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浙西大铜坑斑岩型钨钼矿床成岩成矿年代学

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摘要:浙西淳安大铜坑斑岩型钨钼矿位于扬子陆块东南缘,矿体主要产于花岗岩体与南华系休宁组变质砂岩内外接触带上,是揭示浙皖赣相邻区域成矿规律的重要组成.成矿花岗岩为高钾钙碱性系列准过铝质I型花岗岩,岩石富集Rb、K,亏损Sr、Ba等大离子亲石元素,富集Th、U,相对亏损Nb、Ta、Ti等高场强元素,稀土元素含量较低(ΣREE$=106.2\times10^{-6}\sim211.5\times10^{-6}$),轻重稀土分异明显($\Sigma$LREE/$\Sigma$HREE$=6.4\sim12.2$),中等的Eu负异常($\delta$Eu$=0.50\sim0.63$),具有类似岛弧岩浆岩的特征.锆石SHRIMP U-Pb定年结果表明花岗岩侵位时间为148.3±1.9 Ma,辉钼矿Re-Os等时线年龄显示成矿作用发生于146.47±0.81 Ma,成岩年龄与成矿时代高度耦合,进一步证实钨钼成矿作用与花岗岩体的形成有着密切的成因联系,二者在时间上是一个连续的过程,形成于晚侏罗世古太平洋板块俯冲挤压的构造环境,也是华南地区中生代第2次大规模钨钼成矿作用延续到浙西的响应.

关键词:锆石SHRIMP U-Pb年龄;辉钼矿Re-Os年龄;地球化学;年代学;大铜坑钨钼矿;花岗岩;浙西.
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Chronology of Petrogenesis and Mineralization of Datongkeng Porphyry W-Mo Deposit in West Zhejiang

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Abstract: As an important component to reveal the metallogenic regularity in the Zhejiang-Anhui-Jiangxi border region, the Datongkeng porphyry W-Mo deposit in Chun'an County is located in the southeastern margin of the Yangtze block, and the W-Mo ore bodies are mainly located in the internal or external contact zones between granite and sandstone of Xiuning Formation. The Datongkeng granite is characterized by quasi-aluminous, showing the nature of I-type granite and high-K calc-alkalic series rock. The granite is rich in Rb, K, Th, U, and relatively depleted in Sr, Ba, Nb, Ta, Ti. The total REE contents are relatively low (ΣREE$=106.2\times10^{-6}-211.5\times10^{-6}$), and the rocks show obvious LREE and HREE fractionation (ΣLREE/ΣHREE$=6.4-12.2$), moderately negative Eu anomalies (δEu$=0.50-0.63$), suggesting that these rocks have the characters of typical volcanic arc rocks. The SHRIMP U-Pb zircon age of 148.3±1.9 Ma for granite is close to the Re-Os isochron age of 146.47±0.81 Ma for five molybdenite samples from the Datongkeng W-Mo deposit, indicating magmatism and mineralization are a continuous process, which took place in the compression tectonic environment related to the subduction of pacific plate at

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Late Jurassic, and corresponds to the second large-scale W-Mo mineralization in South China.

Key words: SHRIMP U-Pb dating of zircon; Re-Os age of molybdenite; geochemistry; chronology; Datongkeng W-Mo deposit; granite; West Zhejiang.

随着钦杭成矿带北西缘皖南东源地区钨矿、浙西开化桐村地区铜钼矿、淳安银山地区银多金属矿和安吉港口地区钨钼多金属矿相继取得找矿突破(秦燕等,2010;何国锦等,2011;邱骏挺等,2011;周翔等,2011;胡逸洲等,2013;唐燕文等,2013),浙皖赣相邻地区再掀一股找矿热潮.

众多地质专家、学者相继在浙西地区开展成矿条件和成矿模式研究工作,认为区内成矿作用与燕山期岩浆热液活动相关性较强,如银山银多金属矿、桐村铜钼矿、港口多金属矿、闲林钼铁矿等矿床均与燕山期花岗闪长岩、花岗岩关系密切,并与皖赣相邻区矿床进行对比,以期评价该区找矿潜力(赵海玲等,2007;谢玉玲等,2012a,2012b;张世铭等,2013;唐增才等,2014,2016;张建芳等,2015).

近年,笔者在淳安—开化地区开展矿产远景调查和中生代侵入岩与成矿作用关系工作时发现,淳安大铜坑地区3个斑状花岗岩株均黄铁矿化、黄铜矿化、辉钼矿化、白钨矿化等矿化,外围接触带云英岩蚀变带中见白钨矿化和辉钼矿化,围岩具强烈的矽卡岩化、透闪石化、角岩化、硅化和黄铁矿化蚀变,并套合有较好的磁法和化探异常,经钻孔验证,显示良好的钨钼找矿前景.笔者选择锆石SHRIMP U-Pb和辉钼矿Re-Os同位素测年法对大铜坑花岗岩体成岩和钨钼成矿作用时代进行精确定年,以指导后续找矿工作.

1　区域地质背景和矿床地质特征

研究区位于扬子陆块东南缘,其南东侧以江山—绍兴结合带(钦杭结合带北东段)为界与华夏地

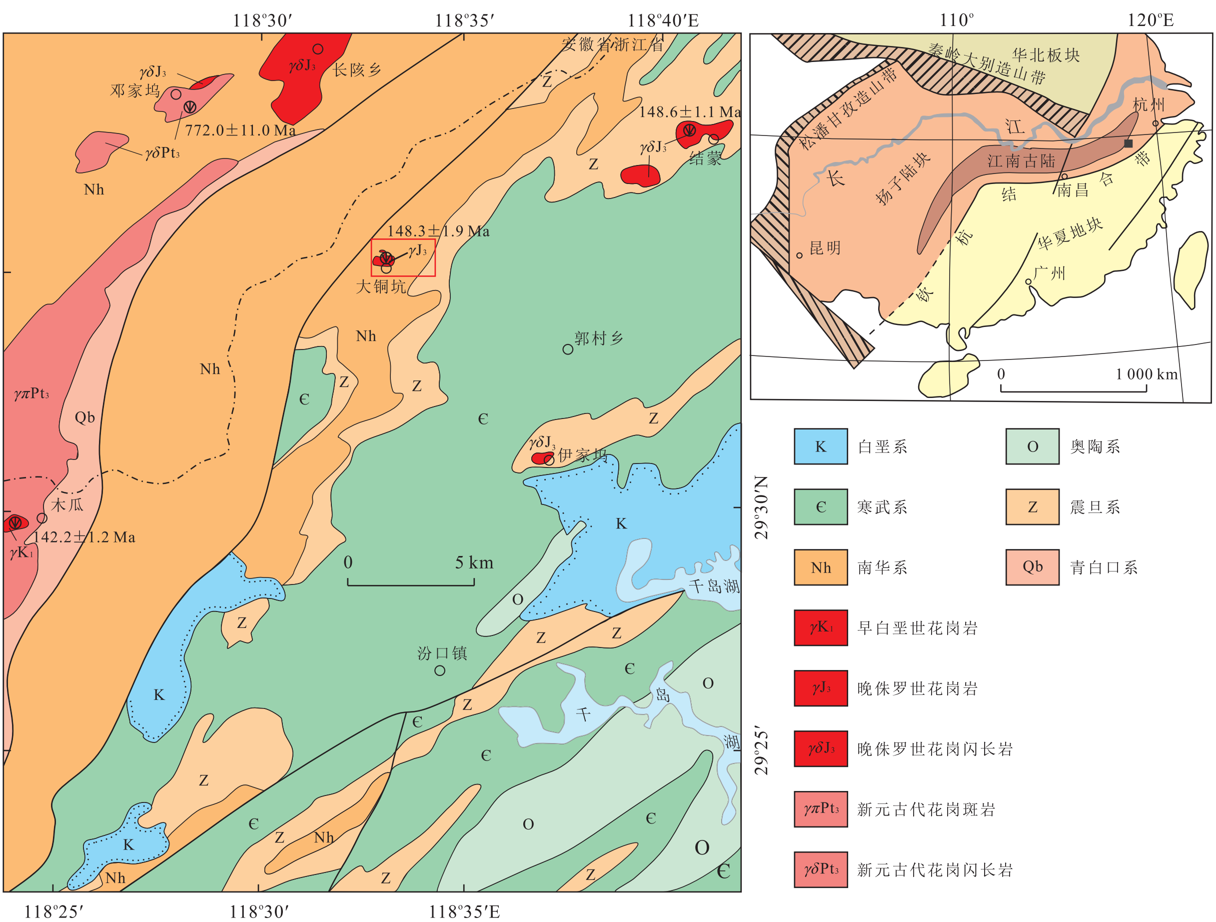

图1　研究区地质略图

Fig.1　Geological map of the study region

块相接，北西侧以下庄一石柱一蔚岭逆冲推覆构造带（浙皖赣断裂带）与江南古陆相邻（图 1）.

