熊耳山地区穆册二长岩体地球化学特征、U-Pb年龄及构造背景

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内容提要:华北克拉通古元古代的构造格局是学术界关注的焦点之一,位于华北克拉通南缘的穆册二长岩体为该研究提供了新的证据。穆册岩体主体为黑云角闪二长岩,边部见二长斑岩,并被同期二长花岗岩脉侵入。二长岩的LA-ICP-MS锆石U-Pb定年为2172±8 Ma(MSWD=0.58,n=17)和2186±7 Ma(MSWD=0.60,n=19),二长花岗岩年龄为2174±8 Ma(MSWD=0.45,n=19),显示该二长岩体形成于古元古代。穆册二长岩不仅具有造山后地球化学特征,还具有典型的岛弧岩浆岩的地球化学特征。综合分析,穆册二长岩可能在古元古代经历了岛弧和裂谷两种环境的共同影响。

关键词:穆册二长岩;古元古代;岛弧岩浆;熊耳山;华北克拉通南缘

华北克拉通是世界上最古老的克拉通之一,其基底通常被分为东部陆块、西部陆块和中部造山带,具有复杂的多阶段构造演化和强烈的后期改造的特点。前人长期研究认为:华北克拉通化的形成过程是由东部陆块和西部陆块沿着中间造山带拼合而成(Zhao Guochun et al., 1998, 2000, 2001, 2005; Zhai Mingguo et al., 2005;李永峰,2005; Kusky et al., 2007),其东部陆块在2.2~2.1 Ga形成胶—辽—吉构造带,而西部陆块由南部鄂尔多斯地块、北部阴山地块和中间的孔兹岩带(吴昌华等,1998)组成,其南、北地块在2.1~2.0 Ga沿着中部孔兹岩带发生碰撞造山并形成西部陆块(Zhao Guochun et al., 2005),之后华北克拉通形成统一的整体,其基底通常具有复杂的多阶段构造演化和强烈的后期改造的特点。其中,中部造山带演化过程是争论的焦点之一。因此,研究中部造山带对华北克拉通地质演化过程具有重要的意义。

中部造山带为东、西陆块的构造拼合带,其以中国东部的两条深大断裂为界,呈南北向展布。但对于中部造山带的形成时代有两种不同的认识:一种是西部陆块向东部陆块从新太古代末期开始俯冲,持续到古元古代末期形成的;另一种是东部陆块向西部陆块在太古代晚期俯冲,新太古代末期拼合,并在古元古代早期发生陆内伸展阶段(Kusky and Li, 2003; Kusky et al., 2007; Li and Kusky, 2007; Polat et al., 2005)。除此之外,还有学者根据中部造山带内沉积岩和古元古代岩浆岩地球化学特征,提出中部造山带内可能存在2.2~2.0 Ga碰撞造山过程(Liu Shuwen et al., 2005; Faure et al., 2007; Trap et al., 2008, 2009, 2012; Wang Junpeng et al., 2013; Wilde, 2010),在后续的研究中,大量的年代学资料显示,中部造山带内2.2~2.1 Ga岩浆活动广泛发生在不同地区,其中有五台山、吕梁山、太行山、蚌埠和胶辽吉造山带等地区,这些地区基本上处于中部造山带和东部陆块位置,其岩浆事件形成于裂谷环境或岛弧环境(杜利林等,2009,2011,2012;杨崇辉等,2011a;赵瑞幅等,2011; Du Lilin et al., 2010, 2012, 2013, 2015, 2016a, b, 2017; Peng Peng et al., 2012, 2017; Zhang Huafeng et al., 2011; Xie Hangqiang et al., 2012; Wang et al., 2014; Zhou

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Yanyan et al., 2014, 2015;杨德彬,2009;李三忠,2001),而对华北克拉通南缘熊耳地区 2.2~2.1 Ga 的侵入体并没有太多的研究,所以研究该地区的岩体对华北克拉通南缘演化具有重要的地质意义。1∶5 万木柴关幅区域地质调查(河南省地质调查院,2001)在熊耳地区穆册乡一带发现有大型中元古代侵入体,并命名为穆册片麻状石英闪长岩,由于该岩体普遍具有较高的碱性长石含量,因此本文建议命名为穆册二长岩体。

1 地质背景

熊耳山地区位于秦岭造山带东段,华北克拉通南缘,是研究华北板块与扬子板块碰撞造山的关键区域(图 1a)。熊耳地体东西两侧为嵩县—栾川和洛宁—卢氏断陷盆地,盆地中发育白垩纪—第四纪沉积物;北沿三宝(三门峡—宝丰)断裂推覆在上中元古界—三叠系地层之上;南界是马超营断裂,为一条倾向北的 A 型俯冲带(范宏瑞等,1993,1998;黎世美等,1996;胡受奚等,1997;王志光等,1997;徐梦罗等,1997;隋颖慧等,2000;王卫星等,2010)。区域出露地层主要是太华群变质岩和熊耳群火山岩(陈衍景等,1992;赵太平等,1994)(图 1b 和 c)。太华群形成于新太古代,是一套深变质岩系,其变质杂岩是中部造山带南部大规模出露的最古老的岩石,岩性以片麻岩为主,构成了华北克拉通南缘的结晶基底(Liu Shuwen et al., 2009; Huang Xiaolong et al., 2010)。在熊耳山—尧山一带,熊耳群火山岩呈角度不整合于太古宙和古元古代结晶基底之上(He Yanhong et al., 2009; 李永峰,2005),是华北克拉通结晶基底形成后规模最大、涉及范围最广的岩浆活动产物(Zhao Guochun et al., 2002)。

熊耳山地区太华群自下而上分为:草沟组、石板沟组、龙潭沟组、龙门店组和段沟组,后来,龙潭沟组和龙门店组被划分到石板沟组(王西午等,1986))。草沟组主要由黑云斜长片麻岩、角闪斜长片麻岩、角闪黑云斜长片麻岩组成,其次为角闪斜长岩和斜长角闪岩;石板沟组主要为角闪斜长片麻岩、斜长角闪片麻岩夹斜长角闪岩,其次为黑云斜长片麻岩和黑

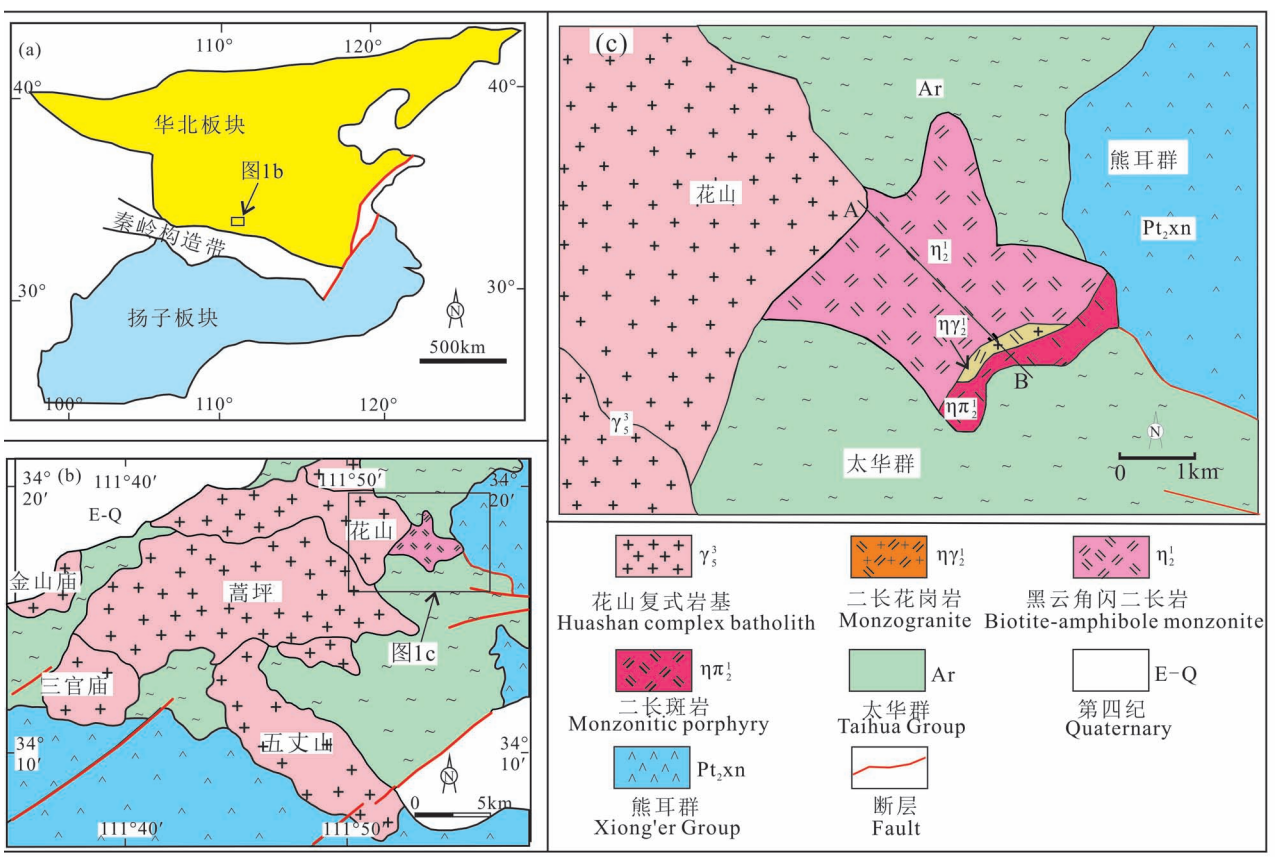


图 1 熊耳山地区地质构造简图和岩体分布图(c, 据 1∶20 万豫西幅地质图[1]修改)

Fig. 1 Geological structure map and intrusive rock distribution map of Xiong 'er Mountains area (c, modified from the 1/200000 Regional Geological Report of Yuxi Area[1])

