Silicic magma reservoirs and pegmatite-type rare-metal mineralization

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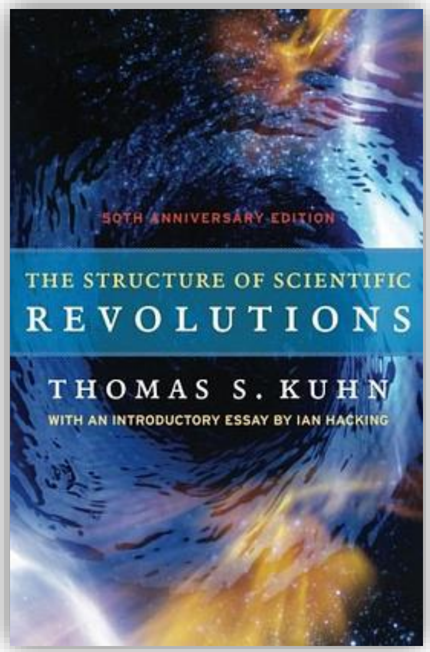
Introduction

Every scientific discipline has its characteristic set of problems and systematic methods for obtaining their solution - that is, its paradigm.

There are four steps in evolution, scientific discovery

- Revolution, developing new paradigm
- Normal science, studies inside paradigm
- Anomalies
- Crisis



Thomas S. Kuhn, 1962

Magma chamber

- **The traditional paradigm held views of magma chambers as large, molten melt bodies (*e.g. Daly, 1933*)**
- **Anomalies**

  The melt content of magma reservoirs are less than 40%, or even lower (*e.g. Huang et al., 2015*).

  Long term residence of crystals in magma reservoirs near the solidus (*e.g. Cooper and Kent, 2014; Rubin et al., 2017*).

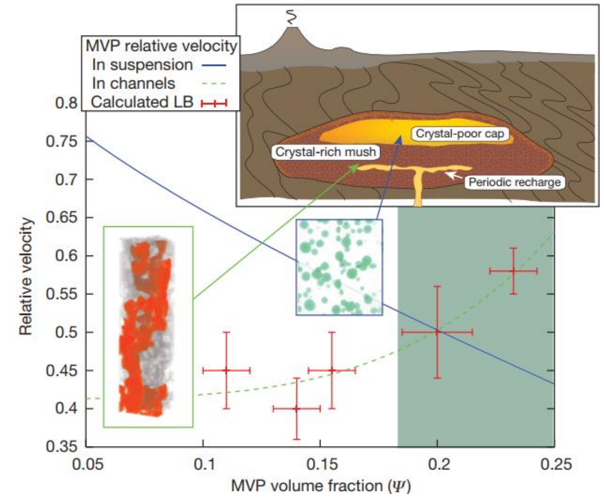
  …
- **Crisis-- the growth and evolution mechanism of continental crust "critically" dependent on the understanding of magma reservoirs.**

Crystal mush storage

- **New paradigm-- A long-lived magmatic system dominated by crystals and mainly cooled by thermal conduction (**e.g. *Bachmann and Bergantz 2004; Hildreth 2004; Marsh 2004; Cooper and Kent 2014; Bachmann and Huber 2016; Huber and Parmigiani 2018; Jackson et al. 2018***)**

- **Keywords:**

- Near-solidus silicic magma reservoirs
- Cold storage
- Rapid remobilization
- Multiple additions and incremental assembly



Bachmann and Huber, (2016) Nature

Crystal mush compaction

- **Relative viscosity (η) of high crystal content melt is the key point：**

$$\eta = (1 + B\phi)$$

φ is the volume fraction of suspended particles and B (=2.5) is the Einstein coefficient (*Einstein, 1905*).

$$\eta = \left(1 - \frac{\phi}{\phi_m}\right)^{-2.5}$$

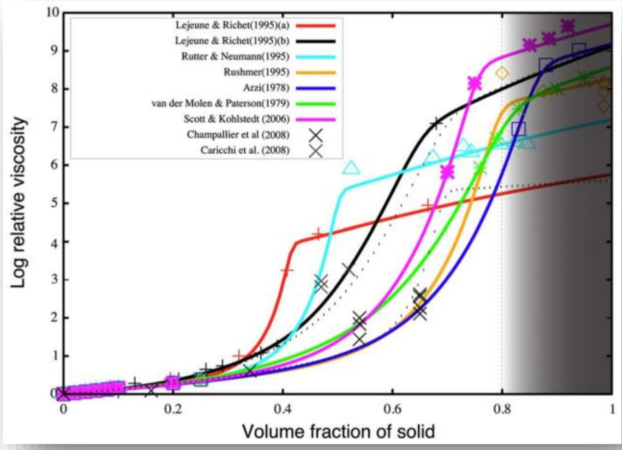
High concentration suspension with rigid particle interactions (*Roscoe, 1952*)

$$\eta = \theta_0 \exp\left\{\operatorname{arctang}[\omega(\phi - \phi*)] + \frac{\pi}{2}\right\}$$

