吉林省中部地区早古生代英云闪长岩的成因：锆石 U-Pb 年代学和地球化学证据*

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Abstract Northeast (NE) China is composed of a Paleozoic orogenic collage that is considered to be the eastern segment of the Central Asian Orogenic Belt (CAOB). In the Paleozoic, NE China evolved from amalgamation of multiple microcontinental massifs, such as the Erguna, Xing'an, Songnen-Zhangguangcai Range, Jiamusi, and Khanka from west to east. The Early Paleozoic tectonic evolutionary history between the microcontinental massifs and the North China Block (NCB) is the key for us to understand the Paleozoic evolution of the NE China. Recently, one of the key issues about the Paleozoic evolutionary history in the eastern segment of the northern margin of the NCB is whether or not the Early Paleozoic accretion belt existed. The previous studies considered that the Early Paleozoic accretion belt existed according to the Early Paleozoic igneous rock belt extending from west to east in the Jilin Province, while others are dubious about the whole idea because they have ascertained that some "Early Paleozoic" intrusion and strata including volcanic rock formed in the Late Paleozoic or Early Mesozoic based on zircon U-Pb dating. The issue clearly requires high precision data on the crystallization ages and geochemical data of the igneous rocks in this area. We conducted LA-ICP-MS zircon U-Pb dating and whole-rock geochemical analysis on "Caledonian granite" in the central Jilin Province, with the aim of constraining the tectonic setting of the eastern segment of the northern margin of the NCB during the Early Paleozoic. The study area in this paper is located at the north to the boundary of geosyncline-platform of the NCB, east to the Songliao Basin, west to the Dunhua-Mishan Fault, and south to Changchun-Yanji suture belt. The oldest strata in this area, Zhangjiatun Formation with the characteristics of molasse construction, distributing near the Zhangjiatun village, is composed of amaranth and motley conglomerate rock at the bottom, pebbly sandstone in the middle, and siltstone and red tuffaceous siltstone above. The coral and brachiopod fossils were found in the middle of the Zhangjiatun Formation, which indicated that it formed in the Late Silurian-Early Devonian. The strata is unconformity upon the granites, which is called Zhangjiatun tonalites in this paper, distributes on the top of the mountain and exposed as wide as $100m^2$. Otherwise, Late Paleozoic to Mesozoic intrusions and volcanic rocks are widespread around the study area. LA-ICP-MS zircon U-Pb geochronology, geochemistry and zircon Hf isotope of the tonalites near Zhangjiatun village, Yongji County, in the central Jilin Province, have been reported, aimed to investigate the source property and tectonic setting. The majority of zircons from the sample are euhedral-subhedral with oscillatory growth zoning, and their Th/U ratios range from 0.26 ~ 1.62, indicating their magmatic origin. $^{206}Pb/^{238}U$ ages for 14 analyses range from 440Ma to 448Ma, yielding a weighted mean $^{206}Pb/^{238}U$ age of 443 ± 5Ma (MSWD = 0.085), interpreted to represent the emplacement age of the Zhangjiatun tonalities. The other 4 spots yield a weighted mean $^{206}Pb/^{238}U$ age of 501 ± 11Ma (MSWD = 0.038), representing the crystallization ages of captured zircons entrained by the tonalites. The Zhangjiatun tonalities are composed of plagioclase (66%), quartz (25%), and biotite (8%), and accessory minerals as apatite, zircon, and opaque mineral (1%). Geochemically, they have SiO_2 = 71.5% ~ 72.9%, MgO = 0.91% ~ 1.36%, $Mg^{\#}$ = 20 ~ 26,

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and $Na_2O + K_2O = 4.38\% \sim 5.25\%$, and exhibit low K_2O (0.22% ~0.76%), high Na_2O (3.82% ~4.49%), and low TiO_2 (0.30% ~0.42%) contents, which indicate they are belonging to low K tholeiitic series. Their A/CNK values and A/NK values range from 0.95 to 1.25 and 1.71 to 1.94, respectively, mainly belong to I type granites. They display relatively flat rare earth element (REE) patterns [$(La/Yb)_N = 5.01 \sim 5.60$], with low total REE abundances ($\sum REE = 15.3 \times 10^{-6} \sim 23.4 \times 10^{-6}$), and obvious positive Eu anomalies ($Eu/Eu^* = 1.85 \sim 2.59$). The tonalites have trace element spidergrams characterized by large ion lithophile elements (LILEs, such as Rb and Ba) and Th, U, and Pb enrichments, and high field strength elements (HFSEs, such as Nb and Ta) depletions. Zircons from the tonalities have $^{176}Hf/^{177}Hf$ values of 0.282815 ~0.282856, $\varepsilon_{Hf}(t)$ values of +9.92 to +13.6, and t_{DM1} values of 567 ~674Ma, together with t_{DM2} values of 648 ~911Ma, which suggest the characteristics of the juvenile source of the Zhangjiatun tonalities. The geochemical characteristics of the Zhangjiatun tonalites are consistent with those of the oceanic plagiogranite, according to their low in TiO_2 (lower than 1%), K_2O and P_2O_5 contents, and in FeO^T/MgO values, suggesting their derivation of the partial melting of cumulate gabbro, the part of oceanic crust. Their enrichment in LILEs and depletion in HFSEs indicate the involvement of the subduction-related fluids during the partial melting of their source. Taken together, the Zhangjiatun tonalities could be derived from the parting melting of the oceanic cumulate gabbro under the high temperature and low pressure environment, similar to the forearc setting of an island arc background. Combined with the unconformity relationship with the overlying Late Silurian-Early Devonian Zhangjiatun Formation, we concluded that the Early Paleozoic accretion belt existed along the eastern segment of the northern margin of the NCB.

Key words Early Paleozoic; Tonalite; Zircon U-Pb chronology; Geochemistry; Northeast China; Eastern segment of the northern margin of the North China Block

