

暗色微粒包体是壳幔岩浆混合作用的证据吗?

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内容提要: 暗色微粒包体常见于钙碱性花岗岩中,已普遍被认为是幔源基性岩浆与壳源酸性岩浆在地壳深部发生混合作用的产物。本文通过大量资料的分析研究,发现暗色微粒包体可以具有很大负值的全岩 $\epsilon_{\text{Nd}}(t)$ 值和锆石 $\epsilon_{\text{Hf}}(t)$ 值,及大于 0.710 的全岩 $[n(^{87}\text{Sr})/n(^{86}\text{Sr})]_i$ 值,不存在幔源岩浆混合的痕迹;而且,大多数暗色微粒包体与寄主花岗岩在晶体化学、形成年龄、全岩和锆石同位素成分等方面显示出完全相似的特征,反映出两者在时空与物质上都具有紧密的成因联系。笔者认为,暗色微粒包体不应该是壳幔岩浆混合作用的产物。基于包体岩浆极小的体量和稍晚的侵位(相对于寄主花岗岩),笔者提出一种新的暗色微粒包体的形成方式:同造山花岗岩浆的主动上侵造成岩浆房内的“负压力”而导致岩浆房下部呈晶粥状态的闪长质层发生等温减压熔融作用,从而形成体量极小的包体岩浆;并即时“注入”地壳上部尚未固结的寄主花岗岩中,快速冷凝形成暗色微粒包体。因此,暗色微粒包体不能被视作为“壳幔岩浆混合作用”的证据。

关键词: 暗色微粒包体;岩浆混合作用;壳幔作用;花岗岩;岩浆房

自从 Didier (1973) 发表了《花岗岩及其包体》专著,国内外岩石学界对花岗岩中的岩石包体展开了全面的研究,从而划分出多种成因类型的岩石包体,如:捕虏体、析离体、残留体、残影体、残浆体、同源体和淬冷体 (Didier, 1973; 徐夕生和周新民, 1988)。根据野外产状及岩相学和地球化学特征(见下述),人们将普遍出现在钙碱性花岗岩中的一种岩石包体泛称为暗色微粒包体或镁铁质微粒包体(图 1)。目前,这种暗色微粒包体已普遍被看作是研究地球深部的“窗口”(莫宣学, 2011),作为探讨寄主花岗岩的岩浆起源和演化及其形成环境的重要证据。

1 暗色微粒包体的基本特征

根据前人的研究成果 (Didier, 1973; 曲晓明等, 1997; 莫宣学, 2002; Barbarin, 2005; 董传万等, 2009; Zhang Shuanhong and Zhao Yue, 2017), 大多数暗色微粒包体(狭义)具有如下标志性的特征:

(1) 在野外,暗色微粒包体的颜色为深灰色—灰黑色,明显地深于寄主花岗岩的灰白色—浅灰色。暗色微粒包体与寄主岩之间的边界在大多数情况下是截然的(图 2a),部分暗色微粒包体还具有冷凝边

或淬火边,因此很容易地将暗色微粒包体与寄主花岗岩区分开来。暗色微粒包体的形态变化较大,大多数呈卵圆形(图 1a),少数呈撕裂状或扭动状等不规则形态(图 1b)。暗色微粒包体的大小悬殊,其长径在几厘米到 1 m 左右范围内变化。

(2) 在显微镜下,暗色微粒包体呈现斑状细粒—微粒结构(图 2),斑晶多为斜长石(以中长石为主)、普通角闪石、黑云母及少量的钾长石和石英。斑晶的边缘多出现熔蚀现象(图 2b、d)。基质呈等粒状的岩浆结晶结构,其中常见细针状矿物(如磷灰石和普通角闪石)。副矿物主要为 Ti—Fe 氧化物、磷灰石和锆石(图 2c)。暗色微粒包体的总体矿物成分以闪长岩相为主,少数为石英闪长岩相。色率为 20~40,故它们常被简称为“暗色包体”或“镁铁质包体”。

(3) 在化学成分上,暗色微粒包体的 SiO_2 含量在 52%~60% 之间变化, FeO^T 含量为 5%~10%, MgO 含量为 2%~5%, CaO 含量为 4%~7%, TiO_2 含量为 0.6%~1.1%, P_2O_5 含量为 0.2%~0.4%, 相当于闪长岩的化学成分。暗色微粒包体的微量元素与稀土元素的配分模式与寄主花岗闪长岩基本相同。

注:本文为国家自然科学基金资助项目(编号:41872047)的成果。

收稿日期:2022-07-27;改回日期:2022-08-25;网络首发:2022-09-20;责任编辑:章雨旭。Doi: 10.16509/j.georeview.2022.09.025

