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辽宁省清原县南口前岩体锆石 U-Pb 年代学、地球化学及 Hf 同位素

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摘要: 华北板块周边地区板块的俯冲与碰撞对华北后来的岩石圈破坏可能产生了重要影响. 对南口前岩体进行了锆石 LA-ICP-MS U-Pb 年代学和岩石地球化学研究, 确定其时代及形成的构造背景. 测年结果表明, 岩石为晚三叠世(224±1 Ma) 岩浆侵入的产物. 地球化学研究表明岩石为高钾钙碱性系列, A/CNK 值为 0.98~1.07, 属准铝质—过铝质花岗岩类. 高 Sr(394×10⁻⁶~545×10⁻⁶), 低 Yb(0.61×10⁻⁶~0.93×10⁻⁶), 判断岩石属于埃达克岩类. 岩石的 ε_{Hf}(t) 值为 -13.2~-6.9, 二阶段模式年龄(T_{DM2}) 变化于 1 669~1 825 Ma 之间, 判断岩石源于元古代地壳岩石的部分熔融. 综合前人研究成果, 认为岩石形成于古亚洲洋闭合后的造山后拉张环境.

关键词: 锆石 U-Pb 年龄; 岩石地球化学; 锆石 Hf 同位素; 埃达克岩; 南口前; 华北; 岩石学.

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Zircon U-Pb Geochronolog, Geochemistry and Hf Isotopes of Nankouqian Granitic Intrusion in Qingyuan Region, Liaoning Province

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Abstract: LA-ICP-MS zircon U-Pb dating and geochemical data of the Nankouqian granitic intrusion were studied to determine its formation time and tectonic background. The zircon U-Pb dating results indicate that the granitic pluton was formed in the Late Triassic (224±1 Ma). The granite shows calc-alkaline and metaluminous to weakly peraluminous affinities, with A/CNK ratio ranging from 0.98 to 1.07. The granitic pluton has features similar to adakitic rock with high Sr (394×10⁻⁶—545×10⁻⁶) and low Yb (0.61×10⁻⁶—0.93×10⁻⁶). The in situ zircon ε_{Hf}(t) value varies from -13.2 to -6.9, and a two-stage model age (T_{DM2}) varies from 1 669 to 1 825 Ma. These characteristics suggest that the primary magma was derived from partial melting of primarily Proterozoic lower crustal materials. Considering the regional tectonic evolution, we suggest the granites formed in the post-orogenic extension setting which could be related to the closure of the Paleo-Asian Ocean.

Key words: zircon U-Pb age; lithogeochemistry; Hf isotopes; adakite; Nankouqian; North China craton; petrology.

研究区位于华北板块北缘东部(图 1), 华北板块是中国最大、最古老的稳定克拉通(Jordan, 1975). 自 18 亿年华北板块形成至古生代, 它就一直保持相对稳定, 并存在巨厚的太古宙岩石圈根(包括下地壳和岩石圈地幔)(Gao *et al.*, 2002). 然而, 自中生代以来遭受了强烈的活化改造(Xu, 2001), 形成了多种类型的盆地, 并伴随产生了大量金属矿产和油气资源, 致使原有的克拉通的结构和性质遭到

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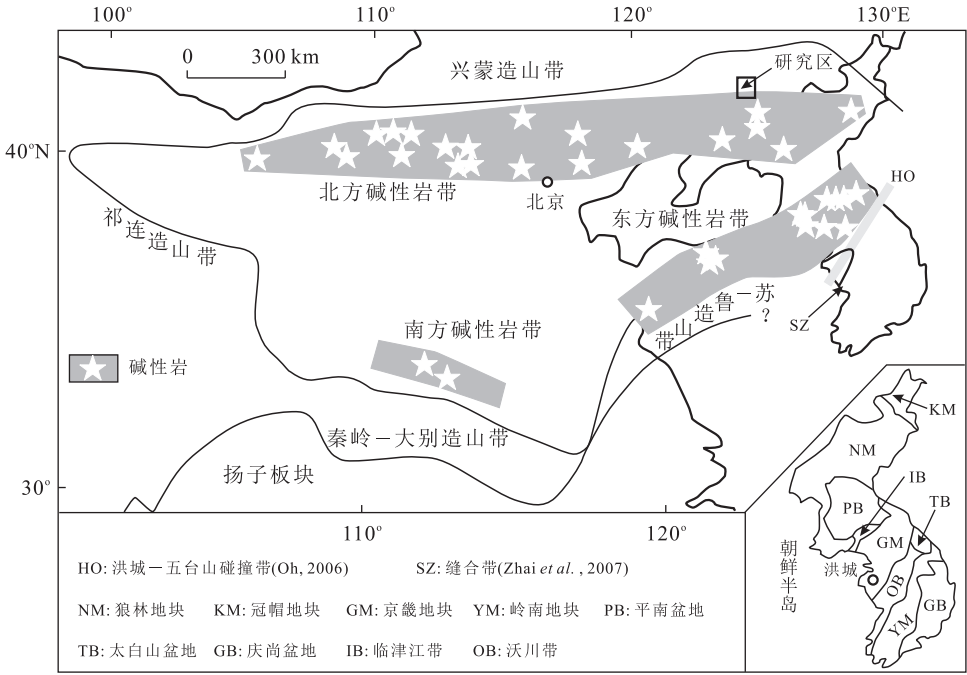


图 1 中—晚三叠世华北板块北缘碱性岩分布

Fig.1 Middle to Late Triassic syenite plutons in the north margin of North China plate
据 Peng *et al.* (2008)