摘 要 本文对吉林省中部地区永吉县张家屯附近出露的早古生代英云闪长岩进行了LA-ICP MS锆石U-Pb年代学、地球化学及锆石Hf同位素的研究,探讨了该英云闪长岩的源区性质及构造背景。张家屯英云闪长岩出露面积约100m²,与其呈沉积接触关系的是具磨拉石建造特点的张家屯组地层。LA-ICP MS锆石U-Pb定年结果显示,张家屯英云闪长岩的形成时代为443±5Ma,即晚奥陶世-早志留世。该英云闪长岩的SiO_2含量介于71.5%~72.9%,具有低K_2O(0.22%~0.76%)、高Na_2O(3.82%~4.49%)和低TiO_2(0.30%~0.42%)的特征,属于低钾拉斑系列。其A/CNK值介于0.95~1.25,A/NK值介于1.71~1.94,主体属于I型花岗岩。张家屯英云闪长岩的稀土总量较低($15.3 \times 10^{-6} \sim 23.4 \times 10^{-6}$),具有轻重稀土弱分异[$(La/Yb)_N = 5.01 \sim 5.60$]和较平坦的重稀土分配型式,并具有明显的铕正异常($Eu/Eu^* = 1.85 \sim 2.59$)。微量元素显示具有大离子亲石元素(Rb、Ba、Cs、Th)富集和高场强元素(Nb和Ta)亏损的特征。另外,它们具有正的$\varepsilon_{Hf}(t)$值(+9.92~+13.6)和年轻的两阶段亏损地幔模式年龄(648~911Ma)。张家屯英云闪长岩的地球化学特征与超俯冲带弧前环境的斜长花岗岩的源区相似,可能来源于低压高温条件下大洋堆晶辉长岩的部分熔融,并有俯冲流体的参与。即张家屯英云闪长岩形成于俯冲背景下的岛弧环境,结合晚志留世-早泥盆世张家屯组磨拉石建造的沉积特征,揭示了加里东运动在华北板块北缘东段的存在。

关键词 早古生代;英云闪长岩;锆石U-Pb年代学;地球化学;中国东北;华北板块北缘东段

中图法分类号 P588.122; P597.3

华北板块北缘东段是否存在早古生代陆缘增生带是近年来地学界研究的热点问题之一,一些学者曾认为吉林省中东部地区出露的一些镁铁-超镁铁质岩为蛇绿岩残片,并结合古生代地质体的时空分布特征将吉林中东部地区划分出早古生代陆缘增生带和晚古生代陆缘增生带,认为华北板块北缘东段古生代陆缘增生带和佳木斯地块西南缘古生代陆缘增生带具有相向增生的特点(陈作文等, 1982; 田昌烈和杨芳林, 1983; 王东方等, 1992; 赵春荆等, 1996)。然而,近年来,华北板块北缘东段的早古生代陆缘增生带遭到部分学者的质疑,这主要表现在蛇绿岩和火成岩研究方面。首先,华北板块北缘东段是否存在蛇绿岩,是地学界一直争论的焦点问题。由于植被的覆盖和后期构造破坏,那些前人曾确定为蛇绿岩的地质体,多残缺不全,不具备完整的蛇绿岩层序,推测多为造山作用的产物(张旗, 1992; 彭玉鲸和王占福, 1997; Wu *et al.*, 2004);另外,随着锆石U-Pb年代学测试方法的改进和应用,许多作为增生带存在重要证据的早古生代地层(如呼兰群、下二台群盘岭组)和花岗质侵入体(大玉山岩体和黄泥岭岩体等)实际上是晚古生代或中生代的产物(张艳斌等, 2002; 孙德有等, 2004; 王志伟等, 2013)。近年来,虽然华北板块北缘东段晚古生代火成岩的研究已经取得了部分成果(曹花花等, 2012; Cao *et al.*, 2013; 王志伟等, 2013; 王子进等, 2013),但由于到目前为止在该地区尚未发现早古生代火成岩,从而造成人们对华北板块北缘东段早古生代构造演化历史的认识一直处于空白。作者在吉林省中部地区进行野外地质调查过程中,在张家屯组底部发现了与张家屯组呈沉积接触关系的早古生代英云闪长岩,进一步通过岩相学、锆石U-Pb年代学、地球化学以及锆石Hf同位素的分析研究,对其源区性质及构造背景进行了探讨,本文的研究对于华北板块北缘东段早古生代构造演化历史的研究提供了重要资料。

1 地质背景与样品描述

研究区位于吉林省中部地区永吉县的西北部。大地构造上位于长春-吉林-蛟河对接带以南(赵春荆等, 1996),松

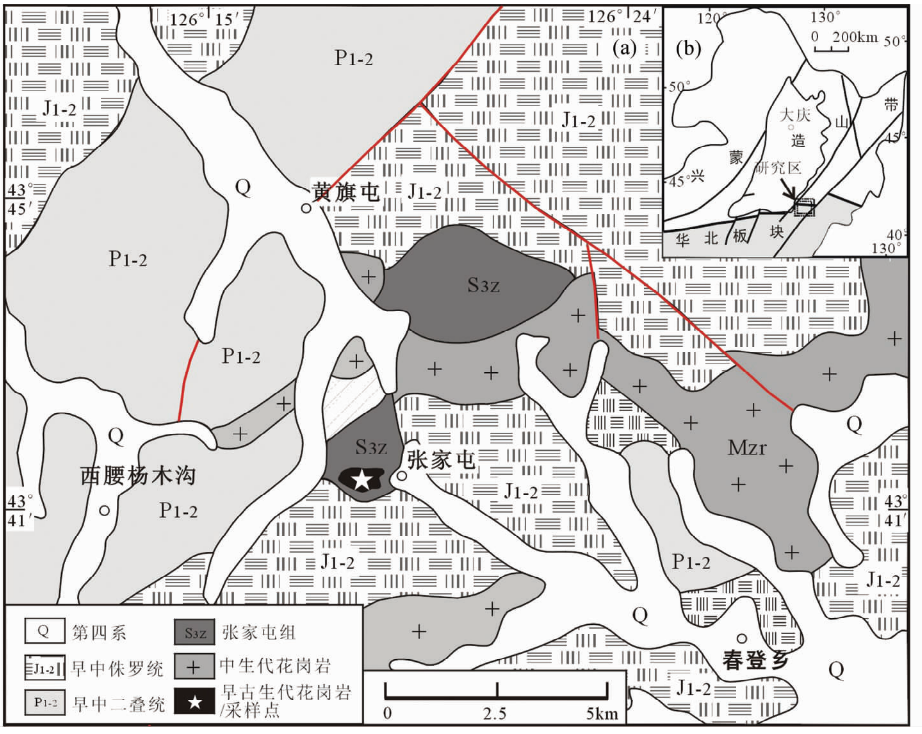

图 1 研究区地质略图(a)和构造分区图(b)

Fig. 1 Geological sketch map of the study area (a) and tectonic division map (b)

辽盆地以东,敦化-密山断裂以西,华北板块北部槽台边界断裂——开原-山城镇断裂的北部,研究区属于张广才岭带的南部(彭玉鲸和陈跃军, 2007)。该区出露的最老地层——晚志留世-早泥盆世张家屯组主要分布于张家屯村附近(廖卫华等, 1995),区内还广泛分布着二叠纪范家屯组、大河深组和杨家沟组、侏罗纪小蜂蜜顶子组、一拉溪组和南楼山组以及晚古生代-中生代的花岗质侵入体(吉林省地质矿产局, 1988)。本文研究的花岗岩主要分布于张家屯村西山上,仅在山脊及南坡产出,出露面积约 $100m^2$(图 1),岩体周围被晚志留世-早泥盆世张家屯组地层覆盖,与张家屯组呈沉积接触关系。张家屯组由底部的砾岩、中部的含砾砂岩及上部的粉砂岩和红色凝灰质粉砂岩组成,底部砾岩中见有花岗质砾石、火山岩砾石以及硅质岩砾石等,其中含有珊瑚和腕足类化石,据生物化石研究结果认为张家屯组形成于晚志留世-早泥盆世(廖卫华等, 1995)。张家屯英云闪长岩被后期的辉绿岩墙侵入,在接触带附近的辉绿岩中残留有英云闪长岩中的粗粒长石和石英等矿物颗粒,同时在英云闪长岩的产出区域附近见有碳酸盐岩,但与张家屯英云闪长岩的接触关系不明。

