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南岭科学钻探一孔中岩浆岩的矿物特征及其对成岩、成矿作用的指示意义

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摘要:南岭科学钻探一孔(SP-NLSD-1)位于南岭成矿带与武夷山成矿带的交汇部位——赣南银坑矿田,该钻孔总进尺 2967.83 m, 钻遇了流纹岩、花岗闪长斑岩、花岗斑岩、辉长闪长玢岩等 4 种岩浆岩。各岩浆岩矿物组成简单, 主要为石英、斜长石、钾长石、黑云母、角闪石及副矿物磷灰石、榍石等, 岩石多发生绿泥石化、碳酸盐化、白云母化等蚀变。钾长石均以正长石为主。花岗闪长斑岩中的斜长石以中长石为主, 少数为钠长石、更长石、拉长石; 花岗斑岩中的斜长石以钠长石为主, 少数为更长石。黑云母为富镁黑云母和镁铁黑云母。白云母均由黑云母蚀变而来, 花岗闪长斑岩中的白云母具有低的 Al^{IV} 、 $Fe/(Fe+Mg)$ 值, 花岗斑岩中的白云母具有高的 Al^{IV} 、 $Fe/(Fe+Mg)$ 值。磷灰石普遍含 F、Cl, 且 F 含量显著高于 Cl 含量。石榴石属钙铝榴石。绿泥石主要为蠕绿泥石(铁绿泥石)–密绿泥石。黑云母矿物化学特征指示花岗闪长斑岩为壳幔混源花岗岩, 具有较高的氧逸度, 在演化过程中发生了岩浆混合作用。根据锆石饱和温度计计算出花岗闪长斑岩、花岗斑岩、辉长闪长玢岩的结晶温度分别为 810~922℃、764~819℃、742~747℃, 成岩后岩浆岩经历了中高温—中低温热液蚀变作用。岩浆岩成岩时代、岩石学和岩相学所反映的岩浆演化过程、成岩物理化学条件、矿物化学特征等方面的综合信息显示, 南岭科学钻探一孔中钻遇的花岗闪长斑岩与南岭地区成 Cu(-Mo)-Pb-Zn-Au-Ag 矿的花岗岩十分相似, 应为钻孔中揭露的银金铅锌铜矿化以及牛形坝—柳木坑银金铅锌铜矿的成矿岩浆岩, 而钨铋铀矿化与岩浆岩的关系还有待于进一步研究。

关键词:矿物学; 岩浆源区; 岩浆混合作用; 燕山期; 成矿作用; 南岭科学钻探一孔

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Mineralogical characteristics of the granitoid exposed in the Nanling Scientific Drill Hole and implications for magmatism and mineralization in the Yinkeng orefield, Southern Jiangxi Province

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Abstract: The Nanling Scientific Drilling-1 (SP-NLSD-1), a subproject of the SinoProbe Program called “Deep Exploration Technology and Experimentation”, is situated at the Yinkeng orefield in the junction of Nanling and Wuyi Mountain metallogenic belts. The drilling project, with footage of 2967.83 meters, revealed rhyolite, granodiorite porphyry, granite porphyry and pyroxene diorite porphyry. The magmatic rocks are mainly composed of quartz, plagioclase, potassium feldspar, biotite, amphibole and some accessory minerals, with chloritization, carbonatization and muscovitization. Potassium feldspar is dominated by orthose. Plagioclases are different in granodiorite and granite porphyry. Andesines and albites are dominant in granodiorite porphyry and granite porphyry, respectively. Most of the biotites are eastonites. Derived from biotites, muscovites in granodiorite porphyry have low Al^{VI} and $Fe/(Fe+Mg)$ values, while muscovites in granite porphyry have high values. Apatites are rich in F and Cl, and garnet belongs to grossularite. Chlorites are prochlorites and pycnochlorites. The chemical composition of biotite suggests that granodiorite porphyry was formed by magma derived from mixture of crust and mantle with relatively high oxygen fugacity, and had undergone magma mixing during the evolution. Granodiorite porphyry, granite porphyry, and pyroxene diorite porphyry crystallized at temperatures of 810–922°C, 764–819°C, 742–747°C, respectively. Comprehensive study suggests that granodiorite porphyry exposed in the Nanling Scientific Drill Hole is similar to granites related to Cu(-Mo)-Pb-Zn-Au-Ag deposits in Nanling region. The granodiorite porphyry is the ore-forming magmatite of Ag-Au-Pb-Zn-Cu mineralization and Niuxingba-Liumukeng deposit. The relationship between W-Bi-U mineralization and magmatism needs further research.

Key words: mineral; magmatic source; magma mixing; Yanshanian Period; metallogeny; Nanling Scientific Drilling-1

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花岗质岩浆活动与成矿作用的问题一直是华南多金属成矿省的研究热点。自新元古代以来,华南地区形成了目前6个主要成矿带:长江中下游成矿带、江南隆起成矿带、赣东北成矿带(钦杭带东段)、武夷-云开成矿带、南岭成矿带和东南沿海(火山岩)成矿带^[1-2]。陈毓川等根据不同时代和构造地质环境将南岭地区与花岗岩有关的矿床划分为5个矿床成矿系列:南岭成矿区与燕山期中浅成酸性花岗岩类有关的稀土、稀有、有色及铀金属矿床成矿系列,赣东北成矿带与燕山期浅成-超浅成中酸性花岗岩类有关的铜、铅、锌、钨、钼、铌、银、金、铀矿床成矿系列,东南沿海成矿带与燕山期中酸性火山-侵入岩有关的钨、锡、铌钽、钼、铜、铅锌(银、金)、非金属矿床成矿系列,武夷-云开成矿带与海西-印支期为主的深变质带混合花岗岩及燕山期花岗岩有关的铌钽、金、锡矿床成矿系列,桂北

地区与前寒武纪花岗岩有关的锡、铜、铅、锌矿床成矿系列^[3]。以揭露南岭、武夷山成矿带结合部位地壳结构、深部控岩控矿构造,探索成矿带结合部位深部岩浆活动与成矿作用的动力学机制为科学目标,通过在银坑矿田开展系统的地质实测剖面、地球化学测量、矿田构造、岩浆活动、典型矿床和综合地球物理探测研究,选址于地球物理工作探测到的柳木坑隐伏岩体顶部,同时也是牛形坝-柳木坑矿区地表与浅部破碎蚀变岩型银金铅锌铜矿化发育、花岗闪长斑岩脉大量分布的矿化中心实施中国深部探测南岭科学钻探一孔,代号SP-NLSD-1,孔口坐标:X2901453.78、Y20364294.34(图1)^[4]。在钻孔选址前期的矿田成岩成矿规律研究过程中发现,银坑矿田内的钨多金属与金银铅锌铜贵多金属成矿、花岗质与花岗闪长质岩浆活动均发生在燕山期^[4]。南岭科学钻探一孔钻遇了流纹岩(381.0 Ma)、花岗

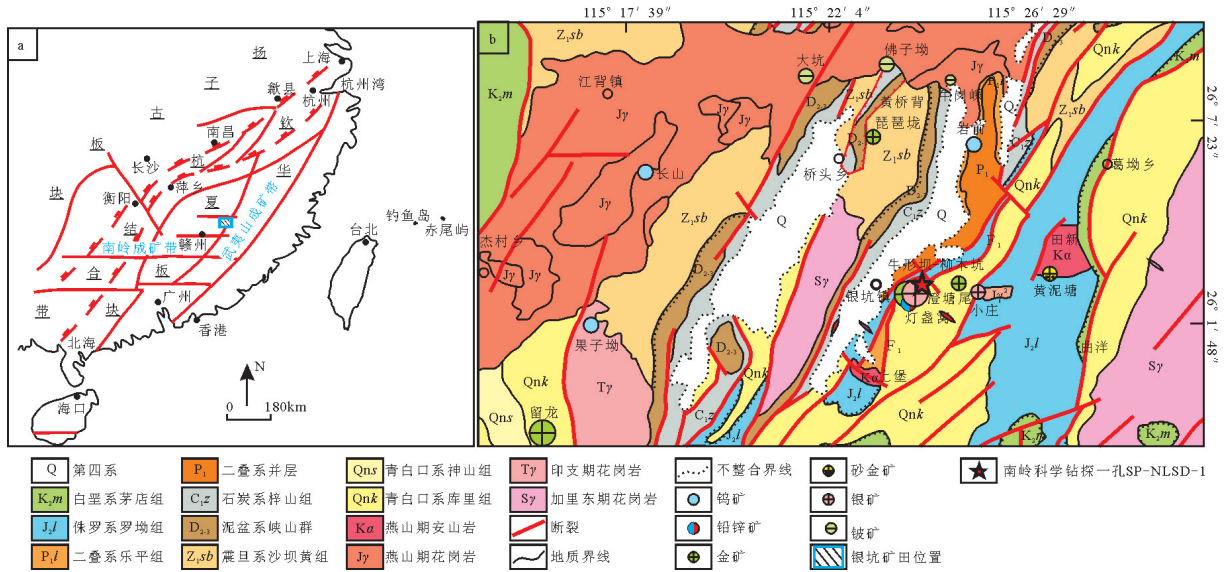


图1 银坑矿田大地构造位置图(a,底图据文献[12])与地质矿产图(b)

Fig.1 Tectonic location of the Yinkeng orefield (a base map after reference [12]) and map of geology and mineral resources of Yinkeng region (b)

闪长斑岩(160.3 Ma)、花岗岩斑(151.7 Ma)、辉长闪长玢岩(161.0 Ma、101.3 Ma)等4种岩浆岩^[5],本文对与成矿关系密切的燕山期岩浆岩脉的矿物学特征进行了报道,并初步讨论了矿物学对岩浆岩成因和矿田成矿作用的指示意义。

1 区域地质背景

银坑矿田位于南岭东段于都—赣县矿集区内,是赣南地区钨、金银铅锌锰铜多金属成矿潜力较好的矿田之一,大地构造上位于东西向南岭成矿带与北东向武夷山成矿带的交汇部位。在地层上,除奥陶系、志留系和三叠系之外,从青白口系到第四系均有出露,其中,青白口系—寒武系构成褶皱基底,泥盆系—二叠系构成褶皱盖层,侏罗系—白垩系为断陷盆地沉积。矿田内的断裂以NNE向为主,其次为NE—NEE向、NW—NWW向,其中,NE—NNE向逆冲推覆构造控制了本区基本的构造格架^[6]。区内岩浆活动频繁,除新元古代火山喷发形成海底火山—沉积建造外,多为酸性—中酸性浅成—超浅成侵入体,如加里东期长潭花岗岩岩体、印支期清溪花岗岩岩体、燕山期江背花岗岩岩体和高山角花岗闪长岩岩瘤。矿田内矿床类型众多,从空间分布和矿化机制角度可以分为2类:一类是与花岗岩有关的钨多金属矿,如画眉坳钨—铍矿、岩前钨—滑石—透

闪石矿、狮吼山硫铁—钨矿,主要分布在江背花岗岩体边缘^[7-9];一类是与花岗闪长岩有关的铜铅锌金银多金属矿,如牛形坝—柳木坑银金铜铅锌矿、老虎头—桥子坑铅锌(银金)矿,矿体多与NEE向、NWW向、近E—W向花岗闪长斑岩脉平行或相互穿插共生^[4-5,10-11]。

南岭科学钻探—孔于2011年6月开孔,2013年7月终孔,总进尺2967.83 m,揭露了丰富的地层、构造、岩浆岩和矿化信息——孔深1373.71 m处揭露了区域上控岩控矿的推覆构造F₁,其上为新元古代青白口系火山碎屑岩地层,其下为二叠系海陆交互相地层;揭露了各类岩浆岩共计37处,均呈岩脉状产出;揭露了浅部细脉—网脉—浸染状铅锌金银铜矿化和深部细脉—浸染状钨铍铀矿化。钻孔柱状图见图2。

2 样品和分析方法

本次工作主要选取南岭科学钻探—孔中燕山期岩浆岩的主要矿物作为研究对象,对其进行了电子探针分析。测试工作在中国地质科学院矿产资源研究所国土资源部成矿作用与资源评价重点实验室完成,仪器型号为JXA-8230,加速电压15 kV,电流20 nA,束斑直径5 μm。