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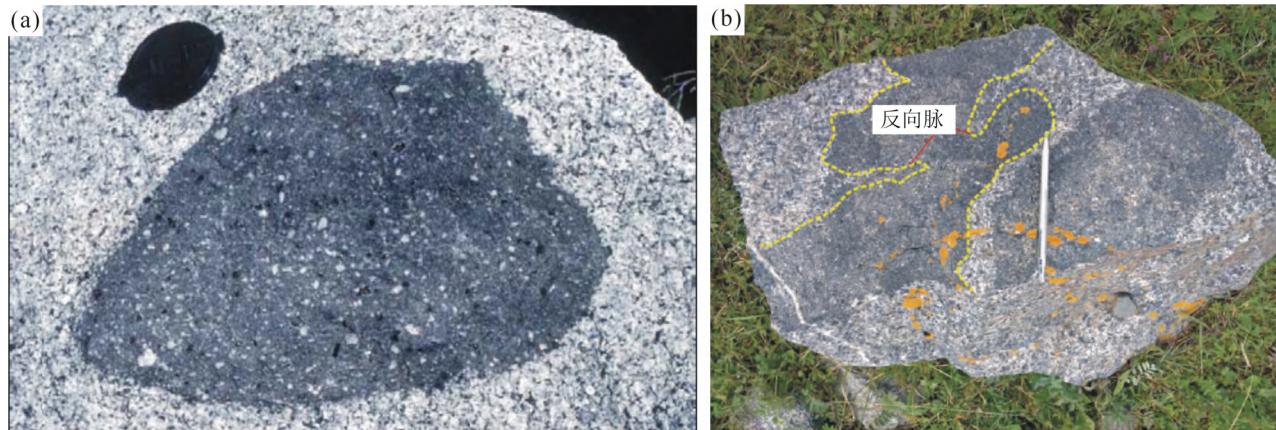


图1 花岗岩及其暗色微粒包体:(a)美国加州 Sierra Nevada 花岗闪长岩及其暗色微粒包体(Barbarin, 2005);
(b)青海马场花岗闪长岩及其暗色微粒包体(牛漫兰等,2021)

Fig. 1 Granite and its dark-colored microgranular enclave: (a) Sierra Nevada granodiorite and its dark-colored microgranular enclave (California, USA) (Barbarin, 2005); (b) Machang granodiorite and its dark-colored microgranular enclaves (Qinghai Province) (Niu Manlan et al., 2021&)

根据暗色微粒包体具有冷凝边构造、细粒—微粒岩浆结晶结构和韵律振荡构造的中长石等特征,可以确定暗色微粒包体是由中性岩浆结晶而来的;又根据暗色微粒包体的流动/扭动和压扁/拉长的形态,大多数作者认为包体岩浆与寄主花岗岩浆曾以熔融体状态共存过,在塑性寄主花岗岩浆的压扭作用下体量极小的包体岩浆被分割成独立的浆团而结晶成暗色微粒包体。

目前,这类暗色微粒包体的成因被普遍地认为:由幔源的基性岩浆与壳源的酸性岩浆在地壳深部混合而成的包体岩浆,注入到地壳上部的花岗岩浆中快速冷凝、结晶成暗色微粒包体(Barbarin, 2005;陈斌等,2009)。进而认为,这种基性岩浆来自上地幔,它与壳源酸性岩浆的混合作用是壳幔作用的主要证据(莫宣学,2011;陈广俊等,2014;陈国超等,2016)。

但是,对于这种类型的暗色微粒包体的成因解释存在许多难以实证/自洽的假定成分而令人存疑。事实上,许多暗色微粒包体的野外地质和岩相学现象及其地球化学分析数据等客观事实(见下述)都有悖于这种“壳幔岩浆混合说”。在此,笔者试从暗色微粒包体的岩浆来源和它们与寄主花岗岩之间的有机联系等方面,对暗色微粒包体的成因机制开展讨论;并在此基础上,笔者提出一种新的暗色微粒包体的形成方式,以解暗色微粒包体的成因之谜。

1.1 壳源性

暗色微粒包体可以具有以下三个方面的壳源特

征:

(1) 在暗色微粒包体中,从未见到来自上地幔和下地壳的捕虏体(如橄榄石和斜方辉石单晶体,或麻粒岩和片麻岩块体),所见到的都是花岗闪长岩中常见的矿物(如角闪石、黑云母、中长石等组成矿物,和磁铁矿、磷灰石、锆石等副矿物)(陈国超等,2016;巨银娟等,2018)。相反,在暗色微粒包体中普遍见有石英、钾长石和较低牌号的斜长石捕虏晶(相当于寄主花岗岩的组成矿物)(Vernon, 1991;范洪海等,2001; Baxter and Feely, 2002; 陈斌等,2009; 董传万等,2009; 付强等,2011; 陈广俊等,2014; 陈国超等,2016; 林蕾等,2018),它们往往具有熔蚀现象,说明暗色微粒包体的岩浆起源与上侵过程与寄主花岗岩浆的源区与上升通道有着密切关系。

(2) 暗色微粒包体的全岩 [$n(^{87}\text{Sr})/n(^{86}\text{Sr})$]_i 值可以大于 0.710,如:三佛山二长花岗岩中的暗色微粒包体的 [$n(^{87}\text{Sr})/n(^{86}\text{Sr})$]_i 值为 0.71225(李增达等,2018);英买来钾长花岗岩的暗色微粒包体的 [$n(^{87}\text{Sr})/n(^{86}\text{Sr})$]_i 值为 0.71036~0.71210(马乐天等,2010)。全岩 $\varepsilon_{\text{Nd}}(t)$ 值可以为很大的负值,如:三佛山二长花岗岩中的暗色微粒包体的 $\varepsilon_{\text{Nd}}(t)$ 值为 -15.1(李增达等,2018);河北白家店花岗岩中的暗色微粒包体的 $\varepsilon_{\text{Nd}}(t)$ 值为 -11.1~-7.0(徐希阳等,2016)。锆石 $\varepsilon_{\text{Hf}}(t)$ 值也可以为很大的负值,如:河北太行山花岗闪长岩中的暗色微粒包体的锆石 $\varepsilon_{\text{Hf}}(t)$ 值为 -25~-14(陈斌等,2009);安徽荞麦山花