明显的破坏(Yang *et al.*, 2012).从古生代到新生代, 华北板块岩石圈厚度减薄大于 100 km, 华北板块东部发生岩石圈减薄或破坏已被众多地质学者认同(Fan and Menzies, 1992; Wu *et al.*, 2006a).然而, 就其减薄的时间、机制以及空间分布范围目前仍存在不同看法(Gao *et al.*, 2004; Yang *et al.*, 2007).三叠纪华北周边地区板块的俯冲与碰撞对华北后来的岩石圈破坏可能产生了重要影响, 它要么是华北板块破坏的开始, 要么就是唤醒了后来的岩石圈减薄, 特别是早期造山带的岩石圈加厚可能为后来的破坏提供了重要前提(Yang *et al.*, 2006; 吴福元等, 2008; Zhang *et al.*, 2014).克拉通破坏主要来源于深部地质作用的影响, 而这一过程非常可能表现为岩石圈厚度的变薄, 这势必引起软流圈的上涌及可能发生的部分熔融, 并诱发地壳范围内的一系列岩浆、变质等地质作用(Yang *et al.*, 2006; 吴福元等, 2008).因此, 本文对辽东三叠纪南口前岩体进行了岩石地球化学、年代学及 Hf 同位素研究, 并从低镁埃达克岩角度展开讨论, 旨在揭示其形成时代及构造背景.

1 地质背景及样品描述

1.1 地质背景

研究区位于胶辽台隆铁岭—靖宇台拱龙岗断凸

的西端, 浑河断裂与下大堡断裂交汇部位.区内太古代上壳岩石棚子岩组以规模不等的残体赋存在中太古代片麻岩中, 其主要岩性为斜长角闪岩、黑云变粒岩和浅粒岩.中太古代片麻岩主要岩性为角闪斜长片麻岩、黑云斜长片麻岩(图 2).区内岩浆岩发育, 以中生代印支晚期和燕山期为主.印支晚期—燕山早期花岗岩以南口前杂岩体为代表(卢崇海, 1988), 岩体受浑河断裂和苏子河断裂控制, 分布在两个断裂相交的锐角区域, 并与十花顶子、西大顶子花岗岩体呈品字形展布(张庆久, 1999).

南口前杂岩体出露面积约 90 km² (包括南口前、十花顶子、西大顶子岩体), 岩石侵入时代由边部向内部逐渐变新.分别是粗粒似斑状花岗闪长岩和粗粒似斑状黑云母花岗岩、中粗粒似斑状黑云母花岗岩、灰白色中细粒花岗岩及中细粒角闪二长花岗岩、中细粒花岗闪长岩及灰黄色细粒花岗岩.杂岩体的岩浆演化序列特征表明, 南口前岩体是同源岩浆经过多次脉动和涌动作用形成的(张庆久, 1999).

1.2 样品描述

南口前岩体中具有代表性的粗粒似斑状黑云母花岗岩(文中简称花岗岩)是杂岩体演化序列第一期次产物.岩石具似斑状结构, 块状构造.斑晶为碱性长石, 大部呈自形板状(1~2 cm), 主要有条纹长石(±15%)和微斜长石(±25%).基质为粗粒花岗结

