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·综述与进展·

长英质富晶体火山岩成因
——岩浆补给与晶粥再活化

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摘 要: 火山是人类窥探深部岩浆系统的窗口。从全球范围来看,贫晶体富熔体的火山岩(尤其是玄武岩和流纹岩)大面积出露,而富晶体的长英质火山岩仅出露于破火山周围。长英质富晶体火山岩主要可分为两类:一类是成分和晶体含量均一的火山岩;另一类是成分和斑晶含量分带的火山岩。富晶体火山岩是冷储存晶粥接受岩浆反复补给后重熔、再活化,重新具备流动能力而喷发形成的,储库中先存物质的成分决定了再活化形成的富晶体火山岩的类型。富晶体火山岩的存在能够很好地解释岩浆储库具有较长的寿命而岩浆汇聚结晶的过程却是迅速的这种看似矛盾的现象。虽然近年来长英质富晶体火山岩的研究已经取得了明显的进展,但仍有许多问题亟待解决,如碎斑熔岩的成因,如何判别晶粥活化,晶粥再活化与火山喷发的关系,岩浆补给和晶粥活化的时间尺度等。对富晶体火山岩的进一步研究将有助于深入揭示熔体演化、运移、在浅部的聚集和喷发的机制,并可为建立更完善的长英质岩浆演化模型提供更多信息。

关键词: 富晶体火山岩; 岩浆补给; 晶粥再活化; 中国东南部; 碎斑熔岩
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Petrogenesis of the felsic crystal-rich volcanic rocks: Magma recharge and reactivation of the crystal mush

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Abstract: Volcanoes are a window for humans to explore deep magma systems. From a global perspective, crystal-poor and melt-rich volcanic rocks (especially basalt and rhyolite) are mainly exposed all over the earth, while crystal-rich felsic volcanic rocks exposed around many calderas. The felsic crystal-rich volcanic rocks can be mainly divided into two types: one type is the volcanic rocks with homogenous composition and crystal contents; the other type is the volcanic rocks with zoned composition and crystal contents. The crystal-rich volcanic rocks erupted due to the cold stored crystal mush was remelted, reactivated, and remobilized after being repeatedly recharged by hot magma. The composition of the preexisting materials in the reservoir constrained the type of crystal-rich volcanic rocks

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formed by reactivation. The existence of crystal-rich volcanic rocks can well explain the contradictory phenomenon that the magma reservoir has a long life, but the process of magma accumulation and crystallization is rapid. Although the research of felsic crystal-rich volcanic rocks has made obvious progress in recent years, there are still many problems to be solved, such as the origin of porphyritic lava, how to reveal the reactivation of crystal mush, the relationship between crystal mush reactivation and volcanic eruption, the time scale of magma recharge and crystal mush reactivation, etc. Further research on crystal-rich volcanic rocks will promote the understanding of the mechanisms of melt evolution, migration, and shallow accumulation and eruption, providing more information for establishing a more comprehensive model of felsic magma evolution.

Key words: crystal-rich volcanic rocks; magma recharge; crystal mush reactivation; Southeast China; porphyritic lava

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现代岩浆储库概念的诞生可追溯至 100 多年前。液态为主的高熔体比例岩浆房模型一度成为人们对地壳岩浆储库的主流认识(Daly, 1911)。然而，对活火山的地球物理观测表明,其深部岩浆储库中的熔体比例并不高,不支持岩浆房中物质以熔体为主的传统认识(Glanzner *et al.*, 2004; Huang *et al.*, 2015; Cashman *et al.*, 2017; 马昌前等, 2020; 贺振宇等, 2021)。近年来锆石 U-Pb 定年、U 系不平衡年龄和矿物扩散年代学等不同方法获得的岩浆房寿命差异较大(周金胜等, 2022; Bo *et al.*, 2023),这一现象也很难利用传统岩浆房理论解释。越来越多的研究者相信,岩浆在地下数十公里处是以高结晶度岩浆体形式存在的(Bachman and Bergantz, 2004; Hildreth, 2004; Lee and Bachmann, 2004; Yan *et al.*, 2016; 吴福元等, 2017; 马昌前等, 2020; Xu *et al.*, 2021; Shi *et al.*, 2022),这些高结晶度岩浆体被称为晶粥(crystal mush)(图 1a) (Bachman and Bergantz, 2004)。晶粥是晶体与硅质岩浆的混合物(Miller and Wark, 2008),高结晶度(>40%)的晶粥原位固结成巨大岩基,有时喷发后形成均一的无成分分带的富晶体的熔结凝灰岩(Bachmann and Bergantz, 2004),高硅、低温(<800℃)的黏性熔体(至多 $10^5 \sim 10^6$ Pas; Scaillet *et al.*, 1998)可在岩浆达到流变学临界状态(体积分数约 50%)时从高结晶体中由于重力作用(晶体沉降、压实作用)缓慢抽离(Brophy, 1991; Thompson *et al.*, 2001; Bachman and Bergantz, 2004; Hildreth, 2004; Solano *et al.*, 2012),并进一步上升喷发形成贫斑晶的火山岩。

实际研究中发现,同一块岩石样品中相邻的晶体颗粒有时具有不同的同位素组成,甚至单个颗粒中同位素组成也会发生显著变化(Bindeman and Valley, 2001; Dungan and Davidson, 2004; Charlier *et al.*, 2007; Davidson *et al.*, 2007; Lange *et al.*, 2013)。这些具有小规模同位素不均一性的颗粒,或是单个颗粒中的不同分带,不太可能来自于同一个大型且持续的熔体,只有更大规模的岩浆系统中的活动使不同岩浆在浅部地壳聚集才能解释如此复杂的晶体生长结构,因此对岩浆储库的认识也应该由封闭变为开放。火山岩中的斜长石往往是最常见的岩浆运移过程中被夹带的矿物晶体,其结晶历史可被记录在其复杂的成分分带中(Cashman *et al.*, 2017),通过解析单个斜长石颗粒中成分的变化并结合相平衡图解,可以解译出相互连通的不同深度的岩浆储库中熔体的迁移与演化历史(Cashman and Blundy, 2013)。岩浆作用贯穿着整个地壳,不同深度的晶粥构成了穿地壳岩浆系统(Transcrustal magmatic system; Cashman *et al.*, 2017),涵盖了从基性岩浆底侵和地壳部分熔融、熔体上升和汇聚、岩浆的演化和分异乃至火山爆发的几乎所有的岩浆作用过程(蒋昌宏等, 2022)。对相平衡计算和矿物结晶过程的深入研究发现,在穿地壳岩浆系统中,晶体-熔体分离控制着晶粥的分异演化(Xu *et al.*, 2021),并进一步造成岩浆岩的地球化学多样性。

