1000-0569/2022/038(05)-1399-18 *Acta Petrologica Sinica* 岩石学报 doi:10.18654/1000-0569/2022.05.09

# 地壳内的岩浆动力学过程及其资源与环境效应*

周金胜[1,2] 王强[1,2,3]

ZHOU JinSheng[1,2] and Wang Qiang[1,2,3]

1. 中国科学院广州地球化学研究所,同位素地球化学国家重点实验室,广州 510640
2. 中国科学院深地科学卓越创新中心,广州 510640
3. 中国科学院大学地球与行星科学学院,北京 100049
1. *State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou* 510640, *China*
2. *CAS Center for Excellence in Deep Earth Science, Guangzhou* 510640, *China*
3. *College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing* 100049, *China*

2022-01-15 收稿, 2022-04-02 改回.

**Zhou JS and Wang Q. 2022. Magma dynamics in the crust and its resource and environmental effects. *Acta Petrologica Sinica*, 38(5):1399-1418, doi:10.18654/1000-0569/2022.05.09**

**Abstract** Magma transfers materials from the Earth's interior into the surface that results in significant environmental effects and ore deposit formation. Magma dynamics addresses the research fields of magma transfer, storage, evolution, emplacement and eruption processes, mainly emphasizing physical mechanisms. These magmatic processes occur within magma plumbing systems that contain magma reservoirs and conduits. This review introduces certain hot topics concerning magma dynamics, including the transition from magma chamber to magma reservoir in concept, the growth of magma reservoir, the timescales of magmatic processes and the growth of magmatic crystals. We also reviewed volatile species and solubilities in magmas, methods for estimating magmatic volatile contents, volatile contents of certain typical mafic magmas, chemical and physical controls on magma degassing, and then briefly discussed the formation of magmatic-hydrothermal ore deposits and the environmental effects of magma dynamics. Finally, we suggest certain important scientific questions and future work concerning magma dynamics.

**Key words** Magma dynamics; Magma reservoir; Timescales; Magma volatiles; Ore-forming process; Carbon cycle

**摘 要** 岩浆是将地球内部物质传送到表层系统的主要载体,并造成显著的资源聚集和环境效应。岩浆动力学是研究岩浆的迁移、储存、演化、就位以及喷发过程,侧重物理机制。这些岩浆过程主要发生在岩浆通道系统中,包括岩浆储库和岩浆管道。本文对目前国际岩浆动力学领域一些热点和前沿进行了介绍,这包括从岩浆房到岩浆储库概念的转变、岩浆储库的生长和动力学演化过程、岩浆过程的时间尺度以及岩浆中晶体的生长。然后阐述了岩浆中挥发分的种类和溶解度、获取天然岩浆挥发分含量的方法、一些典型镁铁质岩浆中的挥发分含量、岩浆去气的化学和物理机制,并简要梳理了热液金属矿床的形成过程和岩浆挥发分进入地表圈层系统引发的环境气候效应。最后列举了一些岩浆动力学有关的重要科学问题并建议了进一步的研究方向。

**关键词** 岩浆动力学;岩浆储库;时间尺度;岩浆挥发分;成矿过程;碳循环

**中图法分类号** P588.11

从地幔和地壳深部起源的岩浆,可以喷出地表形成火山喷发物,或者冷凝固结成侵入体。研究岩浆的起源、迁移、储存、演化、就位以及喷发过程,就属于岩浆动力学的范畴(马昌前,1987)。尤其是岩浆的侵入和喷发这两个过程常常伴随有破坏性的自然灾害、强烈的环境气候扰动以及大规模的资源聚集。火山喷发所释放出的 $SO_2$,进入大气平流层形成

* 本文受国家自然科学基金项目(42021002、91855215)和中科院先导A子专题(XDA2007030402)联合资助.

**第一作者简介:** 周金胜,男,1989年生,副研究员,从事岩浆动力学及其资源与环境效应研究,E-mail: jinshengzhou@gig.ac.cn

硫酸盐的气溶胶(Self, 2006),对全球气候能产生长达数年的影响。例如,发生在7万年前的印尼多巴超级火山喷发,致使全球平均气温在随后的数十年中,下降了3~15℃(Robock, 2015)。悬浮在大气中的 $SO_2$ 能够与 $O_3$ 发生化学反应,从而破坏大气圈中的臭氧层。地质历史中五次大灭绝事件,其中至少有三次与大火成岩省的岩浆活动有关(Clapham and Renne, 2019; Black *et al.*, 2021)。另外,侵入体的就位过程,也与大陆地壳的生长和分异密切相关。岩浆中携带的金属元素、挥发分等物质,若在浅部地壳中富集,可以形成大型-超大型的岩浆-热液金属矿床(Edmonds *et al.*, 2018)。因此,研究岩浆在地壳内的迁移、储存、演化、就位以及喷发过程,对理解地球内部与表层系统物质交换及其资源环境效应具有重要的意义。

## 1 岩浆动力学概述

### 1.1 基本概念

此处对后文涉及的部分概念做一简要介绍。岩浆(magma)指地幔和深部地壳部分熔融形成的高温粘稠体,含有熔体(melt 或 liquid)、晶体(crystal)和挥发分(volatile)的混合物质;岩浆体是指任何岩浆物质的组合体,包括以液态为主的岩浆房(magma chamber)以及晶体和熔体混合(晶体体积含量>50%)的晶粥体(crystal mush);岩浆房,是指以熔体相为主的岩浆体,其中熔体分数足够高,晶体呈悬浮状,整体呈现流体的物理性质;晶粥体,熔体相向完全固结的侵入体的过渡状态,一般指晶体分数>40vol%~50vol%的岩浆,岩浆中晶体和熔体含量不同导致的物理和流变学性质差异如图1所示;侵入体(pluton)指完全固结的岩浆房或晶粥体;岩浆储库(magma reservoir)指处于固相线之上的岩浆体,包括熔体为主的岩浆房和熔体-晶体混合的晶粥体。在大范围的地球科学交流中,岩浆房与岩浆储库可能是同种概念,然而在岩浆动力学领域,广为认同的是岩浆储库由晶粥体和岩浆房共同构成,二者位于储库内的不同位置,熔体为主的岩浆房一般存在于储库的上部,储库的下部和四周为晶粥体;大型的岩浆储库(large magma reservoir)指体积>100km$^3$的岩浆体;岩浆储库内导致晶体和熔体分离最主要的两个过程,即晶体沉降(crystal settling)和压实作用(compaction),前者指晶体在重力作用下堆积到岩浆储库底部的过程,后者则是指较高结晶度的储库中,在晶体-熔体相互作用力的驱动下,粒间熔体向上逃逸的过程。以上概念定义来自 Cashman and Giordano (2014)、Annen *et al.* (2015)、Bachmann and Huber (2016)、Sparks *et al.* (2019)。

### 1.2 岩浆的起源

在地壳内运移和储存的岩浆,主要来自上地幔和地壳物质的部分熔融。上地幔的成分是不均一的,主要包括二辉橄榄岩、方辉橄榄岩以及交代作用形成的地幔岩石,例如辉石岩、角闪岩等,而且这些交代形成的岩石更容易被保存在岩石圈地幔中。岩石发生部分熔融的先决条件是温度高于其固相线,因而导致部分熔融作用的发生可以有两种模式,一是直接加热岩石,让其温度高于固相线;第二就是温度保持不变,降低其固相线温度,例如注入挥发分、减压等。在不同的构造背景中,导致地幔岩石部分熔融产生镁铁质岩浆的机制也不尽相同。例如洋中脊和弧后环境,减压熔融是地幔中产生熔体的主要机制(McKenzie and Bickle, 1988);在俯冲带,俯冲下去的板片释放的流体(主要是 $H_2O$)进入到地幔中,是地幔部分熔融的主要诱因(Grove *et al.*, 2012);而板内的热点,异常高的热以及上涌过程中的减压共同导致了部分熔融,再循环的洋壳组分可能对熔融作用有贡献(Sobolev *et al.*, 2007)。

地壳的部分熔融同样可以产生大量的熔体,混合岩能够直观的反应地壳熔融现象,其中浅色体代表了熔融形成的岩浆,而暗色体多为熔融残留物。如果熔融过程中,体系中存在独立相的自由水,称之为流体存在熔融,这种熔融作用所需的温度最低。相对而言,地壳中最为常见的熔融作用为流体缺失的不一致熔融(Sawyer *et al.*, 2011),即含水矿物(例如白云母、黑云母、角闪石)和长英质矿物共同参与的熔融过程。对于常见的地壳岩石(例如泥质岩和杂砂岩),流体存在熔融需要温度达到650℃以上(Brown, 2013);在流体缺失条件下,含云母的地壳岩石熔融需要温度超过750℃,含角闪石

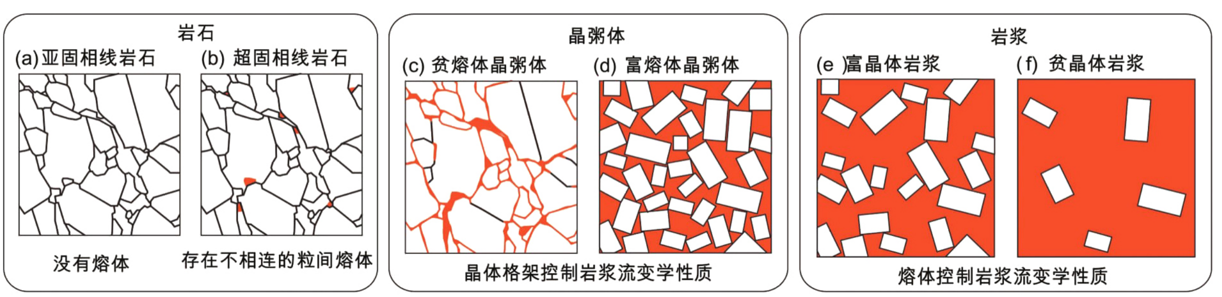


图1 岩浆系统中不同晶体含量对应的岩浆状态及其流变学性质(据 Sparks *et al.*, 2019 修改)

Fig. 1 Diagrams depicting physical and rheological properties of major domains within magmatic systems (modified after Sparks *et al.*, 2019)

的岩石熔融则需要温度高于 850℃（Clemens, 2006）。考虑到地温梯度和岩石低的热传导能力（Whittington *et al.*, 2009），成规模的地壳熔融基本发生在大陆地壳深部，约 25km 以下（Sawyer *et al.*, 2011；Brown, 2013），对应的变质级别至少为高角闪岩相到麻粒岩相。由于很高的温度要求，导致地壳熔融的热源问题一直备受关注。放射性生热、地壳增厚、剪切热等均可能产生高温，但更广为接受的一种观点是幔源镁铁质岩浆的底侵诱发了地壳的熔融（Huppert and Sparks, 1988；Bergantz, 1989；Jahn *et al.*, 2000；Petford *et al.*, 2000；王德滋，2004；Dufek and Bergantz, 2005；Kemp *et al.*, 2007；Chen *et al.*, 2014；王孝磊，2017；翟明国，2017）。基于此，目前较为盛行的观点是玄武质岩浆的侵入和分异伴随地壳物质的同步熔融，两种不同来源的熔体以不同比例进行混合，是产生中酸性岩浆的主要模式，即下地壳的热带模型（Annen *et al.*, 2006），该过程的岩浆系统架构与早先的 MASH 过程基本一致（Hildreth and Moorbath, 1988）。该模型与自然界中一些岩石学观察基本一致（Yang *et al.*, 2007；Tang *et al.*, 2017），同时能够解释很多天然样品的同位素数据（Hildreth and Moorbath, 1988；Annen *et al.*, 2006），即中酸性岩石（尤其在弧环境）的放射性同位素组成，大都呈现地幔端元与地壳端元混合的特征（Zhou *et al.*, 2017）。当然，在缺少地幔能量驱动的区域，可能存在其他的地壳熔融机制（Zhang *et al.*, 2004；Wang *et al.*, 2012, 2016；张泽明等，2017；曾令森和高利娥，2017；Ji *et al.*, 2020）。

### 1.3 从岩浆房到岩浆储库

岩浆房的概念最早可追溯至一个世纪以前，Daly (1911) 在《The nature of volcanic action》一文中提出，火山口与深处的侵入体相连，未固结的侵入体（即岩浆房）供给火山喷发，其中最为关键的证据就是喷发之后，火山口发生崩塌形成破火山口。加之同时代 Bowen 的结晶分异理论（Bowen, 1915）风靡一时，而岩浆房则是发生结晶分异过程的理想场所，因而在随后近百年的研究中，岩浆房供给火山喷发并伴随结晶分异作用的观念深入人心（Hildreth, 1981；Marsh, 1989）。岩浆房的生长过程是岩浆的就位过程和最终的侵入体的形成过程，岩浆房内晶体-熔体分离机制即岩浆化学成分分异的主要机制。层状侵入体和堆晶岩的发现也是这一假说最为有力的证据之一（Wager *et al.*, 1960；Wager and Brown, 1967）。

然而在过去的几十年，多学科研究积累的大量证据，对传统的岩浆房概念提出了挑战。(1)对众多活火山的地球物理探测，并未在深部发现有大规模的以熔体相为主的岩浆房（Iyer *et al.*, 1990；Masturyono *et al.*, 2001；Sherburn *et al.*, 2003；Zandt *et al.*, 2003；Lees, 2007；Chu *et al.*, 2010）；(2)著名的美国内华达 Tuolumne 杂岩体，一直被认为代表了一个固结的岩浆房，该岩体呈现几乎对称的岩相分带，从外部向中心逐渐变酸性，然而随着高精度年代学技术的发展，对其定年的结果表明，该杂岩体形成的时间跨度长达 10Myr（Coleman *et al.*, 2004），显然是由不同批次岩浆堆积形成，并非是一个完整的有流动性的岩浆房固结而成；(3)大体积的岩浆瞬时侵位到中上地壳形成岩浆房，存在空间问题（Menand, 2008），但侵入到冷的中上地壳的小体积岩浆，具有非常快的热丢失和短的热寿命，岩浆温度很快降低到固相线之下，难以汇集形成大的岩浆房（Glazner *et al.*, 2004）；(4)不同的方法所获得的岩浆房寿命相互矛盾，锆石 U-Pb 定年和 U 系不平衡年龄往往指示岩浆房具有较长的寿命（$10^3 \sim 10^6$ 年，Reid, 2008），而基于矿物扩散理论所得到的测年结果却表明岩浆房具有非常短的寿命（$<10^2$ 年；Druitt *et al.*, 2012）。传统的岩浆房模型，难以解释以上观察到的诸多地质现象。

岩浆以晶粥体（crystal mush）形式储存和演化，其实在很早的研究中就以类似概念被提及（Smith, 1960），但 Bachmann and Bergantz (2004) 一文具有较为重要的意义，该文通过理论计算并结合地质现象，论证了浅部岩浆储库分异出贫晶体流纹岩的过程。此后，岩浆在地壳内以晶粥体形式储存和演化的概念模型（图 2）在火山学和岩石学领域引起了高度的关注（Cashman and Giordano, 2014；Bachmann and Huber, 2016；Edmonds *et al.*, 2019；Sparks *et al.*, 2019）。该模型能引起重视的原因，在于其能解释传统岩浆房模型难以解释的许多地质现象：(1)如果岩浆以晶粥体形式储存，传统的地球物理方法难以探测到，这能解释以前火山学和地球物理观察的矛盾。近年来改进后的地球物理探测，则能在中上地壳发现近固相线的岩浆储库（Ward *et al.*, 2014）。(2)晶粥体具有低的储存温度（Cooper and Kent, 2014），相比于传统意义的岩浆房，在冷的中上地壳能够有效维系较长的热寿命，这对岩浆储库的生长和演化至关重要。(3)僵硬的晶粥体与易于流动的岩浆能够快速发生转换，受新的岩浆补给后，能够很快的活化，从而供给火山喷发，喷发完又以晶粥体储存，如此反复循环（Cooper and Kent, 2014）。单批次喷发均可以卷入前期形成的矿物晶体（循环晶），这就能解释为什么同一批次岩浆，不同矿物记录了不同的岩浆储库寿命。(4)中性的火山岩大都是富晶体的，而高硅的流纹岩往往是贫晶体的，因为偏中性火山岩代表了一个活化的晶粥体，而贫晶体的流纹岩是储库上部熔体相喷发的产物（Huber *et al.*, 2012）。另外，其他一些常见的现象，例如 Daly 间断（即同一时代火山岩呈现双峰式，成分具有不连续性），过剩 S 现象（火山喷发出的 S 远远超过喷发出岩浆能溶解的 S 含量），等等。以上都可以从晶粥体这一新的视角得到合理解释（Bachmann and Huber, 2016）。

