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吉林东部大蒲柴河 adakites 锆石 U-Pb 年龄、Hf 同位素特征及其意义*

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Abstract Based on geochemical evidence, the quartz diorites from Dapuchai, eastern Jilin Province, belong to typical adakites derived from partial melting of thickened lower crust. Zircon U-Pb dating by LA-ICPMS technique indicates that the studied plutons were emplaced during Late Jurassic with an age of 164.9 ± 0.8Ma. Zircon Hf analyses conducted by LA-MC-ICPMS show that these adakites have variational ε_{Hf}(165Ma) values from −5.02 to 5.43, and Hf model ages from 965Ma to 1622Ma, indicating that the primary magma of the adakites originated from mixing of two different magma, one from partial melting of pre-existing crustal source that was separated from a depleted mantle source during the Middle Proterozoic; While the other magma from asthenospheric mantle through underplating during 985 ~ 1304Ma, indicative of an important crustal growth beneath the studied area.

Key words Adakites; Zircon U-Pb age; Zircon Hf isotopes; Jurassic

摘 要 地球化学研究表明,大蒲柴河岩体具有典型的埃达克岩特征,来自加厚下地壳的部分熔融作用。本文采用激光等离子质谱对该岩体进行了 U-Pb 同位素定年,结果表明该岩体为晚侏罗世(165Ma)岩浆活动的产物。锆石的 LA-MC-ICPMS Hf 同位素研究结果显示,ε_{Hf}(165Ma)范围为 −5.02 ~ 5.43,二阶段 Hf 模式年龄(t_{DM2})范围为 965 ~ 1622Ma,暗示原始母岩浆为两种不同源区岩浆的混合。另外,Hf 同位素研究表明,研究区在中-新元古代时(965 ~ 1304Ma)曾经历了一次重要的地壳增生事件。

关键词 埃达克岩;锆石 U-Pb 年龄;锆石 Hf 同位素;侏罗世

中图法分类号 P588.122;P597.3

我国东北地区分布有大约 30 万平方千米的不同类型的显生宙花岗岩(吴福元等,1999, 2007)。大量研究显示,该区花岗岩的系统研究具有重要的科学意义:(1)重新准确厘定和划分花岗岩形成的时代和类型(姚玉鹏,1997;Jahn *et al.*, 2001; Wu *et al.*, 2000, 2002, 2003a, b, 2004, 2005; 吴福元等,1997,1998,1999,2007;孙德有等,2001,2005;张艳斌等,2002a, b;郭春丽等,2004;Yang *et al.*, 2004; 葛文春等,2005;程瑞玉等,2006);(2)有助于探讨显生宙东北地区地壳

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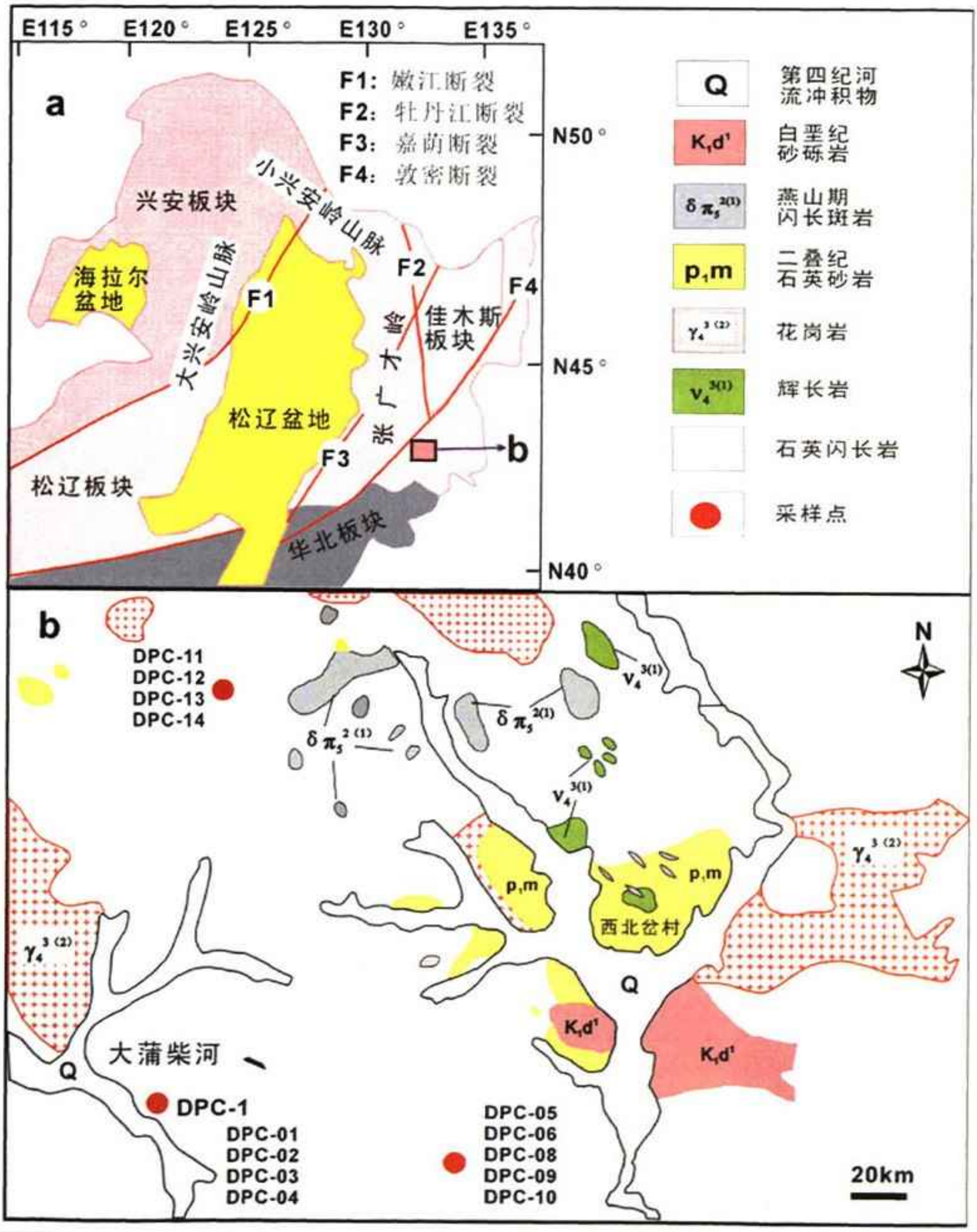