Non-Newtonian fluid (*Melnik and Sparks, 1999, 2002*)

$$\eta(\phi) = \left\{1 - \alpha \operatorname{erf}\left(\frac{\sqrt{\pi}}{2}\phi\left[1 + \frac{\beta}{(1-\phi)^{\gamma}}\right]\right)\right\}^{-B/\alpha}$$

High crystal content silicate melts (*Costa, 2005, 2007, 2009*)

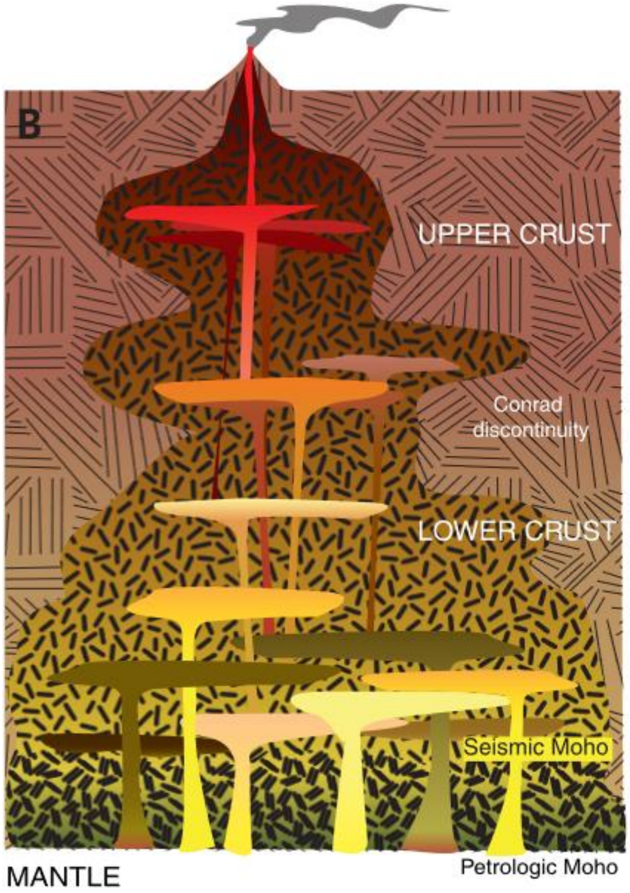


Costa, 2009

Transcrustal magmatic systems

- **Magmatic plumbing systems**
  - Multiple magma reservoirs connected by rock walls/veins
  - Location of magma/crystal-mush storage and evolution
  - Transport of magma and fluids

- **Comprehensive evolution system of plutonic rocks, volcanic rocks and pegmatite.**



Cashman et al., 2017

Challenges to magma evolution

- **Magma evolution theory needs new interpretation**

  Magma mixing;

  Fractional crystallization;

  Water saturation;

  Migration of flux;

  Magmatic-hydrothermal transition …….

- **Pegmatites are recorder of late magmatic and hydrothermal processes.**

• Magmatic volatile phase (MVP): a very general term for fluids and hydrous silicate liquids in magmatic systems.
• Silicate melt: a silicate-rich liquid with minor (<10wt%) amounts of dissolved volatile species.
• H_2O : Similar to incompatible elements, usually tends to enter MVP.
• Fluid: H_2O -dominated phase that contains minor amounts of other components. A fluid can be liquid, gaseous/ vaporous or supercritical in state.

Pegmatite "puzzle": genesis

- **Granite**

  Planetary evolution indicator;

  No water no granite.

- **Highly evolved granite**

  Extremely fractionated and volatile-rich;

  Rare metal (element) enriched (e.g. Ta, Nb, Li, Cs…);

- **Granitic pegmatite**

  Giant grains, clumps, and veins…;

  With high evolved features and chemically close to granite.

- **What is the evolutionary relationship between granite and pegmatite?**

Pegmatite “puzzle”: mineralization

- **Critical industrial resources**

  Spodumene, lepidolite;

  Niobium, tantalum, lithium, beryllium…;

  Li-battery, catalyzer, advanced materials….

- **Gemstone**

  Emerald; Aquamarine; Tourmaline; Amazonite; Topaz.