1.1 区域地质背景

区内出露南华系、震旦系、寒武系、奥陶系和白垩系.加里东期，构造主体表现为抬升；印支期，伴随扬子陆块向华北板块俯冲碰撞，形成了一系列北东向展布的逆冲构造和紧密褶皱体系.燕山期，受滨太平洋构造体系域的影响，岩浆活动强烈，于晚侏罗世一早白垩世，形成了以花岗闪长岩和花岗岩为主的一系列中酸性一酸性侵入体.

1.2 矿床地质特征

大铜坑钨钼矿区地处淳安县城以西 27 km 处.矿区内复式紧密背斜特征明显，呈 NE50°方向展布，核部为休宁组砂岩，两翼主要由南沱组泥岩和蓝田组碳酸盐岩构成.区内 NE、NW 向断层较为发育，受断裂构造和褶皱隆起的制约，大铜坑岩体呈 3 个小岩株侵入于南华系休宁组砂岩，地表累计出露面积 0.30 km²，后期有基性岩墙贯入（图 2a，图 3a）.

大铜坑岩体和围岩具有强烈的蚀变，岩体钾化、绢云母化、硅化蚀变强烈，外接触带围岩普遍角岩化、绿帘石化、绿泥石化、硅化、黄铁矿化.蚀变表现出明显的分带性，自内向外依次为钾化带、云英岩化带和青磐岩化带.同样，区内矿化也显示分带性特征，自岩体向外围依次为辉钼矿化、白钨矿化、黄铜矿化、黄铁矿化→黄铜矿化、黄铁矿化→方铅矿化、闪锌矿化、黄铁矿化（图 2b）.

大铜坑钨钼矿主要产于大铜坑岩体及其外接触带中（图 2b），辉钼矿、白钨矿多呈细脉状产出，局部富集于石英细脉中（图 3b）.含矿石英脉单脉宽度 0.3～3.0 cm.矿物成分主要有辉钼矿、白钨矿、黄铜

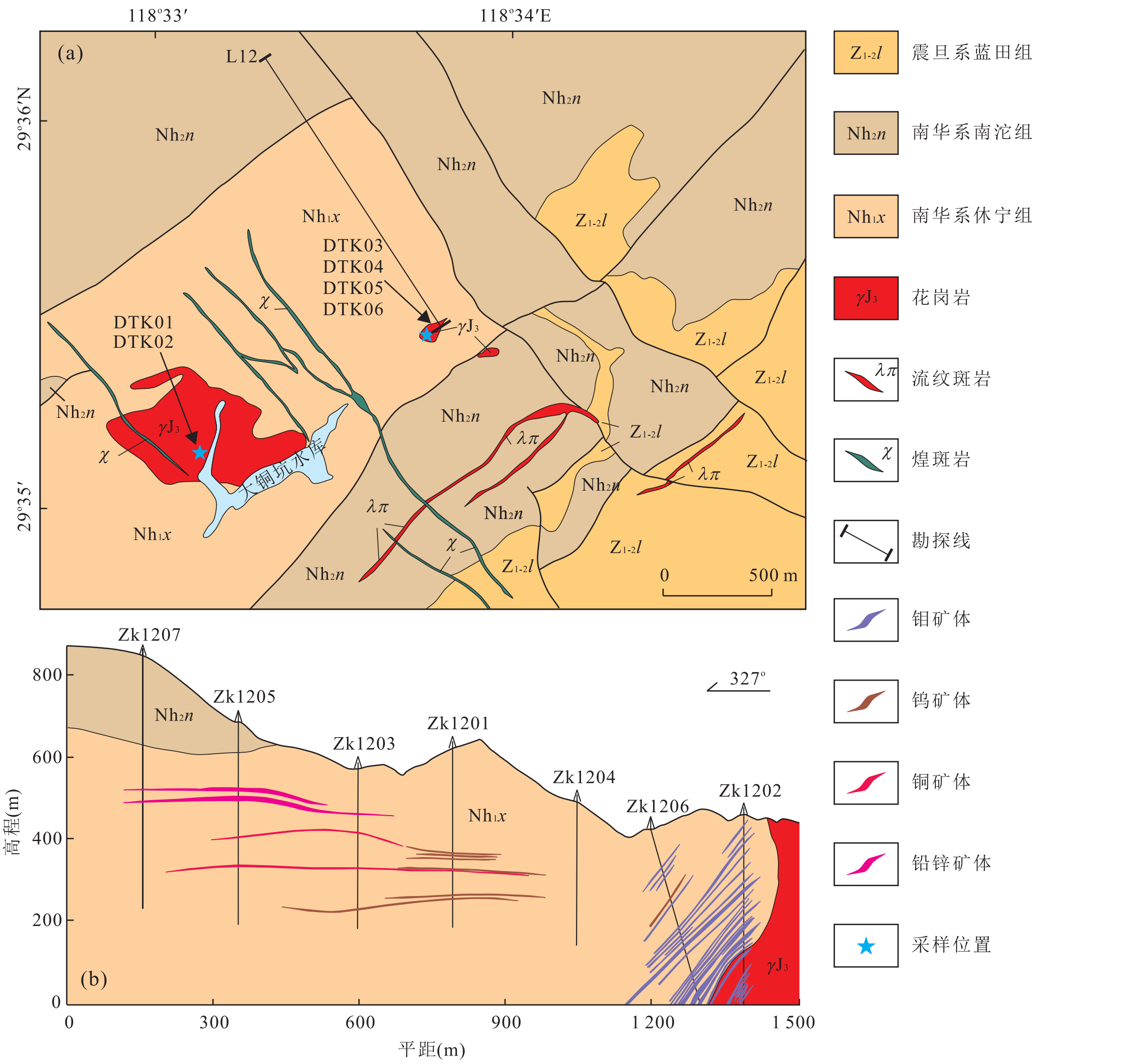

图 2　大铜坑钨钼矿区地质图（a）和 L12 勘探线剖面（b）

Fig.2　Geological map of the Datongkeng tungsten-molybdenum deposit (a) and a profile from No.12 exploration line (b)

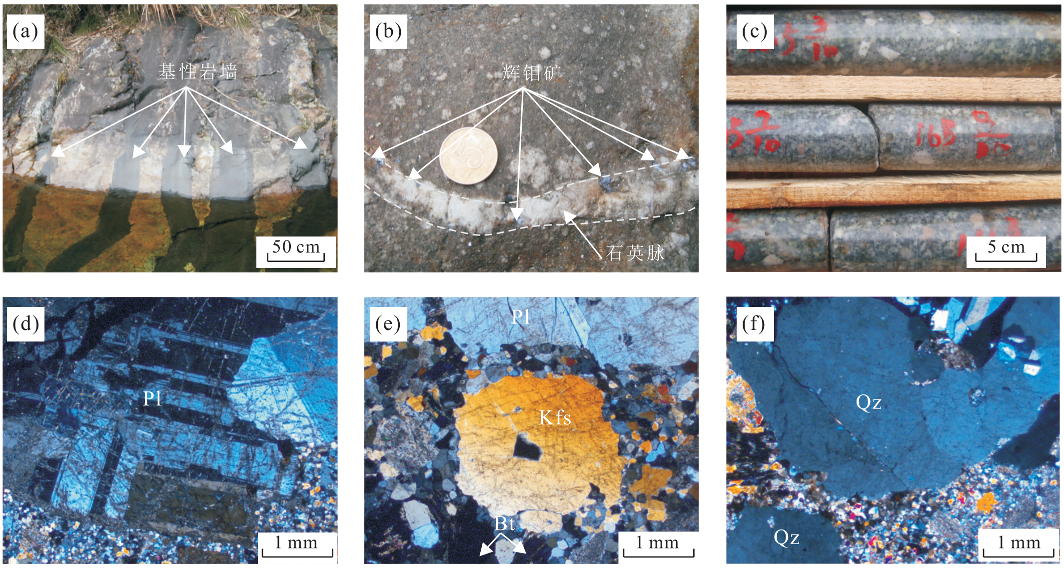

图 3　大铜坑花岗岩地质特征和镜下显微照片

Fig.3　Geological feature and photomicrography of the Datongkeng granite

a.基性岩墙群；b.含辉钼矿石英脉体；c.花岗岩岩心；d.斜长石斑晶，正交偏光；e.钾长石斑晶，正交偏光；f.石英斑晶，正交偏光.Bt.黑云母；Kfs.钾长石；Pl.斜长石；Qz.石英

矿、石英、绢云母、绿泥石等.矿石中 WO_3 品位一般在 0.01%～0.30%，大部分在 0.10%左右，Mo 品位一般在 0.01%～0.10%，大部分在 0.03%～0.04%.

