.90	134.60	43.61
Nb	4.19	3.71	3.05	3.66	4.33	3.96
Cs	1.06	1.29	1.70	1.48	2.05	1.16
Ba	233.60	281.00	133.60	142.10	250.20	147.40
Hf	6.72	6.03	0.96	5.48	6.75	0.64
Ta	0.40	0.37	0.28	0.33	0.42	1.55
Pb	9.60	8.40	8.61	7.72	9.64	7.85
Th	5.23	4.95	4.57	10.00	11.19	3.04
U	1.34	1.34	0.73	0.96	1.20	0.83
La	11.68	11.86	10.35	11.20	10.61	10.81
Ce	25.93	25.33	25.29	24.58	22.25	24.96
Pr	3.56	3.53	3.43	3.52	3.13	3.30
Nd	15.85	15.62	15.57	16.31	13.48	14.07
Sm	3.84	3.80	4.13	4.20	3.09	3.47
Eu	1.12	1.08	0.92	1.05	0.82	1.00
Gd	3.63	3.54	3.53	4.00	2.81	3.09
Tb	0.71	0.68	0.72	0.78	0.54	0.62
Dy	4.16	4.19	4.52	4.54	3.21	3.99
Ho	0.93	0.91	0.90	0.98	0.69	0.79
Er	2.50	2.45	2.43	2.52	1.87	2.26
Tm	0.48	0.48	0.42	0.46	0.38	0.39
Yb	2.30	2.32	2.50	2.21	1.83	2.32
Lu	0.35	0.34	0.34	0.33	0.26	0.32
Y	21.35	21.70	25.63	22.97	17.32	22.11
Σ REE	98.40	97.83	100.68	99.64	82.27	93.50
LREE/HRE	1.70	1.67	1.46	1.57	1.85	1.61
$(La/Yb)_N$	3.42	3.45	2.79	3.42	3.92	3.14
δ Eu	0.92	0.90	0.74	0.78	0.85	0.94
La_N/Sm_N	1.91	1.96	1.57	1.68	2.16	1.96
Gd_N/Yb_N	1.27	1.23	1.14	1.46	1.24	1.07
La/Nb	2.79	3.20	3.40	3.06	2.45	2.73
La/Ta	29.05	32.05	37.10	33.73	25.44	6.96
Dy/Yb	1.81	1.81	1.81	2.06	1.76	1.72
Nb/U	3.12	2.77	4.17	3.82	3.60	4.79

Ma。锆石结晶较好,具有岩浆岩锆石的特征,因此锆石年龄代表了岩体的形成年龄。野外观测到晚石炭世本巴图组、阿木山组呈角度不整合覆盖于石英闪长岩体之上,这也验证了同位素年龄测定结果的正确性。两个石英闪长岩的形成年龄相近,并且在微量元素蛛网图和球粒陨石标准化分配图上所有样品具有相似的曲线分布形式,表明两套岩体具有同源的特点。因此,西乌旗地区的石英闪长岩应该为同一期岩浆作用,岩浆活动时代为晚石炭世。