富晶体火山岩即是穿地壳岩浆系统中长英质晶粥演化过程的一种特殊产物,仅在某些特定的情况下出现(王硕等, 2020)。富晶体火山岩有两类：一类是英安质或流纹质的斑晶含量和成分均匀的熔结凝灰岩(monotonous intermediate or rhyolitic ignimbrites)(图 1b),另一类是具斑晶含量和成分分带的流纹质熔结凝灰岩(zoned ignimbrites)(图 1b)(Hildreth,

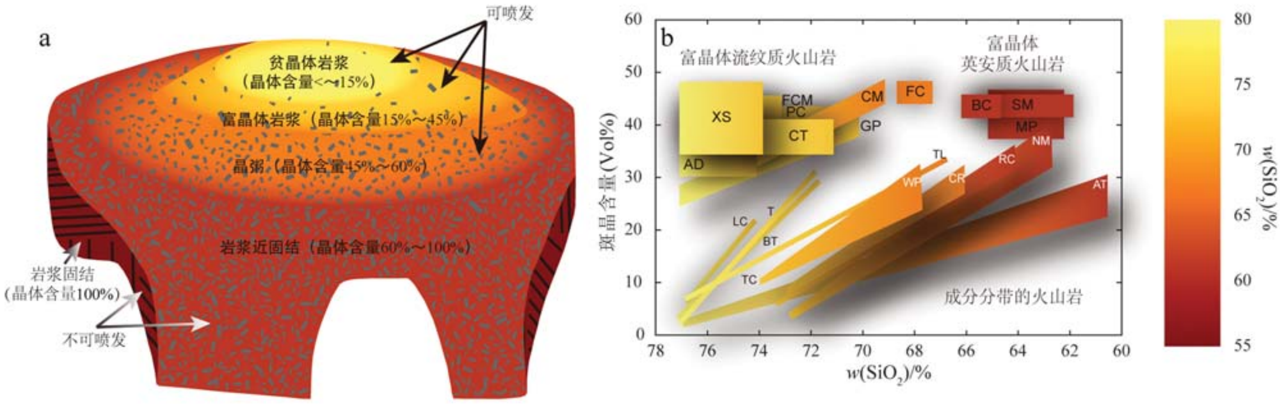

图 1　带状晶粥模型[a，据 Hildreth(2004)、Miller(2016)和颜丽丽等(2022)修改]和富晶体火山岩斑晶含量与 SiO_2 含量协变图[b，据 Huber 等(2012)、Watts 等(2016)修改]

Fig. 1　Schematic cartoon illustrating zoned mush model (a, modified after Hildreth, 2004; Miller, 2016; Yan Lili *et al.*, 2022) and phenocryst content versus SiO_2 content diagram of crystal-rich volcanic rocks (b, modified after Huber *et al.*, 2012 and Watts *et al.*, 2016)

XS—相山流纹质碎斑熔岩；TL—桐庐火山岩(Du *et al.*, 2022)；西内华达火山盆地熔结凝灰岩(Watts *et al.*, 2016)：FCM—Fish Creek Mountains 凝灰岩；CM—Cove Mine 凝灰岩；PC—Poco Canyon 凝灰岩；AD—Arc Dome 凝灰岩；美国西部熔结凝灰岩(Huber *et al.*, 2012)：CT—Caetano 凝灰岩；LC—Lava Creek 凝灰岩；T—Bandelier 凝灰岩中的 Tshigere Member；BT—Bishop 凝灰岩；TC—Tiva Canyon 凝灰岩；WP—Wason Park 凝灰岩；CR—Carpenter Ridge 凝灰岩；RC—Rat Creek 凝灰岩；NM—Nelson Mountain 凝灰岩；AT—Ammonia Tanks 凝灰岩；FC—Fish Canyon 凝灰岩；BC—Blue Creek；SM—Snowshoe Mountain 凝灰岩；MP—Masonic Park 凝灰岩

XS—Xiangshan rhyolitic porphyritic lava; TL—Tonglu volcanic rocks (Du *et al.*, 2022); Abbreviations for ignimbrites of the western Nevada volcanic field (Watts *et al.*, 2016) are as follows: FCM—Fish Creek Mountains tuff; CM—Cove Mine tuff; PC—Poco Canyon tuff; AD—Arc Dome tuff; Abbreviations for ignimbrites of the western USA (Huber *et al.*, 2012) are as follows: CT—Caetano tuff; LC—Lava Creek tuff; T—Tshigere Member of the Bandelier tuff; BT—Bishop tuff; TC—Tiva Canyon tuff; WP—Wason Park tuff; CR—Carpenter Ridge tuff; RC—Rat Creek tuff; NM—Nelson Mountain tuff; AT—Ammonia Tanks tuff; FC—Fish Canyon tuff; BC—Blue Creek; SM—Snowshoe Mountain tuff; MP—Masonic Park tuff

1981; Huber *et al.*, 2012; Bachmann and Huber, 2016)。富晶体火山岩的出现，表明岩浆储库的演化过程极度复杂。Watts 等(2016)通过对 Caetano 地区大型火山口的系统研究，发现该区域的熔结凝灰岩并非简单的由晶体-熔体分离形成，而是经历了岩浆补给、晶粥活化、再均一等过程，由于有高温岩浆的补给，导致已形成的晶粥发生再次活化，从而形成这种富晶体的火山岩。因此，富晶体火山岩的形成过程往往记录了晶粥演化不同过程的信息，对富晶体火山岩的研究可以加深对长英质岩浆储库复杂过程的全面认识。本文总结了晶粥分异演化和储存状态的研究新进展，并综述了富晶体火山岩研究的现状和存在问题，以为进一步了解长英质岩浆储库复杂的分异演化的物理过程、热动力学和时间尺度提供参考。

1　长英质岩浆储库的分异演化

1.1　晶体-熔体分异

火山岩和侵入岩的成因联系是一个争论了上百年的基本科学问题(Read, 1948; Buddington, 1959; Hamilton and Myers, 1967; Pitcher, 1987; Bachmann *et al.*, 2007; Glanzner *et al.*, 2015; Keller *et al.*, 2015)。长英质侵入岩到底是结晶的熔体("未喷出的火山岩"，没有经历过明显的晶体-熔体分离)，还是火山喷发的残余堆晶？通常全岩和矿物的元素地球化学和岩相学特征可以比较好地区分出这两种成因。晶体-熔体分离作用形成的堆晶一般显著富集相容微量元素而亏损不相容元素(Mohamed, 1998; Deering and Bachmann, 2010)，并且堆晶(侵入岩)中会因晶体-熔体分离作用(晶体沉降和/或压实作用)出现某些矿物定向和片理(Arculus and Wills, 1980; Seaman, 2000; Xu *et al.*, 2021; Shi *et al.*, 2022)。