3 岩相学和矿物化学特征

南岭科学钻探—孔揭露的岩浆岩均呈岩脉状

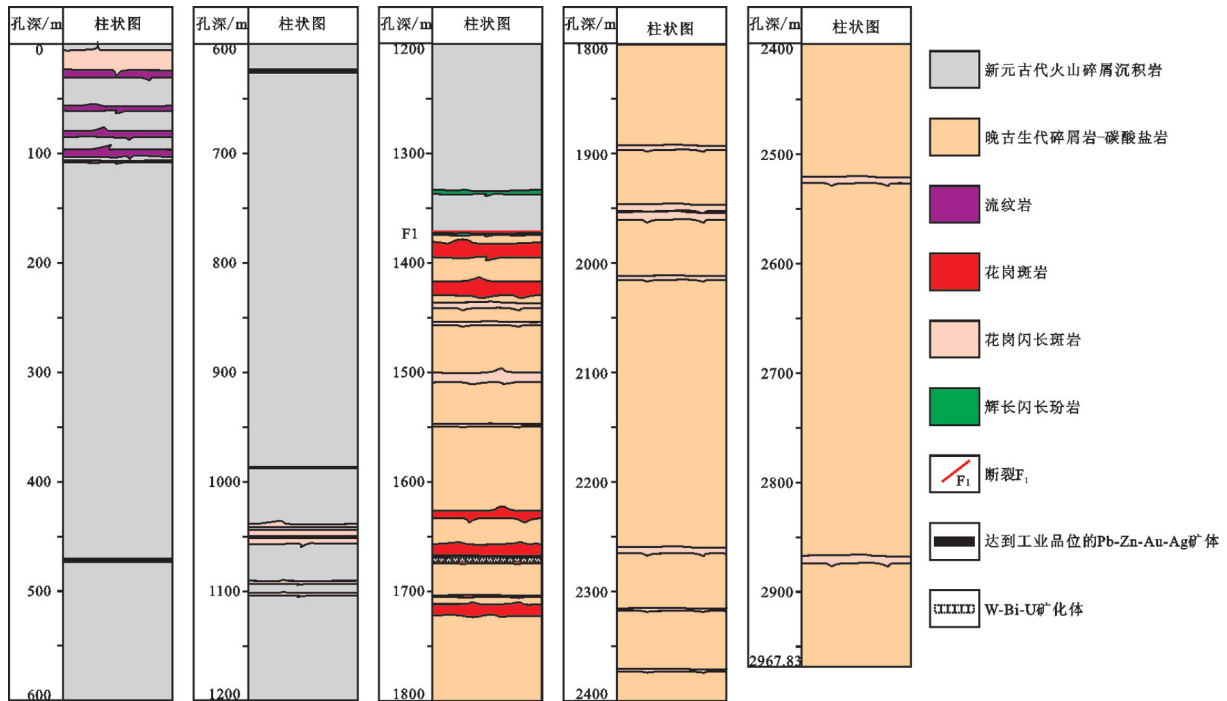


图2 南岭科学钻探一孔简易柱状图

Fig.2 Simplified columnar section of the Nanling Scientific Drill Hole

表1 南岭科学钻探一孔揭露的岩浆岩

Table 1 Magmatic dykes in the Nanling Scientific Drill Hole

孔深/m	视厚度/m	岩性	孔深/m	视厚度/m	岩性
2.9~20.68	17.78	花岗闪长斑岩	1548.42~1549.23	0.81	花岗闪长斑岩
20.68~27.00	6.32	流纹岩	1628.47~1634.06	5.59	花岗斑岩
56.90~60.87	3.97	流纹岩	1657.63~1667.32	9.69	花岗斑岩
80.19~84.83	4.64	流纹岩	1667.68~1670.07	2.39	花岗闪长斑岩
98.39~101.59	3.20	流纹岩	1672.04~1672.92	0.88	花岗斑岩
101.59~104.79	3.20	流纹岩	1705.63~1705.84	0.21	花岗斑岩
105.59~106.19	0.60	流纹岩	1713.46~1723.57	10.11	花岗斑岩
1043.22~1043.97	0.75	花岗闪长斑岩	1892.16~1896.33	4.17	花岗闪长斑岩
1045.42~1052.01	6.59	花岗闪长斑岩	1948.84~1952.06	3.22	花岗闪长斑岩
1052.54~1059.89	7.35	花岗闪长斑岩	1952.95~1961.10	8.15	花岗闪长斑岩
1096.08~1096.38	0.30	花岗闪长斑岩	2011.93~2012.43	0.50	花岗闪长斑岩
1103.94~1105.97	2.03	花岗闪长斑岩	2013.05~2017.50	4.45	花岗闪长斑岩
1334.26~1337.77	3.51	辉长闪长玢岩	2258.48~2264.75	6.27	花岗闪长斑岩
1373.71~1375.37	1.66	辉长闪长玢岩	2365.96~2369.09	3.13	花岗闪长斑岩
1381.49~1399.18	17.69	花岗斑岩	2371.63~2373.56	1.93	花岗闪长斑岩
1418.06~1429.71	11.65	花岗斑岩	2522.93~2527.85	4.92	花岗闪长斑岩
1438.03~1439.91	1.88	花岗闪长斑岩	2528.92~2529.77	0.85	花岗闪长斑岩
1454.08~1455.85	1.77	花岗闪长斑岩	2867.58~2875.92	8.34	花岗闪长斑岩
1502.24~1510.38	8.14	花岗闪长斑岩			

产出,视厚度0.21~17.78 m(图2、表1)。各岩浆岩矿物组成简单,主要为石英、斜长石、钾长石、黑云母、角闪石及副矿物磷灰石、榍石等,岩石多发生绿泥石化、碳酸盐化、白云母化等蚀变^[5]。

3.1 长石

长石在花岗闪长斑岩、花岗斑岩中以斑晶形式

存在。其中,钾长石呈自形-半自形板状,多数发生高岭土化,边部常被熔蚀,内部有时被蠕虫状石英交代。花岗闪长斑岩中的钾长石内部有时包含黑云母或角闪石等暗色矿物。斜长石多呈自形-半自形板状,边部有熔蚀现象。花岗闪长斑岩中的斜长石发育卡式双晶、聚片双晶、环带结构,花岗斑岩中

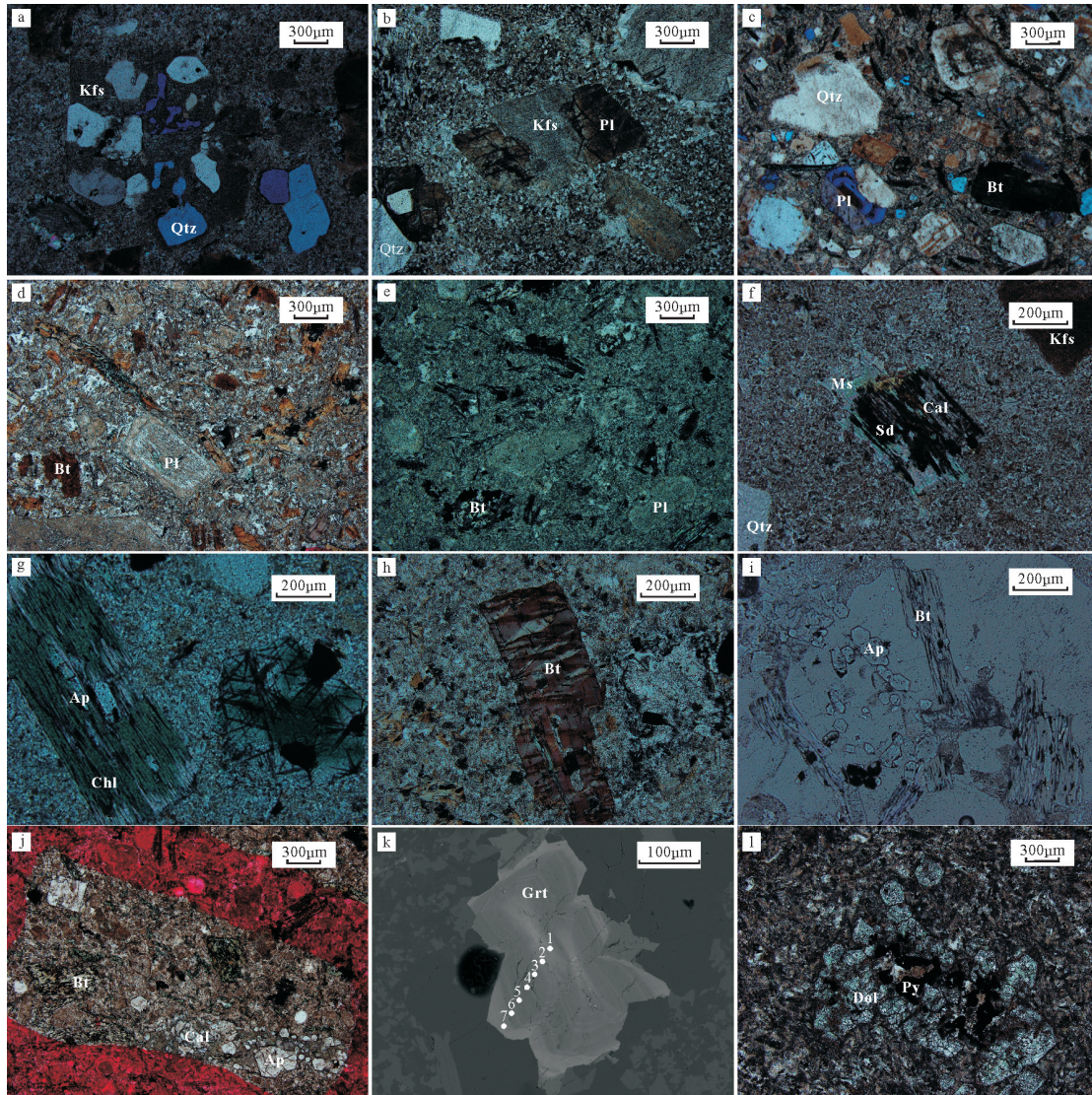


图3 南岭科学钻探—孔所揭露燕山期岩浆岩的岩相学特征

a—钾长石斑晶被石英交代,孔深1380.52 m花岗斑岩,正交偏光;b—长石斑晶高岭土化、绢云母化,孔深1715.02 m花岗斑岩,单偏光;
 c—斜长石斑晶发育环带结构,孔深1892.61 m花岗闪长斑岩,正交偏光;d—e—包体(d)与寄主岩(e)的矿物蚀变程度差异显著,孔深2013.80 m
 花岗闪长斑岩,单偏光;f—黑云母边部蚀变为白云母,核部蚀变为方解石和菱铁矿,孔深1380.52 m花岗斑岩,单偏光;g—黑云母发生绿泥石化,
 析出针状金红石,内部包含磷灰石,孔深1502.06 m花岗闪长斑岩,单偏光;h—未蚀变黑云母,孔深2017.29 m花岗闪长斑岩中暗色包体,单
 偏光;i—石英斑晶中包含大量磷灰石,孔深1052.54 m花岗闪长斑岩,单偏光;j—磷灰石与方解石共生,孔深2371.72 m花岗闪长斑岩,单偏光;
 k—石榴石发育震荡环带,孔深2258.45 m花岗闪长斑岩,背散射;l—白云石化、黄铁矿化,孔深1373.84 m辉长闪长玢岩,单偏光;
 Ap—磷灰石;Bt—黑云母;Cal—方解石;Chl—绿泥石;Dol—白云石;Grt—石榴石;Kfs—钾长石;Ms—白云母;Pl—斜长石;
 Py—黄铁矿;Qtz—石英;Sd—菱铁矿

Fig. 3 Microphysiography of the magmatic dykes exposed in the Nanling Scientific Drill Hole

a—Metasomatic texture in orthoclase phenocryst, granite porphyry at the depth of 1380.52 m, crossed nicols; b—Orthoclase phenocryst with
 kaolinization and sericitization, granite porphyry at the depth of 1715.02 m, plainlight; c—Plagioclase phenocryst with zoned texture, granodiorite
 porphyry at the depth of 1892.61 m, crossed nicols; d—e—Different alteration intensities between enclave (d) and host rock (e), Granodiorite
 porphyry at the depth of 2013.80m, plainlight; f—Biotite turned into muscovite at the edge, and carbonate minerals at the core, granite porphyry at the
 depth of 1380.52 m, plainlight; g—Chloritized biotite with rutile and apatite inside, granodiorite porphyry at the depth of 1502.06m, plainlight;
 h—Biotite without alteration in dark enclave in granodiorite porphyry at the depth of 2017.29 m, plainlight; i—Quartz phenocryst with many apatites,
 granodiorite porphyry at the depth of 1052.54 m, plainlight; j—Associated apatite and calcite, granodiorite porphyry at the depth of 2371.72 m,
 plainlight; k—Garnet with zonal texture, granodiorite porphyry at the depth of 2258.45 m, BSE image; l—Dolomitization and Pyritization, pyroxene
 diorite porphyry at the depth of 1373.84 m, plainlight; Ap—Apatite; Bt—Biotite; Cal—Calcite; Chl—Chlorite; Dol—Dolomite; Grt—Garnet;
 Kfs—Potassium feldspar; Ms—Muscovite; Pl—Plagioclase; Py—Pyrite; Qtz—Quartz; Sd—Siderite

表2 钾长石电子探针分析结果(平均值)(%)
Table 2 EPMA analysis results of potassium feldspars in the Nanling Scientific Drill Hole (mean value)(%)

岩性	采样深度/m	分析 点数	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	F	Cl	Total	An	Ab	Or
	17.48	2	50.56	0.00	32.43	3.12	0.02	1.00	0.06	0.07	8.10	0.00	0.04	0.00	95.38	1	1	98
	1043.60	5	56.13	0.09	27.97	1.56	0.01	0.83	0.28	2.22	9.50	0.01	0.03	0.01	98.63	2	20	78
	1052.54	2	56.93	0.00	24.45	1.73	0.02	0.87	0.01	0.26	13.85	0.00	0.18	0.01	98.31	0	3	97
	1053.78	2	64.30	0.00	18.54	0.06	0.01	0.00	0.04	1.28	14.99	0.04	0.00	0.02	99.27	0	12	88
	1104.07	1	55.09	0.03	27.65	0.94	0.00	0.70	0.20	2.96	6.80	0.01	0.09	0.01	94.50	1	39	59
	1508.04	2	51.76	0.08	32.17	2.16	0.02	1.05	0.01	0.12	10.22	0.01	0.03	0.01	97.62	0	2	98
	1667.75	1	51.99	0.06	38.27	1.06	0.00	1.01	0.00	0.18	7.27	0.00	0.15	0.00	100.00	0	4	96
	1894.37	1	48.02	0.23	34.93	3.49	0.05	0.88	0.04	0.62	9.96	0.13	0.01	0.01	98.37	0	9	91
	2011.94	3	52.52	0.00	30.55	1.45	0.01	3.17	0.13	0.08	9.13	0.01	0.14	0.01	97.20	1	1	97
	2013.80	4	51.48	0.03	30.71	1.09	0.00	2.32	0.06	0.14	9.71	0.02	0.61	0.03	96.20	0	2	97
	2017.29	2	51.96	0.03	28.82	1.00	0.02	3.69	0.09	0.11	9.35	0.00	0.66	0.01	95.74	1	2	97
	2258.45	1	65.27	0.05	18.63	0.03	0.00	0.00	0.13	1.91	13.26	0.00	0.00	0.00	99.26	1	18	82
	2365.76	1	51.03	0.00	30.80	1.27	0.02	4.40	0.28	0.05	4.39	0.00	0.13	0.01	92.37	5	2	93
	2372.60	5	50.20	0.02	32.14	1.29	0.02	2.51	0.13	0.13	9.47	0.01	0.07	0.01	96.00	1	2	97
	2527.48	2	64.73	0.01	18.17	0.02	0.01	0.00	0.03	0.52	16.26	0.00	0.00	0.07	99.83	0	5	95
	2527.48	1	66.72	0.00	19.96	0.09	0.01	0.24	0.58	7.87	3.25	0.02	0.05	0.78	99.57	3	76	21
	1380.52	1	66.94	0.01	25.15	0.32	0.02	0.08	0.08	4.77	3.01	0.02	0.00	0.00	100.40	1	70	29
	1380.52	1	64.06	0.05	19.78	0.00	0.01	0.00	0.01	0.24	16.15	0.00	0.10	0.00	100.41	0	2	98
	1429.73	1	73.35	0.00	20.74	0.02	0.00	0.00	0.00	0.14	8.41	0.00	0.00	0.02	102.68	0	2	98
	1632.95	2	64.64	0.01	17.90	0.04	0.06	0.00	0.00	0.27	17.26	0.01	0.00	0.01	100.18	0	2	98
	1663.23	2	57.58	0.00	26.86	0.95	0.04	0.04	0.02	0.17	11.72	0.01	0.13	0.01	97.53	0	2	98
	1705.36	2	52.49	0.03	34.85	0.52	0.00	0.42	0.25	0.27	7.81	0.00	0.00	0.01	96.66	2	5	93
	1715.02	2	64.41	0.00	18.12	0.06	0.03	0.00	0.01	0.29	17.05	0.00	0.01	0.00	99.98	0	3	97
	1337.12	1	52.23	0.10	30.00	2.23	0.00	2.15	0.05	0.09	10.32	0.01	0.08	0.01	97.26	0	1	98

表3 斜长石电子探针分析结果(平均值)(%)

Table 3 EPMA analysis results of plagioclases of magmatic rocks in the Nanling Scientific Drill Hole (mean value)(%)