大铜坑岩体岩性为浅灰色细粒斑状花岗岩（图 3c），花岗结构，似斑状.斑晶含量 35%～40%，成分以（蚀变）斜长石、石英为主，次为黑云母、钾长石（图 3d～3f）；斜长石斑晶大小悬殊，一般为 0.3 cm×0.5 cm～0.8 cm×1.5 cm，呈板状；石英斑晶大小为 0.1 cm×0.2 cm～0.8 cm×1.0 cm，呈粒状.基质占 60%～65%，为全晶质斜长石、石英、钾长石组成，副矿物有磷灰石、锆石、榍石、萤石等.野外可见斜长石斑晶最大者可达 8 cm×2 cm～10 cm×3 cm.

2　样品采集与测试方法

本次用于全岩主量、微量元素测试的大铜坑花岗岩样品采自岩体地表新鲜露头和不同钻孔深部岩心，用于挑选锆石单矿物进行 SHRIMP U-Pb 定年的样品采自地表新鲜露头，用于辉钼矿 Re-Os 同位素测试的样品采自不同钻孔深部石英脉型辉钼矿脉中.

全岩主量、微量元素在中国地质大学（武汉）地质过程与矿产资源国家重点实验室完成.主量元素含量利用日立 180-70 原子吸收光谱仪、UV-754 紫外可见分光光度计测试；微量元素含量利用 Agilent 7500a ICP-MS 分析，具体的样品处理过程、分析精密度和准确度参见 Govindaraju（1994）和 Liu *et al*.（2008）.

锆石分选在廊坊市科大岩石矿物分选技术服务有限公司完成.测试之前，在北京离子探针中心按常规方法分选出晶形完好、无裂纹和包体少的锆石与标准锆石样品（91500）一起制靶，并对待测样品进行透射光、反射光和阴极发光分析，选定本次所测锆石微区分析靶位.

锆石 SHRIMP U-Pb 年龄分析采用宋彪等（2002）和简平等（2003）所报道的实验流程.锆石微区原位 U-Pb 同位素定年在北京离子探针中心的 SHRIMPⅡ上完成，对测定结果用 SHRIMP 定年标准物质对 U、Th 和 Pb 含量及年龄作了校正.普通铅根据实测 ^{204}Pb 校正.

辉钼矿样品分析在国家地质实验测试中心 Re-Os 同位素实验室进行，采用 Carius 管封闭溶样分解样品（Shirey and Walker，1995）.测试仪器为电感耦合等离子体质谱仪 TJA X-Series ICP-MS.样品具体测试过程及要求见杜安道等（1994）、Shirey and Walker（1995）和 Du *et al*.（2004）.Re-Os 模式年龄按下式计算：

$$t=\frac{1}{\lambda}\ln\left(\frac{^{187}Os}{^{187}Re}+1\right),$$

其中 λ（^{187}Re 衰变常数）$=1.666\times10^{-11}\ a^{-1}$（Smolar *et al*.，1996）.

3　测试结果

3.1　地球化学分析

浙西大铜坑花岗岩岩石化学成分见表 1.

大铜坑花岗岩 SiO_2 含量为 67.33%～70.74%，平均为 68.65%；Al_2O_3 含量为 13.01%～14.84%，平均为 14.15%；K_2O＋Na_2O 含量为 6.45%～8.11%，平均为7.17%；K_2O为3.45%～5.84%，

表 1　大铜坑花岗岩主量元素(%)和微量元素(10^{-6})组成

Table 1　Major elements (%) and trace elements (10^{-6}) of the Datongkeng granite

样品	DTK01	DTK02	DTK03	DTK04	DTK05	DTK06	DTK07	DTK08	DTK09	DTK10	DTK11
SiO_2	68.78	69.16	68.68	67.28	68.47	70.74	67.77	67.33	69.55	68.97	68.38
TiO_2	0.43	0.45	0.40	0.44	0.34	0.39	0.44	0.40	0.43	0.40	0.44
Al_2O_3	14.80	14.27	13.78	14.80	14.68	13.01	13.64	13.64	14.84	14.25	13.97
TFe_2O_3	3.08	3.22	2.56	2.91	3.58	4.04	5.40	4.62	3.01	4.81	6.43
MnO	0.04	0.04	0.04	0.03	0.03	0.03	0.04	0.07	0.09	0.06	0.08
MgO	0.94	0.97	0.86	0.94	0.98	0.78	0.89	0.76	0.82	0.79	0.87
CaO	2.73	2.40	2.45	2.41	2.27	1.3	2.39	3.12	2.33	2.16	2.40
Na_2O	3.33	3.06	2.93	3.31	2.78	2.27	2.63	3.00	3.33	2.95	3.00
K_2O	3.82	4.34	4.43	4.30	4.5	5.84	3.89	3.84	3.91	3.91	3.45
P_2O_5	0.15	0.16	0.14	0.15	0.18	0.17	0.18	0.12	0.13	0.12	0.13
LOI	1.58	1.70	3.28	2.80	1.72	0.98	2.32	2.7	1.1	1.23	0.38
Total	99.68	99.77	99.55	99.37	99.53	99.55	99.59	99.59	99.54	99.66	99.53
A/CNK	1.02	1.01	0.98	1.02	1.08	1.05	1.06	0.92	1.06	1.10	1.07
K_2O/ Na_2O	1.15	1.42	1.51	1.30	1.62	2.57	1.48	1.28	1.17	1.33	1.15
σ	1.98	2.09	2.11	2.39	2.08	2.37	1.71	1.93	1.97	1.82	1.64
$Mg^{\#}$	44	43	46	45	41	33	30	30	41	29	26
A.R	2.23	2.16	2.13	2.25	1.98	3.62	1.98	2.12	2.27	2.12	2.16
DI	79.70	81.18	82.18	81.15	79.60	84.96	76.68	76.72	80.72	78.62	75.26
Ba	386	373	517	383	324	357	347	322	314	410	242
Rb	195	243	252	257	256	241	225	224	234	203	143
Sr	309	242	177	252	198	201	182	190	197	182	182
Y	22.6	24.5	20.0	24.7	24.2	23.9	22.4	21.8	23.9	22.3	21.5
Zr	131	141	128	154	121	118	106	109	115	108	111
Nb	15.4	15.6	13.9	18.5	18.9	21.2	19.4	17.9	19.7	18.3	19
Th	21.5	18.5	19.8	22.4	19.6	18.7	16.4	18.6	19	20.1	17.2
Ga	21.8	20.1	17.6	22.7	18.6	19.4	17.4	17.6	18.7	17.8	18.9
Hf	3.95	4.30	3.90	4.67	3.55	3.69	3.26	3.38	3.64	3.47	3.41
Ta	1.48	1.58	1.40	1.76	2.08	2.21	1.91	1.95	2.19	2.07	1.94
U	9.51	12.2	11.5	9.86	12.8	11.9	9.31	12.3	13	9.9	9.2
La	37.3	26.5	21.9	38.6	38	39	25.6	21.6	19.9	27.8	21.3
Ce	72.4	54.6	43.6	76.5	93	86	51.5	44.2	43.2	56.3	44
Pr	7.91	6.35	5.03	8.71	8.60	10.10	6.00	5.04	4.87	6.38	5.01
Nd	29.1	24.6	20.0	32.2	35	43	22.7	19	18.8	23.6	19
Sm	5.70	5.13	4.08	6.45	6.4	8.6	4.84	4.15	4.36	4.82	4.15
Eu	1.01	0.94	0.80	1.03	1.04	1.35	0.86	0.71	0.78	0.81	0.76
Gd	4.80	4.64	3.72	5.29	5.50	7.80	4.44	3.9	4.2	4.3	3.91
Tb	0.70	0.71	0.57	0.78	0.66	1.15	0.71	0.64	0.7	0.69	0.64
Dy	4.01	4.06	3.34	4.30	3.60	6.20	3.91	3.59	3.96	3.72	3.57
Ho	0.71	0.74	0.61	0.76	0.66	1.14	0.73	0.68	0.75	0.69	0.67
Er	1.94	2.11	1.75	2.14	2.00	3.30	2.02	1.92	2.11	1.97	1.9
Tm	0.30	0.31	0.27	0.31	0.27	0.45	—	—	—	—	—
Yb	1.99	2.24	1.85	2.17	1.9	3.00	2.02	2.04	2.25	2.04	1.98
Lu	0.31	0.34	0.28	0.32	0.28	0.42	0.31	0.31	0.33	0.3	0.3
ΣREE	168.18	133.27	107.80	179.56	196.91	211.51	125.64	107.78	106.21	133.42	107.19
LREE/HREE	10.4	7.8	7.7	10.2	12.2	8.0	7.9	7.2	6.4	8.7	7.3
Rb/Sr	0.63	1.00	1.42	1.02	1.29	1.20	1.24	1.18	1.19	1.12	0.79
Sr/Y	13.67	9.88	8.85	9.20	8.18	8.41	8.13	8.72	8.24	8.16	8.47
La_N/Yb_N	13.4	8.5	8.5	12.8	14.3	9.3	9.1	7.6	6.4	9.8	7.7
La_N/Sm_N	4.2	3.3	3.5	3.9	3.8	2.9	3.4	3.4	3.0	3.7	3.3
Gd_N/Yb_N	2.0	1.7	1.7	2.0	2.4	2.2	1.8	1.6	1.5	1.7	1.6
δEu	0.59	0.59	0.63	0.54	0.54	0.50	0.57	0.54	0.56	0.55	0.58
T_{Zr}(℃)	809	816	804	822	805	803	792	784	801	796	797