### 1.4 岩浆储库的生长

岩浆能够在地壳内储存和演化的前提是能够生长出一定体积的岩浆储库，这一过程也是花岗岩研究中所提到的就位机制。目前，很多观点认为岩浆储库通过多批次岩浆递增

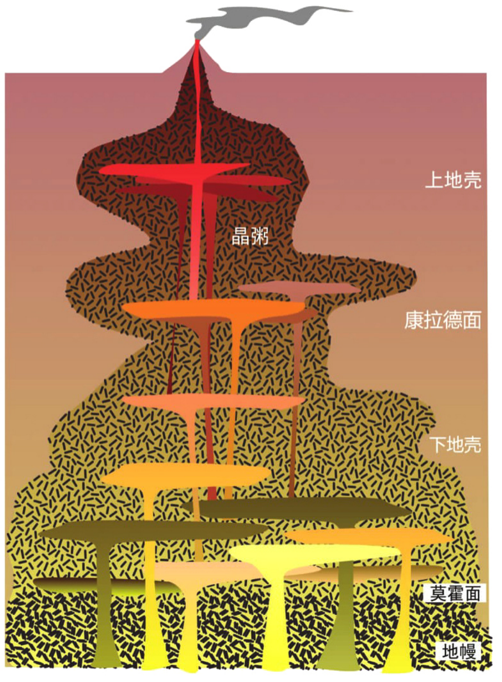


图 2 穿地壳的岩浆通道系统(据 Cashman *et al.*, 2017 修改)

Fig. 2 Trans-crustal magma plumbing system (modified after Cashman *et al.*, 2017)

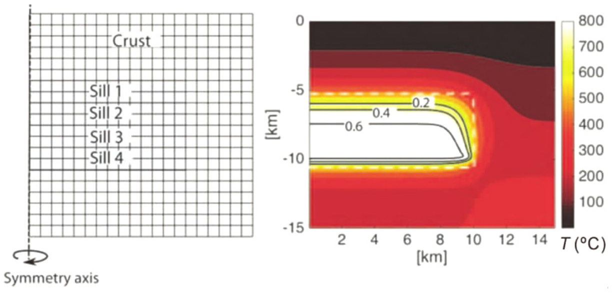


图 3 岩浆体生长的热模型(据 Blundy and Annen, 2016)

左图为岩浆体以递增式灌入岩席模型;右图为岩席叠加侵位的热模型;等值线为熔体分数(F),水平方向为岩席长度,垂向坐标为深度

Fig. 3 Thermal models of the growth of magma bodies (after Blundy and Annen, 2016)

The left figure is the conceptual model that igneous body grows by addition of sills; The right figure is the thermal model of emplacement of sills. Contours show melt fractions (F); the horizontal axis is the length of sills (km); the vertical axis is depth (km)

式累积生长形成(Lipman, 2007; Annen *et al.*, 2015; Coleman *et al.*, 2016; 马昌前和李艳青,2017; Edmonds *et al.*, 2019; Sparks *et al.*, 2019;马昌前等,2020; 徐夕生等,2020),且邻近岩浆储库可以合并形成更大规模的岩浆储库(Biggs and Annen, 2019)。沿着剪切带侵位、底劈、顶蚀等概


图 4 水平层状的智利 Torres del Paine 侵入体(据 Annen *et al.*, 2015)

岩浆储库水平方向递增式灌入生长的野外证据

Fig. 4 Torres del Paine intrusion, Chile (after Annen *et al.*, 2015)

Contacts between granite units (black dashed line) are sharp and indicate magma intrusion into solid rock

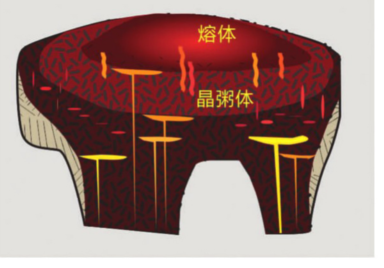


图 5 上地壳岩浆储库的结构(据 Hildreth, 2004; Cashman *et al.*, 2017 修改)

Fig. 5 Architecture of upper crustal magma reservoirs (modified after Hildreth, 2004; Cashman *et al.*, 2017)

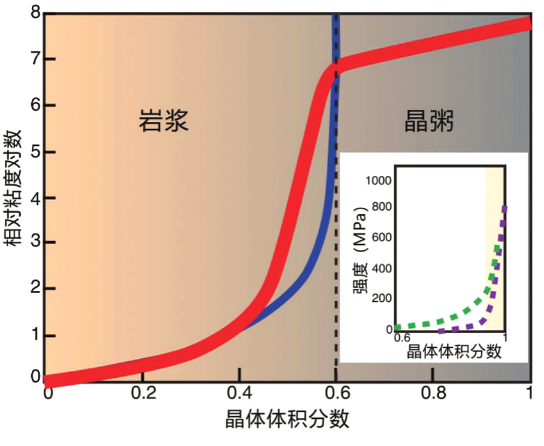


图 6 晶体含量与岩浆粘度的关系(据 Cashman *et al.*, 2017 修改)

Fig. 6 Changes in relative viscosity (suspension viscosity divided by melt viscosity) as a function of crystal content (modified after Cashman *et al.*, 2017)

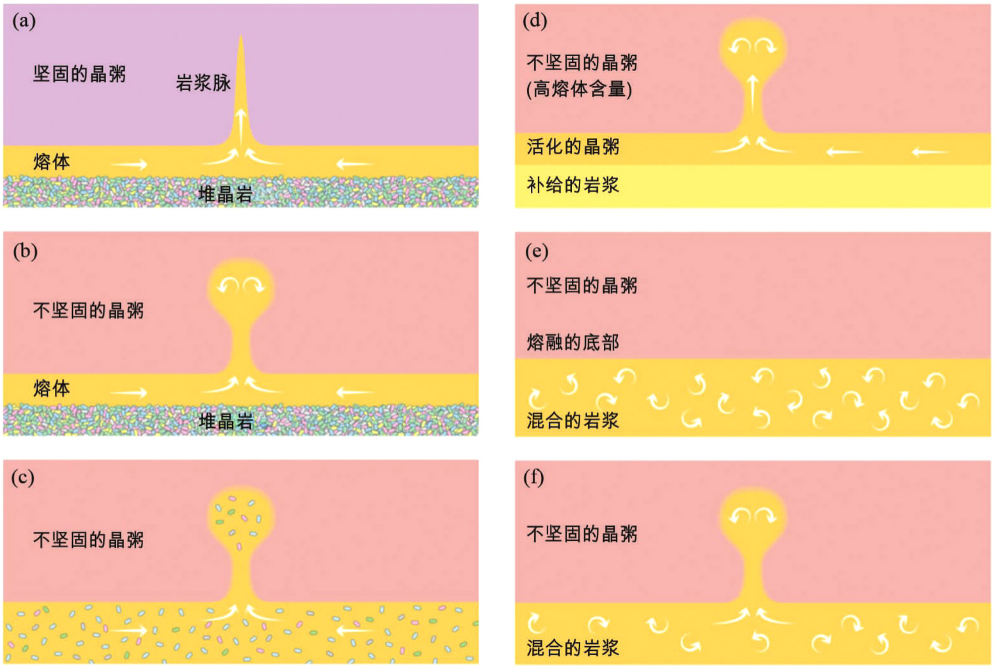


图 7　晶粥体活化的几种形式(据 Sparks *et al.*, 2019 修改)

Fig. 7　Cartoons of mush replenishment showing some variants of possible scenarios (modified after Sparks *et al.*, 2019)

念早已被提出来解释花岗岩的侵位过程(Wang *et al.*, 2000；罗照华等,2007;Brown, 2013；王涛等,2017)。目前,较为流行的生长机制是在水平方向递增式灌入岩浆(Annen *et al.*, 2006, 2015),热模拟证实了这一机制的可行性(图 3),另外也在野外获得了其存在的地质证据(图 4)。岩浆灌入的通量很关键,不能过大,因为过多的岩浆灌入会导致岩浆汇聚产生高压,容易喷发;亦不能过少,如果岩浆补给的量不够,那么早先进入的岩浆批次很容易完全固结(Blundy and Annen, 2016)。有研究表明浅部地壳大型岩浆储库的生长和岩浆喷发,不仅仅受岩浆通量控制,还需要长时间穿地壳的岩浆作用以及下地壳大型岩浆储库的热支持(Karakas *et al.*, 2017),热成熟可能是超级喷发的必备条件(Liu *et al.*, 2021)。

### 1.5　岩浆储库内的动力学过程

在长时间岩浆作用和日积月累的储库生长之后,可以在地壳垂向上形成相互连通的岩浆通道系统(magma plumbing system; 图 2),其中不同地壳深度处均可形成岩浆储库,当然最有利的位置是莫霍面和康拉德面附近(Sparks *et al.*, 2019),因为岩浆从深部向浅表迁移的主要驱动力为浮力,所以上升的岩浆在密度断面处最容易失速。发育成熟的岩浆储库,会形成一定的结构(图 5),即储库的上部为熔体层,下部和四周被晶粥体包围。当岩浆储库处于低的结晶度时,结晶的矿物会通过晶体沉降堆积到储库底部(主要对应镁铁质岩浆),当结晶度较高时(但体积分数不超过 ~80%),则主要通过压实作用(主要对应长英质岩浆),将晶粥体部位的粒间熔体驱离进熔体层(Bachmann and Bergantz, 2004),当然晶体-熔体分离作用也可以由横向构造挤压、剪切应力、气体驱动的压滤作用(Sisson and Bacon, 1999; Pistone *et al.*, 2015)、晶体-熔体反应流等(Jackson *et al.*, 2018)实现。

岩浆的流变学性质(用粘度表示)控制了岩浆的迁移能力,岩浆的粘度受岩浆的成分、挥发分的含量、晶体的含量、晶体的形态等因素控制(Giordano *et al.*, 2008)。一般而言,岩浆中挥发分会有效降低体系的粘度,晶体含量增加则会增加体系的粘度,尤其是晶体含量超过 40vol% ~60vol%,岩浆的流变学性质会从牛顿行为转变为非牛顿行为,随着晶体含量的继续增加,岩浆粘度呈现数量级式的增加(图 6;Mader *et al.*, 2013)。以晶粥体形式存在的岩浆储库,流变学性质决定了其迁移能力较弱。因此,活化晶粥体,使其变成能够灵活迁移的低粘度岩浆,是岩浆储库演化过程中非常重要的一个环节。普遍认为,最佳的活化机制是来自深部新的热岩浆的注入。Sparks *et al.* (2019)总结了多种晶粥体活化的过程(图 7),活化过程也被数值模拟技术动态的还原出来(Bergantz *et al.*, 2015)。新的岩浆注入,除了传输热量给晶粥体,另外一种重要的机制就是提供挥发分并驱动压滤作用(Bachmann and Bergantz, 2006),即补给的岩浆底垫到晶粥体储库的底部,向晶粥体中注入热和挥发分,从而使得晶粥体活化。新岩浆底垫到岩浆储库的位置不同,喷发的产物也不同,如果补充的岩浆通量较大,足以活化整个晶粥体,则喷发出富晶体的中性岩石;而补给的岩浆通量较小,仅仅底垫到储库的熔体相部位,则喷发出贫晶体的流纹岩(Huber *et al.*, 2012)。有研究提出,地壳垂向分布的晶粥体中,岩浆成

分的分异并不是由传统认为的晶体沉降、压实等作用控制，而是通过晶体-熔体反应流动驱使(Jackson *et al.*, 2018)，该假说可以解释岩浆产物中多样化的矿物种群，并能被矿物的成分特征所支持(Lissenberg *et al.*, 2013, 2019; Yang *et al.*, 2019)。

超级火山喷发会产生强的自然灾害和环境扰动，并伴随着大型破火山口的形成(Wilson *et al.*, 2021)，而破火山口是浅部岩浆储库经历岩浆抽取后发生坍塌的地表显示(Sparks *et al.*, 2019)。在浅部岩浆储库研究中，一个最近争议较大的问题就是火山岩与侵入岩的关系。浅部地壳中就位的岩浆储库，能喷发出地表的是储库中心高度演化的熔体部分，而残余的高度结晶的部分更倾向于冷却形成岩体，因此部分学者主张，自然界中火山岩与侵入岩在成分上存在互补性，即火山岩是高度演化形成的熔体，而侵入岩则是残留体(Bachmann *et al.*, 2007; Deering and Bachmann, 2010; Gelman *et al.*, 2014)。而另外一部分学者则对这种观点表示强烈质疑，认为火山岩与侵入岩代表了不同的岩浆批次，而且不存在这种成分互补性(Glazner *et al.*, 2015; Keller *et al.*, 2015)。浅部岩浆储库可以发生结晶分异作用(Huang *et al.*, 2008; Ma *et al.*, 2017; Yan *et al.*, 2018; Zhao *et al.*, 2018; Zhou *et al.*, 2020a; Zhang *et al.*, 2021; Du *et al.*, 2022)，但条件较为苛刻，因为中酸性岩浆中晶体-熔体分离的速率十分缓慢，而浅部岩浆储库的热寿命较为短暂(Wang *et al.*, 2021a)，因此浅部岩浆储库能够发生分异的可能条件之一是早先持续的穿地壳岩浆通道系统加热上地壳(Karakas *et al.*, 2017; Zhou *et al.*, 2020a)，有效延长其热寿命。如果浅部中酸性岩浆储库发生过晶体-熔体分离，那么残留的侵入岩就是“堆晶花岗岩”，这一特殊类型岩石的鉴别具有挑战性，很多学者已经尝试提出一系列的指标和方案(Deering and Bachmann, 2010; Gelman *et al.*, 2014; Lee and Morton, 2015; Fiedrich *et al.*, 2017; 吴福元等, 2017)。基性堆晶岩十分普遍(朱弟成等, 2018; Xu *et al.*, 2021)，且具有非常高的研究程度，因此基性堆晶岩的研究可能对识别花岗质堆晶岩具有借鉴意义，例如对比初始平衡熔体与全岩的微量元素含量可以用来判别压实作用形成的堆晶岩(Zhou *et al.*, 2020b)。

### 1.6 岩浆过程的时间尺度

岩浆过程的时间尺度，即发生该岩浆过程所需的时间长度，这在岩浆动力学研究中具有非常重要的理论和应用价值。例如质疑上地壳岩浆储库能否发生结晶分异的关键论点，就是认为岩浆储库内晶体-熔体发生分离所需的时间远大于岩浆储库的热寿命，在岩浆储库固结之前根本来不及发生结晶分异过程(Lundstrom and Glazner, 2016)。放射性同位素定年技术是传统定年技术的支撑，但很多岩浆过程的时间尺度十分短暂，低于常见放射性定年技术的下限；近年来新兴的扩散定年方法，则能提供很好的约束(Costa *et al.*,

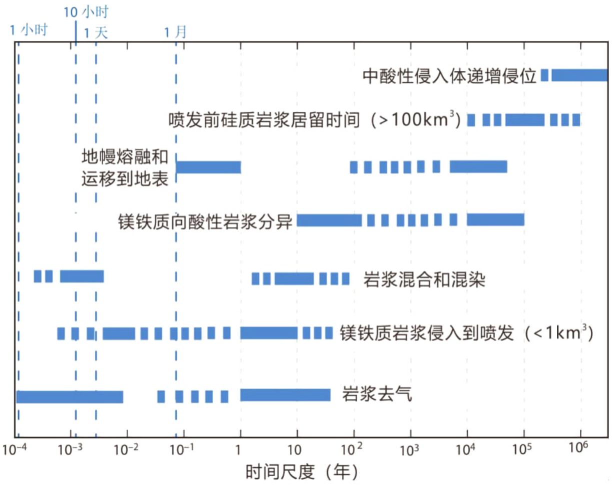


图 8 最近几十年报道的不同岩浆过程的时间尺度(据 Costa, 2021 修改)

Fig. 8 Synthetic and simplified summary of the ranges of timescales that have been determined in the past decades for a variety of magmatic processes (modified after Costa, 2021)

2020)。图 8 总结了已有的岩浆动力学过程时间尺度的报道，可以看出很多岩浆过程的时间跨度均小于 1kyr，其中岩浆的去气以及岩浆混合发生在数天的时间尺度内(Costa, 2021)。这些非常短的时间尺度报道，对火山喷发预警和及时的人员撤离具有参考价值。目前扩散理论测时法的数据报道量依然有限，时间对应何种岩浆过程也存在争议(Bachmann and Huber, 2016)。导致其广泛应用的限制包括：扩散方程求解的计算较为复杂、矿物高精度高空间分辨率剖面的获取并非易事以及区分生长成分剖面和扩散成分剖面存在难度。