图 1 东北地区主要块体分布图(据 Wu *et al.*, 2000)(a)和研究区地质简图(b)

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

增生及壳幔相互作用等深部动力学问题(Jahn *et al.*, 2000, 2001; Wu *et al.*, 2000, 2002, 2003a, b, 2004, 2005; 吴福元等,1999,2007;孙德有等,2001,郭春丽等,2004;程瑞玉等,2006;葛文春等,2007;Yang *et al.*, 2007)。埃达克岩的发现和提出不仅拓宽了人们对岛弧岩浆系列的认识,而且开拓了花岗岩研究的新思路(张旗等,2002)。因为埃达克岩能将岩石地球化学研究与岩浆源区深度联系起来,从而对花岗岩成因具有重要的启示。东北地区显生宙埃达克岩的分布十分广泛,主要分布于吉林东部地区(如,大黑山(175.3Ma)、棉田(189Ma)、东清(156Ma)、石门(184Ma)、小西南岔、朱敦店、

表1 大蒲柴河埃达克岩的锆石 LA-ICPMS U-Pb 分析结果

Table 1 LA-ICPMS zircon U-Pb dating of Dapuchaihe adakites in eastern Jilin Province

DPC-1					Isotopic ratios						Age (Ma)					
Spot	Th($\times10^{-6}$)	U($\times10^{-6}$)	Pb($\times10^{-6}$)	Th/U	$^{207}Pb/^{206}Pb$	1s	$^{207}Pb/^{235}U$	1s	$^{206}Pb/^{238}U$	1s	$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ
1	28.6	225	6.90	0.13	0.0493	0.0030	0.1750	0.0104	0.0260	0.0004	161	108	164	9	166	2
2	46.5	330	10.0	0.14	0.0507	0.0022	0.1788	0.0075	0.0256	0.0003	228	76	167	6	163	2
3	46.0	284	8.86	0.16	0.0515	0.0021	0.1836	0.0072	0.0260	0.0003	264	71	171	6	165	2
4	52.1	285	9.03	0.18	0.0529	0.0025	0.1884	0.0088	0.0258	0.0003	323	83	175	8	164	2
5	39.1	312	9.49	0.13	0.0509	0.0019	0.1786	0.0064	0.0256	0.0003	235	63	167	6	163	2
6	43.0	266	8.27	0.16	0.0495	0.0022	0.1776	0.0081	0.0259	0.0003	174	84	166	7	165	2
7	41.6	270	8.42	0.15	0.0526	0.0027	0.1859	0.0090	0.0259	0.0003	312	87	173	8	165	2
8	48.2	342	10.9	0.14	0.0496	0.0024	0.1806	0.0085	0.0264	0.0003	178	113	169	7	168	2
9	162	750	23.1	0.22	0.0512	0.0015	0.1807	0.0053	0.0256	0.0002	251	50	169	5	163	1
10	225	382	13.2	0.59	0.0513	0.0017	0.1837	0.0063	0.0260	0.0003	253	58	171	5	165	2
11	44.7	293	9.02	0.15	0.0518	0.0021	0.1851	0.0074	0.0259	0.0003	276	71	172	6	165	2
12	142	307	10.0	0.46	0.0510	0.0019	0.1819	0.0067	0.0259	0.0003	241	64	170	6	165	2
13	328	605	20.5	0.54	0.0488	0.0012	0.1770	0.0050	0.0261	0.0003	140	43	165	4	166	2
14	70.1	310	9.63	0.23	0.0508	0.0019	0.1825	0.0069	0.0260	0.0003	231	68	170	6	166	2
15	111	586	17.4	0.19	0.0493	0.0020	0.1751	0.0068	0.0258	0.0003	163	95	164	6	164	2
16	300	700	22.2	0.43	0.0492	0.0015	0.1750	0.0052	0.0259	0.0004	157	41	164	4	165	2
17	40.9	314	9.51	0.13	0.0514	0.0017	0.1845	0.0058	0.0262	0.0003	260	53	172	5	166	2
18	433	988	32.6	0.44	0.0485	0.0011	0.1766	0.0044	0.0262	0.0003	124	40	165	4	167	2
19	72.4	334	10.4	0.22	0.0531	0.0020	0.1924	0.0071	0.0264	0.0003	331	60	179	6	168	2
20	47.7	340	10.2	0.14	0.0545	0.0023	0.1935	0.0081	0.0256	0.0003	393	76	180	7	163	2
21	86.0	372	11.5	0.23	0.0488	0.0017	0.1753	0.0059	0.0261	0.0003	140	57	164	5	166	2

大蒲柴河和延吉地区)(方文昌,1992;张艳斌等,2002b;Wu *et al.*, 2003a, b;张炯飞等,2004;Guo *et al.*, 2007, 2009)。而且它们大多与多金属(Au、Cu 和 Mo)成矿作用有关(张炯飞等,2004)。虽然如此,对上述很多埃达克岩的同位素年龄和成因目前仍缺乏足够的认识(张炯飞等,2004)。如,大蒲柴河岩体,虽然目前一致认为该岩体的侵位时间为中生代,但仍存在很大争议(如,燕山期:吉林省地质矿产局,1988;印支期:方文昌,1992);另外,该岩体的成因研究也是初步的(方文昌,1992;张炯飞等,2004)。因此,该岩体的同位素年龄和成因还有待于进一步确定和探讨(张炯飞等,2004)。本文选择该岩体为研究对象,以元素地球化学以及锆石 U-Pb 年代学和 Hf 同位素为主要手段,准确厘定该岩体的形成时代和成因,同时探讨其与地壳增生的可能关系。