注：A/CNK＝Al_2O_3/(CaO＋Na_2O＋K_2O)mol；$Mg^{\#}$＝(MgO/40.31)/(MgO/40.31＋0.7×TFe_2O_3/71.85)；DTK01～DTK06 数据为本次实测，DTK07～DTK11 数据引自 Li *et al*.(2013).

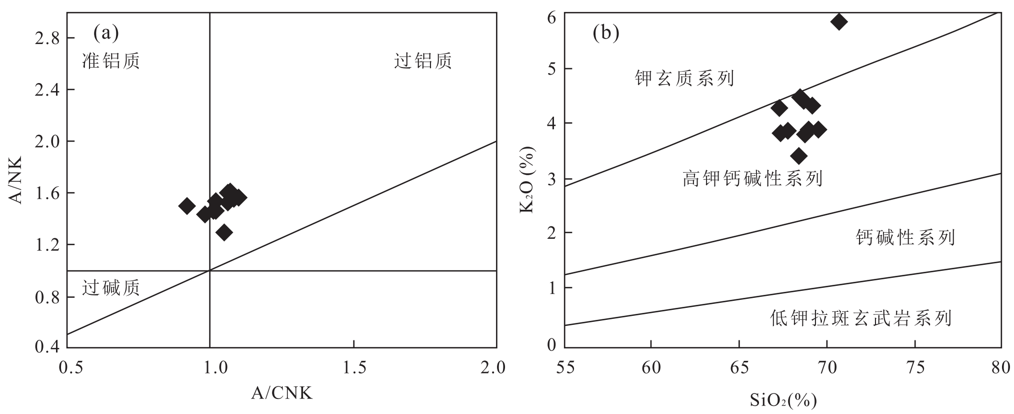

图4 大铜坑花岗岩A/NK-A/CNK(a)及K_2O-SiO_2(b)图解

Fig.4 A/NK vs. A/CNK diagram (a) and K_2O vs. SiO_2 diagram (b) for the Datongkeng granite

图a据Maniar and Piccoli(1989);图b据Rickwood(1989)

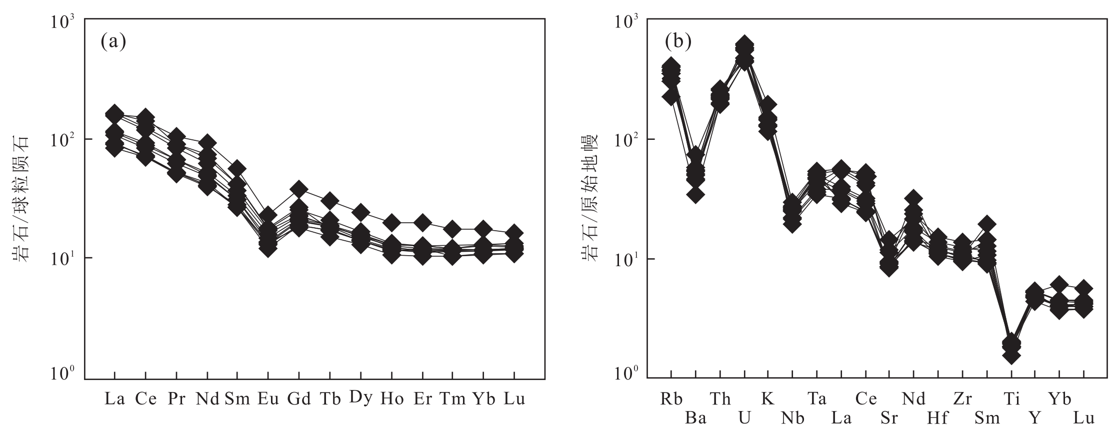

图5 大铜坑花岗岩稀土元素球粒陨石标准化曲线(a)和微量元素蛛网图(b)

Fig.5 Chondrite-normalized REE patterns (a) and trace element spider diagram (b) for the Datongkeng granite

标准值据Sun and McDonough(1989)

K_2O/Na_2O比值为1.15～2.57,属高钾钙碱性系列(图4b);里特曼指数(σ)为1.64～2.39,赖特碱度率($A.R$)为1.98～3.62,镁指数($Mg^{\#}$)为26～46,铝饱和指数(A/CNK)为0.92～1.10,为准铝质特征(图4a);岩石分异指数(DI)为75.26～84.96.

在稀土元素组成(表1)方面,大铜坑花岗岩$\Sigma REE = 106.21\times10^{-6} \sim 211.51\times10^{-6}$,平均值为$143.41\times10^{-6}$;轻重稀土分异明显,LREE/HREE=6.40～12.20,平均值为8.50,$La_N/Yb_N=6.3 \sim 14.3$,平均值为9.8,δEu为0.50～0.63,显示弱负铕异常,球粒陨石标准化图解中稀土配分曲线具有向右弱倾的特征(图5a).

在微量元素组成(表1)方面,大铜坑花岗岩Ba含量($242\times10^{-6} \sim 517\times10^{-6}$),Rb含量($143\times10^{-6} \sim 257\times10^{-6}$),Sr含量($177\times10^{-6} \sim 309\times10^{-6}$),Sr/Y比值(8.13～13.67)偏低,Zr/Hf比值为31.1～34.1,Nb/Ta比值为8.8～10.5.在蛛网图(图5b)上显示富集Rb、K和亏损Sr、Ba等大离子亲石元素(LILE),富集Th、U,相对亏损Nb、Ta、Ti等高场强元素(HFSE),类似岛弧岩浆岩的特征.

3.2 锆石U-Pb定年

在阴极发光(CL)图像中(图6),锆石基本呈半透明短柱状,自形－半自形晶,长为150～200 μm,长宽比约为2∶1.锆石晶体柱面平直,且内部均显示相对较清晰的韵律环带结构,因此所测锆石是典型的岩浆结晶锆石(吴元保和郑永飞,2004).