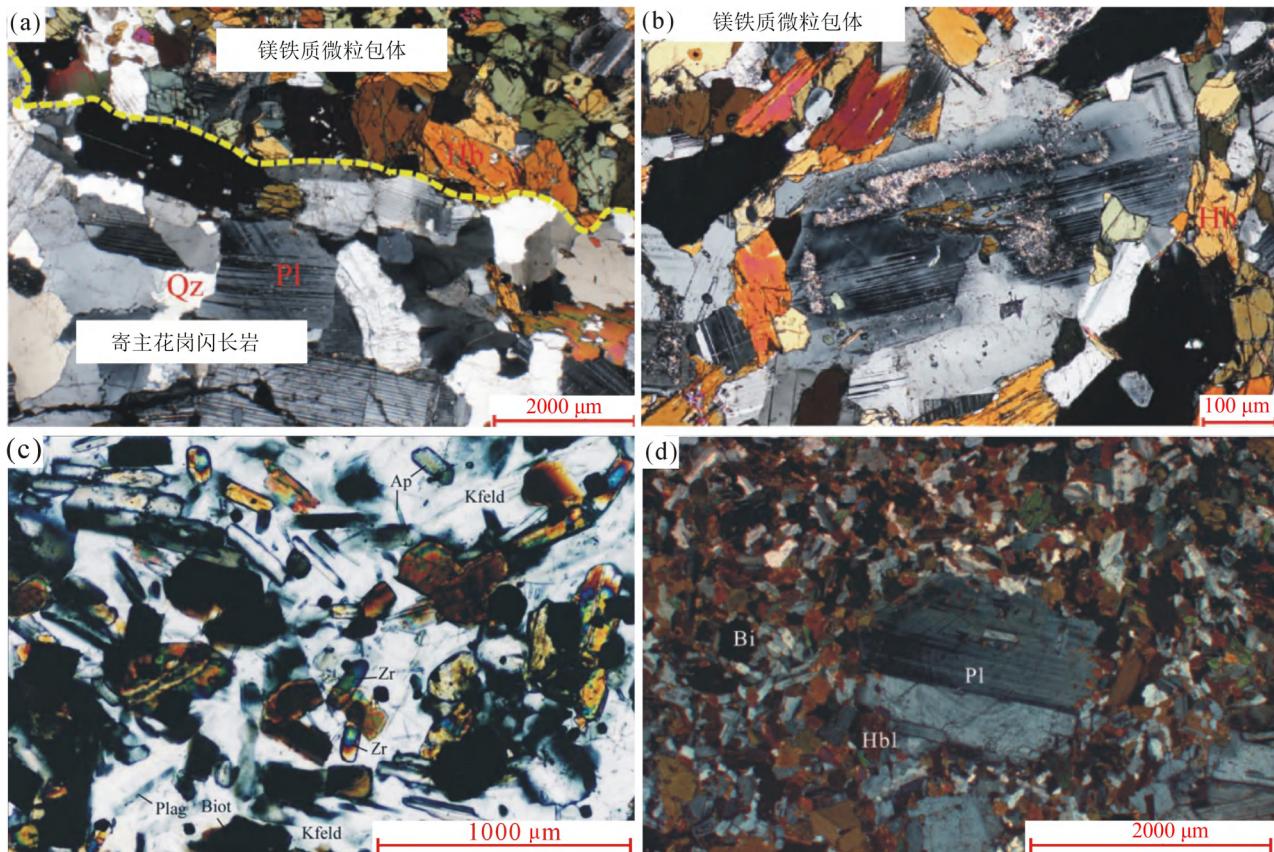


图2 暗色微粒包体的显微照片(正交偏光):(a)青海马场花岗闪长岩与暗色微粒包体的接触边界(牛漫兰等,2021);(b)青海马场暗色微粒包体中的斜长石捕虏晶(牛漫兰等,2021);(c)伊朗Chenar暗色微粒包体中的锆石和磷灰石“析离体或残留体”(Arvin et al.,2004);(d)青海卡而却卡暗色微粒包体中的斜长石捕虏晶(高永宝等,2015)

Fig. 2 Photomicrographs of dark-colored microgranular enclave (crossed polars) : (a) contact boundary between Machang granodiorite and its dark-colored microgranular enclave (Qinghai Province) (Niu Manlan et al. , 2021&) ; (b) plagioclase xenocryst in the Machang dark-colored microgranular enclave (Qinghai Province) (Niu Manlan et al. , 2021&) ; (c) “schlieren or restite” of zircon and apatite in the Chenar dark-colored microgranular enclave (Iran) (Arvin et al. , 2004) ; (d) plagioclase xenocryst in the Kaerqueka dark-colored microgranular enclave (Qinghai Province) (Gao Yongbao et al. , 2021&)

Hb(Hbl)—普通角闪石; Qz—石英; Pl(Plag)—斜长石; Bi(Biot)—黑云母; Kfeld—钾长石; Zr—锆石; Ap—磷灰石

Hb(Hbl)—hornblende; Qz—quartz; Pl(Plag)—plagioclase; Bi(Biot)—biotite; Kfeld—K-feldspar; Zr—zircon; Ap—apatite

