岩浆补给作用对硅质火山岩浆系统演化的制约

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内容提要:硅质火山喷发作为大陆地壳岩浆活动的重要表现,在研究大陆地壳形成与演化、探讨岩浆过程与动力学机制等方面具有重要的价值,其通常所表现的强烈爆炸式喷发,甚至可以导致全球性的环境和气候变迁。硅质岩浆系统在开放体系中不同来源岩浆的贡献和相互作用是目前研究的热点问题。持续的岩浆补给可以延长岩浆存储的时间,促进岩浆房的对流、岩浆的分异演化以及晶体-熔体的分离和晶粥的再活化,同时也是触发火山喷发的重要机制之一。此外,岩浆补给以及硅质岩浆的晶体-熔体演化过程也是火山喷发产物多样性的原因,导致同一火山在其活动过程中喷发产物规律性的变化,如富晶体火山岩、贫晶体火山岩、火山岩成分分层、以及复活岩穹和中央侵入体等。因此,岩浆补给作用是制约硅质火山岩浆系统演化和火山岩成分多样性的重要因素,也是活动火山监测和灾害评估的重要依据。岩石学、岩石地球化学、矿物(长石、石英、石榴子石、锆石等)同位素及成分变化,以及模拟实验、地震层析成像等研究为揭示硅质岩浆系统中的岩浆补给作用和复杂岩浆过程提供了多种视角。

关键词:岩浆补给;硅质火山岩浆系统;火山喷发;成分多样性;火山监测

硅质火山活动一般表现为强烈的爆炸式喷发,形成巨量的火山喷发产物,超级火山喷发甚至可以带来全球性的环境、气候变迁(Miller et al.,2008; Self et al.,2008; Cashman et al.,2013)。同时,硅质火山活动及相关的浅成侵入体与许多金属矿床的形成关系密切(Lipman et al.,1985; John, 2008; Sillitoe, 2010)。近年来的研究揭示了大型硅质火山作用的岩浆系统是地壳尺度的(图1),包含深浅多个地壳岩浆房,但一般只有约10%~20%的岩浆喷出地表,大部分残留在地壳中固结形成侵入体,对地壳的分异演化也具有重要意义,因而硅质火山作用及其穿地壳岩浆系统一直备受关注(Scandone et al.,2007; Lipman et al.,2015a; Bachmann et al.,2016; Frost et al.,2016; Wilson et al.,2016; Cashman et al.,2017; Cooper, 2017; Karakas et al.,2019; 马昌前等, 2020; Xu Xisheng et al.,2020)。

在大多数活动火山之下的浅部地壳(<10 km)存在岩浆储库,这种岩浆储库一般是通过深部来源、规模不同的岩浆以不同频率注入,即岩浆补给作用逐渐建造而成的。补给岩浆注入的通量大小和频率对岩浆储库的建造有十分重要的影响(Schöpa et al.,2013; Liu Boda et al.,2020)。岩浆补给作用是指热的、偏原始的岩浆周期性地注入较冷的、偏演化的岩浆房(Davidson et al.,1997; Tepley et al.,1999; Coombs et al.,2002; Kent et al.,2010),但补给岩浆有时也可能是更酸性的、演化程度偏高的岩浆(Eichelberger et al.,2000a; Schmitt et al.,2001; de Silva et al.,2008; Girard et al.,2009a)。岩浆补给作用可以导致"新-老"岩浆发生相互混合,形成多种成分的岩浆,并为火山岩浆系统提供热量和挥发分,增加熔体的比例,从而延长岩浆存储的时间,促进岩浆房的对流、岩浆的分异演化、晶粥的再活化、晶粥间熔体的运移以及成矿元素的富集作用(Reid, 2003; Martin et al.,2006; de Silva et al.,2008; Girard et al.,2009a; Kent et al.,2010;

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Wolff et al.,2015; Bachmann et al.,2016; Buret et al.,2017)。岩浆补给作用还可能导致岩浆房过压,触发火山喷发(Pallister et al.,1992; de Silva et al.,2008; Ruprecht et al.,2010; Wright et al.,2011; Bergantz et al.,2015; Pistone et al.,2017; Liu Boda et al.,2020)。此外,岩浆补给与岩浆演化之间的动态平衡,也是决定岩浆喷发的关键因素,包括岩浆喷发的持续时间、频率,以及喷发的方式,例如爆炸式喷发或溢流式喷发等(Reid et al.,2003; Moran et al.,2011; Caricchi et al.,2014; Cassidy et al.,2018)。本文简要介绍硅质岩浆系统的起源与演化,并在此基础上着重介绍岩浆补给作用在制约硅质岩浆系统演化的相关研究进展,以及近年来采用的相关研究手段。

1 硅质岩浆系统的起源与演化

关于硅质岩浆起源长期争议的问题是壳、幔来源岩浆的相对贡献,即是先存地壳的部分熔融,还是幔源玄武质岩浆的结晶分异起到主导作用(Keller et al.,2015; Clemens et al.,2016; Frost et al.,2016)。全球岩浆岩的成分总体上呈双峰式分布,中性岩石相对较少(即存在 Daly Gap),关于这种分布特征的含义长期以来还存在多种理解,可能暗示了地壳的部分熔融在硅质岩浆形成过程中起主导作用(Christiansen et al.,2008; Reubi et al.,2009),但也被解释为与岩浆结晶分异有关(Keller et al.,2015; Bachmann et al.,2016)。实验岩石学研究表明玄武岩或闪长岩经历较低程度的部分熔融,能够产生 SiO_2 含量为 70% 或更高的岩浆(Green et al.,1968; Drummond et al.,1990)。富铝沉积岩的部分熔融是形成过铝质硅质岩浆的重要机制之一(Clarke et al.,2005; Frost et al.,2016)。Reubi et al.(2009) 通过对安山岩斑晶中的熔融包裹体的研究表明中性(SiO_2 含量约 59%~66%)的原生熔体较少,从而认为中性岩浆是酸性岩浆和基性岩浆混合形成的。然而,另一方面,热力学模拟研究结果显示玄武质岩浆底侵带来的热流很难造成大规模的地壳熔融,尤其是相对较薄的地壳(Karakas et al.,2017a, 2017b)。一些学者甚至认为,在俯冲带和大陆裂谷环境,硅质岩浆主要由基性岩浆经分离结晶产生而并非来自地壳熔融(如:Keller et al.,2015),单纯地壳来源的岩浆一般形成于加厚地壳的碰撞造山环境(张泽明等, 2020)。Bachmann et al.(2008) 指出在干的岩浆系统中,安山岩和英安岩岩浆由于挥发分不饱和不能喷发,从而会进一步的演化直至达到岩浆喷发所需的挥发分含量,因此形成了基性和酸性双峰式的分布特征。对有限出露的地壳剖面的实际观察,进一步表明酸性岩浆很可能是由基性岩浆演化而成的,即使大量的基性岩浆侵入中-下地壳,也难以观察到大规模的地壳熔融(Barboza et al.,2000; Thompson et al.,2002; Greene et al.,2006)。因此,硅质岩浆的起源和具体的岩浆分异演化过程目前仍是有待深入研究的热点问题。

近年来提出的"晶粥"模型为硅质岩浆、尤其是高硅流纹岩($SiO_2 \geqslant 70\%$; Frost et al.,2016)的产生提供了一种可行的机制,也为同一火山喷发产物的成分多样性和火山岩与侵入岩的成因联系问题提出了较为合理的解释(Reid, 2003; Bachmann et al.,2004; Hildreth, 2004; Kennedy et al.,2016; Yan Lili et al.,2016; 马昌前等, 2017; Wu Fuyuan et al.,2017; Bachmann et al.,2019)。"晶粥"是一种晶体与熔体的混合物,由于具有高的晶体含量(大约 45%~60%),晶体形成一个框架,从而阻碍了岩浆的流动性和可喷发性(图 1; Reid, 2003; Bachmann et al.,2004; Hildreth, 2004; Miller et al.,2008; Miller, 2016)。晶体间的熔体会被抽取、汇聚,最终喷发形成高硅火山岩,而残留的熔体和堆晶体固结形成侵入体,这一过程形成的高硅流纹岩相对于侵入岩来说通常显示出更高分异的特征(图 1;Bachmann et al.,2004, 2007; Yan Lili et al.,2016; Schaen et al.,2018)。尽管有时晶粥也会喷发形成晶体含量高的熔结凝灰岩(Bachmann et al.,2002; Deering et al.,2011),但大多数情况下晶粥最后都固化形成硅质侵入体(Lipman, 2007; Hildreth et al.,2007)。然而,一些浅成的高硅花岗岩也显示了高分异的地球化学特征,表明其岩浆来自浅部地壳的富硅岩浆储库中抽离的熔体,也是晶体-熔体分离的产物(Lee et al.,2015a; Schaen et al.,2017, 2018; Hartung et al.,2017; Chen Jingyuan et al.,2021; Lu Tianyu et al.,2022)。Wu Fuyuan et al.(2017) 提出花岗岩在很多情况下并不能反映源区的特征及岩浆形成的物理化学条件,根据结晶分异程度,花岗岩可划分为低分异花岗岩、高分异花岗岩以及与之伴生的堆晶花岗岩,这一分类系统是未来花岗岩岩石学研究的前沿。

值得说明的是,也有研究认为"晶粥"模型并不具有普适性,提出有些高硅火山岩浆不是通过浅部晶粥岩浆房中熔体抽取、汇聚形成的,而是在岩浆通

量较大的时期，幔源岩浆在下地壳分异以及与地壳岩浆混合形成，侵入岩则形成于岩浆通量较弱的时期，与火山岩不构成地球化学互补的关系（例如：Glazner et al.，2008；Tappa et al.，2011；Zimmerer et al.，2012；Streck，2014）。