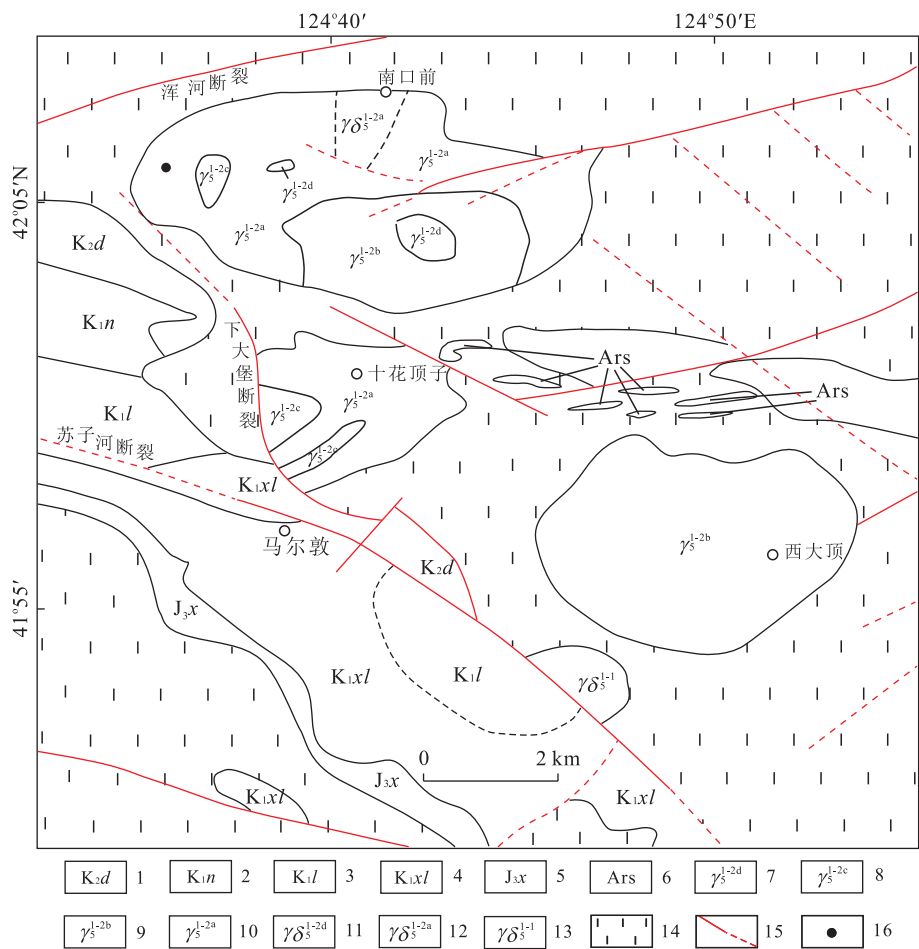


图 2 研究区地质略图

Fig.2 Geological sketch map of the studied area

1.晚白垩世砾岩;2.早白垩世砾岩;3.早白垩世页岩夹泥灰岩;4.早白垩世中性火山岩;5.晚侏罗世凝灰质粉砂岩;6.太古代绿岩;7.三叠纪晚期细粒花岗岩;8.三叠纪晚期中细粒花岗岩;9.三叠纪晚期中粗粒似斑状黑云母花岗岩;10.三叠纪晚期粗粒似斑状黑云母花岗岩;11.三叠纪晚期中细粒花岗岩闪长岩;12.三叠纪晚期似斑状花岗岩闪长岩;13.三叠纪早期花岗岩闪长岩;14.太古代花岗岩;15.断层(推测);16.取样点;据卢崇海(1988)

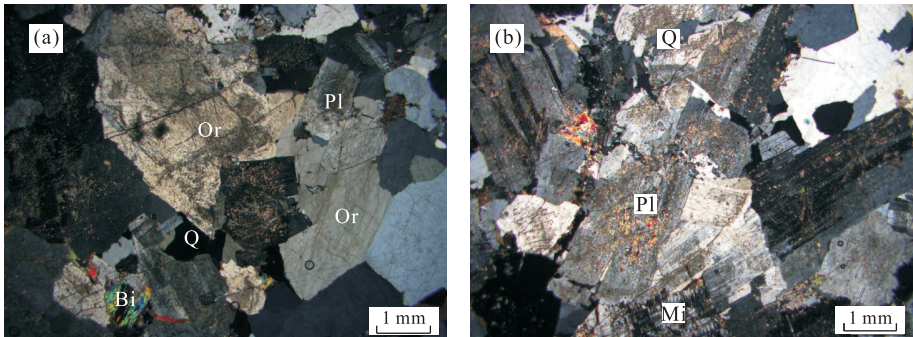


图 3 南口前花岗岩显微照片(+)

Fig.3 Microphotographs of the granite rocks in Nankouqian

Bi.黑云母;Mi.微斜长石;Pl.斜长石;Or.正长石;Q.石英

构.斜长石(20%~25%)半自形—自形,发育聚片双晶,表面有弱绢云母化.石英(>25%)以不规则粒状的集合体形式出现(3~5 mm),局部可见交代斜长石和钾长石现象;黑云母(5%~10%)平均分布于粒

状矿物之间,有少量绿泥石化.副矿物主要有磁铁矿、锆石、绿帘石、榍石和磷灰石等(图 3).

2 分析方法

2.1 锆石 LA-ICP-MS 年代学

锆石挑选由河北省廊坊区域地质调查研究所实验室利用标准重矿物分离技术分选完成.经过双目镜下仔细挑选,将不同特征的锆石粘在双面胶上,并用无色透明的环氧树脂固定;待其固化之后,将表面抛光至锆石中心.在测试前,通过反射光和 CL 图像仔细研究锆石的晶体形态与内部结构特征,以选择最佳测试点.锆石制靶、反射光、阴极发光以及锆石 U-Pb 年龄测定和痕量元素分析均在西北大学大陆动力学国家重点实验室进行.本次测试采用的激光剥蚀束斑直径为 32 μm ,激光剥蚀样品的深度为 20~40 μm ;实验中采用 He 作为剥蚀物质的载气.锆石年龄采用国际标准锆石 91500 作为外标,元素含量采用 NIST SRM610 作为外标,²⁹Si 作为内标元素(锆石中 SiO₂ 的质量分数为 32.8%(袁洪林等, 2003)),分析方法见文献(Yuan *et al.*, 2004);普通铅校正采用 Anderson 推荐的方法(Anderson, 2002);样品的同位素比值及元素含量计算采用 ICP-MS-DATECAL 程序(Liu *et al.*, 2008, 2010),年龄计算及谐和图的绘制采用 Isoplot 程序(Ludwig, 2003).

2.2 岩石地球化学测试

本次实验主量及微量元素的分析测试在澳实分析检测(广州)有限公司完成.主量元素由荷兰 PANalytical 生产的 Axios 仪器利用熔片 X-射线荧光光谱法(XRF)测定,并采用等离子光谱和化学法测定进行相互检测.微量元素和稀土元素采用美国 Perkin Elmer 公司生产的 Elan9000 型电感耦合等离子质谱仪(ICP-MS)测定.主量元素分析精度和准确度优于 5%,微量稀土元素分析精度和准确度优于 10%.

2.3 锆石 Hf 同位素测试

锆石 Lu-Hf 同位素测定在西北大学大陆动力学国家重点实验室的 LA-MC-ICP-MS 仪器上完成,所用仪器为 Nu Plasma,分析方法的详细流程参见文献(Wu *et al.*, 2006a; Yuan *et al.*, 2008),¹⁷⁶Lu 的衰变常数采用 $1.867 \times 10^{-11} \text{ a}^{-1}$ (Scherer *et al.*, 2001), $\epsilon_{\text{Hf}}(t)$ 的计算利用 Blichert-Toft and Albarède(1997)推荐的球粒陨石.¹⁷⁶Hf/¹⁷⁷Hf 比值

(0.282 772)及¹⁷⁶Lu/¹⁷⁷Hf 比值(0.033 2),Hf 模式年龄计算用的是当前亏损地幔的¹⁷⁶Hf/¹⁷⁷Hf 比值(0.283 25)(Nowell *et al.*, 1998)和¹⁷⁶Lu/¹⁷⁷Hf 比值(0.015)(Griffin *et al.*, 2002).