有学者认为相较于镁铁质岩浆，晶体-熔体分离对长英质岩浆演化的贡献很低，因为长英质堆晶中往往具有更多的粒间熔体，岩浆黏度高，不易发生晶体-熔体分离，长英质火山岩和侵入岩中晶体-熔体分离的地球化学、岩相学信号很难被识别(Bachmann *et al.*, 2007; Gelman *et al.*, 2014)。尽管地球化学大数据不能清晰区分长英质火山岩和侵入岩的成分(Glanzner *et al.*, 2015; Keller *et al.*, 2015)，还是有

一些学者发现喷出岩普遍具有更高的全岩 SiO_2 含量(Lipman, 2007; Gelman *et al.*, 2014; Deering *et al.*, 2016)。近年来的一些研究也表明即使存在明显的粒间熔体,长英质侵入岩还是显示出具有高相容元素、低不相容元素的特征(Deering and Bachmann, 2010; Yan *et al.*, 2016; Liang *et al.*, 2022)。对花岗质岩石开展的显微岩相学和 BSE、TIMA 等微区结构的分析也找到了黏度较高的长英质岩浆中矿物压实、沉降的证据(Graeter *et al.*, 2015; Shi *et al.*, 2022)。长英质晶粥通过晶体-熔体分离作用,产生了具有活动性的高硅流纹质岩浆喷发到地表,而留下的相对低硅的残余液相和晶体的混合物就以侵入岩的形式保留在了火山之下(Hildreth, 2004; Lipman, 2007; Lipman and Bachmann, 2015)。

1.2　高硅(高分异)花岗岩

上地壳中的中酸性侵入体主要是花岗闪长质和英云闪长质的(Rudnick, 1995),狭义的花岗岩(石英占长英质矿物的 20%~60%,斜长石占长石的 10%~65%)却十分稀少(Glanzner *et al.*, 2015)。高演化的长英质岩浆储库位于存在大量可出溶挥发分的上地壳(Bachmann and Huber, 2016),而挥发分在熔体中聚集会使熔体具有很高的喷发能力,从而诱发大量的火山喷发(Huppert and Woods, 2002)。这可能造成了在高硅流纹岩的分布区较少出露与之成分相对应的高演化(高分异)花岗岩。

不过,长英质岩浆储库的顶部也能够聚集大量的高硅花岗岩(HSGs)(Hildreth, 1979; Bachl *et al.*, 2001;Bachmann and Bergantz, 2004, 2008)。Lee 和 Morton(2015)在研究高硅花岗岩时发现,在哈克图解中,不相容元素(如 K、Rb)和相容元素(如 Sr)的变化趋势在 71%的 SiO_2 处均发生陡然变化,是因为 SiO_2 含量超过 70%时晶体-熔体分离开始主导分异过程。吴福元等(2017)结合晶粥模型对通常具有高硅特征的高分异花岗岩的成因开展研究,认为很多高分异花岗岩就是通过晶粥体的晶体-熔体分异形成的,即从深部岩浆房中抽取的高硅熔体形成高分异的高硅花岗岩,而残留在岩浆房的物质结晶形成略低硅的富含斑晶的花岗岩类。

此外,同一地区与高硅花岗岩同源、互补的二长花岗岩/花岗闪长岩中出现的钾长石聚晶指示了长石的堆晶作用(Lu *et al.*, 2022)。高硅花岗岩与火山-侵入杂岩中代表抽取的高硅熔体的流纹岩或流纹质凝灰岩存在类似的地球化学特征,也存在明显的 Eu、Ba、Sr 的负异常,其周围也出露成分与之互补的同期深成岩,这些高硅花岗岩与互补的深成岩之间往往也存在 SiO_2 成分间断。因此,高硅花岗岩也很可能是由晶体-熔体分离后抽离出的高硅熔体结晶形成的(Lu *et al.*, 2022; Chen *et al.*, 2022)。

1.3　贫晶体和富晶体火山岩

高硅流纹岩(SiO_2>70%)在地球上十分常见,但其中晶体含量通常较低(Bachmann and Huber, 2016)。全球范围内也存在一些规模巨大、成分均匀的富晶体火山岩,如 Fish Canyon 凝灰岩(Whitney and Stormer, 1985;Bachmann *et al.*, 2002)、Lund 凝灰岩(Maughan *et al.*, 2002)、La Pacana 凝灰岩(Lindsay *et al.*, 2001)等。这类火山岩通常为英安质的晶体含量和成分均匀的熔结凝灰岩(monotonous intermediates;图 1b)(Hildreth, 1981),普遍发育于大火成岩省中,明确记录了上地壳存在着规模巨大、成分均一的富晶体岩浆(Bachmann and Huber, 2016)。这些英安质富晶体火山岩不存在明显的堆晶结构(Hildreth, 1981; Lindsay *et al.*, 2001; Maughan *et al.*, 2002; Huber *et al.*, 2012),但普遍发育低温矿物的熔蚀结构(石英和长石)(Bachmann and Dungan, 2002; Bachmann *et al.*, 2002)。后续研究发现在 Nevada Great Basin、Taupo Volcanic Zone、新西兰以及 Southern Rocky Mountain volcanic field (SRMVF)等地还存在一种流纹质的富晶体火山岩(图 1b)(Matthews *et al.*, 2012; Lipman and Bachmann, 2015; Watts *et al.*, 2016)。与上述成分均匀的富晶体火山岩相对应的,是一些大规模的、具有成分梯度或分带的富晶体火山岩(熔结凝灰岩)(zoned ignimbrites;图 1b),它们由上部贫晶体岩浆(cap of crystal-poor material)和下方紧接着的富晶体带共同组成的带状岩浆储库喷发形成(图 1a)(Bachmann and Huber, 2016),例如著名的 Bishop(Watts *et al.*, 2016)和 Bandelier 凝灰岩(Wolff and Ramos, 2014)。另外,还有一种无成分分带、贫晶体的凝灰岩,晶体含量通常在 10%~20%之间(Dunbar *et al.*, 1989; Nash *et al.*, 2006; Ellis and Wolff, 2012; Ellis *et al.*, 2013),其中聚晶或斑晶的全岩成分更偏镁铁质,斑晶矿物主要包括辉石、斜长石等而缺少透长石、石英(Bachmann and Huber, 2016)。这些辉石和斜长石具有演化的 REE 成分,指示其可能结晶于流纹质熔体(Ellis *et al.*, 2014)。这种凝灰岩被认为是贫水的晶粥重熔形成熔体囊后形成的,当岩浆从下