此外，从高硅岩浆的形成过程来看，由于硅质岩浆黏度相对较大，岩浆房的晶体-熔体的有效分离非常关键（马昌前等，2017；Bachmann et al.，2019）。近年来尽管开展了大量关于晶体-熔体分离机制的研究，但对于晶体-熔体分离的主导机制还没有达成共识。一般认为晶体-熔体分离的机制有受阻沉降、压实，它们都是通过岩浆房内部晶体与熔体之间浮力差驱动的。随着岩浆房中结晶矿物体积分数增加，晶体-熔体分离机制由受阻沉降转变为压实作用；如果矿物体积分数＞70%，晶体-熔体分离主要是通过低熔体分数压实作用进行，但此时渗透率很低，会抑制熔体的分离；模拟发现矿物体积分数为50%～70%时最有利于晶体-熔体的分离，一般可以通过受阻沉降和高熔体分数压实作用有效实现晶体-熔体分离（McKenzie，1985；Philpotts et al.，1996；Bachmann et al.，2004；Dufek et al.，2010；Lee et al.，2015b）。除了内部晶体与熔体之间浮力差驱动之外，其他因素也可能驱动晶体-熔体的有效分离。例如：有学者提出当结晶矿物体积分数≥50%时，岩浆中气体出溶驱动的压滤作用可能是促进晶体-熔体分离的重要机制，并且能够形成大量可喷发的贫晶体岩浆（Sisson et al.，1999；Cashman et al.，2017；Holness，2018）。此外，岩浆补给作用能够使岩浆房内熔体含量和挥发分增加，导致晶粥的活化，控制结晶矿物的比例，也是促进晶体-熔体的分离和熔体抽取的重要机制（Bachmann et al.，2006；Ellis et al.，2014；马昌前等，2017；Holness，2018；Liu Boda et al.，2020）。

2　岩浆补给作用对硅质火山岩浆系统演化的制约

2.1　岩浆补给与火山喷发的触发因素

在研究大型火山喷发机制的过程中，研究者们注意到了基性岩浆补给过程，以及随岩浆补给而带来的热量、物质和挥发分交换的重要性（例如：Pallister et al.，1992；Murphy et al.，2000；Eichelberger et al.，2006；Wark et al.，2007；Martin et al.，2008；Ruprecht et al.，2010；Cashman et al.，2014；Hernando et al.，2016；

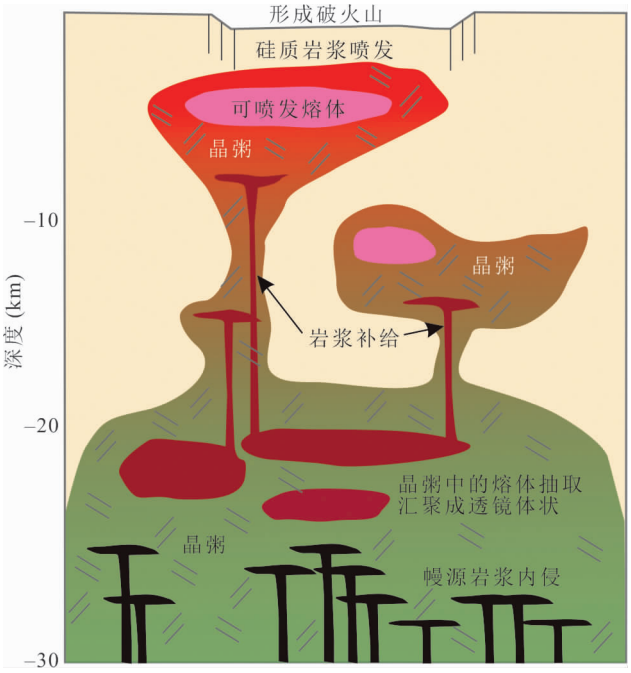

图 1　地壳尺度火山岩浆系统示意图
（据 Karakas et al.，2019 修改）
Fig. 1　Schematic sketch of crustal-scale volcanic magmatic system (modified after Karakas et al.，2019)

Pistone et al.，2017）。在通常情况下，通过晶体-熔体分离作用过程，熔体在晶粥岩浆房的顶部聚集，形成可喷发的高硅岩浆，而富含晶体的堆晶部分则会固结形成侵入体（图 1）。但是，补给岩浆带来的热量和挥发分可以增加岩浆房的压力，降低硅质岩浆的黏度、密度和液相线温度，引起岩浆房的温度波动，可能导致晶粥再活化，促使高黏度富晶体岩浆的喷发（图 2；Murphy et al.，2000；Bachmann et al.，2004；Huber et al.，2010；Pistone et al.，2013，2017；Malfait et al.，2014；Wolff et al.，2015；Liu Boda et al.，2020；Hughes et al.，2021）。1991 年，地质学家在菲律宾皮纳图博火山监测到深部地壳岩浆房之下有低频地震活动，随后的一周内该火山就发生了熔岩的喷出，并且其中含有淬冷包体，表明地壳岩浆储库的基性岩浆补给触发了火山的喷发（Pallister et al.，1992）。Martin et al.（2008）通过对 1925～1928 年希腊圣托里尼卡梅尼火山英安岩所包含的安山岩包体中橄榄石晶体的扩散剖面研究认为该火山喷发是由大约 1 个月前的玄武安山质岩浆补给触发的。

与基性补给岩浆相比，中酸性补给岩浆带来的岩浆房的热量、物质和挥发分的交换可能不那么明显，但是中酸性补给岩浆的注入一样可以导致岩浆

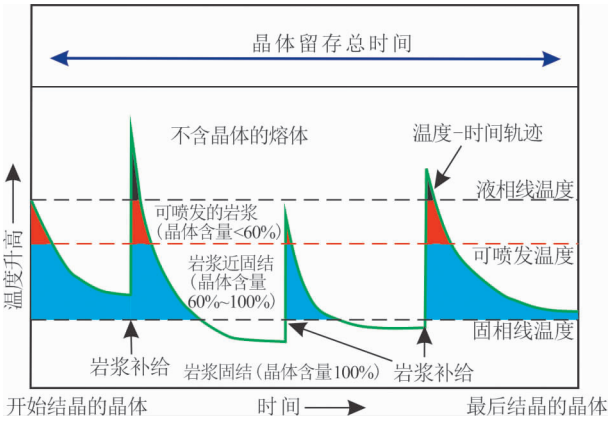

图 2 岩浆补给对火山岩浆系统热力学影响示意图
(据 Cooper et al.,2014; Miller, 2016)

Fig. 2 Schematic diagram illustrates magma recharge constraining thermal histories of the volcanic magmatic system
(after Cooper et al.,2014; Miller, 2016)

房中的原有岩浆或者黏稠的晶粥受到加热,结晶度降低,发生再活化,造成火山喷发,甚至可能引起灾难性的爆炸式喷发(Eichelberger et al.,2000b; Schmitt et al., 2001; Hildreth et al., 2007; Kennedy et al.,2007; de Silva et al.,2008; Wright et al.,2011; Druitt et al.,2012; Yi Jian et al.,2021)。例如,公元 1600 年秘鲁南部的埃纳普蒂纳火山喷发,也是迄今为止南美洲规模最大的火山喷发,研究发现是两种不同的英安质岩浆的混合触发了火山爆发(de Silva et al.,2008)。公元 946 年,长白山火山猛烈喷发,释放了超过 100 km^3 的火山碎屑物质,研究者对天池火山碱流质浮岩中包含的粗安质-粗面质包体和岩浆条带的研究认为地幔来源的粗面玄武质岩浆对地壳岩浆房的补给作用触发了天池火山千年大喷发(樊祺诚等,2005)。此外,在全岩地球化学、矿物学以及同位素研究的基础上,地球物理数据也支持碱流质岩浆房的补给作用与千年大喷发具有密切关系(Yi Jian et al.,2021)。

虽然在硅质火山岩浆系统中岩浆补给事件非常普遍,但并不是每次岩浆补给都能触发火山喷发。根据 Karakas et al. (2017a)和 Schöpa et al. (2013)数值热模拟估算结果,如果补给岩浆通量小($<10^{-4}$ $km^3/(km^2 \cdot a)$),岩浆侵入速率不高($<10^{-3}\sim10^{-2}$ km^3/a),补给持续时间短($<10^4\sim10^5$ a)、或者岩浆上升途中有明显的脱气等因素,补给岩浆的注入将不足以造成岩浆房过压,这种情况下岩浆补给不会触发火山喷发,只会引起火山岩浆房的扰动、异常的地震活动、气体释放以及地表变形等现象(Moran et al.,2011; Xu Jiandong et al.,2012; Biggs et al.,2014; Karakas et al.,2017a)。火山喷发与否还与岩浆房的大小有关,支持火山喷发的临界岩浆房体积大约在 0.01~10 km^3 之间,该变化范围取决于岩浆水含量、岩浆房深度、初始过压等因素(Townsend et al.,2020)。在临界岩浆房体积以下,岩浆房压力在岩浆到达地表之前下降至静岩压力,抑制了喷发;在岩浆房体积中等的情况下,岩浆可以喷发,但喷发的体积小于储存在岩浆上升通道中的岩浆体积;当岩浆房体积到达一定规模后,岩浆可以轻易地到达地表。

2.2 岩浆补给与火山岩的成分多样性

尽管一些大规模硅质火山喷发产物在成分上相对均一(Dunbar et al.,1989; Lindsay et al.,2001; Bachmann et al.,2002; Ellis et al.,2013),但是大部分硅质火山不同阶段的喷发产物显示出成分上的差异,例如:SiO_2 含量、晶体含量、微量元素含量、挥发分含量等,结果产生了火山岩的不同成分分层(Lipman, 1967, 2007; Smith, 1979; Hildreth, 1981; Bachmann et al., 2008, 2014; Lipman et al., 2015b; Forni et al., 2016; Wolff et al., 2020)。硅质火山岩的成分分层现象具有长期的研究历史,一直是火山岩浆作用研究的热点和争议问题,其形成机制总体上可按来源分为两类:① 封闭体系下岩浆房的原位分异作用(图 3;de Silva et al.,1995; Hildreth et al.,2007);② 开放体系下不同来源岩浆的相互作用或来自不同的岩浆房(Hervig et al., 1992; Mills et al., 1997; Eichelberger et al.,2000a; Knesel et al.,2007; Gualda et al.,2013)。

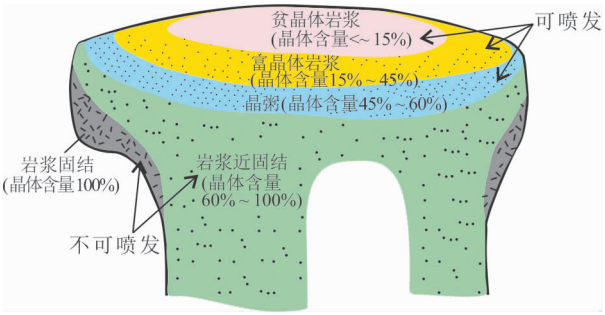

图 3 原位分异引起硅质岩浆房成分分层示意图
(据 Miller, 2016)

Fig. 3 Schematic illustration of composition stratification in silicic magma chambers caused by *in situ* differentiation
(modified after Miller, 2016)

