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安徽铜陵中生代侵入岩及其岩石包体中的硫化物-氧化物包裹体研究^{*}

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摘要 安徽铜陵地区中生代岩浆活动频繁, 形成了一系列与铜、金多金属成矿作用关系密切的中酸性侵入岩。在这些侵入岩中分布有大量的镁铁质团块、堆积晶和微粒闪长质包体。在这些侵入岩及其岩石包体中观察到了一定数量的硫化物-氧化物包裹体。文章对老庙基、小铜官山和小陶家岩体及其岩石包体中的硫化物-氧化物包裹体进行了详细的岩相学观察和电子探针分析。观察和分析结果显示, 镁铁质团块中硫化物包裹体内的矿物主要有磁黄铁矿、黄铜矿、单硫化物固溶体和镍黄铁矿, 这些硫化物相(黄铜矿除外)中的 Ni、Cu 平均含量(w_B , 下同)分别为 6.91% 和 0.44%; 微粒闪长质包体和寄主岩中硫化物包裹体内的矿物主要为磁黄铁矿和黄铜矿, 这些硫化物相(黄铜矿除外)中的 Ni、Cu 平均含量分别为 0.44%、0.07%(微粒闪长质包体)和 0.09%、0.42%(寄主岩)。镁铁质团块、微粒闪长质包体和寄主岩中氧化物包裹体内的矿物分别为铬磁铁矿(Cr_2O_3 平均含量为 4.44%)、磁铁矿(Cr_2O_3 平均含量为 0.44%)和磁铁矿(Cr_2O_3 平均含量为 0.07%), 散布的氧化物颗粒分别为铬磁铁矿(Cr_2O_3 平均含量为 6.58%)、磁铁矿+铬磁铁矿(Cr_2O_3 平均含量为 0.86%)和磁铁矿(Cr_2O_3 平均含量为 0.34%)。从单一包裹体中的矿物共生关系来看, 微粒闪长质包体和寄主岩中的矿物共生组合分别为磁黄铁矿+黄铜矿和磁黄铁矿+磁铁矿。而镁铁质团块中存在 3 种组合: ①单硫化物固溶体+磁黄铁矿; ②单硫化物固溶体+黄铜矿; ③磁黄铁矿+镍黄铁矿+黄铜矿。矿物平衡温压计算结果表明, 角闪石堆积晶、微粒闪长质包体和寄主岩的结晶温度分别为 860~865°C、714~811°C 和 614~733°C, 对应的深度分别为 26~27 km、7~16 km 和 3~6 km。岩相学观察和电子探针分析结果结合已发表的地球化学、矿物学数据显示, 铜陵地区镁铁质团块和角闪石堆积晶、微粒闪长质包体、寄主岩中的辉石和角闪石内的硫化物-氧化物包裹体分别是在上地幔到下地壳范围内, 从碱性玄武质岩浆和轻度演化的底侵碱性玄武质岩浆中熔离出来的不混溶硫化物-氧化物熔浆冷却结晶的产物; 中-上地壳范围内, 从辉长质-闪长质岩浆中熔离出来的不混溶的硫化物-氧化物熔浆冷却结晶的产物; 上地壳范围内, 从辉石(或石英)-长质-花岗闪长质岩浆中熔离出来的不混溶的硫化物-氧化物熔浆冷却结晶的产物。包裹体中的矿物组合及共生关系表明, 从形成镁铁质团块到角闪石堆积晶再到微粒闪长质包体和寄主岩的过程中, 岩浆的结晶温度和深度依次降低, 而受到地壳物质混染的程度逐渐增大。

关键词 地球化学, 中生代, 硫化物-氧化物包裹体, 电子探针分析, 岩石包体, 中酸性侵入岩, 长江中下游

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Sulfide and oxide inclusions in xenoliths and host rocks of Tongling area, Anhui Province

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Abstract

This paper presents new petrographic observations and electron microprobe analyses of sulfide and oxide melt inclusions trapped within amphibole and clinopyroxene in xenoliths and host rocks (HRs) from the Late Jurassic-Early Cretaceous Laomiaojishan, Xiaotongguanshan and Xiaotaojia intrusions in Tongling area, Anhui Province. The plutons vary in composition from quartz monzonitic diorite to granodiorite, and contain mafic clots (MFCs), hornblende cumulates (HCs), and microgranular mafic enclaves (MMEs) with gabbroic to dioritic compositions. Compositions of sulfide inclusions correspond to pyrrhotite, chalcopyrite, single sulfide solution and pentlandite in MFCs, and pyrrhotite and chalcopyrite in MMEs and HRs. Ni and Cu content of the sulfide phases, except for chalcopyrite in single blebs, is averagely 6.91 % and 0.44 %, 0.44 % and 0.07 %, and 0.09 % and 0.42 % in MFCs, MMEs, and HRs, respectively. Compositions of oxide blebs correspond to Cr-magnetite (averagely 4.44 % Cr₂O₃) in MFCs, and magnetite with an average Cr₂O₃ content of 0.44 % in MMEs and 0.07 % in HRs, while compositions of oxide grains are Cr-magnetite (averagely 6.58 % Cr₂O₃) in MFCs, magnetite and Cr-magnetite (averagely 0.86 % Cr₂O₃) in MMEs, and magnetite (averagely 0.34 % Cr₂O₃) in HRs. Paragenetic associations of (1) mono sulfide solution + pyrrhotite, (2) mono sulfide solution + chalcopyrite, and (3) pyrrhotite and pentlandite + chalcopyrite exist within single blebs in MFCs, while paragenetic associations of pyrrhotite + chalcopyrite and pyrrhotite + magnetite occur within single blebs in MMEs and HRs, respectively. Crystallization temperatures of hornblendes in HCs and hornblendes and plagioclases in MMEs and HRs are 860~865°C, 714~811°C and 614~733°C, respectively, based on Al and Ti in calcic amphibole and amphibole-plagioclase geothermometers. The pressures recorded by these phases indicate that they were formed at a depth of 26~27 km, 7~16 km, and 3~6 km, respectively, based on Al and Ti in calcic amphibole and Al-in-hornblende geobarometers. The present petrographic observations and microprobe analyses combined with the published geochemical and mineralogical data of the pyroxene cumulates, HCs, MMEs and HRs support an origin of sulfide and oxide melt inclusions in MFCs and HCs, MMEs, and HRs from crystallization products of sulfide and oxide melts immiscibly separated from alkaline basaltic and somewhat evolved underplated alkaline basaltic magmas from the upper mantle to the lower crust, the gabbroic to dioritic magmas in the middle to upper crust, and the pyroxene (or quartz) monzodioritic to granodioritic magmas in the upper crust, respectively. The variations in the oxide and sulfide assemblage and the sulfide and oxide paragenetic association within single blebs presented above correspond to the increase in the amount of the hybridized lower and middle to upper crustal material in the magmas and the decrease in crystallization temperature and depth of the magmas in the formation process of MFCs and HCs, MMEs, and HRs.

Key words: geochemistry, Mesozoic, sulfide and oxide inclusions, electron microprobe analysis, xenolith, intermediate-acidic intrusion, Lower Yangtze River Valley

已有大量研究指出,在金伯利岩和玄武岩以及幔源包体中的金刚石、铬铁矿、石榴子石、锆石、辉石和角闪石中存在硫化物-氧化物包裹体(Sharp, 1966; Skinner et al., 1969; Bishop et al., 1975; Peterson et al., 1977; Andersen et al., 1987; Botkunov et al., 1987; Chaussidon et al., 1987; 1989; Gurenko et al., 1985; Rudashevskiy et al., 1988; Lorand et al., 1989; Deines et al., 1995; Bulanova et al., 1996; Shaw, 1997; Barashkov et al., 1998; Pearson et al., 1998; 1999; 2002; Hurai et al., 1998; Ruzicka et al., 1999; Xu et al., 1999; 徐九华等, 2000; 樊祺诚等, 2001; Spetsius et al., 2002; Torok et al., 2003; Zajacz et al., 2003; Aulbach et al., 2004; Griffin et al., 2004; Renno et al., 2004; Yurimoto et al., 2004; 岳可芬等, 2005; McNeill et al., 2008)。对硫化物-氧化物包裹体的研究不仅可以提供有关地幔组成、演化以及岩石圈-软流圈相互作用的信息,还有利于对不混溶硫化物熔体在幔源岩浆演化过程中的地球化学行为和与超镁铁质-镁铁质岩浆相关的富Cr氧化物矿床、富Ni硫化物矿床的形成

机制的认识。但是对分布于长英质岩浆及其岩石包体中的矿物内的硫化物-氧化物包裹体的报道甚少。Whitney等(1983)在美国 Fish 峡谷凝灰岩斑晶中发现了磁黄铁矿包裹体并探讨了硫在钙碱性岩浆演化中的特征。Silver等(1985)研究证明,在高度分异的花岗质岩浆结晶晚期可以分离出不混溶的富铁熔浆。Anderson等(2000)通过对美国加利福尼亚州 Bishop 凝灰岩中的包裹体、磁铁矿包裹体和环带状斑晶的研究指出,在岩浆演化过程中存在岩浆混合和结晶分异作用。Qin等(2003, 2004)报道了铜陵地区鸡冠石和金口岭岩体中角闪石堆积晶、巨晶中的氧化物-硫化物包裹体资料,并探讨了它们的起源及其在成矿中的意义。Halter等(2004a; 2004b; 2005)对阿根廷西北部 Farallón Negro 安山质火山杂岩中的硅酸盐包裹体和硫化物包裹体进行了 LA-ICP-MS 分析,其结果为岩浆演化和斑岩型铜-金矿床中的流体的形成提供了证据。很显然,在上地幔到上地壳范围内,镁铁质到长英质岩浆的演化过程中硫化物-氧化物包裹体的演化模型还未建立。因此,为了更好地认识壳幔相互作用过程和与长英