3 分析结果

3.1 锆石 LA-ICP-MS 年代学

样品取自南口前岩体,锆石阴极发光图像(CL)显示锆石生长振荡环带和韵律结构,形态以长柱状为主,少数为短柱状,为典型的岩浆成因的结晶锆石(图 4).它们 U-Pb 同位素年龄分析结果列于表 1.如表 1 所示,U 和 Th 含量分别介于(315~973) $\times 10^{-6}$ 和(155~524) $\times 10^{-6}$ 之间,Th/U 比值介于 0.32~0.87 之间,14 个锆石点数据较为集中,均落在谐和线之上(图 5a),谐和年龄值为 $224 \pm 1 \text{ Ma}$,MSWD=0.012(图 5a);锆石的²⁰⁶Pb/²³⁸U 年龄加权值为 $224 \pm 1 \text{ Ma}$,MSDW = 0.19(图 5b).因此,224 Ma 左右代表了花岗岩的岩浆结晶年龄,属晚三叠世.

3.2 地球化学特征

分析结果见表 2,岩石 SiO₂ 的含量介于 68.93%~71.78%之间;MgO 和 Mg[#] 值含量介于 0.32%~0.66%、28.8~39.2 之间;Na₂O 和 K₂O 含量变化范围分别介于 4.19%~4.44%、3.58%~4.34%之间.岩石在 TAS 和 SiO₂-K₂O 图解中显示属高钾钙碱系列(图 6 和图 7).A/CNK 值介于 0.98~1.07 之间,从 A/CNK-A/NK 图解可以看出岩石为偏铝质—过铝质(图略),为 I 型花岗岩.

从表 2 可以看出岩石稀土元素总量(ΣREE)为 $107 \times 10^{-6} \sim 175 \times 10^{-6}$,LREE/HREE 值为 22.6~

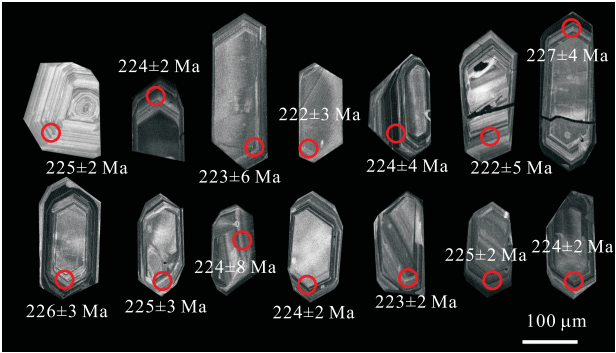


图 4 南口前花岗岩部分锆石阴极发光图像

Fig. 4 CL images of zircons from the granite rocks in Nankouqian

表 1 南口前花岗岩锆石 LA-ICP-MS U-Pb 同位素分析结果

Table 1 LA-ICP-MS zircon U-Pb analyses of the granite rocks in Nankouqian

测点	含量(10^{-6})		同位素比值及误差						年龄(Ma)及误差			
	^{238}U	^{232}Th	$^{207}\text{Pb}/^{206}\text{Pb}$	1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	1σ
XDP-2-1	769	284	0.050 26	0.001 58	0.247 06	0.007 64	0.035 46	0.000 26	224	6	225	2
XDP-2-2	488	179	0.050 51	0.001 18	0.247 18	0.005 57	0.035 37	0.000 31	224	5	224	2
XDP-2-3	829	373	0.050 76	0.004 40	0.24 61	0.019 15	0.035 21	0.000 95	224	16	223	6
XDP-2-4	973	524	0.050 79	0.002 02	0.246 77	0.009 33	0.035 08	0.000 42	224	8	222	3
XDP-2-5	464	204	0.050 61	0.005 09	0.247 08	0.023 76	0.035 40	0.000 58	224	19	224	4
XDP-2-6	931	343	0.050 73	0.004 20	0.246 02	0.020 98	0.035 04	0.000 79	223	17	222	5
XDP-2-7	965	343	0.050 11	0.003 84	0.247 68	0.018 97	0.035 76	0.000 57	225	15	227	4
XDP-2-8	852	378	0.049 69	0.003 27	0.246 06	0.017 04	0.035 69	0.000 41	223	14	226	3
XDP-2-9	895	509	0.049 88	0.003 48	0.246 83	0.017 40	0.035 59	0.000 46	224	14	225	3
XDP-2-10	489	155	0.050 88	0.006 42	0.245 76	0.028 54	0.035 35	0.001 34	223	23	224	8
XDP-2-11	722	269	0.050 39	0.001 60	0.247 39	0.007 71	0.035 41	0.000 32	224	6	224	2
XDP-2-12	800	279	0.050 71	0.001 84	0.246 81	0.008 27	0.035 22	0.000 38	224	7	223	2
XDP-2-13	876	425	0.050 52	0.004 29	0.247 06	0.019 59	0.035 45	0.000 37	224	16	225	2
XDP-2-14	315	273	0.050 29	0.001 96	0.246 89	0.009 40	0.035 41	0.000 38	224	8	224	2