早期的研究一般将火山岩的成分分层与岩浆房的原位分异作用相联系，认为较酸性的贫晶体岩浆位于岩浆房上部，较基性的富晶体岩浆位于岩浆房下部，二者先后喷发形成垂向上的火山岩成分分层（Lipman，1967；Smith，1979；Hildreth，1981）。有些火山岩的成分分层较为复杂，且不符合岩浆分异趋势，有时发育复杂的晶体群和矿物生长环带等现象，难以用单一岩浆房的成分分带解释，被认为可能与岩浆房中不同来源岩浆或补给岩浆的相互作用有关，或者火山岩浆来自多个岩浆房（Mills et al.，1997；Eichelberger et al.，2000a；Shane et al.，2005；Knesel et al.，2007；Wark et al.，2007；Ellis et al.，2012；Gualda et al.，2013）。例如：Eichelberger et al.（2000a）发现阿拉斯加州达顿山的英安岩和包体的全岩成分差别明显，玻璃成分差异却不明显；但该州阿尼亚克查克破火山安山岩和流纹岩之间的全岩和玻璃成分差异都很明显，认为这种差异是补给岩浆成分不同造成的。基性补给岩浆密度大与原有岩浆接触时间长，岩浆之间发生了一定程度的相互作用和均一化，容易发生溢流式喷发，形成的熔岩内部常发育包体；而贫晶体酸性补给岩浆注入岩浆房，会快速穿过原有岩浆，造成爆炸式喷发，岩浆之间的相互作用非常有限。这与很多记录良好的火山喷发的研究是一致的，即溢流式火山喷发大多数是由基性岩浆注入中酸性岩浆引起的，但成分分带的安山岩-流纹岩的爆炸式喷发是酸性补给岩浆注入中酸性岩浆造成的。此外，岩浆的分异演化造成火山岩成分多样性的一个前提是补给岩浆相比于岩浆房中原有岩浆更基性，然而实际上火山岩浆系统的补给岩浆有可能是基性岩浆，也有可能是 SiO_2 含量更高的岩浆。因此，Eichelberger et al.（2000a）提出岩浆补给作用才是造成火山岩成分多样性的主要机制，而不是岩浆的分异演化。

近年来，在上述晶粥模型的基础上，学者们进一步提出了晶体-熔体分离及堆晶体重熔再活化的硅质火山岩成分分层成因模型（图 4；Huber et al.，2010，2012；Bachmann et al.，2012，2014；Wotzlaw et al.，2013；Wolff et al.，2015，2020；Bachmann et al.，2016；Forni et al.，2016，2018）。该模型认为：晶体-熔体分离以及熔体的提取和汇聚，形成顶部为贫晶体，底部为富集堆晶体组成的分带岩浆房；来自低位岩浆房的补给岩浆侵位到高位岩浆房的堆晶层，产生晶粥的重熔作用，形成可运移的相对富集晶体的岩浆。这一过程可以形成共生的贫晶体高硅火山岩到富晶体低硅火山岩，及两者之间的过渡类型。

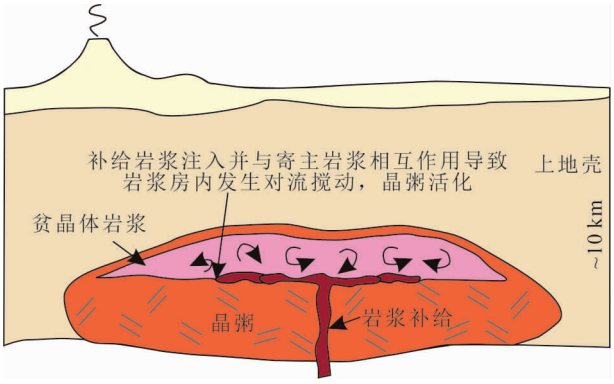

图 4　岩浆补给导致浅部地壳硅质岩浆房成分不均一示意图（据 Bachmann et al.，2008）

Fig. 4　Schematic illustration of heterogeneities in shallow silicic magma chambers due to magma recharge (modified after Bachmann et al.，2008)

3　岩浆补给过程的识别与研究

在补给岩浆与岩浆房内原有岩浆成分差别较大的情况下，补给岩浆与原有岩浆可能会一起喷发到地表，从而形成成分和形态不同的岩浆包体，据此我们可以识别出岩浆补给事件。这类包体相当于花岗岩中常见的暗色微粒包体，一般结晶颗粒较细，成分多为中—基性，与寄主岩呈截然或弥散的接触边界，形态上呈圆状—椭圆状或条带状等，有时具流动状、旋涡状构造（图 5）。其成分和形态取决于补给岩浆与岩浆房中原有岩浆混合的程度、岩浆的温度与黏度差，以及补给岩浆注入岩浆房的流动速度和位置等因素（Hibbard，1981；Vernon，1984，1990；Barbarin et al.，1992；Martin et al.，2006；Perugini et al.，2012；Ginibre et al.，2014）。需要注意的是包体的成因是多样的，有的包体可能是围岩捕掳体成因，例如岩浆房的顶蚀作用会导致围岩碎块进入岩浆房内部。它们一般成分复杂，岩性与寄主火山岩区别明显，直径变化范围也较大，多呈棱角状，与寄主岩接触界线截然，有时可见到烘烤边，一般根据岩石学特征容易与其他类型的包体相甄别（Fulignati et al.，2004）。除此之外，同源岩浆堆晶成因的包体在花岗岩类侵入体中也有报道，与寄主岩同源的岩浆在向浅部地壳运移的岩浆通道中过冷结晶并形成堆晶体，随后被上升的寄主岩浆捕获从而形成包体（Chen Shuo et al.，2021；Xu Wei et al.，2021）。包体年龄和矿物组合与寄主岩一致，同

图 5 雁荡山流纹质熔结凝灰岩和石英正长斑岩及其中暗色微粒包体的野外照片

Fig. 5 Field photos of the rhyolitic welded tuff and porphyritic quartz syenite and their mafic microgranular enclaves in Yandangshan

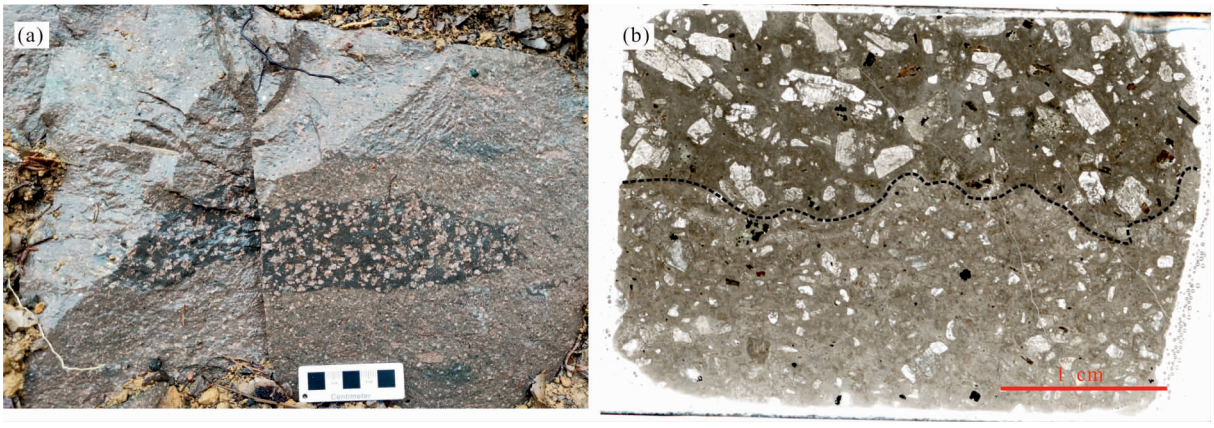

图 6 雁荡山流纹质熔结凝灰岩及其中富晶体粗面质包体的野外照片(a)和岩石薄片扫描照片(b)

Fig. 6 Field photo (a) and scanning photograph of thin section (b) of the rhyolitic welded tuff and its crystal-rich trachytic enclaves in Yandangshan

(b)中颜色较深的上半部分为富晶体粗面质包体,可见粗粒的长石斑晶,发育熔蚀结构,颜色较浅的下半部分是流纹质熔结凝灰岩,两者之间呈港湾状的边界

The upper part (dark) in photo (b) is crystal-rich trachytic enclave which contains coarse resorbed feldspar phenocrysts; the lower part (bright) is rhyolitic welded tuff; embayed boundary can be observed between them

位素组成类似,但角闪石和黑云母含量和成分与寄主岩的有所区别。

硅质火山岩中也常发育一些富晶体的包体,晶体含量较高(可达 50%以上),可见晶体熔蚀结构、聚斑结构、堆晶结构等,形态呈团块状,与寄主岩呈交错状、港湾状的边界(图 6)。这种类型的包体一般认为是岩浆房中的晶粥或分离结晶相的堆晶体,经补给作用活化或再熔融,与火山岩浆一同喷发出地表形成的,直接记录了岩浆房的岩浆结晶分异、堆晶作用、及岩浆补给-晶粥再活化过程信息(Bachmann et al., 2014; Forni et al., 2015; Sliwinski et al., 2015; Wolff et al., 2015; Kennedy et al., 2016; Masotta et al., 2016; Wu Fuyuan et al., 2017; Foley et al., 2020; Lubbers et al., 2020)。

此外,补给岩浆和原有岩浆之间的物理和化学相互作用会导致不平衡的晶体结晶条件,从而使矿物内部具有复杂的成分变化,以及矿物之间不平衡共生。例如:斜长石或角闪石内部出现的复杂环带(正常环带、反环带、振荡环带)连同矿物内部的不平衡结构(筛状结构、不规则的熔蚀的核部等),以及成分的突然变化(图 7;Tepley et al., 2000; Browne et al., 2006; Humphreys et al., 2006; de Silva et al., 2008; Streck, 2008; Druitt et al., 2012; 颜丽丽等, 2015; Hernando et al., 2016)、长石的环斑结构(Hibbard, 1981; 王晓霞等, 2001)、角闪石包裹黑

云母的现象（Barbarin et al.，1992；陆天宇等，2016）、辉石的不平衡结构和环带（Hughes et al.，2021）、锆石多阶段结晶形成的核-边结构（Claiborne et al.，2010；Chamberlain et al.，2014；Klemetti et al.，2014；Yan Lili et al.，2018，2020；贺振宇等，2021）等。通过详细的矿物结构和成分特征研究可以揭示岩浆补给作用过程，以及矿物的不同结晶阶段，例如：在熔体中结晶而成、捕获自晶粥或者结晶自补给岩浆。de Silva et al.（2008）通过详细的斜长石内部结构和电子探针成分分析，在英安岩中识别出 4 类结构和环带不同的斜长石，指出这些斜长石具有 3 种不同的来源和形成过程，包括：在岩浆房原有硅质岩浆中结晶的、来自深部的硅质补给岩浆，以及来自于火山通道壁，从而揭示了岩浆房中原有的硅质岩浆与补给的硅质岩浆之间的相互作用，并提出硅质岩浆补给可以触发大型爆炸式火山喷发，甚至可以引起高黏度晶粥的喷发。