岩性	采样深度/m	分析 点数	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	F	Cl	Total	An	Ab	Or
花岗 闪长 斑岩	20.50	1	68.86	0.00	18.30	0.19	0.00	0.00	0.05	11.81	0.04	0.00	0.00	0.01	99.26	0	100	0
	1045.42	3	57.46	0.02	27.09	0.14	0.01	0.01	8.76	6.30	0.38	0.01	0.01	0.00	100.20	43	55	2
	1045.42	1	65.26	0.02	22.02	0.05	0.00	0.01	2.52	10.24	0.20	0.00	0.02	0.00	100.33	12	87	1
	1104.07	1	65.58	0.02	22.01	0.22	0.00	0.19	0.14	10.34	1.23	0.01	0.00	0.00	99.74	1	92	7
	1455.13	1	58.10	0.00	26.43	0.12	0.02	0.00	9.02	6.10	0.37	0.02	0.00	0.04	100.21	44	54	2
	1894.37	2	54.86	0.01	29.31	0.15	0.01	0.04	10.91	4.98	0.28	0.00	0.00	0.01	100.55	54	45	2
	1894.37	14	59.40	0.01	25.74	0.10	0.01	0.01	6.96	7.24	0.57	0.01	0.02	0.00	100.08	34	63	3
	1894.37	1	62.54	0.00	23.36	0.00	0.01	0.00	4.84	8.54	0.05	0.01	0.02	0.01	99.36	24	76	0
	1949.41	2	56.93	0.00	27.39	0.11	0.00	0.01	9.01	6.05	0.36	0.01	0.08	0.00	99.96	44	54	2
	1949.41	2	54.19	0.01	29.27	0.27	0.01	0.08	10.72	4.89	0.43	0.00	0.06	0.01	99.94	53	44	3
	1949.41	2	60.98	0.04	24.34	0.44	0.01	0.00	5.23	8.27	0.46	0.01	0.05	0.00	99.84	25	72	3
	1953.18	2	67.54	0.00	20.74	0.04	0.01	0.04	0.34	10.92	0.18	0.01	0.03	0.00	99.84	2	97	1
2258.45	5	60.92	0.02	25.11	0.12	0.02	0.03	6.53	6.79	0.69	0.04	0.01	0.00	100.27	33	63	4	
花岗 斑岩	1429.73	1	66.34	0.00	20.64	0.10	0.00	0.04	3.93	7.40	0.41	0.00	0.21	0.01	99.10	22	75	3
	1429.73	1	72.34	0.00	21.61	0.36	0.00	0.49	0.16	6.98	0.08	0.03	0.00	0.00	102.04	1	98	1
	1632.95	3	69.82	0.02	20.18	0.22	0.00	0.02	0.41	8.42	0.27	0.01	0.03	0.00	99.39	3	95	2
	1663.23	2	70.46	0.01	21.23	0.03	0.01	0.00	0.27	6.35	0.11	0.01	0.01	0.01	98.50	2	97	1
	1672.27	2	69.95	0.02	21.34	0.07	0.00	0.00	0.37	6.89	0.38	0.00	0.00	0.01	99.02	3	94	3
	1705.36	1	68.75	0.00	20.08	0.04	0.00	0.02	0.12	8.72	0.08	0.00	0.00	0.02	97.84	1	99	1
	1715.02	3	68.39	0.00	19.93	0.04	0.02	0.00	0.31	10.42	0.12	0.01	0.04	0.03	99.30	2	98	1

的斜长石发育卡式双晶(图3-a~c)。

电子探针分析结果(表2~3)显示,钾长石的SiO₂含量为48.02%~73.35%, Al₂O₃含量为17.90%~38.27%, K₂O含量为3.01%~17.26%, Na₂O含量为0.05%~7.87%; Or值为21~98, Ab值为76~1, An值为0~5。不同岩浆岩中钾长石的成分相似,多为正长石,个别为歪长石。

花岗闪长斑岩与花岗斑岩中斜长石的成分不同。花岗闪长斑岩中的斜长石以中长石为主(Ab₆₃₋₅₄An₃₃₋₄₄),少量为钠长石(Ab₁₀₀₋₉₂An₀₋₂)、更长石(Ab₈₇₋₇₂An₁₂₋₂₄)、拉长石(Ab₄₄₋₄₅An₅₃₋₅₄), SiO₂含量为54.19%~68.86%, Al₂O₃含量为18.30%~29.31%, K₂O含量为0.04%~1.23%, Na₂O含量为4.89%~11.81%; 花岗斑岩中的斜长石以钠长石为主(Ab₉₉₋₉₄An₁₋₃),个别为更长石(Ab₇₅An₂₂), SiO₂含量为66.34%~72.34%, Al₂O₃含量为19.93%~21.61%, K₂O含量为0.08%~0.41%, Na₂O含量为6.35%~10.42%。从花岗闪长斑岩到花岗斑岩,斜长石中SiO₂含量升高, Al₂O₃、CaO、K₂O、Na₂O含量随之降低。且花岗闪长斑岩中的斜长石在SiO₂-Al₂O₃、SiO₂-CaO、SiO₂-Na₂O图中显示相关性良好的演化趋势,而花岗斑岩显示截然不同的特征,说明这两种岩浆岩可能来源于不同的源区,经历了完全不同的结晶过程。

3.2 云母

南岭科学钻探—孔揭露的岩浆岩中的原生云母均为黑云母,在花岗斑岩和花岗闪长斑岩中以斑

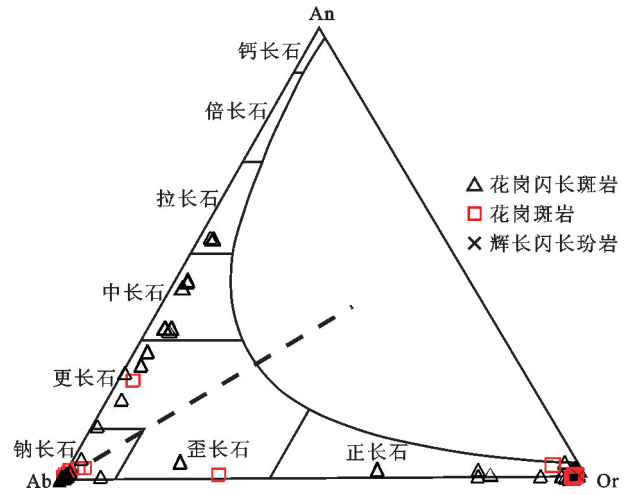


图4 南岭科学钻探—孔所揭露岩浆岩的长石Or-Ab-An图
Fig. 4 Or-Ab-An triangular diagram of feldspars in magmatic rocks exposed in the Nanling Scientific Drill Hole

晶形式产出。花岗斑岩中黑云母含量低,多已蚀变为白云母和碳酸盐;花岗闪长斑岩中的黑云母多色性显著(浅棕色-棕褐色、红棕色-深褐色等),常发生绿泥石化、碳酸盐化,并有针状金红石或粒状磁铁矿析出(图3-f-g)。

电子探针分析结果(表4)显示,花岗闪长斑岩中黑云母的SiO₂含量为31.37%~38.53%, Al₂O₃含量为15.62%~20.46%, TFeO含量为12.14%~21.17%, MgO含量为8.96%~16.33%, TiO₂含量为1.47%~6.60%, K₂O含量为3.45%~10.00%, Na₂O含量为

表4 黑云母电子探针分析结果(%)
Table 4 EPMA analysis results of biotites of magmatic rocks in the Nanling Scientific Drill Hole (%)

岩性 采样深度/m 点号	1045.42										1053.78			1894.37				1949.41				
	11-1	2-1	5-1	5-3	9-1	9-2	3-3	3-3	10-2	11-1	9-2	11-1	11-2	2-1	2-2	2-3	7-1					
SiO ₂	36.49	35.89	38.53	36.98	37.35	36.65	35.95	35.23	33.96	35.43	36.66	36.98	36.83	36.84	36.51	36.74						
TiO ₂	2.48	3.33	2.23	2.35	2.25	2.49	3.83	3.16	3.80	2.57	1.97	3.82	2.14	3.78	3.70	2.47						
Al ₂ O ₃	16.21	16.99	15.62	16.40	16.86	15.87	19.35	16.54	19.98	20.46	16.27	16.37	16.45	16.20	16.49	16.28						
FeO	19.99	17.54	12.14	19.66	16.57	18.98	19.35	21.05	20.25	20.49	17.86	15.70	17.04	16.86	18.21	15.33						
MnO	0.25	0.30	0.08	0.20	0.14	0.19	0.34	0.34	0.58	0.46	0.24	0.35	0.32	0.27	0.44	0.20						
MgO	10.33	10.30	16.33	10.41	12.55	11.35	10.77	10.26	9.45	8.96	11.42	13.48	11.59	12.86	10.96	13.79						
CaO	0.00	0.02	0.04	0.01	0.02	0.00	0.00	0.03	0.50	0.11	0.01	0.01	0.02	0.00	0.02	0.00						
Na ₂ O	0.22	0.55	0.66	0.25	0.42	0.31	0.30	0.14	0.14	0.09	0.29	0.23	0.39	0.29	0.27	0.30						
K ₂ O	9.65	9.56	8.62	9.39	9.18	10.00	9.29	7.13	3.45	4.34	9.47	8.87	9.23	9.03	9.36	8.93						
P ₂ O ₅	0.00	0.00	0.00	0.03	0.01	0.00	0.01	0.00	0.00	0.02	0.01	0.01	0.02	0.00	0.00	0.00						
F	0.17	0.09	0.24	0.14	0.13	0.08	0.24	0.12	0.04	0.06	0.21	0.31	0.39	0.26	0.21	0.69						
Cl	0.09	0.10	0.07	0.09	0.08	0.11	0.16	0.08	0.04	0.05	0.12	0.10	0.14	0.13	0.11	0.10						
Total	95.87	94.66	94.55	95.90	95.54	96.02	95.91	94.09	92.17	93.03	94.51	96.23	94.57	96.52	96.28	94.84						
按22个O计算																						
Si	5.4478	5.3864	5.5899	5.5127	5.4901	5.4174	5.3801	5.4076	5.2130	5.3850	5.4946	5.4193	5.5158	5.4034	5.4173	5.4425						
Al ^{IV}	2.5522	2.6136	2.4101	2.4873	2.5099	2.5826	2.6199	2.5924	2.7870	2.6150	2.5054	2.5807	2.4842	2.5966	2.5827	2.5575						
Al ^{VI}	0.3004	0.3918	0.2608	0.3941	0.4098	0.1831	0.1460	0.4006	0.8270	1.0503	0.3684	0.2465	0.4193	0.2034	0.3007	0.2854						
Ti	0.2787	0.3757	0.2432	0.2635	0.2485	0.2764	0.4314	0.3650	0.4389	0.2934	0.2218	0.4208	0.2414	0.4173	0.4127	0.2753						
Mg [#]	2.2981	2.3047	3.5305	2.3125	2.7490	2.5014	2.4017	2.3484	2.1619	2.0303	2.5507	2.9440	2.5879	2.8113	2.4247	3.0452						
Fe ³⁺	1.5105	1.3506	0.6370	1.6364	1.2007	1.1350	1.5577	2.4102	2.5986	2.6042	1.2594	1.3155	1.2837	1.3473	1.5616	1.0116						
Fe ²⁺	0.9853	0.8508	0.8359	0.8140	0.8352	1.2115	0.8635	0.2917	0.0000	0.0000	0.9787	0.6077	0.8508	0.7204	0.6978	0.8868						
Mn	0.0315	0.0381	0.0096	0.0253	0.0172	0.0234	0.0431	0.0443	0.0751	0.0587	0.0302	0.0437	0.0408	0.0338	0.0547	0.0256						
Ca	0.0005	0.0035	0.0058	0.0021	0.0035	0.0000	0.0000	0.0054	0.0817	0.0178	0.0010	0.0022	0.0032	0.0002	0.0024	0.0006						
K	1.8369	1.8304	1.5954	1.7854	1.7212	1.8857	1.7727	1.3969	0.6746	0.8421	1.8098	1.6580	1.7631	1.6887	1.7721	1.6876						
Na	0.0625	0.1586	0.1861	0.0711	0.1194	0.0877	0.0882	0.0417	0.0414	0.0265	0.0842	0.0659	0.1141	0.0819	0.0776	0.0861						
Mg [#]	0.4794	0.5115	0.7056	0.4855	0.5745	0.5160	0.4980	0.4610	0.4471	0.4326	0.5293	0.5995	0.5433	0.5722	0.5117	0.6128						
Fe ³⁺ /(Fe ³⁺ +Fe ²⁺)	0.3948	0.3865	0.5675	0.3322	0.4102	0.5163	0.3566	0.1080	0.0000	0.0000	0.4373	0.3160	0.3986	0.3484	0.3088	0.4671						
F/Cl	2.0000	0.9010	3.5606	1.5862	1.7600	0.6972	1.5283	1.4699	1.1429	1.0943	1.7395	3.2062	2.7552	2.0233	1.9537	6.8800						