花岗闪长岩中的暗色微粒包体的 $\varepsilon_{\text{Hf}}(t)$ 值为 $-12.7 \sim -5.8$ (李跃等,2019)。这些同位素特征说明暗色微粒包体可以是纯壳源的。即使相当多的暗色微粒包体的同位素成分看上去有幔源成分的加入,也可能是由于产生包体岩浆的源岩属于年轻地壳 (Zeng Renyu et al. , 2016),就像许多年轻的 S 型花岗岩的锆石 $\varepsilon_{\text{Hf}}(t)$ 值可以接近正值,如腾冲地块上盈江 S 型花岗岩的锆石 $\varepsilon_{\text{Hf}}(t)$ 值可达 -2 (Xu Yigang et al. , 2012),保山地块上柯街 S 型花岗岩的锆石 $\varepsilon_{\text{Hf}}(t)$ 值可达 -0.7 (陶琰等,2010)。

(3)事实上,暗色微粒包体可以出现在大量的 S 型花岗岩中 (Pitcher, 1993; 伍光英等,2008; 马乐天

等,2010; Champion and Bultitude, 2013; 崔圆圆等,2013; 李增达等,2018),如:南岭地区晚侏罗世含钨锡矿的改造型花岗岩中存在暗色微粒包体(湖南锡田黑云母花岗岩,据陈迪等,2014;湖南骑田岭黑云母花岗岩,据刘勇等,2011;湖南千里山黑云母花岗岩,据马铁球等,2005);最典型的是,在广西大容山含堇青石的 S 型花岗岩体中也出现暗色微粒包体(方清浩等,1987)。

1.2 同源性

尽管暗色微粒包体与寄主花岗岩在组成矿物和主量元素的相对含量上具有明显的差别,但是在晶体化学和微量元素地球化学方面,两者可以呈现高

度的相似性。

(1) 电子探针分析数据显示,暗色微粒包体与寄主花岗岩中的黑云母和普通角闪石具有相同的晶体化学成分(Barbarin, 2005);暗色微粒包体中斜长石的牌号和寄主花岗岩石中斜长石牌号有较大的重叠(程顺波等, 2009);暗色微粒包体中的斜长石捕虏晶(An_{38-41})的化学成分与寄主花岗岩中的斜长石斑晶(An_{39-40})也近乎相同(范洪海等, 2001)。

(2) 大量的全岩化学分析数据表明,暗色微粒包体常与寄主花岗岩具有完全一致的微量元素和稀土元素(图3)配分模式(Holden et al., 1991; 邱瑞龙, 1996; 范洪海等, 2001; 陈荣等, 2005; 程顺波等, 2009; 董传万等, 2009; 汪传胜等, 2009; 付强等, 2011; 陈广俊等, 2014; 高永宝等, 2015)。

(3) 更确定的是,暗色微粒包体与寄主花岗岩具有相同的全岩 [$n(^{87}\text{Sr})/n(^{86}\text{Sr})$]_i 值、全岩 $\varepsilon_{\text{Nd}}(t)$ 值和锆石 $\varepsilon_{\text{Hf}}(t)$ 值(Holden et al., 1991; 程顺波等, 2009; 刘亮等, 2011; 高永宝等, 2015; 林蕾等, 2018; 牛漫兰等, 2021; Chen Changjian et al., 2021),如:安徽莽麦山花岗闪长岩的 [$n(^{87}\text{Sr})/n(^{86}\text{Sr})$]_i 值为 0.7061~0.7064、 $\varepsilon_{\text{Nd}}(t)$ 值为 -8.7~-7.7, 其锆石 $\varepsilon_{\text{Hf}}(t)$ 值为 -12.1~-8.1、 $\delta^{18}\text{O}$ 值为 5.6‰~7.4‰;而暗色微粒包体的 [$n(^{87}\text{Sr})/n(^{86}\text{Sr})$]_i 值为 0.7059~0.7069、 $\varepsilon_{\text{Nd}}(t)$ 值为 -9.2~-6.0, 其锆石 $\varepsilon_{\text{Hf}}(t)$ 值为 -12.7~-5.8、 $\delta^{18}\text{O}$ 值为 5.8‰~7.7‰;两者的全岩 Sr 和 Nd 同位素成分和锆石 Hf 和 O 同位素成分几乎完全相同(李跃等, 2019)。

1.3 同龄性

锆石是耐熔矿物,在玄武岩中它既可以岩浆结

晶锆石出现,又可以捕获锆石出现(王炎阳等, 2014)。但是,目前在暗色微粒包体中获取的锆石 U-Pb 年龄几乎都与寄主花岗岩的锆石 U-Pb 年龄相等(Qin Jiangfeng et al., 2009; 刘亮等, 2011; 崔圆圆等, 2013; 陈广俊等, 2014; 高永宝等, 2015; 林蕾等, 2018; 李跃等, 2019; 王凯垒等, 2020; Chen Changjian et al., 2021)。而且,暗色微粒包体中的锆石颗粒(图 4b、d),在外部晶型、内部环带和 Th、U 含量及其 Th/U 比值等方面,与寄主花岗岩中的锆石颗粒(图 4a、c)基本一致(高永宝等, 2015; 李跃等, 2019),而完全不同于基性岩浆结晶锆石的特征(如:短柱至等粒状的外形,内部具扇状生长区,图 4e)(张贵山等, 2021)。

上述 3 个特征都显示,在暗色微粒包体中不存在幔源基性岩浆作用的痕迹。相反,我们看到的是它们与寄主花岗岩在时空与物质上的紧密联系,这将导出笔者建议的一种暗色微粒包体形成机制的新假说。