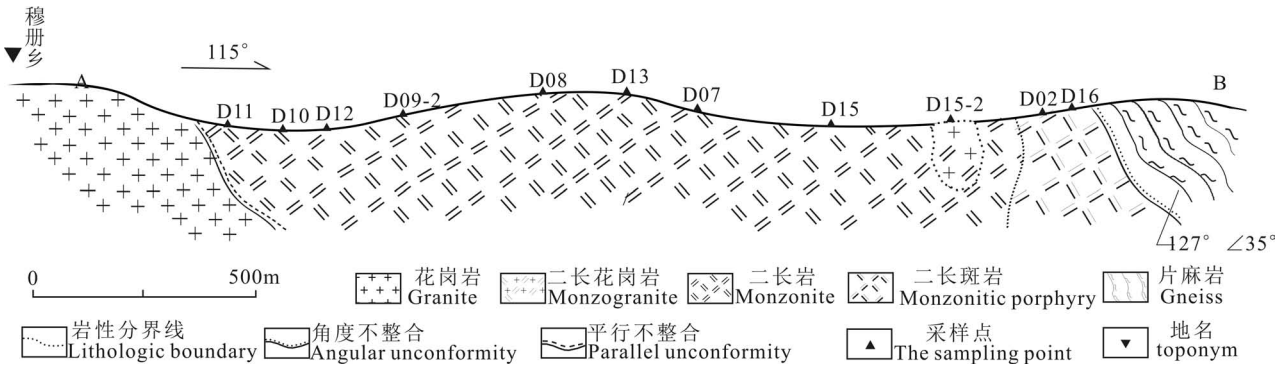


图 2 熊耳山地区穆册二长岩体剖面图

Fig. 2 The profile of the Muce monzonite in Xiong'er Mountains

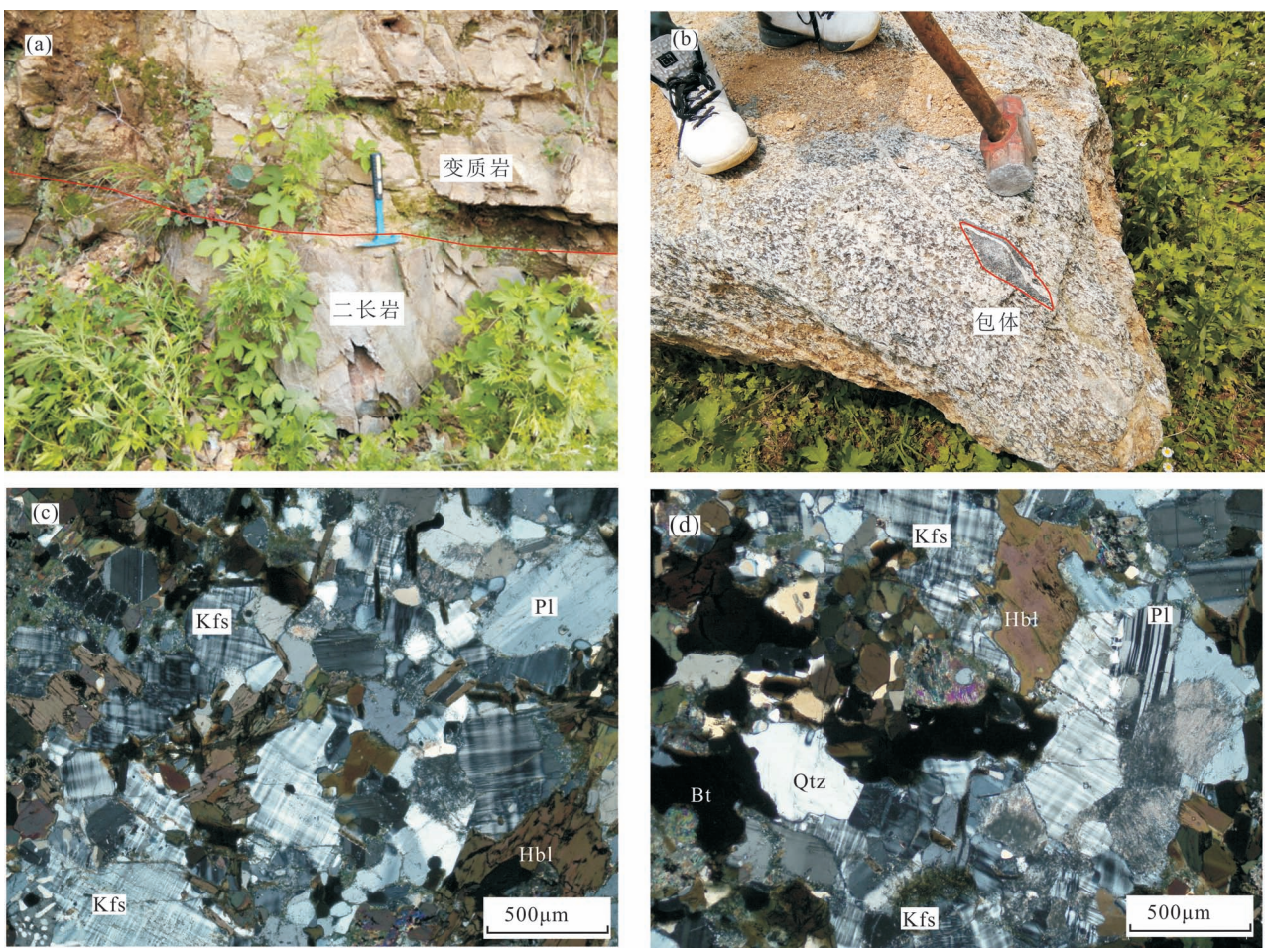


图 3 熊耳山地区穆册二长岩野外照片和显微镜下特征

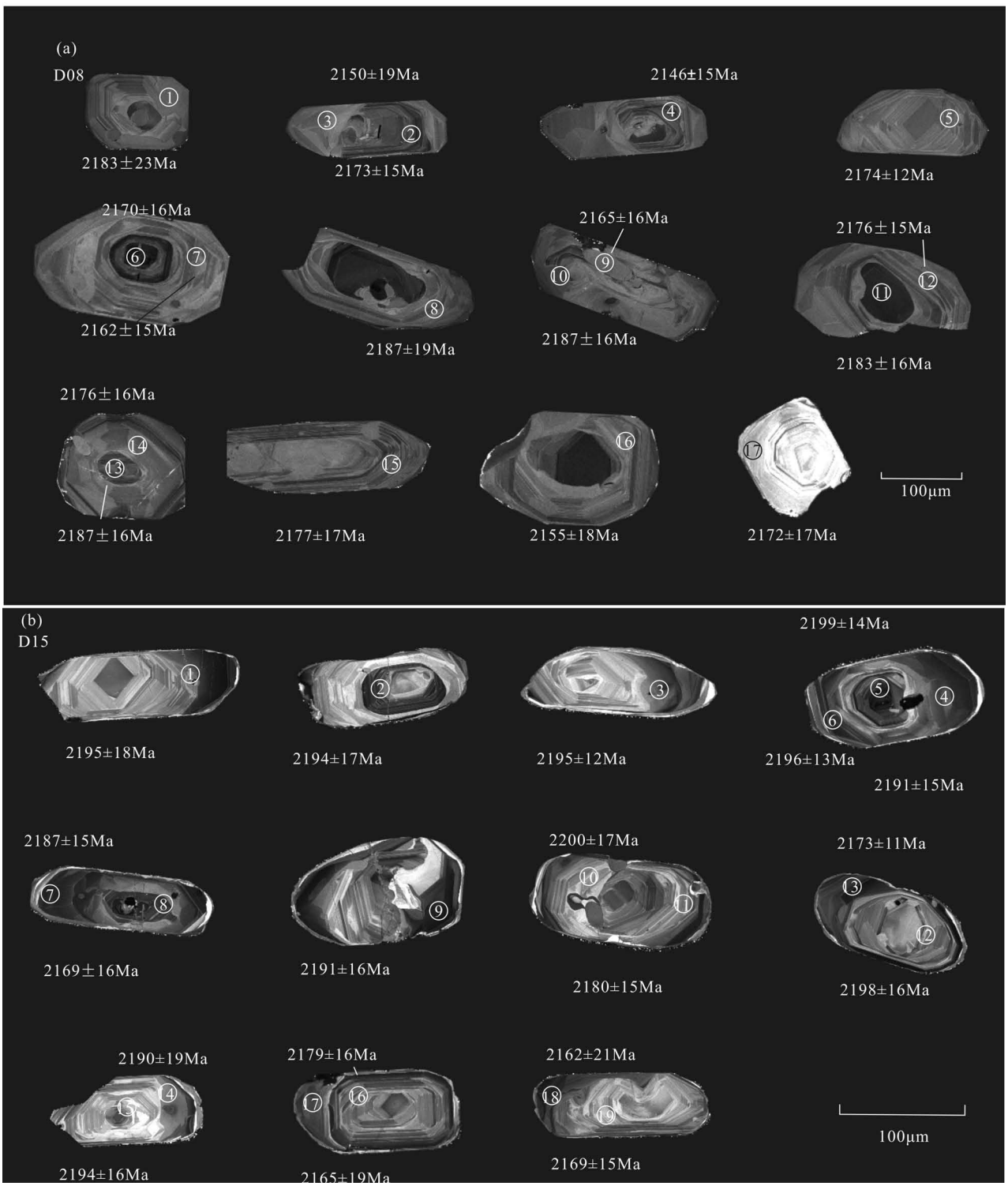
Fig. 3 Field photos and section photographs of the Muce monzonite in Xiong'er Mountains

(a)穆册二长岩侵位于太华群片麻岩中,又被似斑状花岗岩侵位;(b)二长岩中包体常见并被长英质岩脉切穿;(c)钾长石呈格子双晶和聚片双晶,正交偏光;(d)斜长石的卡斯巴双晶,正交偏光;Kfs—具有格子双晶的钾长石;Pl—斜长石;Hbl—普通角闪石;Bt—黑云母;Qtz—石英

(a) Muce monzonite intruded in gneiss of Taihua Group and was intruded by medium—acidic porphyritic granite; (b) inclusions are common in monzonite and are cut through by felsic dykes; (c) potassium feldspar shows a lattice twin and polycrystalline twin, orthogonal polarization; (d) the kasba twin of plagioclase, orthogonal polarized light;; Kfs—microcline with lattice twin crystals; Pl— plagioclase; Hbl— common hornblende; Bt— biotite; Qtz — quartz

云斜长变粒岩等,石板沟组与草沟组呈整合接触,与段沟组呈不整合接触;段沟组主要由含石榴子石或者夕线石黑云斜长片麻岩,黑云斜长变粒岩和石榴黑云斜长变粒岩等组成。草沟组和龙潭沟组以 TTG 质岩石为主体,其基本形成于 2336~2305 Ma(Diwu Chunrong et al., 2014; Huang Xiaolong et al., 2013; Chen Hongxu et al., 2015);段沟组岩石以表壳岩为主,原岩可能是以泥质—碎屑沉积岩为主,局部为火山岩,表壳岩形成年龄限定在 2305~1970 Ma(Diwu Chunrong et al., 2014),但在这个时间段内,Huang Xiaolong 等(2012)仅发现了 1 个英云闪长片麻岩和 1 个钾长花岗片麻岩的年龄分别是 2188 Ma 和 2065 Ma(第五春荣等,2018)。