鉴于矿物的内部结构和主量元素成分变化具有多解性，且难以排除物理化学条件变化产生的复杂结构，近年来，随着分析测试技术的发展，斜长石的原位 Sr 同位素、锆石原位 Hf 同位素、石英和锆石的原位微量元素等，在揭示硅质岩浆系统的岩浆作

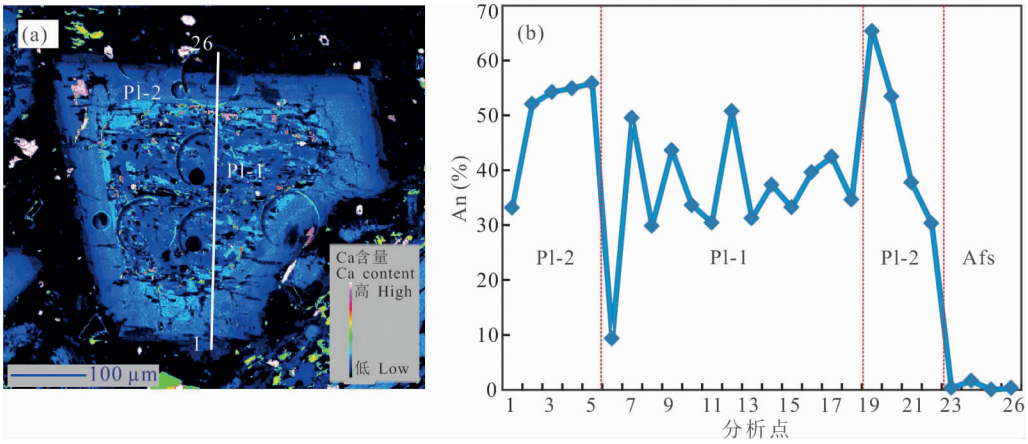

图 7　雁荡山石英正长斑岩的包体中斜长石斑晶的面扫描图像(a)及其 An(钙长石端员)成分变化剖面(b)(据颜丽丽等，2015；Yan Lili et al.，2020)

Fig. 7　Compositional mapping image of the plagioclase phenocryst in enclave of the porphyritic quartz syenite from Yandangshan (a)and its traverse of An (anorthite) contents (b) (after Yan Lili et al.，2015，2020)

斜长石斑晶具有核边结构，核部发生熔蚀呈筛状，核部和边部斜长石交界处 An 成分突然增加，反映基性岩浆补给作用；(a)中白线代表成分剖面位置，数字为分析点号；Pl-1—斜长石核部；Pl-2—斜长石边部；Afs—碱性长石

Plagioclase phenocryst hascore-rim texture，and the core of which shows resorbed and sieved textures；The An content spikes at the boundary between the core and the rim indicates mafic magma recharge；The white line in figure a represents the position of the traverse profile，the number is the analysis point；Pl-1—core of plagioclase；Pl-2—rim of plagioclase；Afs—alkaline feldspar

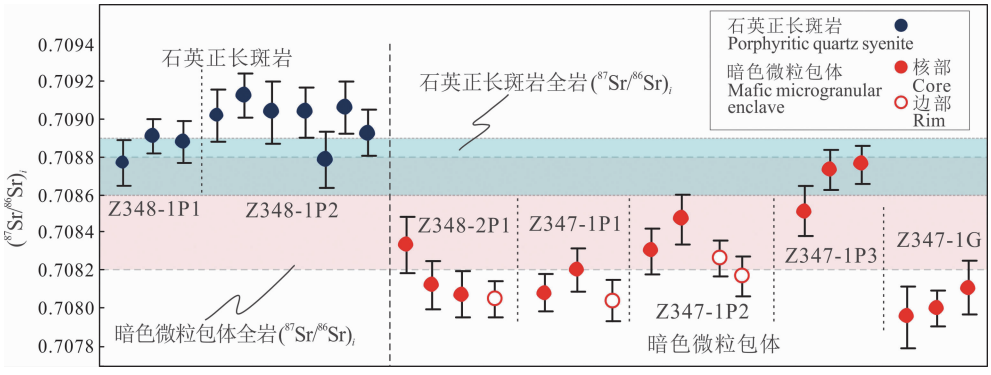

图 8　雁荡山石英正长斑岩以及包体中斜长石颗粒的 $(^{87}Sr/^{86}Sr)_i$ 变化，以及与全岩 Sr 同位素组成对比(据 Yan Lili et al.，2020 修改)

Fig. 8　Inter-grain $(^{87}Sr/^{86}Sr)_i$ variation of plagioclase from the porphyritic quartz syenite and the enclaves，and their whole-rock Sr isotopic composition (modified after Yan Lili et al.，2020)

用过程研究中展示了重要作用和研究潜力，能够更精准地识别补给岩浆与原有岩浆的相互作用过程(Davidson et al.，1997，2007，2008；Griffin et al.，2002；Gagnevin et al.，2005，2007；Wark et al.，2007；Charlier et al.，2008；Ginibre et al.，2014；Buret et al.，2017；Yan Lili et al.，2018，2020；贺振宇等，2021)。Wark et al.(2007)利用石英钛温度计对美国加利福尼亚州 Bishop 流纹质凝灰岩中的石英斑晶进行研究，发现石英核部温度低，边部温度高，并且在核部与边部界线处 Ti 含量突然升高约 40×10^{-6}，表明边部结晶之前石英晶体经历了熔蚀，从而指出岩浆喷发以及破火山塌陷前岩浆房发生了基性岩浆补给。

Davidsonet al.(1997)通过对斜长石斑晶进行原位 Sr 同位素分析，发现斜长石核部到边部的 $^{87}Sr/^{86}Sr$ 比值降低，核部 $^{87}Sr/^{86}Sr$ 比值与寄主岩英安岩全岩 $^{87}Sr/^{86}Sr$ 类似(0.7040～0.7041)，边部与玄武安山质包体全岩 $^{87}Sr/^{86}Sr$ 比值接近(0.7037～0.7038)，认为核部和边部是在不同成分的岩浆中生长的，指示了火山岩浆系统中发生过基性岩浆补给。然而，Yan Lili et al.(2020)对浙江雁荡山破火山中央侵入相石英正长斑岩及其中富晶体包体开展了斜长石原位 Sr 同位素研究，发现石英正长斑岩及其包体中斜长石虽然发育了复杂的内部结构和成分环带(图 7)，颗粒内部的 $(^{87}Sr/^{86}Sr)_i$ 变化却不明显。但是斜长石颗粒之间显示了明显的 $(^{87}Sr/^{86}Sr)_i$ 变化(图 8)，这种颗粒之间的 Sr 同位素不均一性同样指示了岩浆补给和岩浆混合作用，从而制约了酸性岩浆系统的岩浆补给和堆晶体的再活化过程(Yan Lili et al.，2020)。

锆石是硅质火山岩常见的副矿物，含有稀土元素以及 Th、U、Ti、Hf 等多种微量元素，且锆石微量元素含量及比值的系统变化主要反映了其结晶熔体的成分变化过程(Reid et al.，2011；Chelle-Michou et al.，2014；Samperton et al.，2015；Szymanowski et al.，2017；Ellis et al.，2019；贺振宇等，2021)。岩浆补给作用会导致岩浆成分及液相线温度的变化，使锆石由饱和向不饱和转变，导致已结晶锆石发生熔蚀和再生长，形成具核-边结构等多阶段结晶特点的锆石，因而可以反演岩浆补给作用过程(Claiborne et al.，2010；Chamberlain et al.，2014；贺振宇等，2021)。Yan Lili et al.(2018)利用锆石原位微量元素对雁荡山破火山流纹质火山岩的研究发现样品中的锆石广泛发育核-边结构，核部 CL 较暗、环带清晰，具有熔蚀结构，边部 CL 图像较亮、环带不明显，边部相对于核部一般具有低的 Hf、Yb、U 含量，以及高的 Ti 含量、Zr/Hf 和 Eu/Eu* 比值，反映了岩浆补给作用，以及锆石在高温、低演化的补给岩浆中的熔蚀和再生长(图 9)。

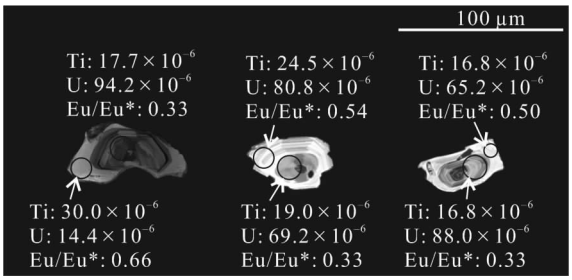

图 9 雁荡山破火山流纹质火山岩中锆石的阴极发光(CL)图像，显示锆石具有熔蚀的核部和 CL 较亮的边部，反映了锆石在高温、低演化的补给岩浆中的熔蚀和再生长(据 Yan Lili et al.，2018)

Fig. 9 Cathodoluminescence (CL) images showing resorbed zircon core and CL-bright rim from the rhyolitic volcanic rocks of the Yandangshan caldera, indicating zircon grains are resorbed and recrystallized in the high temperature and low-evolved recharged magma (after Yan Lili et al.，2018)

利用不同液体代表不同物理性质的岩浆进行模拟实验也是研究岩浆补给过程的重要方法。利用这种模拟实验方法，地质学家可以直接观察到补给岩浆注入岩浆房时的状态以及其与原有岩浆相互作用的过程，包括基性补给岩浆注入基性岩浆房(Huppert et al.，1980，1982；Campbell et al.，1988)、浮力更大的补给岩浆注入中性岩浆房(Huppert et al.，1986；Weinberg et al.，1998)，以及硅质岩浆注入硅质岩浆房等(Girard et al.，2009b)，这种实验不考虑对流和结晶作用可能导致的混合，与自然界中的岩浆系统相比过度简化，但对于评估纯流体动力学过程产生的岩浆相互作用是有效的。例如，Girard et al.(2009b)的模拟实验研究揭示了在无晶体的液态岩浆房与晶粥岩浆房中发生岩浆补给作用时补给岩浆在岩浆房中的运动状态、岩浆房中熔体的动力学特征变化的差异，并观察到岩浆补给所造成的晶粥碎片在岩浆房中的移动和重新分布过程，从而提出流纹岩中发育不平衡结构等特征的晶体可能来自于由岩浆补给造成的再活化晶粥中的晶体。