张家屯英云闪长岩样品的岩相学特征如下(图 2):

灰白色不等粒英云闪长岩(12JL4-1, GPS 坐标: N126°17.674′;E43°41.345′):风化面肉红色,新鲜面灰白色,不等粒结构,块状构造。主要矿物组成:石英,他形粒状,粒度 1 ~ 3mm,含量约 25%;斜长石,自形-半自形板状,可见聚片双晶,粒度 2 ~ 5mm,含量约 66%,部分斜长石显示绿帘石化蚀变,绿帘石呈粒状,粒度 1mm 左右,暗色矿物均已绿泥石化,个别颗粒显示出片状的特点,含量约 8%。副矿物(1%)包括锆石、磷灰石、铁钛氧化物(钛铁矿和钛磁铁矿)等。

2 分析方法

锆石 LA-ICP-MS U-Pb 同位素分析在中国地质大学(武汉)地质过程与矿产资源国家重点实验室的 Agilent 7500a ICP-MS 仪器上采用标准测定程序进行,详细的实验原理和流程见(Liu *et al.*, 2008; Liu *et al.*, 2010a)。应用标准锆石 91500 进行分馏校正,标准锆石 TEMORA 1 作为未知样品测定获得的年龄为 415 ± 4Ma(MSWD = 0.112, n = 24),该锆石的 ID-TIMS 年龄为 416.75 ± 0.24Ma (Black *et al.*, 2003)。激光束的束斑为 32μm。实验获得的数据采用(Andersen, 2002)的方法进行同位素比值的校正,以扣除普通 Pb 的影响,然后用 ISOPLOT 宏程序进行年龄协和图的生成和处理(Ludwig, 2003)。

锆石 Hf 同位素测试在中国地质大学(武汉)地质过程与矿产资源国家重点实验室配有 193nm 激光取样系统的 Neptune 多接收电感耦合等离子体质谱仪(MC-ICP-MS)上进行,仪器的运行条件和详细的分析流程见(Liu *et al.*, 2010b)。测定时用锆石国际标样 91500 作外标,分析时激光束直径为 44μm,所用的激光脉冲速率为 6 ~ 8Hz,激光束脉

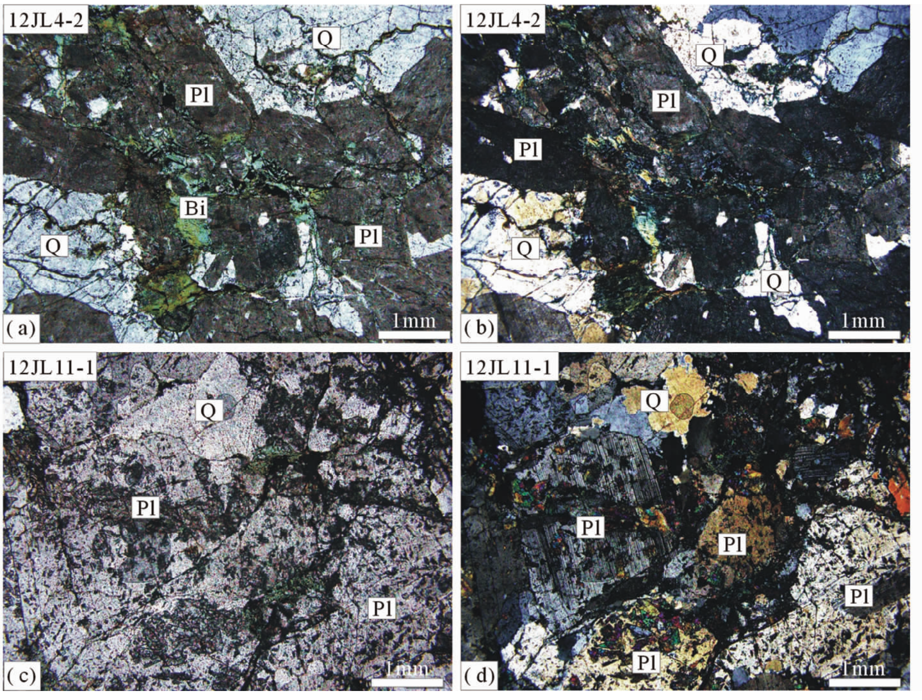

图2 张家屯英云闪长岩显微照片

(a、c)为单偏光下;(b、d)为正交偏光下. Q-石英;Pl-斜长石;Bi-黑云母

Fig. 2 Microphotographs showing mineral compositions and textures of the Zhangjiatun tonalites

(a, c) under plane-polarized light; (b, d) under cross-polarized light. Q-quartz; Pl-plagioclase; Bi-biotite

冲能量为100mJ。

主量和微量元素分析均在中国地质大学(武汉)地质过程与矿产资源国家重点实验室完成(Liu *et al.*, 2008, 2010a)。主要元素采用X-荧光光谱法(XRF)分析;微量元素的分析则采用电感耦合等离子质谱(ICP-MS)分析方法。对国际标样BCR-2(玄武岩)、BHVO-1(玄武岩)和AGV-1(安山岩)的分析结果表明,主要元素分析精度和准确度优于5%,微量元素的分析精度和准确度优于10%。

3 分析结果

张家屯英云闪长岩的LA-ICP MS锆石U-Pb定年结果见表1,锆石CL图像见图3,英云闪长岩的主量和微量元素分析结果见表2,锆石Hf同位素分析结果见表3。

3.1 年代学

张家屯英云闪长岩的锆石CL图像显示(图3),锆石分为两大类,一类锆石具有明显的核边结构,核部显示后期水热变质特征,边部具有岩浆成因振荡生长环带,锆石的Th和U的含量较高(表1);另一类锆石没有核边结构,从核部到边部色调均匀,并具有岩浆成因的生长环带,锆石的Th和U的含量较低。张家屯英云闪长岩中锆石的Th和U的含量分别介于$10\times10^{-6}\sim1800\times10^{-6}$和$32\times10^{-6}\sim1110\times10^{-6}$,