研究表明,中亚造山带形成于"多地体、多俯冲、多岛弧、多碰撞"的复杂构造背景,伴随着古亚洲洋的俯冲和闭合,产生了广泛的岛弧、蛇绿岩、增

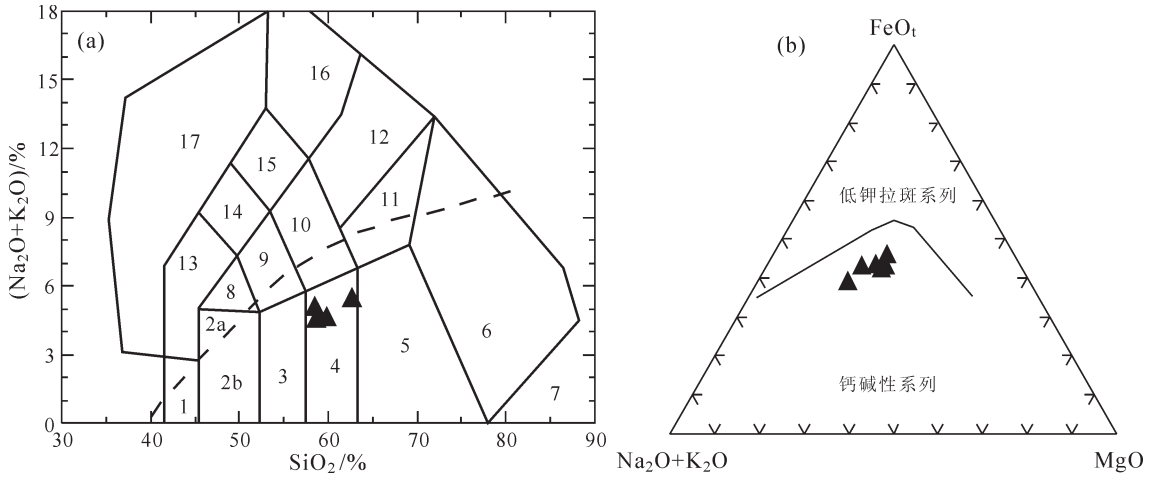

图5 TAS图解(a)和AFM图解(b) (据[22]修改)

1—橄榄辉长岩;2a—碱性辉长岩;2—b亚碱性辉长岩;3—辉长闪长岩;4—闪长岩;5—花岗闪长岩;6—花岗岩;7—硅英岩;8—二长辉长岩;9—二长闪长岩;10—二长岩;11—石英二长岩;12—正长岩;13—副长石辉长岩;14—副长石二长闪长岩;15—副长石二长正长岩;16—副长正长岩;17—副长深成岩虚线下方亚碱性,上方碱性

Fig. 5 TAS diagram (a) and AFM diagram (b) (modified after reference [22])

1−Olive gabbro; 2a−Alkaline gabbro ; 2b−Sub−alkaline gabbro; 3−Gabbro diorite; 4−Diorite; 5−Granodiorite; 6−Granite; 7−Quartzolite; 8− Monzogabbro; 9−Monzodiorite; 10−Monzonite; 11−Quartz monzonite ; 12−Syenite; 13−Foid gabbro; 14−Foid monzodiorite; 15−Foid monzosyenite; 16− Foid syenite; 17−Foid plutonite The sub−alkaline rocks are below the dashed line, whereas the alkaline rocks are above the dashed line

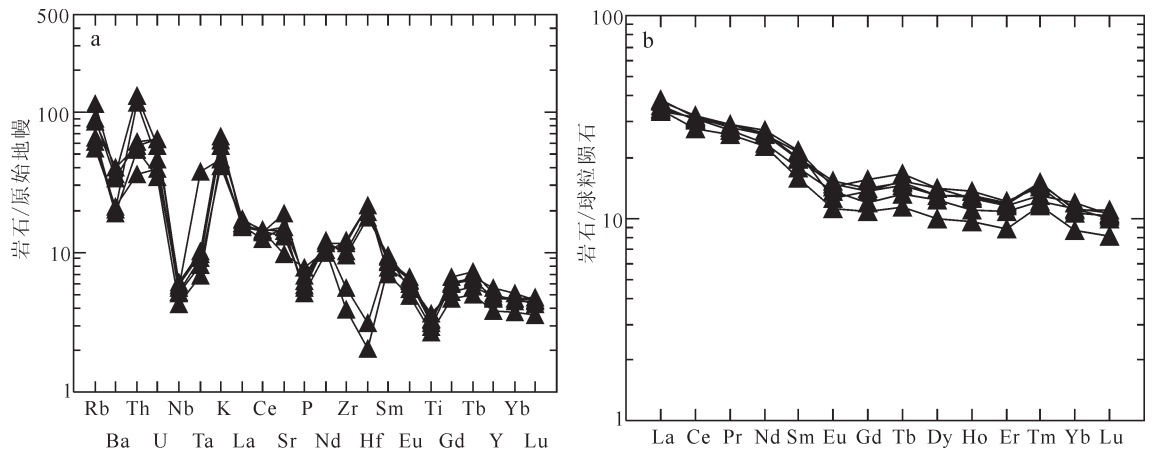

图6原始地幔标准化微量元素蛛网图(a))和稀土元素球粒陨石标准化图(b) (据[23])