2 本文的新假说

虽然寄主花岗岩与暗色微粒包体具有相同的形成年龄(Qin Jiangfeng et al., 2009; 崔圆圆等, 2013; 陈广俊等, 2014; 高永宝等, 2015; 林蕾等, 2018; 李跃等, 2019),但是,根据暗色微粒包体的细粒—微粒岩浆结晶结构、基质中普遍含有针状磷灰石和针状角闪石、冷凝边构造、塑性形态等特征,可推定暗色微粒包体是包体岩浆在注入未完全固结的寄主花岗岩浆后,快速冷凝而形成。这意味着,所有的包体岩浆总是规律性地比寄主花岗岩浆稍晚上升定位的。

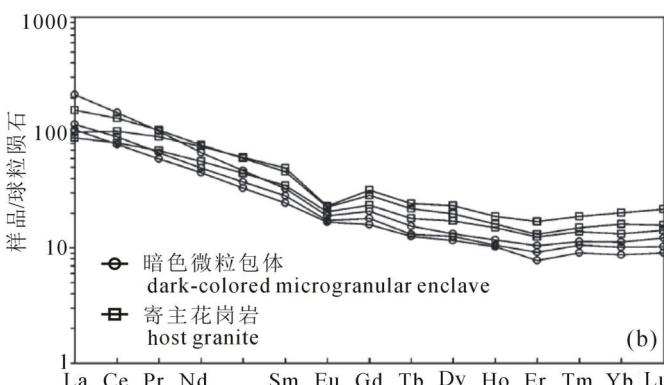
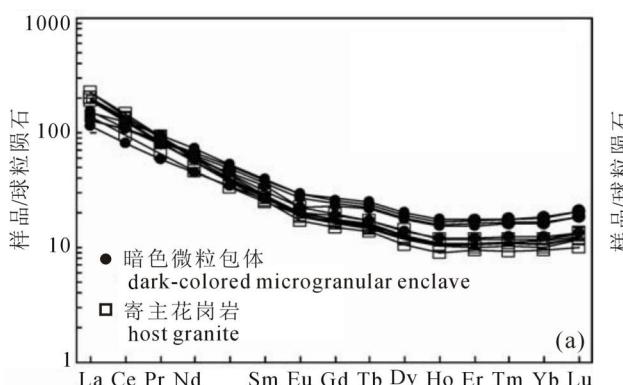


图 3 花岗岩及其暗色微粒包体的球粒陨石标准化稀土分图解:(a)广西米场花岗岩及其暗色微粒包体(付强等,2011);(b)青海卡而却花岗闪长岩及其暗色微粒包体(高永宝等,2015)

Fig. 3 Chondrite-normalized REE diagram for granites and their dark-colored microgranular enclaves: (a) Michang granite and its dark-colored microgranular enclaves(Guangxi Autonomous Region) (Fu Qiang et al., 2011&); (b) Kaerqueka granodiorite and its dark-colored microgranular enclaves(Qinghai Province) (Gao Yongbao et al., 2015&)

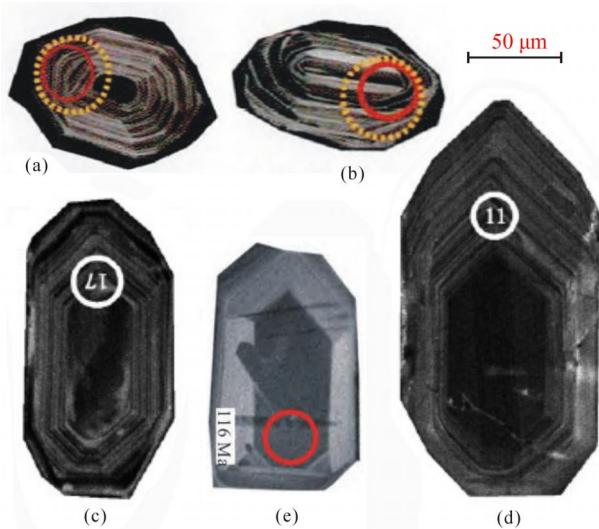


图 4 花岗岩及其暗色微粒包体和基性岩中的锆石颗粒的 CL 照片:安徽莽麦山花岗闪长岩(a)及其暗色微粒包体(b)中的锆石(李跃等,2019);青海卡而却卡花岗闪长岩(c)及其暗色微粒包体(d)中的锆石(高永宝等,2015);福建永定盆地基性岩墙(e)中的锆石(张贵山等,2021)

Fig. 4 CL images of zircon grains from granites and their dark-colored microgranular enclaves, and basic rock: zircon grains from the Qiaomaishan granodiorite (a) and its dark-colored microgranular enclaves (b) (Anhui Province) (Li Yue et al., 2019&); zircon grains from the Kaerqueka granodiorite (c) and its dark-colored microgranular enclaves (d) (Qinghai Province) (Gao Yongbao et al., 2019&); zircon grain from the basic dyke (e) in the Yongding basin (Fujian Province) (Zhang Guishan et al., 2021&)

确实,在寄主花岗岩基内部或周围,我们很少发现稍早于或略晚于寄主花岗岩浆定位的闪长岩脉。这种侵入时间上的差异性规律用上述“壳幔岩浆混合说”是解释不通的,而正是这个一直被忽视的关键事实奠定了新的暗色微粒包体成因假说的基石。