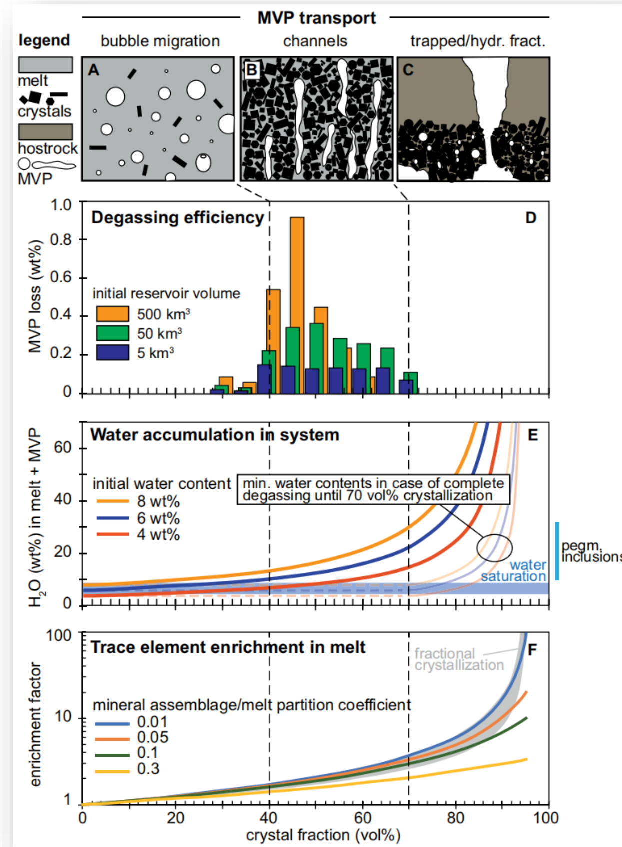
- **However, rare-metal mineralization is also relatively rare in known pegmatite district (**<<1%, *London and Morgan., 2012***).**

- **Why a diversity of mineralization in pegmatites?**

Answers from numerical simulations

- **Physical and chemical constraints**
  - Fractional crystallization cannot explain the formation of pegmatite.
  - At near-solidus conditions, magmatic reservoirs are volumetrically dominated by MVP and crystals rather than melt.
  - Pegmatitic liquids may consist of solute-rich MVP or even single-phase hydrous silicate liquids, and playing a key role in element transport.

- **Can natural samples reveal more information?**



Troch et al., 2022

Our research

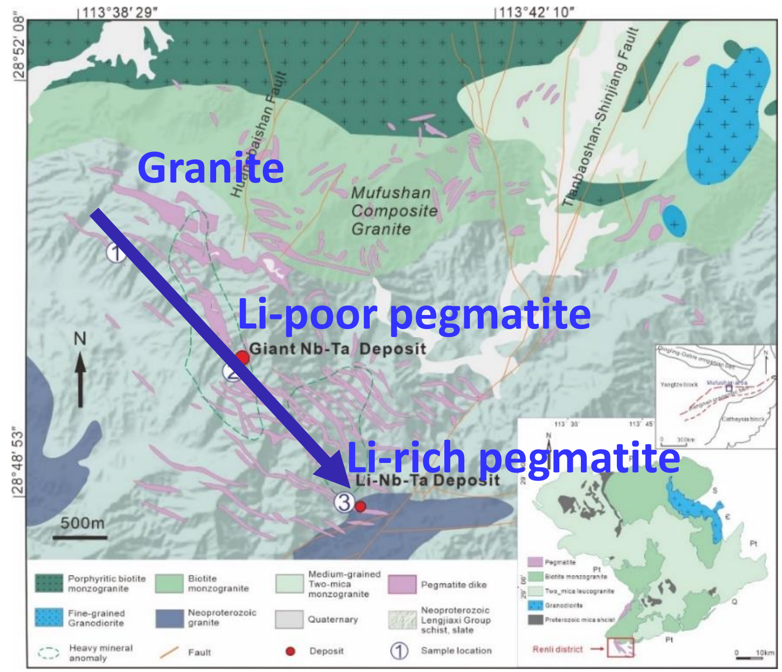
- **Geological setting: highly evolved granite-pegmatite system in Mufushan complex in South China.**
- **Petrography**

  Biotite granite;

  Muscovite granite;

  Tourmaline pegmatite;

  Spodumene pegmatite.



- **Deposit geology**

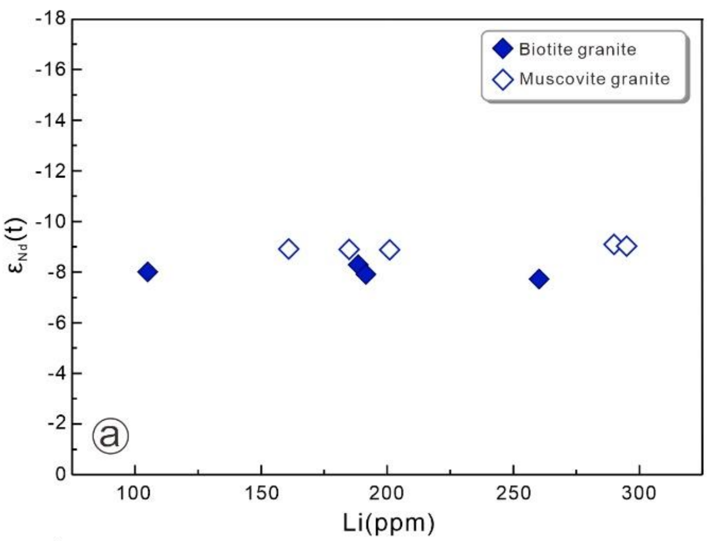
  Giant Nb-Ta deposit;