Fig. 6 Primitive mantle−normalized trace elements spider diagram (a) and chondrite−normalized REE patterns (b) (modified after reference [23])

生楔和增生造山,以及诸多微地块的碰撞造山作用,形成了比较复杂的中亚造山带。晚古生代是兴蒙造山带乃至中亚构造演化的一个关键阶段,古亚洲洋的闭合以及大规模的成矿作用均发生在这一时期[3−5,39]。有关兴蒙造山带石炭纪的构造环境一直存在争议,有些学者认为石炭纪古亚洲洋已经闭合,发育陆表海和裂陷槽,与造山后伸展作用有关[8−10,13];有些学者提出石炭纪仍为俯冲的构造环境[3−4,15,18]。兴蒙造山带石炭—二叠纪广泛发育裂谷活动[40],现在越来越多的资料说明石炭—二叠纪时本区广泛发育双峰式火山岩、碱性花岗岩和基性岩,属于裂谷环境[41−44],与造山后阶段以发育巨量花岗岩和强烈岩

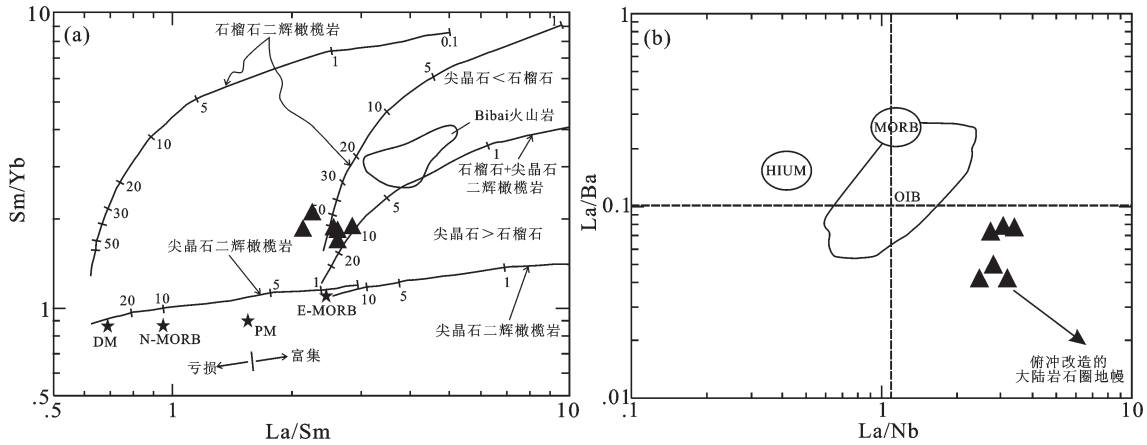

图7 Sm/Yb−La/Sm图解 (a,据[27]) 和La/N b−La/Ba图解 (b,据[30])

DM—亏损地幔;PM—原始地幔;N−MORB—正常洋中脊玄武岩;E−MORB—富集洋中脊玄武岩;MORB—洋中脊玄武岩;OIB—洋岛玄武岩;HIUM—高U/Pb比值地幔

Fig. 7 Sm/Yb−La/Sm diagram (a) (modified after reference [27]) and La/Nb−La/Ba diagram (b) (modified after reference [30])

DM−Depleted mantle; PM−Primitive mantle; N−MORB−Normal mid−ocean ridge basalts; E−MORB−Enriched mid−ocean ridge basalts; MORB− Mid−ocean ridge basalts; OIB−Ocean island basalts; HIUM−High U/Pb ratio mantle