基于花岗岩岩基被认为是同造山阶段(即地壳受挤压而增厚的阶段)的产物(Castro and Fernandez, 1998; Yenes et al., 1999; 莫宣学等, 2005; Chen Shuo et al., 2015; 汪相, 2018, 2022),笔者认为,在加厚地壳深部形成的花岗岩浆房中,高熔点矿物(角闪石和黑云母等铁镁矿物,锆石、Ti—Fe 氧化物、磷灰石等副矿物和钙质斜长石)的比重大于初始花岗岩浆的比重,因此它们的早期结晶作用及其重力分离作用导致一个底部偏中性到顶部更酸性的层状岩浆房的形成(Worner and Schmincke, 1984; Landi et al., 1999)。当区域性挤压作用达到高峰

时,岩浆房上部的酸性岩浆沿着逆冲断层主动侵位(Castro and Fernandez, 1998; Yenes et al., 1999),定位在地壳上部。由于大量花岗岩浆的上侵,使得岩浆房内产生“负压力”(因减荷而降压),导致岩浆房下部呈晶粥状态的闪长质层(即上述高熔点矿物+粒间黏性花岗岩浆)发生等温减压熔融作用(Muller et al., 2005)而形成少量的中性岩浆(即包体岩浆);同时,在大量花岗岩浆上侵作用的虹吸效应下,更少量的中性岩浆(即包体岩浆)沿着花岗岩浆的上升通道,“注入”进较早上侵但并未固结的花岗岩浆中,冷凝而形成暗色微粒包体。通过这个暗色微粒包体的成因机制,我们就能容易地解释有关暗色微粒包体的各种别称(见下述)。

2.1 析离体或残留体

许多作者把暗色微粒包体当作析离体(Dahlquist, 2002; Chen Shuo et al., 2015)或残留体(Bateman and Chappell, 1979; Chappell and White, 1991),原因是暗色微粒包体中的斑晶矿物(如角闪石、黑云母和斜长石)和副矿物(锆石、磷灰石、Ti—Fe 氧化物)正是花岗岩浆房中早期结晶的高熔点矿物(相当于析离体),它们没有被等温减压熔融作用分解掉,因而被等温减压熔融作用形成的包体岩浆带到地壳上部(相当于残留体)。

(1) 暗色微粒包体往往富集锆石(图 2c)、磷灰石(图 2c)、Ti—Fe 氧化物等高熔点的副矿物(Arvin et al., 2004),具体地表现为这些副矿物在暗色微粒包体中的含量比在寄主花岗岩中的含量要高(曲晓明等, 1997; 汪传胜等, 2009)。汪相和 Kienast (2000)在暗色微粒包体中发现有较大粒径和较大晶型指数(I_{pr} 和 I_{py})的锆石颗粒,被确定为包体岩浆定位前结晶的;Barbarin (2005)也在暗色微粒包体中发现具熔蚀凹坑的较大粒径的锆石颗粒。陈荣等(2005)发现暗色微粒包体中的磷灰石含量可以达到 2%;除了细小针状的磷灰石,暗色微粒包体常含有粗短柱状的磷灰石(陶维松等, 1987; 周金城和徐夕生, 1992; 邱瑞龙 1996; Barbarin, 2005; 汪传胜等, 2009; 程顺波等, 2009; 牛漫兰等, 2018),后者代表包体岩浆定位前的结晶产物。这些副矿物的相对富集导致暗色微粒包体中 Zr、P 和 Ti 含量常常远高于寄主花岗岩(Holden et al., 1991; 周金城和徐夕生, 1992; 邱瑞龙, 1996; 陈荣等, 2005; 巨银娟等, 2018)。然而,这种高度富集 Zr、P 和 Ti(主要是 Zr)及其副矿物(主要是锆石)的事实用“壳幔岩浆混合说”是不能解释的,因为玄武岩中的 Zr 含量(约

90×10^{-6} , 据 Pearce, 1983) 远远低于酸性岩中的 Zr 含量(约 170×10^{-6} , 据 Ewart, 1968)。

(2) 在暗色微粒包体中, 常发现正环带构造的斜长石(周金城和徐夕生, 1992; 秦拯纬等, 2018), 其高牌号的核部具有熔融边轮廓, 应该属于花岗岩浆房中早期结晶的矿物; 其低牌号的边部具有半圆形轮廓, 应该属于包体岩浆在上升和定位过程中的结晶产物。在此, 相对于花岗岩浆而言, 核部的斜长石可以当作析离体; 而相对于包体岩浆而言, 它也可以当作残留体。

(3) 在暗色微粒包体中, 偶有普通辉石的残余相(Didier, 1987; 曲晓明等, 1997), 它们被后期结晶的角闪石和黑云母呈反应边形式包裹(陶维松等, 1987; 陈斌等, 2009)。

(4) 在暗色微粒包体中, 也可以见到少量巨粒状的普通角闪石斑晶(陈国超等, 2016), 它们的边缘多被熔蚀成港湾状(陈广俊等, 2014; 高永宝等, 2015), 属于花岗岩浆房中最早结晶的铁镁矿物(相当于析离体)但被包体岩浆捕获而成为暗色微粒包体的斑晶矿物(相当于残留体)。

(5) 当未熔融的铁镁矿物(普通辉石、普通角闪石、黑云母)和副矿物(Ti—Fe 氧化物、磷灰石、锆石)聚集在一起, 并被包体岩浆捕获以后, 常常构成“双包体”, 即暗色微粒包体中包含有颜色更深的岩石包体(Didier, 1987; 陈希节等, 2016)。