熊耳群火山岩不整合于变质结晶基底之上,以



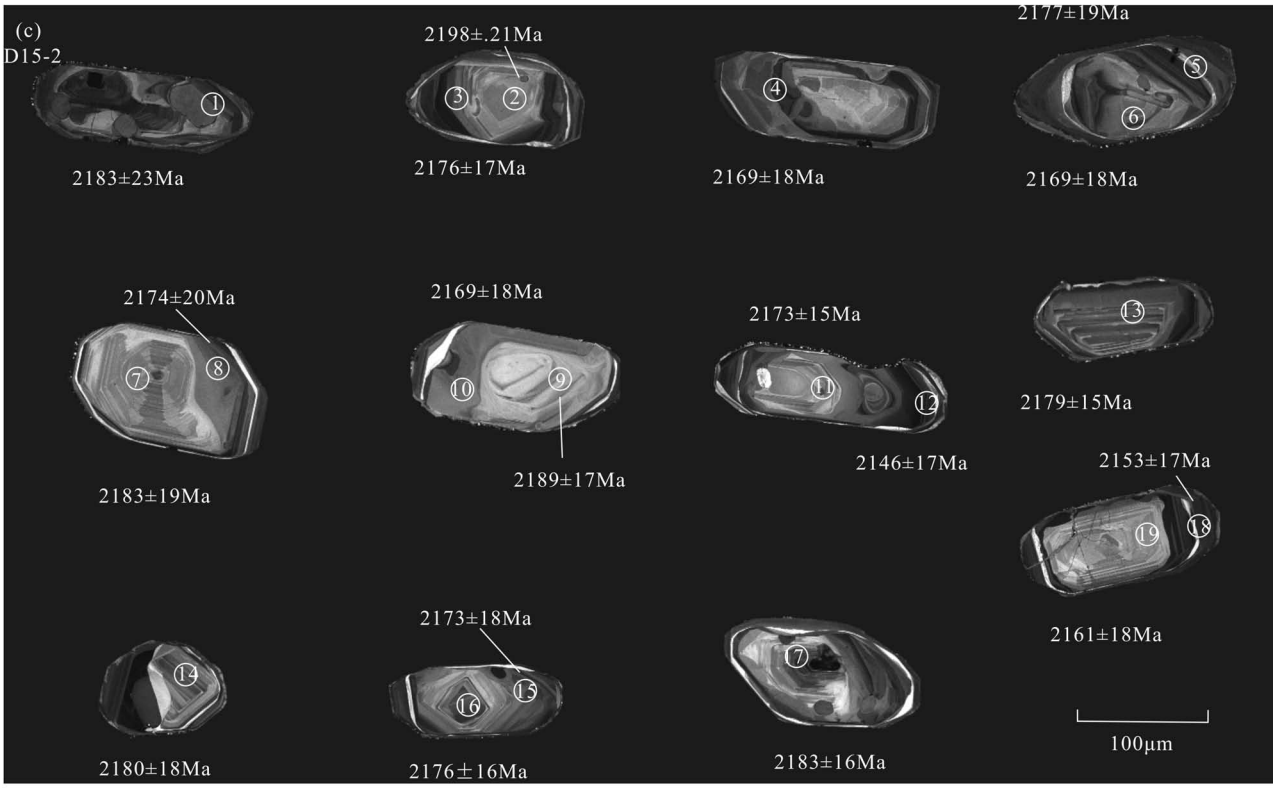


图 4 熊耳山地区穆册二长岩(D08、D15)和二长花岗岩样品(D15-2)锆石阴极发光电子图像

Fig. 4 Cathodoluminescence electron images of the Muce monzonite(D08, D15) and monzogranite(D15-2) zircon samples in Xiong'er Mountains

中—酸性火山熔岩为主,从下至上分别为:大古石组陆相碎屑岩;许山组裂隙式喷发形成的玄武安山质、安山质熔岩;鸡蛋坪组裂隙—中心式喷发形成的英安流纹质熔岩;马家河组裂隙式间隙型喷发形成的玄武安山质、安山质熔岩;它们的形成时代介于1950~1650 Ma 之间,都属于中元古代(孙大中等,1991;任富根等,1991;赵太平等,1994, 2001;Zhao Taiping et al., 2004)。熊耳群火山岩是华北克拉通于中元古代(1.80~1.77 Ga)发生伸展—裂解作用中形成的,并形成了熊耳—中条拗拉谷(陈衍景等,1992; Lu Songnian et al., 2002; Hou Guiting et al., 2006;徐勇航等,2008)。区内岩浆作用在燕山期达到高峰,以中—酸性岩浆侵入为主,由北向南形成了花山岩体、蒿坪岩体、金山庙岩体和五丈山岩体等一系列岩体(图 1b)。熊耳山地区侵入岩主要为花岗岩,主体形成于中生代,年龄介于 130~180 Ma。

前人对熊耳山地区古元古代早期 TTG 片麻岩、中元古代火山岩和中生代花岗岩的报道颇多,而对古元古代晚期即 2.2~2.1 Ga 侵入体鲜有报道。本次在熊耳山地区发现侵位于太华群结晶基底的岩浆活动—穆册二长岩体,其主要岩性为黑云角闪二长岩;其次为二长花岗岩和英云闪长片麻岩,二长岩体被中生代岩浆活动切穿。本文主要分析了该岩体的岩石学特征、地球化学特征和 LA-ICP-MS 锆石 U-Pb 年龄,这将为研究华北克拉通构造演化和秦岭造山带活动提供新的证据。

2　样品描述及分析方法

穆册二长岩侵位于太华群片麻岩中,呈平行不整合接触,又被中酸性似斑状花岗岩呈角度不整合侵位。岩体空间上呈近等轴状,不规则状,出露面积为 9.8 km^2。穆册二长岩体的主体岩性为黑云角闪二长岩,侵入边界处为二长斑岩,局部被二长花岗岩侵入(图 2,图 3a)。黑云角闪二长岩体新鲜面呈灰白色,中粗粒结构,块状构造,且常见包体出现,包体呈灰黑色,椭球状,比二长岩颜色深,被长英质岩脉贯穿(图 3b)。二长岩主要矿物包括碱性长石(30%~40%),斜长石(20%~30%),角闪石(10%~

表 1 熊耳山地区穆册二长岩、二长斑岩和二长花岗岩的主量(%)和微量元素组成($\times10^{-6}$)

Table 1 Major and trace element compositions of the Muce monzonite, monzogranite and monzonitic porphyry in Xiong'er Mountains

点号	WD02	D16	WD07	WD08	D08	WD09-2	WD10	WD11	WD13	D15	D15-2
岩性	二长斑岩		黑云角闪二长岩								二长花岗岩
SiO_2	57.79	55.69	56.54	56.09	56.08	55.47	58.21	55.89	57.82	59.71	70.29
TiO_2	0.46	0.56	0.75	0.74	0.74	0.76	0.76	0.78	0.69	0.63	0.22
TFe_2O_3	5.89	7.53	6.59	6.69	6.6	6.94	6.56	7.43	4.5	4.85	1.93
MnO	0.12	0.14	0.1	0.11	0.1	0.13	0.12	0.12	0.07	0.07	0.03
MgO	1.08	1.85	2.77	2.88	2.85	2.9	2.8	4.03	1.17	1.48	0.5
$Mg^{\#}$	26.84	32.95	45.68	46.27	46.35	45.53	46.06	52.04	34.22	37.91	34.13
CaO	1.65	4.72	4.71	4.84	5.11	4.73	4.87	5.26	4.21	4.01	1.95
Na_2O	4.69	2.97	3.35	3.34	3.62	3.7	3.28	3.19	4.05	3.93	2.69
K_2O	5.45	7.25	4.55	4.37	4.38	4.64	4.24	4.13	5.4	5.31	6.13
P_2O_5	0.25	0.44	0.3	0.3	0.33	0.32	0.29	0.35	0.23	0.25	0.1
烧失量	2.5	0.6	1.45	3.07	1.4	1.61	0.95	0.89	0.56	0.59	0.43
总量	98.04	98.53	99	99.9	99	98.68	99.42	99.35	98.36	99.34	99.12
Li	8.8	5.07	10.48	10.95	10.88	6.3	12.85	20.8	8.56	14.43	7.68
Be	5.2	8.43	2.09	2.28	2.31	2.81	2.69	2.24	2.11	2.89	1.96
Sc	7.68	13.73	15.31	16.17	16.3	16.4	16.21	17.49	11.29	14.12	4.38
Ti	2809	3428	4672	4533	4438	4644	4642	4830	4420	3776	1298
V	105	167	106	95	101	109	97	116	47	55	32
Cr	12.43	31	97	102	85	116	103	183	25.1	49	11.84
Mn	1007	1190	814	922	733	1151	920	1020	574	484	180
Co	9.35	13.09	16.54	17.23	15.95	16.31	16.27	21.5	8.06	9.82	4.01
Ni	9.21	19.29	39	42	37	39	42	74	11.75	17.39	5.8
Cu	10.76	9.9	57	73	63	51	62	45	17.42	26.4	10.52
Zn	60	90	73	81	62	83	71	87	43	52	22.41
Ga	22.4	21	25.4	26.3	25.9	26	25.3	25	23.6	27.3	15.38
As	8.27	2.66	8.24	8.91	3.18	9.84	10.24	10.45	8.55	2.58	1.31
Se	0.94	0.83	0.76	0.89	0.84	1.15	0.73	1.08	0.6	1.07	0.32
Rb	164	277	133	127	147	153	149	158	186	169	171
Sr	648	1254	813	758	680	707	719	859	716	556	452
Y	19.72	21	21.5	24.9	23.5	27.1	25.8	24.6	15.14	28.4	11.6
Zr	196	190	408	327	484	307	317	258	886	781	220
Nb	12.59	12.13	12.4	12.88	12.78	13.96	16.4	11.35	14.92	17.77	7.21
Mo	0.38	0.99	0.33	0.55	0.56	0.76	0.93	0.67	0.73	1.03	1.44
Sn	1.56	2.35	1.44	1.59	1.48	1.93	2.09	1.81	0.86	1.5	0.82
Cs	3.97	3.68	1.78	2.08	2.9	1.67	3.04	3.41	1.59	0.82	1.09
Ba	2571	4330	1612	1602	1425	1680	1701	1833	1765	1322	1881
Hf	4.63	4.75	8.91	7.29	9.88	6.85	7.21	5.73	17.85	16.39	5.26
Ta	0.54	0.6	0.66	0.69	0.72	0.8	0.97	0.66	0.67	0.84	0.4
Pb	54	30	20.1	20.9	17.27	29.3	23.9	20.1	21.3	24.8	24.44
Th	13.11	11.58	3.58	5.7	4.79	8.59	17.25	6.48	2.69	3.05	2.46
U	3.27	2.94	1.05	1.42	1.47	1.93	3	1.63	1.24	0.88	0.46
Th/U	4.01	3.94	3.41	4.01	3.26	4.45	5.75	3.98	2.17	3.47	5.3
La	45	38	41	45	46	48	47	46	32	52	14.08
Ce	77	38	79	88	89	90	94	92	59	103	31
Pr	8.91	8.01	9.2	10.15	9.74	11.45	10.79	10.57	6.75	11.56	3.31
Nd	35	31	36	40	37	45	42	41	24	44	12.63
Sm	5.99	6.3	6.01	6.68	6.72	7.51	6.94	6.71	4.1	8.1	2.53
Eu	1.78	1.88	1.66	1.67	1.64	1.8	1.71	1.66	1.84	1.54	0.97
Gd	4.86	5.32	4.86	5.34	5.4	5.88	5.45	5.41	3.21	6.44	2.2
Tb	0.68	0.73	0.68	0.77	0.78	0.85	0.8	0.76	0.45	0.93	0.33
Dy	3.59	3.8	3.73	4.27	4.24	4.69	4.42	4.22	2.5	5.19	1.97