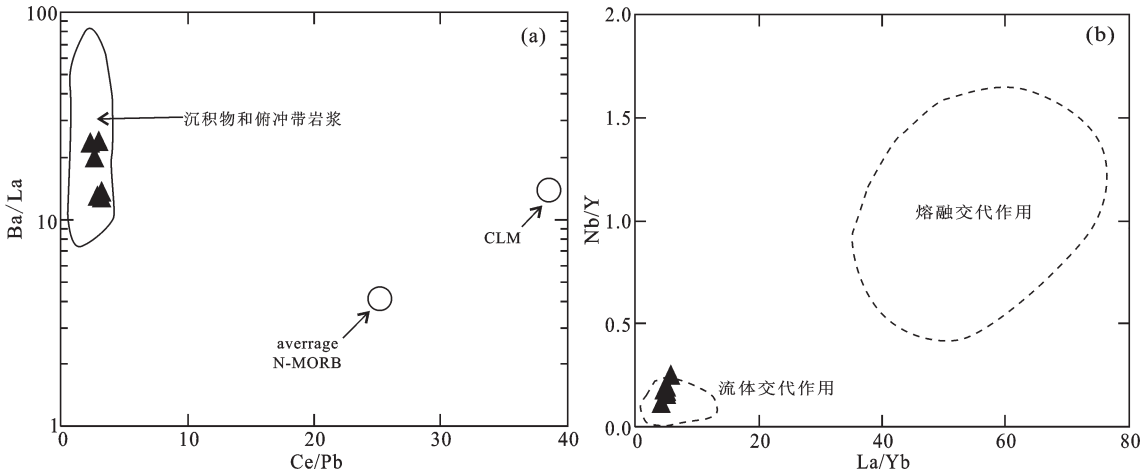

图8 Ce/Pb−Ba/La图解(a) (据[31])和La/Yb−Nb/Y图解(b)(据[32])

average N−MORB—平均正常洋中脊玄武岩; CLM—大陆岩石圈地幔

Fig. 8 Ce/Pb−Ba/La diagram (a) (modified after reference [31]) and La/Yb−Nb/Y diagram (a) (modified after reference [32])

average N−MORB−Average mid−ocean ridge basalts; CLM−Continental lithospheric mantle

浆作用为标志的认识较为一致[45−46]。西乌旗白音高勒地区的晚石炭世石英闪长岩形成于华北板块与亲西伯利亚板块碰撞之后的张性构造环境[19];并且陈彦等[43]认为西乌旗地区早二叠世双峰火山岩具有板内成因特征,形成于碰撞后的伸展环境。从地质特征来看,在东乌旗—西乌旗贺根山蛇绿岩带两侧,局部发育的上石炭统(格根敖包组)滨浅海碎屑岩和碳酸盐岩中夹有大量安山岩、粗安岩和晶屑凝灰岩,反映拉伸减薄作用中地壳成熟度降低的过程[47]。西乌旗地区石炭—二叠纪海槽同期异相地层、大石寨组双峰式火山岩[48]和东乌旗晚石炭−早二叠世宝力高庙组陆相火山岩[49],亦显示了区域伸展构造环境特征。

通过1∶5万区域地质调查在该区新发现超基性

表3 西乌旗地区石英闪长岩不相容元素对比值判别构造环境

Table 3 Incompatible element ratios for discriminating tectonic environment of quartz diorites from Xi Ujimqin Banner

样号	PM105-1YQ1	PM105-15YQ1	D3021YQ1	PM003-25YQ1	PM003-26YQ1	D3014YQ1	平均值
				第一级划分			
Nb/La	0.36	0.31	0.29	0.33	0.41	0.37	0.34
Hf/Ta	16.72	16.30	3.44	16.51	16.18	0.41	11.59
La/Ta	29.05	32.05	37.10	33.73	25.44	6.96	27.39
Ti/Y	201.63	194.50	149.49	175.92	202.53	216.48	190.09
Ti/V	28.27	25.24	26.03	26.77	24.46	36.07	27.81
TiO_2	0.72	0.70	0.64	0.67	0.59	0.80	0.69
Ta	0.40	0.37	0.28	0.33	0.42	1.55	0.56
Nb	4.19	3.71	3.05	3.66	4.33	3.96	3.82
				第二级划分			
Th/Yb	2.27	2.13	1.83	4.53	6.12	1.31	3.03
Th/Nb	1.25	1.33	1.50	2.73	2.59	0.77	1.69
Nb/La	0.36	0.31	0.29	0.33	0.41	0.37	0.34
Hf/Th	1.29	1.22	0.21	0.55	0.60	0.21	0.68
				第三级划分			
Zr/Y	6.16	5.22	2.44	4.65	7.77	1.97	4.70
Ta/Yb	0.17	0.16	0.11	0.15	0.23	0.67	0.25