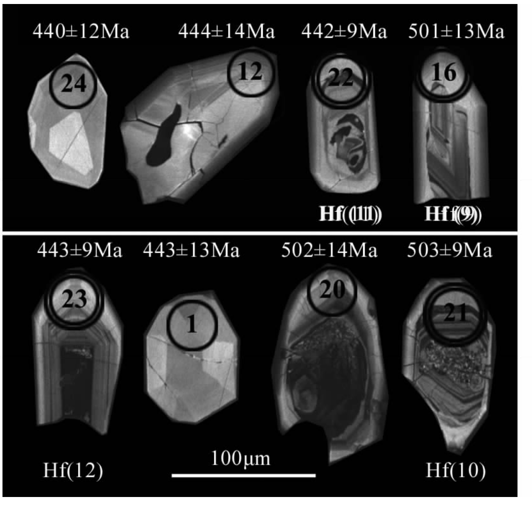

图3 张家屯英云闪长岩中部分锆石的CL图像

图中大圈和Hf(9, 11, 12)分别代表锆石Hf同位素的分析位置及分析点号,小圈及内部数字代表锆石年龄的分析位置及点号

Fig. 3 CL images of selected zircons from the Zhangjiatun tonalites

Th/U比值介于0.26~1.62(表1),上述特征显示所分析的锆石均为岩浆成因。位于谐和线及其附近的测点的$^{206}Pb/^{238}U$年龄可分为两组(图4):较老的一组$^{206}Pb/^{238}U$年龄介于498±12Ma和503±9Ma,4个测点的加权平均年龄为501±

表 1 张家屯英云闪长岩 LA-ICP MS 锆石 U-Pb 分析结果

Table 1 LA-ICP MS zircon U-Pb isotope data for the Zhangjiatun tonalities in the central Jilin Province

分析号	含量($\times10^{-6}$)		Th/U	同位素比值								表面年龄(Ma)					
	Th	U		$^{207}Pb/^{206}Pb$	±(1σ)	$^{207}Pb/^{235}U$	±(1σ)	$^{206}Pb/^{238}U$	±(1σ)	$^{208}Pb/^{232}Th$	±(1σ)	$^{207}Pb/^{206}Pb$	±(1σ)	$^{207}Pb/^{235}U$	±(1σ)	$^{206}Pb/^{238}U$	±(1σ)
1	37	82	0.45	0.07660	0.00856	0.75196	0.08108	0.07120	0.00210	0.02139	0.00051	1111	233	569	47	443	13
2	20	62	0.32	0.08085	0.01945	0.79816	0.18455	0.07160	0.00476	0.02138	0.00136	1218	530	596	104	446	29
3	70	140	0.50	0.06007	0.00429	0.59632	0.04100	0.07098	0.00145	0.02265	0.00141	606	114	475	26	442	9
4	62	132	0.47	0.07437	0.00537	0.73384	0.05223	0.07203	0.00192	0.02387	0.00185	1052	100	559	31	448	12
5	22	66	0.33	0.07658	0.01133	0.73354	0.10587	0.06947	0.00226	0.02087	0.00053	1110	315	559	62	433	14
6	19	32	0.59	0.09616	0.04220	1.10881	0.47481	0.08363	0.00801	0.02452	0.00311	1551	1029	758	229	518	48
7	63	122	0.52	0.06962	0.00503	0.69241	0.04998	0.07173	0.00157	0.02241	0.00162	917	113	534	30	447	9
8	186	229	0.81	0.05393	0.00399	0.53214	0.03778	0.07104	0.00136	0.02106	0.00118	368	126	433	25	442	8
9	21	54	0.38	0.07087	0.01297	0.70075	0.12474	0.07171	0.00304	0.02173	0.00077	954	407	539	74	446	18
10	204	300	0.68	0.06023	0.00437	0.58882	0.04059	0.07093	0.00145	0.02128	0.00101	612	114	470	26	442	9
11	429	283	1.52	0.06403	0.00552	0.62405	0.04939	0.07167	0.00192	0.01495	0.00084	743	122	492	31	446	12
12	59	72	0.82	0.09082	0.00870	0.83174	0.07431	0.07124	0.00228	0.02343	0.00216	1443	122	615	41	444	14
13	1800	1110	1.62	0.05408	0.00227	0.47799	0.01956	0.06322	0.00091	0.01552	0.00058	374	66	397	13	395	6
14	112	135	0.83	0.06699	0.00541	0.70737	0.05434	0.08030	0.00194	0.02372	0.00157	838	120	543	32	498	12
15	678	424	1.60	0.05565	0.00354	0.55170	0.03397	0.07098	0.00152	0.01316	0.00055	438	99	446	22	442	9
16	101	141	0.72	0.05696	0.00475	0.63572	0.04910	0.08077	0.00220	0.02127	0.00126	490	123	500	30	501	13
17	32	71	0.44	0.09154	0.01075	1.03854	0.10262	0.08839	0.00429	0.03073	0.00328	1458	115	723	51	546	25
18	10	40	0.26	0.07887	0.02839	0.70677	0.24813	0.06499	0.00515	0.01946	0.00347	1169	772	543	148	406	31
19	119	125	0.95	0.08938	0.00636	0.49109	0.03493	0.03959	0.00129	0.01197	0.00078	1412	86	406	24	250	8
20	66	112	0.59	0.05778	0.00510	0.63827	0.05148	0.08101	0.00234	0.02265	0.00159	521	126	501	32	502	14
21	404	375	1.08	0.05340	0.00241	0.61291	0.02862	0.08111	0.00149	0.02377	0.00096	346	72	485	18	503	9
22	217	236	0.92	0.05710	0.00372	0.56634	0.03651	0.07101	0.00154	0.01732	0.00085	495	104	456	24	442	9
23	78	135	0.58	0.06742	0.00517	0.65670	0.04730	0.07114	0.00158	0.02240	0.00140	851	113	513	29	443	9
24	28	97	0.28	0.06745	0.00822	0.65712	0.07781	0.07065	0.00202	0.02153	0.00048	852	266	513	48	440	12