### 1.7 岩浆中晶体的生长

岩浆中生长出的晶体，能够有效的还原岩浆系统结构、岩浆动力学过程及其时间尺度。晶体从岩浆中结晶涉及到一系列过程，当温度高于液相线时，结晶的热力学驱动力为负，因此一定程度的过冷($\Delta T$)是晶体成核与生长的前提。过冷度是指系统温度与液相线温度之差(Kirkpatrick *et al.*, 1981; 周金城, 1984)，降温和去气是导致天然岩浆系统过冷的主要两个因素(Hammer, 2008; Mollo and Hammer, 2017)，前者降低系统的温度，后者则是增加液相线温度。在过冷的情况下，过剩的自由能将驱动有效组分形成核子，其可以进一步生长。晶体的成核与生长速率随着过冷度的降低先增加后降低，但成核曲线的峰值会出现在更高的过冷度(Mollo and Hammer, 2017)。核子一旦形成，能够从周围熔体中不断吸收营养元素维持其生长。晶体的生长速率受控于多个因素，包括扩散控制的和界面控制的模式，它们取决于组分在熔体中的移动速率与晶体表面的吸附速率(Hammer,

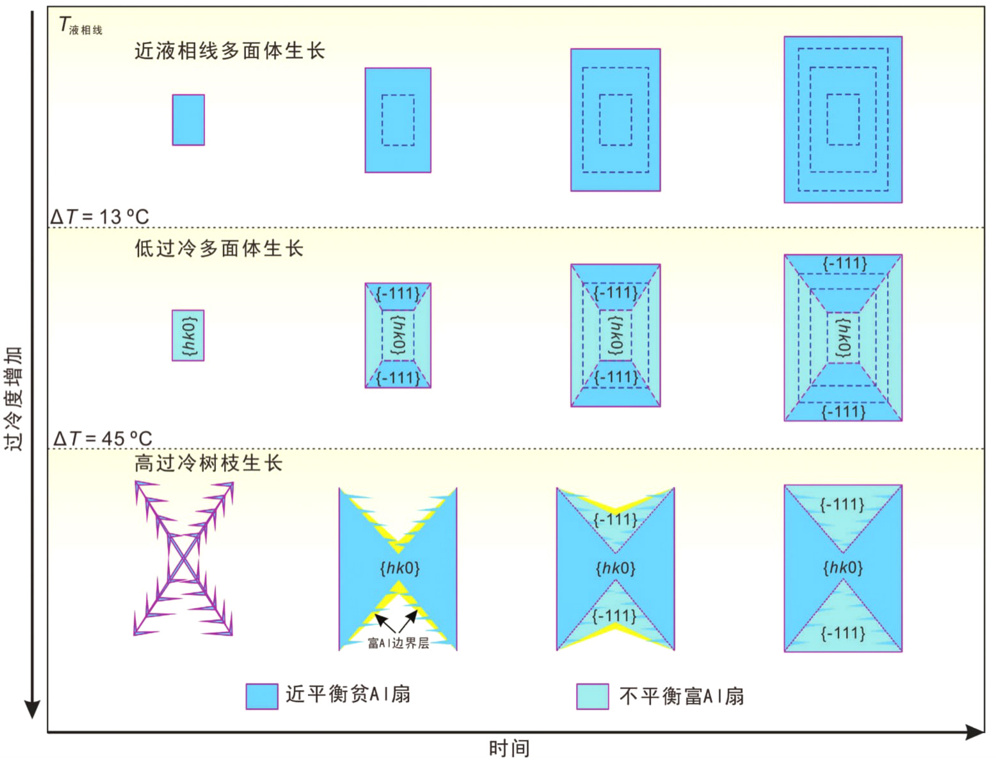


图 9　不同过冷度下单斜辉石的晶体生长机制示意图(据 Zhou *et al.* , 2021a 修改)

Fig. 9　Crystal growth mechanisms of clinopyroxene at different degrees of undercooling (modified after Zhou *et al.* , 2021a)

2008)。晶体生长的速率是过冷度的函数,在低程度的过冷度下,晶体生长是界面控制的且在结构和化学成分上呈现平衡的特征(Herring, 1951);在高程度过冷条件下,晶体生长很有可能会偏离平衡,显示骨骼状或树枝状的生长习性(Faure *et al.* , 2007; Ni *et al.* , 2014; Xing *et al.* , 2017; Pontesilli *et al.* , 2019; Masotta *et al.* , 2020)。

接下来以单斜辉石为例,对晶体生长过程作一简要介绍。单斜辉石是研究不同过冷条件下晶体生长过程的理想对象,因为过冷度对单斜辉石的成分和结构具有相当的影响(Pontesilli *et al.* , 2019; Masotta *et al.* , 2020),特别是在镁铁质的碱性岩浆中(Hollister and Gancarz, 1971; Downes, 1974; Leung, 1974; Shimizu, 1981)。单斜辉石中的扇形分带是晶体快速生长形成的经典结构(Hammer *et al.* , 2016; Welsch *et al.* , 2016; Neave *et al.* , 2019; Ubide *et al.* , 2019a, b)。扇形分带的晶体中,不同的晶面具有不同的生长速率和成分,导致了从晶体中心沿着结晶学方向向外延伸的分带模式。这对基于天然样品的传统岩浆动力学研究造成了挑战,因为不同成分的扇是从同一种熔体、相似的物理化学条件下结晶形成的(Ubide *et al.* , 2019a)。实验岩石学研究(Kouchi *et al.* , 1983; Masotta *et al.* , 2020)已经表明,在低程度过冷情况下($\Delta T = 13 \sim 25$℃),平行于 C 轴的沙漏扇{-111}含较高的 Si 和 Mg,而垂直于 C 轴的棱柱扇{100}、{110}、{010}含有较高的 Al 和 Ti;在高程度过冷度下,晶体内部显示出富 Al 和 Ti 的树枝与富 Si 和 Mg 的增生部分不规则接触的现象(Masotta *et al.* , 2020)。综合天然实例研究和之前的实验岩石学结果(Kouchi *et al.* , 1983; Ni *et al.* , 2014; Masotta *et al.* , 2020; Giuliani *et al.* , 2021),最近有研究提出一种新的单斜辉石生长机制(图 9;Zhou *et al.* , 2021a):在中低程度的过冷情况($\Delta T < 45$℃),所有的结晶方向同步生长,{-111}扇的生长速率高于{*hk*0}扇,而且{-111}扇更接近于平衡,不同扇的元素富集可能受控于特殊晶面对某些阳离子的优先吸收(Nakamura, 1973; Dowty, 1976; Shimizu, 1981)、电价补偿的耦合置换(Hollister and Gancarz, 1971; Ubide *et al.* , 2019a)或者结晶学与扩散的共同控制(Downes, 1974; Leung, 1974; Lofgren *et al.* , 2006; Schwandt and McKay, 2006);在高的过冷度($\Delta T > 45$℃),先形成棱柱扇{*hk*0},然后进一步充填形成沙漏扇{-111}(图 9),早期的树枝生长和成熟形成漏斗状的晶体(也就是{*hk*0}扇),这些漏斗状的晶体具有 V 型腔(即{-111}扇),最终进一步回填{-111}扇,形成自形的单斜辉石晶体。

## 2　岩浆中的挥发分

### 2.1　挥发分概述

岩浆中的挥发分是指具有低沸点的元素或者化合物且它们优先进入气相或流体相中,这类组分只占岩浆很小的质量分数,但却强烈的影响了岩浆的物理化学性质、动力学过

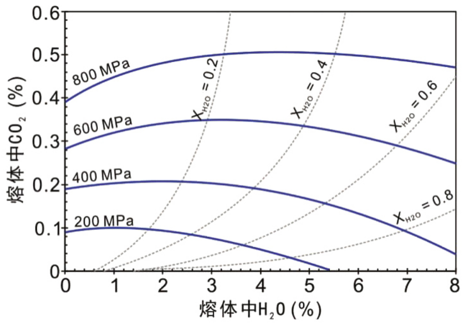


图 10 藏南赛利普钾质岩浆中 $H_2O$ 和 $CO_2$ 的溶解度模型(据 Zhou *et al.*, unpublished data)

Fig. 10 The $H_2O$-$CO_2$ mixed volatile saturation model for the Sailipu potassic magmas (after Zhou *et al.*, unpublished data)

程,也是导致岩浆环境效应和形成岩浆-热液矿床的直接介质。岩浆中最为常见的两种挥发分是 $H_2O$ 和 $CO_2$,其他还包括 S、F、Cl 等(Baker and Alletti, 2012; Wallace *et al.*, 2015; Edmonds and Wallace, 2017)。一般而言,$H_2O$ 是岩浆中含量最高的挥发分,最高可达 15 %(Krawczynski *et al.*, 2012)。水在岩浆中以 $OH^-$ 和 $H_2O$ 分子的形式存在(Ni *et al.*, 2009),在低水含量的岩浆中,主要以 $OH^-$ 形式溶解在岩浆中,随着水含量的增加,$H_2O$ 分子会逐渐增加(Wallace *et al.*, 2015)。岩浆中 $H_2O$ 的溶解度受压力、温度和熔体成分影响,其中压力影响最大(Ni and Keppler, 2013);相同的压力下,$H_2O$ 在低温的酸性岩浆中比在高温的基性岩浆中溶解度更高(Baker and Alletti, 2012)。$CO_2$ 是岩浆中另一种常见的挥发分,但其溶解度比 $H_2O$ 低许多,在相近的温压和熔体成分中,$H_2O$ 的溶解度是 $CO_2$ 溶解度的 50 ~ 100 倍(Wallace *et al.*, 2015)。尽管如此,岩浆中低含量的 $CO_2$ 却能够戏剧性的影响 $H_2O$ 的溶解度(图 10;Ghiorso and Gualda, 2015)。$CO_2$ 在基性的岩浆中,多以 $CO_3^{2-}$ 的形式存在,而在酸性的岩浆中,往往以 $CO_2$ 分子的形式存在(Solomatova *et al.*, 2020),另外,在碱性熔体中,$CO_2$ 则具有更高的溶解度(Ni and Keppler, 2013)。岩浆中 S 的行为则复杂许多,因为 S 存在多种价态,受岩浆的氧化还原状态影响(Baker and Moretti, 2011; Klimm *et al.*, 2012)。在低的氧逸度下,S 主要以 $S^{2-}$ 的形式存在,而在高的氧逸度下,则以 $S^{6+}$ 的形式存在。由于 $S^{6+}$ 具有比 $S^{2-}$ 更高的溶解度,因而在氧化性岩浆中能溶解更多的 S。岩浆中 Cl 和 F 的溶解度强烈受控于熔体成分,一般 Cl 的溶解度随着熔体(Na + K)/Al 比值的增加而增加,而 F 在酸性岩浆中具有比基性岩浆更高的溶解度(Wallace *et al.*, 2015)。此外,需要强调一个重要的概念,就是岩浆中挥发分的饱和是指在一定压力以及温度、特定成分熔体中所有挥发分压力的总和(Wallace *et al.*, 2015),比如岩浆中 $CO_2$ 的存在会急剧降低 $H_2O$ 的溶解度(Ghiorso and Gualda, 2015),因而单一挥发分的溶解度模型很难应用到含有多种挥发分的天然岩浆中。

## 2.2 天然岩浆中的挥发分

在较高的压力下,由于高的溶解度,大部分挥发分都会溶解在岩浆中。随着岩浆的上升(压力逐渐降低),挥发分的溶解度会逐渐降低,当岩浆中所有挥发分的总和超过溶解度时,则会形成独立的气泡,这些气泡会以不混溶相的形式被夹带在岩浆中,但不受溶解度控制。因此在中低压挥发分饱和的岩浆中,挥发分总量往往包括两部分,一部分溶解在岩浆中,而另一部分则赋存在气泡之中。对于天然岩浆,赋存在气泡中的挥发分含量是难以估计的,但溶解在岩浆中的挥发分则可以通过多种方法获取(Wallace *et al.*, 2015)。第一种方法是通过与已知结晶实验的对比,包括矿物组合、结晶顺序以及矿物成分,因为矿物组合和结晶顺序与熔体中的水含量直接相关(Rutherford, 1985),但该方法的缺点是准确限定天然岩浆的结晶顺序存在困难,其次是难以获得定量的结果。第二种方法是直接分析淬火的玻璃或者熔体包裹体中的挥发分含量,尤其是熔体包裹体(图 11;李霓和孙嘉祥,2018;任钟元等,2018;Wallace *et al.*, 2021),该方法是目前获取岩浆挥发分数据的主要方法。由于挥发分具有较强的迁移能力和扩散性,如果长时间驻留在高温的岩浆中,熔体包裹体中的挥发分也可以穿过矿物晶格与熔体进行交换(Portnyagin *et al.*, 2008),从而改造熔体包裹体中的挥发分含量,因此该方法很难应用到缓慢冷却的侵入岩中。第三种方法是矿物湿度计,即先通过实验岩石学的结果建立刻度计,然后去测量天然样品中矿物结晶时的挥发分含量。由于斜长石与熔体之间的 An 和 Ab 分子交换反应对熔体中的水含量极其敏感,使得斜长石-熔体湿度计成为最为常用的矿物湿度计(Lang *et al.*, 2009; Waters and Lange, 2015)。但应用该湿度计的难点是需要已知平衡熔体、压力和温度,尤其是温度,对计算结果的影响十分显著,这一难题可以利用与斜长石同步结晶的矿物来解决,使用这些矿物的温度计与斜长石湿度计迭代应用,就可以有效获取天然样品的岩浆水含量(Zhou *et al.*, 2020c)。第四种方法是依据挥发分在矿物与硅酸盐熔体之间的平衡分配,利用矿物挥发分含量来推算熔体中的挥发分含量(Li and Costa, 2020; Li *et al.*, 2021; Zhang *et al.*, 2022)。此外,其他的一些方法能够定性指示岩浆中挥发分已经发生饱和,即岩浆晶体中存在原生的流体包裹体,例如存在富 $CO_2$ 的原生流体包裹体表明岩浆中的 $CO_2$ 已经达到了饱和,存在原生硫化物的包裹体则表明 $S^{2-}$ 可能达到了饱和(Wallace *et al.*, 2015)。

由于演化路径的差异,挥发分在高度演化的岩浆中的含量是多变的(Zhou *et al.*, 2020c),接下来我们重点介绍镁铁质初始岩浆中的挥发分含量。不同构造背景中产生的玄武质岩浆,挥发分含量往往呈现规律性变化。洋中脊玄武质岩浆往往具有非常低的 $H_2O$ 含量,一般 < 0.5%(Le Roux *et al.*, 2006),富集的洋中脊玄武岩地幔源区可能存在再循环

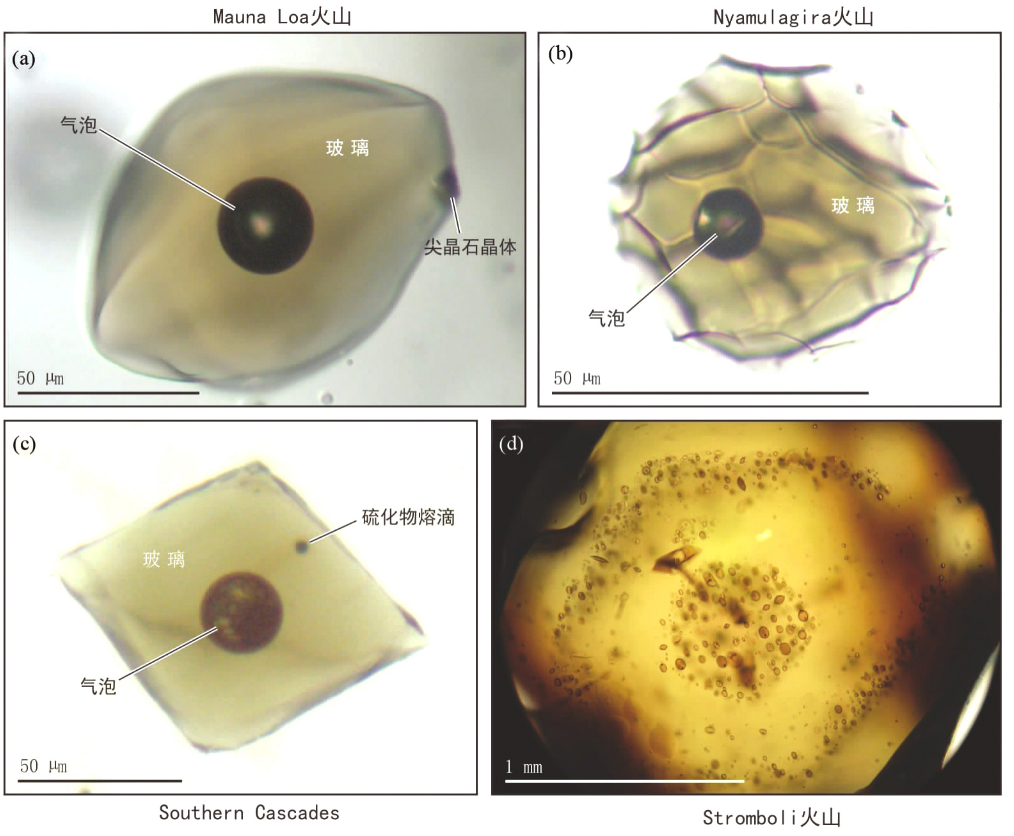


图 11　一些典型熔体包裹体的显微照片(据 Wallace *et al.*, 2021 修改)