岩、基性岩，地球化学特征同李英杰[50-51]新发现内蒙古西乌旗迪彦庙蛇绿岩相似，可能为本区的洋壳残片[52]。白卉[53]对西乌旗迪彦庙蛇绿岩中的辉长岩进行LA-ICP-MS锆石U-Pb测年，获得年龄为(320±1)Ma，与本区辉长岩锆石年龄(321±2Ma)吻合，说明早石炭世末期本区在强烈拉张的环境下形成了裂陷槽，并且在地壳相对较薄或者裂陷较深的部位，可能形成了尚未成熟的新洋盆[54]。在早二叠世时期，满都拉所处的索伦—贺根山一带在强烈拉张的裂谷背景下进一步发育成有限洋盆[55]。通过对贺根山两侧西乌旗和东乌旗地区晚石炭世岩体的研究，虽然大部分岩体被划为后碰撞伸展构造环境的产物[19,43,47,56-57]，但少数岩体具有火山弧的特征[11,58-59]。而且本文的石英闪长岩也具有俯冲带弧岩浆岩的地球化学特征。因此，在综合分析和对比的基础上，结合前人的研究成果，本文认为在早石炭世末—早二叠世时期，贺根山一带处于强烈的裂谷背景下，并且在强烈拉张的环境下逐步形成了新洋盆。其中西乌旗地区洋盆形成于早石炭世末期，由于洋盆发育不成熟或边伸展边向两侧俯冲—消减，导致浅部地幔部分熔融形成了本区具有大陆边缘弧特征的晚石炭世石英闪长岩。

6 结 论

(1)西乌旗地区石英闪长岩LA-ICP-MS锆石U-Pb年龄分别为(304.64±0.82)Ma和(309.84±0.86)Ma，属于晚石炭世。

(2)西乌旗地区晚石炭世石英闪长岩富集Rb、Ba、K大离子亲石元素和强不相容元素Th，亏损Nb、Ta、Ti、P等高场强元素，具有火山弧玄武岩的的特征，显示岩浆源区受到过消减带流体的交代作用；同时TiO_2含量较低(平均0.69%)，强不相容元素比值(La/Nb > 1.5，La/Ta > 22，等)及图解，指示其岩浆来源于浅部的岩石圈地幔，系石榴石+尖晶石二辉橄榄岩源区中等程度(10%~20%)部分熔融的结果。

(3)综合研究区样品的地球化学特征、结合区域地质资料以及对比分析前人研究成果，认为早石炭世末期西乌旗地区在强烈拉张的裂谷环境下形成了有限洋盆，由于洋盆发育不成熟或边伸展边向两侧俯冲-消减，导致浅部地幔部分熔融形成了本区具有大陆边缘弧特征的晚石炭世石英闪长岩。