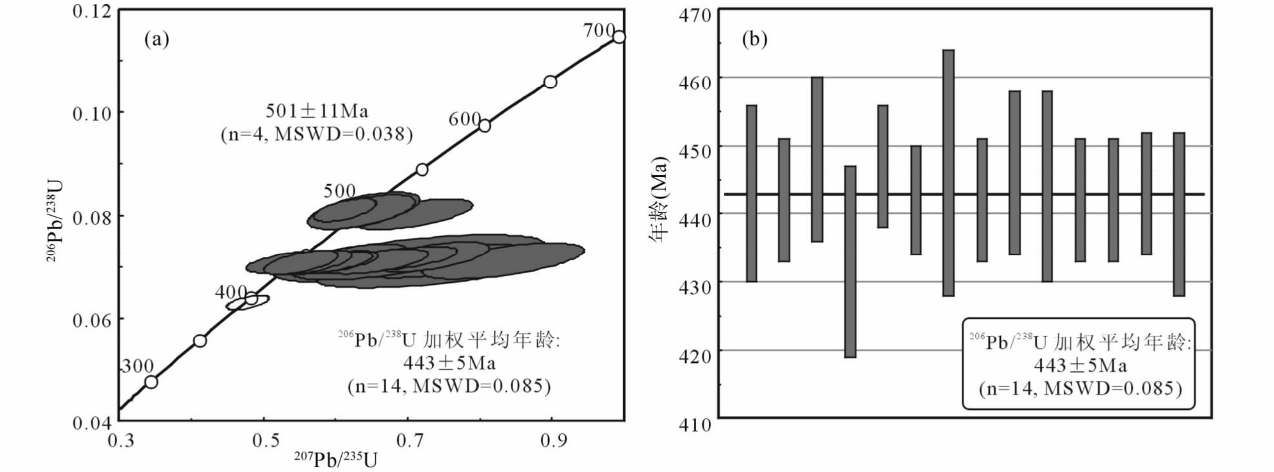

图4 张家屯英云闪长岩锆石U-Pb谐和图(a)和频数图(b)

Fig. 4 Concordia diagram (a) and frequency diagram (b) showing LA-ICP-MS zircon U-Pb dating result for the Zhangjiatun tonalites

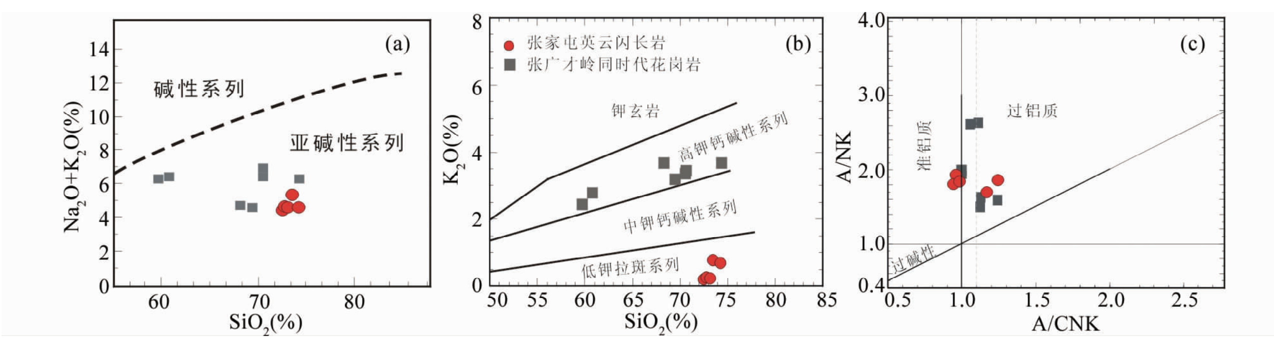

图5 张家屯英云闪长岩主量元素判别图解

(a)-硅碱图;(b)-硅钾图;(c)-A/CNK-A/NK图解

Fig. 5 Discrimination diagrams of major elements for the Zhangjiatun tonalities

(a)-SiO_2 vs. Na_2O+K_2O diagram; (b)-SiO_2 vs. K_2O diagram; (c)-A/CNK vs. A/NK diagram

11Ma(MSWD=0.038),该年龄代表了研究区早期岩浆作用的时代;较年轻的一组$^{206}Pb/^{238}U$年龄介于440±12Ma和448±12Ma,14个测点的加权平均年龄为443±5Ma(MSWD=0.085),该年龄代表了张家屯英云闪长岩的形成时代,即晚奥陶世-早志留世。谐和线最下部395±6Ma的年龄的打点位置打到了变质增生边上,给出的是混合年龄,该年龄明显比岩浆结晶年龄年轻(图4)。

3.2 地球化学

3.2.1 主量元素

张家屯英云闪长岩的SiO_2含量介于71.5%~72.9%,全碱(Na_2O+K_2O)含量介于4.38%~5.25%(图5a),Na_2O/K_2O比值(5.62~18.91)变化较大,并且Na_2O含量远大于K_2O含量,Al_2O_3含量介于13.2%~14.1%,具有低K_2O(0.22%~0.76%)、TiO_2(0.30%~0.42%)和P_2O_5含量(0.051%~0.180%)以及低的FeO^T/MgO(2.53~3.62)比值(表2),该英云闪长岩落入低钾拉斑系列(图5b)。其A/CNK值介于0.95~1.25,A/NK值介于1.71~1.94,主体属于I型花岗岩(图5c)。与岛弧英云闪长岩的Al_2O_3含量相比,张家屯英云闪长岩偏低(<15%)。其高钠低钾的特征也不同于同时代高钾钙碱性系列的张广才岭花岗岩(图5, Wang *et al.*, 2012)。

3.2.2 稀土及微量元素

张家屯英云闪长岩稀土总量介于15.3×10^{-6}~23.4×10^{-6},具有轻稀土呈右倾型[$(La/Sm)_N$=3.65~4.90]和平坦的重稀土分配型式[$(Gd/Yb)_N$=0.94~1.03],并显示明显的正铕异常(Eu/Eu^*=1.85~2.59,图6a)。微量元素蛛网图显示,具有明显的大离子亲石元素Rb、Ba、Th和Sr的富集以及高场强元素Nb和Ta的亏损(图6b)。张家屯英云闪长岩以较低的稀土和微量元素丰度与张广才岭同时代的花

表 2 吉林中部地区张家屯英云闪长岩主量(wt%)及微量元素($\times10^{-6}$)分析数据

Table 2 Major (wt%) and trace ($\times10^{-6}$) element data for the Zhangjiatun tonalite in the central Jilin Province