1 地质概况

张广才岭地块位于松嫩-张广才岭地块东段(图 1)。该地块内显生宙花岗岩极为发育(孙德有等,2001),且年龄主要分布在 230~160Ma 之间(张兴洲等,2006)。大蒲柴河岩体位于张广才岭南段,岩体规模上万平方千米(图 1)。本区出露的沉积地层从老到新主要包括二叠纪庙岭组的灰白色长石石英砂岩(P_1m)和白垩纪下统大拉子组砂砾岩段的砾岩、含砾粗砂岩和砂岩(K_1d^1)等。本区出露的岩浆岩包括黑云母花岗岩和辉长岩、石英闪长岩以及燕山期闪长斑岩(图 1)。石英闪长岩为该岩体的主要岩石类型,具半自形粒状结构,块状构造。主要矿物组成包括石英(0.8~2.5mm, 8%~10%)、半自形板状或柱状斜长石(中长石:0.5~3.0mm, 55%~65%)、钾长石(0.5~2.0mm, 6%~8%)、角闪石(0.5~2.0mm, 5%~7%)和黑云母(0.5~2.0mm, 8%~10%)。石英和钾长石呈他形粒状充填于斜长石粒间。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)。

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 Anderson (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)。测试结果见表 2。主微量元素测试在中国科学院地球化学研究所矿床地球化学国家重点实验室完成。主元素测试采用 Axios PW4400 型 X 荧光光谱仪,分析精度优于 3%;微量元素分析采用 ELAN 6000 ICP-MS 完成,分析精度优于 5%。测试结果列于表 3。

3 分析结果

3.1 锆石 U-Pb 年龄

样品(~2kg, DPC-1)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。阴极发光下所有锆石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 0.13~0.59(表 1),具有岩浆锆石的特征。21 个岩浆锆石的测试结果表明,所测同位素数据均落在谐和线上及其附近(图 2),并给出很好的$^{206}Pb/^{238}U$ 加权平均年龄(164.9±0.8Ma, MSWD=0.71),该年龄代表了大蒲柴河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 DPC-1 总共分析了 19 个点,$^{176}Hf/^{177}Hf$ 比值范围 0.282530~0.282772,加权平均值为 0.282667±0.000021(2σ, n=19)。ε_{Hf}(165Ma)范围为 -5.02~5.43(图 3),平均值为 -0.16。二阶段 Hf 模式年龄(t_{DM2})范围为 965~1622Ma,平均为 1317Ma。

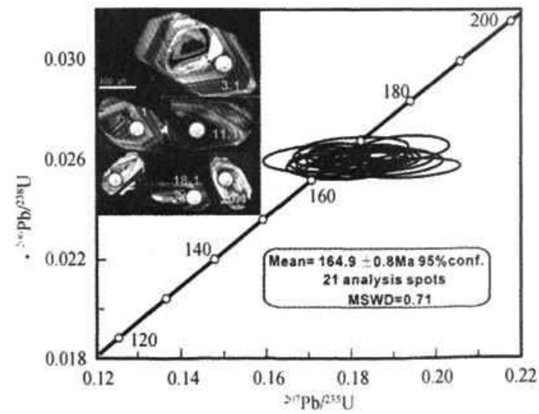

图 2 埃达克岩中代表性锆石的 CL 图像和锆石的 LA-ICPMS U-Pb 谐和年龄

Fig. 2 Representative cathodoluminescence (CL) images and the LA-ICPMS U-Pb concordia age for the zircon grains from the adakites

表2 大蒲柴河埃达克岩 LA-MC-ICPMS 锆石 Hf 同位素分析结果

Table 2 Zircon Hf isotopic compositions of the Dapuchaihe adakites in eastern Jilin Province

DPC-1	$^{176}Yb/^{177}Hf$	2σ	$^{176}Lu/^{177}Hf$	2σ	$^{176}Hf/^{177}Hf$	2σ	$\varepsilon_{Hf}(t)$	t_{DM1}(Ma)	t_{DM2}(Ma)	$f_{Lu/Hf}$
1	0.014739	0.000114	0.000542	0.000004	0.282612	0.000017	-2.09	895	1440	-0.98
2	0.018965	0.000186	0.000691	0.000006	0.282671	0.000019	-0.02	816	1309	-0.98
3	0.020180	0.000384	0.000703	0.000009	0.282772	0.000018	3.55	675	1083	-0.98
4	0.006859	0.000042	0.000285	0.000002	0.282664	0.000024	-0.22	817	1324	-0.99
5	0.008137	0.000046	0.000379	0.000001	0.282695	0.000022	0.86	776	1255	-0.99
6	0.019507	0.000500	0.000643	0.000014	0.282768	0.000022	3.41	680	1092	-0.98
7	0.014886	0.000043	0.000544	0.000002	0.282595	0.000022	-2.70	919	1478	-0.98
8	0.014762	0.000137	0.000599	0.000007	0.282724	0.000024	1.84	741	1192	-0.98
9	0.045274	0.001127	0.001428	0.000028	0.282534	0.000024	-4.96	1028	1615	-0.96
10	0.028560	0.000781	0.000960	0.000027	0.282569	0.000021	-3.65	965	1536	-0.97
11	0.010793	0.000034	0.000418	0.000001	0.282673	0.000016	0.08	807	1304	-0.99
12	0.027930	0.000505	0.000859	0.000013	0.282737	0.000019	2.27	728	1163	-0.97
13	0.020796	0.000195	0.000661	0.000006	0.282633	0.000026	-1.35	868	1393	-0.98
14	0.007413	0.000104	0.000265	0.000003	0.282585	0.000020	-3.02	926	1500	-0.99
15	0.026154	0.000532	0.000836	0.000012	0.282756	0.000026	2.98	699	1118	-0.97
16	0.024346	0.000204	0.000831	0.000007	0.282530	0.000022	-5.02	1016	1622	-0.97
17	0.008713	0.000031	0.000361	0.000001	0.282681	0.000016	0.37	795	1286	-0.99
18	0.016239	0.000238	0.000626	0.000006	0.282650	0.000020	-0.76	844	1356	-0.98
19	0.015253	0.000082	0.000486	0.000002	0.282825	0.000023	5.43	597	965	-0.99