续表4

岩性	花岗岩长英岩												暗色包体																																																																																																																																																																																																																																																																
	1953.18				2258.45				2365.76				2372.60				2527.48				2013.80				2017.29																																																																																																																																																																																																																																																				
采样深度/m	1-1	5-2	6-1	1-2	4-1	6-2	2-2	5-4	6-2	4-1	6-2	2-2	5-4	6-2	7-2	8-1	9-2	9-3	4-1	6-2	6-3	6-4																																																																																																																																																																																																																																																							
Si	5.0304	5.3954	5.0356	5.4436	5.3066	5.6988	4.9239	4.9485	5.2906	5.5577	5.4623	5.4798	5.4014	5.4845	5.4339	5.4767	5.4956	Al ^{IV}	2.9696	2.6046	2.9644	2.5564	2.6934	2.3012	3.0761	3.0515	2.7094	2.4423	2.5377	2.5202	2.5986	2.5155	2.5661	2.5233	2.5044	Al ^{VI}	0.4341	0.3972	0.3643	0.2979	0.6807	1.1133	0.4760	0.2618	0.2583	0.3818	0.2982	0.2350	0.1695	0.3536	0.2387	0.4285	0.3993	Ti	0.2836	0.3713	0.4093	0.3732	0.3047	0.1712	0.2195	0.4486	0.7477	0.2535	0.3991	0.2608	0.3953	0.4080	0.3946	0.2304	0.2663	Mg	2.7628	2.6059	2.9043	2.3293	2.6135	2.2096	3.0727	3.2188	2.4936	2.4681	2.7875	2.5301	2.8032	2.2651	2.7815	2.2740	2.4683	Fe ²⁺	1.2542	2.0388	2.7448	1.7111	2.4654	2.2310	2.4719	2.2862	2.1819	1.4100	1.1853	1.0312	1.0827	1.6581	1.0654	1.4833	1.3361	Fe ³⁺	0.9200	0.3403	0.0000	0.7204	0.0000	0.0000	0.2777	0.1589	0.0000	0.8484	0.7048	1.1792	0.9128	0.6542	0.8531	0.9389	0.8835	Mn	0.0657	0.0630	0.0803	0.0534	0.0516	0.0317	0.0594	0.0433	0.0617	0.0391	0.0572	0.0427	0.0546	0.0487	0.0432	0.0349	0.0253	Ca	0.0236	0.0037	0.0086	0.0021	0.0020	0.0098	0.0020	0.0116	0.0226	0.0000	0.0000	0.0011	0.0030	0.0000	0.0041	0.0010	0.0059	K	1.4827	1.4027	0.7187	1.7446	1.1380	1.2928	0.7035	0.8199	1.3696	1.8413	1.7480	1.9029	1.7717	1.8037	1.7686	1.8149	1.8066	Na	0.0777	0.0814	0.0394	0.0723	0.0295	0.0195	0.0216	0.0552	0.0543	0.0622	0.1242	0.1214	0.1113	0.1131	0.1550	0.0986	0.1130	Mg [#]	0.5523	0.5162	0.5069	0.4838	0.5094	0.4941	0.5224	0.5640	0.5264	0.5179	0.5887	0.5290	0.5776	0.4896	0.5864	0.4807	0.5237	Mg [#] /(Fe ³⁺ +Fe ²⁺)	0.5596	0.5228	0.5141	0.4893	0.5146	0.4976	0.5277	0.5683	0.5333	0.5222	0.5959	0.5337	0.5842	0.4948	0.5918	0.4842	0.5265	F/Cl	0.4231	0.1430	0.0000	0.2963	0.0000	0.0000	0.1010	0.0650	0.0000	0.3757	0.3729	0.5335	0.4574	0.2829	0.4447	0.3876	0.3980	Total	96.78	96.29	92.51	96.43	92.89	91.25	90.71	92.20	95.03	94.06	96.94	97.74	97.35	97.44	98.58	96.69	96.47
Al ^{IV}	2.9696	2.6046	2.9644	2.5564	2.6934	2.3012	3.0761	3.0515	2.7094	2.4423	2.5377	2.5202	2.5986	2.5155	2.5661	2.5233	2.5044	Al ^{VI}	0.4341	0.3972	0.3643	0.2979	0.6807	1.1133	0.4760	0.2618	0.2583	0.3818	0.2982	0.2350	0.1695	0.3536	0.2387	0.4285	0.3993	Ti	0.2836	0.3713	0.4093	0.3732	0.3047	0.1712	0.2195	0.4486	0.7477	0.2535	0.3991	0.2608	0.3953	0.4080	0.3946	0.2304	0.2663	Mg	2.7628	2.6059	2.9043	2.3293	2.6135	2.2096	3.0727	3.2188	2.4936	2.4681	2.7875	2.5301	2.8032	2.2651	2.7815	2.2740	2.4683	Fe ²⁺	1.2542	2.0388	2.7448	1.7111	2.4654	2.2310	2.4719	2.2862	2.1819	1.4100	1.1853	1.0312	1.0827	1.6581	1.0654	1.4833	1.3361	Fe ³⁺	0.9200	0.3403	0.0000	0.7204	0.0000	0.0000	0.2777	0.1589	0.0000	0.8484	0.7048	1.1792	0.9128	0.6542	0.8531	0.9389	0.8835	Mn	0.0657	0.0630	0.0803	0.0534	0.0516	0.0317	0.0594	0.0433	0.0617	0.0391	0.0572	0.0427	0.0546	0.0487	0.0432	0.0349	0.0253	Ca	0.0236	0.0037	0.0086	0.0021	0.0020	0.0098	0.0020	0.0116	0.0226	0.0000	0.0000	0.0011	0.0030	0.0000	0.0041	0.0010	0.0059	K	1.4827	1.4027	0.7187	1.7446	1.1380	1.2928	0.7035	0.8199	1.3696	1.8413	1.7480	1.9029	1.7717	1.8037	1.7686	1.8149	1.8066	Na	0.0777	0.0814	0.0394	0.0723	0.0295	0.0195	0.0216	0.0552	0.0543	0.0622	0.1242	0.1214	0.1113	0.1131	0.1550	0.0986	0.1130	Mg [#]	0.5523	0.5162	0.5069	0.4838	0.5094	0.4941	0.5224	0.5640	0.5264	0.5179	0.5887	0.5290	0.5776	0.4896	0.5864	0.4807	0.5237	Mg [#] /(Fe ³⁺ +Fe ²⁺)	0.5596	0.5228	0.5141	0.4893	0.5146	0.4976	0.5277	0.5683	0.5333	0.5222	0.5959	0.5337	0.5842	0.4948	0.5918	0.4842	0.5265	F/Cl	0.4231	0.1430	0.0000	0.2963	0.0000	0.0000	0.1010	0.0650	0.0000	0.3757	0.3729	0.5335	0.4574	0.2829	0.4447	0.3876	0.3980	Total	96.78	96.29	92.51	96.43	92.89	91.25	90.71	92.20	95.03	94.06	96.94	97.74	97.35	97.44	98.58	96.69	96.47																		
Al ^{VI}	0.4341	0.3972	0.3643	0.2979	0.6807	1.1133	0.4760	0.2618	0.2583	0.3818	0.2982	0.2350	0.1695	0.3536	0.2387	0.4285	0.3993	Ti	0.2836	0.3713	0.4093	0.3732	0.3047	0.1712	0.2195	0.4486	0.7477	0.2535	0.3991	0.2608	0.3953	0.4080	0.3946	0.2304	0.2663	Mg	2.7628	2.6059	2.9043	2.3293	2.6135	2.2096	3.0727	3.2188	2.4936	2.4681	2.7875	2.5301	2.8032	2.2651	2.7815	2.2740	2.4683	Fe ²⁺	1.2542	2.0388	2.7448	1.7111	2.4654	2.2310	2.4719	2.2862	2.1819	1.4100	1.1853	1.0312	1.0827	1.6581	1.0654	1.4833	1.3361	Fe ³⁺	0.9200	0.3403	0.0000	0.7204	0.0000	0.0000	0.2777	0.1589	0.0000	0.8484	0.7048	1.1792	0.9128	0.6542	0.8531	0.9389	0.8835	Mn	0.0657	0.0630	0.0803	0.0534	0.0516	0.0317	0.0594	0.0433	0.0617	0.0391	0.0572	0.0427	0.0546	0.0487	0.0432	0.0349	0.0253	Ca	0.0236	0.0037	0.0086	0.0021	0.0020	0.0098	0.0020	0.0116	0.0226	0.0000	0.0000	0.0011	0.0030	0.0000	0.0041	0.0010	0.0059	K	1.4827	1.4027	0.7187	1.7446	1.1380	1.2928	0.7035	0.8199	1.3696	1.8413	1.7480	1.9029	1.7717	1.8037	1.7686	1.8149	1.8066	Na	0.0777	0.0814	0.0394	0.0723	0.0295	0.0195	0.0216	0.0552	0.0543	0.0622	0.1242	0.1214	0.1113	0.1131	0.1550	0.0986	0.1130	Mg [#]	0.5523	0.5162	0.5069	0.4838	0.5094	0.4941	0.5224	0.5640	0.5264	0.5179	0.5887	0.5290	0.5776	0.4896	0.5864	0.4807	0.5237	Mg [#] /(Fe ³⁺ +Fe ²⁺)	0.5596	0.5228	0.5141	0.4893	0.5146	0.4976	0.5277	0.5683	0.5333	0.5222	0.5959	0.5337	0.5842	0.4948	0.5918	0.4842	0.5265	F/Cl	0.4231	0.1430	0.0000	0.2963	0.0000	0.0000	0.1010	0.0650	0.0000	0.3757	0.3729	0.5335	0.4574	0.2829	0.4447	0.3876	0.3980	Total	96.78	96.29	92.51	96.43	92.89	91.25	90.71	92.20	95.03	94.06	96.94	97.74	97.35	97.44	98.58	96.69	96.47																																				
Ti	0.2836	0.3713	0.4093	0.3732	0.3047	0.1712	0.2195	0.4486	0.7477	0.2535	0.3991	0.2608	0.3953	0.4080	0.3946	0.2304	0.2663	Mg	2.7628	2.6059	2.9043	2.3293	2.6135	2.2096	3.0727	3.2188	2.4936	2.4681	2.7875	2.5301	2.8032	2.2651	2.7815	2.2740	2.4683	Fe ²⁺	1.2542	2.0388	2.7448	1.7111	2.4654	2.2310	2.4719	2.2862	2.1819	1.4100	1.1853	1.0312	1.0827	1.6581	1.0654	1.4833	1.3361	Fe ³⁺	0.9200	0.3403	0.0000	0.7204	0.0000	0.0000	0.2777	0.1589	0.0000	0.8484	0.7048	1.1792	0.9128	0.6542	0.8531	0.9389	0.8835	Mn	0.0657	0.0630	0.0803	0.0534	0.0516	0.0317	0.0594	0.0433	0.0617	0.0391	0.0572	0.0427	0.0546	0.0487	0.0432	0.0349	0.0253	Ca	0.0236	0.0037	0.0086	0.0021	0.0020	0.0098	0.0020	0.0116	0.0226	0.0000	0.0000	0.0011	0.0030	0.0000	0.0041	0.0010	0.0059	K	1.4827	1.4027	0.7187	1.7446	1.1380	1.2928	0.7035	0.8199	1.3696	1.8413	1.7480	1.9029	1.7717	1.8037	1.7686	1.8149	1.8066	Na	0.0777	0.0814	0.0394	0.0723	0.0295	0.0195	0.0216	0.0552	0.0543	0.0622	0.1242	0.1214	0.1113	0.1131	0.1550	0.0986	0.1130	Mg [#]	0.5523	0.5162	0.5069	0.4838	0.5094	0.4941	0.5224	0.5640	0.5264	0.5179	0.5887	0.5290	0.5776	0.4896	0.5864	0.4807	0.5237	Mg [#] /(Fe ³⁺ +Fe ²⁺)	0.5596	0.5228	0.5141	0.4893	0.5146	0.4976	0.5277	0.5683	0.5333	0.5222	0.5959	0.5337	0.5842	0.4948	0.5918	0.4842	0.5265	F/Cl	0.4231	0.1430	0.0000	0.2963	0.0000	0.0000	0.1010	0.0650	0.0000	0.3757	0.3729	0.5335	0.4574	0.2829	0.4447	0.3876	0.3980	Total	96.78	96.29	92.51	96.43	92.89	91.25	90.71	92.20	95.03	94.06	96.94	97.74	97.35	97.44	98.58	96.69	96.47																																																						
Mg	2.7628	2.6059	2.9043	2.3293	2.6135	2.2096	3.0727	3.2188	2.4936	2.4681	2.7875	2.5301	2.8032	2.2651	2.7815	2.2740	2.4683	Fe ²⁺	1.2542	2.0388	2.7448	1.7111	2.4654	2.2310	2.4719	2.2862	2.1819	1.4100	1.1853	1.0312	1.0827	1.6581	1.0654	1.4833	1.3361	Fe ³⁺	0.9200	0.3403	0.0000	0.7204	0.0000	0.0000	0.2777	0.1589	0.0000	0.8484	0.7048	1.1792	0.9128	0.6542	0.8531	0.9389	0.8835	Mn	0.0657	0.0630	0.0803	0.0534	0.0516	0.0317	0.0594	0.0433	0.0617	0.0391	0.0572	0.0427	0.0546	0.0487	0.0432	0.0349	0.0253	Ca	0.0236	0.0037	0.0086	0.0021	0.0020	0.0098	0.0020	0.0116	0.0226	0.0000	0.0000	0.0011	0.0030	0.0000	0.0041	0.0010	0.0059	K	1.4827	1.4027	0.7187	1.7446	1.1380	1.2928	0.7035	0.8199	1.3696	1.8413	1.7480	1.9029	1.7717	1.8037	1.7686	1.8149	1.8066	Na	0.0777	0.0814	0.0394	0.0723	0.0295	0.0195	0.0216	0.0552	0.0543	0.0622	0.1242	0.1214	0.1113	0.1131	0.1550	0.0986	0.1130	Mg [#]	0.5523	0.5162	0.5069	0.4838	0.5094	0.4941	0.5224	0.5640	0.5264	0.5179	0.5887	0.5290	0.5776	0.4896	0.5864	0.4807	0.5237	Mg [#] /(Fe ³⁺ +Fe ²⁺)	0.5596	0.5228	0.5141	0.4893	0.5146	0.4976	0.5277	0.5683	0.5333	0.5222	0.5959	0.5337	0.5842	0.4948	0.5918	0.4842	0.5265	F/Cl	0.4231	0.1430	0.0000	0.2963	0.0000	0.0000	0.1010	0.0650	0.0000	0.3757	0.3729	0.5335	0.4574	0.2829	0.4447	0.3876	0.3980	Total	96.78	96.29	92.51	96.43	92.89	91.25	90.71	92.20	95.03	94.06	96.94	97.74	97.35	97.44	98.58	96.69	96.47																																																																								
Fe ²⁺	1.2542	2.0388	2.7448	1.7111	2.4654	2.2310	2.4719	2.2862	2.1819	1.4100	1.1853	1.0312	1.0827	1.6581	1.0654	1.4833	1.3361	Fe ³⁺	0.9200	0.3403	0.0000	0.7204	0.0000	0.0000	0.2777	0.1589	0.0000	0.8484	0.7048	1.1792	0.9128	0.6542	0.8531	0.9389	0.8835	Mn	0.0657	0.0630	0.0803	0.0534	0.0516	0.0317	0.0594	0.0433	0.0617	0.0391	0.0572	0.0427	0.0546	0.0487	0.0432	0.0349	0.0253	Ca	0.0236	0.0037	0.0086	0.0021	0.0020	0.0098	0.0020	0.0116	0.0226	0.0000	0.0000	0.0011	0.0030	0.0000	0.0041	0.0010	0.0059	K	1.4827	1.4027	0.7187	1.7446	1.1380	1.2928	0.7035	0.8199	1.3696	1.8413	1.7480	1.9029	1.7717	1.8037	1.7686	1.8149	1.8066	Na	0.0777	0.0814	0.0394	0.0723	0.0295	0.0195	0.0216	0.0552	0.0543	0.0622	0.1242	0.1214	0.1113	0.1131	0.1550	0.0986	0.1130	Mg [#]	0.5523	0.5162	0.5069	0.4838	0.5094	0.4941	0.5224	0.5640	0.5264	0.5179	0.5887	0.5290	0.5776	0.4896	0.5864	0.4807	0.5237	Mg [#] /(Fe ³⁺ +Fe ²⁺)	0.5596	0.5228	0.5141	0.4893	0.5146	0.4976	0.5277	0.5683	0.5333	0.5222	0.5959	0.5337	0.5842	0.4948	0.5918	0.4842	0.5265	F/Cl	0.4231	0.1430	0.0000	0.2963	0.0000	0.0000	0.1010	0.0650	0.0000	0.3757	0.3729	0.5335	0.4574	0.2829	0.4447	0.3876	0.3980	Total	96.78	96.29	92.51	96.43	92.89	91.25	90.71	92.20	95.03	94.06	96.94	97.74	97.35	97.44	98.58	96.69	96.47																																																																																										
Fe ³⁺	0.9200	0.3403	0.0000	0.7204	0.0000	0.0000	0.2777	0.1589	0.0000	0.8484	0.7048	1.1792	0.9128	0.6542	0.8531	0.9389	0.8835	Mn	0.0657	0.0630	0.0803	0.0534	0.0516	0.0317	0.0594	0.0433	0.0617	0.0391	0.0572	0.0427	0.0546	0.0487	0.0432	0.0349	0.0253	Ca	0.0236	0.0037	0.0086	0.0021	0.0020	0.0098	0.0020	0.0116	0.0226	0.0000	0.0000	0.0011	0.0030	0.0000	0.0041	0.0010	0.0059	K	1.4827	1.4027	0.7187	1.7446	1.1380	1.2928	0.7035	0.8199	1.3696	1.8413	1.7480	1.9029	1.7717	1.8037	1.7686	1.8149	1.8066	Na	0.0777	0.0814	0.0394	0.0723	0.0295	0.0195	0.0216	0.0552	0.0543	0.0622	0.1242	0.1214	0.1113	0.1131	0.1550	0.0986	0.1130	Mg [#]	0.5523	0.5162	0.5069	0.4838	0.5094	0.4941	0.5224	0.5640	0.5264	0.5179	0.5887	0.5290	0.5776	0.4896	0.5864	0.4807	0.5237	Mg [#] /(Fe ³⁺ +Fe ²⁺)	0.5596	0.5228	0.5141	0.4893	0.5146	0.4976	0.5277	0.5683	0.5333	0.5222	0.5959	0.5337	0.5842	0.4948	0.5918	0.4842	0.5265	F/Cl	0.4231	0.1430	0.0000	0.2963	0.0000	0.0000	0.1010	0.0650	0.0000	0.3757	0.3729	0.5335	0.4574	0.2829	0.4447	0.3876	0.3980	Total	96.78	96.29	92.51	96.43	92.89	91.25	90.71	92.20	95.03	94.06	96.94	97.74	97.35	97.44	98.58	96.69	96.47																																																																																																												
Mn	0.0657	0.0630	0.0803	0.0534	0.0516	0.0317	0.0594	0.0433	0.0617	0.0391	0.0572	0.0427	0.0546	0.0487	0.0432	0.0349	0.0253	Ca	0.0236	0.0037	0.0086	0.0021	0.0020	0.0098	0.0020	0.0116	0.0226	0.0000	0.0000	0.0011	0.0030	0.0000	0.0041	0.0010	0.0059	K	1.4827	1.4027	0.7187	1.7446	1.1380	1.2928	0.7035	0.8199	1.3696	1.8413	1.7480	1.9029	1.7717	1.8037	1.7686	1.8149	1.8066	Na	0.0777	0.0814	0.0394	0.0723	0.0295	0.0195	0.0216	0.0552	0.0543	0.0622	0.1242	0.1214	0.1113	0.1131	0.1550	0.0986	0.1130	Mg [#]	0.5523	0.5162	0.5069	0.4838	0.5094	0.4941	0.5224	0.5640	0.5264	0.5179	0.5887	0.5290	0.5776	0.4896	0.5864	0.4807	0.5237	Mg [#] /(Fe ³⁺ +Fe ²⁺)	0.5596	0.5228	0.5141	0.4893	0.5146	0.4976	0.5277	0.5683	0.5333	0.5222	0.5959	0.5337	0.5842	0.4948	0.5918	0.4842	0.5265	F/Cl	0.4231	0.1430	0.0000	0.2963	0.0000	0.0000	0.1010	0.0650	0.0000	0.3757	0.3729	0.5335	0.4574	0.2829	0.4447	0.3876	0.3980	Total	96.78	96.29	92.51	96.43	92.89	91.25	90.71	92.20	95.03	94.06	96.94	97.74	97.35	97.44	98.58	96.69	96.47																																																																																																																														
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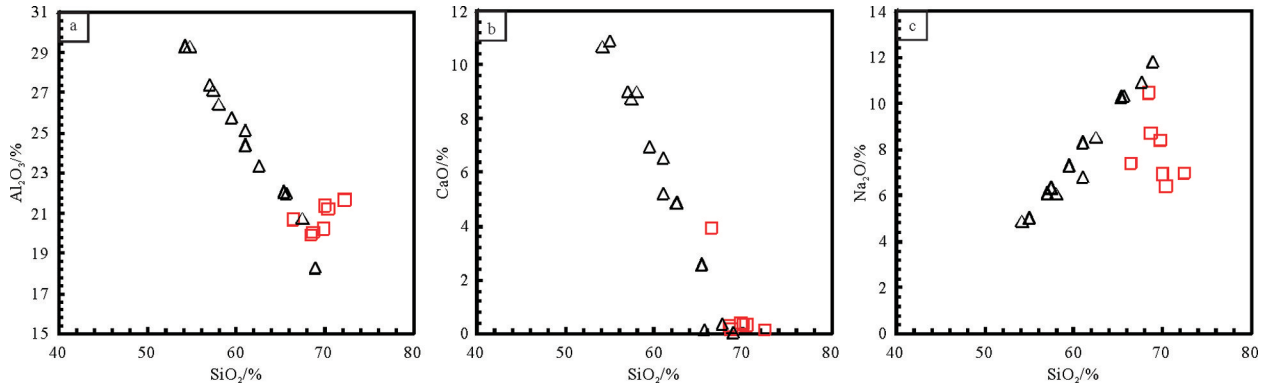