点号	WD02	D16	WD07	WD08	D08	WD09-2	WD10	WD11	WD13	D15	D15-2
岩性	二长斑岩		黑云角闪二长岩								二长花岗岩
Ho	0.66	0.71	0.73	0.83	0.81	0.9	0.87	0.82	0.5	0.98	0.39
Er	1.79	1.87	2.09	2.37	2.25	2.56	2.5	2.31	1.49	2.69	1.07
Tm	0.26	0.27	0.29	0.35	0.34	0.37	0.37	0.33	0.22	0.4	0.16
Yb	1.7	1.67	1.94	2.21	2.12	2.39	2.37	2.16	1.5	2.44	0.98
Lu	0.26	0.26	0.3	0.34	0.32	0.36	0.37	0.33	0.25	0.37	0.15
∑LREE	174	123	173	192	190	204	202	198	128	220	65
∑HREE	13.8	14.4	14.3	16.1	15.9	17.6	16.8	16.0	9.9	19.1	20.1
∑REE	187	138	187	208	206	222	220	214	138	240	72
δEu	1.01	0.99	0.94	0.85	0.83	0.83	0.85	0.84	1.55	0.65	1.65

15%),黑云母(5%~10%),石英(5%~7%),副矿物可见磁铁矿和锆石。黑云角闪二长岩的碱性长石主要为钾长石和微斜长石,晶形较差,多为他形,具有格子状双晶,为晚期结晶矿物;斜长石主要以自形为主,聚片双晶发育;角闪石主要呈半自形到他形,短柱状;黑云母和石英分别呈半自形和他形结构(图 3c、d)。二长花岗岩的钾长石和斜长石都呈半自形到他形,且斜长石有较强的蚀变;石英以半自形为主。二长斑岩以含粗大的斜长石和碱性长石斑晶为特征,大部分斜长石具有较强的蚀变。

锆石分选在廊坊诚信地质有限责任公司完成。野外采集新鲜样品 10 kg,并将其粉碎至 100~200 目,用磁选和重液分选方法选出锆石,最终在双目镜下进行提纯。将晶形较好且无明显裂痕和包体的锆石粘在双面胶上,套上样品靶环灌注环氧树脂,烘干后将其抛光露出锆石表面,然后对其进行反射光、透射光和阴极发光(CL)图像采集。

岩石全岩主微量元素分析在南京聚谱检测科技有限责任公司进行,其中进行主量元素分析的仪器为日本岛津 1800 型 X 射线荧光光谱分析仪;微量元素则采用美国 X-7 型 ICP-MS 进行测定(数据见表 1)。

锆石 LA-ICP-MS U-Pb 定年同位素分析在西北大学大陆动力学国家重点实验室完成。采用 Agilent 7500 型 ICP2MS 和德国 Lambda2Physik 公司的 ComPex102 ArF 准分子激光器以及 MicroLas 公司的 GeoLas 200M 光学系统联机进行激光束斑直径为 30 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。用美国国家标准技术研究院研制的人工合成硅酸盐玻璃标准参考物质 NIST SRM610 进行仪器最佳化。锆石年龄采用国际标准锆石 91500 作为外标标准物质,元素含量采用 NIST SRM610 作为外标,^{29}Si 作为内标。测试结果通过 GLITTER 软件计算得出,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,谐和图的绘制采用 Isoplot3.0 完成。详细的实验分析步骤和数据处理方法见文献 Yuan et al.(2004)。所给定的同位素比值和年龄的误差均在 1σ 水平。

3　分析结果

3.1　LA-ICP-MS 锆石 U-Pb 测年

本次研究分选出穆册二长岩体锆石颗粒一般为 100~200 μm,锆石主体呈不规则粒状,少数呈晶形良好的柱状,部分呈浑圆状,透明度中等。大部分锆石呈核—幔结构,即由中心暗色部分和边缘浅色部分构成,二者接触界线复杂,多呈侵蚀状或港湾状,韵律环带可见于暗色部分和浅色部分,但连续性和发育程度差异极大(图 4),表明锆石具有岩浆成因但发生了后期改造。所有锆石样品 Th/U 值均≥0.1,也指示了原始锆石的岩浆成因。本次研究主要分析了两个黑云角闪二长岩(D08 和 D15)和一个似斑状二长花岗岩样品(D15-2)。

样品 D08 部分锆石呈核—幔结构,但其内部年龄和外部年龄比较接近。对 D08 样品进行了 17 个锆石点位分析,在 U-Pb 年龄谐和图上(图 5a),16 号点具有明显的 Pb 丢失,但其^{207}Pb/^{206}Pb 年龄与其他点年龄结果相近,表明其为锆石自然铅丢失引起的,因而^{207}Pb/^{206}Pb 年龄没有明显影响(Amelin et al., 2000)。利用 17 个锆石分析点获得的^{207}Pb/^{206}Pb加权平均年龄为 2172±8 Ma(MSWD=0.58,n=17)(图 5b)。与前人研究的五台花岗岩成岩年龄一致(2176±12 Ma,王凯怡和 Wilde,2002;2170±17 Ma,杜利林,2018)。

样品 D15 与样品 D08 特征相似,虽然具有核—幔结构,但暗色部分和浅色部分的年龄较接近。对

表 2 熊耳山地区穆册二长岩样品(D08、D15)和二长花岗岩样品(D15-2)锆石 LA-ICP-MS U-Pb 测试结果

Table 2 LA-ICP-MS zircon U-Pb dating data of the Muce monzonite(D08, D15) and monzogranite (D15-2) samples in Xiong'er Mountains

测点号	元素含量(×10⁻⁶)			$\frac{^{232}Th}{^{238}U}$	同位素比值						同位素年龄(Ma)						谐和度(%)
	^{206}Pb	^{232}Th	^{238}U		$n(^{207}Pb)/n(^{206}Pb)$		$n(^{207}Pb)/n(^{235}U)$		$n(^{206}Pb)/n(^{238}U)$		$n(^{207}Pb)/n(^{206}Pb)$		$n(^{207}Pb)/n(^{235}U)$		$n(^{206}Pb)/n(^{238}U)$		
					测值	1σ	测值	1σ	测值	1σ	测值	1σ	测值	1σ	测值	1σ	
D08-01	2.96	55.1	108.1	0.51	0.1364	0.0014	7.650	0.0990	0.4056	0.0043	2183	23	2191	12	2195	20	100.2
D08-02	2.23	189.4	325.3	0.58	0.1357	0.0011	7.634	0.0926	0.4072	0.0047	2173	15	2189	11	2202	22	100.6
D08-03	0.00	77.4	140.2	0.55	0.1339	0.0014	7.451	0.0937	0.4017	0.0041	2150	19	2167	11	2177	19	100.4
D08-04	13.10	111.1	181.2	0.61	0.1336	0.0012	7.518	0.0848	0.4057	0.0038	2146	15	2175	10	2195	18	100.9
D08-05	0.00	63.8	119.6	0.53	0.1357	0.0014	7.553	0.0935	0.4013	0.0041	2174	12	2179	11	2175	19	99.8
D08-06	5.11	85.1	142.5	0.60	0.1355	0.0013	7.635	0.0934	0.4072	0.0044	2170	16	2189	11	2202	20	100.6
D08-07	2.48	194.0	289.6	0.67	0.1349	0.0012	7.705	0.0882	0.4128	0.0042	2162	15	2197	10	2228	19	101.4
D08-08	0.92	408.1	444.4	0.92	0.1368	0.0010	7.596	0.0767	0.3997	0.0034	2187	19	2184	9	2168	16	99.2
D08-09	18.90	127.5	184.5	0.69	0.1350	0.0013	7.343	0.0879	0.3933	0.0043	2165	16	2154	11	2138	20	99.3
D08-10	9.12	99.1	231.8	0.43	0.1367	0.0013	7.602	0.0879	0.4018	0.0042	2187	16	2185	11	2178	20	99.7
D08-11	2.96	255.4	332.5	0.77	0.1364	0.0012	7.656	0.0946	0.4055	0.0048	2183	16	2192	11	2195	22	100.1
D08-12	0.00	94.2	171.0	0.55	0.1359	0.0012	7.756	0.0884	0.4116	0.0041	2176	15	2203	10	2223	19	100.9
D08-13	8.74	87.4	134.9	0.65	0.1367	0.0013	7.700	0.0932	0.4060	0.0043	2187	16	2197	11	2196	20	100.0
D08-14	11.50	176.0	210.8	0.83	0.1358	0.0013	7.504	0.0873	0.3973	0.0036	2176	16	2174	11	2157	17	99.2
D08-15	3.31	98.7	180.1	0.55	0.1360	0.0013	7.668	0.0917	0.4062	0.0041	2177	17	2193	11	2198	19	100.2
D08-16	11.30	89.1	151.4	0.59	0.1343	0.0014	7.432	0.0917	0.4003	0.0043	2155	18	2165	11	2170	20	100.3
D08-17	8.03	76.5	139.7	0.55	0.1355	0.0014	7.596	0.0925	0.4065	0.0047	2172	17	2184	11	2199	22	100.7
D15-01	18.30	334.2	620.2	0.54	0.1375	0.0014	7.507	0.1024	0.3964	0.0053	2195	18	2174	12	2153	24	99.0
D15-02	0.00	107.7	146.2	0.74	0.1373	0.0014	7.570	0.1034	0.3993	0.0049	2194	17	2181	12	2166	23	99.3
D15-03	3.55	85.6	158.7	0.54	0.1374	0.0013	7.617	0.0863	0.3998	0.0036	2195	12	2187	10	2168	17	99.1
D15-04	9.31	220.1	395.6	0.56	0.1370	0.0012	7.779	0.0939	0.4105	0.0047	2191	15	2206	11	2217	21	100.5
D15-05	7.62	260.2	399.4	0.65	0.1377	0.0011	7.968	0.0883	0.4173	0.0041	2198	14	2227	10	2248	19	100.9
D15-06	0.00	220.2	386.2	0.57	0.1375	0.0011	7.539	0.0798	0.3951	0.0037	2196	13	2178	10	2146	17	98.6
D15-07	7.87	247.8	401.0	0.62	0.1367	0.0012	7.497	0.0856	0.3953	0.0041	2187	15	2173	10	2147	19	98.8
D15-08	0.00	156.2	318.2	0.49	0.1353	0.0013	7.281	0.0886	0.3884	0.0043	2169	16	2147	11	2115	20	98.5
D15-09	0.16	101.2	180.9	0.56	0.1371	0.0013	7.676	0.0978	0.4039	0.0046	2191	16	2194	12	2187	21	99.7
D15-10	0.05	86.9	150.3	0.58	0.1362	0.0012	7.606	0.0813	0.4030	0.0037	2180	15	2186	10	2183	17	99.9
D15-11	0.85	80.4	146.7	0.55	0.1378	0.0014	7.560	0.0967	0.3965	0.0044	2200	17	2180	12	2153	20	98.8
D15-12	7.62	80.6	151.1	0.53	0.1376	0.0013	7.479	0.0845	0.3927	0.0038	2198	16	2170	10	2135	18	98.4
D15-13	0.00	151.8	389.0	0.39	0.1357	0.0012	7.382	0.0913	0.3923	0.0040	2173	11	2159	11	2134	19	98.8
D15-14	10.40	57.9	124.3	0.47	0.1371	0.0014	7.689	0.1037	0.4054	0.0044	2190	19	2195	12	2194	20	99.9
D15-15	0.00	87.9	134.7	0.65	0.1373	0.0013	7.589	0.0936	0.3997	0.0044	2194	16	2184	11	2168	20	99.3