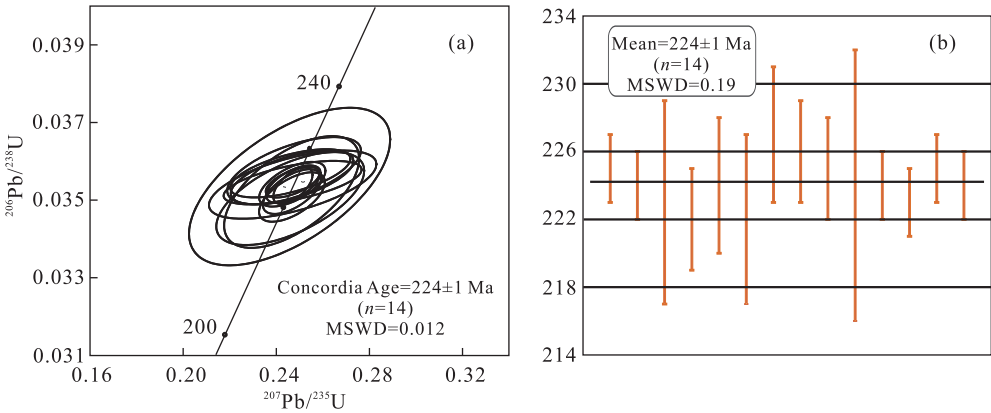


图 5 南口前花岗岩的 U-Pb 年龄谐和图(a)和加权平均年龄(b)

Fig.5 Zircon U-Pb Concordia diagram (a) and weighted average ages diagram (b) from the granite rocks in Nankouqian

26.1, Yb 含量较低($0.61\sim0.93$) $\times10^{-6}$, 高(La/Yb)_N 值(33.3~39.6), 低(Gd/Yb)_N 值(2.12~2.38), 反映轻重稀土分馏明显, 轻稀土富集的特征. 在球粒陨石标准化稀土配分图解(图 8)上, 表现为相似的右倾曲线. Eu/Eu* 值(0.90~0.99)均小于 1, 异常不明显. 认为源区可能残留石榴子石、角闪石等.

微量元素原始地幔标准化蛛网图中(图 9), 富集大离子亲石元素 Ba、Rb、K 和 Th、U 等活泼的不相容元素, 明显亏损 Nb、Ta、P 高场强元素. 样品显示 Sr 多数表现出富集特征($394\sim545$) $\times10^{-6}$, Y 含量较低($6.20\sim9.50$) $\times10^{-6}$ (张旗等, 2003). 其中 P 亏损指示磷灰石的分离结晶, Ti 的富集可能同钛铁矿未发生分离结晶有关.

3.3 锆石 Lu-Hf 同位素

南口前花岗岩中锆石的¹⁷⁶Hf/¹⁷⁷Hf 比值为

0.282 297~0.282 443, $\epsilon_{\text{Hf}}(t)$ 值为 -13.2~-6.9, Hf 同位素单阶段模式年龄(T_{DM1})和二阶段模式年龄(T_{DM2})分别变化于 1 153~1 402 Ma 和 1 669~1 825 Ma 之间(表 3).

4 讨论

4.1 岩浆源区

除了 Sr-Nd 同位素外, 锆石 Hf 同位素对岩浆源区性质也可以给出很好的制约(Amelin *et al.*, 1999; Amelin *et al.*, 2000). 南口前花岗岩的 $\epsilon_{\text{Hf}}(t)$ 值为 -13.2~-6.9, 结合其二阶段模式年龄 T_{DM2} (1 669~1 825 Ma), 认为岩石来源于元古代下地壳的部分熔融(图 10), 与岩石 I 型花岗岩性质契合.

岩石 SiO₂ 含量为 68.93%~71.78%、Al₂O₃ 含

表 2 南口前花岗岩主量元素、稀土元素和微量元素含量及有关参数

Table 2 Major, REE and trace element content and parameter of the granite rocks in Nankouqian

样品	XDP-1-1	XDP-1-2	XDP-1-3	XDP-1-4	XDP-1-5	XDP-1-6	XDP-1-7
SiO ₂	71.64	70.68	68.93	69.8	69.18	70.95	71.78
TiO ₂	0.23	0.30	0.33	0.31	0.33	0.31	0.27
Al ₂ O ₃	13.86	13.98	14.42	14.47	14.49	13.85	14.46
Fe ₂ O ₃	1.82	2.13	1.97	2.08	2.16	2.24	1.57
MnO	0.03	0.03	0.03	0.02	0.03	0.03	0.02
MgO	0.49	0.66	0.64	0.66	0.58	0.62	0.32
CaO	1.45	1.73	1.72	1.29	1.74	1.23	0.95
Na ₂ O	4.19	4.27	4.29	4.41	4.43	4.44	4.30
K ₂ O	4.18	3.81	3.95	4.13	3.83	3.58	4.34
P ₂ O ₅	0.10	0.12	0.13	0.12	0.14	0.13	0.11
LOI	1.01	0.94	2.19	1.51	2.06	1.61	1.51
Total	99.14	98.83	98.73	98.96	99.11	99.13	99.78
Mg [#]	34.8	38.0	39.2	38.6	34.7	35.4	28.8
A/CNK	0.99	0.98	1.00	1.03	0.99	1.03	1.07
Cr	20	20	20	20	20	20	20
V	29	34	35	29	32	34	26
Rb	126	103	119	118	117	104	134
Ba	814	963	822	958	847	840	889
Sr	423	545	509	400	441	395	394
Ce	51.3	72.5	75.8	74.4	78.7	77.9	70.7
Pr	4.8	7.6	8.1	7.0	8.4	7.6	6.6
Nb	15.8	21.1	22.3	19.3	22.1	21.4	25
Ta	1.4	1.8	1.9	1.7	1.8	1.8	2.3
Zr	159	153	190	166	172	186	172
Th	16.5	18.5	17.5	24.8	19.0	19.5	18.6
U	2.60	4.50	3.00	3.20	2.70	3.60	8.30
La	28.3	46.0	47.6	40.6	49.4	45.2	39.7
Nd	15.5	24.4	26.0	22.6	26.8	24.3	21.2
Hf	3.90	3.90	4.90	4.10	4.50	4.90	5.50
Sm	2.22	3.35	3.64	3.16	3.71	3.37	2.83
Eu	0.61	0.91	0.90	0.85	0.92	0.84	0.74
Gd	1.60	2.51	2.59	2.31	2.56	2.27	2.09
Tb	0.21	0.32	0.33	0.30	0.33	0.30	0.25
Dy	1.07	1.66	1.70	1.54	1.72	1.58	1.26
Ho	0.19	0.31	0.30	0.28	0.31	0.28	0.22
Er	0.60	0.91	0.93	0.84	0.92	0.85	0.66
Tm	0.10	0.14	0.14	0.13	0.14	0.14	0.11
Yb	0.61	0.87	0.88	0.80	0.93	0.82	0.72
Lu	0.10	0.12	0.13	0.13	0.14	0.13	0.12
Y	6.20	9.20	9.50	8.50	9.50	9.00	7.10
ΣREE	107	162	169	155	175	166	147
Eu/Eu [*]	0.99	0.96	0.90	0.96	0.91	0.93	0.93
LREE	103	155	162	149	168	159	142
HREE	4.48	6.84	7.00	6.33	7.05	6.37	5.43
LREE/HREE	22.9	22.6	23.2	23.5	23.8	25.0	26.1
(La/Yb) _N	33.3	37.9	38.8	36.4	38.1	39.5	39.6
(Gd/Yb) _N	2.12	2.33	2.38	2.33	2.22	2.23	2.34
(Dy/Yb) _N	1.14	1.24	1.25	1.25	1.20	1.25	1.14