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

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

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

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 Albare'de, 1997; Griffin *et al.*, 2000). $\lambda = 1.867 \times 10^{-11} a^{-1}$ (Soderlund *et al.*, 2004). $(^{176}Lu/^{177}Hf)_C = 0.015$, t = crystallization age of zircon

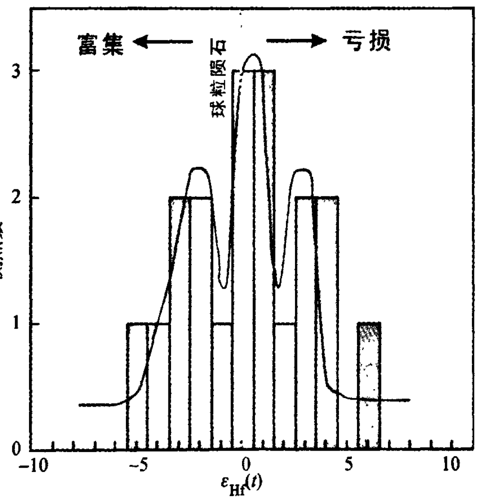

图3 埃达克岩中锆石的 ε_{Hf}(165Ma) 直方图

Fig. 3 Histograms of $\varepsilon_{Hf}(t)$ values of zircons with an age of 165 Ma in the adakites

3.3 主微量元素组成

13 个代表性样品的主微量元素测试结果见表3。所研究样品具有较高的 SiO_2 (64.88% ~ 68.34%)、Al_2O_3 (15.82% ~ 17.33%)、Na_2O (4.50% ~ 6.44%)、Sr ($611 \times 10^{-6} \sim 866 \times 10^{-6}$) 和 Ba ($911 \times 10^{-6} \sim 1350 \times 10^{-6}$) 值;低的 MgO (0.5% ~ 0.86%)、$Mg^{\#}$ (26.4 ~ 35.5)、Yb ($0.52 \times 10^{-6} \sim 1.23 \times 10^{-6}$) 和 Y ($8.9 \times 10^{-6} \sim 17.6 \times 10^{-6}$) 含量;以及较高的 Sr/Y (41.7 ~ 88.9) 和 $(La/Yb)_N$ (20.4 ~ 33.6) 比值(表3)。表现出典型 adakite 的特征(Defant and Drummond, 1990),且与吉林东部中生代埃达克岩(adakites)的范围(张炯飞等,2004)一致(图4a, b)。在 Harker 图(图5)中,SiO_2 与 TiO_2、Al_2O_3、FeO^T、MgO、CaO、Na_2O 和 P_2O_5 具有明显的负相关关系,而与 K_2O 之间具有正相关关系。暗示成岩过程存在明显的矿物(如,橄榄石、单斜辉石、角闪石、斜长石、含钛氧化物以及磷灰石等)的分离结晶作用。在稀土元素球粒陨石标准化(Sun and McDonough, 1989)配分曲线中(图6a),所有样品都表现出轻稀土富集、重稀土亏损以及轻微的负 Eu 异常($Eu^* = 0.72 \sim 0.89$)特征。暗示成岩过程中可能存在少量斜长石的分异作用。在微量元素原始地幔标准化(Sun and McDonough, 1989)蛛网图中(图6b),所有样品都具有富集 Ba、K 和 Sr 以及亏损 Nb、Ta、P 和 Ti 特征。

表3 大蒲柴河埃达克岩主量元素(wt%)和微量元素($\times10^{-6}$)组成

Table 3 Major (wt%) and trace ($\times10^{-6}$) elements compositions of Dapuchaihe adakites in eastern Jilin Province