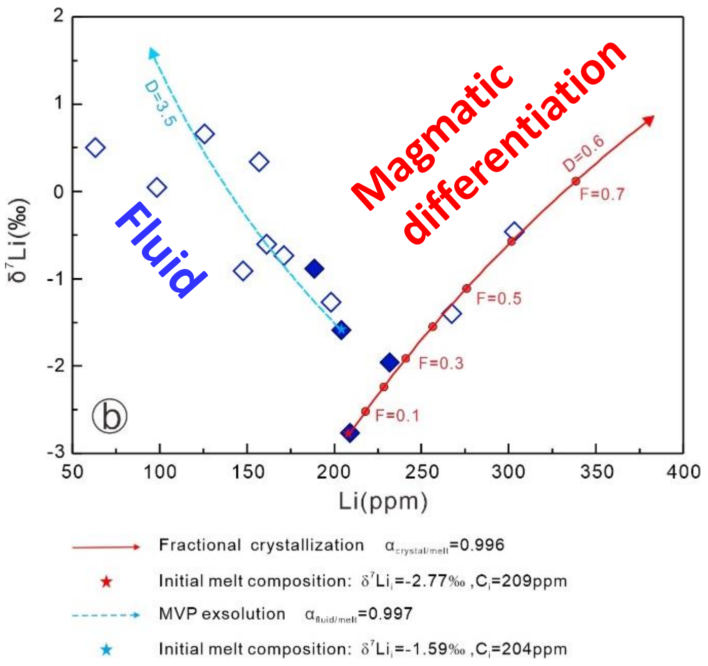
  Li- Nb-Ta deposit;

- **Diversity of Nb-Ta and Li mineralization in pegmatite?**

Granite evolution

- **Granites are from the same, isotopically homogeneous magma reservoir in Mufushan complex (*cf. Wang et al., 2014; Xiong et al., 2020*).**
- **Lithium isotope can identify two processes (*cf. Li J et al., 2018, GCA*).**
  - ★ Fractional crystallization (60-65 vol%)
  - ★ Obvious hydrothermal processes





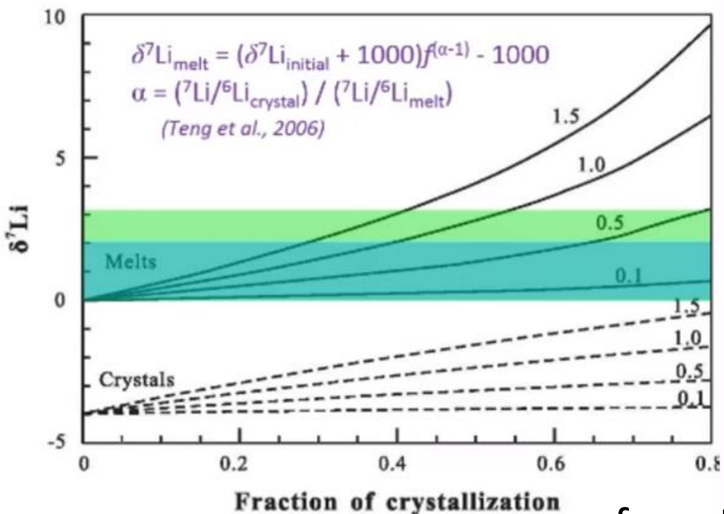
Rayleigh fractionation model

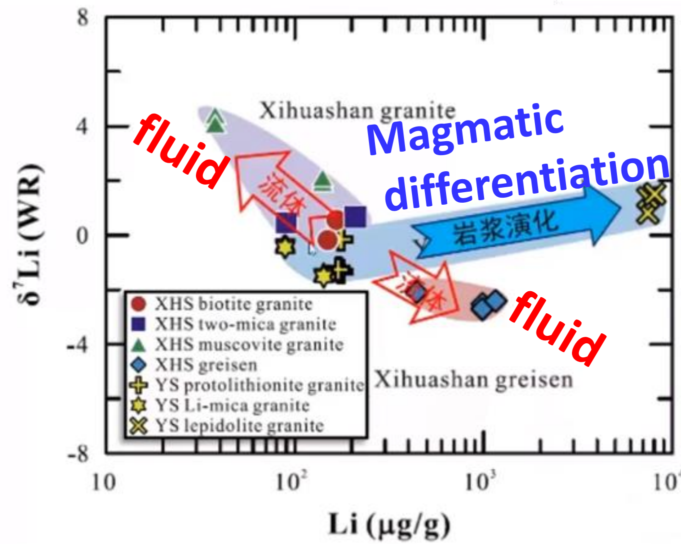
Comment

$D_{Li}^{mica/melt} = \sim 0.8\text{–}1.67$ *(Icenhower and London, 1995)*

$D_{Li}^{feldspar/melt} = 0.09\text{–}0.68$; mostly < 0.5 *(Tomascak et al., 2016)*

