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吉林东部海西期花岗岩锆石 U-Pb 年龄、Hf 同位素特征与地壳增生*

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Abstract Paleozoic granites are widely spread in northeastern China, and they are very important for revealing crustal growth. Nevertheless, the study on the Paleozoic granites in east part is relatively weak; therefore, Paleozoic granite research in east part requires special attention. Zircon U-Pb dating by LA-ICPMS technique indicates that the studied granitic pluton was emplaced during Late Paleozoic (Hercynian) with a weighted age of 262.2 ± 1.2Ma. Meanwhile, zircon Hf analyses conducted by LA-MC-ICPMS show that this pluton has variational ε_{Hf}(262Ma) values from 1.35 to 5.62, indicating that the primary magma of the granites mainly resulted from a depleted asthenospheric mantle. In addition, the Hf two-stage modal ages change from 1091Ma to 1357Ma, suggesting an important crustal growth event beneath the studied area.

Key words Granites; Zircon U-Pb age; Zircon Hf isotopes; Hercynian; Eastern Jilin Province

摘 要 东北地区古生代花岗岩分布范围非常广泛,花岗岩研究对反演地壳增生意义重大。虽然如此,东部地区古生代花岗岩的研究仍相对薄弱,需要特别关注。LA-ICPMS U-Pb 同位素定年结果表明,本研究花岗岩体为晚中生代海西期(262Ma)岩浆活动的产物。锆石的 LA-MC-ICPMS Hf 同位素研究结果显示,$\varepsilon_{Hf}(t)$ 范围为 1.35 ~ 5.62,二阶段 Hf 模式年龄(t_{DM2})范围为 1.1 ~ 1.4Ga,暗示花岗岩源区物质主要来自亏损地幔,同时暗示了一次重要的地壳增生事件。

关键词 花岗岩; 锆石 U-Pb 年龄; 锆石 Hf 同位素; 海西期; 吉林东部

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东北是我国显生宙花岗岩极为发育(约 30 万平方千米)的地区,由于东北地区被称为海西褶皱带,因此其中的花岗岩被认为是在晚古生代形成的(吴福元等,1999)。但近来研究表明,东北地区花岗岩的主体形成于中生代(230 ~ 120Ma),只有少数岩体形成于古生代,而以前认为的大量海西期和加里东期花岗岩其实质大多都是中生代的侵人体(吴福元等,2007)。虽然东北地区海西期花岗岩的存在已成为事实(张德全,1993; 黑龙江省地质矿产局,1993; Wilde *et al.*, 1997; 吴福元等,1999),然而,由于目前可靠的年龄数据仍较少(尤其是东北东部地区),从而难以准确把握该期花岗岩的时空分布特点。另外,新元古代-显生宙是东北地区地壳增生的重要时期(吴福元等,1999),而该区花岗岩研

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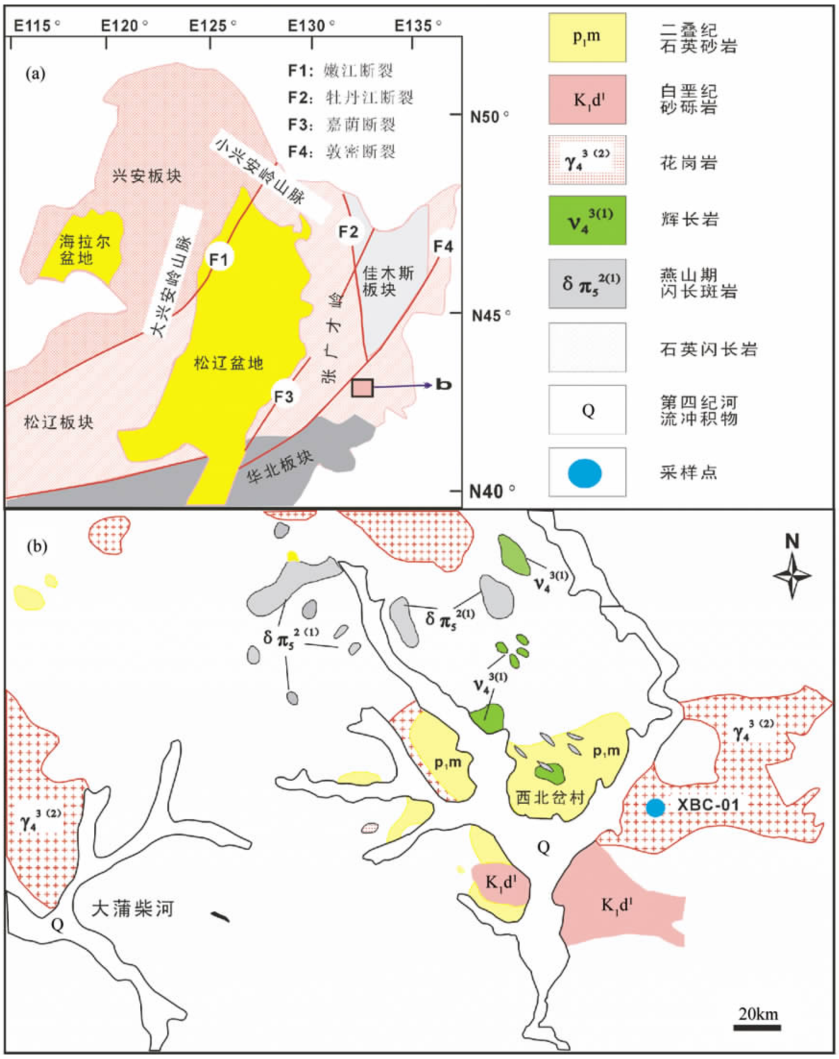