质岩浆有关的 Fe、Cu 多金属矿床的形成机制,有必要对长英质岩浆及其岩石包体中的硫化物-氧化物包裹体进行更加详细的研究。

安徽铜陵中生代中酸性侵入岩中分布有大量的镁铁质团块、角闪石堆积晶和微粒闪长质包体。在这些包体及其寄主岩中的角闪石和辉石内含有一系列硫化物-氧化物包裹体。因此,铜陵地区成为研究形成于不同环境中的硫化物-氧化物包裹体的天然实验室。本文对区内老庙基、小铜官山和小陶家岩体及其岩石包体中的硫化物-氧化物包裹体进行了详细的岩相学观察和电子探针分析,并初步探讨了上地幔到上地壳范围内岩浆中的硫化物-氧化物包裹体的演化规律。

1 区域地质背景

安徽铜陵地区位于长江中下游岩浆岩带中部(图 1A),构造上隶属于扬子板块东北缘下扬子坳陷中部的相对隆起区。区域地质和地球物理资料显示(陈沪生, 1988; 唐永成等,

1998; Lü et al., 2004),自中生代以来,本区莫霍面深度未发生明显变化,其岩石圈结构可分为 6 大构造层,自上而下依次为:①中-新生界陆相碎屑岩及火山岩,对应深度约为 0~4 km;②中-古生界海相碳酸盐岩和碎屑岩,对应深度约为 4~8 km;③中-新元古界绿片岩相浅变质岩系,对应深度约为 8~12 km;④太古宇-古元古界角闪岩相-麻粒岩相深变质岩系,对应深度约为 12~18 km;⑤硅镁层,对应深度约为 18~32 km;⑥地幔盖层,深度大于 32 km。

铜陵地区地层从志留系至第四系均较发育,岩性主要为浅海相碳酸盐岩、少量的半深海相硅质岩和海陆交互的碎屑岩及陆相碎屑岩夹火山岩。燕山晚期区内断裂构造发育并诱发了强烈的岩浆活动,形成了一条宽约 25 km、近东西向的构造-岩浆活动带。区内岩浆岩岩体规模较小(图 1B),主要为小岩株、岩墙,其次为岩床、岩枝及岩脉,出露面积为 0.5~5 km²,成岩时代集中于晚侏罗世-早白垩世(136~142 Ma, Xu et al., 2004; 王彦斌等, 2004; Cao et al., 2009)。岩石类型主要为辉石二长闪长岩、石英二长闪长岩和花岗闪长岩。

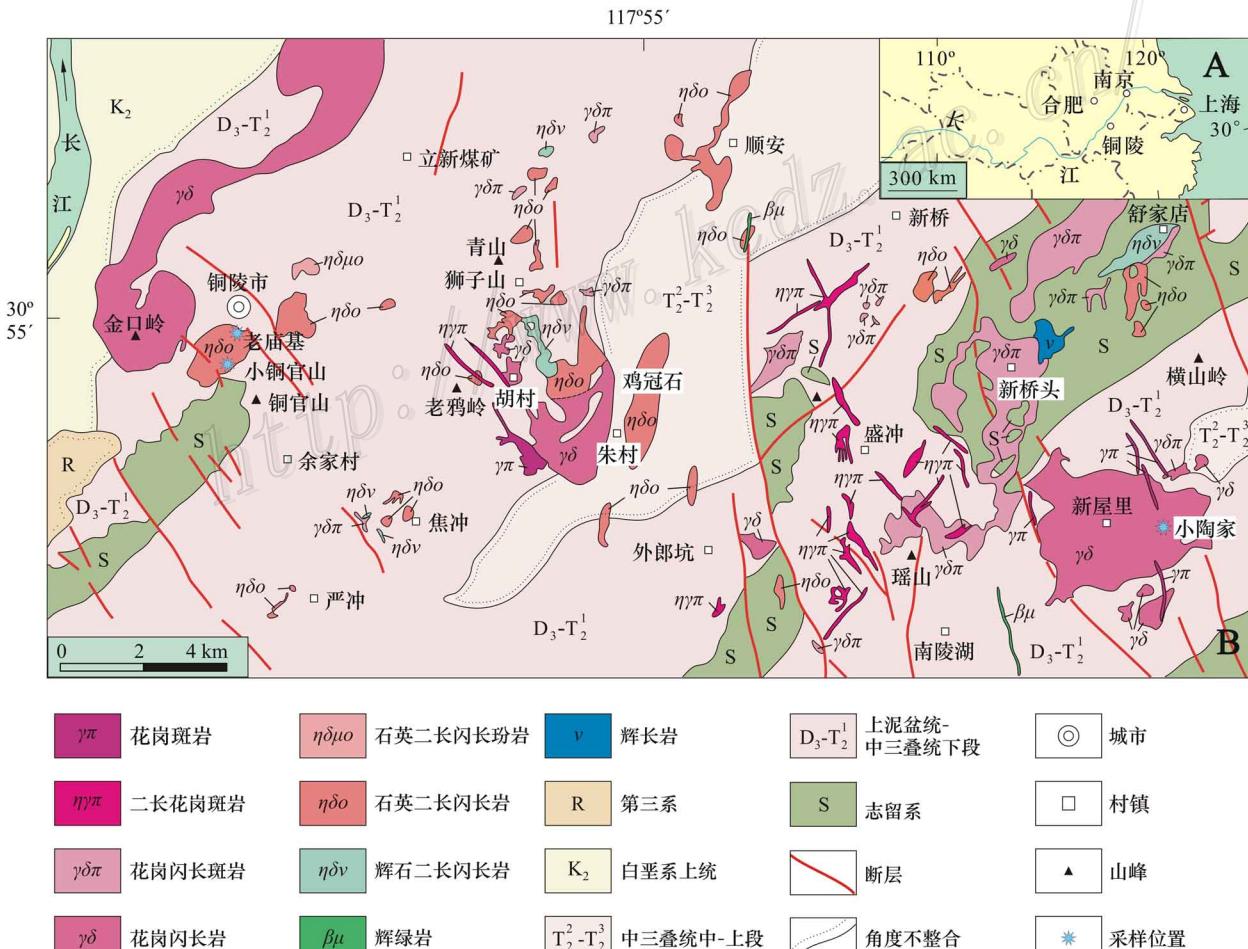


图 1 铜陵地区地质略图(B)及其在长江中下游地区的位置(A)(据杜杨松等, 2004a)

Fig. 1 Geological sketch map of Tongling area, Anhui Province (A) and its location in the Lower Yangtze River Valley (B) (after Du et al., 2004a)

侵入岩中含有多种岩石包体。在这些岩石包体及其寄主岩中的角闪石和辉石内含有一系列硫化物-氧化物包裹体。

2 岩相学

对老庙基、小铜官山和小陶家岩体及其微粒闪长质包体、角闪石堆积晶的岩相学特征已有不少报道(Du, 1999; 杜杨松等, 2004a, 2004b; Cao et al., 2009)。

老庙基、小铜官山和小陶家岩体的岩性主要为石英二长闪长岩和花岗闪长岩。其中老庙基和小铜官山侵入岩为斑状结构, 斑晶以斜长石和角闪石为主, 偶见单斜辉石和石英, 基质呈中细粒结构, 主要由斜长石、钾长石、石英、角闪石和少量黑云母组成, 副矿物以磷灰石和磁铁矿为主。小陶家岩浆岩呈中细粒花岗结构, 主要由斜长石、石英、钾长石、角闪石和黑云母组成, 副矿物以磷灰石和磁铁矿为主。

上述3个岩体中含有许多岩石包体。包体的类型主要为微粒闪长质包体、角闪石堆积晶和镁铁质团块。

微粒闪长质包体主要为辉长质到闪长质岩石, 呈次棱角状-圆形, 粒径为20~50 mm。其中辉长质包体主要由斜长石、单斜辉石、角闪石和黑云母组成, 副矿物以磁铁矿(铬磁铁矿)和磷灰石为主。闪长质包体的主要矿物为斜长石、角闪石、钾长石、黑云母, 少量单斜辉石和石英, 副矿物主要为磷灰石和磁铁矿(铬磁铁矿)。

角闪石堆积晶具有典型的堆积结构, 局部为嵌晶结构, 主要矿物为角闪石和少量单斜辉石, 副矿物主要为磷灰石和铬磁铁矿。在角闪石中偶尔可见辉石残留晶, 这些辉石残留晶无扭折和出熔现象, 形成于高压环境下(杜杨松等, 2004c)。

镁铁质团块呈椭圆形-圆形, 粒径为0.35~3.00 mm, 不均匀地分布于微粒闪长质包体中, 局部明显集中(图2A)。每个镁铁质团块都由浅色的核部和深色的薄边组成。核部主要由细粒阳起石、透闪石、透辉石(图2B)和普通角闪石(图2C)组成, 其中透辉石和普通角闪石局部已蚀变为阳起石(或者透闪石)并析出铬磁铁矿(图2D)。边部主要由中细粒镁铁闪石组成, 它们多已蚀变为黑云母。

硫化物-氧化物包裹体呈椭圆形-圆形, 粒径为4.0~12.0 μm, 多以孤立的形式散布于寄主岩、微粒闪长质包体、镁铁质团块和角闪石堆积晶中的角闪石和辉石中。寄主岩和微粒闪长质包体中的硫化物包裹体主要由磁黄铁矿和黄铜矿(图2E、2G)组成; 镁铁质团块中的硫化物包裹体主要由磁黄铁矿、单硫化物固溶体、镍黄铁矿和黄铜矿组成(图2F、2H、2I、2J)。寄主岩、微粒闪长质包体、镁铁质团块和角闪石堆积晶中的氧化物包裹体内的矿物分别为磁铁矿、磁铁矿、铬磁铁矿和铬磁铁矿。从单个包裹体中的矿物共生关系来看, 寄主岩中的矿物共生组合为磁黄铁矿+磁铁矿, 微粒闪长质包体中的矿物共生组合为磁黄铁矿(核)+黄铜矿(边)(图2G); 而镁铁质团块中存在3种组合: ①单硫化物固溶体(核)+磁黄