图5 南岭科学钻探一孔所揭露岩浆岩中斜长石的SiO₂-Al₂O₃(a)、SiO₂-CaO(b)、SiO₂-Na₂O(c)图(图例同图4)
Fig. 5 SiO₂-Al₂O₃(a), SiO₂-CaO (b) and SiO₂-Na₂O (c) diagrams of plagioclases in magmatic rocks exposed in the Nanling Scientific Drill Hole (symbols as for Fig. 4)

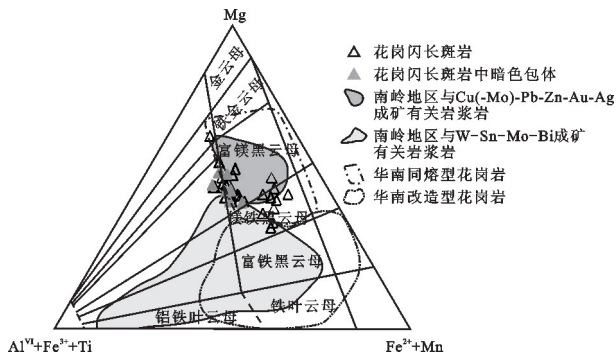


图6 南岭科学钻探一孔所揭露岩浆岩中黑云母分类图解(底图据文献[13-15]修改)
Fig. 6 The classification diagram of biotites in magmatic rocks exposed in the Nanling Scientific Drill Hole (modified after references [13-15])

0.07%~0.66%, $Mg^{\#}$ ($Mg/(Mg+Fe^{2+}+Fe^{3+})$) 为 0.44~0.71, $Fe^{3+}/(Fe^{2+}+Fe^{3+})$ 值为 0~0.57, 并含有少量的 F、Cl。孔深 2013.05~2017.50 m 钻遇的花岗闪长斑岩中含暗色包体, 与花岗闪长斑岩中的黑云母相比, 包体中的黑云母具有较高的 K₂O、Na₂O、Cl 含量(分别为 9.32%~10.10%、0.21%~0.55%、0.09%~0.19%) 和 $Fe^{3+}/(Fe^{2+}+Fe^{3+})$ 值(0.28~0.53), 以及显著高的 F 含量(0.37%~2.07%)。在黑云母分类图(图6)中, 少数黑云母落在镁铁黑云母区域, 大部分黑云母落在富镁黑云母区域。

花岗斑岩和花岗闪长斑岩中的白云母均由黑云母蚀变而来, 二者相比, 花岗斑岩中的白云母具有高铝、低镁钾的特点(表5)。在 Al^{VI}-Mg 图和

Al^{VI}-Fe/(Fe+Mg)图(图7)中, 两种次生白云母可以分为截然不同的两类: 花岗斑岩中的白云母具有高的 Al^{VI} 值(3.30~4.15)、Fe/(Fe+Mg) 值(0.72~0.89) 和低的 Mg 原子数, 花岗闪长斑岩中的白云母则具有低的 Al^{VI} 值(2.55~3.47)、Fe/(Fe+Mg) 值(0.14~0.59) 和高的 Mg 原子数。

3.3 磷灰石

磷灰石主要见于花岗闪长斑岩中, 呈自形粒状、柱状, 粒径 0.1~0.5 mm, 个别可达 1.5~3 mm, 主要赋存于基质中, 部分包裹于石英、长石或黑云母斑晶中(图3-g、i-j)。电子探针分析结果(表6)表明, 磷灰石中 CaO 含量为 53.95%~55.81%, P₂O₅ 含量为 39.62%~44.54%, SO₃ 含量为 0.01%~0.11%, F 含量为 0.47%~2.96%, Cl 含量为 0.01%~0.52%。磷灰石中 F 含量显著高于 Cl 含量, $X_F/(X_{Cl}+X_F)$ 值为 0.74~1.00。与铜厂花岗闪长斑岩中的磷灰石^[16]相比, 南岭科学钻探一孔中的磷灰石具有较低的 P₂O₅、F、Cl 含量和稍高的 $X_F/(X_{Cl}+X_F)$ 值。

3.4 石榴石

石榴石仅见于孔深 2258.45~2264.75 m 的花岗闪长斑岩中, 发育环带结构(图3-k), 属于钙铝榴石, 其 Pyr(镁铝榴石) 分子含量为 0.26%~0.51%, Spe(锰铝榴石) 分子含量为 0.91%~1.93%, Gro(钙铝榴石) 分子含量为 51.59%~62.49%, Alm(铁铝榴石) 分子含量为 22.35%~29.36%, 其他端元分子含量为 7.72%~24.18%(表7)。从核部到边部, 石榴石的 X_{Ca} 值 ($Ca/(Ca+Fe+Mn+Mg)$) 与 X_{Fe} 值 ($Fe/(Ca+Fe+Mn+$

表5 白云母电子探针分析结果(平均值)(%)

Table 5 EPMA analysis results of muscovites of magmatic rocks in the Nanling Scientific Drill Hole (mean value) (%)

岩性	花岗闪长斑岩											花岗斑岩		
	17.48	20.5	1045.42	1052.54	1502.06	1508.04	2011.94	2014.3	2017.29	2365.76	2870	1380.52	1429.73	1663.23
采样深度/m	2	2	1	1	1	2	1	2	2	1	1	3	2	1
分析点数	2	2	1	1	1	2	1	2	2	1	1	3	2	1
SiO ₂	50.52	50.84	48.53	49.29	50.55	50.09	48.41	53.15	50.50	55.59	51.55	51.54	52.68	50.86
TiO ₂	0.41	0.21	0.59	0.32	0.61	0.59	0.07	0.20	0.24	0.13	0.22	0.13	0.10	0.02
Al ₂ O ₃	30.27	31.38	29.79	28.38	30.30	28.82	34.81	30.47	29.91	29.14	29.84	32.01	35.44	35.58
FeO	4.34	3.29	3.94	4.10	3.73	5.37	1.10	0.98	1.18	2.89	2.20	4.98	3.45	1.26
MnO	0.02	0.00	0.00	0.04	0.04	0.03	0.04	0.02	0.00	0.06	0.00	0.59	0.03	0.04
MgO	1.82	1.47	2.35	2.54	1.85	3.07	0.42	2.47	2.66	3.89	2.62	0.55	0.64	0.15
CaO	0.02	0.02	0.10	0.00	0.02	0.00	0.03	0.01	0.00	0.15	0.07	0.04	0.01	0.15
Na ₂ O	0.05	0.03	0.14	0.12	0.15	0.16	0.13	0.05	0.14	0.03	0.09	0.14	0.11	0.09
K ₂ O	7.73	7.94	10.91	11.15	10.01	10.98	10.77	10.85	10.82	4.77	10.79	7.33	6.95	7.54
P ₂ O ₅	0.01	0.02	0.00	0.00	0.00	0.02	0.03	0.00	0.01	0.00	0.00	0.02	0.00	0.01
F	0.25	0.13	0.06	0.30	0.01	0.02	0.04	0.12	0.85	0.18	0.08	0.54	0.30	0.00
Cl	0.00	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.03	0.02	0.00	0.01	0.01	0.00
Total	95.43	95.33	96.42	96.25	97.27	99.14	95.85	98.33	96.34	96.84	97.46	97.89	99.70	95.70
Si	6.4398	6.4811	6.1865	6.2831	6.4432	6.3844	6.1707	6.7754	6.4369	7.0862	6.5714	6.5701	6.7153	6.4835
Al	4.5482	4.7146	4.4760	4.2646	4.5523	4.3305	5.2298	4.5784	4.4947	4.3789	4.4838	4.8100	5.3241	5.3461
Al ^{IV}	1.5602	1.5189	1.8135	1.7169	1.5568	1.6156	1.8293	1.2246	1.5631	0.9138	1.4286	1.4299	1.2847	1.5165
Al ^{VI}	2.9879	3.1957	2.6624	2.5477	2.9955	2.7150	3.4004	3.3538	2.9316	3.4651	3.0552	3.3801	4.0394	3.8295
Ti	0.0388	0.0204	0.0566	0.0304	0.0585	0.0562	0.0063	0.0193	0.0228	0.0121	0.0212	0.0127	0.0094	0.0015
Fe	0.4623	0.3512	0.4199	0.4372	0.3974	0.5720	0.1172	0.1048	0.1263	0.3083	0.2344	0.5309	0.3681	0.1346
Mn	0.0020	0.0000	0.0000	0.0041	0.0038	0.0033	0.0045	0.0026	0.0000	0.0060	0.0000	0.0638	0.0027	0.0039
Mg	0.3464	0.2785	0.4458	0.4834	0.3521	0.5835	0.0802	0.4688	0.5059	0.7390	0.4971	0.1041	0.1208	0.0277
Ca	0.0027	0.0022	0.0137	0.0000	0.0026	0.0000	0.0044	0.0007	0.0003	0.0202	0.0089	0.0056	0.0008	0.0205
Na	0.0135	0.0074	0.0351	0.0294	0.0371	0.0395	0.0311	0.0129	0.0334	0.0064	0.0232	0.0349	0.0279	0.0225
K	1.2571	1.2911	1.7750	1.8142	1.6276	1.7854	1.7520	1.7646	1.7603	0.7764	1.7555	1.1924	1.1300	1.2262
Fe/(Fe+Mg)	0.57	0.56	0.49	0.47	0.53	0.50	0.59	0.18	0.20	0.29	0.32	0.84	0.75	0.83