测点号	元素含量($\times10^{-6}$)			$\frac{^{232}Th}{^{238}U}$	同位素比值						同位素年龄(Ma)						谐和度(%)
	^{206}Pb	^{232}Th	^{238}U		$n(^{207}Pb)/n(^{206}Pb)$		$n(^{207}Pb)/n(^{235}U)$		$n(^{206}Pb)/n(^{238}U)$		$n(^{207}Pb)/n(^{206}Pb)$		$n(^{207}Pb)/n(^{235}U)$		$n(^{206}Pb)/n(^{238}U)$		
					测值	1σ	测值	1σ	测值	1σ	测值	1σ	测值	1σ	测值	1σ	
D15-16	5.68	109.0	179.7	0.61	0.1362	0.0013	7.541	0.0964	0.4005	0.0046	2179	16	2178	12	2171	21	99.7
D15-17	1.36	117.2	243.7	0.48	0.1350	0.0011	7.344	0.0761	0.3929	0.0035	2165	19	2154	9	2136	17	99.2
D15-18	7.09	64.7	125.4	0.52	0.1348	0.0013	7.398	0.0958	0.3959	0.0044	2162	21	2161	12	2150	20	99.5
D15-19	7.77	191.1	426.7	0.45	0.1354	0.0012	7.308	0.0861	0.3896	0.0042	2169	15	2150	11	2121	20	98.7
D15-2-01	57.02	124.1	254.1	0.49	0.1364	0.0015	7.603	0.1135	0.4030	0.0057	2183	23	2185	13	2183	26	99.9
D15-2-02	0.00	75.7	113.7	0.67	0.1376	0.0016	7.663	0.1106	0.4031	0.0054	2198	21	2192	13	2183	25	99.6
D15-2-03	8.59	282.2	567.5	0.50	0.1360	0.0013	7.644	0.0971	0.4058	0.0049	2176	17	2190	12	2196	22	100.3
D15-2-04	7.10	107.3	220.0	0.49	0.1353	0.0014	7.659	0.1051	0.4096	0.0053	2169	18	2192	12	2213	24	101.0
D15-2-05	0.00	226.3	520.1	0.44	0.1360	0.0015	7.511	0.1103	0.4016	0.0060	2177	19	2174	13	2176	27	100.1
D15-2-06	7.96	116.8	181.1	0.65	0.1354	0.0014	7.589	0.1059	0.4057	0.0053	2169	18	2184	13	2195	24	100.5
D15-2-07	44.86	82.5	159.2	0.52	0.1365	0.0015	7.656	0.1152	0.4071	0.0058	2183	19	2191	14	2202	27	100.5
D15-2-08	1.06	77.5	122.1	0.63	0.1357	0.0015	7.561	0.1145	0.4039	0.0058	2174	20	2180	14	2187	27	100.3
D15-2-09	44.22	79.1	128.4	0.62	0.1369	0.0014	7.412	0.1026	0.3913	0.0050	2189	17	2162	12	2129	23	98.4
D15-2-10	12.11	73.9	158.1	0.47	0.1354	0.0014	7.357	0.0870	0.3928	0.0040	2169	18	2156	11	2136	19	99.1
D15-2-11	1.39	276.6	531.7	0.52	0.1357	0.0012	7.662	0.0935	0.4073	0.0048	2173	15	2192	11	2203	22	100.5
D15-2-12	0.00	104.2	167.3	0.62	0.1336	0.0013	7.262	0.0849	0.3914	0.0038	2146	17	2144	11	2129	18	99.3
D15-2-13	33.12	176.8	234.8	0.75	0.1362	0.0012	7.614	0.0914	0.4026	0.0041	2179	15	2187	11	2181	19	99.7
D15-2-14	14.37	205.7	234.0	0.88	0.1362	0.0014	7.599	0.1013	0.4028	0.0049	2180	18	2185	12	2182	22	99.9
D15-2-15	0.00	127.6	251.4	0.51	0.1357	0.0014	7.510	0.1044	0.4000	0.0052	2173	18	2174	13	2169	24	99.8
D15-2-16	40.80	108.4	165.9	0.65	0.1359	0.0013	7.468	0.0898	0.3956	0.0040	2176	16	2169	11	2149	19	99.1
D15-2-17	25.09	107.6	173.8	0.62	0.1365	0.0013	7.594	0.0922	0.4017	0.0043	2183	16	2184	11	2177	20	99.7
D15-2-18	20.2	203.3	536.8	0.38	0.1342	0.0013	7.460	0.0932	0.4007	0.0046	2153	17	2168	11	2172	21	100.2
D15-2-19	44.6	83.5	127.3	0.66	0.1347	0.0015	7.441	0.0989	0.3980	0.0046	2161	18	2166	12	2160	21	99.7

D15 样品进行了 19 个锆石点位的测定,在锆石 U-Pb 年龄谐和图上(图 5c),17 个分析点的结果都在谐和线附近,$^{207}Pb/^{206}Pb$ 加权平均年龄为 2186±7 Ma(MSWD = 0.60,n = 19)(图 5d)。与 D08 样品结果相近,代表了二长岩的侵位时代——古元古代。

样品 D15-2 锆石中核—幔结构同样存在,但其年龄相差不大。对 D15-2 样品做了 20 个分析点,在 U-Pb 年龄谐和图上(图 5e),11 号点具有明显的 Pb 丢失,但其$^{207}Pb/^{206}Pb$ 年龄与其他点年龄结果相近,表明其为锆石自然铅丢失引起的,因而$^{207}Pb/^{206}Pb$ 年龄没有明显影响(Amelin et al., 2000)。利用 20 个锆石分析点获得的$^{207}Pb/^{206}Pb$ 加权平均年龄为 2174±8 Ma(MSWD = 0.45,n = 19)(图 5f)。与前人研究的五台花岗岩成岩年龄一致同时,也与样品 D08 年龄一致。

3.2　主量元素

穆册二长岩体地球化学测试见表 1。SiO_2 含量介于 55.47%~59.71%之间,平均值 56.98%;Al_2O_3 含量介于 17.28%~19.66%之间,平均为 17.93%。铝饱和指数(A/CNK)介于 0.89~0.97 之间,在 A/CNK—A/NK 关系图上(图 6a),样品落在准铝质到过铝质区域。在 SiO_2—K_2O 关系图中(图 6b),部分样品投在钾玄岩系列,少数投在高钾钙碱性系列。K_2O+Na_2O 介于 7.32%~9.45%之间,在 TAS 图中(图 6c),样品基本都落入二长岩区域;MgO 含量变化较大,在 1.17%~4.03%之间,平

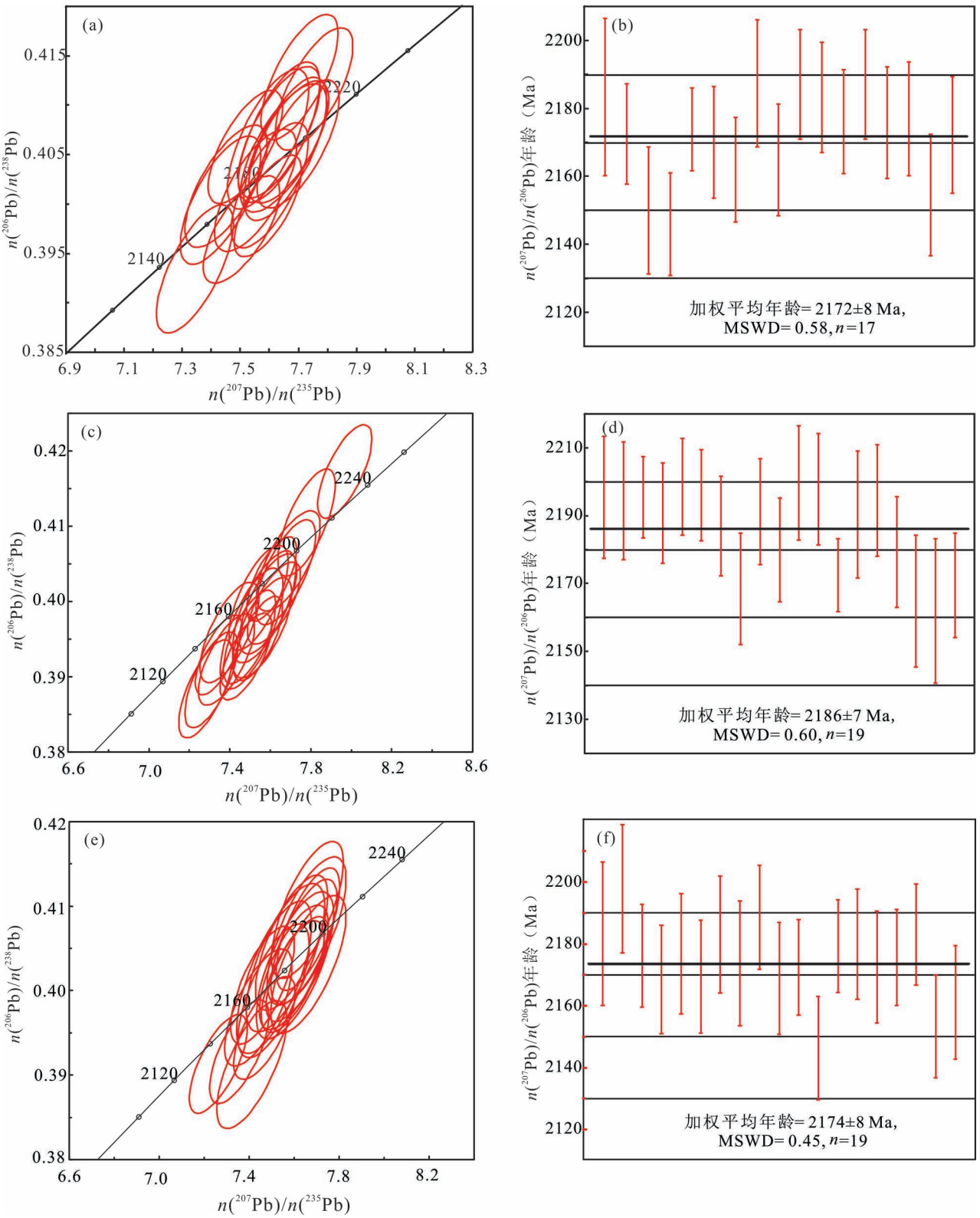
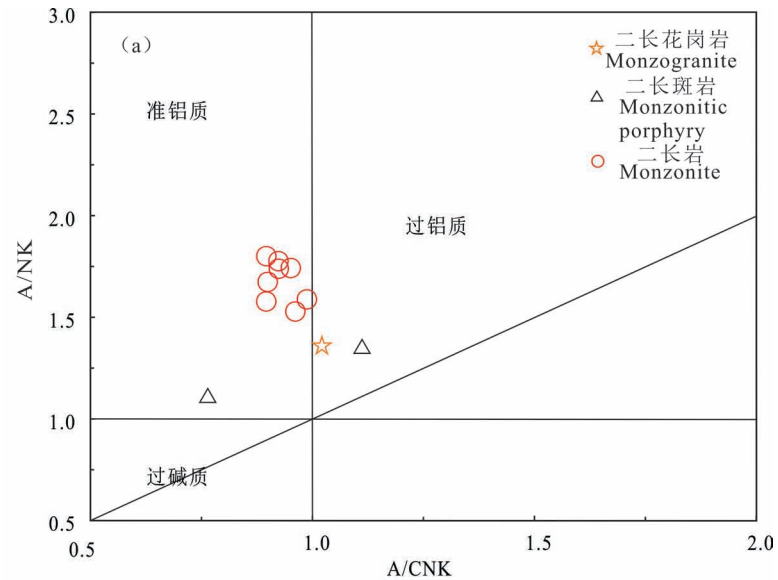
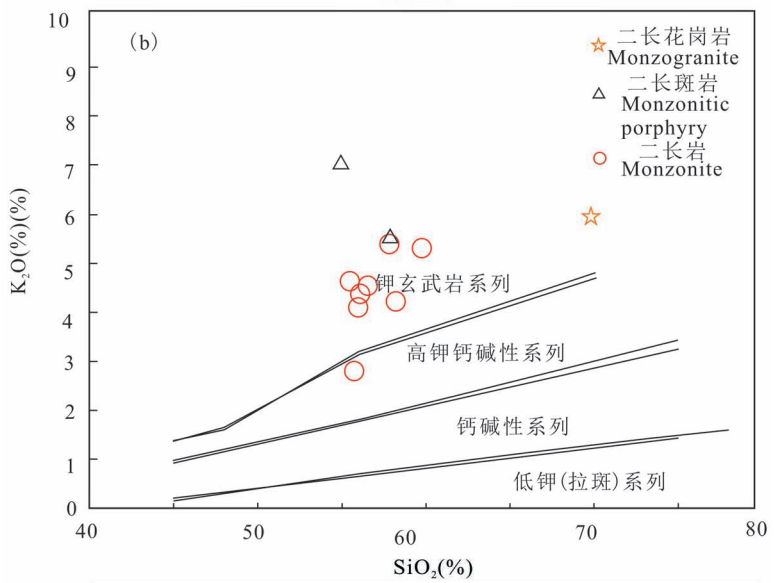
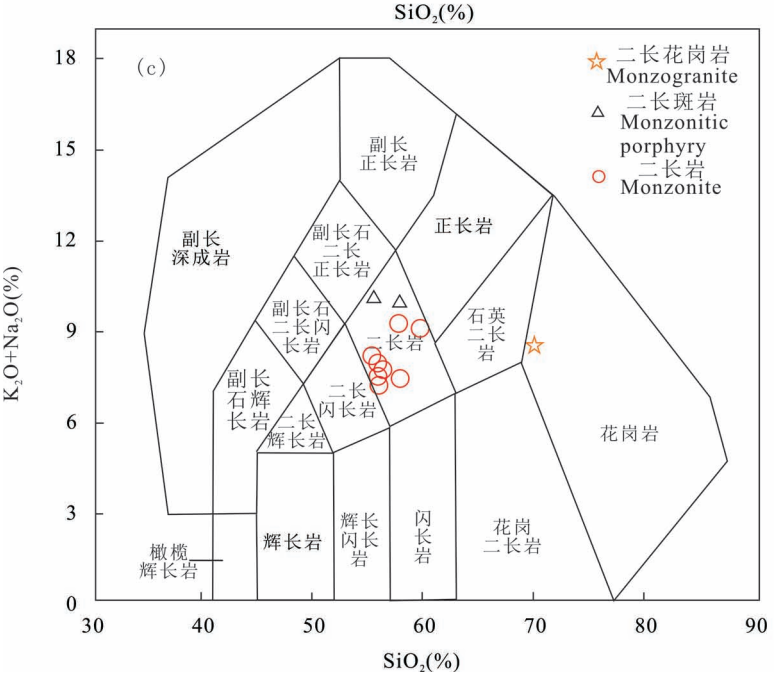