铁矿(边)(图2H); ②单硫化物固溶体(核)+黄铜矿(边)(图2I); ③磁黄铁矿和镍黄铁矿(核)+黄铜矿(边)(图2J)。

3 矿物化学和平衡温压计算

利用中国地质大学(北京)Superprobe 733型电子探针分析仪对文中所涉及的硅酸盐、硫化物和氧化物等矿物进行了成分分析。其中, 硅酸盐和氧化物矿物的测试条件为: 加速电压15 kV, 样品电流20 nA, 束斑直径1 μm, 检测时间100 s, 分析精度±2%, 对SiO₂、TiO₂、Al₂O₃、Cr₂O₃、FeO、MnO、MgO、CaO、Na₂O、K₂O和P₂O₅分别采用石英、金红石、斜长石、铬铁矿、铁铝榴石、蔷薇辉石、方解石、钠长石、透长石和磷灰石作标样。硫化物矿物的测试条件为: 加速电压20 kV, 样品电流10 nA, 束斑直径1 μm, 检测时间100 s, 分析精度±2%。S、Fe和Cu由黄铁矿和黄铜矿作标样, Co、Ni、Au和Ag为100%元素标样, Pb、Zn、Sb、Se、As和Te分别由方铅矿、闪锌矿、辉锑矿、镍化硒、毒砂和碲锑矿作标样。角闪石的阳离子系数以O为23求出, 其三价铁按照电位差值法(Stout, 1972)求出, 并按照Leake等(1997)的分类法对角闪石进行了分类。

硅酸盐矿物的电子探针分析结果(表1、表2、表3)显示, 镁铁质团块和角闪石堆积晶中的角闪石主要为阳起石、透闪石和韭闪石, 微粒闪长质包体中的角闪石主要为镁钙闪石、镁绿钙闪石、浅闪石和镁铁闪石, 斜长石多为奥长石-中长石($An_{28}-An_{35}$)和拉长石($An_{51}-An_{56}$), 寄主岩中的角闪石以镁铁闪石为主, 斜长石以奥长石-中长石($An_{25}-An_{38}$)为主, 寄主岩及其岩石包体中辉石均为透辉石。

硫化物电子探针分析结果(表4、表5、表6)表明, 镁铁质团块中的硫化物包裹体内的矿物主要为磁黄铁矿、黄铜矿、单硫化物固溶体和镍黄铁矿, 这些硫化物相(除黄铜矿外)中的Ni和Cu的含量分别为1.79%~13.23%(平均6.91%)和0.02%~2.14%(平均0.44%), 微粒闪长质包体和寄主岩中的硫化物包裹体内的矿物主要为磁黄铁矿和黄铜矿, 其中, 微粒闪长质包体中的硫化物包裹体(黄铜矿除外)内的Ni、Cu平均含量分别为0.31%~0.59%(平均0.44%)、0~0.22%(平均0.07%), 寄主岩中的硫化物包裹体(黄铜矿除外)内的Ni、Cu平均含量分别为0~0.26%(平均0.09%)、0~1.48%(平均0.42%)。

氧化物电子探针分析结果(表7、表8、表9、表10)表明, 镁铁质团块中的氧化物包裹体内的矿物为铬磁铁矿, 其Cr₂O₃含量为2.42%~7.73%(平均4.44%), 微粒闪长质包体和寄主岩中的氧化物包裹体内的矿物均为磁铁矿, 其Cr₂O₃含量分别为0.41%~0.47%(平均0.44%)和0~0.21%(平均0.07%)。散布于寄主岩中的磁铁矿颗粒、微粒闪长质包体中磁铁矿颗粒+铬磁铁矿颗粒、镁铁质团块中的铬磁铁矿颗粒的Cr₂O₃含量分别为0.25%~0.52%(平均0.34)、0.39%~1.19%(平均0.86%表8、表9)和1.59%~33.77%(平均6.58%表10)。从以上资料可以看出, 氧化物中

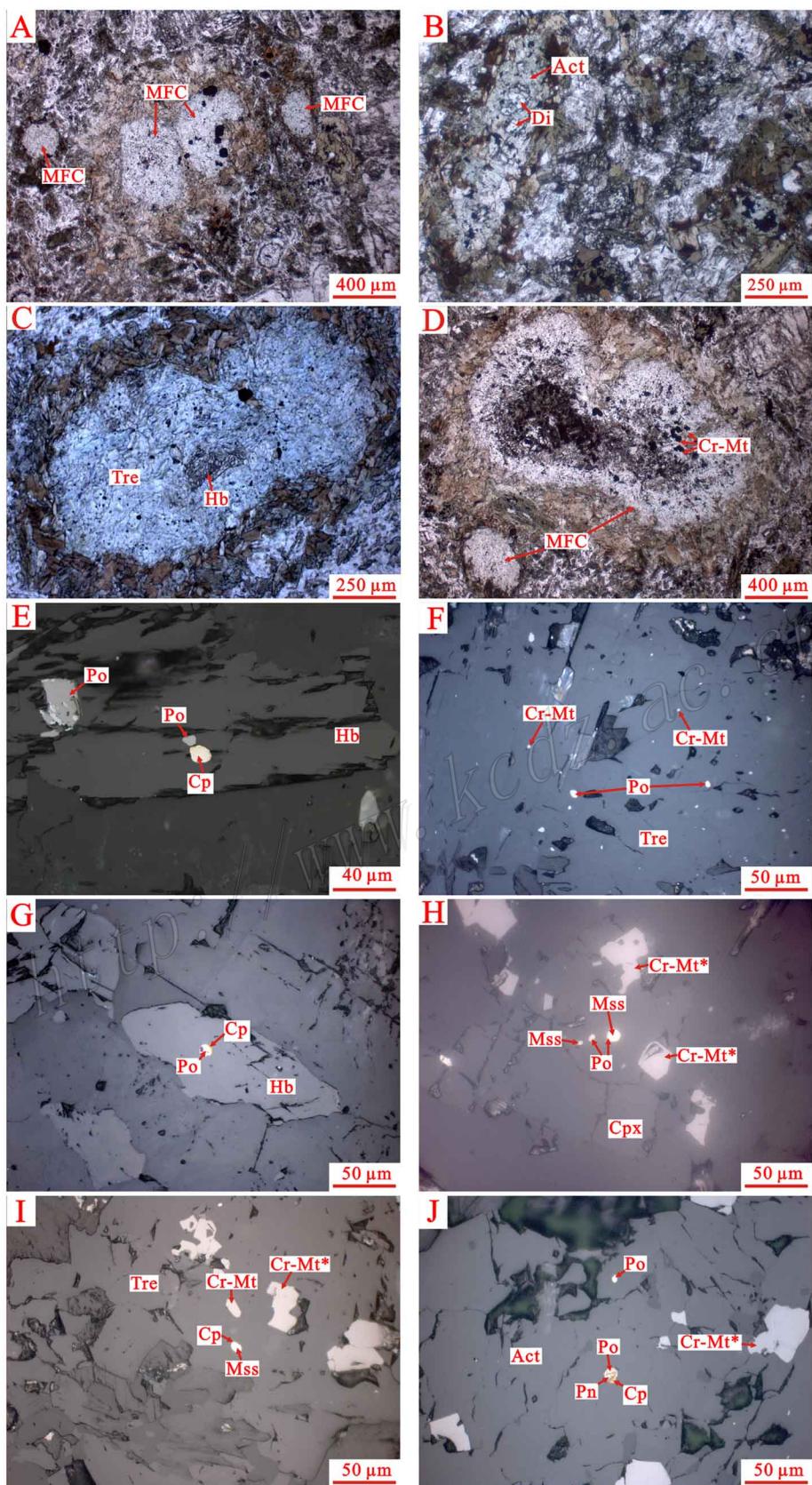


图 2 镁铁质团块和硫化物-氧化物包裹体显微照片图(图说见下页)

A. 镁铁质团块在微粒闪长质包体中呈局部集中现象(老庙基,透射光);B. 镁铁质团块由浅色的核部和深色的薄边组成,其核部为阳起石和残留的透辉石(小铜官山,透射光);C. 镁铁质团块由浅色的核部和深色的薄边组成,其核部为透闪石和残留的普通角闪石(老庙基,透射光);D. 镁铁质团块核部分布有铬磁铁矿颗粒(老庙基,透射光);E. 小陶家花岗闪长岩中的角闪石内的磁黄铁矿和黄铜矿包裹体(反射光);F. 镁铁质团块中的透闪石内孤立的铬磁铁矿和磁黄铁矿包裹体(老庙基,反射光);G. 微粒闪长质包体中的角闪石内的磁黄铁矿(核)+黄铜矿(边)包裹体(小陶家,反射光);H. 镁铁质团块中的辉石内的单硫化物固溶体(核)+磁黄铁矿(边)包裹体、单硫化物固溶体包裹体和磁黄铁矿包裹体,以及分布于辉石和阳起石颗粒间的铬磁铁矿颗粒(小铜官山,反射光);I. 镁铁质团块中的透闪石内的单硫化物固溶体(核)+黄铜矿(边)包裹体和分布于透闪石颗粒间的铬磁铁矿颗粒(小铜官山,反射光);J. 镁铁质团块中的阳起石内的磁黄铁矿和镍黄铁矿(核)+黄铜矿(边)包裹体、孤立的磁黄铁矿包裹体和分布于阳起石颗粒间的铬磁铁矿颗粒(小陶家,反射光)。矿物代号:MFC—镁铁质团块;Di—透辉石;Hb—角闪石;Tre—透闪石;Act—阳起石;Cr-Mt—铬磁铁矿;Cr-Mt^{*}—充填于颗粒间或裂隙间的铬磁铁矿;Po—磁黄铁矿;Cp—黄铜矿;Mss—单硫化物固溶体;Pn—镍黄铁矿

Fig. 2 Microphotographs of mafic clots and sulfide and oxide inclusions within amphibole and clinopyroxene of host rocks, microgranular mafic enclaves and mafic clots in Tongling area