$D_{Li}^{quartz/melt} < 0.01$





from Li J et al. (2018)

- **Li is a moderately or strongly incompatible element in the granite system.**
- **Can magmatic differentiation enrich two orders of magnitude of Li?**

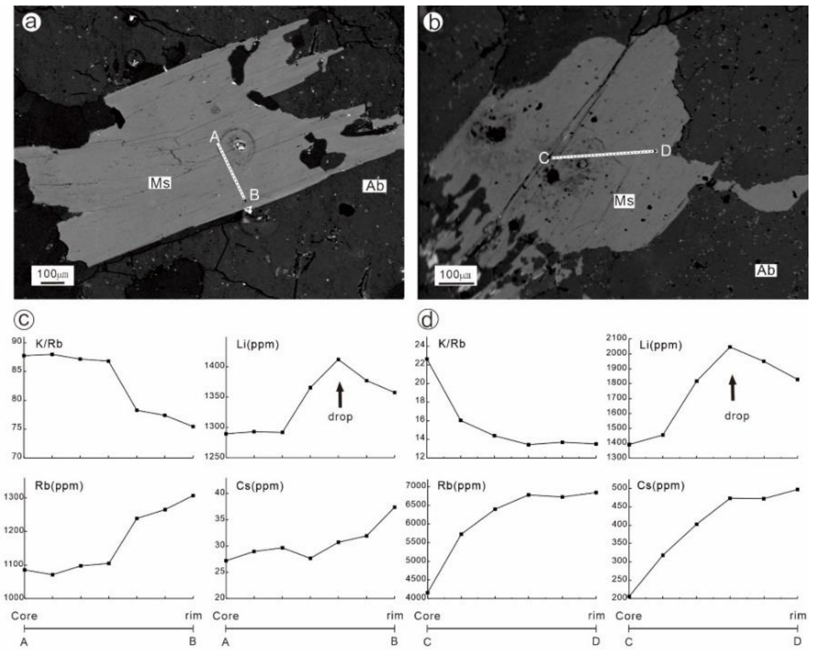
Fluid-rock interaction vs. MVP exsolution?

- **Small range of trace element changes related to a closed magmatic-hydrothermal system.**
- **Rb tends to enter the melt during fluid-melt interactions (*e.g. Audétat et al., 2020; Borchert et al., 2010*).**

  There are two trends in the concentration of Li.

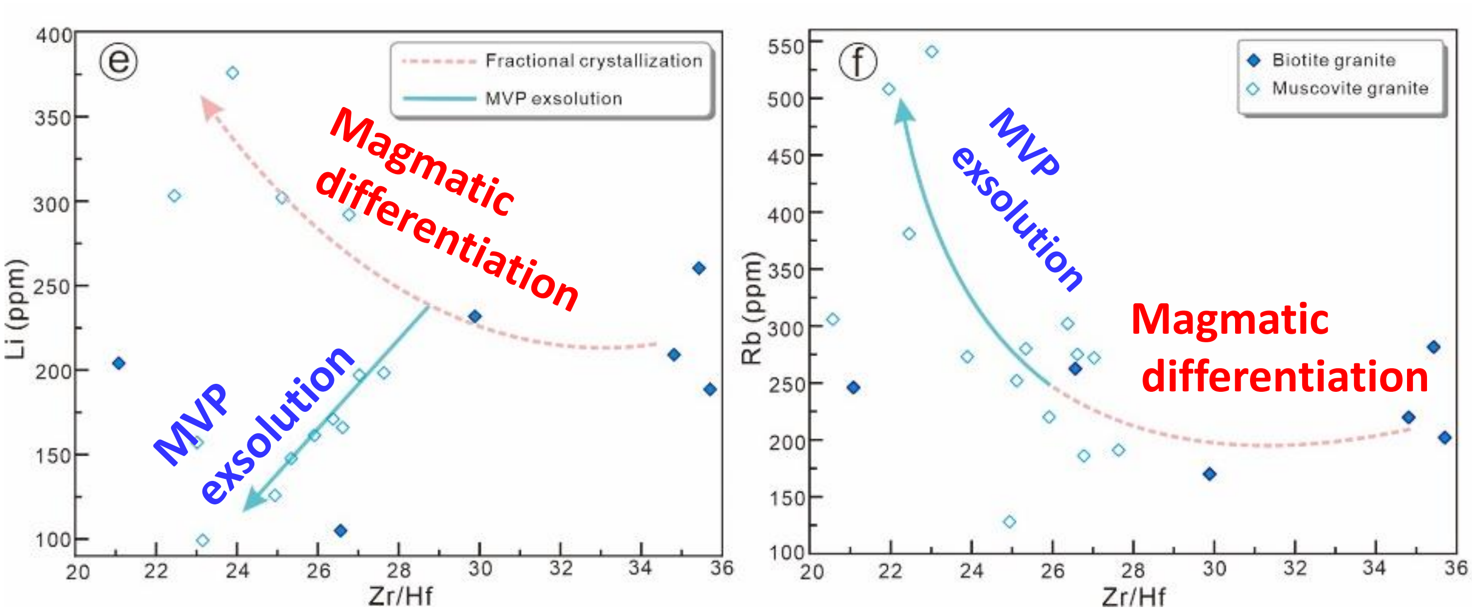
  The Rb concentrations increase sharply.