Fig. 11　Photomicrographs of some representative melt inclusions (modified after Wallace *et al.*, 2021)

的含水物质,因而会含有更高的 $H_2O$ 含量,但也不超过 1.5%(Wallace *et al.*, 2015)。此外,洋中脊玄武质岩浆中 $CO_2$ 的含量一般 $<350\times10^{-6}$,S 的含量 $<2000\times10^{-6}$,Cl 的含量 $<500\times10^{-6}$,F 的含量 $<600\times10^{-6}$(Le Roux *et al.*, 2006),其中部分样品高的 Cl 含量可能是混染了被海水蚀变过的围岩(Wallace *et al.*, 2015)。洋岛玄武质岩浆中 $H_2O$ 含量一般 <1%,$CO_2$ 的含量一般 $<120\times10^{-6}$,Cl 的含量 $<1400\times10^{-6}$,S 的含量 $<2200\times10^{-6}$(Dixon and Clague, 2001);同样,源区含有再循环物质的碱性洋岛玄武岩则含有更高的 $H_2O$(<1.5%)和 $CO_2$ 含量($<800\times10^{-6}$)(Dixon *et al.*, 1997)。由于地幔源区产生岩浆的机制为水致熔融,形成于俯冲带的弧岩浆往往具有最高的挥发分含量,初始弧岩浆含有 2% ~6% 的 $H_2O$,平均为 4%(Plank *et al.*, 2013),$CO_2$ 含量最高可达 $2500\times10^{-6}$,S 的含量 $<2500\times10^{-6}$,Cl 的含量 $<2500\times10^{-6}$(Wallace *et al.*, 2015)。但对初始弧岩浆中的 $H_2O$ 含量,依然存在争议,实验岩石学家们拟合出的初始弧岩浆应该含有高达 14% 的 $H_2O$(Krawczynski *et al.*, 2012),而天然熔体包裹体实测到的 $H_2O$ 含量均 <6%(Wallace, 2005; Plank *et al.*, 2013),最近有研究表明这可能是熔体包裹体的形成机制导致,即熔体包裹体只能记录低含水量的熔体(Gavrilenko *et al.*, 2019)。此外,绝大部分弧岩浆中挥发分是以 $H_2O$ 为主,但也存在更富 $CO_2$ 的实例(Blundy *et al.*, 2010)。形成于大火成岩省的玄武质岩浆一般具有与洋中脊玄武岩相似的挥发分含量(Wallace *et al.*, 2015)。

### 2.3　岩浆中挥发分的逃逸——去气作用

岩浆中挥发分的逃逸,对控制火山喷发的灾害性、环境和气候的影响以及热液金属成矿至关重要。挥发分能否有效的脱离岩浆,涉及到两个过程:挥发分达到饱和并生长出气泡(化学过程)、气泡能够在岩浆体系中有效的迁移(物理过程)。岩浆从深部上升至中上地壳,挥发分会发生两次饱和,也就是两次沸腾作用。第一次沸腾是指未结晶的岩浆穿过相应的挥发分饱和线而发生去气,主要受压力和岩浆自身挥发分含量控制;第二次沸腾则发生在浅部岩浆储库中,岩浆储库的恒压结晶,会使残余熔体的挥发分含量持续增加,超过饱和线后再次去气。由于 $CO_2$ 在岩浆中的溶解度较低且对压力十分敏感,所以岩浆中的 $CO_2$ 一般在深部第一次沸腾过程中去气,而 $H_2O$ 多以第二次沸腾作用而去气(Edmonds and Woods, 2018)。一旦岩浆中挥发分达到了饱和并生长出气泡,气泡能够自由汇聚和迁移同样是去气作用发生的必要条件。第一次沸腾作用发生在运动的岩浆中,气泡迁移存在很大随机性,这里重点介绍第二次沸腾过程,即岩浆储库冷却过程中的气泡行为。岩浆储库中气泡的迁移

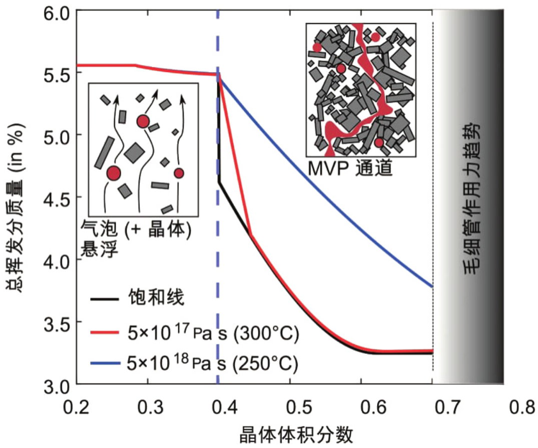


图 12 岩浆储库不同区域气泡的丢失(据 Degruyter *et al.*, 2019 修改)

图中实心红圈代表了挥发分饱和后形成的气泡;灰色长方形代表岩浆中结晶的矿物晶体;MPV 代表低密度低粘度的岩浆挥发分相

Fig. 12 Example of a reservoir scale simulation showing the total amount of MVP loss for the different regimes (modified after Degruyter *et al.*, 2019)

Red circle is magmatic bubbles; gray rectangle is magmatic crystals; MVP is low-density, low-viscosity magmatic volatile phase

能力主要受控于三个作用力:浮力、粘性阻力和毛细管作用力(Mungall, 2015; Parmigiani *et al.*, 2017; Degruyter *et al.*, 2019)。岩浆储库处于低的结晶度时,残余熔体分数较高,挥发分还未达到饱和;处于非常高的结晶度时,结晶的矿物会形成致密的晶体格架,造成空隙间存在强的毛细管作用力,即使存在气泡,也很难在岩浆体系中迁移(Degruyter *et al.*, 2019)。目前多项研究表明,在处于中等结晶度的晶粥体中,气泡的迁移能力最强,即岩浆体系的渗透性最好(图 12; Boudreau, 2016; Parmigiani *et al.*, 2017; Degruyter *et al.*, 2019)。岩浆的结晶度可能对去气的成分有影响,岩浆储库演化早期更容易排放低相容性的挥发分(例如 $SO_2$、$H_2S$、$CO_2$、Ar、$N_2$、Cl),晚期则释放出更多的高相容性的挥发分(例如 F、Br、He、Li)(Degruyter *et al.*, 2019)。除了上述过程外,岩浆从近地表的岩浆导管到喷发出地表过程中,由于快速的降压导致岩浆气泡的猛烈生长,从而撕碎硅酸盐熔体,即火山喷发时的岩浆碎片化(Gonnermann, 2015)。

## 3 岩浆动力学的资源效应

不同于基性-超基性岩中的金属矿床,其形成过程主要发生在高温的岩浆阶段(Song *et al.*, 2013; 张招崇等,2014; Hou *et al.*, 2018; Yao and Mungall, 2020; 王焰等,2020),岩浆-热液型矿床中的成矿物质则主要从岩浆逃逸出的热液流体中沉淀形成,这类矿床常见的类型包括:斑岩型(Cooke *et al.*, 2005; Seedorff *et al.*, 2005; Sillitoe, 2010; 侯增谦等, 2012)、矽卡岩型(Meinert *et al.*, 2005)以及浅成低温热液型(Hedenquist *et al.*, 1998; Simmons *et al.*, 2005)。岩浆中的挥发分对形成这类矿床起到了关键作用,例如 S 是金属硫化物的组成元素、$H_2O$ 是形成矿床蚀变带的主要物质、Cl(或者 F)与金属结合形成的络合物是其在流体中有效迁移的介质。目前绝大部分的证据均支持浅部岩浆储库提供了形成这类矿床所必须的金属、S、Cl 和 $H_2O$(Hedenquist and Lowenstern, 1994; Candela, 1997; Meinert *et al.*, 2003; Richards, 2003; Williams-Jones and Heinrich, 2005; Sillitoe, 2010; Audétat and Simon, 2012)。正常金属含量的岩浆(例如 $<100\times10^{-6}$ 的 Cu)就具有形成矿床的潜力(Cline and Bodnar, 1991; Chelle-Michou *et al.*, 2017; Zhang and Audétat, 2017),因为大部分金属元素具有非常高的流体/熔体分配系数(Zajacz *et al.*, 2008; Audétat, 2019),使得金属在岩浆去气(或者说流体出溶)过程中得到高度的富集,例如 Cu 可以在出溶的岩浆流体中富集几十倍至近百倍(Audétat, 2019)。当然,从成矿岩浆的起源到金属物质的最终沉淀,中间任何一个过程,如果对有益组分富集有贡献,都是对成矿有利的(陈华勇和吴超, 2020),这些可能的过程包括熔融过程(Mungall, 2002)、熔体与地幔岩石反应(Wang *et al.*, 2006)、成矿物质在下地壳的预富集(Lee *et al.*, 2012; Chiaradia, 2014; Hou *et al.*, 2015; Chiaradia and Caricchi, 2017; Zheng *et al.*, 2019; Luo *et al.*, 2020)、岩浆中硫化物的饱和(Wilkinson, 2013)、镁铁质岩浆输入有用组分(Blundy *et al.*, 2015; Yang *et al.*, 2015; Cao *et al.*, 2018; Wang *et al.*, 2021b)、流体的反复注入(Mercer *et al.*, 2015; Li *et al.*, 2017)以及金属从岩浆中的抽取效率(Zhou *et al.*, 2022)。目前成矿岩浆过程研究中一个重要的方向是将岩浆动力学领域的新进展和新认识与成矿物质的迁移富集相结合(图 13; Chelle-Michou *et al.*, 2017; Blundy *et al.*, 2021; Chelle-Michou and Rottier, 2021)。此外,从实验岩石学的角度约束岩浆以及去气过程中金属、S、Cl 的行为依然是认识成矿物质迁移富集规律的基础(Zajacz *et al.*, 2008; Li and Audétat, 2012; Liu *et al.*, 2015; Tattitch and Blundy, 2017; 熊小林等,2020),尤其是络合物例如 S 和 Cl(Zajacz and Tsay, 2019; Tattitch *et al.*, 2021),它们可能直接控制了金属在岩浆去气过程中的抽取效率(Zhou *et al.*, 2022)。

另外一种值得重视的含矿岩石是伟晶岩,其常常含有高品位的战略性关键金属元素(王汝成等,2019;秦克章等,2021)。伟晶岩十分特殊,由于其结晶温度非常低(约 400 ~ 600℃; London, 2018),低于硅酸盐熔体的最低固相线(~650℃),因而形成伟晶岩的熔体并非正常的岩浆。同时,其又非岩浆出溶的流体,因为伟晶岩脉的周围通常缺少成规模的热液蚀变(London and Morgan, 2012)。伟晶岩中常见的文象结构以及其粗大的晶体颗粒,是伟晶岩熔体在高过冷条件下晶体快速生长的结果(London and Morgan, 2017; Sirbescu *et al.*, 2017)。稀有和稀土元素如何在伟晶岩中得

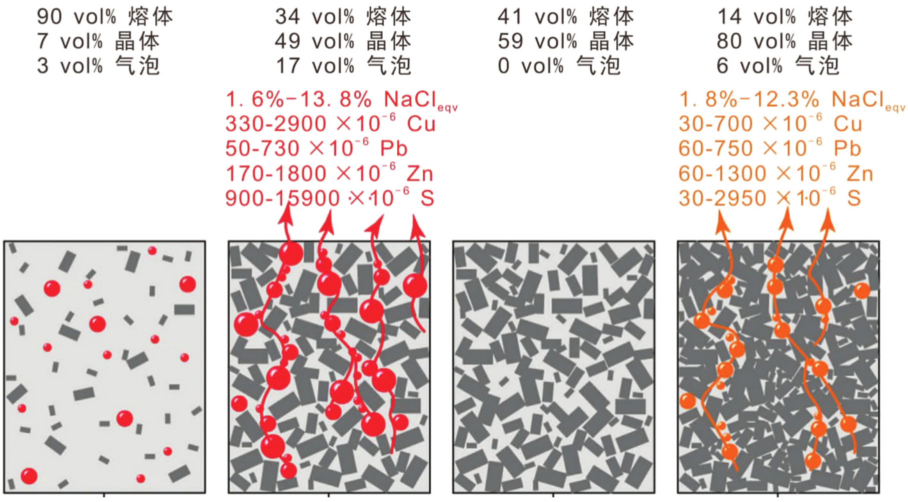


图 13　不同结晶度下岩浆去气成分的差异(据 Chelle-Michou *et al.*, 2017)

Fig. 13　Compositional difference of the fluids formed by mama degassing at different crystallinities (modified after Chelle-Michou *et al.*, 2017)

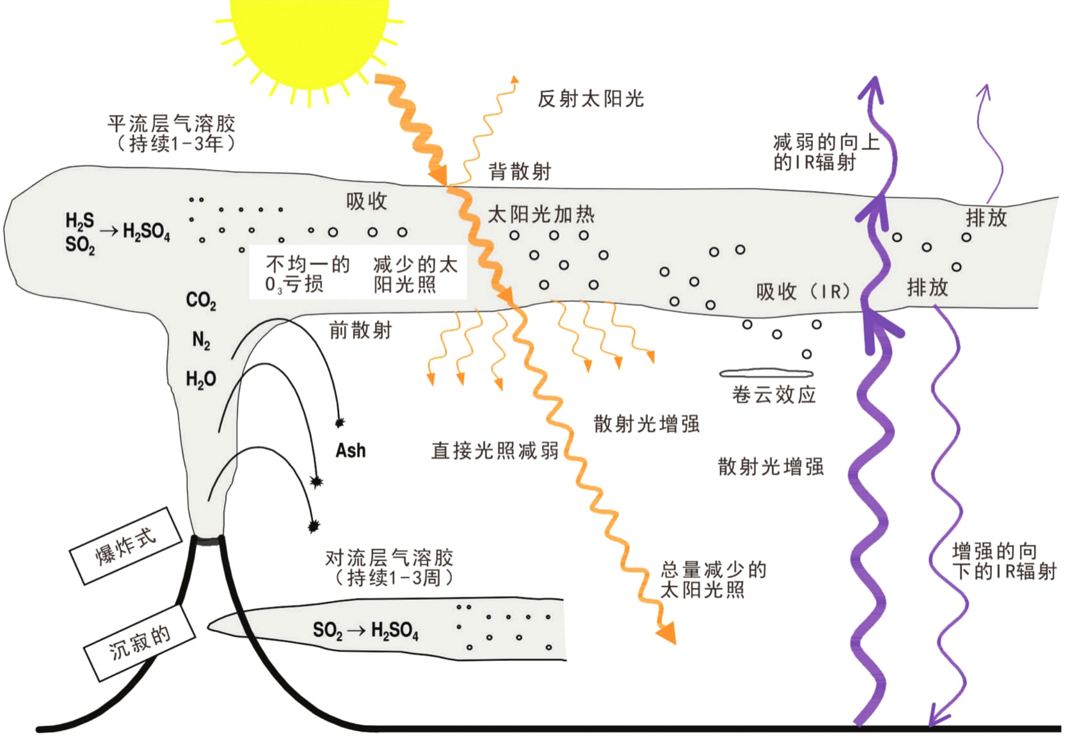


图 14　火山喷发释放挥发分对环境和气候的影响(据 Robock, 2015 修改)

Fig. 14　Schematic diagram of volcanic inputs to the atmosphere and their effects (modified after Robock, 2015)

到超常富集是伟晶岩矿床研究的核心问题之一(Linnen *et al.*, 2012)。由于部分稀有元素(例如 Li)具有非常强的迁移能力和扩散性，即使在伟晶岩脉侵位的时间尺度内，都有可能通过颗粒边界扩散作用向周围的地层中迁移，因而快速冷却可能是形成富 Li 伟晶岩的必要条件之一(Zhou *et al.*, 2021b)。