图1 东北地区主要块体分布图(a,据 Wu *et al.*, 2002)和研究区地质简图(b)

Fig. 1 Distribution of major terrenes in northeastern China (a, after Wu *et al.*, 2000) and the simplified geological map of the studied area (b)

究对反演地壳增生有重要意义(姚玉鹏,1997; 吴福元等,1999,2007; Jahn *et al.*, 2000, 2001; Wu *et al.*, 2000, 2002, 2003a, b, 2004, 2005; 孙德有等,2001,郭春丽等,2004; 程瑞玉等,2006; 葛文春等,2007)。因此,该区花岗岩精确年代学和 Hf 同位素研究尤为重要。

1 地质概况

研究区位于吉林省东北部张广才岭南段(图1a),花岗岩体在岩体组成上主要为黑云母花岗闪长岩,岩体规模有几千平方千米。主要矿物组成包括石英(0.5~2.5mm, 20%~30%)、斜长石(0.6~3.0mm, 45%~55%)、碱长石(0.5~2.5mm, 15%~20%)、黑云母(0.5~2.0mm, 5%~7%)和少量角闪石(3.0%)。副矿物有锆石、榍石、少量磷灰石和不透明矿物(磁铁矿和钛铁矿)。虽然前期研究认为该岩体侵位时期为海西期(吉林省地质矿产局,1988),但对该花岗岩的准确侵位年龄目前仍缺乏认识。另外,研究区还出露辉长岩、石英闪长岩(埃达克岩)(165Ma)(刘燊等,2009)和燕山期闪长斑岩等岩浆岩(图1b)。

2 测试方法

样品的破碎和锆石的挑选工作在河北廊坊区调院完成。锆石阴极发光图像处理在西北大学"大陆动力学国家重点实验室"完成; 锆石 LA-ICPMS 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"完成。本次实验所采用的激光束斑直径为 24μm 。普通铅校正方法见 Andersen(2002),详细的测试流程见 Yuan *et al.* (2004),

年龄计算采用 GLITTER 和 ISOPLOT（Ludwig，2003）程序。锆石 91500 和 NIST 610 分别作为标准锆石和结果标定锆石。单个分析可信度为 95%（1σ）。锆石 LA-ICPMS U-Pb 同位素分析结果见表 1。锆石原位 Lu-Hf 同位素分析在中国科学院地质与地球物理研究所进行，所用仪器为配有 193nm 激光取样系统的 Neptune 多接收电感耦合等离子体质谱仪（LA-MC-ICPMS），激光束斑直径为 63μm，激光脉冲宽度为 15ns，试验中采用 He 气作为剥蚀物质载气。详细测试流程以及仪器运行条件等参见 Wu *et al.*（2006）。锆石原位 Lu-Hf 同位素测试结果见表 2。

表 1　研究区花岗岩（样品 XBC-01）的锆石 LA-ICPMS U-Pb 分析结果

Table 1　LA-ICPMS zircon U-Pb dating of the studied granite (sample XBC-01) in eastern Jilin Province