Sample	DPC-01	DPC-02	DPC-03	DPC-04	DPC-05	DPC-06	DPC-08	DPC-09	DPC-10	DPC-11	DPC-12	DPC-13	DPC-14
SiO_2	68.31	65.68	68.04	68.34	64.88	69.50	66.53	68.05	69.78	66.50	67.35	67.50	68.29
TiO_2	0.41	0.56	0.53	0.38	0.51	0.32	0.38	0.39	0.32	0.51	0.39	0.44	0.41
Al_2O_3	16.56	16.99	16.37	16.20	17.30	15.96	15.93	16.85	15.82	17.33	16.66	16.30	16.38
Fe_2O_3	3.02	3.73	3.23	2.87	3.86	2.62	3.46	3.10	2.73	3.63	3.04	3.33	3.14
MgO	0.68	0.83	0.64	0.79	0.86	0.53	0.62	0.62	0.50	0.81	0.59	0.75	0.61
CaO	2.86	3.01	2.65	2.55	3.10	2.38	2.76	2.78	2.42	3.00	2.70	2.77	2.68
Na_2O	4.96	6.04	4.81	5.45	5.97	4.73	6.44	5.00	4.50	5.17	5.05	6.02	5.03
K_2O	3.08	2.89	3.40	3.59	3.10	3.72	3.22	3.49	3.61	3.10	3.29	3.19	3.40
MnO	0.07	0.08	0.08	0.07	0.10	0.07	0.09	0.07	0.08	0.08	0.07	0.08	0.08
P_2O_5	0.14	0.17	0.16	0.14	0.18	0.12	0.14	0.15	0.13	0.17	0.14	0.15	0.15
LOI	0.55	0.75	0.86	0.44	0.51	0.53	0.49	0.41	0.49	0.58	0.61	0.49	0.55
Total	100.63	100.74	100.76	100.83	100.36	100.50	100.06	100.91	100.39	100.89	99.90	101.03	100.71
$Mg^\#$	31.1	30.9	28.4	35.5	30.9	29.0	26.4	28.6	27.0	30.9	28.0	31.1	28.0
Sc	3.35	2.04	2.05	3.18	2.46	1.03	1.29	2.17	2.16	2.39	2.90	2.61	2.32
V	23.1	33.1	27.0	36.1	33.5	22.0	24.8	26.6	18.4	31.2	29.3	31.4	26.6
Cr	17.9	12.3	13.9	19	18.2	12.8	29.9	18.8	11.4	13.5	47.3	16.4	19.9
Co	3.41	5.13	3.94	6.05	5.83	3.16	3.86	3.64	3.03	4.61	4.10	4.97	4.13
Ni	7.15	4.92	4.41	64.4	6.59	5.07	11.9	6.27	7.39	8.30	28.1	8.7	13.6
Ga	19.3	21.9	20.2	24.4	22.8	19.5	19.7	19.5	15.2	22.3	21.5	21.1	19.9
Ge	0.75	0.74	0.70	0.86	0.76	0.70	0.72	0.70	0.57	0.78	0.69	0.81	0.80
Rb	77.0	69.7	71.9	82.7	77.1	76.6	70.9	63.6	73.4	83.3	79.5	98.7	95.9
Sr	721	731	734	866	772	718	702	659	611	743	786	776	729
Y	13.2	14.5	17.6	16.1	15.2	8.9	11.9	12.6	6.87	14.8	13.8	12.9	10.9
Zr	151	175	168	232	249	155	157	134	102	157	126	143	168
Nb	8.15	9.70	11.10	10.40	10.20	6.05	7.72	8.23	4.85	10.4	8.24	10.2	8.79
Cs	1.47	1.46	1.03	1.43	1.42	1.24	1.13	1.16	1.05	1.48	0.92	1.72	1.54
Ba	1350	911	1250	1330	1030	1410	1200	1250	1090	1020	1250	1150	1200
La	39.6	45.9	35.0	42.1	48.8	30.3	33.1	35.1	24.2	46.0	36.4	39.6	38.0
Ce	71.1	85.1	70.8	78.3	88.3	54.0	60.1	57.9	44.6	84.9	66.0	73.4	68.0
Pr	8.27	9.61	9.16	9.31	10.1	6.23	7.15	7.63	4.83	9.58	7.81	8.33	7.78
Nd	30.4	35.1	35.7	35.2	35.7	22.6	26.3	28.3	17.1	34.2	29.1	30.3	27.2
Sm	5.59	6.00	7.04	6.63	5.97	3.79	4.94	5.30	2.86	5.82	5.68	5.32	4.53
Eu	1.17	1.32	1.44	1.40	1.28	0.85	1.03	1.11	0.69	1.29	1.11	1.10	0.97
Gd	3.97	4.13	5.00	4.68	4.08	2.65	3.35	3.71	1.97	3.95	3.91	3.63	3.22
Tb	0.56	0.58	0.71	0.66	0.59	0.38	0.50	0.52	0.27	0.59	0.57	0.50	0.44
Dy	2.40	2.55	3.19	3.11	2.81	1.70	2.38	2.48	1.27	2.69	2.64	2.44	2.06
Ho	0.47	0.51	0.64	0.59	0.54	0.34	0.45	0.45	0.25	0.53	0.50	0.46	0.39
Er	1.20	1.37	1.62	1.52	1.43	0.85	1.12	1.15	0.67	1.40	1.27	1.22	1.02
Tm	0.15	0.17	0.20	0.18	0.18	0.10	0.15	0.14	0.09	0.17	0.16	0.15	0.13
Yb	0.92	1.08	1.23	1.13	1.15	0.70	0.85	0.87	0.52	1.10	0.94	0.94	0.85
Lu	0.12	0.14	0.15	0.14	0.15	0.09	0.11	0.11	0.07	0.15	0.12	0.12	0.11
Hf	3.59	3.96	3.91	5.30	6.06	3.98	3.82	3.08	2.65	3.92	3.17	3.59	4.19
Ta	0.73	0.83	0.93	0.90	0.88	0.49	0.72	0.71	0.41	0.89	0.76	0.90	0.75
Pb	17.2	16.2	17.3	20.8	18.9	19.6	18.6	16.2	18.2	19.6	18.9	22.2	20.7
Th	7.94	10.60	7.31	9.48	11.1	6.87	7.33	7.35	5.61	10.8	7.89	9.45	8.81
U	0.78	1.08	0.93	0.96	0.97	0.62	0.78	0.71	0.80	0.93	1.39	0.90	1.11
Sr/Y	54.6	50.4	41.7	53.8	50.8	80.4	59.0	52.3	88.9	50.2	57.0	60.2	66.9
$(La/Yb)_N$	30.8	30.5	20.4	26.7	30.4	31.3	28.0	28.9	33.6	30.0	27.7	30.3	31.9
Eu^*	0.76	0.81	0.74	0.77	0.79	0.82	0.77	0.77	0.89	0.82	0.72	0.76	0.77
T_{Zr}(℃)	820	825	830	856	858	823	808	808	787	822	802	806	828
A/CNK	1.2	1.1	1.2	1.1	1.1	1.1	1.0	1.2	1.2	1.2	1.2	1.0	1.1
A/NK	1.4	1.3	1.4	1.3	1.3	1.4	1.1	1.4	1.4	1.5	1.4	1.2	1.4