## 4　岩浆动力学的环境效应

岩浆动力学产生的环境效应包括很多方面，这里重点介绍由岩浆挥发分导致的环境扰动。不同圈层之间的挥发分交换，控制着地球的气候和环境，使得其在适宜生物和人类

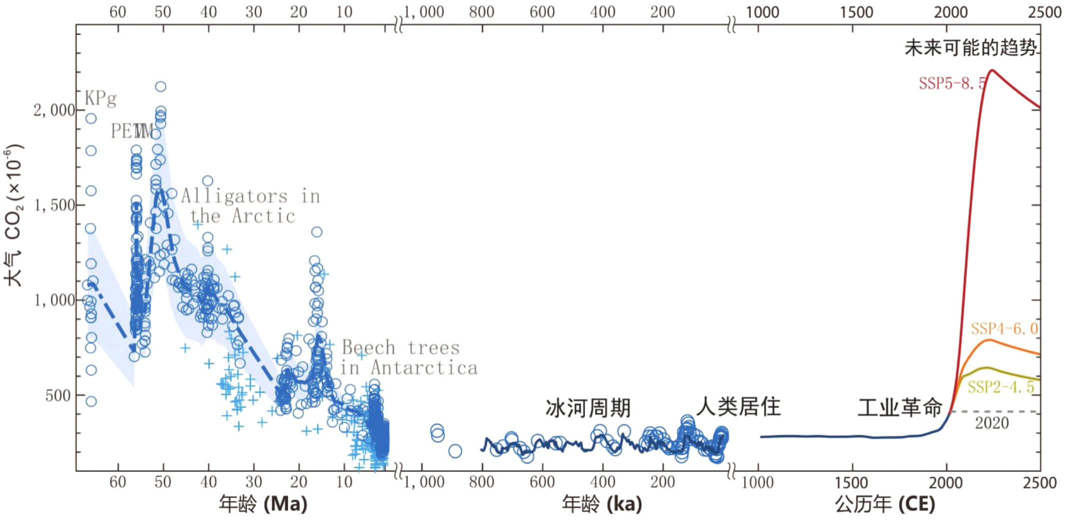


图 15 过去的 66Ma 内大气中 $CO_2$ 的浓度变化以及预测的可能变化趋势(据 Rae *et al.*, 2021 修改)

Fig. 15 Paleo-$CO_2$ context for future $CO_2$ change scenarios (modified after Rae *et al.*, 2021)

生存的空间内波动。这种交换既包括短时间尺度(数年到千年)的大气圈、水圈和生物圈之间循环,也包括长时间尺度(百万年)的地球内部与表层系统之间的循环(徐义刚等,2017)。岩浆则是连接地球内部与表层系统的纽带(莫宣学,2011)。在地幔以及深部地壳的部分熔融过程中,挥发分往往表现出不相容性并汇聚在熔体相中(Foley and Pintér, 2018),随着岩浆的上升和喷发,从而传输到地球表层系统中。地壳中运移以及储存的岩浆,可以通过两种方式向表层系统中释放气体,一种是随着火山喷发直接进入大气或者海水中(刘嘉麒等,2015;Edmonds and Wallace, 2017;郭正府等,2017);第二种方式则较为隐蔽,岩浆在地下深处去气,释放的气体通过断裂带扩散进入表层系统中(Lee *et al.*, 2016)。岩浆释放的气体主要包括 $H_2O$、$CO_2$、$SO_2$、$H_2S$、卤化氢(例如 HF、HCl),同时含有少量的稀有气体、$H_2$、$CH_4$、CO、COS 和金属(例如 Hg)(Mather and Schmidt, 2021)。爆炸式的火山喷发不仅产生大量的火山灰,释放的 $SO_2$ 进入大气对流层和平流层中,则会形成剧烈的环境扰动(Robock, 2000)。进入大气层中的 $SO_2$,会形成硫酸盐的气溶胶,平流层中的硫酸盐气溶胶可以持续数年,它们会反射太阳光从而使地表温度降低,也会通过化学反应破坏臭氧层(图 14;Robock, 2015)。例如,1815 年印度尼西亚的坦博拉火山喷发,导致 1816 年失去了夏季;1991 年菲律宾皮纳图博火山喷发,导致中纬度地区臭氧层减少了约 5%(Robock, 2015)。然而,并非所有的火山喷发均会产生类似的环境效应,只有部分能够在大气圈中形成含 $SO_2$ 的积云,例如 2008 年阿拉斯加奥克莫克火山喷发在大气圈中形成了大规模的 $SO_2$ 积云(Edmonds and Wallace, 2017),而发生在同一年的智利沙伊顿喷发,则形成了明显不同的贫硫积云(Carn *et al.*, 2009)。显然,岩浆去气及其伴随的环境效应受岩浆中挥发分的含量以及岩浆动力学过程联合控制。

在全球持续变暖以及我国“双碳目标”的背景下,研究岩浆中 $CO_2$ 的问题尤为迫切。自工业革命以来,人类大量使用化石燃料,导致大气中 $CO_2$ 的含量持续攀升。在过去的四十万年中,大气中的 $CO_2$ 含量一直稳定在 $190\times10^{-6}\sim280\times10^{-6}$ 的范围内波动(Zeebe and Caldeira, 2008),经过人类一个多世纪的排放,使得大气中的 $CO_2$ 含量在 2020 年升高到 $414\times10^{-6}$,如果不加控制,几十年至数百年后大气中的 $CO_2$ 含量则会急剧攀升到地质历史时期的高位(图 15;Rae *et al.*, 2021)。大气中过高的 $CO_2$ 含量,不仅导致地表温度的增加,还将导致海洋的酸化(Hönisch *et al.*, 2012),这将对地球上生物(包括我们人类)的生存造成巨大的威胁。实际上,地球表层系统对大气中 $CO_2$ 含量天然具有调控能力,例如大气中 $CO_2$ 的升高导致温度增加,温度增加则会增强地表的风化作用,从而吸收并降低大气中的 $CO_2$ 含量(Burton *et al.*, 2013)。从地质历史时期来看,大气中 $CO_2$ 含量的波动往往发生在千年到百万年的时间尺度上,这使得地表圈层系统具有足够的时间来缓冲其带来的环境效应(PALAEOSENS Project Members, 2012)。尽管现今大气中 $CO_2$ 含量远远低于地质历史时期的较高水平,但人类活动导致大气中 $CO_2$ 含量在数十年至上百年的时间尺度内发生快速变化,从而打破了地表圈层系统的调节平衡。据估计,在过去的 66Ma 中,人类排放导致的气候环境改变速率比地质历史中最剧烈的波动时期高 10 倍左右(Zeebe *et al.*, 2016)。因此,研究地质历史时期大气 $CO_2$ 含量变化的驱动机制和时间尺度,是评估大气 $CO_2$ 升高对人类威胁的重要依据(Rae *et al.*, 2021)。长时间尺度的大气 $CO_2$ 含量变化可能受控于板块构造循环(Raymo and Ruddiman, 1992; Suarez *et al.*, 2019);而较短时间尺度的波动则可能与某些特定的岩浆活动以及风化过程有关(Jiang and Lee, 2019; Bond and Sun, 2021; Bryan, 2021; Guo *et al.*, 2021)。

## 5 结语

岩浆动力学不仅是岩石学和火山学研究的核心内容，也是与岩浆有关的其他学科方向的认知基础。在今后的研究中，建议重视如下几个方面的问题：

(1)岩浆动力学中的一些传统且重要的问题，例如岩浆储库生长的空间问题、岩浆的存留时间、火山喷发的触动机制、火山岩与侵入岩的关系、花岗质岩浆的分异过程、不同构造背景中岩浆系统的结构和动力学过程，依然值得深入剖析。另外就是一些国际上关注度很高的热点前沿问题，包括岩浆过程的时间尺度、岩浆动力学数值模拟、热模拟、仿真实验、不平衡的动力学过程等。

(2)将岩浆动力学与其他学科方向相结合，是取得新认识的重要突破口之一。例如与地球物理相结合，能够更加客观真实反应岩浆通道系统的三维架构；与岩浆有关矿床的成因研究，包括岩浆矿床、岩浆-热液矿床、伟晶岩矿床等，这些矿床的成矿机制与岩浆动力学过程密切相关，很多成矿元素的富集也受控于岩浆动力学过程；另外就是一些新兴学科方向，例如高温过程中非传统同位素的分馏机制及其应用研究，理应建立在清晰的岩浆过程还原之上。

(3)关注岩浆动力学有关的环境效应，既涵盖对现今岩浆活动区的实时观测，也包括揭示地质历史时期岩浆活动与环境气候扰动的时间尺度和耦合机制。这些研究要重视岩浆挥发分的定量分析、岩浆去气过程、排放量估算等，还需探究地球内部与表层系统挥发分交换的宏观控制(例如板块构造循环)。

**致谢** 感谢吴福元院士邀请撰写本文；感谢纪伟强研究员在成文过程中提供的帮助；感谢马昌前教授和王孝磊教授建设性的修改意见和建议。此外，很多前人优秀的成果给予作者很大的启发，由于篇幅有限，未能一一以参考文献的形式列出，谨表歉意。

## References

Annen C, Blundy JD and Sparks RSJ. 2006. The genesis of intermediate and silicic magmas in deep crustal hot zones. Journal of Petrology, 47(3): 505－539

Annen C, Blundy JD, Leuthold J and Sparks RSJ. 2015. Construction and evolution of igneous bodies: Towards an integrated perspective of crustal magmatism. Lithos, 230: 206－221

Audétat A and Simon AC. 2012. Magmatic controls on porphyry copper genesis. In: Hedenquist JW, Harris M and Camus F (eds.). Geology and Genesis of Major Copper Deposits and Districts of the World: A Tribute to Richard H. Sillitoe. Society of Economic Geologists, 553－572

Audétat A. 2019. The metal content of magmatic-hydrothermal fluids and its relationship to mineralization potential. Economic Geology, 114(6): 1033－1056

Bachmann O and Bergantz GW. 2004. On the origin of crystal-poor rhyolites: Extracted from batholithic crystal mushes. Journal of Petrology, 45(8): 1565－1582

Bachmann O and Bergantz GW. 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(1－2): 85－102

Bachmann O, Miller CF and de Silva SL. 2007. The volcanic－plutonic connection as a stage for understanding crustal magmatism. Journal of Volcanology and Geothermal Research, 167(1－4): 1－23

Bachmann O and Huber C. 2016. Silicic magma reservoirs in the Earth's crust. American Mineralogist, 101(11): 2377－2404

Baker DR and Moretti R. 2011. Modeling the solubility of sulfur in magmas: A 50-year old geochemical challenge. Reviews in Mineralogy and Geochemistry, 73(1): 167－213

Baker DR and Alletti M. 2012. Fluid saturation and volatile partitioning between melts and hydrous fluids in crustal magmatic systems: The contribution of experimental measurements and solubility models. Earth-Science Reviews, 114(3－4): 298－324

Bergantz GW. 1989. Underplating and partial melting: Implications for melt generation and extraction. Science, 245(4922): 1093－1095

Bergantz GW, Schleicher JM and Burgisser A. 2015. Open-system dynamics and mixing in magma mushes. Nature Geoscience, 8(10): 793－796

Biggs J and Annen C. 2019. The lateral growth and coalesence of magma systems. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 377(2139): 20180005

Black BA, Karlstrom L and Mather TA. 2021. The life cycle of large igneous provinces. Nature Reviews Earth & Environment, 2(12): 840－857

Blundy J, Cashman KV, Rust A and Witham F. 2010. A case for $CO_2$-rich arc magmas. Earth and Planetary Science Letters, 290(3－4): 289－301

Blundy J, Mavrogenes J, Tattitch B, Sparks S and Gilmer A. 2015. Generation of porphyry copper deposits by gas－brine reaction in volcanic arcs. Nature Geoscience, 8(3): 235－240

Blundy J, Afanasyev A, Tattitch B, Sparks S, Melnik O, Utkin I and Rust A. 2021. The economic potential of metalliferous sub-volcanic brines. Royal Society Open Science, 8(6): 202192

Blundy JD and Annen CJ. 2016. Crustal magmatic systems from the perspective of heat transfer. Elements, 12(2): 115－120

Bond DPG and Sun YD. 2021. Global warming and mass extinctions associated with large igneous province volcanism. In: Ernst RE, Dickson AJ and Bekker A (eds.). Large Igneous Provinces: A Driver of Global Environmental and Biotic Changes. Hoboken: Wiley, 83－102

Boudreau A. 2016. Bubble migration in a compacting crystal-liquid mush. Contributions to Mineralogy and Petrology, 171(4): 32

Bowen NL. 1915. Crystallization-differentiation in silicate liquids. American Journal of Science, s4-39(230): 175－191

Brown M. 2013. Granite: From genesis to emplacement. GSA Bulletin, 125(7－8): 1079－1113

Bryan SE. 2021. Environmental impact of silicic magmatism in large igneous province events. In: Ernst RE, Dickson AJ and Bekker A (eds.). Large Igneous Provinces: A Driver of Global Environmental and Biotic Changes. Hoboken: Wiley, 133－151

Burton MR, Sawyer GM and Granieri D. 2013. Deep carbon emissions from volcanoes. Reviews in Mineralogy and Geochemistry, 75(1): 323－354

Candela PA. 1997. A review of shallow, ore-related granites: Textures, volatiles, and ore metals. Journal of Petrology, 38(12): 1619－1633

Cao MJ, Hollings P, Cooke DR, Evans NJ, McInnes BIA, Qin KZ, Li GM, Sweet G and Baker M. 2018. Physicochemical processes in the magma chamber under the Black Mountain porphyry Cu-Au deposit, Philippines: Insights from mineral chemistry and implications for mineralization. Economic Geology, 113(1): 63－82

Carn SA, Pallister JS, Lara L, Ewert JW, Watt S, Prata AJ, Thomas RJ and Villarosa G. 2009. The unexpected awakening of Chaitén volcano, Chile. Eos, Transactions American Geophysical Union, 90(24): 205-206

Cashman KV and Giordano G. 2014. Calderas and magma reservoirs. Journal of Volcanology and Geothermal Research, 288: 28-45

Cashman KV, Sparks RSJ and Blundy JD. 2017. Vertically extensive and unstable magmatic systems: A unified view of igneous processes. Science, 355(6331): 1280

Chelle-Michou C, Rottier B, Caricchi L and Simpson G. 2017. Tempo of magma degassing and the genesis of porphyry copper deposits. Scientific Reports, 7(1): 40566

Chelle-Michou C and Rottier B. 2021. Transcrustal magmatic controls on the size of porphyry Cu systems: State of knowledge and open questions. Society of Economic Geologists Special Publications, 24(1): 87-100

Chen B, Ma XH and Wang ZQ. 2014. Origin of the fluorine-rich highly differentiated granites from the Qianlishan composite plutons (South China) and implications for polymetallic mineralization. Journal of Asian Earth Sciences, 93: 301-314

Chen HY and Wu C. 2020. Metallogenesis and major challenges of porphyry copper systems above subduction zones. Science China (Earth Sciences), 63(7): 899-918

Chiaradia M. 2014. Copper enrichment in arc magmas controlled by overriding plate thickness. Nature Geoscience, 7(1): 43-46

Chiaradia M and Caricchi L. 2017. Stochastic modelling of deep magmatic controls on porphyry copper deposit endowment. Scientific Reports, 7: 44523

Chu RS, Helmberger DV, Sun DY, Jackson JM and Zhu LP. 2010. Mushy magma beneath Yellowstone. Geophysical Research Letters, 37(1): L01306

Clapham ME and Renne PR. 2019. Flood basalts and mass extinctions. Annual Review of Earth and Planetary Sciences, 47: 275-303

Clemens JD. 2006. Melting of the continental crust: Fluid regimes, melting reactions, and source-rock fertility. In: Brown M and Rushmer T (eds.). Evolution and Differentiation of the Continental Crust. Cambridge, UK: Cambridge University Press, 297-331

Cline JS and Bodnar RJ. 1991. Can economic porphyry copper mineralization be generated by a typical calc-alkaline melt? Journal of Geophysical Research: Solid Earth, 96(B5): 8113-8126

Coleman DS, Gray W and Glazner AF. 2004. Rethinking the emplacement and evolution of zoned plutons: Geochronologic evidence for incremental assembly of the Tuolumne Intrusive Suite, California. Geology, 32(5): 433-436

Coleman DS, Mills RD and Zimmerer MJ. 2016. The pace of plutonism. Elements, 12(2): 97-102

Cooke DR, Hollings P and Walshe JL. 2005. Giant porphyry deposits: Characteristics, distribution, and tectonic controls. Economic Geology, 100(5): 801-818

Cooper KM and Kent AJR. 2014. Rapid remobilization of magmatic crystals kept in cold storage. Nature, 506(7489): 480-483

Costa F, Shea T and Ubide T. 2020. Diffusion chronometry and the timescales of magmatic processes. Nature Reviews Earth & Environment, 1(4): 201-214