另外，对于活动或者休眠火山，常采用地震层析成像、GPS 测量等手段监测其岩浆系统中是否存在

岩浆补给活动，并可依据岩浆房深度范围异常的地震信号，解析出岩浆房的位置、岩浆和流体的迁移路径，恢复岩浆管道系统的结构，进而开展火山再次活动或喷发的预测分析（Pallister et al.，1992；Xu Jiandong et al.，2012；Spica et al.，2017；Sychev et al.，2019；Yi Jian et al.，2021）。Xu Jiandong et al.（2012）通过对长白山火山的火山地震活动、地表变形、火山气体地球化学进行连续长达 12 a 的监测，监测数据显示在 2002～2006 年之间火山地震的频率相对于该区域背景值增加了两个数量级，地表发生了膨胀，观察点向远离天池方向移动，破火山边部 3 个热泉释放的火山气体中 CO_2、He、H_2 含量增高，N_2/O_2、$^3He/^4He$ 比值升高，认为这可能是增量的岩浆补给引起的岩浆房压力增加的表现。另外，通过对 GPS 和精密水准测量的地面变形数据进行模拟，指出相应的变形源位于火山顶部之下 2～6 km 的深度，与探测到的地震群位置一致，从而认为自 1903 年以来一直处于休眠状态的长白山火山，在 2002～2006 年之间开始苏醒并恢复活动发生了岩浆扰动。

4　主要认识与展望

岩浆补给作用是制约地壳硅质岩浆系统演化过程的重要因素。岩浆补给作用引起不同成分与来源的岩浆相互混合，形成多种成分的岩浆，为火山岩浆系统提供热量和挥发分，增加熔体的比例，延长岩浆存储的时间，促进岩浆房内岩浆的对流、岩浆的分异演化、晶粥间熔体的提取和运移、晶粥的再活化以及成矿元素的富集。岩浆补给作用同时还能造成岩浆房过压，触发火山喷发，是驱动火山活动的重要机制。一般可以通过岩浆包体、矿物内部不平衡的结构和成分环带、矿物原位微区微量元素及同位素，以及模拟实验和地震层析成像等手段，来揭示火山岩浆系统的岩浆补给作用过程以及补给岩浆的来源。岩浆补给作用的持续时间、频率和规模以及补给岩浆与原有岩浆之间相互作用的研究，可为活动火山监测、火山喷发预测和灾害评估提供参考依据。

目前关于岩浆补给过程研究仍有许多问题有待深入研究。例如：补给岩浆上升运移的机制、补给触发岩浆喷发的机制、岩浆补给速率、岩浆从补给到喷发的时间尺度、补给岩浆自深部晶粥岩浆房中的分离机制、补给岩浆在晶粥再活化过程中的作用方式等。建议从硅质岩浆的晶体-熔体-流体演化的视角，从硅质火山岩中晶体的不同来源、晶体与熔体之间的不平衡现象及时间尺度、晶体内部元素扩散再平衡时间尺度、以及挥发分在火山岩浆过程中的作用等方面入手，才能更好地理解硅质火山岩浆系统的内部结构和岩浆补给过程的时间尺度及动力学机制。

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References

Bachmann O, Dungan M A, Lipman P W. 2002. The Fish Canyon magma body, San Juan volcanic field, Colorado: rejuvenation and eruption of an upper-crustal batholith. Journal of Petrology, 43: 1469～1503.

Bachmann O, Bergantz G W. 2004. On the origin of crystal-poor rhyolites: extracted from batholithic crystal mushes. Journal of Petrology, 45: 1565～1582.

Bachmann O, Bergantz G W. 2006. Gas percolation in upper-crustal silicic crystal mushes as a mechanism for upward heat advection and rejuvenation of near-solidus magma bodies. Journal of Volcanology and Geothermal Research, 149: 85～102.

Bachmann O, Miller C, De Silva S. 2007. The volcanic-plutonic connection as a stage for understanding crustal magmatism. Journal of Volcanology and Geothermal Research, 167: 1～23.

Bachmann O, Bergantz G W. 2008. Deciphering magma chamber dynamics from styles of compositional zoning in large silicic ash flow sheets. Reviews in Mineralogy and Geochemistry, 69: 651～674.

Bachmann O, Deering C D, Ruprecht J S, Huber C, Skopelitis A, Schnyder C. 2012. Evolution of silicic magmas in the Kos-Nisyros volcanic center, Greece: a petrological cycle associated with caldera collapse. Contributions to Mineralogy and Petrology, 163: 151～166.

Bachmann O, Deering C D, Lipman P W, Plummer C. 2014. Building zoned ignimbrites by recycling silicic cumulates: insight from the 1,000 km^3 Carpenter Ridge tuff, CO. Contributions to Mineralogy and Petrology, 167: 1025.

Bachmann O, Huber C. 2016. Silicic magma reservoirs in the Earth's crust. American Mineralogist, 101: 2377～2404.

Bachmann O, Huber C. 2019. The inner workings of crustal distillation columns; the physical mechanisms and rates controlling phase separation in silicic magma reservoirs. Journal of Petrology, 60: 3～18.

Barbarin B, Didier J. 1992. Genesis and evolution of mafic microgranular enclaves through various types of interaction between coexisting felsic and mafic magmas. Transactions of the Royal Society of Edinburgh (Earth Science), 83: 145～153.

Barboza S A, Bergantz G W. 2000. Metamorphism and anatexis in the mafic complex contact aureole, Ivrea Zone, northern Italy. Journal of Petrology, 41: 1307～1327.

Bergantz G W, Schleicher J M, Burgisser A. 2015. Open-system dynamics and mixing in magma mushes. Nature Geoscience, 8: 793～796.

Biggs J, Ebmeier S K, Aspinall W P, Lu Z, Pritchard M E, Sparks R S J, Mather T A. 2014. Global link between deformation and volcanic eruption quantified by satellite imagery. Nature Communications, 5: 3471.

Browne B L, Eichelberger J C, Patino L C, Vogel T A, Dehn J, Uto K, Hoshizumi H. 2006. Generation of porphyritic and equigranular mafic enclaves during magma recharge events at Unzen volcano, Japan. Journal of Petrology, 47: 301～328.

Buret Y, Wotzlaw J F, Roozen S, Guillong M, von Quadt A, Heinrich C A. 2017. Zircon petrochronological evidence for a plutonic-volcanic connection in porphyry copper deposits.