Spot	Th	U	Pb	Th/U	Isotopic ratios						Age (Ma)					
	($\times10^{-6}$)				$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ	$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ
1	25.9	95.6	4.69	0.27	0.0541	0.0036	0.2936	0.0175	0.0413	0.0007	376	103	261	14	261	4
2	88.4	216	11.1	0.41	0.0523	0.0028	0.2911	0.0150	0.0416	0.0006	300	92	259	12	263	4
3	104	265	13.6	0.39	0.0529	0.0025	0.2966	0.0140	0.0417	0.0005	325	85	264	11	264	3
4	42.7	181	8.76	0.24	0.0544	0.0022	0.3043	0.0123	0.0416	0.0005	387	69	270	10	263	3
5	59.9	282	14.0	0.21	0.0515	0.0021	0.2955	0.0116	0.0416	0.0005	264	70	263	9	263	3
6	96.8	237	12.5	0.41	0.0523	0.0020	0.3023	0.0117	0.0414	0.0005	297	65	268	9	262	3
7	84.7	229	11.9	0.37	0.0536	0.0020	0.3018	0.0107	0.0413	0.0005	354	57	268	8	261	3
8	174	460	24.4	0.38	0.0514	0.0015	0.3003	0.0088	0.0416	0.0004	258	50	267	7	263	2
9	36.9	124	6.21	0.30	0.0522	0.0027	0.2999	0.0158	0.0417	0.0007	295	92	266	12	263	4
10	84.5	217	11.0	0.39	0.0526	0.0022	0.3014	0.0125	0.0411	0.0005	313	73	268	10	260	3
11	221	605	31.9	0.37	0.0508	0.0012	0.3008	0.0073	0.0418	0.0004	230	37	267	6	264	3
12	119	443	22.3	0.27	0.0523	0.0035	0.2986	0.0195	0.0415	0.0008	297	116	265	15	262	5
13	80.7	185	9.59	0.44	0.0530	0.0027	0.2960	0.0144	0.0412	0.0005	327	87	263	11	260	3
14	55.0	208	10.2	0.27	0.0550	0.0027	0.3073	0.0141	0.0413	0.0006	410	77	272	11	261	4
15	81.0	257	13.4	0.32	0.0511	0.0014	0.3010	0.0081	0.0418	0.0004	245	43	267	6	264	3
16	97.5	261	13.4	0.37	0.0518	0.0022	0.2942	0.0117	0.0413	0.0005	277	68	262	9	261	3
17	57.3	178	9.14	0.32	0.0509	0.0021	0.2935	0.0120	0.0413	0.0005	234	73	261	9	261	3
18	79.3	220	11.7	0.36	0.0521	0.0026	0.3039	0.0145	0.0416	0.0007	290	80	269	11	263	4
19	40.4	168	8.50	0.24	0.0516	0.0017	0.3015	0.0099	0.0414	0.0005	266	54	268	8	262	3

表 2　研究区花岗岩（样品 XBC-01）LA-MC-ICPMS 锆石 Hf 同位素分析结果

Table 2　Zircon Hf isotopic compositions of the studied granite (sample XBC-01) in eastern Jilin Province

Spot	$^{176}Yb/^{177}Hf$	2σ	$^{176}Lu/^{177}Hf$	2σ	$^{176}Hf/^{177}Hf$	2σ	$\varepsilon_{Hf}(t)$	t_{DM1} (Ma)	t_{DM2} (Ma)	$f_{Lu/Hf}$
1	0.015977	0.000112	0.000499	0.000006	0.282708	0.000016	3.43	761	1227	−0.98
2	0.007198	0.000024	0.000237	0.000000	0.282676	0.000014	2.35	800	1298	−0.99
3	0.007592	0.000034	0.000259	0.000000	0.282708	0.000020	3.47	756	1227	−0.99
4	0.004515	0.000019	0.000148	0.000000	0.282671	0.000015	2.20	804	1309	−1.00
5	0.006174	0.000134	0.000204	0.000003	0.282768	0.000017	5.62	671	1091	−0.99
6	0.014915	0.000109	0.000522	0.000006	0.282690	0.000015	2.81	786	1266	−0.98
7	0.009002	0.000393	0.000280	0.000012	0.282758	0.000018	5.24	687	1115	−0.99
8	0.015104	0.000501	0.000518	0.000012	0.282709	0.000021	3.48	759	1223	−0.98
9	0.006426	0.000034	0.000221	0.000000	0.282683	0.000013	2.61	789	1282	−0.99
10	0.016234	0.000032	0.000583	0.000004	0.282650	0.000018	1.35	844	1357	−0.98
11	0.005102	0.000042	0.000175	0.000002	0.282715	0.000016	3.73	745	1211	−0.99
12	0.006579	0.000029	0.000228	0.000000	0.282667	0.000015	2.03	812	1318	−0.99
13	0.010096	0.000159	0.000358	0.000005	0.282689	0.000016	2.78	784	1269	−0.99
14	0.012888	0.000047	0.000455	0.000001	0.282702	0.000014	3.23	768	1240	−0.99
15	0.010367	0.000033	0.000360	0.000001	0.282665	0.000016	1.93	818	1323	−0.99
16	0.006919	0.000108	0.000253	0.000003	0.282652	0.000016	1.50	833	1351	−0.99
17	0.023801	0.000041	0.000838	0.000004	0.282659	0.000016	1.63	837	1337	−0.97
18	0.012390	0.000109	0.000481	0.000003	0.282719	0.000018	3.81	745	1203	−0.99
19	0.010880	0.000040	0.000378	0.000000	0.282656	0.000015	1.61	831	1343	−0.99