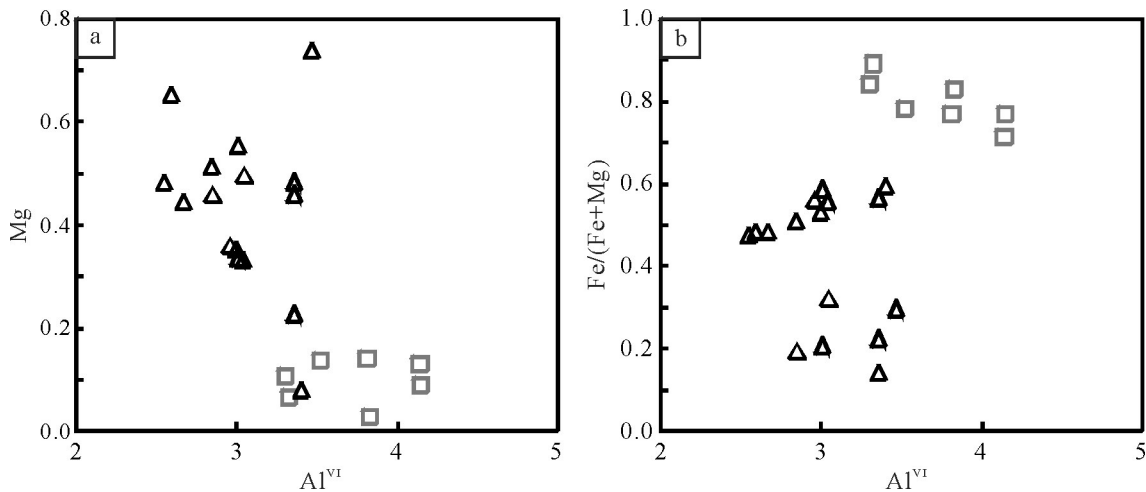


图7 南岭科学钻探—孔中揭露岩浆岩中白云母的Al^{VI}-Mg图(a)和Al^{VI}-Fe/(Fe+Mg)图(b)(图例同图4)
Fig. 7 Al^{VI}-Mg (a) and Al^{VI}-Fe/(Fe+Mg) (b) diagrams of muscovites in magmatic rocks exposed in the Nanling Scientific Drill Hole (symbols as for Fig. 4)

Mg))发生反向震荡性变化, X_{Ca}值总体稍呈降低趋势, X_{Fe}值总体稍呈升高趋势(图8)。具有较高钙铝榴石组分的石榴石的产出,说明岩石的成岩温度高,且岩浆的同化能力强^[17]。

3.5 绿泥石

绿泥石在花岗闪长斑岩中广泛存在,主要是在热液蚀变过程中由黑云母、角闪石蚀变而来(图3-e, g, i),大部分属于蠕绿泥石(铁绿泥石)-密绿泥石

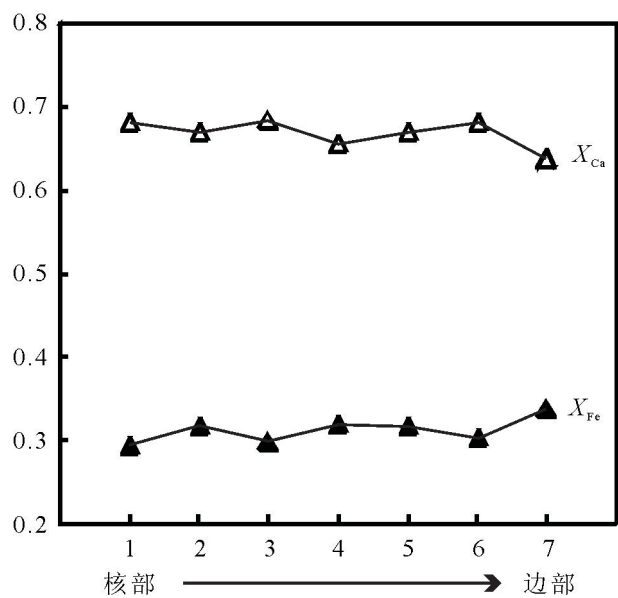


图8 石榴石从核部到边部的 X_{Fe} 值与 X_{Ca} 值变化特征
Fig. 8 The variation of X_{Fe} and X_{Ca} value from core to edge in garnet

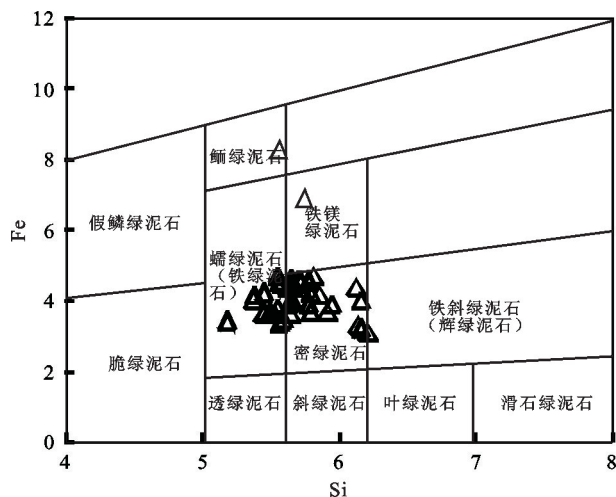


图9 南岭科学钻探一孔所揭露岩浆岩中绿泥石分类图解(底图据文献[18])(图例同图4)
Fig. 9 The classification diagram of chlorites in magmatic rocks exposed in the Nanling Scientific Drill Hole (after reference [18]) (symbols as for Fig. 4)

表6 花岗闪长斑岩中磷灰石电子探针分析结果(平均值)(%)

Table 6 EPMA analysis results of apatites of granodiorite porphyry in the Nanling Scientific Drill Hole (mean value) (%)

样品深度/m	分析点数	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	F	Cl	SO ₃	Total	$X_F/(X_F+X_{Cl})$
17.48	1	0.11	0.05	0.00	0.13	0.23	0.04	55.01	0.06	0.00	41.18	2.02	0.28		99.11	0.93
1043.6	1	0.25	0.03	0.01	0.28	0.18	0.07	54.48	0.29	0.04	39.62	0.66	0.43		96.33	0.74
1045.42	1	0.02	0.02	0.00	0.12	0.19	0.04	54.26	0.08	0.00	40.95	0.70	0.21		96.59	0.86
1052.54	1	0.26	0.00	0.02	0.25	0.19	0.07	54.63	0.26	0.02	39.78	2.71	0.46		98.64	0.92
1053.78	1	0.04	0.02	0.00	0.21	0.22	0.04	54.29	0.13	0.00	41.25	1.67	0.52	0.08	98.45	0.86
1104.07	2	0.09	0.00	0.00	0.13	0.30	0.05	54.21	0.13	0.00	41.23	1.78	0.32	0.08	98.31	0.91
1438.79	2	0.05	0.02	0.03	0.15	0.17	0.18	54.62	0.14	0.01	40.46	2.25	0.17		98.26	0.96
1455.13	3	0.10	0.02	0.02	0.20	0.28	0.02	54.28	0.07	0.01	42.16	1.04	0.22		98.42	0.90
1502.06	1	0.09	0.02	0.00	0.37	0.29	0.02	55.13	0.05	0.01	40.44	1.03	0.38		97.82	0.83
1667.75	1	0.12	0.00	0.07	0.23	0.23	0.06	54.14	0.16	0.03	41.69	2.18	0.16		99.07	0.96
1894.37	1	0.01	0.03	0.01	0.06	0.12	0.00	55.21	0.13	0.00	40.47	0.75	0.15		96.93	0.90
1949.41	3	0.31	0.00	0.02	0.25	0.22	0.06	54.44	0.16	0.01	40.71	1.83	0.33		98.35	0.91
1953.18	2	0.07	0.00	0.01	0.12	0.18	0.02	54.49	0.05	0.00	41.49	2.12	0.21	0.03	98.78	0.94
2011.94	3	0.10	0.00	0.02	0.20	0.21	0.03	55.05	0.06	0.02	40.87	1.06	0.29		97.89	0.87
2013.8	1	0.02	0.00	0.00	0.16	0.39	0.05	54.38	0.12	0.00	40.56	2.32	0.28		98.30	0.94
2014.3	1	0.15	0.00	0.02	0.21	0.37	0.03	54.05	0.17	0.02	41.15	1.68	0.20		98.04	0.94
2017.29	3	0.10	0.00	0.01	0.15	0.14	0.04	54.37	0.11	0.01	41.00	2.79	0.09		98.81	0.98
2372.6	3	0.06	0.01	0.00	0.19	0.17	0.04	54.72	0.13	0.01	40.65	0.58	0.27		96.83	0.79

注： $X_i/(X_i+X_c)$ 为原子数之比。

表7 花岗闪长斑岩中石榴石电子探针分析结果(%)

Table 7 EPMA analysis results of garnet of granodiorite porphyry in the Nanling Scientific Drill Hole (%)

分析点号	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	F	Cl	Total	Pyr	Spe	Gro	Alm	Other	X _{Mg}	X _{Fe}	X _{Mn}	X _{Ca}
1	37.59	0.26	20.58	9.72	0.62	0.11	17.52	0.18	0.06	0.03	0.11	0.02	86.78	0.43	1.45	51.59	22.35	24.18	0.0057	0.2947	0.0191	0.6805
2	36.75	0.04	20.66	12.76	0.39	0.10	21.04	0.00	0.00	0.07	0.00	0.00	91.81	0.41	0.91	61.72	29.23	7.72	0.0045	0.3167	0.0099	0.6689
3	37.06	0.17	21.72	11.50	0.56	0.07	20.47	0.01	0.00	0.00	0.05	0.01	91.61	0.26	1.24	57.12	25.04	16.33	0.0032	0.2993	0.0149	0.6827
4	36.21	0.21	20.47	11.90	0.68	0.12	19.06	0.00	0.00	0.05	0.01	0.01	88.71	0.51	1.59	56.43	27.49	13.98	0.0059	0.3195	0.0185	0.6560
5	37.58	0.08	21.27	13.14	0.42	0.07	21.61	0.00	0.02	0.06	0.04	0.00	94.29	0.27	0.93	61.56	29.23	8.01	0.0029	0.3177	0.0102	0.6692
6	36.80	0.09	20.53	12.07	0.41	0.10	21.17	0.05	0.04	0.03	0.00	0.01	91.30	0.42	0.95	62.49	27.82	8.31	0.0046	0.3034	0.0104	0.6816
7	34.45	0.00	19.24	11.94	0.77	0.08	17.52	0.00	0.01	0.05	0.00	0.00	84.07	0.36	1.93	55.19	29.36	13.17	0.0041	0.3381	0.0222	0.6356

注: X_{Mg} =Mg/(Fe+Mn+Mg+Ca); X_{Fe} =Fe/(Fe+Mn+Mg+Ca); X_{Mn} =Mn/(Fe+Mn+Mg+Ca); X_{Ca} =Ca/(Fe+Mn+Mg+Ca)。

表8 绿泥石电子探针分析结果(平均值)(%)

Table 8 EPMA analysis results of chlorites of magmatic rocks in the Nanling Scientific Drill Hole (mean value) (%)

采样深度/m	1043.60	1045.42	1104.07	1455.13	1502.06	1508.04	1667.75	1667.75	1894.37	2011.94	2258.45	2365.76	2372.60	2527.48	2870.00	
分析点数	5	1	3	4	1	1	3	2	6	2	2	4	4	1	1	
SiO ₂	27.42	27.38	27.08	27.43	26.54	27.46	26.06	25.33	27.33	27.62	28.41	26.51	29.40	26.61	28.08	
TiO ₂	1.73	0.04	1.93	0.10	0.06	0.15	0.06	0.04	0.84	0.13	0.13	0.04	0.14	0.80	0.06	
Al ₂ O ₃	20.61	21.83	20.38	21.47	20.39	20.99	22.70	20.56	19.48	19.19	19.00	20.25	21.47	20.01	20.16	
FeO	20.54	19.77	22.26	22.28	26.83	22.61	22.77	40.44	25.02	22.97	25.34	25.46	21.38	24.69	21.29	
MnO	0.18	0.69	0.28	0.46	0.46	0.58	0.35	0.12	0.54	0.13	0.61	0.56	0.24	0.72	0.62	
MgO	16.33	18.35	15.78	15.73	14.80	16.29	15.66	2.39	13.20	16.62	14.17	14.56	15.40	14.22	17.28	
CaO	0.03	0.01	0.04	0.03	0.03	0.39	0.01	0.05	0.49	0.02	0.04	0.02	0.06	0.00	0.02	
Na ₂ O	0.05	0.03	0.02	0.06	0.03	0.07	0.11	0.54	0.04	0.01	0.02	0.04	0.06	0.02	0.02	
K ₂ O	0.66	0.01	0.19	0.20	0.00	0.13	0.01	0.59	0.25	0.01	0.27	0.02	0.56	0.08	0.06	
P ₂ O ₅	0.01	0.00	0.01	0.01	0.02	0.05	0.02	0.00	0.00	0.02	0.00	0.01	0.01	0.00	0.00	
F	0.04	0.05	0.02	0.06	0.00	0.10	0.04	0.00	0.05	0.06	0.05	0.06	0.06	0.02	0.01	
Cl	0.01	0.01	0.01	0.01	0.00	0.01	0.03	0.12	0.01	0.01	0.01	0.01	0.01	0.00	0.00	
Total	87.60	88.16	87.99	87.83	89.15	88.82	87.82	90.19	87.24	86.78	88.04	87.54	88.79	87.17	87.61	
按28个O计算																
Si	5.6335	5.5541	5.5877	5.6581	5.5370	5.6210	5.3933	5.6417	5.7849	5.7842	5.9467	5.5991	5.9313	5.6294	5.7765	
Al ^{IV}	2.3665	2.4459	2.4123	2.3419	2.4630	2.3790	2.6067	2.3583	2.2151	2.2158	2.0533	2.4009	2.0687	2.3706	2.2235	
Al ^{VI}	2.6301	2.7755	2.5458	2.8756	2.5519	2.6874	2.9305	3.0259	2.6505	2.5265	2.6350	2.6415	3.0436	2.6179	2.6666	
Ti	0.2707	0.0064	0.2991	0.0148	0.0093	0.0228	0.0089	0.0066	0.1318	0.0208	0.0203	0.0066	0.0216	0.1279	0.0088	
Fe	3.5341	3.3538	3.8430	3.8439	4.6819	3.8718	3.9422	7.5729	4.4346	4.0338	4.4368	4.4986	3.6241	4.3685	3.6628	
Mn	0.0310	0.1177	0.0482	0.0808	0.0818	0.1002	0.0613	0.0232	0.0974	0.0230	0.1085	0.0992	0.0408	0.1283	0.1088	
Mg	5.0110	5.5500	4.8485	4.8344	4.6033	4.9702	4.8327	0.7932	4.1695	5.1856	4.4238	4.5840	4.6421	4.4832	5.3009	
Ca	0.0056	0.0017	0.0091	0.0062	0.0056	0.0845	0.0017	0.0121	0.1092	0.0045	0.0078	0.0055	0.0136	0.0000	0.0046	
Na	0.0217	0.0114	0.0096	0.0239	0.0109	0.0282	0.0452	0.2404	0.0145	0.0043	0.0083	0.0173	0.0249	0.0086	0.0092	
K	0.1700	0.0018	0.0510	0.0516	0.0000	0.0350	0.0019	0.1645	0.0657	0.0015	0.0714	0.0067	0.1413	0.0208	0.0160	
Fe/(Fe+Mg)	0.41	0.38	0.44	0.44	0.5042	0.44	0.45	0.90	0.52	0.44	0.50	0.50	0.44	0.49	0.41	
T/°C-a	319	332	326	315	335	321	358	318	295	295	269	325	271	320	296	
T/°C-b	322	333	330	319	340	324	361	336	301	298	274	330	275	325	299	

注: T/°C-a 根据文献[35]计算: T=321.98Al^{IV}/2-61.92; T/°C-b 根据文献[36]计算: T=319[Al^{IV}/2+0.1Fe/(Fe+Mg)]-69。