部补给时,干热的晶粥不存在包含透长石、石英的湿冷熔体,因此不会形成成分分带(Bachmann and Huber, 2016)。显然,火山岩的晶体含量取决于其喷发前的晶粥演化过程,火山岩的多样性暗示了晶粥演化过程的复杂性。

2 长英质晶粥的冷储存

喷发物质(熔岩或火山碎屑)的成分和结构可用于推断岩浆存储的状态(Cashman *et al.*, 2017),而通过相平衡实验可以将熔体、固体各相的物质成分和比例与喷发前的岩浆存储状态建立对应关系(Rutherford *et al.*, 1985; Moore and Carmichael, 1998; Blundy and Cashman, 2008)。

大多数的地壳岩浆活动最开始是由幔源玄武质岩浆驱动的(Cashman *et al.*, 2017)。演化程度低的玄武质岩浆从地幔逐渐进入地壳,它们的初始状态由温度决定。若岩浆体量足够小,能够迅速与其定位的周围环境达到热平衡,那么根据环境温度不同可能会出现岩浆完全固结、形成(不能喷发的)晶粥和形成(可喷发)的岩浆这3种情况(Cashman *et al.*, 2017)。在下地壳,高的环境温度接近固相线并且在热力学上有利于使补给的原始玄武质岩浆保持在固相线之上,因此岩浆积累所需的通量较低,这种环境是玄武质岩浆滞留、冷却或结晶形成富熔体的晶粥及熔体演化的有利环境(Hildreth and Moorbath, 1988; Annen *et al.*, 2006; Xu *et al.*, 2021),岩浆储库能持续足够长的时间来充分演化分异(Solano *et al.*, 2012)。熔体分离有两方面的影响因素: ① 晶粥压实,挤出演化程度高的熔体; ② 与周围环境之间的温度差。温度降低使分离出的熔体发生的结晶分异通常比压实快得多。演化的熔体可以继续上升到地壳上部,并残留难熔的堆晶。

在浅部地壳,只有当熔体的输入速率足够高或体积足够大时,才能保持高于固相线的温度(Solano *et al.*, 2012)。在这种情况下,含一定量熔体的晶粥可以持续存在很长时间,并且在岩浆储库中持续积累可喷发的岩浆(Annen *et al.*, 2006; 颜丽丽等, 2022)。岩浆储库冷却速率取决于熔体的体积和形态。大规模的熔体若发生侵位并内部对流则会迅速冷却,它可能会与之前存在的较冷熔体混合,熔融并同化部分围岩,或与上覆地壳的水热环境有关。小型侵入体可能因体积小而无法产生对流,但可以通过热传导迅速散失热量,因此,当熔体与围岩之间的温度差较小,或当晶体含量足够高以至于不能产生对流时,冷却速率将极大程度地降低(Dufek and Bachmann, 2010)。在上地壳,移动到较冷区域的岩浆可以在 10^3 a 内实现局部热平衡(Huang *et al.*, 2015),但是大型岩浆系统(空间尺度10~100 km)的寿命可能为 10^5~10^7 a。中、上地壳要在这样的时间跨度内容纳大量可喷发岩浆,需要比正常岩浆通量高1~2个数量级且持续的岩浆通量(Gelman *et al.*, 2013; Annen *et al.*, 2015)。相对来说,保留无喷发能力的晶粥所需的温度条件较低,仅需要高于固相线而非流变学锁定(~50%熔融)的温度范围即可,因此,晶粥存在的温度可以比可喷发的岩浆低上几百度(Gelman *et al.*, 2013; Carrichi *et al.*, 2015)。晶粥由于黏度高,对流难以发生,即使发生也十分缓慢(Dufek and Bachmann, 2010),因此,其冷却主要受控于热传导,所以上地壳晶粥系统的寿命通常较长。晶粥能否达到可喷发状态的熔体含量(约40%)(Gelman *et al.*, 2014; Pamigiani *et al.*, 2014)或是接近固结(Cooper and Kent, 2014),这取决于岩浆成分、岩浆补给速率、局部应力场以及和环境的热交换等因素。

该现象也得到了年代学研究的支持。锆石定年结果(CA-ID-TIMS锆石U-Pb定年、U系不平衡定年、离子探针U-Pb定年)(Chamberlain *et al.*, 2014a; Matthews *et al.*, 2015; Stelten *et al.*, 2015; Schoene and Baxter, 2017)指示岩浆分异时间通常为 10^4~10^6 a,而喷发前岩浆在上地壳维持较高温度的时间要短得多(<1~约 10^3 a,来自矿物环带的扩散年代学研究结果)(Zellmer *et al.*, 2003; Costa *et al.*, 2010; Druiit *et al.*, 2012; Allan *et al.*, 2013)。马昌前等(2020)认为,地壳中的花岗质晶粥体可以在比火山喷发时的岩浆温度低200~300℃的条件下长时间储存,属于冷储存;只有外来热的岩浆的补充,才会使近固态的富晶体岩浆发生活化,进而发生岩浆储库的分异或达到火山喷发的条件。

低温花岗岩的发现也支持这种认为晶粥具冷储存状态的认识。花岗质岩浆中的矿物普遍认为结晶于650~700℃或更高的温度(Tuttle and Bowen, 1958; Piwinskii, 1973),而加利福尼亚的Tuolumne侵入岩套的石英颗粒记录了474~561℃的结晶温度(Ackerson *et al.*, 2018)。能在明显低于湿固相线温度(约500℃)结晶形成花岗岩的,只能是成分比较极

端的过碱性(Na+K>Al)熔体(Ackerson *et al.*, 2018)。

3　岩浆补给和晶粥活化

晶粥本身是很难喷发的,因为它的流变能力受制于晶体格架的结构(Marsh, 1981)。晶粥中晶体格架的结构对熔体占比十分敏感。熔体含量越低,晶体-熔体的结合强度就越大(Rosenberg and Handy, 2005)。岩浆向晶粥转变过程中晶体含量是一个很窄的范围,然而体系的黏度在此区间却有数个数量级的变化(Costa *et al.*, 2009)。通常来说,流变性质转变发生在晶体含量介于 50%~65%的范围内,在自然界里该范围可能甚至更窄(Whitney, 1988;Caricchi and Blundy, 2015)。