从锆石外部形态及内部结构来看,所测锆石大致可分为3类:第1类锆石(CA1-10.1、CA1-12.1、CA1-15.1、CA1-20.1～CA1-22.1)发育生长边结构,内部环带清晰,与外围生长边环带不协调,显然遭受了后期构造热事件;第2类锆石(CA1-1.1～CA1-2.1、CA1-16.1～CA1-19.1、CA1-23.1～CA1-28.1)

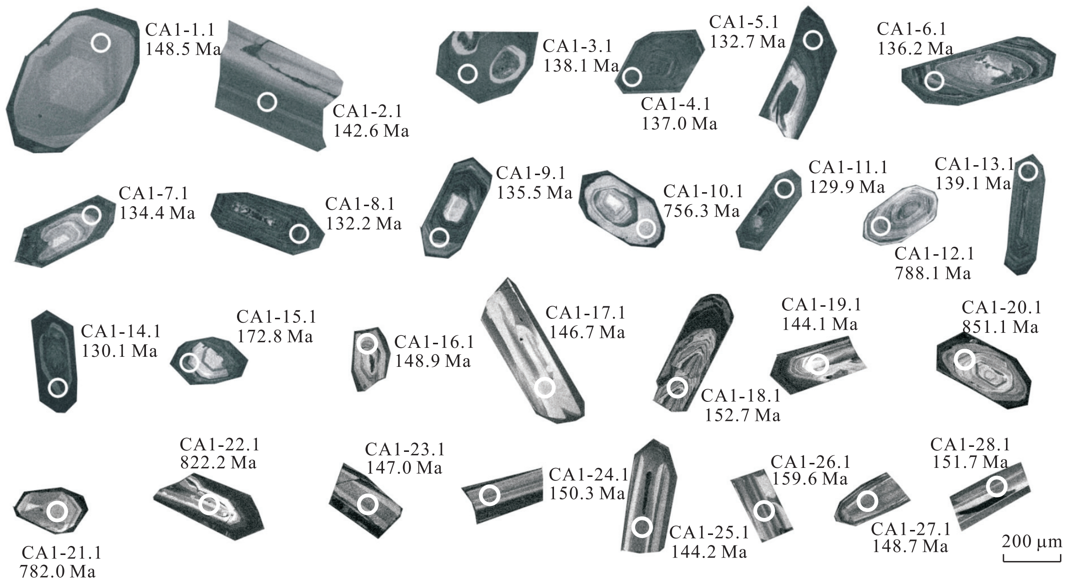

图 6　大铜坑花岗岩锆石的阴极发光图像及 SHRIMP 分析点位和 ^{206}Pb-^{238}U 视年龄

Fig.6　CL photomicrographs, meansured points and age data ($^{206}Pb/^{238}U$) of zircons from the Datongkeng granite

表 2　大铜坑花岗岩体中锆石的 SHRIMP U-Pb 年龄测定结果

Table 2　SHRIMP U-Pb dating result of zircons from the Datongkeng granite

点号	$^{206}Pb_c$ (%)	U (10^{-6})	Th (10^{-6})	$^{232}Th/^{238}U$	$^{206}Pb*$ (10^{-6})	年龄(Ma)	$^{206}Pb/^{238}U$	±1σ (%)	$^{207}Pb*/^{206}Pb*$	±1σ (%)	$^{207}Pb*/^{235}U$	±1σ (%)	$^{206}Pb*/^{238}U$
CA1-1.1	1.96	225	222	1.02	4.6	148.5	3.9	0.046 3	7.9	0.153 0	8.4	0.023 3	2.7
CA1-2.1	0.73	693	814	1.21	13.4	142.6	3.4	0.056 3	3.0	0.146 8	3.9	0.022 4	2.4
CA1-3.1	0.31	1 750	300	0.18	32.6	138.1	3.2	0.046 5	2.3	0.143 1	3.3	0.021 6	2.3
CA1-4.1	0.47	1 712	288	0.17	31.8	137.0	3.2	0.048 6	2.2	0.139 3	3.2	0.021 5	2.3
CA1-5.1	0.12	2 178	361	0.17	39.0	132.7	4.0	0.047 4	1.9	0.137 5	3.6	0.020 8	3.1
CA1-6.1	0.44	1 119	146	0.13	20.6	136.2	3.2	0.048 0	3.0	0.141 4	3.8	0.021 4	2.4
CA1-7.1	0.20	1 815	361	0.21	32.9	134.4	3.1	0.046 9	2.0	0.140 4	3.1	0.021 1	2.3
CA1-8.1	0.26	2 145	424	0.20	38.3	132.2	3.0	0.047 7	1.9	0.136 5	3.0	0.020 7	2.3
CA1-9.1	0.07	1 724	362	0.22	31.5	135.5	3.5	0.047 8	2.0	0.140 8	3.3	0.021 2	2.6
CA1-10.1	0.46	158	150	0.98	17.0	756.3	17.7	0.064 8	2.6	1.126 0	3.6	0.124 5	2.5
CA1-11.1	0.43	1 938	377	0.20	34.0	129.9	3.0	0.049 8	2.3	0.137 9	3.2	0.020 4	2.3
CA1-12.1	0.22	447	184	0.43	50.0	788.1	17.5	0.069 2	1.4	1.185 0	2.8	0.130 0	2.4
CA1-13.1	0.53	1 057	345	0.34	19.9	139.1	3.2	0.049 9	2.6	0.145 8	3.5	0.021 8	2.4
CA1-14.1	0.34	2 440	536	0.23	42.9	130.1	3.0	0.049 2	1.8	0.139 1	2.9	0.020 4	2.3
CA1-15.1	0.32	1 184	253	0.22	27.7	172.8	4.1	0.037 3	3.7	0.209 8	4.4	0.027 2	2.4
CA1-16.1	0.18	894	1 161	1.34	18.0	148.9	3.1	0.048 7	1.9	0.152 4	2.9	0.023 4	2.1
CA1-17.1	/	146	30	0.21	2.88	146.7	3.6	0.047 8	5.0	0.156 3	5.9	0.023 0	2.5
CA1-18.1	0.02	1 046	336	0.33	21.5	152.7	3.1	0.050 1	1.6	0.165 0	2.9	0.024 0	2.1
CA1-19.1	10.09	2 154	3 173	1.52	46.4	144.1	3.1	0.131 5	6.6	0.160 0	23	0.022 6	2.2
CA1-20.1	/	488	465	0.99	59.1	851.1	16	0.066 5	0.90	1.293 0	2.2	0.141 1	2.0
CA1-21.1	0.69	95	74	0.81	10.5	782.0	17	0.066 2	2.1	1.075 0	4.6	0.129 0	2.3
CA1-22.1	0.02	1 078	871	0.84	126	822.2	15	0.065 5	0.66	1.226 0	2.2	0.136 1	2.0
CA1-23.1	4.82	568	405	0.74	11.8	147.0	3.2	0.090 9	1.7	0.168 0	12	0.023 1	2.2
CA1-24.1	0.00	139	203	1.51	2.81	150.3	3.6	0.050 2	4.6	0.163 2	5.2	0.023 6	2.4
CA1-25.1	0.18	799	1 062	1.37	15.6	144.2	3.0	0.051 8	2.0	0.157 1	3.5	0.022 6	2.1
CA1-26.1	/	481	54	0.12	9.71	149.6	3.2	0.047 2	2.5	0.154 7	3.3	0.023 5	2.1
CA1-27.1	0.01	539	779	1.49	10.8	148.7	3.1	0.049 2	2.3	0.158 0	3.1	0.023 3	2.1
CA1-28.1	/	322	524	1.68	6.58	151.7	3.3	0.048 2	3.2	0.164 9	5.6	0.023 8	2.2

注:误差为 1σ;Pb_c 和 Pb* 分别代表普通铅和放射性成因铅;标准校正值的误差为 0.40%(不包括在上述误差内,但包括不同样品靶的数据比较).应用实测 ^{204}Pb 校正普通铅.

颜色较亮,环带结构清晰,少数发育生长边,但内外环带结构保持一致,指示锆石未受后期热事件影响或受热事件影响甚微,其年龄可代表岩浆结晶年龄;第3类锆石(CA1-3.1～CA1-9.1、CA1-11.1、CA1-13.1～CA1-14.1)环带与第2类锆石特征相似,但其颜色较暗,结构略显模糊,可能为热事件强烈影响所致,其年龄可能是后期构造热事件的记录.