Costa F. 2021. Clocks in magmatic rocks. Annual Review of Earth and Planetary Sciences, 49: 231-252

Daly RA. 1911. The nature of volcanic action. Proceedings of the American Academy of Arts and Sciences, 47(3): 47-122

Deering CD and Bachmann O. 2010. Trace element indicators of crystal accumulation in silicic igneous rocks. Earth and Planetary Science Letters, 297(1-2): 324-331

Degruyter W, Parmigiani A, Huber C and Bachmann O. 2019. How do volatiles escape their shallow magmatic hearth? Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 377(2139): 20180017

Dixon JE, Clague DA, Wallace P and Poreda R. 1997. Volatiles in Alkalic basalts form the North Arch Volcanic field, Hawaii: Extensive degassing of deep submarine-erupted Alkalic series lavas. Journal of Petrology, 38(7): 911-939

Dixon JE and Clague DA. 2001. Volatiles in basaltic glasses from Loihi Seamount, Hawaii: Evidence for a relatively dry plume component. Journal of Petrology, 42(3): 627-654

Downes MJ. 1974. Sector and oscillatory zoning in calcic augites from M. Etna, Sicily. Contributions to Mineralogy and Petrology, 47(3): 187-196

Dowty E. 1976. Crystal structure and crystal growth: II. Sector zoning in minerals. American Mineralogist, 61(5-6): 460-469

Druitt TH, Costa F, Deloule E, Dungan M and Scaillet B. 2012. Decadal to monthly timescales of magma transfer and reservoir growth at a caldera volcano. Nature, 482(7383): 77-80

Du DH, Wang XL, Wang S, Miller CF, Xu X, Chen X and Zhang FF. 2022. Deciphering cryptic multi-stage crystal-melt separation during construction of the Tonglu volcanic-plutonic complex, SE China. Journal of Petrology, 63(1): egab098

Dufek J and Bergantz GW. 2005. Lower crustal magma genesis and preservation: A stochastic framework for the evaluation of basalt-crust interaction. Journal of Petrology, 46(11): 2167-2195

Edmonds M and Wallace PJ. 2017. Volatiles and exsolved vapor in volcanic systems. Elements, 13(1): 29-34

Edmonds M and Woods AW. 2018. Exsolved volatiles in magma reservoirs. Journal of Volcanology and Geothermal Research, 368: 13-30

Edmonds M, Mather TA and Liu EJ. 2018. A distinct metal fingerprint in arc volcanic emissions. Nature Geoscience, 11(10): 790-794

Edmonds M, Cashman KV, Holness M and Jackson M. 2019. Architecture and dynamics of magma reservoirs. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 377(2139): 20180298

Faure F, Schiano P, Trolliard G, Nicollet C and Soulestin B. 2007. Textural evolution of polyhedral olivine experiencing rapid cooling rates. Contributions to Mineralogy and Petrology, 153(4): 405-416

Fiedrich AM, Bachmann O, Ulmer P, Deering CD, Kunze K and Leuthold J. 2017. Mineralogical, geochemical, and textural indicators of crystal accumulation in the Adamello Batholith (Northern Italy). American Mineralogist, 102(12): 2467-2483

Foley SF and Pintér Z. 2018. Primary melt compositions in the Earth's mantle. In: Kono Y and Sanloup C (eds.). Magmas Under Pressure: Advances in High-Pressure Experiments on Structure and Properties of Melts. Amsterdam: Elsevier, 3-42

Gavrilenko M, Krawczynski M, Ruprecht P, Li WL and Catalano JG. 2019. The quench control of water estimates in convergent margin magmas. American Mineralogist, 104(7): 936-948

Gelman SE, Deering CD, Bachmann O, Huber C and Gutiérrez FJ. 2014. Identifying the crystal graveyards remaining after large silicic eruptions. Earth and Planetary Science Letters, 403: 299-306

Ghiorso MS and Gualda GAR. 2015. An $H_2O$-$CO_2$ mixed fluid saturation model compatible with rhyolite-melts. Contributions to Mineralogy and Petrology, 169(6): 53

Giordano D, Russell JK and Dingwell DB. 2008. Viscosity of magmatic liquids: A model. Earth and Planetary Science Letters, 271(1-4): 123-134

Giuliani L, Iezzi G and Mollo S. 2021. Dynamics of volcanic systems: Physical and chemical models applied to equilibrium versus disequilibrium solidification of magmas. In: Vetere F (ed.). Dynamic Magma Evolution. Hoboken: Wiley, 101-132

Glazner AF, Bartley JM, Coleman DS, Gray W and Taylor RZ. 2004. Are plutons assembled over millions of years by amalgamation from small magma chambers? GSA Today, 14(4-5): 4-11

Glazner AF, Coleman DS and Mills RD. 2015. The volcanic-plutonic connection. In: Breitkreuz C and Rocchi S (eds.). Physical Geology of Shallow Magmatic Systems: Dykes, Sills and Laccoliths. Cham: Springer, 1-22

Gonnermann HM. 2015. Magma fragmentation. Annual Review of Earth and Planetary Sciences, 43: 431-458

Grove TL, Till CB and Krawczynski MJ. 2012. The role of $H_2O$ in subduction zone magmatism. Annual Review of Earth and Planetary

Sciences, 40: 413 – 439

Guo ZF, Zheng GD, Sun YT, Zhang ML, Zhang LH and Cheng ZH. 2017. Greenhouse gases emitted from geological sources in China. Bulletin of Mineralogy, Petrology and Geochemistry, 36(2): 204 – 212 (in Chinese with English abstract)

Guo ZF, Wilson M, Dingwell DB and Liu JQ. 2021. India-Asia collision as a driver of atmospheric $CO_2$ in the Cenozoic. Nature Communications, 12(1): 3891

Hammer J, Jacob S, Welsch B, Hellebrand E and Sinton J. 2016. Clinopyroxene in post-shield Haleakala ankaramite: 1. Efficacy of thermobarometry. Contributions to Mineralogy and Petrology, 171: 7

Hammer JE. 2008. Experimental studies of the kinetics and energetics of magma crystallization. Reviews in Mineralogy and Geochemistry, 69(1): 9 – 59

Hedenquist JW and Lowenstern JB. 1994. The role of magmas in the formation of hydrothermal ore deposits. Nature, 370(6490): 519 – 527

Hedenquist JW, Arribas A and Reynolds TJ. 1998. Evolution of an intrusion-centered hydrothermal system: Far Southeast-Lepanto porphyry and epithermal Cu-Au deposits, Philippines. Economic Geology, 93(4): 373 – 404

Herring C. 1951. Some theorems on the free energies of crystal surfaces. Physical Review, 82(1): 87 – 93

Hildreth W. 1981. Gradients in silicic magma chambers: Implications for lithospheric magmatism. Journal of Geophysical Research: Solid Earth, 86(B11): 10153 – 10192

Hildreth W and Moorbath S. 1988. Crustal contributions to arc magmatism in the Andes of central Chile. Contributions to Mineralogy and Petrology, 98(4): 455 – 489

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(3 – 4): 169 – 198

Hollister LS and Gancarz AJ. 1971. Compositional sector-zoning in clinopyroxene from the Narce area, Italy. American Mineralogist, 56(5 – 6): 959 – 979

Hou T, Charlier B, Holtz F, Veksler I, Zhang ZC, Thomas R and Namur O. 2018. Immiscible hydrous Fe-Ca-P melt and the origin of iron oxide-apatite ore deposits. Nature Communications, 9(1): 1415

Hou ZQ, Zheng YC, Yang ZM and Yang ZS. 2012. Metallogenesis of continental collision setting: Part Ⅰ. Gangdese Cenozoic porphyry Cu-Mo systems in Tibet. Mineral Deposits, 31(4): 647 – 670 (in Chinese with English abstract)

Hou ZQ, Yang ZM, Lu YJ, Kemp A, Zheng YC, Li QY, Tang JX, Yang ZS and Duan LF. 2015. A genetic linkage between subduction- and collision-related porphyry Cu deposits in continental collision zones. Geology, 43(2): 247 – 250

Hönisch B, Ridgwell A, Schmidt DN, Thomas E, Gibbs SJ, Sluijs A, Zeebe R, Kump L, Martindale RC, Greene SE, Kiessling W, Ries J, Zachos JC, Royer DL, Barker S, Marchitto Jr TM, Moyer R, Pelejero C, Ziveri P, Foster GL and Williams B. 2012. The geological record of ocean acidification. Science, 335(6072): 1058 – 1063

Huang XL, Xu YG, Li XH, Li WX, Lan JB, Zhang HH, Liu YS, Wang YB, Li HY, Luo ZY and Yang QJ. 2008. Petrogenesis and tectonic implications of Neoproterozoic, highly fractionated A-type granites from Mianning, South China. Precambrian Research, 165(3 – 4): 190 – 204

Huber C, Bachmann O and Dufek J. 2012. Crystal-poor versus crystal-rich ignimbrites: A competition between stirring and reactivation. Geology, 40(2): 115 – 118

Huppert HE and Sparks RSJ. 1988. The generation of granitic magmas by intrusion of basalt into continental crust. Journal of Petrology, 29(3): 599 – 624

Iyer HM, Evans JR, Dawson PB, Stauber DA and Achauer U. 1990. Differences in magma storage in different volcanic environments as revealed by seismic tomography: 1. Silicic volcanic centers and subduction-related volcanoes. In: Ryan MP (ed.). Magma Transport and Storage. New York: Geophysikalisches Institute, 293 – 316

Jackson MD, Blundy J and Sparks RSJ. 2018. Chemical differentiation, cold storage and remobilization of magma in the Earth's crust. Nature, 564(7736): 405 – 409

Jahn BM, Wu FY and Chen B. 2000. Granitoids of the Central Asian Orogenic Belt and continental growth in the Phanerozoic. Earth and Environmental Science Transactions of the Royal Society of Edinburgh, 91(1 – 2): 181 – 193

Ji WQ, Wu FY, Liu XC, Liu ZC, Zhang C, Liu T, Wang JG and Paterson SR. 2020. Pervasive Miocene melting of thickened crust from the Lhasa terrane to Himalaya, southern Tibet and its constraint on generation of Himalayan leucogranite. Geochimica et Cosmochimica Acta, 278: 137 – 156

Jiang HH and Lee CTA. 2019. On the role of chemical weathering of continental arcs in long-term climate regulation: A case study of the Peninsular Ranges batholith, California (USA). Earth and Planetary Science Letters, 525: 115733

Karakas O, Degruyter W, Bachmann O and Dufek J. 2017. Lifetime and size of shallow magma bodies controlled by crustal-scale magmatism. Nature Geoscience, 10(6): 446 – 450

Keller CB, Schoene B, Barboni M, Samperton KM and Husson JM. 2015. Volcanic-plutonic parity and the differentiation of the continental crust. Nature, 523(7560): 301 – 307

Kemp AIS, Hawkesworth CJ, Foster GL, Paterson BA, Woodhead JD, Hergt JM, Gray CM and Whitehouse MJ. 2007. Magmatic and crustal differentiation history of granitic rocks from Hf-O isotopes in zircon. Science, 315(5814): 980 – 983

Kirkpatrick RJ, Kuo LC and Melchior J. 1981. Crystal growth in incongruently-melting compositions: Programmed cooling experiments with diopside. American Mineralogist, 66(3 – 4): 223 – 241

Klimm K, Kohn SC and Botcharnikov RE. 2012. The dissolution mechanism of sulphur in hydrous silicate melts: II. Solubility and speciation of sulphur in hydrous silicate melts as a function of $f_{O_2}$. Chemical Geology, 322 – 323: 250 – 267

Kouchi A, Sugawara Y, Kashima K and Sunagawa I. 1983. Laboratory growth of sector zoned clinopyroxenes in the system $CaMgSi_2O_6$-$CaTiAl_2O_6$. Contributions to Mineralogy and Petrology, 83(1 – 2): 177 – 184

Krawczynski MJ, Grove TL and Behrens H. 2012. Amphibole stability in primitive arc magmas: Effects of temperature, $H_2O$ content, and oxygen fugacity. Contributions to Mineralogy and Petrology, 164(2): 317 – 339

Lange RA, Frey HM and Hector J. 2009. A thermodynamic model for the plagioclase-liquid hygrometer/thermometer. American Mineralogist, 94(4): 494 – 506

Le Roux PJ, Shirey SB, Hauri EH, Perfit MR and Bender JF. 2006. The effects of variable sources, processes and contaminants on the composition of northern EPR MORB (8° ~ 10°N and 12° ~ 14°N): Evidence from volatiles ($H_2O$, $CO_2$, S) and halogens (F, Cl). Earth and Planetary Science Letters, 251(3 – 4): 209 – 231

Lee CTA, Luffi P, Chin EJ, Bouchet R, Dasgupta R, Morton DM, Le Roux V, Yin QZ and Jin D. 2012. Copper systematics in arc magmas and implications for crust-mantle differentiation. Science, 336(6077): 64 – 68

Lee CTA and Morton DM. 2015. High silica granites: Terminal porosity and crystal settling in shallow magma chambers. Earth and Planetary Science Letters, 409: 23 – 31

Lee H, Muirhead JD, Fischer TP, Ebinger CJ, Kattenhorn SA, Sharp ZD and Kianji G. 2016. Massive and prolonged deep carbon emissions associated with continental rifting. Nature Geoscience, 9(2): 145 – 149

Lees JM. 2007. Seismic tomography of magmatic systems. Journal of Volcanology and Geothermal Research, 167(1 – 4): 37 – 56

Leung IS. 1974. Sector-zoned titanaugites: Morphology, crystal chemistry, and growth. American Mineralogist, 59(1 – 2): 127 – 138

Li N and Sun JX. 2018. A review on research progress of melt Inclusion in volcanic rocks. Bulletin of Mineralogy, Petrology and Geochemistry, 37(3): 414 - 423 (in Chinese with English abstract)

Li WR and Costa F. 2020. A thermodynamic model for F-Cl-OH partitioning between silicate melts and apatite including non-ideal mixing with application to constraining melt volatile budgets. Geochimica et Cosmochimica Acta, 269: 203 - 222

Li WR, Costa F and Nagashima K. 2021. Apatite crystals reveal melt volatile budgets and magma storage depths at Merapi volcano, Indonesia. Journal of Petrology, 62(4): egaa100

Li Y and Audétat A. 2012. Partitioning of V, Mn, Co, Ni, Cu, Zn, As, Mo, Ag, Sn, Sb, W, Au, Pb, and Bi between sulfide phases and hydrous basanite melt at upper mantle conditions. Earth and Planetary Science Letters, 355 - 356: 327 - 340

Li Y, Selby D, Condon D and Tapster S. 2017. Cyclic magmatic-hydrothermal evolution in porphyry systems: High-precision U-Pb and Re-Os geochronology constraints on the Tibetan Qulong porphyry Cu-Mo deposit. Economic Geology, 112(6): 1419 - 1440

Linnen RL, Van Lichtervelde M and Černý P. 2012. Granitic pegmatites as sources of strategic metals. Elements, 8(4): 275 - 280

Lipman PW. 2007. Incremental assembly and prolonged consolidation of Cordilleran magma chambers: Evidence from the Southern Rocky Mountain volcanic field. Geosphere, 3(1): 42 - 70

Lissenberg CJ, MacLeod CJ, Howard KA and Godard M. 2013. Pervasive reactive melt migration through fast-spreading lower oceanic crust (Hess Deep, equatorial Pacific Ocean). Earth and Planetary Science Letters, 361: 436 - 447

Lissenberg CJ, MacLeod CJ and Bennett EN. 2019. Consequences of a crystal mush-dominated magma plumbing system: A mid-ocean ridge perspective. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 377(2139): 20180014

Liu JQ, Chen SS, Guo WF, Sun CQ, Zhang ML and Guo ZF. 2015. Research advances in the Mt. Changbai Volcano. Bulletin of Mineralogy, Petrology and Geochemistry, 34(4): 710 - 723 (in Chinese with English abstract)

Liu PP, Caricchi L, Chung SL, Li XH, Li QL, Zhou MF, Lai YM, Ghani AA, Sihotang T, Sheldrake TE and Simpson G. 2021. Growth and thermal maturation of the Toba magma reservoir. Proceedings of the National Academy of Sciences of the United States of America, 118(45): e2101695118

Liu XC, Xiong XL, Audétat A and Li Y. 2015. Partitioning of Cu between mafic minerals, Fe-Ti oxides and intermediate to felsic melts. Geochimica et Cosmochimica Acta, 151: 86 - 102

Lofgren GE, Huss GR and Wasserburg GJ. 2006. An experimental study of trace-element partitioning between Ti-Al-clinopyroxene and melt: Equilibrium and kinetic effects including sector zoning. American Mineralogist, 91(10): 1596 - 1606