A. Locally concentrated mafic clots in microgranular mafic enclave(Laomiao jishan , transmitted light);B. A mafic clot in microgranular mafic enclave indicating occurrence of residual diopside grains in the light-colored principal core consisting of actinolite and enclosed by a dark-colored thin shell(Xiaotongguanshan , transmitted light);C. A mafic clot in microgranular mafic enclave showing occurrence of residual hornblende grains in the light-colored principal core consisting of tremolite and enclosed by a dark-colored thin shell(Laomiao jishan , transmitted light);D. Cr-magnetite grains occurring in the light-colored principal core of a mafic clot(Laomiao jishan , transmitted light);E. Pyrrhotite and chalcopyrite blebs within hornblende in granodiorite(Xiaotao jia , transmitted light);F. Independent Cr-magnetite and pyrrhotite blebs within tremolite in a mafic clot(Laomiao jishan , reflective light);G. A paragenetic bleb of pyrrhotite(core) + chalcopyrite(outer ring) within amphibole in a microgranular mafic enclave(Xiaotao jia , reflective light);H. A paragenetic bleb of single sulfide solution(core) + pyrrhotite(outer ring) and independent single sulfide solution and pyrrhotite blebs within clinopyroxene as well as Cr-magnetite grains between clinopyroxene and actinolite in a mafic clot(Xiaotongguanshan , reflective light);I. A paragenetic bleb of mono sulfide solution(core) + chalcopyrite(outer ring) within tremolite and Cr-magnetite grains among tremolite grains in a mafic clot(Xiaotongguanshan , reflective light);J. A paragenetic bleb of pyrrhotite and pentlandite(core) + chalcopyrite(outer ring) and an independent pyrrhotite bleb within single actinolite grains as well as Cr-magnetite among actinolite grains in a mafic clot(Xiaotao jia , reflective light). MFC—Mafic clot; Di—Diopside; Hb—Hornblende; Tre—Tremolite; Act—Actinolite; Cr-Mt—Cr-magnetite; Cr-Mt^{*}—Cr-Magnetite grains; Po—Pyrrhotite; Cp—Chalcopyrite; Mss—Single sulfide solution; Pn—Pentlandite

包裹体的 Cr_2O_3 含量明显低于相应的氧化物颗粒的 Cr_2O_3 含量。

利用钙角闪石中的 Al-Ti 温度计(Ernst et al. , 1998)、角闪石中的铝压力计(Schmidt , 1992)和角闪石-斜长石地质温度计(Holland et al. , 1994)等方法对寄主岩及其岩石包体形成的温压条件进行了估算。其结果(表 1、表 2)显示,角闪石堆积晶中的角闪石的结晶温度为 $860\sim865^\circ\text{C}$,压力为 $7.88\times10^8\sim8.05\times10^8\text{ Pa}$,相当于 $26\sim27\text{ km}$ 深,微粒闪长质包体中的斜长石、角闪石的结晶温度为 $714\sim811^\circ\text{C}$,压力 $2.32\times10^8\sim3.86\times10^8\text{ Pa}$,对应深度为 $7\sim16\text{ km}$;寄主岩中斜长石、角闪石的结晶温度为 $614\sim733^\circ\text{C}$,压力为 $0.93\times10^8\sim1.93\times10^8\text{ Pa}$,对应深度为 $3\sim6\text{ km}$ 。

4 讨 论

本区鸡冠石角闪石堆积晶中的熔蚀的辉石残留晶(杜杨松等,2004b)、角闪石堆积晶中的角闪石、微粒闪长质包体中的斜长石和角闪石以及寄主岩中的斜长石和角闪石的结晶温度分别为 $1170\sim1185^\circ\text{C}$ 、 $860\sim865^\circ\text{C}$ 、 $714\sim811^\circ\text{C}$ 和 $614\sim733^\circ\text{C}$,对应深度分别为 $40\sim45\text{ km}$ 、 $26\sim27\text{ km}$ 、 $7\sim16\text{ km}$ 和 $3\sim6\text{ km}$ 。它们分别代表了上地幔岩浆房、深位岩浆房、浅位岩浆房和岩浆侵位处矿物结晶的温度和深度。其中,深位

岩浆房的深度对应于下地壳硅镁层的深度,浅位岩浆房的深度对应于太古宇-上元古界深变质岩系的深度。

镁铁质团块主要由辉石(透辉石)、角闪石(镁铁闪石、阳起石和透闪石)和不等量的铬磁铁矿组成。同时在镁铁质团块中可观察到如下现象:辉石和角闪石中的硫化物包裹体内的矿物组合中镍黄铁矿逐渐变为单硫化物固溶体;②辉石和角闪石中存在铬磁铁矿包裹体;③透辉石蚀变为阳起石(或者透闪石)。以上特征表明,镁铁质团块可能是上地幔部分熔融形成的碱性玄武质岩浆在上地幔经结晶分异形成的辉石岩发生蚀变的产物。

已发表的主量元素、稀土元素、Rb-Sr 和 Sm-Nd 同位素以及矿物学资料(唐永成等,1998;Du,1999;杜杨松等,2004a;2004b;2007;Cao et al. , 2009)表明,铜陵地区晚侏罗世-早白垩世侵入岩及其微粒闪长质包体和角闪石堆积晶可能是由基性到中酸性岩浆通过慢源岩浆底侵、同化混染和分离结晶过程形成的,而基性到中酸性岩浆则是由底侵的玄武质岩浆与不同量的中下地壳物质发生一系列复杂的相互作用形成的。

由以上资料可知,镁铁质团块和角闪石堆积晶是上地幔中的碱性玄武质岩浆和下地壳中的轻度演化的底侵玄武质(可能为辉长质)岩浆结晶分异的产物。微粒闪长质包体既可以由深位岩浆房中的辉长质岩浆或浅位岩浆房中的闪长质

岩浆直接冷却结晶形成,也可以由深位岩浆房中的岩浆与浅位岩浆房中的岩浆混合形成;其中辉长质岩浆是底侵的玄武质岩浆与下地壳硅镁层物质发生同化混染形成的,而闪长质岩浆则是源于深位岩浆房中的辉长质岩浆同化中上地壳中的变质岩形成的。寄主岩是浅位岩浆房中的闪长质岩浆在侵位过程中与中-新元古界浅变质岩发生同化混染作用形成的辉石(或石英)闪长质-花岗闪长质岩浆直接冷却结晶的产物。

角闪石堆积晶、微粒闪长质包体和寄主岩中的平均 Cr 含量分别为 533.12×10^{-6} 、 318.23×10^{-6} 和 18.59×10^{-6} , 平均 Ni 含量分别为 107.97×10^{-6} 、 102.57×10^{-6} 和 18.35×10^{-6} (秦新龙, 2007)。与此相对应, 包裹体中的氧化物和硫化物矿物(不含黄铜矿)中的 Cr₂O₃ 和 Ni 的平均含量也呈规律性变化, 从镁铁质团块和角闪石堆积晶(6.58% 和 6.91%)到微粒闪长质包体(0.86% 和 0.44%), 再到寄主岩(0.34% 和 0.09%)逐渐降低, 镁铁质团块、微粒闪长质包体和寄主岩中

的氧化物矿物颗粒中的平均 Cr₂O₃ 含量分别为 6.58%、0.86% 和 0.34%, 与包裹体中的 Cr₂O₃ 含量具有相同的变化趋势。除了 Cr 和 Ni 的含量成规律性变化外, 单一氧化物-硫化物包裹体中的矿物共生组合也具规律性变化, 在镁铁质团块和角闪石堆积晶中为富 Ni 的硫化物组合(单硫化物固溶体+磁黄铁矿, 单硫化物+黄铜矿和磁黄铁矿+镍黄铁矿+黄铜矿), 在微粒闪长质包体中为较富 Ni 的硫化物组合(磁黄铁矿+黄铜矿), 而在寄主岩中为贫 Ni 的硫化物和贫 Cr 的氧化物组合(磁黄铁矿+磁铁矿)。上述变化特征可能是从形成镁铁质团块到角闪石堆积晶, 再到微粒闪长质包体和寄主岩的过程中, 岩浆受到地壳物质混染的程度逐渐增大, 而结晶温度和深度依次降低的结果(Craig et al., 1969; Kullerud et al., 1969; Naldrett, 1969; Cabri, 1973)。岩石包体及其寄主岩中的硫化物-氧化物包裹体中的矿物组合是由捕获于硅酸盐矿物中的不混溶的氧化物和硫化物熔体直接冷却结晶形成的。形成镁铁质团块和角闪石堆积晶中的富

表 1 寄主岩中的辉石、角闪石和斜长石的电子探针分析结果

Table 1 Major oxide composition of clinopyroxene, amphiboles and plagioclases in host rocks from Laomiaojishan,