注：$\varepsilon_{Hf}(t) = 10{,}000\{[(^{176}Hf/^{177}Hf)_S - (^{176}Lu/^{177}Hf)_S \cdot (e^{\lambda t} - 1)] / [(^{176}Hf/^{177}Hf)_{CHUR,0} - (^{176}Lu/^{177}Hf)_{CHUR} \cdot (e^{\lambda t} - 1)] - 1\}$;

$t_{DM1} = 1/\lambda \times \ln\{1 + [(^{176}Hf/^{177}Hf)_S - (^{176}Hf/^{177}Hf)_{DM}] / [(^{176}Lu/^{177}Hf)_S - (^{176}Lu/^{177}Hf)_{DM}]\}$;

$t_{DM2} = 1/\lambda \times \ln\{1 + [(^{176}Hf/^{177}Hf)_{S,t} - (^{176}Hf/^{177}Hf)_{DM,t}] / [(^{176}Lu/^{177}Hf)_C - (^{176}Lu/^{177}Hf)_{DM}]\} + t$;

The $^{176}Hf/^{177}Hf$ and $^{176}Lu/^{177}Hf$ ratios of chondrite and depleted mantle at the present are 0.282772 and 0.0332, 0.28325 and 0.0384, respectively (Blichert-Toft and Albarède, 1997; Griffin *et al.*, 2000); $\lambda = 1.867 \times 10^{-11}\ a^{-1}$ (Söderlund *et al.*, 2004); $(^{176}Lu/^{177}Hf)_C = 0.015$, t = crystallization age of zircon

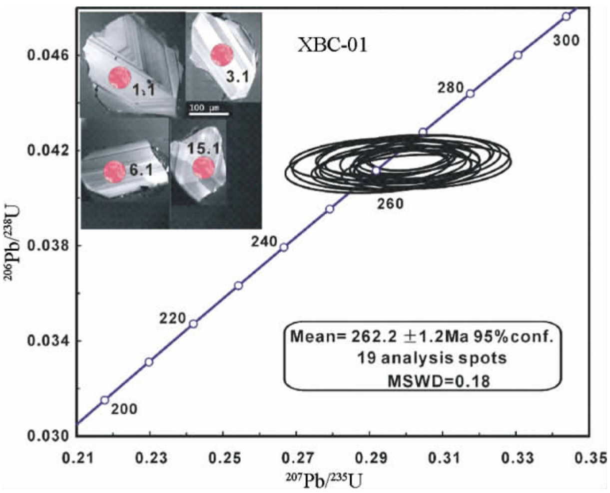

图2 花岗岩中代表性锆石的 CL 图像和锆石的 LA-ICP-MS U-Pb 谐和年龄

Fig. 2 Representative cathodoluminescence (CL) images and the LA-ICP-MS U-Pb concordia age for the zircon grains from the granitic pluton

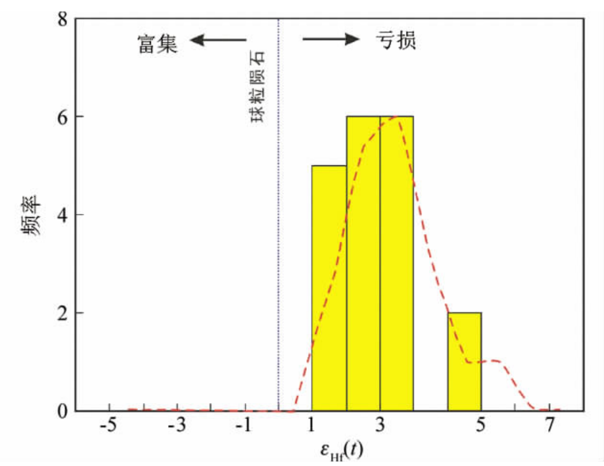

图3 花岗岩中锆石的 ε_{Hf}(262Ma) 直方图

Fig. 3 Histograms of $\varepsilon_{Hf}(t)$ values of zircons with an age of 262Ma in the granitic pluton