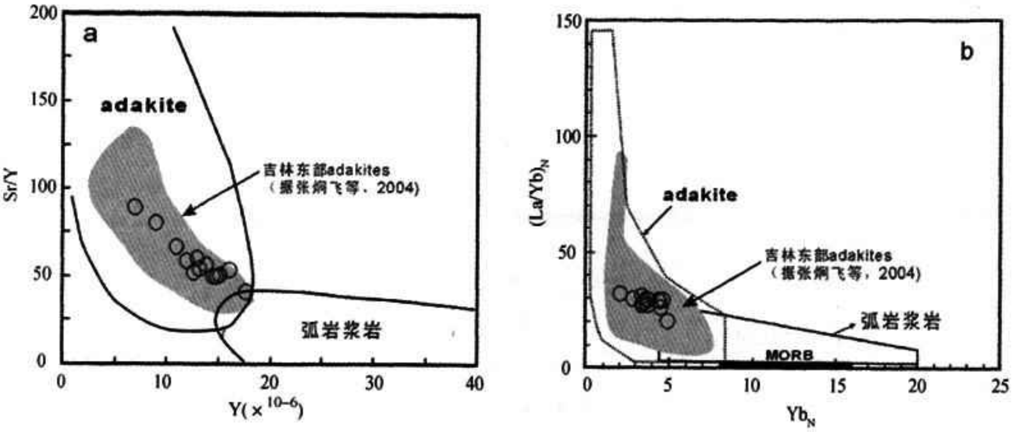

图4 埃达克岩 Sr/Y-Y (a) 和 $(La/Yb)_N$-Yb_N (b) 相关图

Fig. 4 Sr/Y vs. Y (a) and $(La/Yb)_N$ vs. Yb_N (b) diagrams of the adakites

4 大蒲柴河 Adakites 成因讨论

4.1 成因机制

目前，埃达克岩石至少有五种成因机制：(1)俯冲大洋板块的部分熔融作用(Defant and Drummond, 1990; Kay and Kay, 1993; Stern and Kilian, 1996; Li and Li, 2003; Martin *et al.*, 2005; Zhou *et al.*, 2006; Wang *et al.*, 2007a)；(2)同期玄武质母岩浆的地壳混染和分离结晶作用(Castillo *et al.*, 1999; Macpherson *et al.*, 2006)；(3)含水地幔橄榄岩部分熔融作用(Stern and Hanson, 1991)；(4)加厚下地壳的部分熔融作用(Atherton and Petford, 1993; Petford and Atherton, 1996; Johnson *et al.*, 1997; Arculus *et al.*, 1999; Chung *et al.*, 2003; Xiong *et al.*, 2003; Hou *et al.*, 2004; Wang *et al.*, 2005; Guo *et al.*, 2006; Xu *et al.*, 2006)；(5)拆沉下地壳的部分熔融作用(Kay and Kay, 1993; Defant *et al.*, 2002; Xu *et al.*, 2002; Gao *et al.*, 2004; Wang *et al.*, 2004, 2006, 2007b; Guo *et al.*, 2006; Lai *et al.*, 2007; Liu *et al.*, 2008a, b, c)。

研究区埃达克岩具有非常低的 MgO 含量(0.5% ~ 0.88%)(表3,图7)，与加厚下地壳部分熔融形成的 adakites 以及变质玄武岩和榴辉岩实验熔体(1 ~ 4.0Gpa)一致，而明显不同于俯冲大洋板块和拆沉下地壳部分熔融形成的 adakites。另外，大多数样品(除 DPC-01、DPC-05 和 DPC-11)具有低的 Th 含量($5.61\times10^{-6}\sim9.48\times10^{-6}$)(表3)，也暗示它们不可能来自拆沉下地壳的部分熔融(Wang *et al.*, 2007a)。同样地，大蒲柴河埃达克岩也不可能来自含水地幔橄榄岩的部分熔融，因为含水地幔橄榄岩产生的熔体通常具有较低的 SiO_2 含量(< 55%)(Green, 1980; Jahn and Zhang, 1984; Baker *et al.*, 1995)。研究区埃达克岩在 Harker 图(图5)上表现出明显的结晶分异趋势。另外，负的 Nb、Ta、Ti 和 P 也表明可能存在金红石、钛铁矿、榍石和磷灰石的分异作用。以上特征表明结晶分异在成岩过程起着重要作用。既然如此，是否可以用第二种机制来解释本文埃达克岩的成因呢？如果该区埃达克岩是由同期玄武质母岩浆的地壳混染和分离结晶作用形成，那么在研究区内应该存在大面积同期侵入的基性岩浆活动，然而，已有资料(吉林省地质矿产局,1988)和野外证据表明并非如此。另外，与上地壳($Th=10.5\times10^{-6}$、$U=2.7\times10^{-6}$、$Rb=84\times10^{-6}$、$Nb=25\times10^{-6}$、$Pb=20\times10^{-6}$)(Rudnick and Fountain, 1995; Rudnick and Gao, 2003)相比，除极少数样品外，研究区埃达克岩具有相对低的 Th($5.61\times10^{-6}\sim9.48\times10^{-6}$)、U($0.62\times10^{-6}\sim1.39\times10^{-6}$)、Rb($63\times10^{-6}\sim84\times10^{-6}$)、Nb($4.85\times10^{-6}\sim11.1\times10^{-6}$)和 Pb($16\times10^{-6}\sim20\times10^{-6}$)(表3)，排除了明显的地壳混染作用。而且继承锆石的缺乏以及锆石正到轻微的负 ε_{Hf} 值(−5.02 ~ 5.43，平均值为 −0.16)也说明地壳混染的影响不大。由此可见，我们完全有理由排除第二种成因机制的可能性。综上所述，加厚下地壳的部分熔融作用是大蒲柴埃达克岩最可能的成因机制。