Xiaotongguanshan and Xiaotaojia plutons in Tongling area, Anhui Province

| 成分及参数 | 老庙基英二长闪长岩 | | | | | 小铜官山石英二长闪长岩 | | | | | 小陶家花岗闪长岩 | | | | | | |
|--------------------------------|------------|-------------|-------------|--------------|--------------|--------------|--------------|---------------|---------------|----------------|----------------|--------------|--------------|---------------|---------------|---------------|---------------|
| | LMJ 1-5 | LMJ 3-4* | LMJ 3-5* | LMJ 5-1-1 | LMJ 5-1-2 | XTGS 4-3* | XTGS 4-2* | XTGS 6-8-1 | XTGS 6-8-2 | XTGS 13-1-3 | XTGS 13-1-4 | XTJ 1-1-5 | XTJ 1-1-7 | XTJ 13-1-1 | XTJ 13-1-2 | XTJ 24-1-1 | XTJ 24-1-2 |
| | Di | Ct | Oc | Ct | Oc | Ct | As | Ct | Oc | Ct | Oc | Ct | As | Ct | Oc | Ct | Oc |
| wt% / % | | | | | | | | | | | | | | | | | |
| SiO ₂ | 51.06 | 48.73 | 60.77 | 47.32 | 61.25 | 49.15 | 59.99 | 50.70 | 60.87 | 50.33 | 60.52 | 48.23 | 59.19 | 49.95 | 61.67 | 51.15 | 61.49 |
| TiO ₂ | 0.00 | 1.22 | 0.06 | 1.47 | 0.01 | 1.10 | | 1.04 | 0.05 | 1.13 | 0.09 | 1.26 | 0.03 | 1.04 | 0.10 | 1.22 | |
| Al ₂ O ₃ | 0.27 | 5.17 | 23.77 | 5.39 | 22.64 | 4.76 | 24.71 | 5.12 | 23.78 | 4.77 | 24.36 | 4.88 | 25.62 | 6.02 | 24.48 | 5.44 | 23.93 |
| Cr ₂ O ₃ | 0.00 | - | - | - | - | | 0.14 | - | 0.24 | - | - | - | 0.18 | - | 0.10 | - | |
| FeO | 14.45 | 14.04 | 0.22 | 12.53 | 0.35 | 14.65 | 0.17 | 12.94 | 0.26 | 15.05 | 0.19 | 15.36 | 0.14 | 13.31 | | 12.57 | 0.26 |
| MnO | 0.34 | 0.27 | | 0.46 | | 0.43 | 0.13 | 0.77 | 0.11 | 0.64 | | 0.50 | | 0.57 | 0.07 | 0.49 | 0.10 |
| MgO | 10.95 | 14.55 | | 15.38 | | 15.09 | | 14.04 | | 12.93 | | 14.39 | | 13.34 | | 14.07 | |
| CaO | 23.80 | 11.87 | 5.88 | 11.53 | 5.36 | 11.72 | 7.06 | 11.53 | 6.07 | 10.58 | 6.07 | 11.89 | 8.00 | 11.67 | 6.03 | 11.55 | 5.67 |
| Na ₂ O | 0.14 | 1.44 | 7.88 | 1.51 | 8.78 | 1.39 | 6.98 | 0.53 | 8.24 | 0.90 | 8.06 | 0.76 | 6.86 | 0.36 | 7.56 | 0.48 | 7.81 |
| K ₂ O | 0.03 | 0.58 | 0.61 | 0.81 | 0.21 | 0.52 | 0.55 | 0.75 | 0.28 | 0.46 | 0.27 | 0.56 | 0.31 | 0.70 | 0.32 | 0.58 | 0.52 |
| P ₂ O ₅ | 0.00 | - | - | 0.06 | 0.44 | - | - | 0.13 | | - | - | - | - | - | - | - | |
| 总和 | 101.04 | 97.87 | 99.19 | 96.46 | 99.04 | 98.81 | 99.59 | 97.69 | 99.66 | 97.03 | 99.56 | 97.83 | 100.15 | 97.14 | 100.23 | 97.65 | 99.78 |
| Al ^{IV} | 0.012 | 0.864 | | 0.938 | | 0.809 | | 0.625 | | 0.593 | | 0.838 | | 0.697 | | 0.594 | |
| Al ^{VII} | 0.000 | 0.026 | | 0.000 | | 0.000 | | 0.252 | | 0.234 | | 0.000 | | 0.340 | | 0.334 | |
| Mg [#] | 0.66 | 0.68 | | 0.74 | | 0.72 | | 0.69 | | 0.65 | | 0.72 | | 0.67 | | 0.69 | |
| Wo | 47 | | | | | | | | | | | | | | | | |
| En | 30 | | | | | | | | | | | | | | | | |
| Fs | 23 | | | | | | | | | | | | | | | | |
| Or | | 4 | | 1 | | 3 | | 2 | | 1 | | 2 | | 2 | | 3 | |
| Ab | | 68 | | 74 | | 62 | | 70 | | 70 | | 60 | | 68 | | 69 | |
| An | | 28 | | 25 | | 35 | | 28 | | 29 | | 38 | | 30 | | 28 | |
| 温压参数 | | | | | | | | | | | | | | | | | |
| $p_S/10^8 \text{Pa}$ | 1.28 | | 1.45 | | 0.84 | | 1.16 | | 0.93 | | 0.98 | | 1.93 | | 1.41 | | |
| d/km | 4 | | 5 | | 3 | | 4 | | 3 | | 3 | | 6 | | 5 | | |
| $t_{\text{BH}}/^\circ\text{C}$ | 663 | | 691 | | 716 | | 617 | | 614 | | 733 | | 640 | | 614 | | |

* 数据引自 Cao et al., 2009; -" 为未分析项, 空白为低于检测限。矿物代号 Di—透辉石 Ct—镁铁闪石 Oc—奥长石 As—中长石。Mg[#] = Mg/(Mg + Fe²⁺); p_S —利用角闪石中的铝压力计(Schmidt, 1992)估算得到的矿物结晶压力值; d —深度 t_{BH} —利用角闪石-斜长石地质温压计(Holland et al., 1994)估算出的矿物结晶温度值。

Table 2 Major oxide composition of clinopyroxenes, amphiboles and plagioclases in microgranular mafic enclaves from Laomiaoqijishan, Xiaotongguanshan and Xiaotaojiaojia plutons in Tongling area, Anhui Province

| 成分及参数 | 老庙基岩石英二长闪长岩(寄主岩) | | | | | | | | | | | | 小陶家花岗闪长岩(寄主岩) | | | | | | XTGS | | | XTGS | | | XTGS | | |
|--|------------------|-------|-------|--------|-------|--------|-------|-------|-------|-------|-------|--------|---------------|-------|--------|-------|-------|-------|-------|-------|-------|-------|-------|-------|------|--|--|
| | LMJ | | | | | | LMJ | | | | | | LMJ | | | | | | XTGS | | | XTGS | | | XTGS | | |
| | Ts | 1-2* | 1-3 | 1-4* | 3-1* | Mh | Oc | Ts** | Lf** | As | Mh | Oc | Di | Ed | Oc | Di | Ed | Di | Ed | Di | Ed | Ct | As | Ct | As | | |
| SiO ₂ | 43.00 | 63.08 | 45.94 | 55.43 | 42.18 | 62.60 | 42.48 | 59.38 | 44.87 | 60.46 | 51.15 | 51.86 | 51.00 | 45.46 | 56.19 | 46.38 | 61.35 | 47.20 | 60.73 | 46.72 | 59.47 | | | | | | |
| TiO ₂ | 2.09 | | 1.66 | 0.13 | 2.32 | 2.16 | | | | 1.89 | 0.09 | 0.21 | 0.19 | 0.14 | 1.88 | 0.14 | 1.53 | 0.06 | 1.08 | | 1.49 | | | | | | |
| Al ₂ O ₃ | 8.11 | 23.38 | 6.41 | 27.93 | 8.98 | 24.03 | 9.17 | 24.53 | 8.42 | 23.21 | 0.78 | 0.38 | 0.27 | 7.00 | 27.65 | 7.04 | 24.00 | 6.46 | 23.98 | 6.22 | 24.50 | | | | | | |
| Cr ₂ O ₃ | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | | |
| FeO | 18.71 | 0.27 | 15.78 | 0.38 | 17.79 | 0.29 | 16.57 | 0.27 | 14.52 | 0.45 | 11.43 | 12.88 | 14.11 | 15.15 | 0.26 | 13.76 | 0.41 | 13.66 | 0.22 | 13.45 | 0.21 | | | | | | |
| MnO | 0.58 | | 0.17 | | 0.41 | | 0.51 | | 0.54 | | 0.39 | 0.41 | 0.52 | 0.21 | | 0.45 | | 0.94 | 0.05 | 0.50 | | | | | | | |
| MgO | 11.78 | 13.69 | 11.14 | 11.73 | 11.73 | 11.20 | 7.07 | 11.25 | 13.01 | 12.21 | 11.48 | 10.66 | 13.77 | 0.33 | 14.43 | 0.11 | 14.26 | | | | | | | | | | |
| CaO | 11.15 | 5.65 | 11.80 | 11.45 | 11.58 | 5.59 | 11.20 | 7.94 | 2.11 | 23.13 | 23.14 | 22.29 | 11.39 | 10.22 | 11.48 | 5.80 | 11.16 | 6.26 | 11.71 | 7.25 | | | | | | | |
| Na ₂ O | 1.41 | 6.82 | 1.41 | 4.86 | 1.89 | 7.72 | 2.11 | 1.86 | 8.33 | 0.35 | 0.17 | 0.48 | 1.63 | 5.32 | 1.12 | 7.43 | 1.35 | 7.60 | 1.58 | 7.22 | | | | | | | |
| K ₂ O | 1.04 | 0.62 | 0.49 | 0.16 | 1.21 | 0.30 | 0.97 | 0.26 | 0.76 | 0.23 | 0.00 | 0.02 | 0.00 | 0.82 | 0.26 | 0.99 | 0.40 | 0.65 | 0.11 | 0.62 | 0.16 | | | | | | |
| P ₂ O ₅ | — | — | — | — | — | — | 0.43 | 0.23 | 0.09 | 0.13 | — | — | — | — | 0.35 | — | 0.29 | 0.27 | 0.24 | 0.39 | | | | | | | |
| 总和 | 97.87 | 99.82 | 97.35 | 100.34 | 97.50 | 100.53 | 97.33 | 99.68 | 97.21 | 99.22 | 99.65 | 100.53 | 99.52 | 97.31 | 100.37 | 97.69 | 99.56 | 97.05 | 99.22 | 97.01 | 99.20 | | | | | | |
| Al ^{IV} | 1.425 | | 1.114 | | 1.592 | | 1.581 | | 1.337 | | 0.035 | 0.017 | 0.012 | 1.220 | | 1.181 | | 1.052 | | 1.068 | | | | | | | |
| Al ^{VII} | 0.000 | 0.000 | 0.000 | 0.007 | 0.049 | 0.136 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.034 | 0.068 | 0.068 | 0.068 | 0.068 | 0.068 | 0.068 | 0.068 | 0.068 | 0.068 | | | |
| Mg [#] | 0.65 | 0.69 | 0.62 | 0.58 | 0.62 | 0.66 | 0.73 | 0.65 | 0.64 | 0.69 | 0.66 | 0.73 | 0.65 | 0.64 | 0.69 | 0.73 | 0.73 | 0.73 | 0.73 | 0.73 | 0.71 | | | | | | |
| Wo | | | | | | | | | | | 47 | 47 | 46 | | | | | | | | | | | | | | |
| En | | | | | | | | | | | 34 | 32 | 31 | | | | | | | | | | | | | | |
| Fs | | | | | | | | | | | 19 | 21 | 23 | | | | | | | | | | | | | | |
| Or | 4 | | 1 | 2 | | 1 | | 1 | | 1 | | | | | | | 1 | 2 | 1 | 1 | | | | | | | |
| Ab | 66 | | 43 | 70 | | 66 | | 70 | | 70 | | | | | | | 48 | 68 | 68 | 64 | | | | | | | |
| An | 30 | | 56 | 28 | | 33 | | 29 | | 29 | | | | | | | 51 | 30 | 31 | 35 | | | | | | | |
| <i>t_{13H}</i> /℃ | 811 | | 809 | 792 | | 782 | | 732 | | | | | | | | | 806 | 746 | 714 | 734 | | | | | | | |
| <i>p_S</i> /10 ⁸ Pa | 3.86 | | 2.38 | 4.60 | | 4.75 | | 4.00 | | | | | | | | | 2.80 | 2.77 | 2.32 | 2.14 | | | | | | | |
| <i>d'/km</i> | 13 | | 8 | 15 | | 16 | | 13 | | | | | | | | | 9 | 8 | 8 | 7 | | | | | | | |