(图9),其SiO₂含量为24.56%~31.74%,平均值27.42%;TiO₂含量为0~4.78%,平均值0.59%;Al₂O₃含量为18.15%~23.03%,平均值20.57%;FeO含量为18.92%~26.83%,平均值23.06%;MgO含量为11.69%~18.35%,平均值15.27%,Fe/(Fe+Mg)值为0.38~0.56(表8)。1667.75 m出现富铁的鲕绿泥石、铁镁绿泥石,其FeO含量为38.64%~42.25%,MgO含量为2.14%~2.65%,Fe/(Fe+Mg)值为0.89~0.92。

4 讨论

4.1 岩浆岩成因类型和岩浆源区特征

岩石的矿物组合和矿物成分是岩浆成分的直接反映,岩浆岩中的长石、云母等造岩矿物中蕴含大量成因信息,对岩浆岩成因类型和岩浆源区等方面具有重要的指示意义。徐克勤等提出同熔型花岗岩中的黑云母具有较高的Mg/(Mg+Fe²⁺+Fe³⁺)和

$Fe^{3+}/(Fe^{2+}+Fe^{3+})$ 比值,改造型花岗岩中黑云母的上述两比值较低^[19]。在 $Mg/(Mg+Fe^{2+}+Fe^{3+})-Fe^{3+}/(Fe^{2+}+Fe^{3+})$ 图解(图 10-a)中,南岭科学钻探一孔花岗闪长斑岩中的黑云母分为 2 组,一组落在同熔型花岗岩范围,一组落在改造型花岗岩范围,而落在改造型花岗岩范围的 9 个黑云母所属的花岗闪长斑岩分别产于孔深 1892.16~1896.33 m、1952.95~1961.10 m、2365.96~2527.77 m,其围岩为含炭质泥岩、含炭质粉砂岩、泥灰岩夹含炭质泥岩,还原性围岩可能是导致其 $Fe^{3+}/(Fe^{2+}+Fe^{3+})$ 值偏低的主要原因。在 $Mg-(Al^{VI}+Fe^{3+}+Ti)-(Fe^{2+}+Mn)$ 图(图 6)中,花岗闪长斑岩中的黑云母大部分也落在华南同熔型花岗岩范围内。Abdel-Rahman 提出 I 型花岗岩中的黑云母相对富镁,S 型花岗岩中的黑云母相对富铝,A 型花岗岩中的黑云母相对富铁^[20],南岭科学钻探一孔中花岗闪长斑岩中的黑云母为富镁黑云母-镁铁黑云母,指示花岗闪长斑岩具有 I 型花岗岩特征。在 $Si-Mg/(Mg+Mn+Fe^{2+}+Fe^{3+})$ 图(图 10-b)中,黑云母落在华南同熔型花岗岩区域。在黑云母的 $MgO-TFeO/(TFeO+MgO)$ 图解(图 10-c)中,本文所研究黑云母一个落在壳源区,一个落在幔源区,其余均落于壳幔混源区域。黑云母矿物化学特征指示南岭科学钻探一孔中花岗闪长斑岩的源区同时有地壳和地幔物质的参与,这与其锆石 Hf 同位素所反映的岩石成因信息一致^[5]。

4.2 暗色包体对岩浆演化的指示信息

南岭科学钻探一孔 2011.93~2017.50 m 孔段花岗闪长斑岩中含暗色包体,包体呈灰黑色水滴状、不规则状,大小 4~10 cm,与寄主岩界线清晰截然

(图 11-a~c),寄主岩一侧发育宽 1~2 mm 的褪色边。不规则包体中见寄主岩呈细脉状穿入,形成反向脉。上述现象指示了岩浆混合作用的存在^[23]。在包体与寄主岩的边界上,可以观察到球状石英斑晶跨越边界(图 11-e);暗色矿物呈细长片状,且长轴方向与边界一致(图 11-d);寄主岩中石英斑晶发育变形纹(图 11-g),包体中黑云母斑晶显示塑性变形特征(图 11-f),说明包体与寄主岩经历了液态共存阶段^[24]。寄主岩斑晶为石英、长石、黑云母,岩石蚀变强烈,并发育稠密浸染状黄铁矿化;包体中斑晶主要为长石和黑云母,且蚀变微弱,发育稀疏浸染状黄铁矿化(图 3-e~f、图 11-e);二者的黑云母成分存在差异,以上特征说明参与混合作用的两种岩浆成分不同,相较于寄主岩,包体岩浆更贫硅、富碱,高 F/Cl 值则指示包体岩浆分异程度更高^[25]。包体与寄主岩矿物粒度相似,可能说明二者温度差异较小。

此外,矿物不平衡现象十分普遍:斜长石斑晶被熔蚀呈卵状,内部发育针状磷灰石(图 11-i)。花岗闪长斑岩中观察到反环带斜长石,被熔蚀圆滑的斜长石颗粒外部生长自形环边(图 11-j),电子探针结果显示,边部较核部更偏基性,在核部为更长石(孔深 1045.42~1052.01 m, $Ab_{87}An_{12}$)或中长石(1949.41 m, $Ab_{57}An_{40}$)时,边部分别为中长石($Ab_{52}An_{47}$)、拉长石($Ab_{43}An_{56}$);石英斑晶边部被拉长石熔蚀交代(图 11-l),这些现象指示花岗闪长质岩浆可能与更基性的岩浆发生了混合作用^[26-27]。石英斑晶内部包含细粒的长石、云母、钛铁矿物集合体(图 11-k),这是一种更小尺度的包体。综合以上信息发现,花岗闪长斑岩在形成过程中普遍存在岩浆

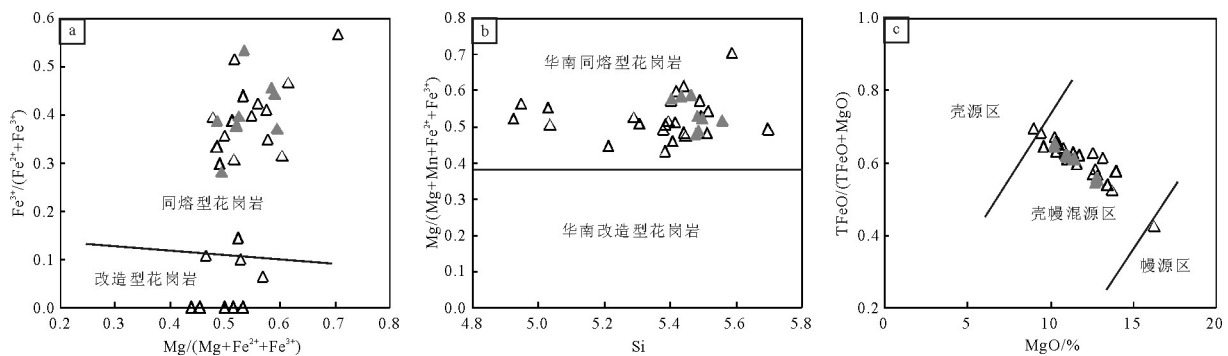


图 10 黑云母判别岩石成因类型图解(a底图据文献[19];b底图据文献[21];c底图据文献[22])(图例同图 6)

Fig. 10 Discrimination diagrams of biotite for granite genetic types (diagram a after reference [19], b after reference [21], and c after reference [22]) (symbols as for Fig. 6)

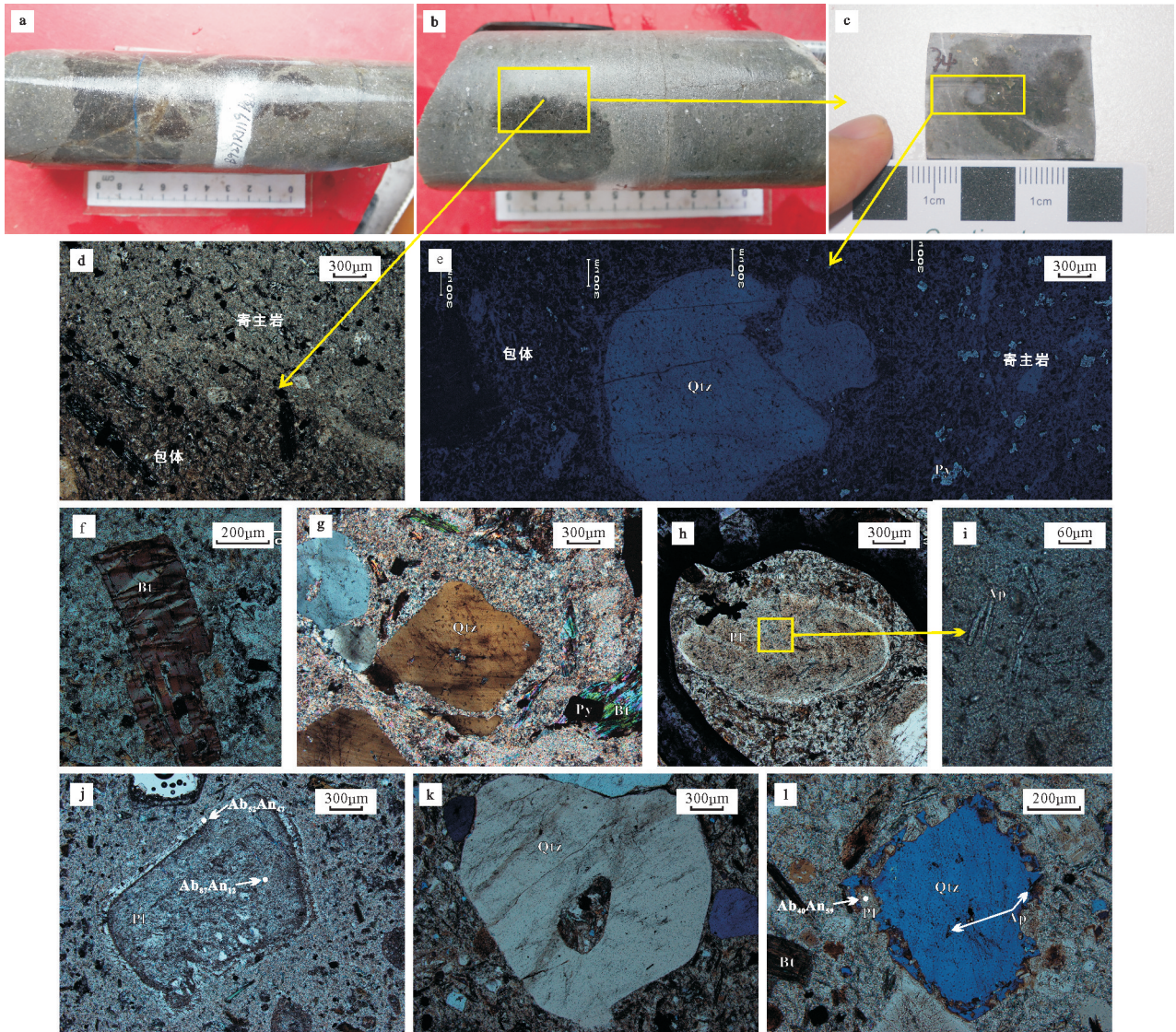


图 11 南岭科学钻探一孔中岩浆混合作用的岩石学、岩相学特征

a-c—2011.93~2017.50 m 花岗闪长斑岩中暗色包体;d—包体与寄主岩的界线清晰截然,单偏光;e—熔蚀的石英斑晶横跨包体和寄主岩,包体和寄主岩中黄铁矿含量显著不同,反射光;f—包体中黑云母发生塑性变形,单偏光;g—寄主岩中石英斑晶发育变形纹,并发生破裂,正交偏光;h-i—斜长石斑晶被熔蚀呈卵形,内部含针状磷灰石,孔深 1949.41 m 花岗闪长斑岩,单偏光;j—更长石斑晶被熔蚀后外部生长中长石环边,1045.42 m 花岗闪长斑岩,单偏光;k—石英斑晶内部包含小颗粒斜长石、云母、钛铁氧化物,1892.61 m 花岗闪长斑岩,正交偏光;l—石英斑晶边部被拉长石熔蚀交代,内部含针状磷灰石,1892.61 m 花岗闪长斑岩,正交偏光;Ap—磷灰石;Bt—黑云母;Pl—斜长石;Py—黄铁矿;Qtz—石英

Fig. 11 Petrology and petrography suggesting magma mixing in the Nanling Scientific Drill Hole

a-c—Dark enclaves in granodiorite porphyry at the depth of 2011.93~2017.50 m; d—Distinct boundary between enclave and host rock, plainlight; e—Corroded quartz phenocryst steps over the boundary between enclave and host rock. Pyrite content in enclave and host rock is markedly different. Reflected light; f—Biotite in enclave was plastic deformed, plainlight; g—Quartz phenocryst in host rock displays deformation lamellae, crossed nicols; h-i—Egg-shaped plagioclase phenocryst, with needle-like apatite inside, granodiorite porphyry at the depth of 1949.41m, plainlight; j—Corroded oligoclase phenocryst with andesine rim, granodiorite porphyry at the depth of 1045.42m; k— Quartz phenocryst wraps aggregation of fine-grain plagioclase, mica and oxide, granodiorite porphyry at the depth of 1892.61 m, crossed nicols; l—Rim of quartz phenocryst replaced by labradorite, with needle-like apatite inside, granodiorite porphyry at the depth of 1892.61m, crossed nicols

Ap—Apatite; Bt—Biotite; Pl—Plagioclase; Py—Pyrite; Qtz—Quartz

混合作用,与之相对的是,花岗斑岩中未见岩浆混合现象。从早侏罗世开始,在古太平洋板块向东亚板块东缘低角度俯冲的背景下,武夷山西侧赣南地区处于弧后伸展环境,发育大规模断裂构造和岩浆活动,切入岩石圈地幔的线型带状深大断裂引起地幔物质减压熔融生成玄武质岩浆并底侵于下地壳,壳幔物质共同参与花岗闪长质岩浆的形成;切至硅铝质地壳的区域性网格状断裂引起区域性减压,壳源岩石重熔形成花岗质岩浆^[5]。源区深度以及源区物质组成的差异可能是造成花岗闪长斑岩中存在岩浆混合作用而花岗斑岩中没有发生岩浆混合作用的主要原因。

4.3 成岩物理化学条件

花岗岩中的铁镁硅酸盐矿物对岩浆形成过程中的物理化学条件,如压力、温度、氧逸度等有很好的指示作用^[28-29]。

(1) 温度

南岭科学钻探一孔中的岩浆岩均挑出了大量锆石,岩相学研究也观察到锆石颗粒,且包含较多继承锆石,尤其是花岗闪长斑岩和辉长闪长玢岩中继承锆石的比例相当大^[5],据此可以认为岩浆源区中的锆达到了饱和,锆石饱和温度代表了岩浆温度的上限^[30],可以近似代表花岗质岩石近液相线温度,根据 Watson et al.提出的锆石饱和温度计^[31],计算出花岗闪长斑岩、花岗斑岩、辉长闪长玢岩的结晶温度分别为810~922℃、764~819℃、742~747℃(表9)。