- **No obvious metasomatic texture.**



- **Magmatic melt has reached water saturation at muscovite granite crystallization stage.**

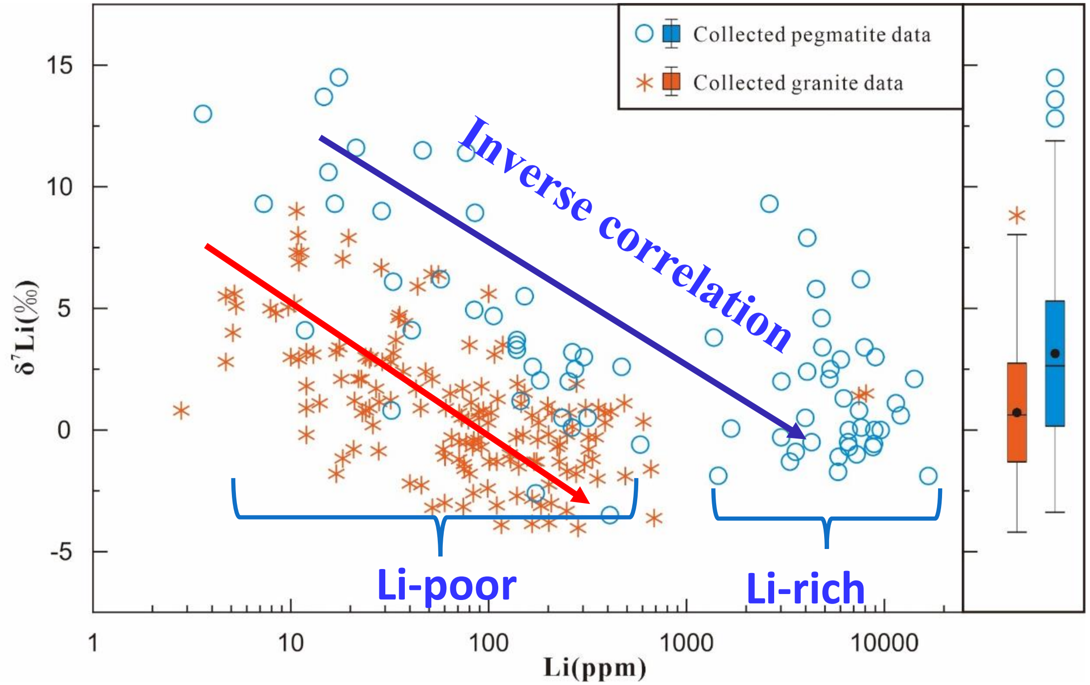
MVP: high Li, low Rb, and Low δ⁷Li



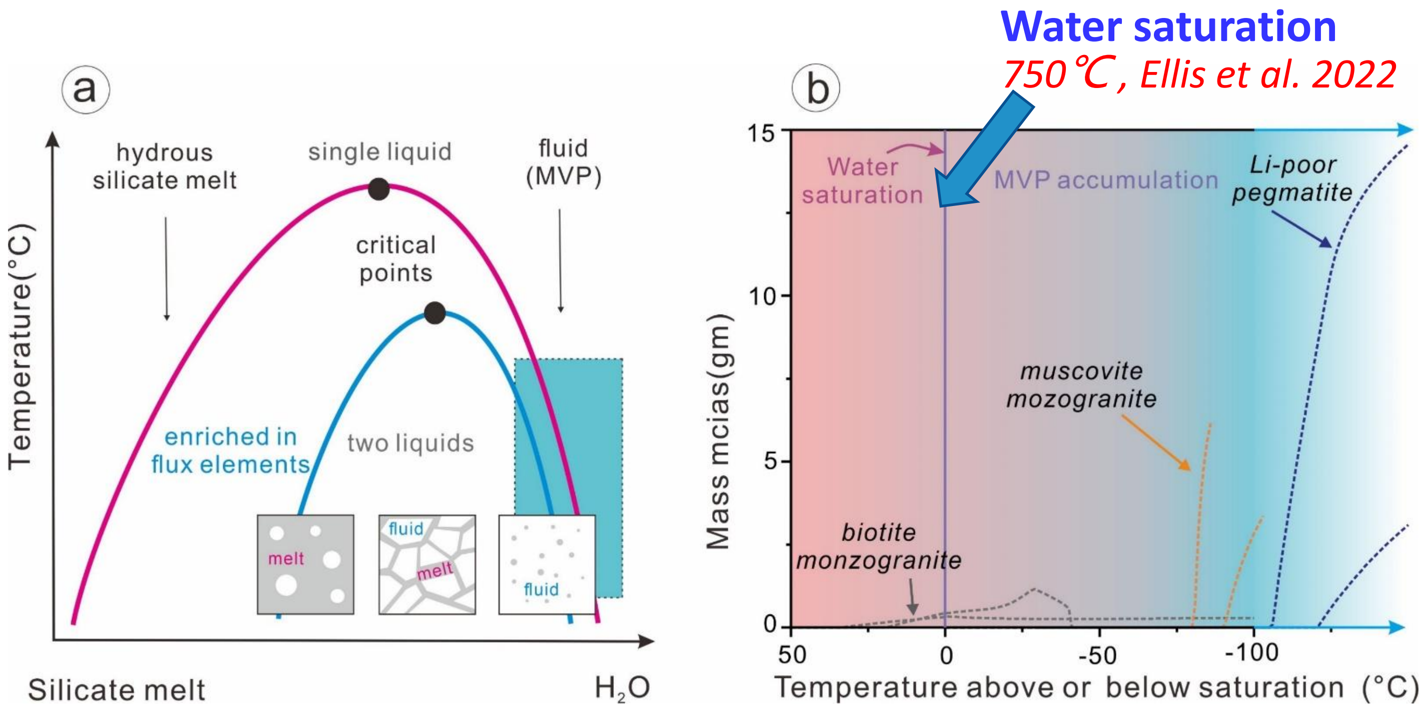
- **Granites with low Li contents reflect the remaining silicic melt after MVP exsolution.**