岩浆补给经常被认为是火山喷发的诱因(Matthews *et al.*, 2012; Saunders *et al.*, 2012; 颜丽丽等,2022),体现在直接使岩浆房体积增大导致围岩被破坏(Jellinek and Depaolo, 2003)、累积岩浆的浮力驱动效应(Carrichi *et al.*, 2014)以及饱和气体和携带晶体的增加(Wark *et al.*, 2007)等方面。岩浆补给诱发的火山喷发可形成富晶体英安质和贫晶体流纹质熔结凝灰岩,二者的差异体现了两个时间尺度之间的竞争(Huber *et al.*, 2012):① 再活化,使不具备流动性的流变学锁定(rheological lock-up)的晶粥重新具备喷发能力(晶体少于 50%)的时间尺度;② 使岩浆储库均一化的对流搅动的时间尺度。Huber 等(2012)通过对岩浆储库建立热力耦合模型,结果表明晶粥解锁的再活化时间远长于使储库均一的对流搅动的时间。因此,经历过再活化的富晶体岩浆不可避免地会被充分搅动。相对而言,贫晶体岩浆没有再活化时就已具备流变学喷发能力,同时也无需搅动均一。

当岩浆中对流发生时,岩浆储库的边缘与围岩的温差加大从而加剧冷却。这种能加速冷却的对流只发生于低结晶度状态下(Huber *et al.*, 2009)。例如,高演化的高硅岩浆在降温过程中能够迅速达到低共熔点,英安质岩浆在晶体含量(体积分数,下同)为 40%~50%时达到接近低共熔状态(Bachmann *et al.*, 2002)。岩浆补给能够提供足够的焓来减缓甚至反转岩浆储库冷却的趋势,使其保持在长时间的低熔体状态(Annen and Sparks, 2002; Annen *et al.*, 2006; Annen, 2009; Gutierrez *et al.*, 2013)。

在穿地壳岩浆系统中,补给岩浆来自于系统更深处的熔体积累(颜丽丽等,2022),还携带了挥发分、再循环晶(antecrysts)、聚晶(glomerocrysts)和来自结晶度更高的晶粥的堆晶。尽管补给岩浆有时以淬冷包体呈现,但更多喷出岩中遍布的再循环晶和聚晶证实了补给岩浆能够在岩浆积累过程中充分混合。挥发分的出溶有助于这种混合(Cashman *et al.*, 2017)。熔体上升过程中,挥发分可以运动至晶体颗粒边缘使其熔融(升高 p_{H_2O})或结晶(降低 p_{H_2O}),或大量释放于岩浆系统更浅部发生反应,抑或是通过被动脱气逃离至地表,这些均是引起火山喷发的重要因素(Girona *et al.*, 2015)。

对于岩浆补给和晶粥再活化的时间尺度的研究,主要依赖于扩散年代学方法(Watts *et al.*, 2016; Rubin *et al.*, 2017)。放射性同位素定年是传统定年技术的基础,但许多岩浆活动的时间尺度很短,低于放射性同位素定年技术的下限(周金胜等,2022)。扩散年代学可以用于精细岩浆活动时间尺度的补充,岩浆补给的证据通常来自于岩浆房中的晶体环带(Morgan *et al.*, 2004; Wark *et al.*, 2007; Zhao *et al.*, 2023b)。扩散年代学可以计算出具有环带的矿物成分剖面的成分(例如石英中的 Ti 元素、斜方辉石中的 Fe-Mg 元素、透长石中的 Ba 和 Sr 元素等)变化所经历的时间(Chamberlain *et al.*, 2014b; Zhao *et al.*, 2023b)。Rubin 等(2017)结合锆石 Li 扩散年代学和锆石^{238}U-^{230}Th 定年还原出了新西兰 Taupo 火山带的热历史,发现相较于岩浆储存的时间,Li 扩散时间是相对快速的,结果暗示接近固结的晶粥可以长期储存,期间穿插着由岩浆补给引起的快速加热和快速冷却,这种岩浆补给具有规模小且多次的特征。虽然已有一些成功的研究案例,但目前利用扩散年代学研究岩浆补给和晶粥再活化的时间尺度,仍受到矿物微区分析的精度和空间分辨率以及不同扩散系数计算结果迥异等问题的制约(Cherniak *et al.*, 2007; Jollands *et al.*, 2020; Audétat *et al.*, 2021; Zhao *et al.*, 2023b)。

4　富晶体火山岩的成因研究

4.1　富晶体火山岩的研究进展

目前的研究认为,无晶体含量和成分梯度的富晶体火山岩(图 1b)具有非常好的均一性,需要在喷发前经历彻底的搅动才可形成,可能是由岩浆补给和再活化导致的(Huber *et al.*, 2012)。低温矿物的

熔蚀结构也指示喷发前岩浆储库经历了再次加热(Bachmann and Huber, 2016)。尽管岩浆补给促使被流变学锁定的区域发生热力学再活化在岩浆储库中十分常见,但是该过程往往并不能直接导致岩浆喷发。富晶体的、贫水的物质发生重熔,新熔体是干的熔体(Evans and Bachmann, 2013; Caricchi and Blundy, 2015; Wolff *et al.*, 2015)。随着形成体系的温度不断降低(Johannes and Holtz, 2012),新熔体反过来又抑制熔体的形成(Huber *et al.*, 2010a; Woltzlaw *et al.*, 2013)。能够引起喷发的再活化或许需要岩浆补给带来大量的热或者注入一定量的挥发分(Bachmann and Huber, 2016)。具有斑晶含量和成分梯度的富晶体火山岩(图 1b)的成因被解释为带状晶粥的富熔体盖先喷出,随后位于晶粥底部的堆晶被再活化后喷发(图 1a)(Wolff *et al.*, 2015; Evans *et al.*, 2016),而由于晶粥所处的岩浆环境过于贫水以至于出溶的挥发分达不到使岩浆储库具有效热交换的体量时(Huber *et al.*, 2010b),岩浆补给不能将晶粥再活化,则可能形成无成分分带、贫晶体到中等晶体含量的火山碎屑岩(Ellis *et al.*, 2014; Wolff *et al.*, 2015)。

被记录的最大的火山碎屑喷发物(>5 000 km^3, Lipman, 2000)Fish Canyon 凝灰岩是 Hildreth(1981)提出的无晶体含量和成分梯度的富晶体火山岩的典型代表之一。该英安质熔结凝灰岩中含有的全晶质的捕掳体被视作是镁铁质岩浆侵入时产生的固化边缘捕掳体中的石英、长石的熔蚀结构和环带,长石由核部向边部出现的 An 陡然升高的峰,不同于斑晶斜长石的高 SiO_2 玻璃基质具有高 Sr、Ba、Eu 值,自形角闪石斑晶中存在振荡环带、反环带,这些证据均支持是晚期升温导致的岩浆演化过程。岩浆房范围内成分均一,小规模范围的结构、化学成分却存在差异,均表明其中晶体反复经历生长和熔蚀的过程。故 Fish Canyon 晚阶段演化的岩浆被认为是接近固结的上地壳晶粥再活化的产物(Bachmann *et al.*, 2002)。