样品号	12JL4-1	12JL4-2	12JL11-1	12JL11-3	12JL11-5
岩性	英云闪长岩				
SiO_2	72.30	72.90	71.50	71.60	72.20
TiO_2	0.30	0.42	0.34	0.36	0.30
Al_2O_3	14.10	13.20	13.80	13.50	13.60
$Fe_2O_3{}^T$	3.15	3.83	3.66	3.48	3.44
MnO	0.05	0.06	0.08	0.07	0.07
MgO	1.09	1.36	0.91	0.93	0.90
CaO	2.10	1.91	3.96	3.73	3.55
Na_2O	4.49	3.82	4.16	4.33	4.31
K_2O	0.76	0.68	0.22	0.25	0.23
P_2O_5	0.06	0.08	0.06	0.18	0.05
LOI	1.74	1.92	1.48	1.54	1.50
Total	100.10	100.10	100.10	100.00	100.20
$Mg^{\#}$	26	26	20	21	21
K_2O+Na_2O	5.25	4.50	4.38	4.58	4.54
A/CNK	1.17	1.25	0.96	0.95	0.99
A/NK	1.71	1.87	1.94	1.83	1.86
La	3.58	3.78	4.99	5.10	5.38
Ce	5.89	6.81	7.85	8.10	7.92
Pr	0.65	0.76	0.94	0.98	0.98
Nd	2.41	2.89	3.78	3.87	3.83
Sm	0.46	0.61	0.86	0.85	0.80
Eu	0.40	0.41	0.55	0.53	0.60
Gd	0.48	0.57	0.90	0.89	0.91
Tb	0.079	0.093	0.15	0.16	0.16
Dy	0.49	0.61	0.99	1.05	1.01
Ho	0.11	0.13	0.21	0.22	0.21
Er	0.30	0.43	0.63	0.67	0.63
Tm	0.055	0.067	0.093	0.11	0.11
Yb	0.39	0.49	0.64	0.73	0.71
Lu	0.063	0.082	0.11	0.10	0.12
∑REE	15.3	17.7	22.7	23.3	23.4
Eu/Eu^*	2.59	2.10	1.90	1.85	2.15
$(La/Yb)_N$	6.59	5.54	5.6	5.01	5.44
Li	9.85	11.4	7.39	7.25	8.29
Be	0.47	0.42	0.41	0.40	0.44
Sc	3.24	4.29	6.19	7.01	6.27
V	40.9	48.6	62.5	62.9	62.6
Cr	2.21	3.16	2.01	5.09	4.95
Co	5.2	6.49	4.93	5.33	5.3
Ni	1.21	1.53	1.18	1.47	1.56
Cu	10.3	10.7	3.91	3.73	3.55
Zn	27.6	33.2	20.4	22.1	23.6
Ga	10.6	10.4	13.8	13.4	14.3
Rb	17.6	16.4	4.69	5.16	5.26
Cs	1.59	1.54	1.17	1.10	1.30
Sr	292	250	347	340	367
Ba	195	171	74.1	83.7	85.2
Zr	33.1	46.1	39.4	43.4	34.8
Hf	0.76	1.09	0.99	1.04	0.90
U	0.27	0.30	0.31	0.33	0.34
Th	1.00	1.08	1.06	1.15	1.21
Pb	2.64	3.00	5.40	5.07	5.55
Nb	0.50	0.68	0.77	0.83	0.72
Ta	0.043	0.053	0.055	0.06	0.057
Y	4.04	5.01	7.55	7.38	6.58

注:$Mg^{\#}=100\times Mg^{2+}/(Mg^{2+}+TFe^{2+})$; $A/CNK=Al_2O_3/[CaO+K_2O+Na_2O]$摩尔比; $A/NK=Al_2O_3/[K_2O+Na_2O]$摩尔比; $Eu/Eu^*=Eu_N/(Sm_N\times Gd_N)^{1/2}$球粒陨石标准化

岗岩相区别(Wang *et al.*, 2012)。

3.3 锆石 Hf 同位素

张家屯英云闪长岩的 Hf 同位素分析结果见表 3,样品的$^{176}Lu/^{177}Hf$值变化较大(0.001061~0.005838),$^{176}Hf/^{177}Hf$值介于 0.282815~0.282856,$\varepsilon_{Hf}(t)$值介于 9.92~13.6,从 501Ma 到 443Ma,其$\varepsilon_{Hf}(t)$值逐渐降低,显示早期岩浆事件的源区亏损较强(图 7)。其单阶段亏损地幔模式年龄介于 567~674Ma,两阶段亏损地幔模式年龄介于 648~911Ma。其$\varepsilon_{Hf}(t)$值明显高于同时代的张广才岭花岗岩(图 7, Wang *et al.*, 2012)。

4 讨论

4.1 张家屯英云闪长岩的形成时代

对于张家屯英云闪长岩的形成时代,目前为止没有同位素定年资料,前人仅根据与其呈沉积接触关系的张家屯组地层中化石的时代(晚志留世-早泥盆世),将其时代确定为加里东期(李东津, 1997)。本文中锆石具有岩浆成因的生长环带,它们的 Th/U 比值介于 0.26~1.62,暗示这些锆石为岩浆成因,其定年结果应代表了岩浆事件的时代,因此,张家屯英云闪长岩(443±5Ma)的产出表明吉林中部地区存在晚奥陶世-早志留世岩浆事件。这与张广才岭地区早古生代花岗岩的形成时代(443~451Ma)相对应(Wang *et al.*, 2012)。同时 501Ma 的捕获锆石的年龄暗示该地区可能还存在寒武纪晚期的岩浆事件。

4.2 张家屯英云闪长岩的源区特征

张家屯英云闪长岩虽具有轻稀土元素略富集的特征,但其 K_2O 和不相容元素含量偏低,暗示来源于强烈亏损的源区,这也被较高的$\varepsilon_{Hf}(t)$值所证实。尽管张家屯英云闪长岩的 Na_2O 的含量较高,Yb 的含量较低,但其较低的 Sr 含量和 Sr/Y 比值以及 Al_2O_3 含量不同于洋壳部分熔融形成的埃达克岩(Defant and Drummond, 1990)。张家屯英云闪长岩极低的 K_2O 和 TiO_2 含量、微量元素丰度以及低的$(La/Yb)_N$值也明显不同于加厚陆壳环境或俯冲带环境源区残留石榴石和角闪石条件下(≥8kbar)变玄武质岩石部分熔融的熔体成份(Rapp *et al.*, 1991; Rapp and Watson, 1995)。岩相学上,张家屯英云闪长岩矿物组成与大洋斜长花岗岩相似(Le Maitre *et al.*, 1989),同时张家屯英云闪长岩也与大洋斜长花岗岩具有相似的地球化学特征(图 8, Barker *et al.*, 1985; Rapp *et al.*, 1991; Koepke *et al.*, 2004, 2007)。关于大洋斜长花岗岩的成因,主要有以下四种观点:(1)大洋中脊拉斑玄武质岩浆(MORB 型)结晶分异成因(Coleman and Donato, 1979; Aldiss, 1981; Floyd *et al.*, 1998);(2)含水流体存在条件下,堆晶辉长岩高温(>900℃)低压下部分熔融成因

表 3 吉林中部地区张家屯英云闪长岩锆石 Lu-Hf 同位素分析结果

Table 3 Lu-Hf isotopic analyzed data of zircons from the Zhangjiatun tonalite in the central Jilin Province