2.2 捕虏体

也有作者把暗色微粒包体当作捕虏体(Didier, 1973), 原因是暗色微粒包体中存在较大粒径的石英、钾长石、更长石捕虏晶(或被称为嵌晶)(Vernon, 1991; 范洪海等, 2001; Baxter and Feely, 2002; 陈斌等, 2009; 董传万等, 2009; 付强等, 2011; 陈广俊等, 2014; 陈国超等, 2016; 林蕾等, 2018)。

(1) 在暗色微粒包体中, 见有大颗粒的石英、钾长石和更长石(粒度可达 1 cm 以上)。这些捕虏晶矿物的颜色、形态与成分与寄主花岗岩中的长英质斑晶几乎完全相同(Vernon, 1991; 范洪海等, 2001; 陈广俊等, 2014; 林蕾等, 2018)。笔者认为, 这些原为寄主花岗岩的石英和长石颗粒可以出现在减压熔融区的正上方或在包体岩浆上侵的通道内, 因此, 很容易“掉入”上侵过程中的包体岩浆中。当它们“掉入”包体岩浆后, 被不同程度地熔蚀成港湾状(图 2b), 其外围生长了一圈“过冷”结晶的微粒暗色矿物(角闪石、黑云母等), 构成镶边结构(或暗色环边结构)(Baxter and Feely, 2002; 付强等, 2011; 陈

广俊等, 2014; 陈国超等, 2016)。有时, 钾长石捕虏晶被一层斜长石包裹, 形成环斑结构(Vernon, 1991)。

(2) 在暗色微粒包体中, 常出现反环带构造的斜长石(Baxter and Feely, 2002; 秦拯纬等, 2018), 其核部成分均一, 为中长石(An_{31-34} , 据陈斌等, 2009), 相当于花岗岩浆房中正常结晶的斜长石, 后被上侵的包体岩浆捕获并在边部结晶出拉长石(An_{54-58} , 据陈斌等, 2009)。或者, 暗色微粒包体中出现的斑晶斜长石为牌号较低的更长石, 而基质斜长石为牌号较高的中长石(陶维松等, 1987), 前者也可认作为捕虏晶矿物。

上述两种现象, 用“壳幔岩浆混合说”也是很困难解释的, 因为低熔点的较大粒径的长英质矿物在地壳深部遇到高温基性岩浆是很难存留下来的。

2.3 淬冷体

寄主花岗岩浆与包体岩浆温度可以相差 300°C 左右(王德滋和谢磊, 2008; 陈广俊等, 2014), 当高温的包体岩浆注入进低温的寄主花岗岩浆中时, 前者会快速冷却和结晶, 形成针状磷灰石和针状角闪石以及冷凝边, 故暗色微粒包体也被称为“淬冷包体”(徐夕生和周新民, 1988)。但是, 笔者认为, 这些暗色微粒包体的“淬冷”特征并不是由两种岩浆之间的较大温差引起的, 而是由(暗色微粒包体的)中性岩浆具有较高的固相线温度造成的。这一点可以得到以下事实的支持:

(1) 如果包体岩浆与寄主花岗岩浆之间有 300°C 左右的温差(王德滋和谢磊, 2008; 陈广俊等, 2014), 那么, 包体岩浆注入进寄主花岗岩浆后, 应该快速冷凝固结为闪长玢岩脉体。事实上, 暗色微粒包体普遍有扭动或撕裂等塑性形态, 并被寄主花岗岩浆分割成独立的浆团。在暗色微粒包体边部常见有寄主花岗岩浆穿插进来的反向脉(图 1b), 后者被认为是“包体岩浆与寄主花岗岩浆之间的相互挤压、揉动造成的”(范洪海等, 2001)。

(2) 在同一寄主花岗岩中, 与“淬冷包体”一起出现的部分暗色微粒包体的边界可以是弥散的(董传万等, 2009; 陈希节等, 2016; 牛漫兰等, 2018), 后者的出现说明“两种岩浆的温度差别不大”(Hibbard, 1995; 陈国超等, 2016);

(3) 暗色微粒包体内部并没有出现由外向内矿物粒级变大的快速冷凝构造(图 2a); 也没有在寄主花岗岩一侧, 出现高温烘烤下的任何岩石学现象(如寄主花岗岩中斑晶矿物的熔融作用和/或基质