表2列出了大铜坑花岗岩体28颗锆石的SHRIMP U-Pb年龄测定数据,第1类锆石的6个测点$^{206}Pb_c$含量范围为0.02%～0.69%,放射成因铅($^{206}Pb*$)含量变化范围为10.5×10^{-6}～126×10^{-6},U含量范围为95×10^{-6}～$1\,184\times10^{-6}$,Th含量变化范围为74×10^{-6}～871×10^{-6},$^{232}Th/^{238}U$为0.43～0.99;第2类锆石的12个测点$^{206}Pb_c$含量范围为0.01%～10.09%,放射成因铅($^{206}Pb*$)含量变化范围在2.88×10^{-6}～46.4×10^{-6},U含量范围在139×10^{-6}～$2\,154\times10^{-6}$,Th含量变化范围为30×10^{-6}～$3\,173\times10^{-6}$,$^{232}Th/^{238}U$为0.12～1.68;第3类锆石的10个测点$^{206}Pb_c$含量范围为0.07%～0.53%,放射成因铅($^{206}Pb*$)含量变化范围为19.9×10^{-6}～42.9×10^{-6},U含量范围为$1\,057\times10^{-6}$～$2\,440\times10^{-6}$,Th含量变化范围为146×10^{-6}～536×10^{-6},$^{232}Th/^{238}U$为0.13～0.34.上述数据表明,大铜坑岩体第2类和第3类锆石的Th含量变化范围不大,但后者U含量明显增高,Th/U比值明显小于岩浆锆石特征值0.4,显示其在锆石形成后,封闭体系曾因遭受后期热事件影响而一度开放.

第1类锆石5个测点(CA1-15.1除外)的年龄数据分布范围为756～851 Ma(图7a,7b),指示其可能为继承锆石,与区域新元古代构造岩浆事件相一致.第2类锆石11个测点(CA1-19.1除外)的谐和年龄为148.3±1.9 Ma(95%可信度),其MSWD=0.96,与用^{206}Pb-^{238}U比值年龄进行加权平均所得的年龄完全一致(图7c,7f),说明岩浆结晶年龄为148.3±1.9 Ma.第3类锆石10个测点的谐和年龄为134.0±2.0 Ma(95%可信度),其MSWD=1.07,一致于用加权平均^{206}Pb-^{238}U比值年龄(图7d,7e),说明岩体在134.0±2.0 Ma左右曾遭受构造－热事件影响,可能与区内晚期基性岩墙群有关.

3.3 辉钼矿Re-Os测定

大铜坑辉钼矿床5件辉钼矿样品Re-Os同位素测试结果见表3.^{187}Re的含量为6.096×10^{-6}～73.37×10^{-6},^{187}Os的含量为14.83×10^{-9}～178.80×10^{-9}.辉钼矿Re-O模式年龄为145.8±2.2～146.8±2.0 Ma,等时线年龄为146.47±0.81 Ma(图8a),与加权平均模式年龄146.32±0.88 Ma基本一致(图8b),显示数据精确可靠.

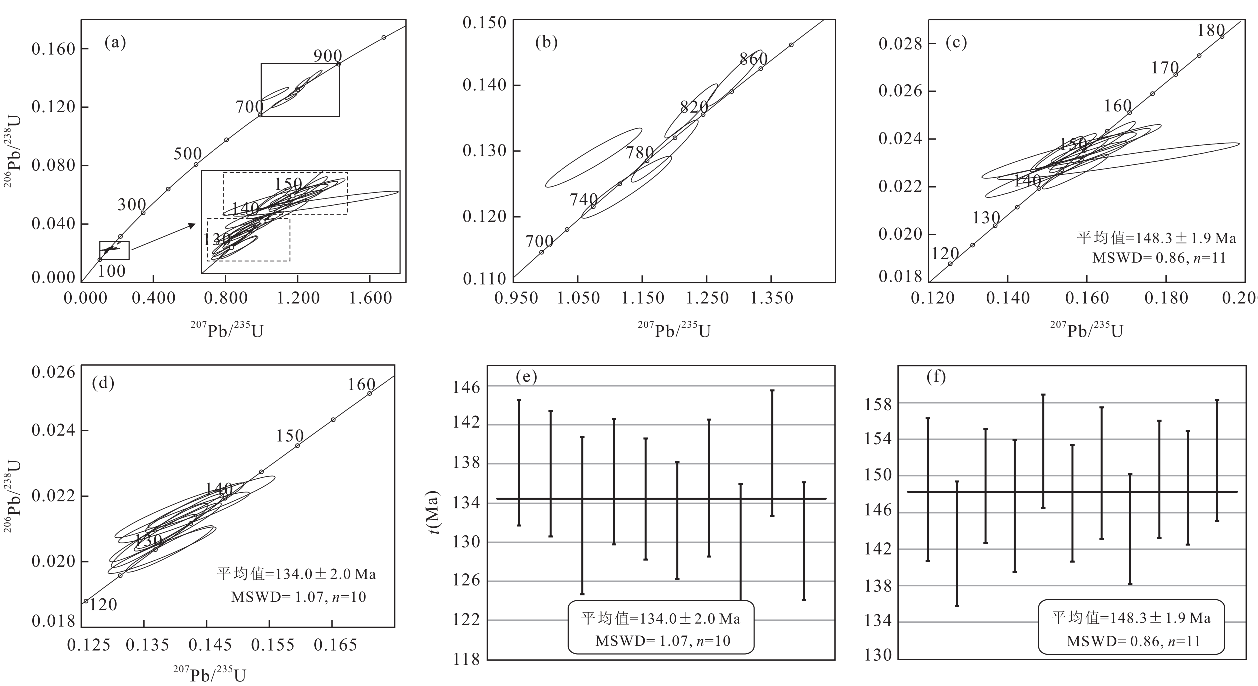

图7 大铜坑花岗岩锆石SHRIMP U-Pb年龄谐和图(a,b,c,d)和加权平均年龄(e,f)

Fig.7 SHRIMP U-Pb concordia ages (a,b,c,d) and average model ages (e,f) of zircons from the Datongkeng granite

表 3　大铜坑钨钼矿区辉钼矿 Re-Os 同位素组成

Table 3　Re-Os isotopic analyses of molybdenite from ores of the Datongkeng W-Mo deposit

编号	样号	样重(g)	Re(10^{-6})	$Os_{普}$(10^{-9})	^{187}Re(10^{-6})	^{187}Os(10^{-9})	模式年龄(Ma)
150417-4	DTK01	0.002 10	116.70±0.80	0.473 2±0.057 1	73.37±0.49	178.80±1.00	146.1±1.9
150417-5	DTK02	0.002 20	28.63±0.18	0.391 9±0.108 7	17.99±0.11	44.01±0.36	146.6±2.1
150417-6	DTK03	0.002 18	9.70±0.08	0.376 2±0.100 0	6.10±0.05	14.83±0.11	145.8±2.2
150417-7	DTK04	0.002 41	94.34±0.64	0.390 5±0.079 7	59.30±0.40	145.21±0.90	146.8±2.0
150417-8	DTK05	0.002 35	94.22±0.66	1.066 3±0.080 2	59.22±0.41	144.40±0.91	146.2±2.0

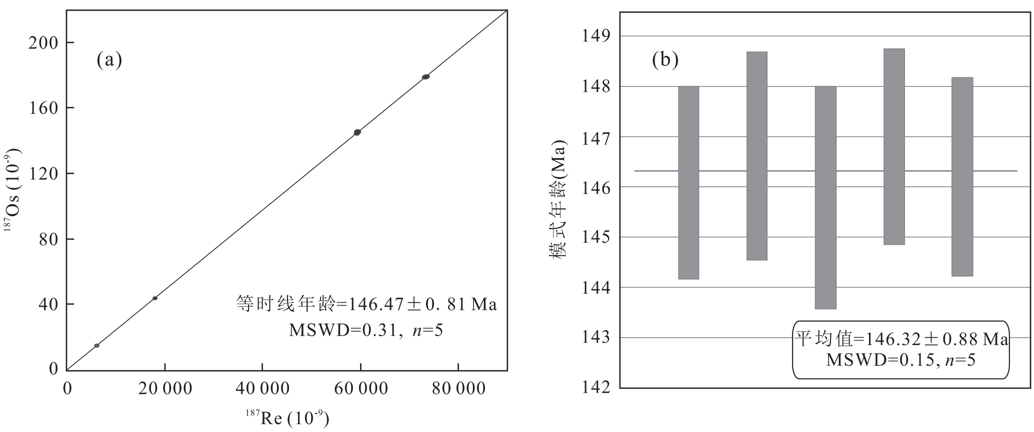

图 8　大铜坑钨钼矿床辉钼矿 Re-Os 同位素等时线年龄(a)及模式年龄加权平均值(b)