Spot No.	t(Ma)	$^{176}Yb/^{177}Hf$	$^{176}Lu/^{177}Hf$	$^{176}Hf/^{177}Hf$	1σ	$\varepsilon_{Hf}(t)$	1σ	t_{DM1}(Ma)	t_{DM2}(Ma)	$f_{Lu/Hf}$
12JL4-1-01	443	0.057749	0.002059	0.282855	0.000008	12.1	0.62	579	741	−0.94
12JL4-1-02	443	0.027339	0.001061	0.282815	0.000011	11.0	0.68	621	845	−0.97
12JL4-1-03	443	0.067653	0.002520	0.282843	0.000012	11.6	0.72	603	791	−0.92
12JL4-1-04	443	0.142248	0.004845	0.282825	0.000011	10.2	0.71	674	911	−0.85
12JL4-1-05	443	0.052614	0.001853	0.282818	0.000007	10.8	0.60	630	855	−0.94
12JL4-1-06	443	0.044219	0.001739	0.282852	0.000009	12.1	0.64	579	744	−0.95
12JL4-1-07	395	0.161904	0.005838	0.282850	0.000011	9.92	0.68	654	905	−0.82
12JL4-1-08	443	0.063988	0.002392	0.282835	0.000009	11.3	0.64	613	814	−0.93
12JL4-1-09	501	0.038692	0.001396	0.282856	0.000006	13.6	0.59	567	648	−0.96
12JL4-1-10	501	0.052147	0.001979	0.282838	0.000009	12.7	0.64	602	723	−0.94
12JL4-1-11	443	0.056000	0.001978	0.282834	0.000006	11.4	0.59	608	807	−0.94
12JL4-1-12	443	0.036077	0.001364	0.282816	0.000009	10.9	0.64	625	849	−0.96

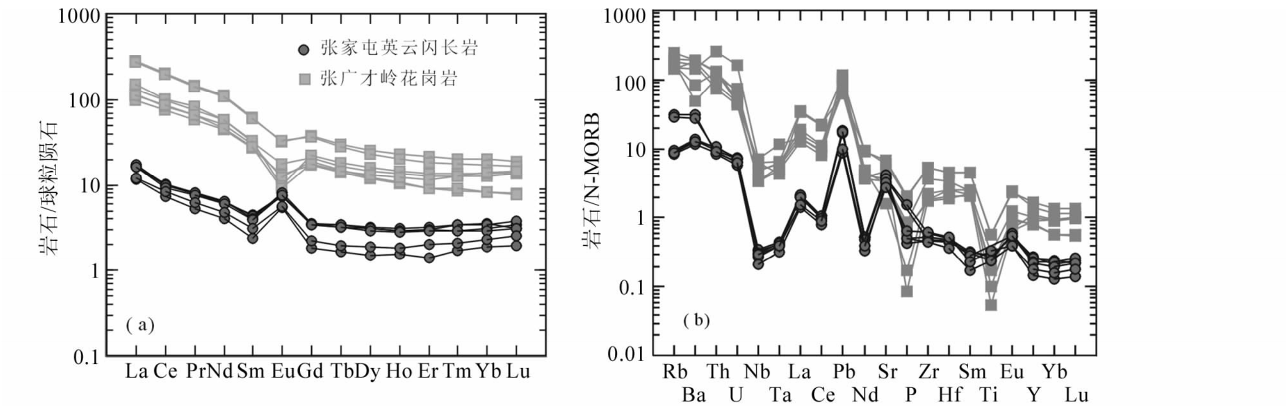

图 6 张家屯英云闪长岩球粒陨石标准化稀土元素配分图(a,标准化值据 Henderson, 1984)和正常大洋中脊标准化微量元素蛛网图(b,标准化值据 Sun and McDonough, 1989)

Fig. 6 Chondrite-normalized REE patterns (a, normalization values after Henderson, 1984) and N-MORB-normalized trace element spider diagrams (b normalization values after Sun and McDonough, 1989) for the Zhangjiatun tonalities

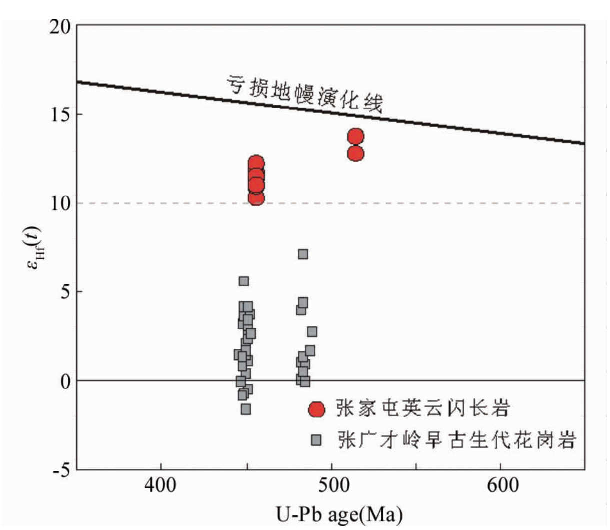

图 7 张家屯英云闪长岩锆石 Hf 同位素特征

Fig. 7 Zircon Hf isotopic compositions for the Zhangjiatun tonalites

(Koepke *et al.*, 2004, 2007);(3)与大洋拉斑玄武质熔体有关的不混熔成因(Dixon and Rutherford, 1979);(4)变玄武质岩石部分熔融成因(Gerlach *et al.*, 1981; Pedersen and Malpas, 1984; Kimura *et al.*, 2002)。首先,张家屯英云闪长岩具有轻稀土和大离子亲石元素富集,高场强元素及重稀土亏损的特征,这明显不同于传统意义上的大洋斜长花岗岩(大洋拉斑玄武质岩浆结晶分异成因)。其次,张家屯英云闪长岩的具有低 TiO_2(小于 1%)、K_2O、P_2O_5 含量以及 FeO^T/MgO 比值(图 8),排除了其它玄武质岩石(或变玄武质岩石)部分熔融形成的长英质岩石或不混熔成因的高硅侵入岩的成因模式。张家屯英云闪长岩的地球化学特征与大洋岩石圈中堆晶辉长岩富水条件和高温低压条件下部分熔融形成的斜长花岗岩的地球化学特征相似(Koepke *et al.*, 2004, 2007),具有 MORB 型亏损的 Hf 同位素特征也说明了这一点。其大离子亲石元素富集和高场强元素亏损的特征可能与俯冲流体的加入有关。基于上述分析认为,张家屯英云闪长岩的原始熔体可能来源于有俯冲流体参与的高温低压条