3 分析结果

3.1 锆石 U-Pb 年龄

样品(2kg,XBC-01)中锆石非常丰富,挑选出的锆石为自形无色透明状,大多锆石直径接近或大于 100μm。阴极发光下所有都具有振荡环带结构(图2)。所测试的锆石颗粒的 Th/U 比值范围为 0.21~0.44(表1),具有岩浆锆石的特征。19 个岩浆锆石的测试结果给出一个很好的 $^{206}Pb/^{238}U$ 加权平均年龄(262.2±1.2Ma,MSWD=0.18)(图2),该年龄代表了该花岗岩体的岩浆结晶年龄。

3.2 锆石 Hf 同位素组成

本次实验标准锆石 91500 的测定结果是 0.282296±22,该值与目前用溶液法获得的值在误差范围内一致(Woodhead *et al.*, 2004)。样品 XBC-01 总共分析了 19 个点(表2),$^{176}Hf/^{177}Hf$ 比值范围 0.282650~0.282768,加权平均值为 0.282692± 0.000016(2σ, $n=19$)。ε_{Hf}(262Ma) 范围为 1.35~5.62(图3),平均值为 2.89。二阶段 Hf 模式年龄(t_{DM2})范围为 1091~1357Ma,平均为 1263Ma。

4 讨论

目前,已有的高精度年代学数据表明,东北地区花岗岩从古生代到晚中生代都有分布(500~100Ma)(吴福元等,1997,1998,1999,2007; Wu *et al.*, 2000, 2002, 2003a, b, 2004, 2005; 孙德有等,2001,2005; 张艳斌等,2002a,b; 郭春丽等,2004; Yang *et al.*, 2004,2006; 张炯飞等,2004; 葛文春等,2005, 2007; 程瑞玉等,2006; 张兴洲等,2006; 武广等,2008)。但主体形成于 230~120Ma 之间,并可进一步划分为晚三叠-中侏罗世(230~160Ma)和早白垩(130~120Ma)两期(吴福元等,2007),只有少数形成于古生代,且主要分布在大兴安岭地区(张德全,1993; 黑龙江省地质矿产局,1993; 吴福元等,1999; Wu *et al.*, 2000, 2002; 隋振民等,2006; 葛文春等,2007)、牡丹江地区(颉颃强等,2008)和吉林省东部的延吉地区(Guo *et al.*, 2007, 2009)。而东北东部地区分布较少,目前仍未见报道,可能是由于以前认为的大量海西期和加里东期花岗岩其实质大多都是中生代的侵入体。通过本文研究,研究区花岗岩 LA-ICPMS 锆石 U-Pb 定年结果表明,该岩体的精确侵位年龄为 262.2±1.2Ma,为晚古生代海西期岩浆活动的产物。

以往研究表明,中新元古代-显生宙(1400~500Ma)是东北地区地壳增生的重要地质历史时期(吴福元等,1999; Wu *et al.*, 2000, 2003b; 程瑞玉等,2006; 葛文春等,2007),并由此引起了不同地区不同时代花岗岩源区的多样性。通过对花岗岩中 XBC-01 锆石样品 Hf 同位素研究显示,$\varepsilon_{Hf}(t)$ 都为正值(1.35~5.62),而且在 $\varepsilon_{Hf}(t)$ 直方图上,该花岗岩体的数据都落在球粒陨石演化线的右侧(图3),表明花岗岩的源区物质主要来自亏损地幔。另外,锆石 Hf 二阶段模式年龄介于 1.1~1.4Ga,暗示研究区在中-新元古代时期曾发生了一次重要的地壳增生事件。

5 结论

(1) 锆石 LA-ICP-MS U-Pb 定年结果表明研究区花岗岩成岩年龄为 262.2±1.2Ma,为晚中生代海西期岩浆作用的产物;

(2) 锆石 Hf 同位素结果显示，花岗岩源区物质主要来源于亏损地幔，在中-新元古代时通过底侵进入下地壳(地壳增生)。

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