Fig.8　Re-Os weighted isochronage (a) and average model ages (b) of molybdenite from the Datongkeng W-Mo deposit

4　讨论

4.1　成岩时代及动力学背景

浙皖赣相邻区岩浆活动主要发生于新元古代和中生代.吴荣新等(2007)在浙西开化地区青白口系井潭组获取英安质凝灰岩 LA-ICP-MS 锆石 U-Pb 年龄数据 779±7 Ma 和 835±9 Ma,李双等(2012)在皖南歙县地区获取邓家坞花岗闪长岩体锆石 U-Pb年龄为 772±11 Ma,大铜坑花岗岩第 1 类锆石 U-Pb 同位素年龄数据为 756～851 Ma,与区域新元古代构造岩浆事件相一致.淳安结蒙地区花岗闪长岩体锆石 U-Pb 年龄为 148.6±1.1 Ma(Li *et al*., 2013),木瓜地区花岗斑岩体形成于 142.2±1.2 Ma(厉子龙等,2013),开岭脚和里程家花岗闪长岩分别形成于 151±3 Ma 和 148±2 Ma(汪建国等,2010),这与大铜坑花岗岩体第 2 类锆石年龄数据分布范围(143～153 Ma)大致相当,加权平均为 148.3±1.9 Ma,大致代表了岩浆结晶年龄.李福林等(2011a,2011b)在淳安木瓜地区获取基性岩墙群和含斑基性岩形成年龄为 135±2 Ma,与大铜坑岩体第 3 类锆石 U-Pb 加权平均年龄数据 134.0±2.0 Ma基本吻合,结合大铜坑岩体内部侵入有基性岩墙群(图 2),暗示岩体在早白垩世早期曾遭受构造一热事件的影响.

众多学者认为,华南受太平洋构造域的制约始于中侏罗世,持续性或周期性至白垩纪洋对陆消减过程中的区域性大规模岩石圈拉张减薄伸展造山作用形成了晚中生代燕山期花岗岩一火山岩(Chen *et al*., 2002; Li *et al*., 2003, 2007; Zhou *et al*., 2006).华南中侏罗世(约 165±5 Ma)进入太平洋构造域的活动大陆边缘挤压造山阶段(邢光福等,2008;张岳桥等,2009),在 145 Ma 左右,进入由挤压向伸展扩张的转换期(Li,2000;华仁民等,2003;毛建仁等,2009;Wu *et al*.,2012).

大铜坑花岗岩地球化学和同位素年代学特征显示岩浆主要来自于地壳物质的部分熔融.在 Sr/Y-Y 和 La_N/Yb_N-Yb_N 图解上(图 9a,9b),大铜坑花岗岩均落在经典岛弧岩石区域.在 Pearce *et al*.(1984)微量元素构造判别图解中(图 10a～10d),岩石均落在同碰撞花岗岩和弧花岗岩界线附近,在 Hf-Rb/10−3×Ta 和 R_1-R_2 图解中(图 10e,10f),岩石分别落在火山弧花岗岩与板内花岗岩界线附近和同碰撞花岗岩区域,指示其形成于晚侏罗世时期古太平洋俯冲碰撞机制下的岛弧环境,与皖南泾县榔桥、绩溪县靠背尖和浙西余杭闲林、富阳千家等同时期中

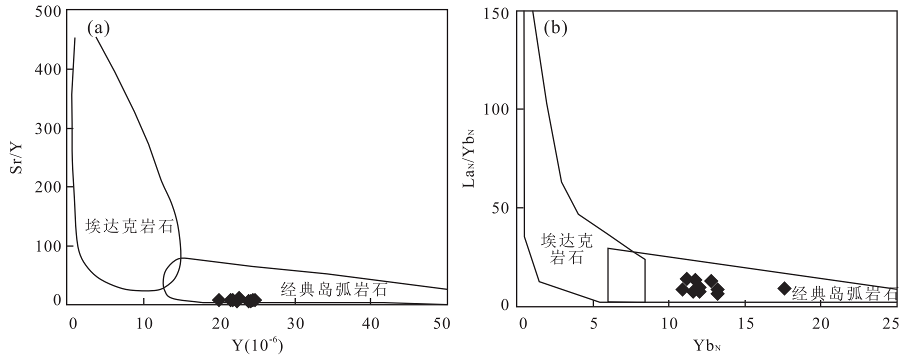

图9 大铜坑花岗岩 Sr/Y-Y(a)和 La_N/Yb_N-Yb_N(b)图解

Fig.9 Sr/Y vs. Y diagram (a) and La_N/Yb_N vs. Yb_N(b) diagram for the Datongkeng granite

据 Defant and Drummond(1990)和 Defant and Kepezhinskas(2001)

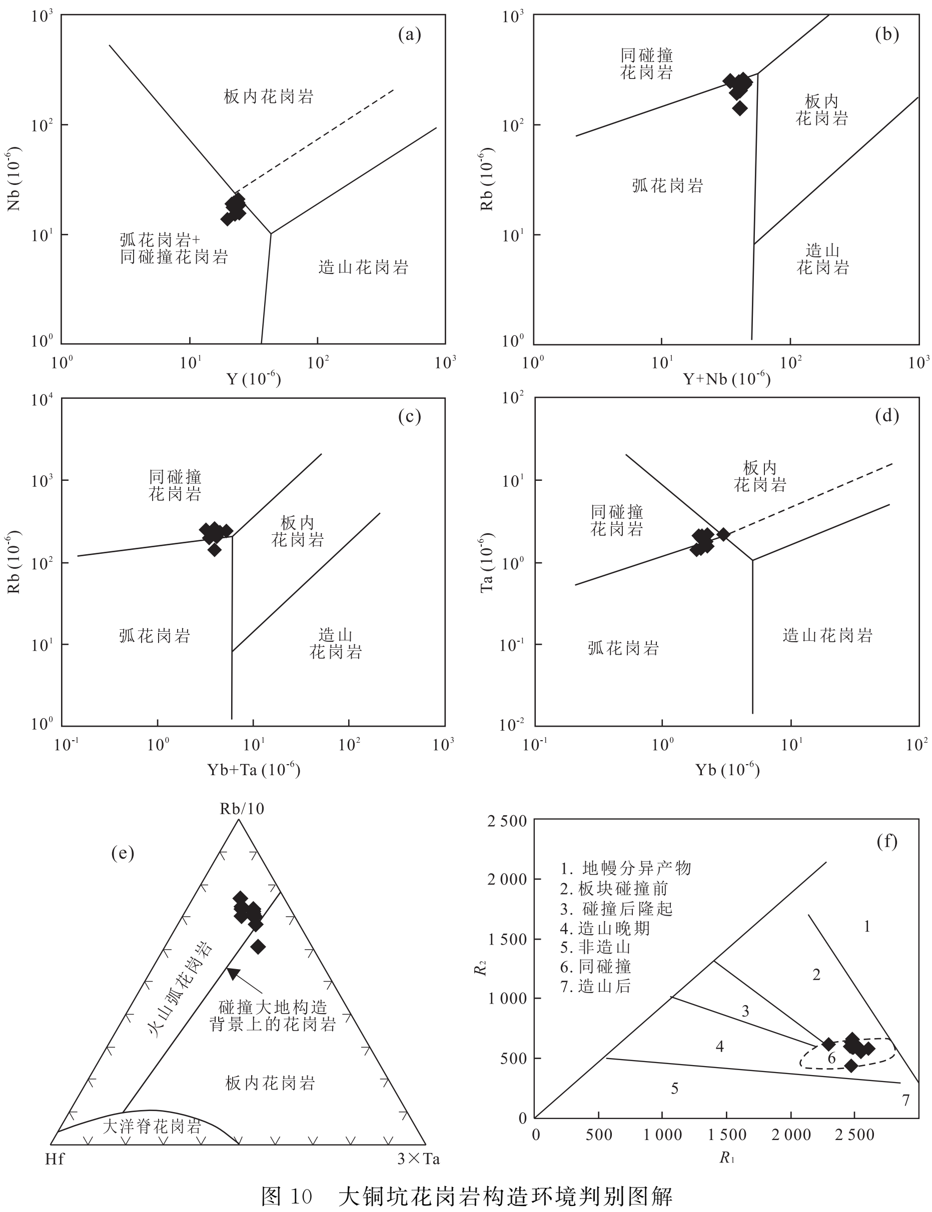

图10 大铜坑花岗岩构造环境判别图解

Fig.10 Tectonic setting discriminative diagram for the Datongkeng granite

图 a,b,c,d 据 Pearce *et al*.(1984);图 e 据 Harris *et al*.(1986);图 f 据 Batchelor and Bowden(1985)