* 数据引自 Cao et al., 2009; **为未分析项; “-”为细粒晶体; “奥长石”指斜长石; Mh—镁铁闪石; As—中长石; Ed—浅闪石; Di—透辉石; Cr₂O₃—镁铁闪石。Mg[#]=Mg/(Mg+Fe²⁺); *p_S*—利用角闪石中的铝压力量值(Schmidt, 1992)估算得到的矿物结晶压力值; *d'*—深度; *t_{13H}*—利用角闪石斜长石地质温度计(Holland et al., 1994)估算出的矿物结晶温度值。

表3 镁铁质团块中的辉石和角闪石的电子探针分析结果

Table 3 Major oxide composition of clinopyroxenes and amphiboles in mafic clots from Laomiaojishan, Xiaotongguanshan and Xiaotaojia plutons in Tongling area, Anhui Province

| 成分及参数 | 老庙基英二长闪长岩 (寄主岩) | | | | 小铜官山石英二长闪长岩 (寄主岩) | | | | 小陶家花岗闪长岩 (寄主岩) | |
|--------------------------------|--------------------|--------------|-----------------|------------------|----------------------|-----------------|---------------|-------------|-------------------|--------------|
| | LMJ 1-7-2 | LMJ 1-8-5 | XTGS 3-1-7-7 | XTGS 3-1-7-15 | XTGS 3-1-7-8 | XTGS 3-1-8-3 | XTGS 5-1-1 | XTGS 5-2 | XTJ 3-2-5 | XTJ 3-3-3 |
| | Ac | Ac | Di | Di | Ac | Ac | Pa* | Pa* | Ac | Tr |
| $\omega(\text{B})\%$ | | | | | | | | | | |
| SiO ₂ | 56.38 | 55.95 | 53.54 | 53.14 | 54.16 | 53.62 | 42.19 | 42.28 | 54.35 | 53.42 |
| TiO ₂ | 0.19 | 0.12 | 0.00 | 0.01 | 0.05 | 0.03 | 2.12 | 2.26 | 0.18 | 0.26 |
| Al ₂ O ₃ | 0.41 | 1.08 | 0.18 | 0.22 | 1.25 | 1.45 | 13.36 | 13.29 | 1.27 | 1.80 |
| Cr ₂ O ₃ | 0.22 | 0.00 | — | — | 0.12 | 0.44 | — | 0.09 | 0.00 | 0.00 |
| FeO | 5.41 | 4.14 | 8.23 | 8.56 | 9.34 | 9.66 | 10.42 | 9.38 | 9.67 | 10.32 |
| MnO | 0.00 | 0.28 | 0.33 | 0.29 | 0.38 | 0.04 | — | — | 0.59 | 0.74 |
| MgO | 23.06 | 23.17 | 13.60 | 13.97 | 19.33 | 19.12 | 13.49 | 14.59 | 18.56 | 18.78 |
| CaO | 11.64 | 11.99 | 23.13 | 22.90 | 11.43 | 12.06 | 11.92 | 12.11 | 11.73 | 11.81 |
| Na ₂ O | 0.00 | 0.00 | 1.08 | 0.64 | 0.00 | 0.00 | 2.39 | 1.61 | 0.00 | 0.00 |
| K ₂ O | 0.08 | 0.20 | 0.00 | 0.06 | 0.29 | 0.17 | 1.60 | 1.58 | 0.16 | 0.22 |
| P ₂ O ₅ | 0.45 | 0.00 | 0.00 | 0.00 | 0.45 | 0.16 | — | 0.25 | 0.20 | 0.44 |
| 总和 | 97.84 | 96.93 | 100.09 | 99.79 | 96.80 | 96.75 | 97.49 | 97.44 | 96.71 | 97.79 |
| Al ^{IV} | 0.066 | 0.175 | 0.008 | 0.010 | 0.208 | 0.242 | 1.766 | 1.822 | 0.212 | 0.299 |
| Al ^{VI} | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.558 | 0.465 | 0.000 | 0.000 |
| Mg [#] | 0.96 | 0.98 | 0.83 | 0.81 | 0.90 | 0.89 | 0.70 | 0.77 | 0.86 | 0.90 |
| 温压参数 | | | | | | | | | | |
| $p_S/10^8 \text{ Pa}$ | | | | | | | 8.05 | 7.88 | | |
| d/km | | | | | | | 27 | 26 | | |
| $t/^\circ\text{C}$ | | | | | | | 860 | 865 | | |

*堆积晶；—为未分析项；空白为低于检测限。矿物代号：Ac—阳起石；Di—透辉石；Pa—韭闪石；Tr—透闪石。 $\text{Mg}^{\#} = \text{Mg}/(\text{Mg} + \text{Fe}^{2+})$ 。 p_S —利用角闪石中的铝压力计(Schmidt, 1992)估算得到的矿物结晶压力值； d —深度； t —利用钙角闪石中的Al-Ti温度计(Ernst et al., 1998)估算出的矿物结晶温度值。

表4 寄主岩中代表性硫化物包裹体中的硫化物矿物电子探针分析结果($w_B/\%$)Table 4 Representative analyses ($w_B/\%$) of sulfide phases in sulfide inclusions from host rocks of Laomiaojishan, Xiaotongguanshan and Xiaotaojia plutons in Tongling area, Anhui Province

| 寄主矿物及编号 | 硫化物及编号 | S | Fe | Co | Ni | Cu | Ag | Sb | As | Se | Te | 总和 |
|----------------|----------------|-------|-------|------|------|-------|------|------|------|------|------|-------|
| Ct, LMJ5-1-1 | Po, LMJ5-1-1-1 | 38.99 | 59.65 | 0.63 | 0.21 | | | | | 0.06 | | 99.54 |
| Ct, XTGS6-8-1 | Po, XTGS6-8-4 | 39.53 | 57.46 | 0.25 | | 1.48 | 0.13 | | 0.55 | | | 99.4 |
| Ct, XTGS13-1-3 | Po, XTGS13-1-5 | 39.43 | 58.06 | 1.26 | | 0.14 | | 0.02 | 0.07 | | 0.1 | 99.08 |
| Ct, XTGS13-1-3 | Cp, XTGS13-1-6 | 34.3 | 30.53 | | 0.54 | 34.18 | | | 0.12 | | | 99.67 |
| Ct, XTJ13-1-1 | Po, XTJ13-1-4 | 39.13 | 58.17 | 1.17 | | 0.5 | 0.22 | | 0.07 | | 0.34 | 99.6 |
| Ct, XTJ24-1-1 | Po, XTJ24-1-3 | 37.11 | 60.81 | 0.73 | 0.26 | | 0.09 | 0.07 | | | 0.22 | 99.29 |

空白为低于检测限。矿物代号：Ct—镁铁闪石；Po—磁黄铁矿；Cp—黄铜矿。

表5 微粒闪长质包体中代表性硫化物包裹体中的硫化物矿物电子探针分析结果($w_B/\%$)Table 5 Representative analyses ($w_B/\%$) of sulfide phases in sulfide inclusions from microgranular mafic enclaves of Laomiaojishan, Xiaotongguanshan and Xiaotaojia plutons in Tongling area, Anhui Province

| 寄主矿物及编号 | 硫化物及编号 | S | Fe | Co | Ni | Cu | Zn | Ag | As | Se | Te | 总和 |
|-----------------|-------------------|-------|-------|------|------|-------|------|------|------|------|------|-------|
| Mh, LMJ3-10-2 | Po, LMJ3-10-1 | 37.89 | 59.09 | 0.49 | 0.35 | 0.44 | 0.6 | 0.15 | 0.16 | | | 99.17 |
| Mh, LMJ3-10-2 | Po, LMJ3-11-1 | 38.4 | 59.45 | 0.42 | 0.83 | | 0.02 | 0.42 | 0.15 | | | 99.69 |
| Ct, XTJ1-1-12-3 | Po, XTJ3-1-1-12-1 | 39.71 | 58.33 | 0.69 | 0.43 | | | 0.07 | 0.44 | 0.21 | | 99.88 |
| Ct, XTJ1-1-12-3 | Cp, XTJ3-1-1-12-2 | 34.91 | 29.36 | 0.14 | 0.26 | 34.04 | | | 0.5 | 0.12 | | 99.33 |
| Ct, XTJ3-1-3 | Po, XTJ3-1-1 | 39.8 | 58.4 | 0.6 | 0.31 | | | | 0.21 | 0.05 | 0.11 | 99.48 |
| Ct, XTJ3-1-3 | Cp, XTJ3-1-2 | 35.31 | 29.89 | 0.28 | 0.29 | 32.96 | 0.05 | 0.17 | 0.36 | 0.12 | | 99.43 |