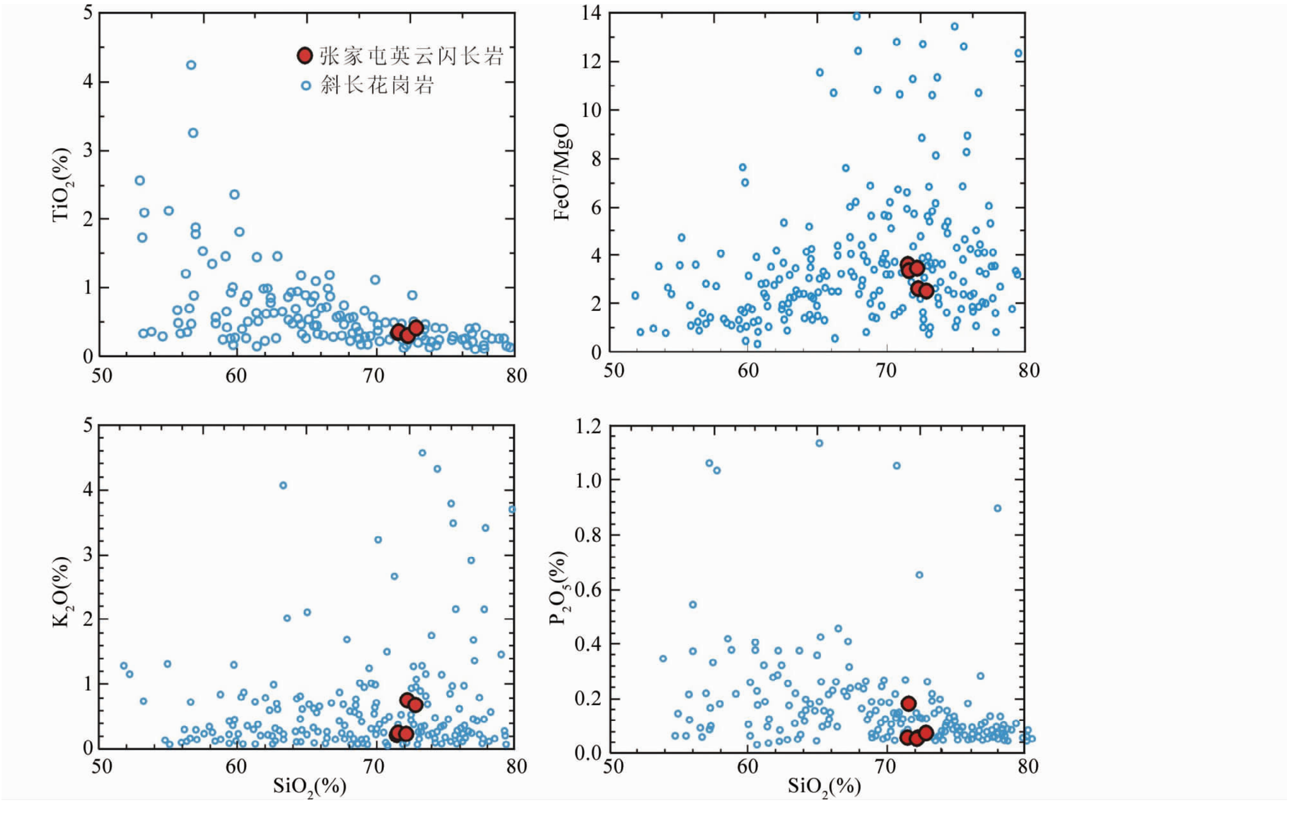

图 8 张家屯英云闪长岩 TiO_2、FeO^T/MgO、K_2O 和 P_2O_5 与 SiO_2 相关图

图中斜长花岗岩主量元素数据来自 Koepke *et al.* (2007)中相关文献

Fig. 8 Plots of SiO_2 vs. TiO_2, FeO^T/MgO, K_2O and P_2O_5 for the Zhangjiatun tonalities

Major element data of plagiogranites from the relative references in Koepke *et al.* (2007)

件下大洋堆晶辉长岩的部分熔融。

4.3 张家屯早古生代英云闪长岩的构造背景

斜长花岗岩可以产出于多种构造环境中(如大洋中脊附近以及超俯冲带的弧前、弧内裂谷和弧后环境)。张家屯英云闪长岩具有 Nb 和 Ta 亏损以及轻稀土富集的特征,暗示与俯冲带环境的亲缘性,张家屯英云闪长岩中锆石的 Th、U 含量变化较大(表 1),锆石核部显示退变质现象,表明源区可能经历了强烈的高温流体作用,暗示张家屯英云闪长岩可能形成于构造活动带,其正铕异常和平坦的重稀土分配型式暗示为低压条件下的部分熔融,源区不存在石榴石的残留,说明张家屯英云闪长岩可能形成于俯冲带的弧前环境(Shervais, 2001)。其年轻的 Hf 模式年龄表明源岩——堆晶辉长岩的时代略早于张家屯英云闪长岩。上述特征说明晚奥陶世-早志留世研究区可能存在大洋板块的俯冲作用,同时也说明至少在早志留世之前,研究区存在古大洋。那么,到底是洋陆俯冲背景下的大陆边缘环境还是洋洋俯冲背景下的岛弧环境?首先,张家屯英云闪长岩较低 K_2O 和微量元素含量以及强烈亏损的 Hf 同位素组成(最高为 12.7),暗示源区主要由亏损地幔来源的、新增生的物质组成。其次,区域上同时代的桃山组笔石页岩具有弧间盆地的沉积特征,另外,其地球化学特征也与弧前环境相似,这些特点都明显不同于同时代的张广才岭早古生代花岗岩,暗示张家屯英云闪长岩形成于岛弧环境(Floyd *et al.*, 1998; Shervais, 2001; Stern, 2002; Dilek and Flower, 2003; Dilek and Furnes, 2011)。前人研究表明,与张家屯英云闪长岩呈沉积接触关系的晚志留世-早泥盆世张家屯组具有磨拉石建造的沉积特征,吉中地区晚志留世-早泥盆世张家屯组、二道沟组和小绥河组的沉积建造特征以及古生物特征可与内蒙古中部的西别河组(Upper Ludlovian)进行对比(王友勤等, 1997; Johnson *et al.*, 2001; 张允平等, 2010),而且,张家屯组、二道沟组和小绥河组中的珊瑚和腕足动物化石显示为华北北缘型(廖卫华等, 1995; 赵春荆等, 1996),上述事实证明华北板块北缘东段早古生代陆缘增生带是存在的,晚奥陶世-早志留世研究区处于岛弧环境,晚志留世-早泥盆世可能发生了弧陆或陆陆碰撞,形成了具磨拉石建造特点的西别河组沉积,西别河组与下伏加里东期花岗岩之间区域性的角度不整合的接触关系是加里东运动在华北板块北缘的体现(张允平等, 2010)。

5 结论

根据张家屯英云闪长岩的锆石 U-Pb 定年结果、全岩主量和微量元素以及锆石 Hf 同位素特征，同时结合前人的研究成果，得出如下结论：

（1）LA-ICP MS 锆石 U-Pb 定年结果显示，张家屯英云闪长岩形成于 443 ± 5Ma，即晚奥陶世-早志留世。

（2）张家屯英云闪长岩的矿物组成和地球化学特征与超俯冲带环境下的大洋斜长花岗岩相似，来源于俯冲流体参与下大洋堆晶辉长岩在低压高温条件下的部分熔融。

（3）张家屯英云闪长岩形成于洋壳俯冲背景下的岛弧环境，暗示华北板块北缘东段早古生代陆缘增生带的存在。

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