Caetano 凝灰岩是成分均一的流纹质富晶体熔结凝灰岩,分为上部熔结凝灰岩(晶体含量 40%~42%)和下部熔结凝灰岩(晶体含量 38%)。从下到上 SiO_2 含量由高到低逐渐降低。在晶体-熔体分异的过程中,岩浆储库内部演化程度更高的粒间熔体从演化程度更低的晶粥中抽离上升,聚集在岩浆储库上部的熔体持续结晶、分异、混合,形成均一的盖层覆于具有成分梯度的原晶粥之上(Watts *et al.*, 2016)。新西兰的 Taupo 火山带中石英 Ti 扩散年代学结果显示,Whakamaru 岩浆储库经历了 10^3~10^4 a 的再活化和数十至百年的喷发(Matthews *et al.*, 2012)。Southern Rocky Mountain 火山区记录了上地壳接近固结的晶粥受到高频率岩浆补给而形成的持续了数百万年的熔结凝灰岩的反复喷发(Lipman and Bachmann, 2015)。多阶段的岩浆补给导致在固相线温度上下振荡变化的环境使岩浆系统断断续续地演化,由于多期加热事件并不一定会使流纹质岩浆房结构完全破坏、促使对流均一化,从而会保留一定的成分梯度(Watts *et al.*, 2016)。

成分分带的火山岩 Bandelier 凝灰岩早期喷发的正常凝灰岩和晚期喷发的富晶体凝灰岩具有变化范围较大的 $^{87}Sr/^{86}Sr$ 值,ID-TIMS 测试结果揭示同位素不均一不仅存在于全岩,还存在于石英-透长石聚晶等相同的矿物之间,这体现了岩浆补给对储库成分的改变(Wolff and Ramos, 2014)。相比早期贫晶体流纹质凝灰岩,Bishop 凝灰岩晚期富晶体流纹质凝灰岩具有更高的岩浆温度(Fe-Ti 氧化物、透长石-斜长石、$\Delta^{18}O$ 石英-磁铁矿矿物组温度计均指示更高的温度),结合矿物环带的存在指示晚期凝灰岩经历了岩浆补给和加热(Evans *et al.*, 2016)。

Zhao 等(2023a)研究发现不同构造背景下火山岩晶体含量有显著差异。大陆裂谷或热点以发育典型的双峰式火山岩为特征,贫晶体的流纹岩常见;而典型大陆弧一般发育大量富晶体的安山岩和英安岩,贫晶体的流纹岩相对较少。他们指出岩浆中的 H_2O 可能是解开这一谜团的钥匙。岩浆中 H_2O 含量可以显著影响岩浆动力学过程和喷发能力,通过模拟岩浆上升通道中气-液两相流体动力学,并利用热传导模型制约岩浆上升的临界最小速率,他们进一步揭示出大陆裂谷或热点火山岩中的流纹质熔体的 H_2O 含量在相同温度下比大陆弧火山岩流纹质熔体低约 1.5%,导致前者熔体黏度比后者高一个数量级(分别为 105.5±0.2 和 104.5±0.2 Pas)。大陆弧岩浆储库中具有更强烈的对流和更高的混合效率,使得晶粥可以发生活化和均一化,形成大量可喷发的富晶体(可达约 50%)中性岩;而大陆裂谷或热点背景下,流纹质熔体喷发时不能携带较多晶体,于是形成大量贫晶体(<30%)流纹岩。

4.2 中国东南沿海的富晶体火山岩

中国东南部晚中生代火山活动强烈,酸性岩占绝对优势,花岗岩与流纹岩往往在空间上伴生(图

2),这类具有时、空、源一致性的花岗质岩石被称作火山-侵入杂岩(王德滋等, 2000)。中国东南沿海有许多破火山,这些大型的环状火山塌陷中又包含众多小的火口(Lipman, 2000; Xu *et al.*, 2021)。在这些破火山中,常出露富晶体的火山岩(图 2)。这些富晶体的火山岩常以富晶体的凝灰岩、流纹岩中的粗面质包体以及侵出相的碎斑熔岩的形式产出。

富晶体的凝灰岩出露于浙江雁荡山、半山、芙蓉山等破火山(图 2)。雁荡山发育富晶体的流纹质熔结晶屑角砾凝灰岩(第 1 阶段火山岩;图 3a),其中常见长石聚晶和长石熔蚀结构,表明其有可能经历了堆晶重熔(Yan *et al.*, 2016)。浙东半山富晶体流纹质火山岩中含有石榴子石,研究发现石榴子石是岩浆分异演化晚期在相对低温低压和富流体环境下形成的,暗示岩浆曾达到类似花岗岩的高结晶度(Yan and He, 2022)。半山富晶体火山岩中的石榴子石、石英、长石也具有熔蚀现象,部分石榴子石还被石英包裹(Yan and He, 2022)。Yan 和 He(2022)据此提出晶粥由于岩浆补给带来的热量和挥发分而发生了强烈的扰动、再活化,最终形成了富晶体流纹质火山岩。浙江芙蓉山破火山的第 4 喷发阶段也产出富晶体的流纹质熔结凝灰岩(图 3b)(俞云文, 1993)。

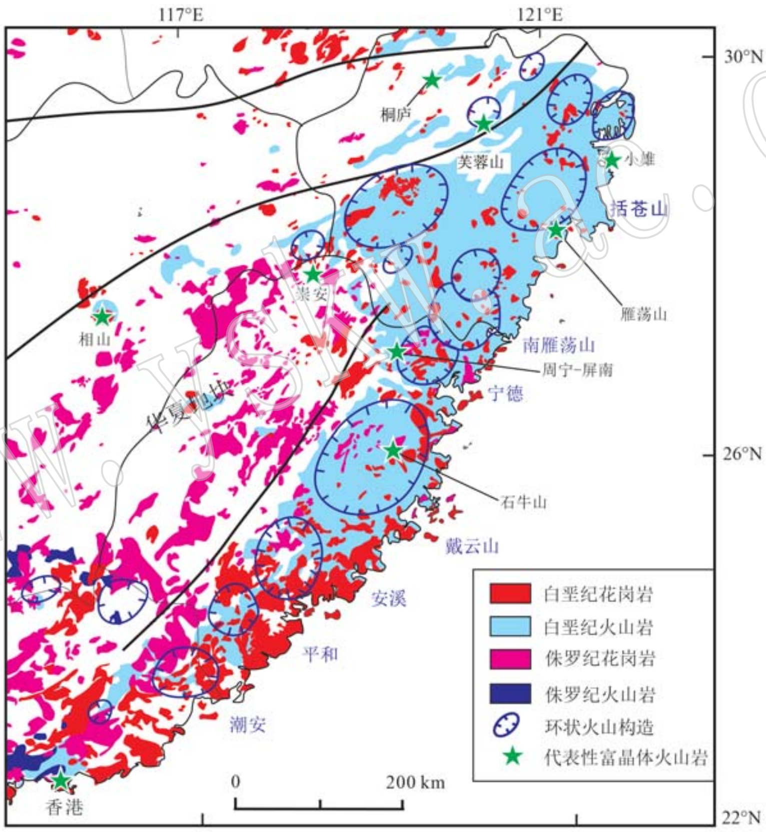

图 2　中国东南沿海富晶体火山岩分布图(据 Zhou *et al.*, 2006 修改)