注：主量元素单位： 10^{-2} ；微量、稀土元素单位： 10^{-6} 。

量为 13.85%~14.47%、Na₂O 含量为 4.19%~4.44%、MgO 含量为 0.32%~0.66%、Sr 含量为 $394\times10^{-6}\sim545\times10^{-6}$ 、Y 含量为 $6.20\times10^{-6}\sim9.50\times10^{-6}$ 、Yb 含量为 $0.61\times10^{-6}\sim0.93\times10^{-6}$ ，弱负铕异常($\delta\text{Eu}=0.90\sim0.99$)。岩石在 Y-Sr/Y 上样品全部落在埃达克岩范围内，认为岩石属于华北

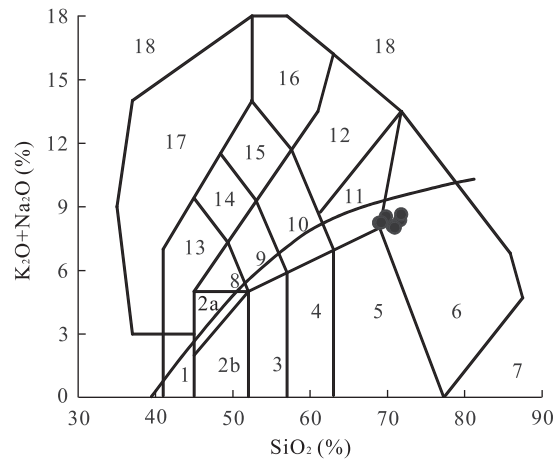


图 6 南口前花岗岩的 TAS 图

Fig.6 TAS diagram for the granite rocks in Nankouqian
1.橄榄辉长岩;2a.碱性辉长岩;2b.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.石英英岩;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;15.副长石二长正长岩;16.副长正长岩;17.副长深成岩;18.霓方钠岩/磷霞岩/粗白榴岩;分界线上方为碱性,下方为亚碱性据 Irvine and Baragar(1971)

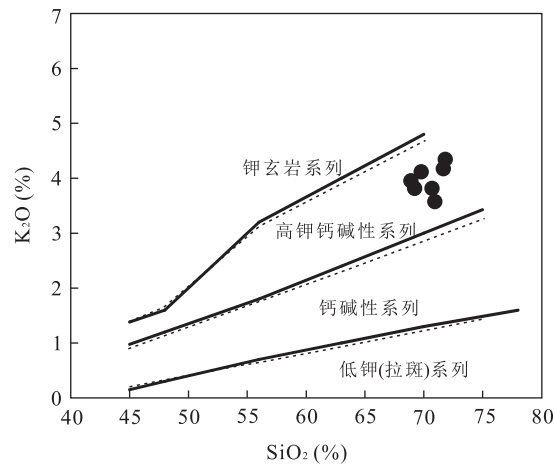


图 7 南口前花岗岩的 SiO₂-K₂O 图

Fig.7 K₂O-SiO₂ diagram of the granite rocks in Nankouqian

东部普遍存在的化学成分类似于“埃达克岩”的中生代高锆花岗岩类岩石 (Defant and Drummond, 1990)(图 11).有关埃达克岩成因主要有以下几种模式:俯冲板片部分熔融 (Kay, 1978; Defant and Drummond, 1990);拆沉的下地壳熔融 (Guo *et al.*, 2006; Huang *et al.*, 2008);结晶分异作用影响 (Macpherson *et al.*, 2006);加厚下地壳部分熔融 (翟明国等, 2005; Wang *et al.*, 2007; Xu *et al.*, 2012);岩浆混合作用 (Guo *et al.*, 2007).