Geology, 45: 623～626.
Campbell I H, Turner J S. 1988. Fountains in magma chambers. Journal of Petrology, 30: 885～923.
Cashman K V, Sparks R S J. 2013. How volcanoes work: a 25 year perspective. GSA Bulletin, 125: 664～690.
Cashman K V, Giordano G. 2014. Calderas and magma reservoirs. Journal of Volcanology and Geothermal Research, 288: 28～45.
Cashman K V, Sparks R S J, Blundy J D. 2017. Vertically extensive and unstable magmatic systems: a unified view of igneous processes. Science, 355: eaag3055.
Caricchi L, Annen C, Blundy J, Simpson G, Pinel V. 2014. Frequency and magnitude of volcanic eruptions controlled by magma injection and buoyancy. Nature Geoscience, 7: 126～130.
Cassidy M, Manga M, Cashman K, Bachmann O. 2018. Controls on explosive-effusive volcanic eruption styles. Nature Communications, 9: 2839.
Chamberlain K J, Wilson C J, Wooden J L, Charlier B L, Ireland T R. 2014. New perspectives on the Bishop Tuff from zircon textures, ages and trace elements. Journal of Petrology, 55: 395～426.
Charlier B L A, Wilson C J N, Davidson J P. 2008. Rapid open-system assembly of a large silicic magma body: time-resolved evidence from cored plagioclase crystals in the Oruanui eruption deposits, New Zealand. Contributions to Mineralogy and Petrology, 156: 799～813.
Chelle-Michou C, Chiaradia M, Ovtcharova M, Ulianov A, Wotzlaw J F. 2014. Zircon petrochronology reveals the temporal link between porphyry systems and the magmatic evolution of their hidden plutonic roots (the Eocene Coroccohuayco deposit, Peru). Lithos, 198: 129～140.
Chen Jingyuan, Yang Jinhui, Zhang Jiheng, Sun Jinfeng, Zhu Yusheng, Hartung E. 2021. Generation of Cretaceous high-silica granite by complementary crystal accumulation and silicic melt extraction in the coastal region of southeastern China. GSA Bulletin, 134: 201～222.
Chen Shuo, Niu Yaoling, Wang Xiaohong, Xue Qiqi, Sun Wenli. 2021. Identifying crystal accumulation in granitoids through amphibole composition and *in situ* zircon O isotopes in North Qilian Orogen. Journal of Petrology, 62(12): egab096.
Christiansen E H, McCurry M. 2008. Contrasting origins of Cenozoic silicic volcanic rocks from the western Cordillera of the United States. Bulletin of Volcanology, 70: 251～267.
Claiborne L L, Miller C F, Wooden J L. 2010. Trace element composition of igneous zircon: a thermal and compositional record of the accumulation and evolution of a large silicic batholith, Spirit Mountain, Nevada. Contributions to Mineralogy and Petrology, 160: 511～531.
Clarke D B, Dorais M, Barbarin B, Barker D, Cesare B, Clarke G. 2005. Occurrence and origin of andalusite in peraluminous felsic igneous rocks. Journal of Petrology, 46: 441～472.
Clemens J D, Stevens G. 2016. Melt segregation and magma interactions during crustal melting: breaking out of the matrix. Earth Science Reviews, 160: 333～349.
Coombs M L, Eichelberger J C, Rutherford M J. 2002. Experimental and textural constraints on mafic enclave formation in volcanic rocks. Journal of Volcanology and Geothermal Research, 119: 125～144.
Cooper K M, Kent A J R. 2014. Rapid remobilization of magmatic crystals kept in cold storage. Nature, 506: 480～483.
Cooper K M. 2017. What does a magma reservoir look like? The "Crystal's-Eye" view. Elements, 13: 23～28.
Davidson J P, Tepley F J. 1997. Recharge in volcanic systems: evidence from isotope profiles of phenocrysts. Science, 275: 826～829.
Davidson J P, Morgan D J, Charlier B L A, Harlou R, Hora J M. 2007. Microsampling and isotopic analysis of igneous rocks: implications for the study of magmatic systems. Annual Review of Earth and Planetary Sciences, 35: 273～311.
Davidson J P, Laura F, Charlier B L A, Tepley F J. 2008. Mineral-scale Sr isotope variation in plutonic rocks-a tool for unravelling the evolution of magma systems. Transactions of the Royal Society of Edinburgh (Earth Science), 97: 357～367.
de Silva S, Wolff J. 1995. Zoned magma chambers: the influence of magma chamber geometry on sidewall convective fractionation. Journal of Volcanology and Geothermal Research, 65: 111～118.
de Silva S, Salas G, Schubring S. 2008. Triggering explosive eruptions-the case for silicic magma recharge at Huaynaputina, southern Peru. Geology, 36: 387～390.
Deering C D, Bachmann O, Vogel T A. 2011. The Ammonia Tanks tuff: erupting a melt-rich rhyolite cap and its remobilized crystal cumulate. Earth and Planetary Science Letters, 310: 518～525.
Druitt T H, Costa F, Deloule E, Dungan M, Scaillet B. 2012. Decadal to monthly timescales of magma transfer and reservoir growth at a caldera volcano. Nature, 482: 77～80.
Drummond M S, Defant M J. 1990. A model for trondhjemite-tonalite-dacite genesis and crustal growth via slab melting: Archean to modern comparisons. Journal of Geophysical Research: Solid Earth, 95: 21503～21521.
Dufek J, Bachmann O. 2010. Quantum magmatism: magmatic compositional gaps generated by melt-crystal dynamics. Geology, 38: 687～690.
Dunbar N W, Kyle P R, Wilson C J N. 1989. Evidence for limited zonation in silicic magma systems, Taupo volcanic zone. New Zealand. Geology, 17: 234～236.
Eichelberger J C, Chertkoff D G, Dreher S T, Nye C J. 2000a. Magmas in collision: rethinking chemical zonation in silicic magmas. Geology, 28: 603～606.
Eichelberger J C, Izbekov P E. 2000b. Eruption of andesite triggered by dyke injection: contrasting cases at Karymsky volcano, Kamchatka and Mt. Katmai, Alaska. Philosophical Transactions of the Royal Society of London, Series A: Mathematical and Physical Sciences, 358: 1465～1485.
Eichelberger J C, Izbekov P E, Browne B L. 2006. Bulk chemical trends at arc volcanoes are not liquid lines of descent. Lithos, 87: 135～154.
Ellis B S, Wolff J A. 2012. Complex storage of rhyolite in the central Snake river plain. Journal of Volcanology and Geothermal Research, 211-212: 1～11.
Ellis B S, Wolff J A, Boroughs S, Mark D F, Starkel W A, Bonnichsen B. 2013. Rhyolitic volcanism of the central Snake river plain: a review. Bulletin of Volcanology, 75: 745.
Ellis B S, Bachmann O, Wolff J A. 2014. Cumulate fragments in silicic ignimbrites: the case of the Snake River Plain. Geology, 42: 431～434.
Ellis B S, Schmitz M D, Hill M. 2019. Reconstructing a Snake river plain 'super-eruption' via compositional fingerprinting and high-precision U/Pb zircon geochronology. Contributions to Mineralogy and Petrology, 174: 101.
Fan Qicheng, Sui Jianli, Sun Qian, Li Ni, Wang Tuanhua. 2005. Preliminary research of magma mixing and explosive mechanism of the Millennium eruption of Tianchi volcano. Acta Petrologica Sinica, 21: 1703～1708 (in Chinese with English abstract).
Foley M L, Miller C F, Gualda G A R. 2020. Architecture of a super-sized magma chamber and remobilization of its basal cumulate (Peach Spring Tuff, USA). Journal of Petrology, 61: egaa020.
Forni F, Ellis B S, Bachmann O, Lucchi F, Tranne C A, Agostini S, Dallai L. 2015. Erupted cumulate fragments in rhyolites from Lipari (Aeolian Islands). Contributions to Mineralogy and Petrology, 170: 49.
Forni F, Bachmann O, Mollo S, De Astis G, Gelman S E, Ellis B S. 2016. The origin of a zoned ignimbrite: insights into the Campanian Ignimbrite magma chamber (Campi Flegrei, Italy). Earth and Planetary Science Letters, 449: 259～271.

Forni F, Petricca E, Bachmann O, Mollo S, De Astis G, Piochi M. 2018. The role of magma mixing/mingling and cumulate melting in the Neapolitan Yellow Tuff caldera-forming eruption (Campi Flegrei, Southern Italy). Contributions to Mineralogy and Petrology, 173: 45.

Frost C D, Frost B R, Beard J S. 2016. On silica-rich granitoids and their eruptive equivalents. American Mineralogist, 101: 1268～1284.

Fulignati P, Marianelli P, Santacroce R, Sbrana A. 2004. Probing the Vesuvius magma chamber-host rock interface through xenoliths. Geological Magazine, 141: 417～428.

Greene A R, Debari S M, Kelemen P B, Blusztajn J, Clift P D. 2006. A detailed geochemical study of island arc crust: the Talkeetna Arc section, south-central Alaska. Journal of Petrology, 47: 1051～1093.

Holness M B. 2018. Melt segregation from silicic crystal mushes: a critical appraisal of possible mechanisms and their microstructural record. Contributions to Mineralogy and Petrology, 173: 48.

Hughes G E, Petrone C M, Downes H, Varley N R, Hammond S J. 2021. Mush remobilisation and mafic recharge: a study of the crystal cargo of the 2013-17 eruption at Volcán de Colima, Mexico. Journal of Volcanology and Geothermal Research, 416: 107296.

Huppert H E, Sparks R S J. 1980. The fluid dynamics of a basaltic magma chamber replenished by influx of hot, dense ultrabasic magma. Contributions to Mineralogy and Petrology, 75: 279～289.

Huppert H E, Turner J S, Sparks R S J. 1982. Replenished magma chambers: effects of compositional zonation and input rates. Earth and Planetary Science Letters, 57: 345～ 357.

Huppert H E, Sparks J R S, Whitehead J A, Hallworth M A. 1986. Replenishment of magma chambers by light inputs. Journal of Geophysical Research: Solid Earth, 91: 6113～ 6122.

Gagnevin D, Daly J S, Poli G, Morgan D. 2005. Microchemical and Sr isotopic investigation of zoned K-feldspar megacrysts: insights into the petrogenesis of a granitic system and disequilibrium crystal growth. Journal of Petrology, 46: 1689～1724.

Gagnevin D, Waight T E, Daly J S, Poli G, Conticelli S. 2007. Insights into magmatic evolution and recharge history in Capraia Volcano (Italy) from chemical and isotopic zoning in plagioclase phenocrysts. Journal of Volcanology and Geothermal Research, 168: 28～54.

Ginibre C, Davidson J P. 2014. Sr isotope zoning in plagioclase from Parinacota volcano (northern Chile): quantifying magma mixing and crustal contamination. Journal of Petrology, 55: 1203～1238.

Girard G, Stix J. 2009a. Magma recharge and crystal mush rejuvenation associated with early post-collapse upper basin member rhyolites, Yellowstone Caldera, Wyoming. Journal of Petrology, 50: 2095～2125.

Girard G, Stix J. 2009b. Buoyant replenishment in silicic magma reservoirs: experimental approach and implications for magma dynamics, crystal mush remobilization, and eruption. Journal of Geophysical Research: Solid Earth, 114(B8).

Glazner A F, Coleman D S, Bartley J M. 2008. The tenuous connection between high-silica rhyolites and granodiorite plutons. Geology, 36: 183～186.

Green T H, Ringwood A. 1968. Genesis of the calc-alkaline igneous rock suite. Contributions to Mineralogy and Petrology, 18: 105～162.

Griffin W L, Wang X, Jackson S E, Pearson N J, O'Reilly S Y, Xu X S, Zhou X M. 2002. Zircon chemistry and magma mixing, SE China: *in-situ* analysis of Hf isotopes, Tonglu and Pingtan igneous complexes. Lithos, 61: 237～269.

Gualda G A R, Ghiorso M S. 2013. The Bishop Tuff giant magma body: an alternative to the standard model. Contributions to Mineralogy and Petrology, 166: 755～775.

Hartung E, Caricchi L, Floess D, Wallis S, Harayama S, Kouzmanov K, Chiaradia M. 2017. Evidence forresidual melt extraction in the Takidani pluton, central Japan. Journal of Petrology, 58: 763～788.

He Zhenyu, Yan Lili. 2021. Zircon trace element geochemistry constrains on the silicic volcanic system. Acta Petrologica et Mineralogica, 40: 939 ～ 951 (in Chinese with English abstract).

Hernando I R, Petrinovic I A, Llambías E J, D'Elia L, González P D, Aragón E. 2016. The role of magma mixing and mafic recharge in the evolution of a back-arc quaternary caldera: the case of Payún Matrú, Western Argentina. Journal of Volcanology and Geothermal Research, 311: 150～169.

Hervig R L, Dunbar N W. 1992. Cause of chemical zoning in the Bishop (California) and Bandelier (New Mexico) magma chambers. Earth and Planetary Science Letters, 111: 97～108.

Hibbard M J. 1981. The magma mixing origin of mantled feldspars. Contributions to Mineralogy and Petrology, 76: 158～170.

Hildreth W. 1981. Gradients in silicic magma chambers: implications for lithospheric magmatism. Journal of Geophysical Research: Solid Earth, 86: 10153～10192.

Hildreth W. 2004. Volcanological perspectives on Long Valley, Mammoth Mountain, and Mono Craters: several contiguous but discrete systems. Journal of Volcanology and Geothermal Research, 136: 169～198.

Hildreth W, Wilson C J N. 2007. Compositional zoning of the Bishop Tuff. Journal of Petrology, 48: 951～999.

Huber C, Bachmann O, Dufek J. 2010. The limitations of melting on the reactivation of silicic mushes. Journal of Volcanology and Geothermal Research, 195: 97～105.

Huber C, Bachmann O, Dufek J. 2012. Crystal-poor versus crystal-rich ignimbrites: a competition between stirring and reactivation. Geology, 40: 115～118.

Humphreys M C, Blundy J D, Sparks R S J. 2006. Magma evolution and open-system processes at Shiveluch volcano: insights from phenocryst zoning. Journal of Petrology, 47: 2303～2334.

John D A. 2008. Supervolcanoes and metallic ore deposits. Elements, 4: 22～22.