4.2 源区特征

在 Harker 图中(图5)，SiO_2 与 Al_2O_3 之间具有明显的负相关关系，结合埃达克岩弱的负 Eu 异常特征(图6a)，暗示成岩过程中可能存在斜长石的分离结晶。但 Sr 的富集(图6b)以及丰富的斜长石斑晶排除了源区存在斜长石的可能。另外，研究区埃达克岩具有高的 La/Yb 和 Sr/Y 比值以及低的 Y 和 Yb 含量(表3;图4a, b)，也表明源区存在石榴石而缺少斜长石(Defant and Drummond, 1990; Atherton and Petford, 1993; Rapp and Watson, 1995; Drummond *et al.*, 1996; Rapp *et al.*, 1999, 2003; Defant and Kapezhinskas,

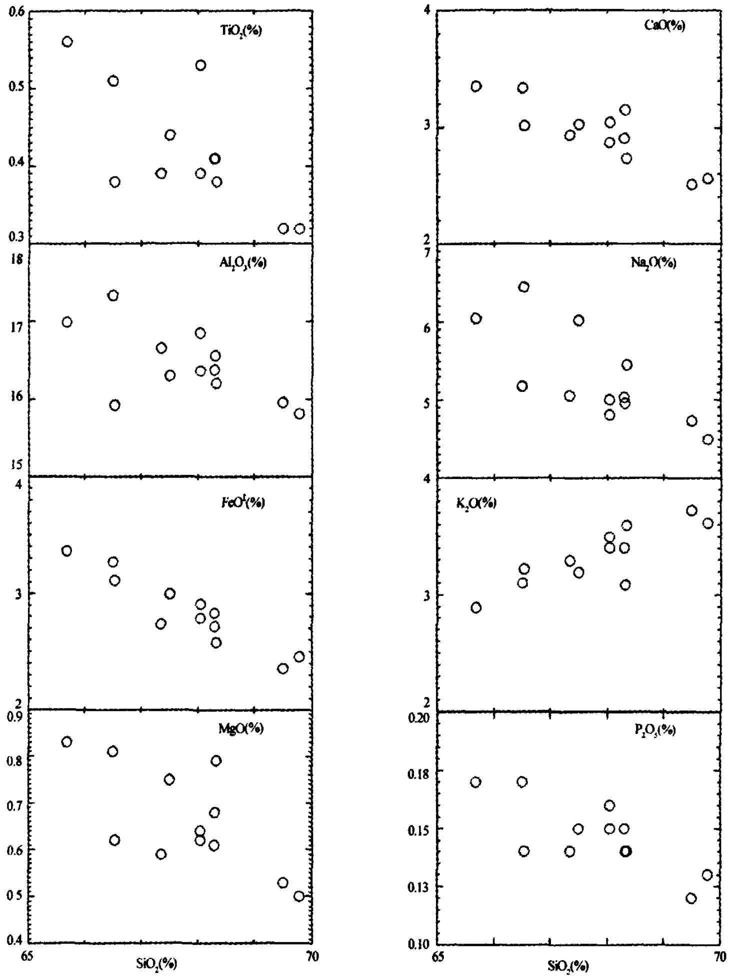

图5 埃达克岩的Harker图解

Fig. 5 Harker diagrams of the adakites

2001; Castillo, 2006)。除此之外,埃达克岩具有高的Rb/Sr比值(0.09~0.13),暗示源区中还存在角闪石相。因为角闪石一般具有与原始地幔相当的Rb/Sr比值(~0.03)(Ionov *et al.*, 1997),因此如果源区有角闪石存在,所形成的岩浆将会具有高于原始地幔的Rb/Sr比值(0.03)。源区中石榴石的存在需要有厚的地壳(>40km)存在(Rapp and Watson, 1995; Petford and Atherton, 1996),表明埃达克岩形成时(晚侏罗世)研究区的地壳厚度应至少大于40km。

近期研究表明,锆石Hf同位素组成可反映岩浆源区特征以及花岗质岩石形成中的岩浆混合过程(Griffin *et al.*, 2002; Wang *et al.*, 2003; Hawkesworth and Kemp, 2006; Yang *et al.*, 2006, 2007)。本文埃达克岩岩浆锆石(165Ma)的ε_{Hf}值可以分为两组(表3):一组表现为正值(0.08~5.43);而另一组具有负的ε_{Hf}值(-5.02~-0.02)。表明研究区埃达克岩源区为两种不同源岩浆的混合。一种岩浆来源于先存的从早期亏损地幔(t_{DM2}=1309~1622Ma)分离来的地壳源;另一种为随后(t_{DM2}=965~1304Ma)底侵的亏损幔源岩浆,并反映了一次重要的地壳增生事件。

4.3 成岩过程

通过对广布于辽东半岛侏罗世I-型花岗岩的研究,Wu *et al.* (2005)认为这些岩石为加厚下地壳部分熔融的产物,形成于古太平洋板块俯冲作用影响下的活动挤压的大陆边缘环境。而且,已发现沿亚洲大陆边缘确实存在大量与古大洋板块(古太平洋板块)俯冲有关的侏罗世增生混杂岩(Isozaki, 1997; Maruyama, 1997)。吉林和黑龙江东部同样属于中生代环太平洋构造带的组成部分(李之彤和赵春荆, 1992;方文昌,1992;李锦轶,1998;邵济安等,2001)。按时空分布判断,上述地区大量存在的埃达克岩(如,棉田、东清、朱敦店、大蒲柴河、大黑山和团结沟等)通常被认为是滨西太平