考虑到俯冲板片部分熔融和拆沉的下地壳熔融

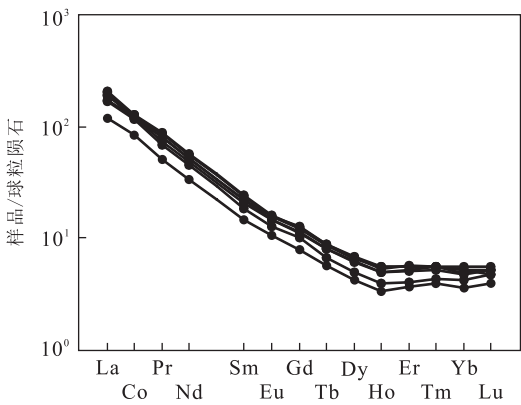


图 8 南口前花岗岩稀土元素球粒陨石标准化配分图
Fig.8 Chondrite-normalized REE patterns of the granite rocks in Nankouqian

据 Boynton(1984)

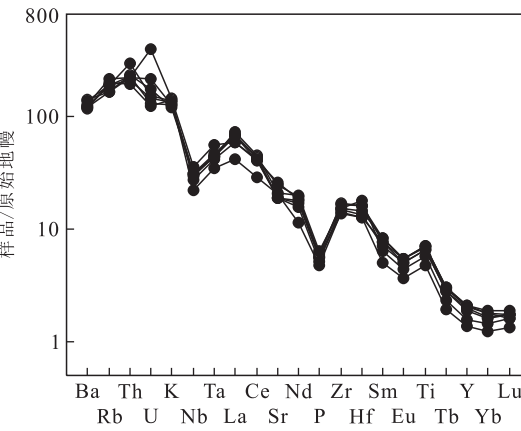


图 9 南口前花岗岩微量元素原始地幔标准化蛛网图
Fig.9 Primitive mantle-normalized trace element spider diagrams of the granite rocks in Nankouqian

据 Sun and McDonough(1989)

成因的埃达克岩石有地幔成分参与,因此应该具有镁含量高和 $Mg^\#$ 值高等特征 (Wang *et al.*, 2007).然而,岩石 MgO 含量和 $Mg^\#$ 值较低,分别为 0.32~0.66 和 28.8~39.2,因此排除俯冲板片部分熔融和拆沉的下地壳熔融成因模式.岩石 MREE 和 HREE 之间不是以上凹曲线模式分布 (图 8),而且 $(Dy/Yb)_N$ 值和 SiO_2 的含量不存在明显的负相关性,认为结晶分异过程不是控制岩浆演化的主要途径 (Macpherson *et al.*, 2006).岩石 MgO 和 $Mg^\#$ 值含量介于 0.32%~0.66%、28.8~39.2 之间,结合 $\epsilon_{Hf}(t)$ 值及 T_{DM2} (图 10),认为岩石由加厚地壳部分熔融形成.

4.2 构造背景

早二叠世,华北板块北缘中东段形成了一条呈

表 3 南口前花岗岩锆石 Hf 同位素分析结果

Table 3 LA-ICP-MS zircon U-Pb analyses of the granite rocks in Nankouqian

测点	<i>t</i> (Ma)	¹⁷⁶ Yb/ ¹⁷⁷ Hf	¹⁷⁶ Lu/ ¹⁷⁷ Hf	¹⁷⁶ Hf/ ¹⁷⁷ Hf	2σ	ε _{Hf} (0)	ε _{Hf} (<i>t</i>)	2σ	<i>T</i> _{DM1} (Hf)	<i>T</i> _{DM2} (Hf)	<i>f</i> _{Lu/Hf}
XDP-2-1	224	0.019 675	0.000 891	0.282 279	0.000 018	−18.2	−13.2	0.6	1 402	1 738	−0.97
XDP-2-2	224	0.018 344	0.000 825	0.282 301	0.000 010	−17.5	−12.5	0.4	1 369	1 698	−0.98
XDP-2-3	224	0.015 698	0.000 703	0.282 317	0.000 012	−16.9	−11.9	0.4	1 343	1 669	−0.98
XDP-2-4	224	0.037 096	0.001 511	0.282 431	0.000 009	−12.1	−7.4	0.3	1 177	1 724	−0.95
XDP-2-5	224	0.018 782	0.000 799	0.282 427	0.000 008	−12.2	−7.4	0.3	1 160	1 726	−0.98
XDP-2-6	224	0.029 544	0.001 203	0.282 423	0.000 008	−12.3	−7.6	0.3	1 178	1 738	−0.96
XDP-2-7	224	0.032 310	0.001 317	0.282 443	0.000 008	−11.6	−6.9	0.3	1 153	1 693	−0.96
XDP-2-8	224	0.019 214	0.000 788	0.282 398	0.000 008	−13.2	−8.4	0.3	1 200	1 791	−0.98
XDP-2-9	224	0.026 329	0.001 129	0.282 384	0.000 009	−13.7	−9.0	0.3	1 231	1 825	−0.97
XDP-2-10	224	0.033 696	0.001 513	0.282 411	0.000 007	−12.8	−8.1	0.3	1 205	1 768	−0.95
XDP-2-11	224	0.040 009	0.001 573	0.282 416	0.000 008	−12.6	−7.9	0.3	1 200	1 758	−0.95
XDP-2-12	224	0.030 837	0.001 217	0.282 397	0.000 006	−13.3	−8.5	0.2	1 216	1 797	−0.96
XDP-2-13	224	0.026 481	0.001 119	0.282 408	0.000 007	−12.9	−8.1	0.2	1 196	1 770	−0.97
XDP-2-14	224	0.017 691	0.000 748	0.282 399	0.000 007	−13.2	−8.4	0.2	1 197	1 788	−0.98