Fig. 2　Distribution of crystal-rich volcanic rocks in the coastal area of Southeast China (modified after Zhou *et al.*, 2006)

在东南沿海的一些流纹岩中还发现了一种富晶体的粗面质包体,如雁荡山第 4 阶段的流纹质晶屑-玻屑熔结凝灰岩中发育有这种富含晶体的包体,在雁荡山破火山中央侵入相石英正长斑岩中也发育这种次圆状或不规则状的富晶体包体,目前认为这种类型的包体可能与岩浆房的晶粥活化作用有关(Yan 形式注入分异程度较高、富含挥发分、贫晶体的聚集在岩浆房顶部的流纹质岩浆中,形成了岩浆的自混 *et al.*, 2020)。浙东小雄破火山的熔结凝灰岩中也存在富晶体的粗面质包体(图 3c)。高丽等(2020)将其称为粗面质岩浆团块,其中的正长石普遍具强烈的熔蚀现象,被认为代表了长英质岩浆的自混合。高丽等(2020)认为当基性岩浆聚集到地壳浅部岩浆房底部时,使得先存的粗面质晶粥活化并以热柱的合现象。

中国东南沿海出露最多的富晶体火山岩是碎斑

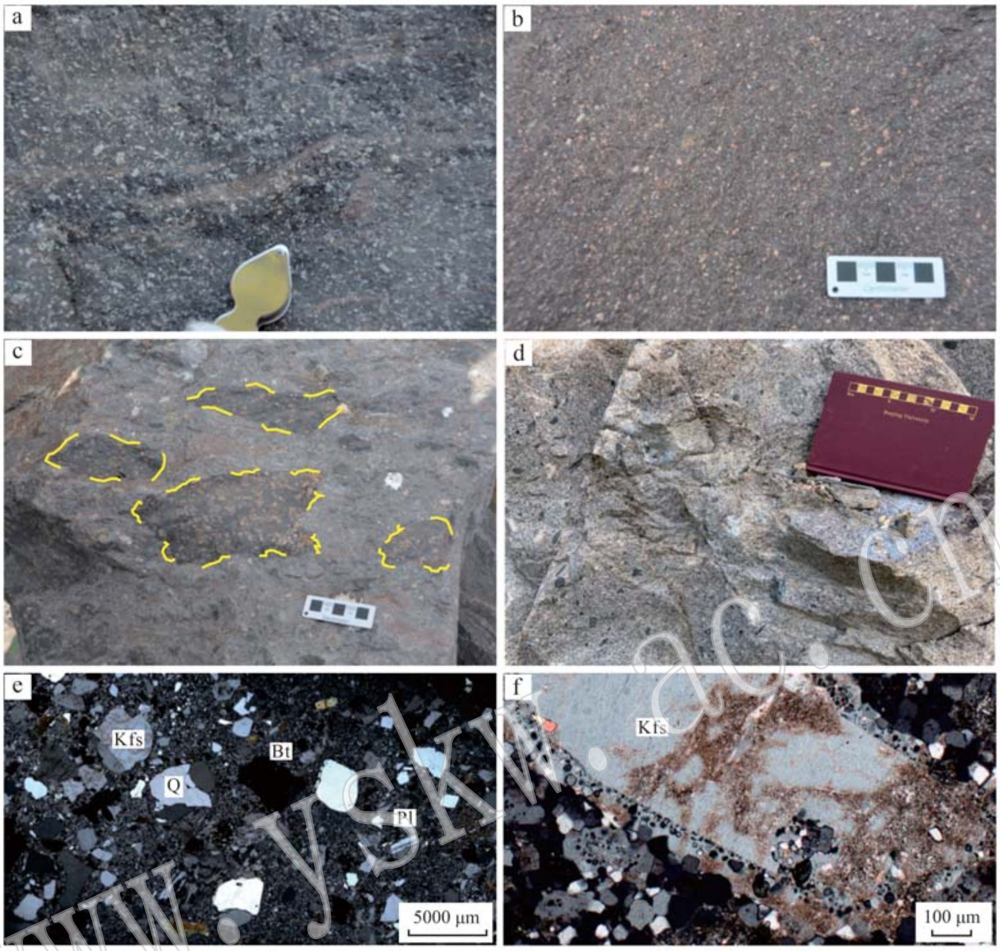

图 3　中国东南沿海富晶体火山岩野外和岩相学照片

Fig. 3　Photographs and photomicrographs of crystal-rich volcanic rocks in the coastal area of Southeast China

a—雁荡山第 1 阶段火山岩流纹质熔结晶屑角砾凝灰岩; b—芙蓉山第 4 喷发阶段流纹质熔结凝灰岩; c—小雄流纹质熔结凝灰岩中粗面质包体(黄色虚线); d—相山流纹质碎斑熔岩; e—相山流纹质碎斑熔岩(正交偏光); f—桐庐碎斑熔岩中钾长石的珠边结构(正交偏光); Bt—黑云母; Kfs—钾长石; Pl—斜长石; Q—石英

a—Yandangshan rhyolitic crystal-lapilli tuff of the first volcanic unit; b—Furongshan rhyolitic ignimbrite of the fourth volcanic unit; c—Xiaoxiong trachytic enclaves (yellow dashed lines) distributed in the rhyolitic ignimbrites; d—Xiangshan rhyolitic porphyritic lava; e—Xiangshan rhyolitic porphyritic lava (crossed polarized); f—pearlitic border of K-felspar in Tonglu porphyritic lava (crossed nicols); Bt—biotite; Kfs—K-feldspar; Pl—plagioclase; Q—quartz