图 5 熊耳山地区穆册二长岩(D08、D15)和二长花岗岩(D15-2)锆石 U-Pb 年龄谐和图和 $n(^{207}Pb)/n(^{206}Pb)$加权平均年龄图

Fig. 5 U-Pb age harmonics and $n(^{207}Pb)/n(^{206}Pb)$ average age of the Muce monzonite(D08, D15) and monzogranite(D15-2) samples in Xiong'er Mountains







均为 2.61%;$Mg^{\#}$值为 34.22~52.04,$Mg^{\#}$的计算公式见文献邓晋福等(2015),平均为 44.26;TiO_2、TFe_2O_3 含量分别是 0.63%~0.78%和 4.5%~7.43%,平均值分别为 0.73% 和 6.27%;二长花岗岩 SiO_2 含量较高,其他主量元素含量相对较低;综上所述,穆册二长岩体为一套高碱低镁的中性岩体,其主量元素 MgO 与 TFe_2O_3、TiO_2、CaO、P_2O_5 都呈正相关关系(图 7a、b、c、d)。

3.3　稀土和微量元素

穆册二长岩稀土元素总量变化较大,介于 138.39×10^{-6}~221.2×10^{-6}之间,轻稀土含量在 $\sum LREE = 128.27\times10^{-6}$~$220.27\times10^{-6}$之间;重稀土含量在 $\sum HREE = 9.88\times10^{-6}$~$19.08\times10^{-6}$之间。轻稀土元素明显富集,LREE/HREE 值为 11.52~12.98,平均为 12.05,显示轻重稀土强烈分馏。δEu=0.65~1.55,平均为 0.92,多数为负 Eu 异常(仅有 WD13 一个样品表现为弱正异常)。稀土配分曲线图上样品的变化趋势基本一致且呈右倾式(图 8a);而二长花岗岩在 $\sum REE$ 含量上明显低于二长岩和二长斑岩,且二长花岗岩的 Eu 为正异常。

岩石具有相似的微量元素含量特征(图 8b),穆册二长岩和二长花岗岩表现出富集大离子亲石元素(LILEs)Ba、Pb、U 等和轻稀土元素(LREEs)La、Ce、Sm 等,亏损高场强元素(HFSEs)Th、Zr、Ta、Ti 等,其在微量元素原始地幔标准化蛛网图上呈现明显的“V”型谷,显示存在锆石、钛铁矿、磷灰石等矿物的分离结晶。

图 6 熊耳山地区穆册二长岩、二长斑岩和二长花岗岩的 A/CNK—A/NK 关系图(a)、SiO_2—K_2O 关系图(b)、TAS 分类图(c)(据 Cox et al.,1979;Irvine et al.,1971)

Fig. 6 A/CNK—A/CN diagram (a), SiO_2—K_2O diagram (b), TAS diagram (c) of the Muce Monzonite, Monzonitic porphyry and Monzogranite in Xiong'er Mountains (after Cox et al.,1979;Irvine et al.,1971

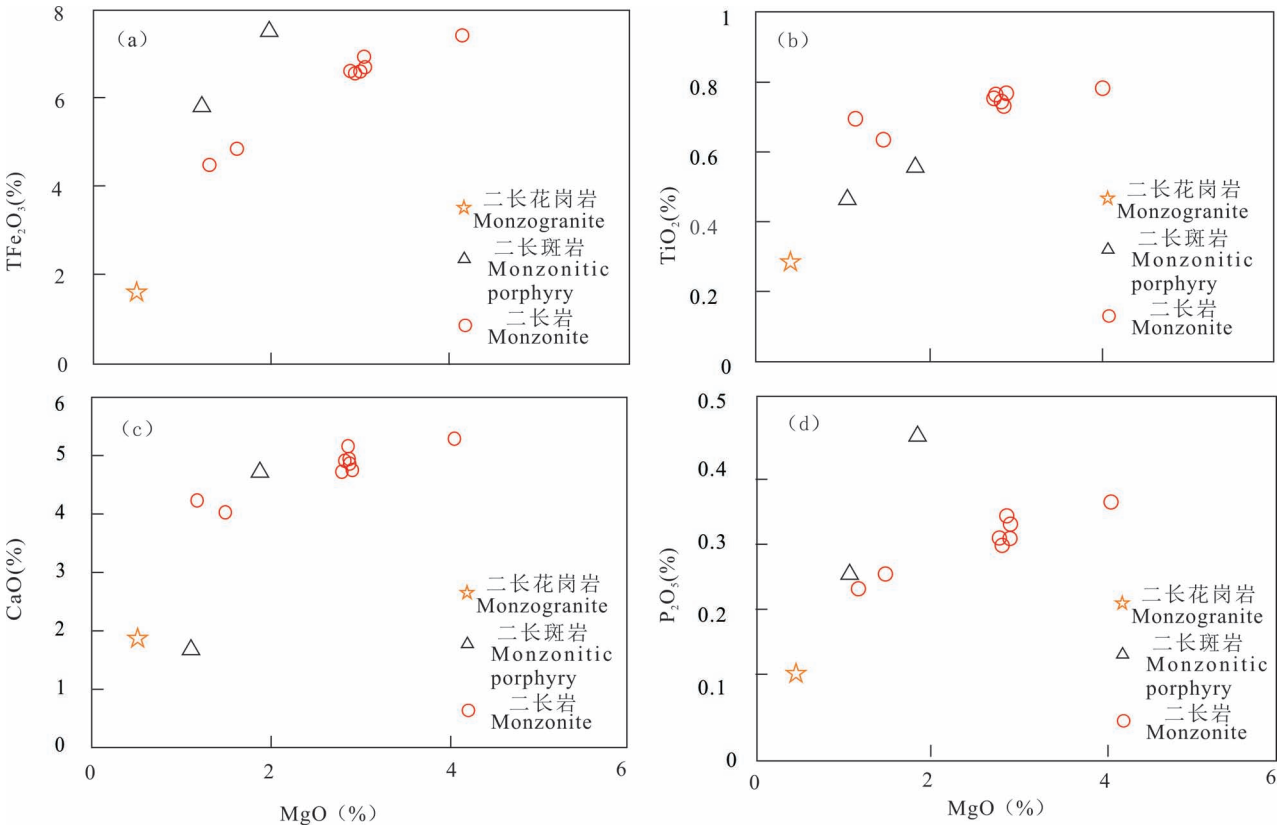


图 7 熊耳地区穆册二长岩、二长斑岩和二长花岗岩主量元素关系图解

Fig. 7 Diagrammatic diagram of principal component elements of the Muce monzonite, monzonitic porphyry and monzogranite in Xiong'er Mountains