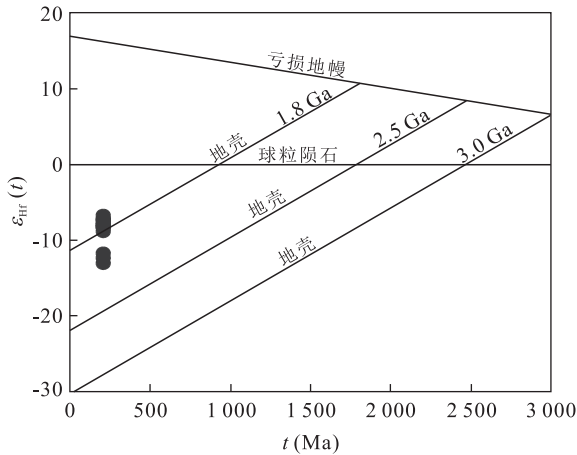


图 10 南口前花岗岩的 Hf 同位素特征

Fig.10 Hf isotopic compositions of the granite rocks in Nankouqian

据 Yang *et al.* (2006)

—陆碰撞作用.吉林中部地区由下地壳加厚熔融而

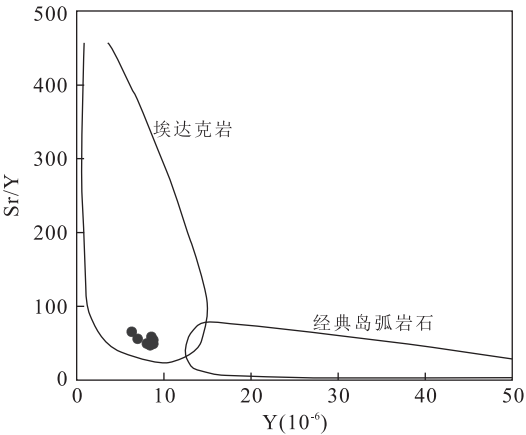


图 11 南口前花岗岩 Sr/Y-Y 图解

Fig.11 Sr/Y-Y diagram for the granite rocks in Nankouqian

据 Defant and Drummond (1990)

东西向展布的具有活动大陆边缘属性的火成岩带：内蒙古地区大石寨组火山岩以及大量钙碱性侵入体(刘建峰,2009;张拴宏等,2010),吉林中部地区大河深组钙碱性火山岩、延边地区英云闪长岩(Zhang *et al.*,2004)等.表明古亚洲洋向华北板块之下俯冲,华北板块北缘中东段处于活动大陆边缘的构造环境.

在中二叠世期间,内蒙古地区和吉林中部地区形成了多个过铝质含石榴石花岗岩体和与碰撞相关的花岗质岩体(王鑫琳等,2007;赵庆英等,2007;章永梅等,2009;柳长峰等,2010),并伴随着赤城以北的原红旗营子群片麻岩的变质作用,表明北部的松嫩—张广才岭地块与南部的华北板块北缘发生了陆

成的埃达克质花岗岩和延边地区的同碰撞花岗岩(249~245 Ma)(孙德有等,2004;Zhang *et al.*,2004),呼兰群发生顺时针中压相变质作用,同时海相沉积地层和沉积夹层全部消失,古生物地理分区消失,表明到了早三叠世长春—延吉缝合线最终闭合,古亚洲洋彻底消失(孙德有等,2004;Wu *et al.*,2002,2006b,2011;彭玉鲸等,2012).

研究表明,整个兴蒙造山带东段和华北板块北缘均广泛发育中—晚三叠世岩浆活动(Wu *et al.*,2004;张拴宏等,2010).华北板块北缘出露大量碱性岩(240~190 Ma)(Peng *et al.*,2008),A 型花岗岩(220~222 Ma)和基性—超基性岩(郗爱华等,2006;刘建峰,2009;Zhang *et al.*,2012).此外,晚三叠世广泛发育磨拉石建造,标志着晚三叠世整个兴

蒙造山带和华北板块北缘东段已经由造山隆起环境转变为两大板块最终碰撞拼合后的造山后拉张环境。

中二叠世一早三叠世华北板块北缘与兴蒙造山带东段的微陆块发生碰撞造山运动,导致华北东部地区岩石圈增厚,使下地壳镁铁质岩石转变成高密度的榴辉岩相岩石。岩石圈因重力不稳定而拆沉到软流圈中,并发生不同程度的部分熔融,形成来源于古老岩石圈地幔的镁铁质和碱性岩浆,上涌的软流圈发生减压部分熔融,形成亏损地幔来源的镁铁质岩浆。上升的幔源岩浆诱发未发生拆沉的下地壳物质发生部分熔融,从而形成南口前岩体(Zhang *et al.*, 2009, 2012)。

5 结论

(1)获得南口前花岗岩杂岩体中粗粒似斑状黑云母花岗岩岩浆锆石 LA-ICP-MS U-Pb 加权平均年龄值为 224 ± 1 Ma, 属晚三叠世。(2)岩石属埃达克岩类,源于元古代地壳岩石部分熔融。(3)岩石形成于古亚洲洋闭合后的造山后拉张环境。

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《地球科学》

2016 年 2 月 第 41 卷 第 2 期 要目预告

豫西火神庙岩体锆石 U-Pb 年代学、地球化学及 Hf 同位素组成	王 赛等
陕西双王金矿床矿化富集规律对成矿构造的指示意义	宫勇军等
陕北黄土高原不同地貌类型区黄土滑坡频率分布	邱海军等
黔湘渝毗邻区南华纪武陵裂谷盆地结构及其对锰矿的控制作用	周 琦等
频率域航空电磁三维矢量有限元正演模拟	黄 威等
塘沽地区湖相白云岩储层裂缝特征及其控制因素	赵 耀等
黔西南卡林型金矿剥蚀程度评价	骆地伟等
含煤盆地转化为含煤—含气(油)盆地的构造地质环境	王庭斌等