矿物的粒径变大)(图 2a)。

无论我们把暗色微粒包体归于何种成因类型,它有另一个一直被忽视的重要特征:在野外,暗色微粒包体可以成群出现,但它们单个的粒径很少超过 2 m(图 1),且它们仅出现在花岗岩基的局部露头上(以花岗岩基的中心部位为多见),而在露头上它们的分布面积很少超过 10%(马铁球等,2005),因此,相对寄主花岗岩的岩基产状,暗色微粒包体的体积总量是极小的。用笔者的新假说可以解释这一关键现象:①因寄主花岗岩浆上侵造成的岩浆房内的“负压力”状态是瞬间的,所以,通过等温减压熔融作用形成的包体岩浆的体量是有限的;②因寄主花岗岩浆上侵造成的虹吸效应不是一种强力作用,所以,包体岩浆上侵的体量更是有限的。然而,用目前流行的“壳幔岩浆混合说”(莫宣学,2011;陈广俊等,2014;陈国超等,2016)就很难回答:“由于岩石圈伸展作用,引起富集的岩石圈地幔发生部分熔融,并形成大量的玄武质岩浆。这些玄武质岩浆随后底侵到下地壳,其高温促使下地壳物质发生部分熔融而形成大规模花岗质岩浆”(陈斌等,2009),为什么在拉张环境中如此宏大的(!)壳幔作用最终产生的总是如此微量的(!)包体岩浆?在此,笔者必须指出暗色微粒包体形成的一个必要条件——挤压的构造环境。在挤压的构造环境中,加厚地壳的深熔作用造成大量的钙碱性准铝质花岗岩浆,并沿逆冲断裂主动侵位而形成(陆内)花岗岩基(Castro and Fernandez, 1998; Yenes et al., 1999; 莫宣学等, 2005; Chen Shuo et al., 2015; 汪相, 2018, 2022);当包体岩浆“注入”进这些已经定位但尚未固结的寄主花岗岩浆时,因后者受到不同方向的扭剪作用,导致包体岩浆被分割成独立的浆团而形成暗色微粒包体(Vernon, 1991; 范洪海等, 2001; 董传万等, 2009)。事实上,暗色微粒包体主要出现在同造山花岗岩中,如:印支早期(湖南)紫云山花岗岩(曾认宇等, 2016)、燕山早期(湖南)铜山岭花岗岩(刘勇等, 2011)、黄山早期(江西)灵山花岗岩(汪相, 2022)、喜山早期(云南)马厂箐花岗岩(郭晓东等, 2011)。相反,关于暗色微粒包体成因的“壳幔岩浆混合说”(莫宣学, 2011; 陈广俊等, 2014; 陈国超等, 2016)却是建立在拉张构造背景条件下的,难以解释钙碱性花岗岩中暗色微粒包体的普遍性、滞后侵入时间和极小的体量等特征。

3 结论

汪相和 Kienast(2000)对浙江青田钙碱性花岗

岩中暗色微粒包体的锆石进行了晶型和成分研究,得到结论:“在抽取了寄主花岗岩浆的部分熔融区,部分残留物质(含有大量暗色矿物和副矿物)遭受熔融作用而形成包体岩浆”,而完全否定了包体岩浆的“壳幔岩浆混合说”。笔者通过对最新文献资料的深度讨论,获得了与汪相和 Kienast(2000)的观点基本一致但更深入的推断:在同造山阶段,加厚地壳的深熔作用产生同造山花岗岩浆房;随后,岩浆房上部的花岗岩浆的主动上侵造成岩浆房内的“负压力”而导致岩浆房下部呈晶粥状态的闪长质层(即高熔点矿物+粒间黏性花岗岩浆)发生等温减压熔融作用,从而形成体量很小的包体岩浆;并即时“注入”地壳上部尚未固结的寄主花岗岩中,快速冷凝形成暗色微粒包体。因此,暗色微粒包体是一种壳源花岗岩浆作用范畴内的岩石学现象,而不能视作为“壳幔岩浆混合作用”的证据。

致谢:本文受章雨旭副主编邀约而作,他怀疑偶发的壳幔岩浆混合作用作为很常见的暗色微粒包体的成因机制的合理性,而笔者近期的科研成果和大量的文献资料可以试着答疑解惑,遂成此文;汪洋教授[中国地质大学(北京)]等 3 位评审专家对本文提出了许多建设性的修改意见;在此一并表示衷心感谢。

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Dark-colored microgranular enclaves are not the evidence for magma mixing under crust—mantle interaction

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Abstract: The dark-colored microgranular enclaves often occur in calc-alkaline granites, and have been considered to be product of magma mixing between mantle-derived basic magma and crust-derived acid magma in deep crust. After analysis on a large amount of documents, it is found that the dark-colored microgranular enclaves could show very negative whole-rock $\varepsilon_{\text{Nd}}(t)$ values and zircon $\varepsilon_{\text{Hf}}(t)$ values, and whole-rock $[n(^{87}\text{Sr})/n(^{86}\text{Sr})]$ values of more than 0.710, thus indicating no mantle-derived magma. In addition, most dark-colored microgranular enclaves and host granites are very similar in crystal chemistry, formation age, and isotopic composition of zircons, reflecting that both are cogenetic based on their temporal—spatial and material relationship. This paper considers that the dark-colored microgranular enclave could not be regarded as product of crust—mantle interaction. On the basis of very small volume and a little later emplacement of magma of the dark-colored microgranular enclaves (relative to the host granites), this paper proposes a new formation mechanism for the dark-colored microgranular enclaves: the forceful emplacement of syn-orogenic granitic magma caused “negative pressure” in magma chamber, which resulted in isothermal decompressing melting of the dioritic layer in the form of crystal mush and located in lower part of magma chamber, and formation of a small volume of magma of the dark-colored microgranular enclaves; then, the latter injected into unconsolidated host granitic magma in upper crust and rapidly crystallized and formed the dark-colored microgranular enclaves. Therefore, the dark-colored microgranular enclave could not be regarded as the evidence for magma mixing under crust—mantle interaction.

Keywords: dark-colored microgranular enclave; magma mixing; crust—mantle interaction; granite; magma chamber

Acknowledgments: This paper is written for the invitation of the deputy editor-in-chief ZHANG Yuxu, who

has a suspicion if the frequently observed dark-colored microgranular enclaves were formed by magma mixing under accidental crust—mantle interaction. The author can handle queries through his recent results and reference material and successfully completed this paper. The author thanks to Professor WANG Yang in China University of Geoscience (Beijing) and two other reviewers for very helpful comments. This paper is a result of the National Natural Science Foundation of China (No. 41872047)

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Manuscript received on: 2022-07-27; **Accepted on:** 2022-08-25; **Network published on:** 2022-09-20

Doi: 10.16509/j.georeview.2022.09.025

Edited by: ZHANG Yuxu