空白为低于检测限。矿物代号：Mh—镁绿钙闪石；Ct—镁铁闪石；Po—磁黄铁矿；Cp—黄铜矿。

表 6 镁铁质团块中代表性硫化物包裹体中的硫化物矿物电子探针分析结果($w_B/\%$)Table 6 Representative analyses($w_B/\%$) of sulfide phases in sulfide inclusions from mafic clots of Laomiaoishan , Xiaotongguanshan and Xiaotaojia plutons in Tongling area , Anhui Province

| 寄主矿物及编号 | 硫化物及编号 | S | Fe | Co | Ni | Cu | Pb | Zn | Ag | Sb | As | Se | Te | 总和 |
|------------------|-------------------|-------|-------|------|-------|-------|------|------|------|------|------|------|------|--------|
| Ac , LMJ1-7-2 | Po , LMJ1-7-1 | 39.48 | 57.15 | 0.7 | 3.21 | 0.11 | | | | 0.16 | | | | 100.81 |
| Ac , LMJ1-8-5 | Mss , LMJ1-8-1 | 38.19 | 52.68 | 0.75 | 9.13 | | | 0.12 | | | 0.09 | | | 100.96 |
| Ac , LMJ1-8-5 | Mss , LMJ1-8-2 | 39.4 | 52.83 | 0.84 | 6.62 | 0.06 | | | | | 0.15 | | 0.14 | 100.04 |
| Ac , LMJ1-8-5 | Po , LMJ1-8-3 | 38.75 | 57.54 | 0.62 | 2.23 | | | 0.43 | 0.06 | | 0.22 | | | 99.85 |
| Ac , LMJ1-8-5 | Mss , LMJ1-8-4 | 38.55 | 53.09 | 0.53 | 6.11 | 0.38 | | 0.22 | | | 0.12 | | 0.28 | 99.28 |
| Di , XTGS3-1-7-7 | Mss , XTGS3-1-7-1 | 36.36 | 44.7 | 1.13 | 16.88 | | | | | | | | | 99.07 |
| Di , XTGS3-1-7-7 | Mss , XTGS3-1-7-2 | 36.47 | 49.42 | 1.15 | 11.48 | 0.06 | | 0.38 | | | 0.16 | | | 99.12 |
| Di , XTGS3-1-7-7 | Mss , XTGS3-1-7-3 | 38.52 | 58.3 | 0.75 | 1.76 | | 0.17 | | | | 0.15 | 0.11 | | 99.76 |
| Ac , XTGS3-1-8-3 | Po , XTGS3-1-8-1 | 38.11 | 59.04 | 0.64 | 0.68 | | | 0.1 | 0.27 | | 0.17 | | | 99.01 |
| Ac , XTGS3-1-8-3 | Mss , XTGS3-1-8-2 | 34.14 | 43.05 | 2.12 | 13.66 | 4.28 | | 0.21 | | | 1.49 | | | 98.95 |
| Ac , XTJ3-2-5 | Po , XTJ3-2-1 | 40.19 | 55.18 | 0.79 | 3.32 | | | | 0.19 | | 0.07 | | | 99.74 |
| Ac , XTJ3-2-5 | Cp , XTJ3-2-2 | 34.92 | 29.98 | 0.36 | 0.86 | 33.51 | | 0.01 | | 0.09 | 0.26 | | 0.05 | 100.04 |
| Ac , XTJ3-2-5 | Pn , XTJ3-2-3 | 36.16 | 27.32 | 1.66 | 34.3 | 0.35 | | 0.56 | | | 0.26 | | 0.08 | 100.69 |
| Ac , XTJ3-2-5 | Po , XTJ3-2-4 | 40.09 | 56.27 | 0.95 | 2.08 | 0.2 | | 0.09 | | | 0.15 | | | 99.83 |
| Tr , XTJ3-3-3 | Po , XTJ3-3-1 | 39.24 | 57.06 | 0.77 | 1.62 | 0.07 | | 0.48 | 0.17 | | 0.33 | | | 99.74 |
| Tr , XTJ3-3-3 | Po , XTJ3-3-2 | 39.17 | 56.02 | 0.2 | 2.56 | 0.22 | | 0.55 | 0.13 | | 0.07 | | | 98.92 |
| Tr , XTJ3-3-3 | Po , XTJ3-4-1 | 39.5 | 57.88 | 0.97 | 1.18 | | 0.16 | | | 0.09 | 0.16 | | 0.24 | 100.18 |
| Tr , XTJ3-3-3 | Cp , XTJ3-4-2 | 35.31 | 29.87 | 0.37 | | 34.61 | | 0.2 | | 0.07 | 0.02 | | | 100.45 |

空白为低于检测限。矿物代号 : Ac—阳起石 ; Di—透辉石 ; Tr—透闪石 ; Po—磁黄铁矿 ; MSS—单硫化物固溶体 ; Cp—黄铜矿 ; Pn—镍黄铁矿。

表 7 寄主岩、微粒闪长质包体和镁铁质团块中的氧化物包裹体电子探针分析结果($w_B/\%$)Table 7 Major oxide composition of oxide inclusions($w_B/\%$) in host rocks , microgranular mafic enclaves , and mafic clots from Laomiaoishan , Xiaotongguanshan and Xiaotaojia plutons in Tongling area , Anhui Province

| 寄主矿物及编号 | 氧化物及编号 | SiO ₂ | TiO ₂ | Al ₂ O ₃ | Cr ₂ O ₃ | FeO | Fe ₂ O ₃ | MnO | MgO | CaO | Na ₂ O | K ₂ O | P ₂ O ₅ | 总和 |
|------------------|-------------------|------------------|------------------|--------------------------------|--------------------------------|-------|--------------------------------|------|------|------|-------------------|------------------|-------------------------------|-------|
| Ct , XTGS6-8-1 | Mt , XTGS6-8-3 | 1.18 | 0.16 | 0.17 | | — | 91.82 | 0.08 | 0.34 | 0.56 | 0.29 | | | 94.6 |
| Ct , XTGS13-1-3 | Mt , XTGS13-1-2 | 0.68 | 37.34 | 0.03 | | — | 57.55 | 1.99 | 0.25 | 0.55 | | | | 98.39 |
| Ct , XTJ13-1-1 | Mt , XTJ13-1-3 | 0.34 | 0.19 | 0.32 | 0.09 | — | 90.91 | 0.18 | | 0.36 | | 0.11 | | 92.5 |
| Ct , XTJ13-1-1 | Mt , XTJ13-2 | 0.36 | | 0.19 | 0.33 | — | 90.52 | | 0.25 | 0.39 | | | | 92.04 |
| Di , XTGS1-1-4 | Mt , XTGS1-1-10-4 | 0.32 | 0.33 | 0.29 | 0.41 | 90.14 | — | | 0.07 | 0.23 | 0.21 | 0.12 | | 92.12 |
| Ct , XTJ1-1-12-3 | Mt , XTJ1-1-9-1 | 0.18 | 0.19 | 0.35 | 0.47 | 88.58 | — | 1.33 | 0.1 | 0.67 | | 0.15 | 0.16 | 92.18 |
| Ac , LMJ1-7-2 | Cr-Mt , LMJ1-7-3 | 0.06 | | | 4.55 | — | 87.93 | 0.03 | 0.22 | 0.42 | 0.07 | | 0.16 | 93.44 |
| Ac , LMJ1-7-2 | Cr-Mt , LMJ1-7-4 | 0.43 | 0.11 | | 3.25 | — | 88.7 | | 0.38 | 0.52 | 0.15 | | | 93.54 |
| Ac , LMJ1-7-2 | Cr-Mt , LMJ1-7-5 | 0.06 | 0.1 | | 7.6 | — | 84.37 | | 0.26 | 0.67 | 0.28 | | | 93.34 |
| Ac , LMJ1-8-5 | Cr-Mt , LMJ1-8-6 | | | 0.31 | 8.52 | — | 83.84 | 0.38 | 0.23 | 0.4 | | 0.03 | | 93.71 |
| Ac , LMJ1-8-5 | Cr-Mt , LMJ1-8-7 | | | 0.42 | 6.93 | — | 83.58 | 1.34 | 0.82 | 0.5 | | | | 93.59 |
| Pa , XTGS5-1-1 | Cr-Mt , XTGS5-1-2 | 0.22 | 0.26 | 0.52 | 2.79 | 90.47 | — | | | | 0.17 | 0.02 | | 94.45 |
| Pa , XTGS5-1-1 | Cr-Mt , XTGS5-1-3 | 0.33 | | 0.42 | 2.13 | 92.42 | — | | | | | | | 95.3 |
| Tr , XTJ3-3-3 | Gr-Mt , XTJ3-3-4 | 0.32 | 0.18 | 2.05 | — | 89.22 | | 0.05 | 0.21 | | | 0.01 | | 92.04 |
| Tr , XTJ3-3-3 | Cr-Mt , XTJ3-3-5 | 0.33 | | 2.79 | — | 89.24 | 0.31 | | 0.28 | 0.23 | | | | 93.18 |

“—”为未分析项, 空白为低于检测限。Ct—镁铁闪石 ; Di—透辉石 ; Ac—阳起石 ; Pa—霏闪石 ; Tr—透闪石 ; Mt—磁铁矿 ; Cr-Mt—铬磁铁矿。