4 讨论

4.1 穆册岩体成因时代

熊耳地区穆册岩体黑云角闪二长岩和二长花岗岩普遍发育具有核—幔结构的锆石,其核—幔年龄相差不大,其二长岩年龄为 2172±8 Ma(MSWD = 0.58,n = 17)和 2186±7 Ma(MSWD = 0.60,n = 19),二长花岗岩的年龄为 2174±8 Ma(MSWD = 0.45,n = 19)。对于熊耳地区古元古代岩浆事件,洛宁太华变质杂岩也保存着 2100~2200 Ma 记录。陈鸿旭等(2016)在洛宁东部发现含榴长英质片麻岩的 U-Pb 年龄为 2177 Ma;Huang Xiaolong 等(2012,2013)对洛宁干树沟的钾质片麻岩定年得到 2070~2200 Ma 的岩浆年龄,对华山地区灞源 TTG 片麻岩的研究计算出 2160 Ma 的岩浆年龄。Zhou Yanyan 等(2014,2015)对同属于太华变质杂岩区的鲁山地区钾质花岗岩和正长岩定年获得 2130~2190 Ma 的岩浆年龄。显然,太华变质杂岩保存着 2100~2200 Ma 的岩浆事件。这与华北中部造山带部分地区记录的 2100~2200 Ma 岩浆事件一致。杜利林等(2012)在吕梁杜家沟发现的长石斑岩的 U-Pb 年龄为 2190 Ma,恶虎滩的闪长质片麻岩年龄为 2182 Ma;在五台大洼梁发现似斑状花岗岩 U-Pb 年龄为 2170 Ma(杜利林等,2018);耿元生等(2000)在吕梁地区野鸡山群发现的二云浅粒岩 U-Pb 年龄为 2124 Ma;白瑾等(1992)利用全岩 Sm-Nd 技术发现中条斜长角闪岩年龄为 2191 Ma。综上所述,穆册岩体也记录着古元古代(2100~2200 Ma)岩浆事件,这与华北中部造山带其他地区的研究结果一致,说明穆册岩体与华北中部造山带中—北段各杂岩区共同经历了华北克拉通古元古代(2100~2200 Ma)的岩浆事件。

4.2 岩体成因及构造背景

穆册二长岩具有高硅、高钾、富碱和铝,低镁、钛的特点,A/CNK 为 1.015,为过铝质岩石,矿物可见黑云母和角闪石,未见白云母、堇青石等过铝质矿物,因而与 S 型花岗岩(强烈富铝、含石榴子石、白云母等富铝矿物(A/CNK>1.1)的特点不符。岩体中 P_2O_5 含量普遍较低,一般低于 0.20%(Chappell.,

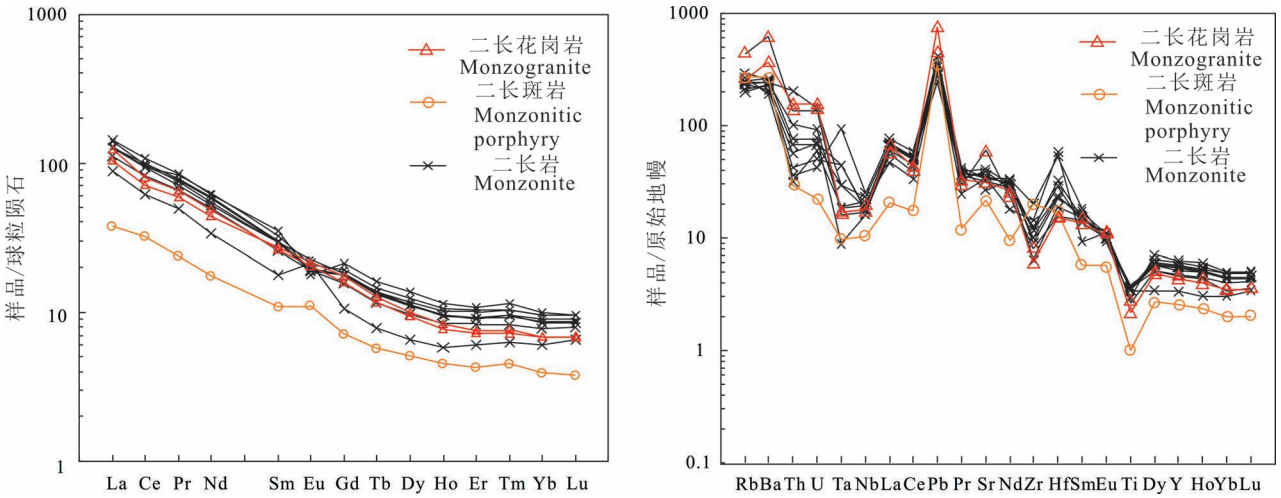


图 8 熊耳山地区穆册二长岩、二长斑岩和二长花岗岩稀土元素球粒陨石标准化配分图(a)和微量元素原始地幔标准化蛛网图(b)(球粒陨石和原始地幔标准值据 Sun and Mc Donough,1989)

Fig. 8 Chondrite-normalized REE patterns (a) and Primitive mantle-normalized spidergrams (b) of the Muce monzonite, monzonitic porphyry and monzogranite in Xiong'er Mountains (Chondrites and primitive mantle standard values according to Sun and Mc Donough, 1989)

1999),亦与 S 型花岗岩特点不同,因此可排除岩体属于 S 型花岗岩的可能。穆册岩体富集大离子亲石素 Rb、Ba、K 及 REEs、Nb、Y 等高场强元素,与典型 A 型花岗岩特征相似(Collins et al., 1982; Whalen et al., 1987; Eby, 1990; Patiño Douce, 1997)。但已有研究表明,一些高分异的 I 型花岗岩也具有 A 型花岗岩的地球化学特征(Whalen et al., 1987; Jiang Neng et al., 2009)。二长斑岩和二长岩 10000Ga/Al 值(介于 2.19~2.74)>2.1,与 A 型花岗岩 10000Ga/Al 接近。而二长花岗岩样品 10000Ga/Al 值(1.89),明显低于世界 A 型花岗岩 10000Ga/Al 值的下限值 2.6 和平均值 3.75,但却与 I 型花岗岩 10000Ga/Al 值接近 2.1(由于仅有一个花岗岩样品,其不具有普遍性)。在图 9a,b,c 中,穆册岩体多落于 A 型花岗岩或与 I&S 型成因区域边界处,显示更多 A 型花岗岩特征,与其富碱性质一致,可能因其低程度部分熔融所致。高分异的花岗岩通常具有高 Rb 低 Sr 特征,同时高场强元素(Zr、Nb 和 Y 等)含量随着岩浆中锆石等副矿物分离结晶而显著降低。因此,高 Zr+Nb+Y+Ce 总量是区分 A 型花岗岩与高分异型花岗岩的又一重要标志。穆册二长斑岩 Zr+Nb+Y+Ce 总量较低(269.54×10^{-6}),低于 A 型花岗岩下限值(350×10^{-6},Whalen et al., 1987);而二长岩 Zr+Nb+Y+Ce 含量(介于 452.78×10^{-6}~975.06×10^{-6})>350×10^{-6},在(K_2O+Na_2O)/CaO—(Zr+Nb+Ce+Y)判别图解中(图 9),穆册岩体基本落于 A 型花岗岩区域或与 I&S 型成因区域边界处。综上分析,穆册岩体应属于 A 型成因类型。

A 型花岗岩可来源于 3 种不同的源区:幔源(Loiselle and Wones, 1979; Turner et al., 1992; Litvinovsky et al., 2002; Mushkin et al., 2003)、壳源(Collins et al., 1982; White and Chappell, 1983; Clemens et al., 1986; Whalen et al., 1987; King et al., 1997; Anderson, 1983; Creaser et al., 1991; Skjerlie and Johnson, 1993; Patio Douce, 1997)等不同的物质源区和形成于壳幔混合作用(Bédard, 1990; Kerr and Fryer, 1993; Mingramet al., 2000; Yang Jinhui et al., 2006)。穆册岩体的 SiO_2、Al_2O_3、Fe_2O_3含量与下地壳岩石含量相当,而 K_2O 和 Na_2O 含量略高于下地壳,MgO 与下地壳相比偏低(Taylor & McLennan, 1985);微量元素中,相容性元素 Cr、Ni 低于下地壳值,与一些 TTG 质岩石含量相当(Martin, 1994)。所以,从主微量元素初步分析,穆册岩体不可能直接由地幔部分熔融而成,可能是下地壳岩石部分熔融形成的,同时有少量地幔物质加入。此外,穆册岩体的 Nb/U 平均值为 9.54 接近于地壳物质值(6.2),远小于地幔岩浆值(47)(Hofmann, 1988; Rudnick and Gao, 2003; Taylor et al., 1985),说明岩浆主要来源于下地壳的部分熔融

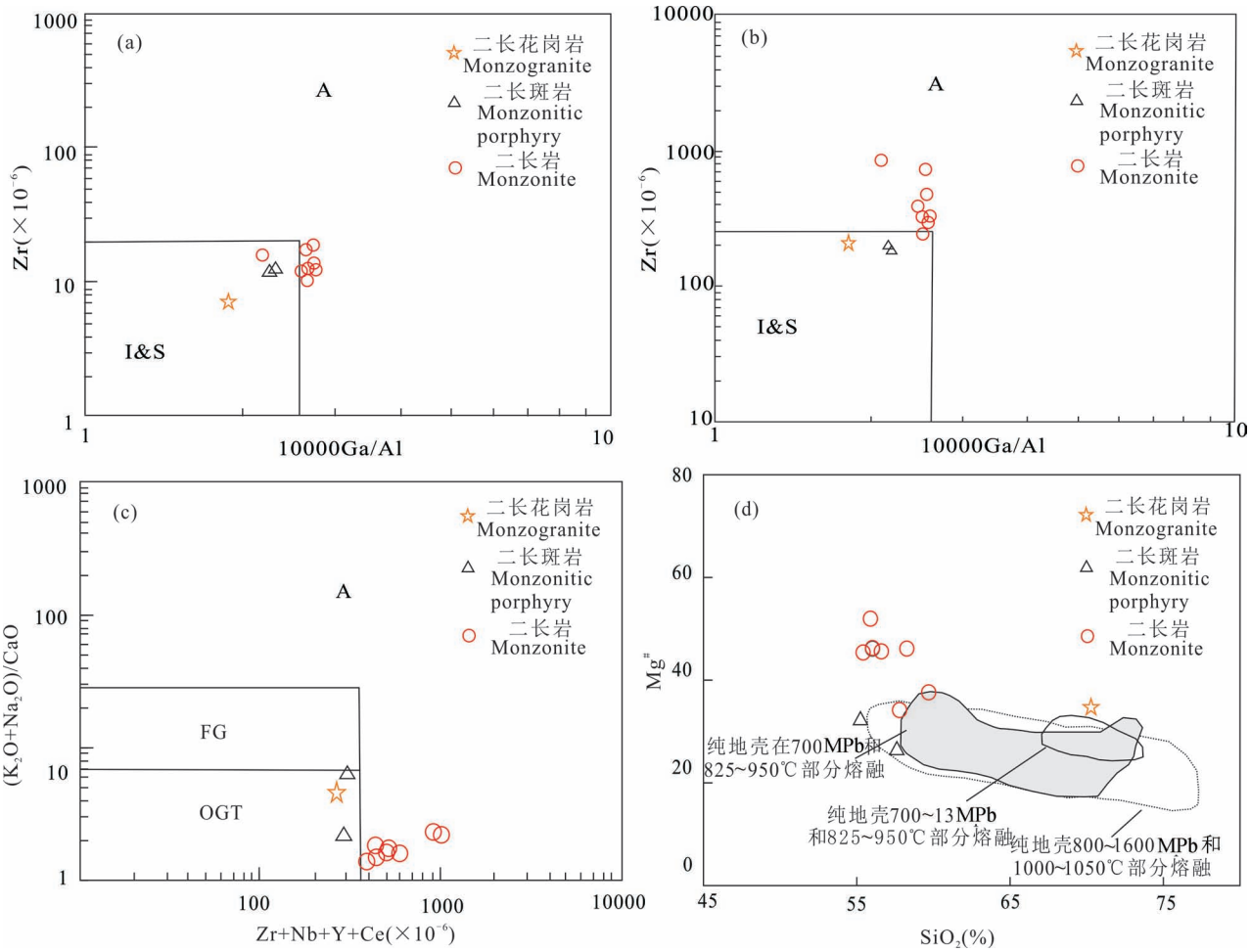


图 9 熊耳山地区穆册二长岩、二长斑岩和二长花岗岩的类型图解和 SiO_2—$Mg^{\#}$图解

Fig. 9 Relationship between SiO_2—$Mg^{\#}$ of the Muce Monzonite, Monzonitic porphyry and Monzogranite in Xiong'er Mountains