London D and Morgan VI GB. 2012. The pegmatite puzzle. Elements, 8(4): 263 - 268

London D and Morgan VI GB. 2017. Experimental crystallization of the Macusani obsidian, with applications to lithium-rich granitic pegmatites. Journal of Petrology, 58(5): 1005 - 1030

London D. 2018. Ore-forming processes within granitic pegmatites. Ore Geology Reviews, 101: 349 - 383

Lundstrom CC and Glazner AF. 2016. Silicic magmatism and the volcanic-plutonic connection. Elements, 12(2): 91 - 96

Luo BJ, Zhang HF, Zhang LQ, Zhang C, Shen LM, Xiao ZQ, Pan FB, Yang H, Li ZK, Xu WC, Guo L and Tao L. 2020. The magma plumbing system of Mesozoic Shanyang porphyry groups, South Qinling and implications for porphyry copper mineralization. Earth and Planetary Science Letters, 543: 116346

Luo ZH, Huang ZM and Ke S. 2007. An overview of granitoid. Geological Review, 53(Suppl. 1): 180 - 226 (in Chinese with English abstract)

Ma CQ. 1987. A emerging frontier subject: Magma dynamics. World Science, (6): 45 - 47 (in Chinese)

Ma CQ and Li YQ. 2017. Incremental growth of granitoid plutons and highly crystalline magmatic differentiation. Acta Petrologica Sinica, 33(5): 1479 - 1488 (in Chinese with English abstract)

Ma CQ, Zou BW, Gao K and Wen X. 2020. Crystal mush storage, incremental pluton assembly and granitic petrogenesis. Earth Science, 45(12): 4332 - 4351 (in Chinese with English abstract)

Ma L, Wang Q, Kerr AC, Yang JH, Xia XP, Ou Q, Yang ZY and Sun P. 2017. Paleocene (c. 62Ma) leucogranites in southern Lhasa, Tibet: Products of syn-collisional crustal anatexis during slab roll-back? Journal of Petrology, 58(11): 2089 - 2114

Mader HM, Llewellin EW and Mueller SP. 2013. The rheology of two-phase magmas: A review and analysis. Journal of Volcanology and Geothermal Research, 257: 135 - 158

Marsh BD. 1989. Magma chambers. Annual Review of Earth and Planetary Sciences, 17: 439 - 472

Masotta M, Pontesilli A, Mollo S, Armienti P, Ubide T, Nazzari M and Scarlato P. 2020. The role of undercooling during clinopyroxene growth in trachybasaltic magmas: Insights on magma decompression and cooling at Mt. Etna volcano. Geochimica et Cosmochimica Acta, 268: 258 - 276

Masturyono, McCaffrey R, Wark DA, Roecker SW, Fauzi and Sukhyar GI. 2001. Distribution of magma beneath the Toba caldera complex, North Sumatra, Indonesia: Constrained by three-dimensional P wave velocities, seismicity, and gravity data. Geochemistry, Geophysics, Geosystems, 2(4): 2000GC000096

Mather TA and Schmidt A. 2021. Environmental effects of volcanic volatile fluxes from subaerial large igneous provinces. In: Ernst RE, Dickson AJ and Bekker A (eds.). Large Igneous Provinces: A Driver of Global Environmental and Biotic Changes. Hoboken: Wiley, 103 - 116

McKenzie DAN and Bickle MJ. 1988. The volume and composition of melt generated by extension of the lithosphere. Journal of Petrology, 29(3): 625 - 679

Meinert LD, Hedenquist JW, Satoh H and Matsuhisa Y. 2003. Formation of anhydrous and hydrous skarn in Cu-Au ore deposits by magmatic fluids. Economic Geology, 98(1): 147 - 156

Meinert LD, Dipple GM and Nicolescu S. 2005. World skarn deposits. In: Hedenquist JW, Thompson JFH, Goldfarb RJ and Richards JP (eds.). Economic Geology One Hundredth Anniversary Volume. Society of Economic Geologists, 299 - 336

Menand T. 2008. The mechanics and dynamics of sills in layered elastic rocks and their implications for the growth of laccoliths and other igneous complexes. Earth and Planetary Science Letters, 267(1 - 2): 93 - 99

Mercer CN, Reed MH and Mercer CM. 2015. Time scales of porphyry Cu deposit formation: Insights from titanium diffusion in quartz. Economic Geology, 110(3): 587 - 602

Mo XX. 2011. Magma and magmatic/igneous rocks: A lithoprobe into the deep earth and records of the earth's evolution. Chinese Journal of Nature, 33(5): 255 - 259 (in Chinese with English abstract)

Mollo S and Hammer JE. 2017. Dynamic crystallization in magmas. In: Heinrich W and Abart R (eds.). Mineral Reaction Kinetics: Microstructures, Textures, Chemical and Isotopic Signatures. European Mineralogical Union and Mineralogical Society of Great Britain and Ireland, 373 - 418

Mungall JE. 2002. Roasting the mantle: Slab melting and the genesis of major Au and Au-rich Cu deposits. Geology, 30(10): 915 - 918

Mungall JE. 2015. Physical controls of nucleation, growth and migration of vapor bubbles in partially molten cumulates. In: Charlier B, Namur O, Latypov R and Tegner C (eds.). Layered Intrusions. Dordrecht: Springer, 331 - 377

Nakamura Y. 1973. Origin of sector-zoning of igneous clinopyroxenes. American Mineralogist, 58(11 - 12): 986 - 990

Neave DA, Bali E, Guefinnsson GH, Halldórsson SA, Kahl M, Schmidt AS and Holtz F. 2019. Clinopyroxene-liquid equilibria and geothermobarometry in natural and experimental tholeiites: The 2014 - 2015 Holuhraun eruption, Iceland. Journal of Petrology, 60(8): 1653 - 1680

Ni HW, Liu Y, Wang LJ and Zhang YX. 2009. Water speciation and diffusion in haploandesitic melts at 743 ~ 873K and 100MPa. Geochimica et Cosmochimica Acta, 73(12): 3630 – 3641

Ni HW and Keppler H. 2013. Carbon in silicate melts. Reviews in Mineralogy and Geochemistry, 75(1): 251 – 287

Ni HW, Keppler H, Walte N, Schiavi F, Chen Y, Masotta M and Li ZJ. 2014. In situ observation of crystal growth in a basalt melt and the development of crystal size distribution in igneous rocks. Contributions to Mineralogy and Petrology, 167(5): 1003

PALAEOSENS Project Members. 2012. Making sense of palaeoclimate sensitivity. Nature, 491(7426): 683 – 691

Parmigiani A, Degruyter W, Leclaire S, Huber C and Bachmann O. 2017. The mechanics of shallow magma reservoir outgassing. Geochemistry, Geophysics, Geosystems, 18(8): 2887 – 2905

Petford N, Cruden AR, McCaffrey KJW and Vigneresse JL. 2000. Granite magma formation, transport and emplacement in the earth's crust. Nature, 408(6813): 669 – 673

Pistone M, Arzilli F, Dobson KJ, Cordonnier B, Reusser E, Ulmer P, Marone F, Whittington AG, Mancini L, Fife JL and Blundy JD. 2015. Gas-driven filter pressing in magmas: Insights into in-situ melt segregation from crystal mushes. Geology, 43(8): 699 – 702

Plank T, Kelley KA, Zimmer MM, Hauri EH and Wallace PJ. 2013. Why do mafic arc magmas contain ~4wt% water on average? Earth and Planetary Science Letters, 364: 168 – 179

Pontesilli A, Masotta M, Nazzari M, Mollo S, Armienti P, Scarlato P and Brenna M. 2019. Crystallization kinetics of clinopyroxene and titanomagnetite growing from a trachybasaltic melt: New insights from isothermal time-series experiments. Chemical Geology, 510: 113 – 129

Portnyagin M, Almeev R, Matveev S and Holtz F. 2008. Experimental evidence for rapid water exchange between melt inclusions in olivine and host magma. Earth and Planetary Science Letters, 272(3 – 4): 541 – 552

Qin KZ, Zhao JX, He CT and Shi RZ. 2021. Discovery of the Qongjiagang giant lithium pegmatite deposit in Himalaya, Tibet, China. Acta Petrologica Sinica, 37(11): 3277 – 3286 (in Chinese with English abstract)

Rae JWB, Zhang YG, Liu XQ, Foster GL, Stoll HM and Whiteford RDM. 2021. Atmospheric $CO_2$ over the past 66 million years from marine archives. Annual Review of Earth and Planetary Sciences, 49: 609 – 641

Raymo ME and Ruddiman WF. 1992. Tectonic forcing of late Cenozoic climate. Nature, 359(6391): 117 – 122

Reid MR. 2008. How long does it take to supersize an eruption? Elements, 4(1): 23 – 28

Ren ZY, Zhang L, Wu YD, Xu XB, Zhang L, Mei SW, Yu YF, Luo QC and Zhang QL. 2018. Melt inclusions and their applications on the origin of mafic volcanic rocks. Bulletin of Mineralogy, Petrology and Geochemistry, 37(3): 395 – 413 (in Chinese with English abstract)

Richards JP. 2003. Tectono-magmatic precursors for porphyry Cu-(Mo-Au) deposit formation. Economic Geology, 98(8): 1515 – 1533

Robock A. 2000. Volcanic eruptions and climate. Reviews of geophysics, 38(2): 191 – 219

Robock A. 2015. Climatic impacts of volcanic eruptions. In: Sigurdsson H (ed.). The Encyclopedia of Volcanoes. 2nd Edition. Amsterdam: Elsevier, 935 – 942

Rutherford MJ, Sigurdsson H, Carey S and Davis A. 1985. The May 18, 1980, eruption of Mount St. Helens: 1. Melt composition and experimental phase equilibria. Journal of Geophysical Research: Solid Earth, 90(B4): 2929 – 2947

Sawyer EW, Cesare B and Brown M. 2011. When the continental crust melts. Elements, 7(4): 229 – 234

Schwandt CS and Mckay GA. 2006. Minor- and trace-element sector zoning in synthetic enstatite. American Mineralogist, 91(10): 1607 – 1615

Seedorff E, Dilles JH, Proffett Jr JM, Einaudi MT, Zurcher L, Stavast WJA, Johnson DA and Barton MD. 2005. Porphyry deposits: Characteristics and origin of hypogene features. In: Hedenquist JW, Thompson JFH, Goldfarb RJ and Richards JP (eds.). Economic Geology One Hundredth Anniversary Volume. Society of Economic Geologists, 251 – 298

Self S. 2006. The effects and consequences of very large explosive volcanic eruptions. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 364(1845): 2073 – 2097

Sherburn S, Bannister S and Bibby H. 2003. Seismic velocity structure of the central Taupo volcanic zone, New Zealand, from local earthquake tomography. Journal of Volcanology and Geothermal Research, 122(1 – 2): 69 – 88

Shimizu N. 1981. Trace element incorporation into growing augite phenocryst. Nature, 289(5798): 575 – 577

Sillitoe RH. 2010. Porphyry copper systems. Economic Geology, 105(1): 3 – 41

Simmons SF, White NC and John DA. 2005. Geological characteristics of epithermal precious and base metal deposits. In: Hedenquist JW, Thompson JFH, Goldfarb RJ and Richards JP (eds.). Economic Geology One Hundredth Anniversary Volume. Society of Economic Geologists, 485 – 522

Sirbescu MLC, Schmidt C, Veksler IV, Whittington AG and Wilke M. 2017. Experimental crystallization of undercooled felsic liquids: Generation of pegmatitic texture. Journal of Petrology, 58(3): 539 – 568

Sisson TW and Bacon CR. 1999. Gas-driven filter pressing in magmas. Geology, 27(7): 613 – 616

Smith RL. 1960. Ash flows. GSA Bulletin, 71(6): 795 – 842

Sobolev AV, Hofmann AW, Kuzmin DV, Yaxley GM, Arndt NT, Chung SL, Danyushevsky LV, Elliott T, Frey FA, Garcia MO, Gurenko AA, Kamenetsky VS, Kerr AC, Krivolutskaya NA, Matvienkov VV, Nikogosian IK, Rocholl A, Sigurdsson IA, Sushchevskaya NM and Teklay M. 2007. The amount of recycled crust in sources of mantle-derived melts. Science, 316(5823): 412 – 417

Solomatova N, Caracas R and Cohen R. 2020. Carbon speciation and solubility in silicate melts. In: Manning CE, Lin JF and Mao WL (eds.). Carbon in Earth's Interior. Wiley, 179 – 194

Song XY, Qi HW, Hu RZ, Chen LM, Yu SY and Zhang JF. 2013. Formation of thick stratiform Fe - Ti oxide layers in layered intrusion and frequent replenishment of fractionated mafic magma: Evidence from the Panzhihua intrusion, SW China. Geochemistry, Geophysics, Geosystems, 14(3): 712 – 732

Sparks RSJ, Annen C, Blundy JD, Cashman KV, Rust AC and Jackson MD. 2019. Formation and dynamics of magma reservoirs. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 377(2139): 20180019

Suarez CA, Edmonds M and Jones AP. 2019. Earth catastrophes and their impact on the carbon cycle. Elements, 15(5): 301 – 306

Tang GJ, Wang Q, Zhang C, Wyman DA, Dan W, Xia XP, Chen HY and Zhao ZH. 2017. Sr-Nd-Hf-O isotope geochemistry of the Ertaibei pluton, East Junggar, NW China: Implications for development of a crustal-scale granitoid pluton and crustal growth. Geochemistry, Geophysics, Geosystems, 18: 3340 – 3358

Tattitch B, Chelle-Michou C, Blundy J and Loucks RR. 2021. Chemical feedbacks during magma degassing control chlorine partitioning and metal extraction in volcanic arcs. Nature Communications, 12(1): 1774

Tattitch BC and Blundy JD. 2017. Cu-Mo partitioning between felsic melts and saline-aqueous fluids as a function of $X_{NaCleq}$, $f_{O_2}$, and $f_{S_2}$. American Mineralogist, 102(10): 1987 – 2006

Ubide T, Mollo S, Zhao JX, Nazzari M and Scarlato P. 2019a. Sector-zoned clinopyroxene as a recorder of magma history, eruption triggers, and ascent rates. Geochimica et Cosmochimica Acta, 251: 265 – 283

Ubide T, Caulfield J, Brandt C, Bussweiler Y, Mollo S, Di Stefano F, Nazzari M and Scarlato P. 2019b. Deep magma storage revealed by multi-method elemental mapping of clinopyroxene megacrysts at stromboli volcano. Frontiers in Earth Science, 7: 239

Wager LR, Brown GM and Wadsworth WJ. 1960. Types of igneous cumulates. Journal of Petrology, 1(1): 73 – 85

Wager LR and Brown GM. 1967. Layered Igneous Rocks. Edinburgh: Oliver and Boyd, 588

Wallace PJ. 2005. Volatiles in subduction zone magmas: Concentrations and fluxes based on melt inclusion and volcanic gas data. Journal of Volcanology and Geothermal Research, 140(1 – 3): 217 – 240

Wallace PJ, Plank T, Edmonds M and Hauri EH. 2015. Volatiles in magmas. In: Sigurdsson H (ed.). The Encyclopedia of Volcanoes. $2^{nd}$ Edition. Amsterdam: Elsevier, 163 – 183

Wallace PJ, Plank T, Bodnar RJ, Gaetani GA and Shea T. 2021. Olivine-hosted melt inclusions: A microscopic perspective on a complex magmatic world. Annual Review of Earth and Planetary Sciences, 49: 465 – 494

Wang CY, Zhong H, Cao YH, Wei B and Chen C. 2020. Genetic classification, distribution and ore genesis of major PGE, Co and Cr deposits in China: A critical review. Chinese Science Bulletin, 65(33): 3825 – 3838 (in Chinese)

Wang D, Wang XL, Bindeman IN, Du DH, Li JY and Jiang CH. 2021a. Ephemeral magma reservoirs during the incremental growth of the Neoproterozoic Jiuling composite batholith in South China. Journal of Geophysical Research: Solid Earth, 126: e2021JB022758

Wang DZ. 2004. The study of granitic rocks in South China: Looking back and forward. Geological Journal of China Universities, 10(3): 305 – 314 (in Chinese with English abstract)

Wang Q, Xu JF, Jian P, Bao ZW, Zhao ZH, Li CF, Xiong XL and Ma JL. 2006. Petrogenesis of adakitic porphyries in an extensional tectonic setting, Dexing, South China: Implications for the genesis of porphyry copper mineralization. Journal of Petrology, 47(1): 119 – 144