熔岩(图 3d),其一般兼具火山碎屑岩与次火山岩的双重特征(福建省区测队火山岩组、岩矿组, 1982)。碎斑熔岩主要分布在浙、闽、赣、粤、桂等地区(邢光福等, 2011),如赣东北的玉华山、相山,闽西北的崇安,浙西的桐庐,闽东的屏南-周宁地区还发育一条碎斑熔岩带(图 2)。碎斑熔岩主要呈侵出相出露于火山构造中心,多形成于各地区火山活动的晚期,碎斑熔岩富含斑晶,平均可达 40%左右,最高可达 50%~60%(图 3e)(陶奎元等,1985)。碎斑熔岩多是具有成分梯度的“三相一体”,即从火山口中心的显微粒状碎斑熔岩、过渡的霏细状碎斑熔岩到边缘的隐晶质碎斑熔岩(杨丽贞等, 2011; 刘成俊, 2017),代表着溢流-侵出-侵入三相。碎斑熔岩与空间上相伴生的凝灰岩、花岗斑岩往往具有同时性(周万蓬等, 2015)。

碎斑熔岩的斑晶常常呈碎斑结构(图 3e),自形斑晶矿物破碎,“碎而不散、散而不远”,晶体碎片可拼接出完整的原始晶形(邢光福等, 2011)。碎斑形成可能是由于: ① 浅部岩浆的沸腾作用; ② 具有裂纹的斑晶在流动运移过程中裂开; ③ 矿物转变过程中收缩系数的差异(陶奎元等, 1985)。碎斑熔岩中另一个特征的现象是钾长石的珠边结构(图 3f)(林

子瑜等, 2002; 林国辉, 2003; 张岩等, 2017),这是由于形成碎斑熔岩的岩浆的冷却速度比一般的酸性熔岩流慢,岩浆不断结晶的同时,斑晶能够继续生长并捕获周缘的小晶体(周金城等, 1999; 邢光福等, 2011)。珠边形成的原因最早认为是物理过冷,由于钾长石斑晶与近地表岩浆的温度差以及不同矿物的成核密度、生长速度不同导致(王德滋等, 1982; 陶奎元等, 1985)。后来又提出了“组分过冷”的观点:珠边中的钾长石比碎斑中更富碱性长石组分(An 偏低),钾长石斑晶在生长过程中逐渐将岩浆中的 SiO_2 排除出来,在钾长石周围的熔体中形成了一层富 SiO_2 的边界层,边界层的液相线低于周围岩浆的液相线,两者的差异造成“组分过冷”,结晶出石英(周金城等, 1999)。但这些碎斑熔岩常见的结构是否与岩浆补给和晶粥活化过程存在关联,尚不清楚。

王德滋等(1993)根据地球化学和矿物组成提出碎斑熔岩存在两种不同成因:以桐庐为代表的 Ⅰ 型和以相山为代表的 S 型。桐庐 Ⅰ 型碎斑熔岩中暗色矿物除黑云母外还存在角闪石,相山 S 型碎斑熔岩主要镁铁矿物为黑云母,未发现角闪石;黑云母成分、全岩主-微量元素上其二者也有明显区分。之后,Jiang 等(2005)在石英二长斑岩中发现了角闪石,角闪石温度计显示较高的温度,结合 Ga、Al、高场强元素等指标显示的 A 型花岗岩的特征将相山火山-侵入杂岩划分为 A 型。目前对碎斑熔岩的岩浆起源是壳源还是壳幔混源存在明显争议(王德滋等, 1993; 付建明等, 2004; Jiang *et al*., 2005; 张岩等, 2017),显然碎斑熔岩的成因仍需进一步探索。碎斑熔岩 SiO_2 含量普遍较高(付建明等, 2004; 邢光福等, 2011; 潘登等, 2013; 张岩等, 2017),普遍富集大离子亲石元素和高场强元素,亏损 Ba、Sr、P、Ti 和 Eu(林子瑜等, 2002; 付建明等, 2004; 张岩等, 2017),具有成分梯度的流纹质富晶体火山岩的特征。

Du 等(2022)通过地球化学、热力学模拟、质量平衡计算研究桐庐碎斑熔岩(富晶体的流纹英安岩),认为碎斑熔岩是岩浆储库受阻沉降过程中没有充分完成晶体-熔体分离的介于贫晶体盖和底部堆晶之间的富晶体带,后期的玄武质岩浆补给并未使岩浆储库再活化、破坏岩浆储库的结晶框架,但未讨论富晶体岩浆喷发的动力学过程。Liang 等(2022)通过岩相学、地球化学、锆石微量元素等方法研究石牛山碎斑熔岩(富晶体流纹岩),认为碎斑熔岩是晶粥中抽离出的熔体,但并未对其富晶体的特征做出较好的解释。

目前对碎斑熔岩的研究依然存在一定的局限性,尤其是没有将富晶体火山岩研究的最新认识引入碎斑熔岩的成因研究中。碎斑熔岩为何富晶体?碎斑熔岩是否也是晶粥再活化的产物? 如果这一假设成立,是否存在岩浆补给、堆晶重熔的证据? 晶体含量不同的“三相一体”的碎斑熔岩各相带的成因联系如何? 这些问题均有待进一步研究来解密。

5　主要认识和展望

晶粥模型和穿地壳岩浆系统为研究火山岩、次火山岩和侵入岩间的成因联系提供了很好的理论基础。晶粥再活化解释了富晶体火山岩中常见的看似不相关的特征,如晶体含量高、矿物的熔蚀结构和环带结构、矿物聚晶、连续无间断的化学成分等。然而,还有许多待解决的问题,我们仍面临着一些挑战:

(1) 碎斑熔岩的形成过程是怎样的,是否经历了岩浆补给和晶粥再活化? 作为最晚期的侵出相与破火山中其他火山岩和侵入岩的成因联系是怎样的? 这些问题还需要进一步研究。

(2) 除富晶体火山岩外,还有没有能够识别晶粥再活化过程的其他岩石学或矿物学标志? 如石英、长石等矿物环带的微量元素和同位素组成是否可以指示晶粥的再活化? 为什么有的晶粥活化并没有导致火山喷发? 什么样的活化可以导致火山喷发? 这些也是亟需研究的问题。

(3) 对长英质岩浆储库中补给岩浆的通量和晶粥活化过程的时间尺度的理解还很有限,晶粥活化与超级火山喷发(例如 Fish Canyon, Woltzlaw *et al*., 2013)的联系也不清楚。通过提高矿物定年的精度和空间分辨率,利用扩散年代学约束岩浆过程的时间尺度,结合热力学模拟和补给岩浆的通量的定量计算,可以帮助我们更加深入地理解长英质岩浆储库的分异演化。

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