FG—分异的花岗岩; OGT—未分异的 M-,I-和 S-型花岗岩

FG—differentiated granite; OGT— undifferentiated M-, I- and S- granites

以及幔源物质混入。暗色微粒岩石包体(MME)的出现也很好地证明了这一点,即发生岩浆混合过程(马昌前等,1992; 刘亮等,2011;张建军等,2012;桑学镇, 2013;张永明等, 2017);同时在 $Mg^{\#}$—SiO_2 图上(图 9d),样品大多落在纯地壳部分熔融之内或边缘,可能是下地壳岩石部分熔融形成的,同时有少量地幔物质加入。其与吕梁恶虎滩地区的片麻岩形成相同——由下地壳岩石部分熔融形成的,同时有少量地幔物质加入(杜利林等,2012)。

A 型花岗岩通常是在伸展的构造背景下侵位的,但其可以出现于板内裂谷环境,也可以形成于造山后环境(Eby, 1990, 1992; Hong Dawei et al., 1996)。在 Pearce 等(1984)的花岗岩构造环境判别图中,穆册二长岩主要位于火山弧区域和后碰撞花岗岩区域(图 10),这与它们所具有的的 A 型花岗岩的性质相一致,进一步暗示穆册岩体应形成于伸展的构造背景。它们与同时代的吕梁山恶虎滩和五台山王家会花岗岩的样品一同投影于火山弧区域和后碰撞花岗岩区域(杜利林等,2018,2012;王月然等,2005;张许平和耿威,2016),反映他们之间应形成于一个相似的构造背景。吕梁山杜家沟岩体是大陆边缘裂谷环境形成的火山岩,同时由于陆块边缘洋壳俯冲作用叠加了部分岛弧岩浆的特征,即在伸展环境下形成;五台山王家会花岗岩具有后碰撞花岗岩的特征,形成于拉张(王月然等,2005)或后造山环境(许平和耿威,2016),也形成于伸展环境。上述研究进一步暗示,穆册岩体形成于伸展的构造背景。

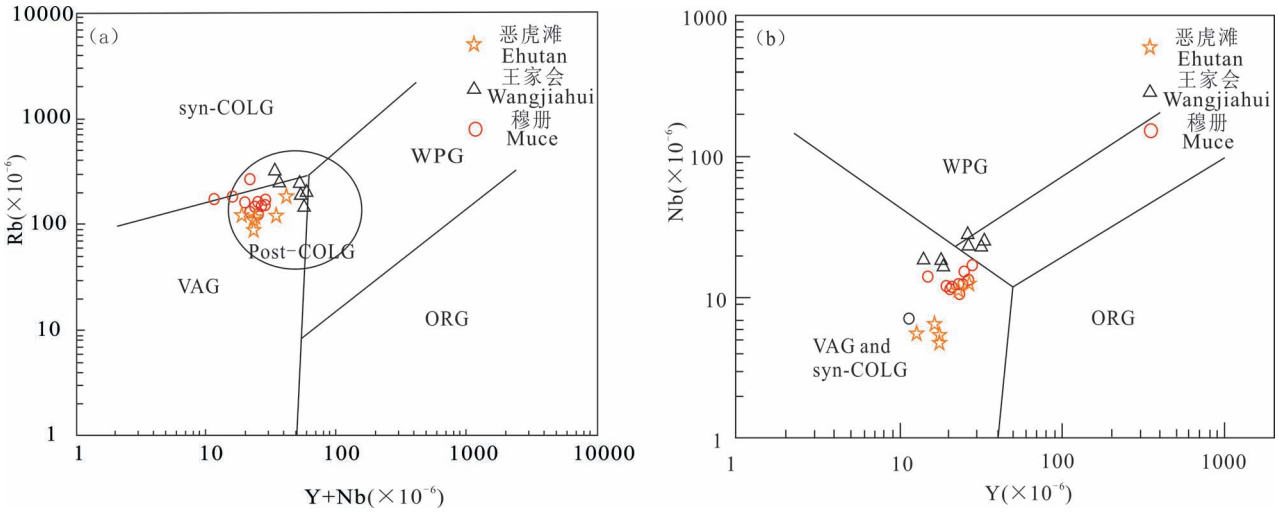


图 10 熊耳山地区穆册岩体的构造环境 Rb—Y+Nb(a)和 Nb—Y(b)判别图(据 Pearce, 1984)

Fig. 10 Tectonic environment of the Muce monzonite Rb—Y+Nb(a) and Nb—Y(b) discriminant diagrams in Xiong'er Mountains (by Pearce, 1984)

syn-COLG—碰撞同期花岗岩;Post-COLG—碰撞后期花岗岩;VAG—火山弧花岗岩;WPG—板内花岗岩;ORG—洋脊花岗岩

syn-COLG—collision granite; Post-COLG—late collision granite; VAG—volcanic arc granite; WPG—in-plate granite; ORG—ocean granite

此外,在蚌埠、五台、吕梁、太华和辽吉等地区分布的同一时代花岗岩和片麻岩均是在伸展的构造体制下形成的(杨德彬等,2009;Wilde, 2005; 王月然, 2005;张许平, 2016; Du Lilin et al., 2010, 2012, 2015; 赵瑞福,2011;路孝平,2004a,2004b),其可能与华北克拉通地区 2.2~2.1 Ga 的裂谷活动有关(Du Lilin et al., 2010, 2012;杜利林等,2009,2011, 2012,2018)。而在中部造山带,吕梁山地区的野鸡山群和吕梁群的基性火山岩和花岗岩具有岛弧岩浆岩特征,有人认为是西边陆块向东边陆块俯冲在华北克拉通内部的中间带形成部分岩浆弧(刘树文, 2009;Zhao Guochun et al., 2008);耿元生等(2000, 2003)认为吕梁群周峪组和野鸡山群白龙山组基性火山岩具有陆内或大陆边缘裂谷型火山岩特征,于津海等(1998)认为杜家口组酸性火山岩形成双峰式岩浆组合;Du Lilin 等(2017)发现五台山地区花岗岩和富铁玄武岩具有陆内裂谷型环境,以及古元古代滹沱群的沉积组合也指示其形成于裂谷环境。杜利林等(2011,2012,2018)认为吕梁山地区可能受岛弧和裂谷两种体制制约。以上研究进一步暗示,穆册岩体形成于裂谷环境。

根据本文研究,穆册二长岩高 K 和 Na、低 Mg、准铝质—过铝质和高钾钙碱性系列等特征,还富集大离子亲石元素(LILEs)Ba、Sr 和 Pb 和轻稀土元素(LREEs)La、Ce 和 Sm,亏损高场强元素(HFSEs)Th、Zr 和 Ti,其具有火山岛弧或后碰撞岩浆岩特征。根据已有的资料,本文也认为,中部造山带 2.2~2.1 Ga 的岩浆岩与裂谷有关(杜利林等, 2009, 2011, 2018;Du Lilin et al., 2010, 2012; 杨崇辉等,2011b; 赵瑞幅等, 2011; 颉颃强等, 2013)。Zhao Guochun 等(2008)认为古元古代华北克拉通内部以西向东俯冲古大洋;Zhai and Santosh(2011)指出华北克拉通在 2.3~2.0 Ga 之间经历了陆内裂谷或陆间残留小洋盆的进一步扩展。而穆册岩体可能不同程度的受到这两种模式的影响,其岩体既具有火山岛弧又具有后碰撞岩浆岩特征。综上所述,华北克拉通中部造山带 2.2~2.1 Ga 处于陆内裂谷伸展阶段,而熊耳地区可能处于华北克拉通古陆块的南缘,其 2.2~2.1 Ga 的岩浆岩可能经历了裂谷和岛弧两种体制的影响。

5　结论

(1) 穆册二长岩形成的时间是二长岩的 LA-ICP-MS 锆石 U-Pb 定年为 2172±8 Ma(MSWD = 0.58, n = 17)和 2186±7 Ma(MSWD = 0.60, n = 19),二长花岗岩年龄为 2174±8 Ma(MSWD = 0.45, n = 19),说明穆册二长岩体形成于古元古代。

(2) 穆册二长岩体为一套低镁-高碱的 A 型花岗岩,具有岛弧或后碰撞岩浆特征,其具有这样复杂的岩浆地球化学特征,可能与其在中部造山带上的

位置有关,中部造山带 2.2~2.1 Ga 处于陆内裂谷阶段,而熊耳山地区处于中部造山带的南缘,其 2.2~2.1 Ga 的岩浆岩可能经历了裂谷和岛弧两种体制的影响。

注 释 / Note

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Geochemical characteristics, U-Pb ages and tectonic setting of the Muce Monzonite in Xiong'er Mountains

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Objectives: The Muce monzonite in Xiong'er Mountains is distributed in the southern margin of the North China Craton. It is of great geological significance to study the tectonic evolution of the southern margin of the North China Craton. Combined with petrological study, geochemical characteristics of the monzonite and the LA-ICP-MS zircon U-Pb age, we briefly discuss the formation age, origin and tectonic background of the monzonite.

Methods: Based on the field work, through the microscope observation, the whole rock chemical analysis and LA-IPC-MS U-Pb zircon dating of Muce monzonitic feldspar and monzogranite were carried out.

Results: The geochemical analysis of the Muce monzonite shows that that belongs to type A genetic type and is formed in the rifting environment under the extensional structure. The monzonite is riched in large ion lithophile elements (LILEs) Rb, Ba, Sr, Pb and light rare earth elements (LREEs). The monzonite is deficient in high field strength elements (HFSEs) Th, Nb, Zr, and strong depletion of Ti and Ta, which show the characteristics of typical island arc magmatic rocks. LA-ICP-MS U-Pb zircon dating of the monzonite samples yield the ages of 2172 ±8 Ma (MSWD=0.58, n=17) and 2186±7 Ma(MSWD=0.60, n=19). Respectivesly, monzogranite sample gets a LA-ICP-MS U-Pb zircon age of 2174±8 Ma(MSWD=0.45, n=19), indicating the Muce monzonite was formed in Paleoproterozoic.

Conclusions: Combined with the previous study, it is considered that the Muce monzonite was formed in the Paleoproterozoic and may have experienced the influence of rifting and island arc.

Keywords: Muce monzonite; Paleoproterozoic; island-arc magma; Xiong'er Mountains; North China craton

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