Wang Q, Chung SL, Li XH, Wyman D, Li ZX, Sun WD, Qiu HN, Liu YS and Zhu YT. 2012. Crustal melting and flow beneath northern Tibet: Evidence from Mid-Miocene to Quaternary strongly peraluminous rhyolites in the southern Kunlun Range. Journal of Petrology, 53(12): 2523 – 2566

Wang Q, Hawkesworth CJ, Wyman D, Chung SL, Wu FY, Li XH, Li ZX, Gou GN, Zhang XZ, Tang GJ, Dan W, Ma L and Dong YH. 2016. Pliocene-Quaternary crustal melting in central and northern Tibet and insights into crustal flow. Nature Communications, 7: 11888

Wang R, Luo CH, Xia WJ, He WY, Liu B, Huang ML, Hou ZQ and Zhu DC. 2021b. Role of alkaline magmatism in formation of porphyry deposits in non-arc settings: Gangdese and Sanjiang metallogenic belts. Society of Economic Geologists Special Publications, 24: 205 – 229

Wang RC, Xie L, Zhu ZY and Hu H. 2019. Micas: Important indicators of granite-pegmatite-related rare-metal mineralization. Acta Petrologica Sinica, 35(1): 69 – 75 (in Chinese with English abstract)

Wang T, Wang XX and Li WP. 2000. Evaluation of multiple emplacement mechanisms: The Huichizi granite pluton, Qinling orogenic belt, central China. Journal of Structural Geology, 22(4): 505 – 518

Wang T, Wang XX, Guo L, Zhang L, Tong Y, Li S, Huang H and Zhang JJ. 2017. Granitoid and tectonics. Acta Petrologica Sinica, 33(5): 1459 – 1478 (in Chinese with English abstract)

Wang XL. 2017. Some new research progresses and main scientific problems of granitic rocks. Acta Petrologica Sinica, 33(5): 1445 – 1458 (in Chinese with English abstract)

Ward KM, Zandt G, Beck SL, Christensen DH and McFarlin H. 2014. Seismic imaging of the magmatic underpinnings beneath the Altiplano-Puna volcanic complex from the joint inversion of surface wave dispersion and receiver functions. Earth and Planetary Science Letters, 404: 43 – 53

Waters LE and Lange RA. 2015. An updated calibration of the plagioclase-liquid hygrometer-thermometer applicable to basalts through rhyolites. American Mineralogist, 100(10): 2172 – 2184

Welsch B, Hammer J, Baronnet A, Jacob S, Hellebrand E and Sinton J. 2016. Clinopyroxene in postshield Haleakala ankaramite: 2. Texture, compositional zoning and supersaturation in the magma. Contributions to Mineralogy and Petrology, 171(1): 6

Whittington AG, Hofmeister AM and Nabelek PI. 2009. Temperature-dependent thermal diffusivity of the Earth's crust and implications for magmatism. Nature, 458(7236): 319 – 321

Wilkinson JJ. 2013. Triggers for the formation of porphyry ore deposits in magmatic arcs. Nature Geoscience, 6(11): 917 – 925

Williams-Jones AE and Heinrich CA. 2005. $100^{th}$ anniversary special paper: Vapor transport of metals and the formation of magmatic-hydrothermal ore deposits. Economic Geology, 100(7): 1287 – 1312

Wilson CJ, Cooper GF, Chamberlain KJ, Barker SJ, Myers ML, Illsley-Kemp F and Farrell J. 2021. No single model for supersized eruptions and their magma bodies. Nature Reviews Earth & Environment, 2(9): 610 – 627

Wu FY, Liu XC, Ji WQ, Wang JM and Yang L. 2017. Highly fractionated granites: Recognition and research. Science China (Earth Sciences), 60(7): 1201 – 1219

Xing CM, Wang CY and Tan W. 2017. Disequilibrium growth of olivine in mafic magmas revealed by phosphorus zoning patterns of olivine from mafic-ultramafic intrusions. Earth and Planetary Science Letters, 479: 108 – 119

Xiong XL, Ni HW, Chen W, Ruan MF, Wang JT, Liu XC and Li L. 2020. Element migration of supercritical fluids in subduction zones: Progress and problems of experimental researches. Bulletin of Mineralogy, Petrology and Geochemistry, 39(3): 502 – 508 (in Chinese with English abstract)

Xu W, Zhu DC, Wang Q, Weinberg RF, Wang R, Li SM, Zhang LL and Zhao ZD. 2021. Cumulate mush hybridization by melt invasion: Evidence from compositionally diverse amphiboles in ultramafic-mafic arc cumulates within the eastern Gangdese Batholith, Southern Tibet. Journal of Petrology, 62(11): Egab073

Xu XS, Wang XL, Zhao K and Du DH. 2020. Progresses and tendencies of granite researches in last decade: A review. Bulletin of Mineralogy, Petrology and Geochemistry, 39(5): 899 – 911 (in Chinese with English abstract)

Xu YG, Zhong YT, Wei X, Chen J, Liu HQ, Xie W, Luo ZY, Li HY, He B, Huang XL, Wang Y and Chen Y. 2017. Permian mantle plumes and earth's surface system evolution. Bulletin of Mineralogy, Petrology and Geochemistry, 36(3): 358 – 373 (in Chinese with English abstract)

Yan LL, He ZY, Beier C and Klemd R. 2018. Geochemical constraints on the link between volcanism and plutonism at the Yunshan caldera complex, SE China. Contributions to Mineralogy and Petrology, 173(1): 4

Yang AY, Wang CG, Liang Y and Lissenberg CJ. 2019. Reaction between mid-ocean ridge basalt and lower oceanic crust: An experimental study. Geochemistry, Geophysics, Geosystems, 20(9): 4390 – 4407

Yang JH, Wu FY, Wilde SA, Xie LW, Yang YH and Liu XM. 2007. Tracing magma mixing in granite genesis: In situ U-Pb dating and Hf-isotope analysis of zircons. Contributions to Mineralogy and Petrology, 153(2): 177 – 190

Yang ZM, Lu YJ, Hou ZQ and Chang ZS. 2015. High-Mg diorite from Qulong in southern Tibet: Implications for the genesis of adakite-like intrusions and associated porphyry Cu deposits in collisional orogens. Journal of Petrology, 56(2): 227 – 254

Yao ZS and Mungall JE. 2020. Flotation mechanism of sulphide melt on vapour bubbles in partially molten magmatic systems. Earth and Planetary Science Letters, 542: 116298

Zajacz Z, Halter WE, Pettke T and Guillong M. 2008. Determination of fluid/melt partition coefficients by LA-ICPMS analysis of co-existing fluid and silicate melt inclusions: Controls on element partitioning. Geochimica et Cosmochimica Acta, 72(8): 2169 – 2197

Zajacz Z and Tsay A. 2019. An accurate model to predict sulfur concentration at anhydrite saturation in silicate melts. Geochimica et Cosmochimica Acta, 261: 288 – 304

Zandt G, Leidig M, Chmielowski J, Baumont D and Yuan X. 2003.

Seismic detection and characterization of the Altiplano-Puna magma body, Central Andes. Pure and applied geophysics, 160(3-4): 789-807

Zeebe RE and Caldeira K. 2008. Close mass balance of long-term carbon fluxes from ice-core $CO_2$ and ocean chemistry records. Nature Geoscience, 1(5): 312-315

Zeebe RE, Ridgwell A and Zachos JC. 2016. Anthropogenic carbon release rate unprecedented during the past 66 million years. Nature Geoscience, 9(4): 325-329

Zeng LS and Gao LE. 2017. Cenozoic crustal anatexis and the leucogranites in the Himalayan collisional orogenic belt. Acta Petrologica Sinica, 33(5): 1420-1444 (in Chinese with English abstract)

Zhai MG. 2017. Granites: Leading study issue for continental evolution. Acta Petrologica Sinica, 33(5): 1369-1380 (in Chinese with English abstract)

Zhang C, Li XY, Behrens H and Holtz F. 2022. Partitioning of OH-F-Cl between biotite and silicate melt: Experiments and an empirical model. Geochimica et Cosmochimica Acta, 317: 155-179

Zhang DH and Audétat A. 2017. What caused the formation of the giant Bingham Canyon porphyry Cu-Mo-Au Deposit? Insights from melt inclusions and magmatic sulfides. Economic Geology, 112(2): 221-244

Zhang HF, Harris N, Parrish R, Kelley S, Zhang L, Rogers N, Argles T and King J. 2004. Causes and consequences of protracted melting of the mid-crust exposed in the North Himalayan antiform. Earth and Planetary Science Letters, 228(1-2): 195-212

Zhang YZ, Wang XL, Li JY, He ZY, Zhang FF, Chen X, Wang S, Du DH, Huang Y and Jiang CH. 2021. Oligocene leucogranites of the Gangdese batholith, southern Tibet: fractional crystallization of felsic melts from juvenile lower crust. Journal of Petrology, 62(11): egab076

Zhang ZC, Hou T, Li HM, Li JW, Zhang ZH and Song XY. 2014. Enrichment mechanism of iron in magmatic hydrothermal system. Acta Petrologica Sinica, 30(5): 1189-1204 (in Chinese with English abstract)

Zhang ZM, Dong X, Ding HX, Tian ZL and Xiang H. 2017. Metamorphism and partial melting of the Himalayan orogen. Acta Petrologica Sinica, 33(8): 2313-2341 (in Chinese with English abstract)

Zhao K, Xu XS and Erdmann S. 2018. Thermodynamic modeling for an incrementally fractionated granite magma system: Implications for the origin of igneous charnockite. Earth and Planetary Science Letters, 499: 230-242

Zheng YC, Liu SA, Wu CD, Griffin WL, Li ZQ, Xu B, Yang ZM, Hou ZQ and O'Reilly SY. 2019. Cu isotopes reveal initial Cu enrichment in sources of giant porphyry deposits in a collisional setting. Geology, 47(2): 135-138

Zhou JC. 1984. The amount of Undercooling and the texture of acidic rocks. Journal of Mineralogy and Petrology, 4(4): 26-32 (in Chinese with English abstract)

Zhou JS, Yang ZS, Hou ZQ, Liu YC, Zhao XY, Zhang X, Zhao M and Ma W. 2017. The geochemical evolution of syncollisional magmatism and the implications for significant magmatic-hydrothermal lead-zinc mineralization (Gangdese, Tibet). Lithos, 288-289: 143-155

Zhou JS, Yang ZS, Wang Q, Zheng YC, Hou ZQ and Wyman DA. 2020a. Extraction of high-silica granites from an upper crustal magma reservoir: Insights from the Narusongduo magmatic system, Gangdese arc. American Mineralogist, 105(10): 1572-1584

Zhou JS, Yang ZS, Hou ZQ and Wang Q. 2020b. Amphibole-rich cumulate xenoliths in the Zhazhalong intrusive suite, Gangdese arc: Implications for the role of amphibole fractionation during magma evolution. American Mineralogist, 105(2): 262-275

Zhou JS, Wang Q, Wyman DA and Zhao ZH. 2020c. Petrologic reconstruction of the Tieshan magma plumbing system: Implications for the genesis of magmatic-hydrothermal ore deposits within originally water-poor magmatic systems. Journal of Petrology, 61(5): egaa056

Zhou JS, Wang Q, Xing CM, Ma L, Hao LL, Li QW, Wang ZL and Huang TY. 2021a. Crystal growth of clinopyroxene in mafic alkaline magmas. Earth and Planetary Science Letters, 568: 117005

Zhou JS, Wang Q, Xu YG, Cempírek J, Wang H, Ma JL, Wei GJ, Huang TY, Zhu GH and Zhang L. 2021b. Geochronology, petrology, and lithium isotope geochemistry of the Bailongshan granite-pegmatite system, northern Tibet: Implications for the ore-forming potential of pegmatites. Chemical Geology, 584: 120484

Zhou JS, Wang Q, Wyman DA, Zhao ZH, Zhang L and He PL. 2022. The efficiency of copper extraction from magma bodies: Implications for mineralization potential and fluid-silicate melt partitioning of copper. American Mineralogist, doi: 10.2138/am-2021-7951

Zhu DC, Wang Q, Zhao ZD, Niu YL, Hou ZQ, Pan GT and Mo XX. 2018. Magmatic origin of continental arcs and continental crust formation. Earth Science Frontiers, 25(6): 67-77 (in Chinese with English abstract)

## 附中文参考文献

陈华勇，吴超. 2020. 俯冲带斑岩铜矿系统成矿机理与主要挑战. 中国科学(地球科学)，50(7)：865-886

郭正府，郑国东，孙玉涛，张茂亮，张丽红，成智慧. 2017. 中国大陆地质源温室气体释放. 矿物岩石地球化学通报，36(2)：204-212

侯增谦，郑远川，杨志明，杨竹森. 2012. 大陆碰撞成矿作用：Ⅰ. 冈底斯新生代斑岩成矿系统. 矿床地质，31(4)：647-670

李霓，孙嘉祥. 2018. 火山岩中熔体包裹体研究进展. 矿物岩石地球化学通报，37(3)：414-423

刘嘉麒，陈双双，郭文峰，孙春青，张茂亮，郭正府. 2015. 长白山火山研究进展. 矿物岩石地球化学通报，34(4)：710-723

罗照华，黄忠敏，柯珊. 2007. 花岗质岩石的基本问题. 地质论评，53(增1)：180-226

马昌前. 1987. 一门新兴的边缘学科——岩浆动力学. 世界科学，(6)：45-47

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(5)：1479-1488

马昌前，邹博文，高珂，文霞. 2020. 晶粥储存、侵入体累积组装与花岗岩成因. 地球科学，45(12)：4332-4351

莫宣学. 2011. 岩浆与岩浆岩：地球深部“探针”与演化记录. 自然杂志，33(5)：255-259

秦克章，赵俊兴，何畅通，施睿哲. 2021. 喜马拉雅琼嘉岗超大型伟晶岩型锂矿的发现及意义. 岩石学报，37(11)：3277-3286

任钟元，张乐，吴亚东，徐晓波，张磊，梅盛旺，于亚锋，罗清晨，张庆霖. 2018. 熔体包裹体在镁铁质火山岩成因研究中的应用. 矿物岩石地球化学通报，37(3)：395-413

王德滋. 2004. 华南花岗岩研究的回顾与展望. 高校地质学报，10(3)：305-314

王汝成，谢磊，诸泽颖，胡欢. 2019. 云母：花岗岩-伟晶岩稀有金属成矿作用的重要标志矿物. 岩石学报，35(1)：69-75

王涛，王晓霞，郭磊，张磊，童英，李舢，黄河，张建军. 2017. 花岗岩与大地构造. 岩石学报，33(5)：1459-1478

王孝磊. 2017. 花岗岩研究的若干新进展与主要科学问题. 岩石学报，33(5)：1445-1458

王焰，钟宏，曹勇华，魏博，陈晨. 2020. 我国铂族元素、钴和铬主要矿床类型的分布特征及成矿机制. 科学通报，65(33)：3825-3838

吴福元，刘小驰，纪伟强，王佳敏，杨雷. 2017. 高分异花岗岩的识别与研究. 中国科学(地球科学), 47(7): 745 - 765
熊小林，倪怀玮，陈伟，阮梦飞，王锦团，刘星成，李立. 2020. 俯冲带超临界流体的元素迁移：实验研究进展和存在问题. 矿物岩石地球化学通报, 39(3): 502 - 508
徐夕生，王孝磊，赵凯，杜德宏. 2020. 新时期花岗岩研究的进展和趋势. 矿物岩石地球化学通报, 39(5): 899 - 911
徐义刚，钟玉婷，位荀，陈军，刘海泉，颉炜，罗震宇，李洪颜，何斌，黄小龙，王焰，陈赟. 2017. 二叠纪地幔柱与地表系统演变. 矿物岩石地球化学通报, 36(3): 359 - 373
曾令森，高利娥. 2017. 喜马拉雅碰撞造山带新生代地壳深熔作用与淡色花岗岩. 岩石学报, 33(5): 1420 - 1444
翟明国. 2017. 花岗岩：大陆地质研究的突破口以及若干关键科学问题——"岩石学报"花岗岩专辑代序. 岩石学报, 33(5): 1369 - 1380
张招崇，侯通，李厚民，李建威，张作衡，宋谢炎. 2014. 岩浆-热液系统中铁的富集机制探讨. 岩石学报, 30(5): 1189 - 1204
张泽明，董昕，丁慧霞，田作林，向华. 2017. 喜马拉雅造山带的变质作用与部分熔融. 岩石学报, 33(8): 2313 - 2341
周金城. 1984. 过冷度与酸性岩结构. 矿物岩石, 4(4): 26 - 32
朱弟成，王青，赵志丹，牛耀龄，侯增谦，潘桂棠，莫宣学. 2018. 大陆边缘弧岩浆成因与大陆地壳形成. 地学前缘, 25(6): 67 - 77