- **MVP exsolved from magma has the characteristics of low Rb, high Li contents, and relatively low δ^7Li value (*Fan et al.,2020; Ellis et al., 2022*).**

Widespread MVP exsolution

- Li concentration is negatively correlated with Li isotope composition.
- Li-rich pegmatite has relatively low δ^7Li value.
- MVP exsolution is widespread in granite and pegmatite systems.



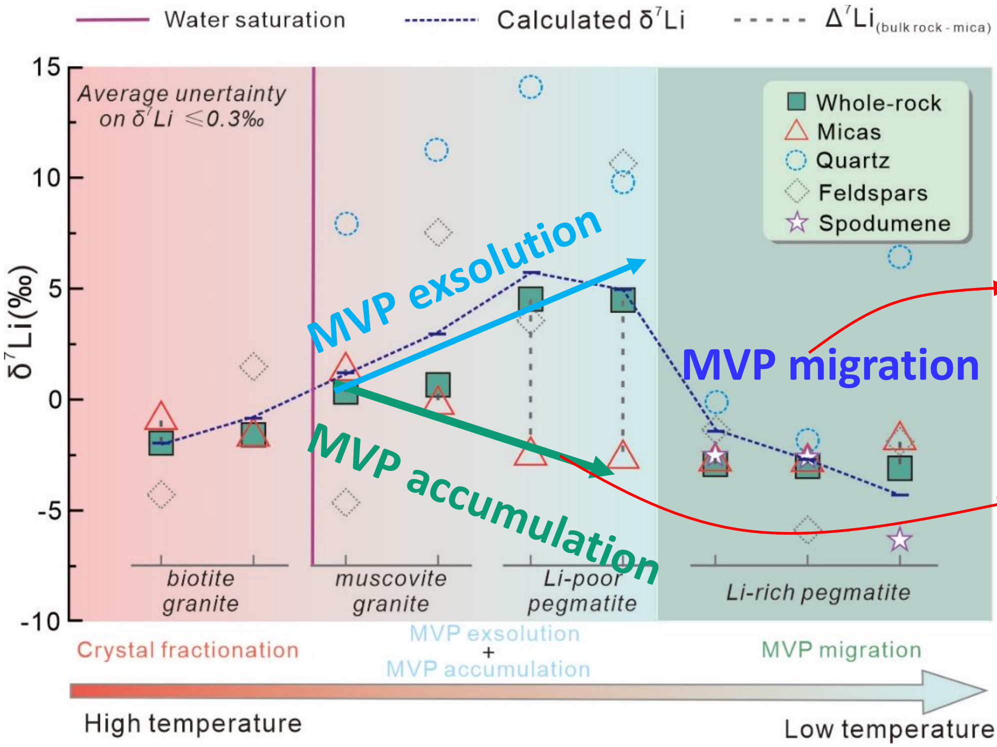
Transformation from granite to pegmatite