(2) 氧化还原环境

花岗闪长斑岩中黑云母的 $Fe^{3+}/(Fe^{2+}+Fe^{3+})$ 值为0~0.57,平均值0.26;暗色包体中黑云母的 $Fe^{3+}/(Fe^{2+}+Fe^{3+})$ 值为0.28~0.53,平均值0.41。在 $Fe^{3+}-Fe^{2+}-Mg$ 图解(图12)中,除前述1892.16~1896.33 m、1952.95~1961.10 m、2365.96~2527.77 m孔段可能受到还原性地层影响的黑云母外,其余大部分黑云母均落在 $Fe_2O_3-Fe_3O_4$ 氧缓冲线上,与赣东北永平

表9 锆石饱和温度计算结果

Table 9 Zircon saturation temperatures calculated according to major and trace element values

岩性	采样深度/m	SiO ₂ /%	Al ₂ O ₃ /%	CaO/%	Na ₂ O/%	K ₂ O/%	Zr/10 ⁻⁶	锆石饱和温度/℃
花岗闪长斑岩	13.55	62.58	13.75	4.4	0.08	4.34	137	810
	17.48	63.53	15.11	3.51	0.92	4.38	145	823
	17.8	63.46	15.24	3.52	1.62	4.08	169	834
	20.48	65.32	15.35	2.73	2.1	3.59	150	831
	20.5	65.69	15.25	2.87	2.43	3.5	142	822
	1043.6	59.86	14.77	4.87	2.27	3.55	209	832
	1048.72	65.08	14.84	2.94	2.63	4.38	200	845
	1052.78	65.26	15.01	3.01	0.07	4.87	190	860
	1056.84	57.98	14.75	4.84	1.75	5.15	194	817
	1104.07	60.8	15.2	3.06	2.59	3.86	200	844
	1373.14	70.7	14.3	0.99	0.47	3.95	224	899
	1438.79	58.8	15.2	2.44	0.14	4.29	179	857
	1455.13	63.6	14.9	1.79	0.27	4.02	170	862
	1506.21	65.8	15.1	3	2.75	3.21	196	850
	1508.04	67.4	15.1	3.07	3.36	3.39	176	835
	1667.75	62.2	15.1	0.82	0.48	3.11	188	885
	1894.37	65.66	17.01	2.81	3.67	2.08	239	878
	1950.66	62.08	15.52	5.58	4.15	1.03	248	847
	1952.54	69.19	15.29	1.95	2.9	3.27	195	862
	2012.07	57.84	16.31	1.2	0.4	3.3	276	922
	2015.63	64.9	14.62	3.56	0.22	5.11	199	854
	2261.55	64.16	15.29	3.03	1.89	3.75	210	860
	2367.53	67.41	14.91	2.68	0.45	3.61	175	860
2372.6	61.23	15.46	3.19	0.41	3.54	244	886	
2527.48	63.04	14.45	2.53	2.41	2.74	197	855	
2867.83	62.85	15.49	3.72	0.1	3.8	202	865	
2872.54	67.74	13.61	4.47	0.07	3.64	141	821	
花岗斑岩	1389.97	75.9	13	1.1	3.29	4.45	82	776
	1424.03	76.4	13.1	0.55	2.8	4.66	67	767
	1631.5	75.7	13.1	0.96	2.95	4.26	85.7	785
	1663.23	76	13.3	1.22	3.82	3.18	68.6	764
	1672.22	71.9	16.9	0.47	0.86	4.16	93.9	819
	1705.6	78.7	12.9	0.15	1.31	2.42	83.9	812
	1715.02	76.8	13	0.85	3.66	3.86	79.9	777
辉长闪长玢岩	1336.3	47.8	13.3	8.53	1.04	2.56	144	742
	1374.58	47.3	13.8	7.47	1.12	3.08	133	747

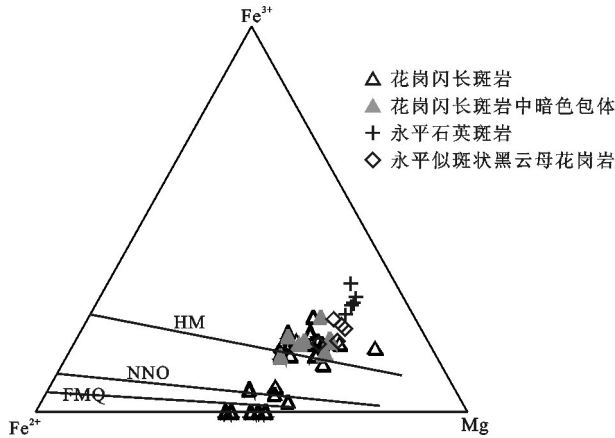


图12 南岭科学钻探一孔中花岗闪长斑岩的黑云母 $Fe^{3+}-Fe^{2+}-Mg$ 图解(底图据文献[33])

HM— $Fe_2O_3-Fe_3O_4$ 的氧缓冲线; NNO—Ni-NiO的氧缓冲线;
FMQ— $Fe_2SiO_4-SiO_2-Fe_3O_4$ 的氧缓冲线

Fig. 12 Diagram of $Fe^{3+}-Fe^{2+}-Mg$ for biotites in granodiorite porphyry exposed in the Nanling Scientific Drill Hole (after reference [33])

HM—Oxygen buffer line of $Fe_2O_3-Fe_3O_4$; NNO—Oxygen buffer line of Ni-NiO; FMQ—Oxygen buffer line of $Fe_2SiO_4-SiO_2-Fe_3O_4$

铜矿区花岗岩中的黑云母^[32]相似,说明花岗闪长斑岩,连同其中的暗色包体在成岩时岩浆的氧逸度均较高。

4.4 热液蚀变信息

南岭科学钻探一孔中的岩浆岩均遭受了不同程度的热液蚀变作用,导致花岗斑岩发生白云母化/绢云母化、碳酸盐化(方解石、菱铁矿),花岗闪长斑岩发生硅化、绿泥石化、白云母化/绢云母化、碳酸盐化(方解石、白云石),辉长闪长玢岩发生碳酸盐化(方解石、白云石)。在岩石蚀变过程中,产生绿泥石的方式有两种:由铁、镁硅酸盐矿物直接分解,在这种情况下,铁、镁组分没有从热液中带入;由热液中带入铁、镁组分^[34]。本文所研究绿泥石的 $Fe/(Fe+Mg)$ 值为0.38~0.56,黑云母的 $Fe/(Fe+Mg)$ 值为0.29~0.56,二者十分相近,且随着钻孔深度变化,二者同步变化(图13-a),说明绿泥石成分主要受岩石原始成分控制,热液流体对其成分影响有限。根据Cathelineau与Jowett提出的绿泥石温度计^[35-36]计算出绿泥石的形成温度分别为226~395°C、230~396°C,且随着钻孔深度增大,绿泥石的形成温度整体呈现略微降低的逆向变化趋势(图13-b)。蚀变矿物组合与蚀变矿物形成温度表明南岭科学钻探一孔中的岩浆

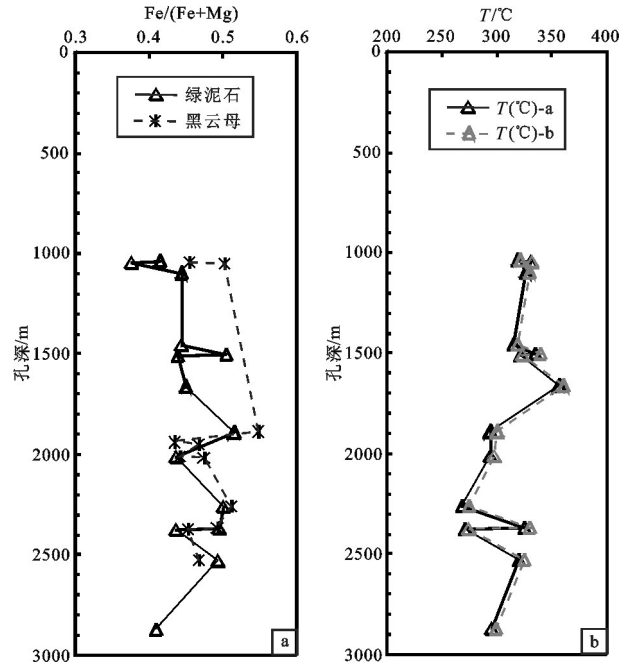


图13 绿泥石与黑云母 $Fe/(Fe+Mg)$ 值随钻孔深度变化图(a)与绿泥石形成温度随钻孔深度变化图(b)

Fig. 13 $Fe/(Fe+Mg)$ value of chlorites and biotites (a) and formation temperature of chlorites (b) varying with depth of the Nanling Scientific Drill Hole

岩受到了中高温-中低温热液流体影响。

4.5 对成矿的指示

华南地区中生代铜铅锌金银成矿作用集中在179~160 Ma,成矿岩浆岩主要为花岗闪长岩,如德兴、七宝山、宝山、水口山等^[37];大规模钨锡成矿作用集中在165~150 Ma,成矿岩浆岩主要为黑云母花岗岩,如西华山、淘锡坑、盘古山等^[3, 38-40],上述二者分属两种矿床成矿系列^[3]。南岭科学钻探一孔位于银坑矿田牛形坝-柳木坑矿区内,既揭露了银金铅锌铜矿化和钨铋铀矿化^[41],同时揭露了花岗闪长斑岩和花岗斑岩,且花岗闪长斑岩和花岗斑岩的成岩时代((160.3±0.8) Ma、(151.7±1.1) Ma)^[5]分别与上述华南地区中生代两次成矿岩浆活动时间相对应。

在南岭科学钻探一孔的花岗闪长斑岩中识别出岩浆混合作用,而岩浆混合作用与多种金属成矿作用有着密切的成因关系,尤其是斑岩(-矽卡岩)型铜-钼-金矿床,如西藏甲玛铜多金属矿^[42]、铜陵地区的铜-铁-金矿^[43]、新疆北部的包古图铜钼金矿^[44]等矿区,均报道存在岩浆混合作用。与长英质岩浆相比,幔源岩浆中亲铜元素和硫的浓度更

高^[45]。岩浆混合作用不仅使富含亲铜元素和硫的幔源岩浆不断补充到长英质岩浆中,还由于不同端元岩浆组分差异造成岩浆房内温度、压力、化学成分不均匀,使岩浆发生对流循环,利于挥发性组分和成矿物质上升、聚集、成矿^[46]。中生代时期,武夷山西侧赣南地区处于弧后伸展环境,发育大规模的断裂构造与岩浆活动,武夷山构造-成矿带西缘的NNE向鹰潭-一定南深大断裂即穿过银坑地区,在牛形坝-柳木坑矿区内表现为推覆构造F₁,南岭科学钻探一孔即位于该推覆构造的上盘。在该断裂影响下,地幔橄榄岩减压熔融,生成玄武质岩浆,并底侵于下地壳,引起壳源岩石重熔,在此过程中有幔源物质的加入。同时,前已述及,花岗闪长质岩浆及暗色包体具有较高的氧逸度,而高氧逸度有利于源区硫化物中的Cu、Au等成矿元素随硫化物的氧化富集到岩浆熔体中,其后随岩浆演化和上侵从熔体中释放发生大规模成矿作用^[47-48]。

前人通过研究,认为华南地区与不同矿种(组合)有关成矿岩浆岩在岩石类型、矿物组合、矿物化学、岩石地球化学、同位素地球化学等方面均存在显著差异,即岩浆岩的成矿专属性,如芮宗瑶等认为与斑岩型矿床及玢岩型铁(铜)矿床有关岩体中的黑云母主要是镁质黑云母,在岩浆-热液演化过程中向富镁方向演化^[49]。郭娜欣等通过统计南岭地区中生代与钨锡钼铀和铜(钼)铅锌金银成矿有关两类花岗岩类的岩石学和矿物学特征,提出与钨锡钼铀成矿有关花岗岩类以黑云母花岗岩为主,其次为白云母花岗岩、二云母花岗岩、花岗闪长岩,岩石中的斜长石An值较低,平均为8;黑云母多属富铁黑云母-铁叶云母-铝铁叶云母,MF值为0.0001~0.5311,Fe³⁺/(Fe³⁺+Fe²⁺)值为0.0625~0.8778;白云母常见;角闪石体积含量一般<3%,Mg[#]值为0.21~0.53。与铜(钼)铅锌金银成矿有关花岗岩类以花岗闪长岩为主,其次为花岗岩、石英闪长岩,斜长石An值较高,平均为22;黑云母以富镁黑云母为主,MF值为0.5120~0.7216,Fe³⁺/(Fe³⁺+Fe²⁺)值为0.1085~0.3378;白云母不常见;角闪石一般>5%,Mg[#]值为0.48~1^[15]。南岭科学钻探一孔中花岗斑岩的斜长石主要为钠长石,An值多数为1~3;由黑云母蚀变而成的白云母具有高铝、高Fe/(Fe+Mg)值特征,指示原黑云母富铁。花岗闪长斑岩中的斜长石以中

长石为主,An值多集中在33~44;黑云母多为富镁黑云母,MF值为0.43~0.70,Fe³⁺/(Fe³⁺+Fe²⁺)值为0~0.57;黑云母蚀变而成的白云母具有低铝、低Fe/(Fe+Mg)值、高镁特征,同样指示黑云母富镁。在黑云母的Mg-(Al^{VI}+Fe³⁺+Ti)-(Fe²⁺+Mn)分类图解中,花岗闪长斑岩中的黑云母与南岭地区成铜(钼)铅锌金银矿的花岗岩类中黑云母落在相同的区域。

岩石学、岩相学、矿物化学等特征表明,南岭科学钻探一孔揭露的花岗闪长斑岩与银金铅锌铜矿化有关,而钨铀矿化与岩浆岩的关系还有待于进一步研究。

5 结 论

通过对南岭科学钻探一孔中燕山期岩浆岩进行矿物学研究,得出以下结论:

(1)南岭科学钻探一孔中揭露的燕山期岩浆岩主要为花岗闪长斑岩、花岗斑岩、辉长闪长玢岩。钾长石以正长石为主。斜长石在花岗闪长斑岩和花岗斑岩中明显不同,花岗闪长斑岩中的斜长石以中长石为主,花岗斑岩中的斜长石以钠长石为主。黑云母主要见于花岗闪长斑岩中,为富镁黑云母。白云母均为次生成因,花岗闪长斑岩中的白云母具有低Al^{VI}、Fe/(Fe+Mg)值,花岗斑岩中的白云母具有高Al^{VI}、Fe/(Fe+Mg)值。磷灰石普遍含F、Cl,且F含量显著高于Cl含量。石榴石属钙铝榴石。绿泥石主要为蠕绿泥石(铁绿泥石)-密绿泥石。

(2)黑云母矿物化学特征指示花岗闪长斑岩为壳幔混源花岗岩,具有较高的氧逸度。岩石学、岩相学、矿物化学特征指示在花岗闪长质岩浆演化过程中发生了岩浆混合作用。

(3)花岗闪长斑岩、花岗斑岩、辉长闪长玢岩的结晶温度分别为810~922℃、764~819℃、742~747℃,成岩后岩浆岩经历了中高温-中低温热液蚀变。

(4)花岗闪长斑岩与银金铅锌铜矿化有关,钨铀矿化与岩浆岩的关系有待进一步研究。

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