表 8 寄主岩中的氧化物颗粒电子探针分析结果($w_B/\%$)Table 8 Major oxide composition of oxide grains($w_B/\%$) in host rocks from Laomiaoishan , Xiaotongguanshan and Xiaotaojia plutons in Tongling area , Anhui Province

| 寄主矿物及编号 | 氧化物及编号 | SiO ₂ | TiO ₂ | Al ₂ O ₃ | Cr ₂ O ₃ | Fe ₂ O ₃ | MgO | CaO | Na ₂ O | K ₂ O | P ₂ O ₅ | 总和 |
|---------------|------------------|------------------|------------------|--------------------------------|--------------------------------|--------------------------------|------|------|-------------------|------------------|-------------------------------|--------|
| Di , LMJ1-5 | Mt , LMJ1-10-1 | 0.04 | | 0.16 | 0.59 | 92.92 | | 0.24 | 0.11 | | | 94.06 |
| Di , LMJ1-5 | Mt , LMJ1-10-2 | 0.33 | 0.37 | 0.19 | 0.45 | 90.97 | 0.1 | 0.17 | 0.32 | 0.05 | | 92.95 |
| Ct , LMJ3-4 | Mt , LMJ3-16-1 | 0.37 | 43.99 | | 0.38 | 54.37 | 0.21 | 0.48 | 0.32 | | | 100.12 |
| Ct , LMJ3-4 | Mt , LMJ3-16-2 | 0.34 | 0.14 | | 0.12 | 93.05 | | 0.01 | 0.09 | | | 93.75 |
| Ct , XTJ1-1-5 | Mt , XTJ1-1-16-1 | 0.46 | 0.09 | 0.2 | 0.36 | 91.15 | | | 0.16 | | 0.15 | 92.57 |
| Ct , XTJ1-1-5 | Mt , XTJ1-1-16-2 | 0.28 | 0.01 | 0.11 | 0.23 | 91.81 | | 0.03 | | | 0.02 | 92.49 |

空白为低于检测限。矿物代号 : Di—透辉石 ; Ct—镁铁闪石 ; Mt—磁铁矿。

表 9 微粒闪长质包体中的氧化物颗粒电子探针分析结果($w_B/\%$)Table 9 Major oxide composition of oxide grains($w_B/\%$) in microgranular mafic enclaves from Laomiaoishan , Xiaotongguanshan and Xiaotaojia plutons in Tongling area , Anhui Province

| 寄主矿物及编号 | 氧化物及编号 | SiO ₂ | TiO ₂ | Al ₂ O ₃ | Cr ₂ O ₃ | FeO | MnO | MgO | CaO | Na ₂ O | K ₂ O | P ₂ O ₅ | 总和 |
|------------------|---------------------|------------------|------------------|--------------------------------|--------------------------------|-------|-------|------|------|-------------------|------------------|-------------------------------|-------|
| Mh , LMJ3-10-2 | Mt , LMJ3-15-1 | 0.18 | 45.13 | | 0.36 | 53.61 | | 0.2 | 0.13 | | | | 99.61 |
| Mh , LMJ3-10-2 | Cr-Mt , LMJ3-15-2 | 0.23 | 0.22 | 0.29 | 1.02 | 91.36 | | 0.14 | 0.5 | 0.09 | | | 93.81 |
| Ed , XTGS3-1-2 | Mt , XTGS3-1-10-1 | 0.19 | 0.31 | 0.2 | 0.34 | 92.19 | 0.18 | | 0.24 | 0.12 | | | 93.77 |
| Ed , XTGS3-1-2 | Mt , XTGS3-1-10-2 | 0.22 | 0.11 | 0.01 | 0.43 | 91.44 | 0.16 | 0.15 | 0.28 | 0.12 | | | 92.92 |
| Ct , XTJ1-1-12-3 | Cr-Mt , XTJ1-1-13-1 | 0.28 | | | 1.27 | 91.87 | | 0.01 | 0.18 | | | | 93.61 |
| Ct , XTJ1-1-12-3 | Cr-Mt , XTJ1-1-13-2 | 0.26 | | | 0.05 | 1.04 | 90.49 | | 0.21 | 0.31 | 0.08 | | 92.44 |
| Ct , XTJ3-1-3 | Cr-Mt , XTJ3-5-1 | 0.27 | 0.4 | 0.26 | 1.51 | 91.26 | 0.78 | | 0.15 | 0.1 | 0.01 | 0.1 | 94.84 |
| Ct , XTJ3-1-3 | Mt , XTJ3-5-2 | 0.6 | | 0.22 | 0.87 | 90.75 | 0.74 | | 0.25 | 0.07 | 0.16 | | 93.66 |

空白为低于检测限。矿物代号 : Mh—镁绿钙闪石 ; Ed—浅闪石 ; Ct—镁铁闪石 ; Mt—磁铁矿 ; Cr-Mt—铬磁铁矿。

表 10 镁铁质团块中的氧化物颗粒电子探针分析结果($w_B/\%$)Table 10 Major oxide composition of oxide grains($w_B/\%$) in mafic clots from Laomiaoishan , Xiaotongguanshan and Xiaotaojia plutons in Tongling area , Anhui Province

| 寄主矿物及编号 | 氧化物及编号 | SiO ₂ | TiO ₂ | Al ₂ O ₃ | Cr ₂ O ₃ | Fe ₂ O ₃ | MnO | MgO | CaO | Na ₂ O | K ₂ O | 总和 |
|------------------|---------------------|------------------|------------------|--------------------------------|--------------------------------|--------------------------------|------|------|------|-------------------|------------------|--------|
| Ac , LMJ1-8-5 | Cr-Mt , LMJ1-9-1 | 0.1 | 0.81 | 0.18 | 10.98 | 80.07 | 1.12 | 0.22 | 0.1 | | | 93.58 |
| Ac , LMJ1-8-5 | Cr-Mt , LMJ1-9-2 | 0.24 | 0.53 | 0.2 | 8.95 | 83.39 | 0.92 | 0.09 | | | | 94.32 |
| Ac , LMJ1-8-5 | Cr-Mt , LMJ1-9-3 | 0.27 | 0.06 | 0.15 | 4.41 | 88.53 | 0.27 | 0.23 | | | | 93.92 |
| Ac , LMJ1-8-5 | Cr-Mt , LMJ1-9-4 | 0.42 | 0.23 | 0.04 | 6.2 | 85.99 | 0.8 | 0.2 | | | | 93.88 |
| Ac , LMJ1-8-5 | Cr-Mt , LMJ1-9-5 | 0.32 | 0.83 | 0.62 | 33.77 | 60.31 | 3.05 | 1.35 | 0.12 | 0.45 | | 100.82 |
| Ac , XTGS3-1-8-3 | Cr-Mt , XTGS3-1-8-4 | | 0.13 | 0.24 | 3.19 | 88.75 | | 0.09 | 0.44 | 0.17 | 0.12 | 93.13 |
| Ac , XTGS3-1-8-3 | Cr-Mt , XTGS3-1-8-5 | | 0.32 | 0.16 | 1.59 | 89.89 | | 0.29 | 0.42 | 0.11 | 0.03 | 92.81 |
| Ac , XTGS3-1-8-3 | Cr-Mt , XTGS3-1-8-6 | 0.29 | 0.04 | 0.22 | 4.93 | 89.38 | | | 0.23 | | | 95.09 |
| Ac , XTJ3-2-5 | Cr-Mt , XTJ3-2-6 | 0.47 | 0.03 | 0.11 | 3.23 | 87.58 | 0.26 | | 0.28 | 0.11 | 0.14 | 92.21 |
| Ac , XTJ3-2-5 | Cr-Mt , XTJ3-2-7 | | 0.19 | | 4.04 | 86.96 | 0.62 | 0.21 | | 0.08 | 0.04 | 92.14 |

空白为低于检测限。矿物代号 : Ac—阳起石 ; Mt—磁铁矿 ; Cr-Mt—铬磁铁矿。

Cr 氧化物和富 Ni 硫化物组合的不混溶氧化物和硫化物熔体是在上地幔到下地壳范围内 , 分别在大于 1 100℃ 和 860~865℃ 的温度条件下由正在结晶分异的玄武质岩浆和轻度演化的底侵玄武质岩浆中的硅酸盐矿物捕获的 , 形成微粒闪长质包体中的比较富 Cr 的氧化物和比较富 Ni 的硫化物组合的不混溶氧化物和硫化物熔体是在中上地壳范围内 , 710~810℃ 温度条件下由正在结晶的辉长质-闪长质岩浆中的硅酸盐矿物捕获的 , 形成寄主岩中的贫 Cr 氧化物和贫 Ni 硫化物组合的不混溶的氧化物和硫化物熔体是在上地壳范围内 , 610~730℃ 间由正在结晶的辉石(或石英)二长质-花岗闪长质岩浆中的硅酸盐矿物捕获的。

5 结 论

铜陵地区镁铁质团块和角闪石堆积晶、微粒闪长质包体、寄主岩中的辉石和角闪石内的硫化物-氧化物包裹体分别是在上地幔到下地壳范围内 , 从碱性玄武质岩浆和轻度演化的底侵碱性玄武质岩浆中熔离出来的不混溶的硫化物-氧化物熔浆冷却结晶的产物 , 在中上地壳范围内 , 从辉长质-闪长质

岩浆中熔离出来的不混溶的硫化物-氧化物熔浆冷却结晶的产物 , 在上地壳范围内 , 从辉石(或石英)二长质-花岗闪长质岩浆中熔离出来的不混溶的硫化物-氧化物熔浆冷却结晶的产物。

铜陵地区中生代中酸性侵入岩及其岩石包体中的氧化物和硫化物矿物(不含黄铜矿)组合呈规律性变化 , 在镁铁质团块和角闪石堆积晶中为富 Cr 氧化物和富 Ni 硫化物组合、在微粒闪长质包体中为比较富 Cr 的氧化物和比较富 Ni 的硫化物组合 , 而在寄主岩中为贫 Cr 氧化物和贫 Ni 的硫化物组合。与此对应 , 孤立的氧化物-硫化物包裹体中的矿物共生组合也具规律性变化 , 在镁铁质团块和角闪石堆积晶中为富 Ni 的硫化物组合(单硫化物固溶体 + 磁黄铁矿 , 单硫化物 + 黄铜矿和磁黄铁矿 + 镍黄铁矿 + 黄铜矿) , 在微粒闪长质包体中为较富 Ni 的硫化物组合(磁黄铁矿 + 黄铜矿) , 而在寄主岩中为贫 Ni 的硫化物和贫 Cr 的氧化物组合(磁黄铁矿 + 磁铁矿)。这些变化特征是从形成镁铁质团块到角闪石堆积晶 , 再到微粒闪长质包体和寄主岩的过程中 , 岩浆受到地壳物质混染的程度逐渐增大 , 而结晶温度和深度依次降低的结果。

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