表 4　浙皖赣相邻区钨钼矿区成岩年龄及成矿时代

Table 4　The formation age of plutons from the important deposits in West Zhejiang and adjacent regions

矿区名称	岩体岩性	成岩年龄和成矿时代	测试方法	资料来源
乐平塔前钨钼矿	花岗闪长岩	159.7±1.8 Ma	LA-ICP-MS 锆石 U-Pb	刘善宝等,2014
乐平塔前钨钼矿	花岗闪长岩	162±2 Ma	辉钼矿 Re-Os	黄安杰等,2013
铅山永平铜钨钼矿	花岗岩	160.0±2.3 Ma	SIMS 锆石 U-Pb	丁昕等,2005
铅山永平铜钨钼矿	花岗岩	156.7±2.8 Ma	辉钼矿 Re-Os	李晓峰等,2007
桐庐彰坞钨矿	花岗岩	159.7±2.6 Ma	LA-ICP-MS 锆石 U-Pb	笔者,未发表
绩溪背靠山钨矿	花岗闪长斑岩	152.7～147.7 Ma	SHRIMP 锆石 U-Pb	周翔等,2012
淳安县开岭脚钼矿	花岗闪长岩	151±3 Ma	SHRIMP 锆石 U-Pb	汪建国等,2010
余杭闲林铁钼(铜钨)矿	花岗闪长岩	151.8±2.2 Ma	SHRIMP 锆石 U-Pb	唐增才等,2014
余杭闲林铁钼(铜钨)矿	花岗闪长岩	149.7 Ma	辉钼矿 Re-Os	王永彬等,2013
武宁石门寺钨矿	花岗岩	144.2±1.3 Ma	LA-ICP-MS 锆石 U-Pb	黄兰椿和蒋少涌,2012
武宁石门寺钨矿	花岗岩	149.6±1.2 Ma	辉钼矿 Re-Os	项新葵等,2013
绍兴漓渚铁钼(钨)矿	花岗闪长岩	150.1±2.6 Ma	LA-ICP-MS 锆石 U-Pb	顾明光等,2011
绍兴漓渚铁钼(钨)矿	花岗闪长岩	149.3 Ma	辉钼矿 Re-Os	王永彬等,2013
淳安大铜坑钨钼矿	花岗岩	148.3±1.9 Ma	SHRIMP 锆石 U-Pb	本文
淳安大铜坑钨钼矿	花岗岩	146.47±0.81 Ma	辉钼矿 Re-Os	本文
祁门东源钨钼矿	花岗闪长斑岩	146±1 Ma	SHRIMP 锆石 U-Pb	周翔等,2011
淳安大铜坑钨钼矿	花岗岩	146.4±2.3 Ma	辉钼矿 Re-Os	周翔等,2011
淳安木瓜钨矿	花岗斑岩	142.2±1.2 Ma	LA-ICP-MS 锆石 U-Pb	厉子龙等,2013
歙县邓家坞钼矿	花岗闪长斑岩	141.8±2.2 Ma	辉钼矿 Re-Os	李双等,2012
安吉港口铅锌钨钼矿	花岗闪长岩	141.0±1.4 Ma	LA-ICP-MS 锆石 U-Pb	唐燕文等,2013
安吉港口铅锌钨钼矿	花岗闪长岩	141.2±1.1 Ma	辉钼矿 Re-Os	唐燕文等,2013
龙泉毛断钼多金属矿	花岗岩	140.0±1.6 Ma	LA-ICP-MS 锆石 U-Pb	李艳军等,2011
龙泉毛断钼多金属矿	花岗岩	139.0±0.8 Ma	辉钼矿 Re-Os	李艳军等,2011

酸性侵入体形成的构造背景一致(周翔等,2012;李双等,2014;唐增才等,2014,2016),表明此时浙皖相邻地区仍然处于古太平洋板块俯冲挤压的构造环境.

4.2　成矿时代与成矿物质来源

辉钼矿 Re-Os 体系封闭温度较高(约 500 ℃),不易受后期热液、变质和构造事件干扰,其同位素年龄能准确地表示成矿时代(Suzuki *et al*.,1996;Stein *et al*.,1997,1998,2001;Watanabe and Stein,2000;Selby and Creaser,2001a,2001b;Selby *et al*.,2002).浙西淳安大铜坑钨钼矿床辉钼矿等时线年龄为 146.47±0.81 Ma,代表了大铜坑钨钼矿床的成矿时代,显示钨钼成矿作用发生于晚侏罗世.

Mao *et al*.(1999)认为辉钼矿的 Re 含量可以指示成矿物质的来源,从幔源、I 型到 S 型花岗岩相关的矿床,Re 含量具有从 $n\times100\times10^{-6}\rightarrow n\times10\times10^{-6}\rightarrow n\times10^{-6}$ 逐渐降低的变化规律.大铜坑钨钼矿的辉钼矿 Re 含量为 $9.70\times10^{-6}\sim116.70\times10^{-6}$(表 3),暗示成矿物质以壳源为主的特征.

4.3　成岩成矿作用关系

大铜坑钨钼矿体主要赋存于岩体与围岩内外接触带,岩体本身也具有矿化蚀变,具备斑岩型矿床的典型特征,说明大铜坑花岗岩即为成矿岩体.大铜坑花岗岩 SHRIMP 锆石 U-Pb 年龄为 148.3±1.9 Ma,辉钼矿 Re-Os 同位素等时线年龄为 146.47±0.81 Ma,成岩成矿时代基本一致,两者均为晚侏罗世壳源岩浆作用的产物,同样表明大铜坑钨钼成矿作用与大铜坑花岗岩的形成有着密切的成因联系,而且二者在时间上构成一个连续的过程.

华仁民等(2005)认为华南地区中生代的 3 次大规模成矿作用是岩石圈发展演化的产物,与拉张的动力学背景、壳-幔相互作用、深部热和流体的参与有着成因上的密切关系.毛景文等(2011)对钦杭成矿带地质特征和矿床分布规律进行研究,认为中生代第 2 次成矿事件,即晚侏罗世(160～150 Ma)与花岗岩有关的钨锡多金属成矿事件主要集中在南岭地区及邻区.近年来,浙皖赣相邻区钨钼矿床研究取得了重要进展(表 4),显示晚侏罗世-早白垩世(160～140 Ma)是该区钨钼的一次重要成矿期,暗示中生代钨钼成矿作用可能从南岭一直延伸到浙皖赣交界区.

5　结论

(1) 大铜坑花岗岩体成岩时间为晚侏罗世

148.3±1.9 Ma,形成于古太平洋板块俯冲挤压背景下的岛弧构造环境,是地壳物质部分熔融的的产物,经历了华南早白垩世 134.0±2.0 Ma 岩石圈伸展减薄机制下的构造-热事件.

(2)大铜坑钨钼矿床辉钼矿 Re-Os 加权平均年龄为 146.32±0.88 Ma,等时线年龄为 146.47±0.81 Ma辉钼矿 Re 含量为 $9.70\times10^{-6}\sim116.70\times10^{-6}$,成矿物质以壳源为主.

(3)大铜坑地区成岩成矿时代具有较好的一致性,岩石地球化学特征和成矿物质来源均指向壳幔混合成因,表明大铜坑花岗岩为成矿岩体,显示了良好的斑岩型钨钼矿床找矿前景.

(4)晚侏罗世-早白垩世浙皖赣相邻区钨钼的成矿作用是华南中生代第 2 次成矿事件往北东方向的延续.

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