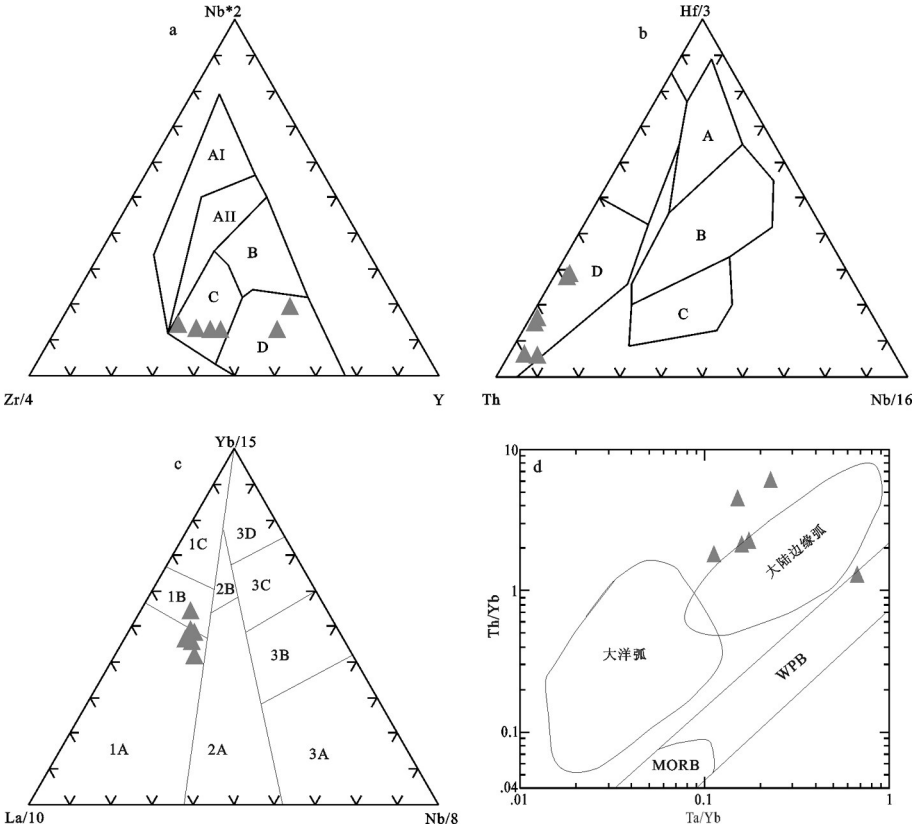

图9 微量元素构造环境判别图解(据[35−38])

a:AⅠ+AⅡ—板内碱性玄武岩;B—富集型洋中脊玄武岩;C—板内拉斑玄武岩+火山弧玄武岩;D—正常洋中脊玄武岩+火山弧玄武岩。

b:A—正常洋中脊玄武岩;B—富集型洋中脊玄武岩;C—板内碱性玄武岩及分异产物;D—火山弧拉斑玄武岩及分异产物。

c:1A—钙碱性大陆火山弧玄武岩;1B—钙碱性大陆火山弧玄武岩和大陆火山弧拉斑玄武岩区过渡区;1C—大陆火山弧拉斑玄武岩区;2A—大陆玄武岩;2B—弧后盆地玄武岩;3A—大陆裂谷碱性玄武岩;3B和3C—异常洋中脊玄武岩;3D—正常洋中脊玄武岩。

d: MORB—洋中脊玄武岩;WPB—板内玄武岩

Fig. 9 Tectonic environmental discriminative diagrams of trace elements(modified after references [35−38])

(Fig. a. modified after reference [37]; Fig. b. modified after reference [35]; Fig. c. modified after reference [36]; Fig. d. modified after reference [38])

a: AⅠ+AⅡ−Intraplate alkali basalts; B, E−MORB, Enriched mid−ocean ridge basalts; C, Intraplate tholeiites and volcanic−arc basalts; D−N−MORB and volcanic−arc basalts. b: A−N−MORB, Normal mid−ocean ridge basalts; B−E−MORB, Enriched mid−ocean ridge basalts; C−Intraplate alkaline basalts; D−Island−arc tholeiites. c: 1A−Calcium alkaline continental island arc basalts; 1B−Transition zone; 1C−Volcanic arc tholeiite; 2A−Continental basalts; 2B−Arc−back basin basalts; 3A−Continental rift alkaline basalts; 3B and 3C, Abnormal mid−ocean ridge basalts; 3D−Normal mid−ocean ridge basalts. d: MORB−Mid−ocean ridge basalts; WPB−Intraplate basalt

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