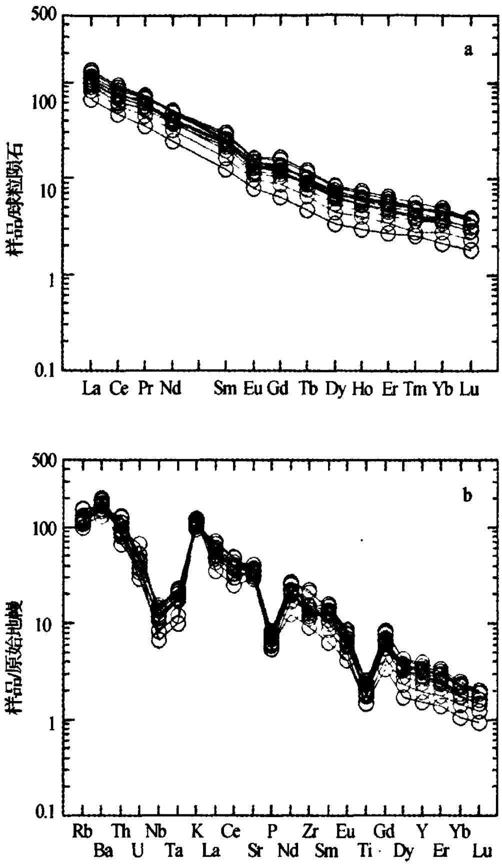

图6 埃达克岩稀土元素球粒陨石标准化配分模式(a)和微量元素原始地幔标准化蛛网图(b)(标准值据 Sun and McDonough, 1989)

Fig. 6 Chondrite-normalized (a) and primitive mantle-normalized spidergrams (b) of the adakites from eastern Jilin Province (Normalized values are after Sun and McDonough, 1989)

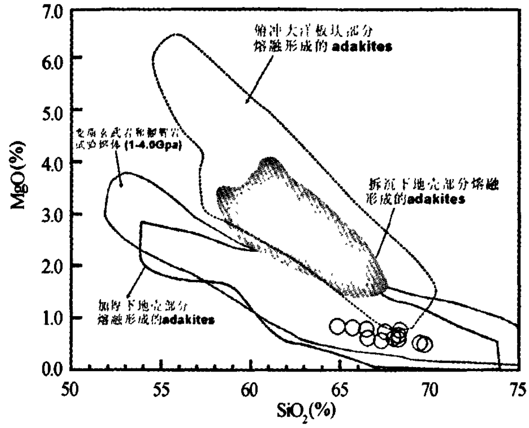

图7 埃达克岩 MgO (%)与 SiO_2(%)相关图

其中,俯冲大洋板块成因的埃达克岩数据来自 Defant and Drummond (1990), Kay and Kay (1993), Drummond *et al.* (1996), Stern and Kilian (1996), Sajona *et al.* (2000), Aguillón-Robles *et al.* (2001), Defant *et al.* (2002), Martin *et al.* (2005)和其中的文献;加厚下地壳来源埃达克岩数据引自 Atherton and Petford (1993), Muir *et al.* (1995), Petford and Atherton (1996), Johnson *et al.* (1997) 和 Xiong *et al.* (2005);变质玄武岩和榴辉岩试验熔体(1 ~4.0Gpa)据 Rapp *et al.* (1999, 2003), Rapp and Watson (1995), Skjerlie and Patiño Douce (2002)和其中文献

Fig. 7 MgO (%) vs. SiO_2(%) diagrams for the adakites

The field of subducted oceanic crust-derived adakites is constructed using data from Defant and Drummond (1990), Kay and Kay(1993), Drummond *et al.* (1996), Stern and Kilian (1996), Sajona *et al.* (2000), Aguillón-Robles *et al.* (2001), Defant *et al.* (2002) and Martin *et al.* (2005), and references therein. Data for thick lower crust-derived adakitic rocks are from Atherton and Petford (1993), Muir *et al.* (1995), Petford and Atherton (1996), Johnson *et al.* (1997) and Xiong *et al.* (2005). The field of metabasaltic and eclogite experimental melts (1 ~4.0 GPa) is from Rapp *et al.* (1999, 2003), Rapp and Watson (1995), Skjerlie and Patiño Douce (2002), and references therein

洋带的活动大陆边缘环境的产物(张炯飞等,2004)。因此,埃达克岩成因上无疑与古太平洋板块的俯冲作用有关。由于太平洋板块的俯冲作用影响,研究区处于汇聚的活动大陆边缘环境,并导致了岩石圈地幔以及下地壳的加厚(下地壳厚度>40km)和随后的岩石圈(包括岩石圈地幔和加厚下地壳)拆沉。从而引起热的软流圈地幔物质的上涌和新的地壳增生,在热的软流圈物质的底侵和烘烤下,先存的下地壳混合源区发生部分熔融作用,产生初始岩浆。初始岩浆在上升侵位过程中一方面经历了橄榄石、单斜辉石、角闪石、含钛氧化物以及磷灰石等矿物的分离结晶作用;另一方面发生了减压和降温。当达到结晶温度(800 ~860℃,表3)时,岩浆最终在浅部结晶并形成埃达克岩(石英闪长岩)。

5 结论

(1)锆石 LA-ICPMS U-Pb 定年结果表明大蒲柴埃达克岩形成于晚侏罗世,成岩年龄为 164.9 ±0.8Ma;

(2)地球化学研究表明,研究区埃达克岩为加厚下地壳部分熔融的产物,成因上与古太平洋板块的俯冲作用有关;

(3)锆石 Hf 同位素结果显示,埃达克岩的源区为两种岩浆混合作用形成的,一种岩浆来自先存的大陆地壳源;而另一种为通过底侵作用进入下地壳的亏损幔源岩浆,代表了一次重要的地壳增生事件(前寒武纪)。

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