Karakas O, Degruyter W, Bachmann O, Dufek J. 2017a. Lifetime and size of shallow magma bodies controlled by crustal-scale magmatism. Nature Geoscience, 10: 446～450.

Karakas O, Dufek J, Mangan M T, Wright H M, Bachmann O. 2017b. Thermal and petrologic constraints on lower crustal melt accumulation under the Salton Sea geothermal field. Earth and Planetary Science Letters, 467: 10～17.

Karakas O, Wotzlaw J F, Guillong M, Ulmer P, Brack P, Economos R, Bergantz G W, Sinigoi S, Bachmann O. 2019. The pace of crustal-scale magma accretion and differentiation beneath silicic caldera volcanoes. Geology, 47: 719～723.

Keller C B, Schoene B, Barboni M, Samperton K M, Husson J M. 2015. Volcanic-plutonic parity and the differentiation of the continental crust. Nature, 523: 301～307.

Kennedy B, Stix J. 2007. Magmatic processes associated with caldera collapse at Ossipee ring dyke, New Hampshire. GSA Bulletin, 119: 3～17.

Kennedy B, Stix J, Hon K, Deering C, Gelman S. 2016. Magma storage, differentiation, and interaction at Lake City caldera, Colorado, USA. GSA Bulletin, 128: 764～776.

Kent A, Darr C, Koleszar A M, Salisbury M J, Cooper K M. 2010. Preferential eruption of andesitic magmas through recharge filtering. Nature Geoscience, 3: 631～636.

Klemetti E W, Clynne M A. 2014. Localized rejuvenation of a crystal mush recorded in zircon temporal and compositional variation at the Lassen volcanic center, northern California. PLoS One, 9: e113157.

Knesel K M, Duffield W A. 2007. Gradients in silicic eruptions caused by rapid inputs from above and below rather than

protracted chamber differentiation. Journal of Volcanology and Geothermal Research, 167: 181～197.

Lee C T A, Morton D M. 2015a. High silica granites: terminal porosity and crystal settling in shallow magma chambers. Earth and Planetary Science Letters, 409: 23～31.

Lee C T A, Morton D M, Farner M J, Moitra P. 2015b. Field and model constraints on silicic melt segregation by compaction/hindered settling: the role of water and its effect on latent heat release. American Mineralogist, 100: 1762～1777.

Lindsay J M, de Silva S L, Trumbull R B, Emmermann R, Wemmer K. 2001. La Pacana caldera, N. Chile: a re-evaluation of the stratigraphy of one of the world's largest resurgent calderas. Journal of Volcanology and Geothermal Research, 106: 145～173.

Lipman P W. 1967. Mineral and chemical variations within an ash-flow sheet from Aso caldera, southwestern Japan. Contributions to Mineralogy and Petrology, 16: 300～327.

Lipman P W. 2007. Incremental assembly and prolonged consolidation of Cordilleran magma chambers: evidence from the Southern Rocky Mountain volcanic field. Geosphere, 3: 42～70.

Lipman P W, Sawyer D A. 1985. Mesozoic ash-flow caldera fragments in southeastern Arizona and their relation to porphyry copper deposits. Geology, 13: 652～656.

Lipman P W, Bachmann O. 2015a. Ignimbrites to batholiths: integrating perspectives from geological, geophysical, and geochronological data. Geosphere, 11: 705～743.

Lipman P W, Zimmerer M J, McIntosh W C. 2015b. An ignimbrite caldera from the bottom up: exhumed floor and fill of the resurgent Bonanza caldera, southern Rocky Mountain volcanic field, Colorado. Geosphere, 11: 1902～1947.

Liu Boda, Lee C T. 2020. Large silicic eruptions, episodic recharge, and the transcrustal magmatic system. Geochemistry, Geophysics, Geosystems, 21: e2020GC009220.

Lu Tianyu, He Zhenyu, Zhang Zeming, Shui Xinfang, Yan Lili. 2016. Magma mixing of the Nyemo post-collisional granite from the Gangdese magmatic belt, Tibet: evidence of microstructures. Acta Petrologica Sinica, 32: 3613～3623 (in Chinese with English abstract).

Lu Tianyu, He Zhenyu, Klemd R. 2022. Identifying crystal accumulation and melt extraction during formation of high-silica granite. Geology, 50: 216～221.

Lubbers J, Deering C, Bachmann O. 2020. Genesis of rhyolitic melts in the upper crust: fractionation and remobilization of an intermediate cumulate at Lake City caldera, Colorado, USA. Journal of Volcanology and Geothermal Research, 392: 106750.

Ma Changqian, Li Yanqing. 2017. Incremental growth of granitoid plutons and highly crystalline magmatic differentiation. Acta Petrologica Sinica, 33: 1479～1488 (in Chinese with English abstract).

Ma Changqian, Zou Bowen, Gao Ke, Wen Xia. 2020. Crystal mush storage, incremental pluton assembly and granitic petrogenesis. Earth Science, 45: 4332～4351 (in Chinese with English abstract).

Malfait W J, Seifert R, Petitgirard S, Perrillat J P, Mezouar M, Ota T Nakamura E, Lerch P, Sanchez-Valle C. 2014. Supervolcano eruptions driven by melt buoyancy in large silicic magma chambers. Nature Geoscience, 7: 122～125.

Martin V M, Holness M B, Pyle D M. 2006. Textural analysis of magmatic enclaves from the Kameni Islands, Santorini, Greece. Journal of Volcanology and Geothermal Research, 154: 89～102.

Martin V M, Morgan D J, Jerram D A, Caddick M J, Prior D J, Davidson J P. 2008. Bang! Month-scale eruption triggering at Santorini Volcano. Science, 321: 1178.

Masotta M, Mollo S, Gaeta M, Freda C. 2016. Melt extraction in mush zones: the case of crystal-rich enclaves at the Sabatini Volcanic District (central Italy). Lithos, 248: 288～292.

McKenzie D P. 1985. The extraction of magma from the crust and mantle. Earth and Planetary Science Letters, 74: 81～91.

Miller C F. 2016. Eruptible magma. Proceedings of the National Academy of Sciences, 113: 13941～13943.

Miller C F, Wark D A. 2008. Supervolcanoes and their explosive supereruptions. Elements, 4(1): 11～16.

Mills Jr J G, Saltoun B W, Vogel T A. 1997. Magma batches in the Timber Mountain magmatic system, southwestern Nevada volcanic field, Nevada, USA. Journal of Volcanology and Geothermal Research, 78: 185～208.

Moran S C, Newhall C, Roman D C. 2011. Failed magmatic eruptions: late-stage cessation of magma ascent. Bulletin of Volcanology, 73: 115～122.

Murphy M, Sparks R, Barclay J, Carroll M, Brewer T. 2000. Remobilization of andesite magma by intrusion of mafic magma at the Soufriere Hills Volcano, Montserrat, West Indies. Journal of Petrology, 41: 21～42.

Pallister J S, Hoblitt R P, Reyes A G. 1992. A basalt trigger for the 1991 eruptions of Pinatubo volcano? Nature, 356: 426～428.

Perugini D, Poli G. 2012. The mixing of magmas in plutonic and volcanic environments: analogies and differences. Lithos, 153: 261～277.

Philpotts A R, Carrol M, Hill J M. 1996. Crystal-mush compaction and the origin of pegmatitic segregation sheets in a thick flood-basalt flow in the Mesozoic Hartford basin, Connecticut. Journal of Petrology, 37: 811～836.

Pistone M, Caricchi L, Ulmer P, Reusser E, Ardia P. 2013. Rheology of volatile-bearing crystal mushes: mobilization vs. viscous death. Chemical Geology, 345: 16～39.

Pistone M, Blundy J, Brooker R A. 2017. Water transfer during magma mixing events: insights into crystal mush rejuvenation and melt extraction processes. American Mineralogist, 102: 766～776.

Reid M R. 2003. Timescales of magma transfer and storage in the crust. In: Rudnick R L, ed. Treatise on Geochemistry. Amsterdam: Elsevier, 3: 167～193.

Reid M R, Vazquez J A, Schmitt A K. 2011. Zircon-scale insights into the history of a Supervolcano, Bishop Tuff, Long Valley, California, with implications for the Ti-in-zircon geothermometer. Contributions to Mineralogy and Petrology, 161: 293～311.

Reubi O, Blundy J. 2009. A dearth of intermediate melts at subduction zone volcanoes and the petrogenesis of arc andesites. Nature, 461: 1269～1273.

Ruprecht P, Bachmann O. 2010. Pre-eruptive reheating during magma mixing at Quizapu volcano and the implications for the explosiveness of silicic arc volcanoes. Geology, 38: 919～922.

Samperton K M, Schoene B, Cottle J M, Brenhin Keller C, Crowley J L, Schmitz M D. 2015. Magma emplacement, differentiation and cooling in the middle crust: integrated zircon geochronological-geochemical constraints from the Bergell Intrusion, Central Alps. Chemical Geology, 417: 322～340.

Scandone R, Cashman KV, Malone S D. 2007. Magma supply, magma ascent and the style of volcanic eruptions. Earth and Planetary Science Letters, 253: 513～529.

Schaen A J, Cottle J M, Singer B S, Keller C B, Garibaldi N. 2017. Complementary crystal accumulation and rhyolite melt segregation in a Late Miocene Andean pluton. Geology, 45: 835～838.

Schaen A J, Singer B S, Cottle J M, Garibaldi N, Schoene B, Satkoski A M, Fournelle J. 2018. Textural and mineralogical record of low-pressure melt extraction and silicic cumulate formation in the Late Miocene Risco Bayo-Huemul plutonic complex, Southern Andes. Journal of Petrology, 59: 1991～2016.

Schöpa A, Annen C. 2013. The effects of magma flux variations on the formation and lifetime of large silicic magma chambers. Journal of Geophysical Research: Solid Earth, 118: 926～942.

Schmitt A, de Silva S L, Trumbull R, Emmermann R. 2001. Recharge in the Cerro Purico magma system: implications for compositional zonations in silicic magma chambers. Contributions to Mineralogy and Petrology, 140: 180～200.

Self S, Blake S. 2008. Consequences of explosive supereruptions. Elements, 4: 41～46.

Shane P, Smith V, Nairn I. 2005. High temperature rhyodacites of the 36 ka Hauparu pyroclastic eruption, Okataina volcanic centre, New Zealand: change in a silicic magmatic system following caldera collapse. Journal of Volcanology and Geothermal Research, 147: 357～376.

Sillitoe R H. 2010. Porphyry copper systems. Economic Geology, 105: 3～41.

Sisson T W, Bacon C R. 1999. Gas-driven filter pressing in magmas. Geology, 27: 613～616.

Sliwinski J T, Bachmann O, Ellis B S, Dávila-Harriset P, Nelson B K, Dufek J. 2015. Eruption of shallow crystal cumulates during explosive phonolitic eruptions on Tenerife, Canary Islands. Journal of Petrology, 56: 2173～2194.

Smith R L. 1979. Ash-flow magmatism. In: Chapin C E, Elston W E, eds. Ash-flow tuffs. Geological Society of America Special Papers, 180: 5～27.

Spica Z, Perton M, Legrand D. 2017. Anatomy of the Colima volcano magmatic system, Mexico. Earth and Planetary Science Letters, 459: 1～13.

Streck M J. 2008. Mineral textures and zoning as evidence for open system processes. Reviews in mineralogy and geochemistry, 69: 595～622.

Streck M J. 2014. Evaluation of crystal mush extraction models to explain crystal-poor rhyolites. Journal of Volcanology and Geothermal Research, 284: 79～94.

Sychev I V, Koulakov I, Egorushkin I, Zhuravlev S, West M, El Khrepy S, Al-Arifi N, Alajmi M S. 2019. Fault-associated magma conduits beneath Volcán de Colima revealed by seismic velocity and attenuation tomography studies. Journal of Geophysical Research: Solid Earth, 124: 8908～8923.

Szymanowski D, Wotzlaw J F, Ellis B S, Bachmann O, Guillong M, von Quadt A. 2017. Protracted near-solidus storage and pre-eruptive rejuvenation of large magma reservoirs. Nature Geoscience, 10: 777～782.

Tappa M J, Coleman D S, Mills R D, Samperton K M. 2011. The plutonic record of a silicic ignimbrite from the Latir volcanic field, New Mexico. Geochemistry, Geophysics, Geosystems, 12: Q10011.

Tepley F J III, Davidson J P, Clynne M A. 1999. Magmatic interactions as recorded in plagioclase phenocrysts of Chaos Crags, Lassen Volcanic Center, CA. Journal of Petrology, 40: 787～806.

Tepley F J III, Davidson J P, Tilling R I, Arth J G. 2000. Magma mixing, recharge and eruption histories recorded in plagioclase phenocrysts from El Chichón volcano, Mexico. Journal of Petrology, 41: 1397～1411.

Thompson A B, Matile L, Ulmer P. 2002. Some thermal constraints on crustal assimilation during fractionation of hydrous, mantle-derived magmas with examples from Central Alpine batholiths. Journal of Petrology, 43: 403～422.

Townsend M, Huber C. 2020. A critical magma chamber size for volcanic eruptions. Geology, 48: 431～435.

Vernon R H. 1984. Microgranitoid enclaves in granites-globules of hybrid magma quenched in a plutonic environment. Nature, 309: 438～439.

Vernon R H. 1990. Crystallization and hybridism in microgranitoid enclave magmas: microstructural evidence. Journal of Geophysical Research, 95: 17849～17859.

Wang Xiaoxia, Wang Tao, Lu Xinxiang. 2001. Studies and problems on rapakivi granites. Geological Science and Technology Information, 20: 19～23 (in Chinese with English abstract).

Wark D, Hildreth W, Spear F, Cherniak D, Watson E. 2007. Pre-eruption recharge of the Bishop magma system. Geology, 35: 235～238.

Weinberg R F, Leitch A M. 1998. Mingling in mafic magma chambers replenished by light felsic inputs: fluid dynamical experiments. Earth and Planetary Science Letters, 157: 41～56.

Wilson C J N, Charlier B L A. 2016. The life and times of silicic volcanic systems. Elements, 12: 103～108.

Wolff J A, Ellis B, Ramos F C, Starkel W A, Boroughs S, Olin P H, Bachmann O. 2015. Remelting of cumulates as a process for producing chemical zoning in silicic tuffs: a comparison of cool, wet and hot, dry rhyolitic magma systems. Lithos, 236: 275～286.

Wolff J A, Forni F, Ellis B S, Szymanowski D. 2020. Europium and barium enrichments in compositionally zoned felsic tuffs: a smoking gun for the origin of chemical and physical gradients by cumulate melting. Earth and Planetary Science Letters, 540: 116251.

Wotzlaw J F, Schaltegger U, Frick D A, Dungan M A, Gerdes A, Günther D. 2013. Tracking the evolution of large-volume silicic magma reservoirs from assembly to supereruption. Geology, 41: 867～870.

Wright H M, Folkes C B, Cas R A, Cashman K V. 2011. Heterogeneous pumice populations in the 2.08-Ma Cerro Galán Ignimbrite: implications for magma recharge and ascent preceding a large-volume silicic eruption. Bulletin of Volcanology, 73: 1513～1533.

Wu Fuyuan, Liu Xiaochi, Ji Weiqiang, Wang Jiamin, Yang Lei. 2017. Highly fractionated granites: recognition and research. Science China Earth Science, 60: 1201～1219.

Xu Jiandong, Liu Guoming, Wu Jianping, Ming Yuehong, Wang Qingliang, Cui Duxin, Shangguan Zhiguan, Pan Bo, Lin Xudong, Liu Junqing. 2012. Recent unrest of Changbaishan volcano, northeast China: a precursor of a future eruption? Geophysical Research Letters, 39: L16305.

Xu Wei, Zhu Dicheng, Wang Qing, Weinberg R F, Wang Rui, Li Shimin, Zhang Liangliang, Zhao Zhidan. 2021. Mafic microgranular enclaves formed by gas-driven filter pressing during rapid cooling: an example from the Gangdese batholith in southern Tibet. Journal of Petrology, 61(11-12): egab3.

Xu Xisheng, Zhao Kai, He Zhenyu, Liu Lei, Hong Wentao. 2020. Cretaceous volcanic-plutonic magmatism in SE China and a genetic model. Lithos, 402-403: 105728.

Yan Lili, He Zhenyu, Liu Lei, Zhao Zhidan. 2015. Magma mixing in the Yandangshan volcanic-intrusive complex, Zhejiang Province: evidence from feldspar zoning of the mafic microgranular enclave. Geological Bulletin of China, 34: 466～473 (in Chinese with English abstract).

Yan Lili, He Zhenyu, Jahn Borming, Zhao Zhidan. 2016. Formation of the Yandangshan volcanic-plutonic complex (SE China) by melt extraction and crystal accumulation. Lithos, 266-267: 287～308.

Yan Lili, He Zhenyu, Beier C, Klemd R. 2018. Zircon trace element constrains on the link between volcanism and plutonism in SE China. Lithos, 320: 28～34.

Yan Lili, He Zhenyu, Klemd R, Beier C, Xu X S. 2020. Tracking crystal-melt segregation and magma recharge using zircon trace element data. Chemical Geology, 542: 119596.

Yi Jian, Wang Pujun, Shan Xuanlong, Ventura G, Wu Chengzhi, Guo Jiannan, Liu Pencheng, Li Jiahui. 2021. Modeling the multi-level plumbing system of the Changbaishan caldera from geochemical, mineralogical, Sr-Nd isotopic and integrated geophysical data. Geoscience Frontiers, 12: 101171.

Zhang Zeming, Ding Huixia, Dong Xing, Tian Zuolin. 2020. Partial melting of subduction zones. Acta Petrologica Sinica, 36: 2589～2615(in Chinese with English abstract).

Zimmerer M J, McIntosh W C. 2012. An investigation of caldera-forming magma chambers using the timing of ignimbrite eruptions and pluton emplacement at the Mt. Aetna caldera

complex. Journal of Volcanology and Geothermal Research, 245: 128～148.

参 考 文 献

樊祺诚,隋建立,孙谦,李霓,王团华,2005. 天池火山千年大喷发的岩浆混合作用与喷发机制初步探讨. 岩石学报,21:1703～1708.

贺振宇,颜丽丽. 2021. 锆石微量元素地球化学对硅质火山岩浆系统的制约. 岩石矿物学杂志,40:939～951.

陆天宇,贺振宇,张泽明,水新芳,颜丽丽. 2016. 西藏冈底斯尼木后碰撞花岗岩的岩浆混合作用:显微结构证据. 岩石学报,32:3613～3623.

马昌前,李艳青. 2017. 花岗岩体的累积生长与高结晶度岩浆的分异. 岩石学报,33:1479～1488.

马昌前,邹博文,高珂,文霞. 2020. 晶粥储存、侵入体累计组装与花岗岩成因. 地球科学,45:4332～4351.

王晓霞,王涛,卢欣祥. 2001. 环斑花岗岩研究及存在的问题. 地质科技情报,20: 19～23.

颜丽丽,贺振宇,刘磊,赵志丹. 2015. 浙江雁荡山火山-侵入杂岩的岩浆混合作用—暗色包体中长石环带的证据. 地质通报,34:466～473.

张泽明,丁慧霞,董昕,田作林. 2020. 俯冲带部分熔融. 岩石学报,36:2589～2615.

Influence of magma recharge on the evolution of silicic volcanic system

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Abstract

As an important manifestation of continental crust magmatic activity, silicic volcanic eruption is of great significance in studying the formation and evolution of continental crust, and understanding the magmatic processes and dynamic mechanisms. The violent explosive eruption which is usually manifested by silicic volcanic eruption can even cause global environmental and climate change. The contribution and interaction of magma from different sources in open silicic magmatic system is still a hot issue to be further studied. The continuous magma recharge can prolong magma storage time, promote convection in magma chamber, magma differentiation, crystal-melt separation and mush rejuvenation, and is also one of the important mechanisms triggering eruption. Furthermore, magma recharge and crystal-melt evolution processes of silicic magma are also responsible for the diversity of volcanic eruption products. They cause regular variations in eruption products of the same volcano during its eruptive activity, such as crystal-rich volcanic rocks, crystal-poor volcanic rocks, composition stratification of volcanic rocks, as well as the resurgent dome and central intrusive rocks. Therefore, magma recharge is an important constraint factor for the evolution of silicic volcanic magma system and volcanic composition diversity, and can also provide important information for active volcano monitoring and disaster assessment. Petrology, geochemistry, isotope and composition variation of minerals (feldspar, quartz, garnet, zircon, etc.), as well as experiments and seismic tomography studies, provide a variety of perspectives to reveal the magma recharge and complex magmatic processes in silicic magmatic systems.

Key words: magma recharge; silicic magmatic system; volcanic eruption; composition diversity; volcano monitoring