- **MVP exsolution is more likely a precondition of pegmatite than a direct reason for making coarse crystal particles.**
- **MVP accumulation may be one of the important factors for the formation of pegmatite (*Fig. b by MELTS model*).**

Granite-pegmatite evolution

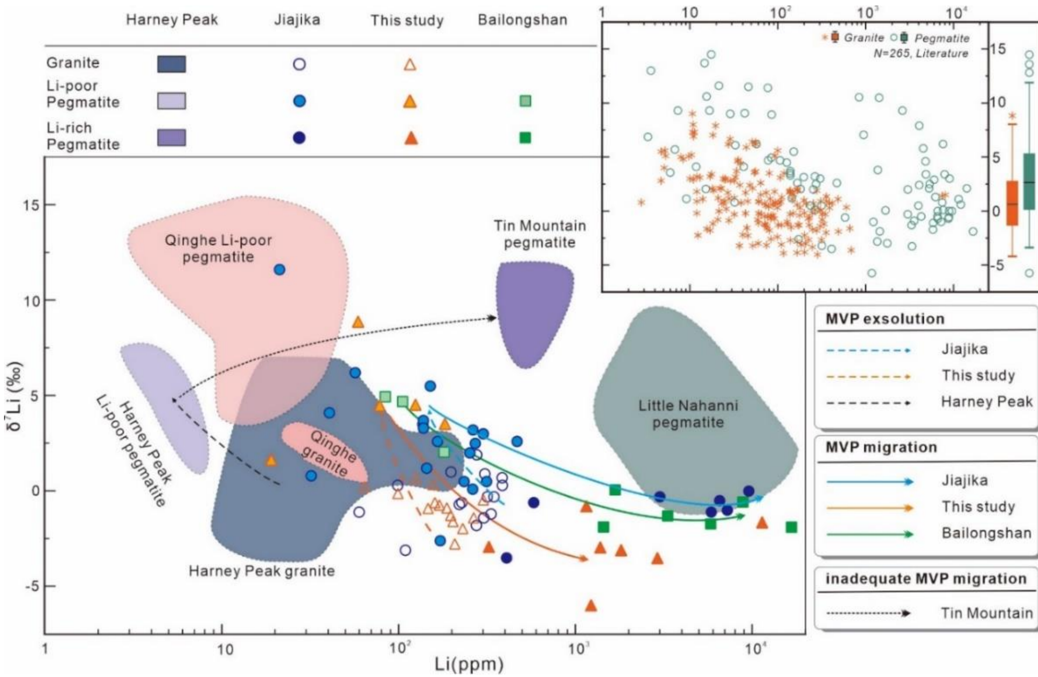
- **Li-poor pegmatite formed during MVP exsolution and MVP accumulation period.**
- **Li-rich pegmatite was formed by low-temperature long-distance migration.**

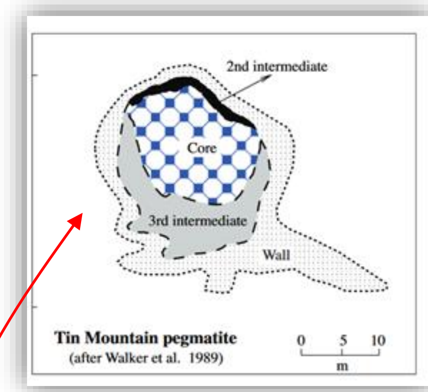


MVP exsolved from silicic magmas trend toward **high Li contents and low δ^7Li**.

Magmatic volatile phase trapped between **layers of mica crystals** (*Ellis et al., 2022*).

Granite-pegmatite evolution



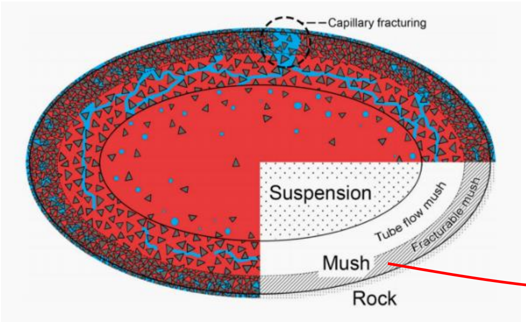


The zoned ringlike crystal distribution (*Teng et al., 2006*) is conducive to **mixing**, rather than **MVP migration**.

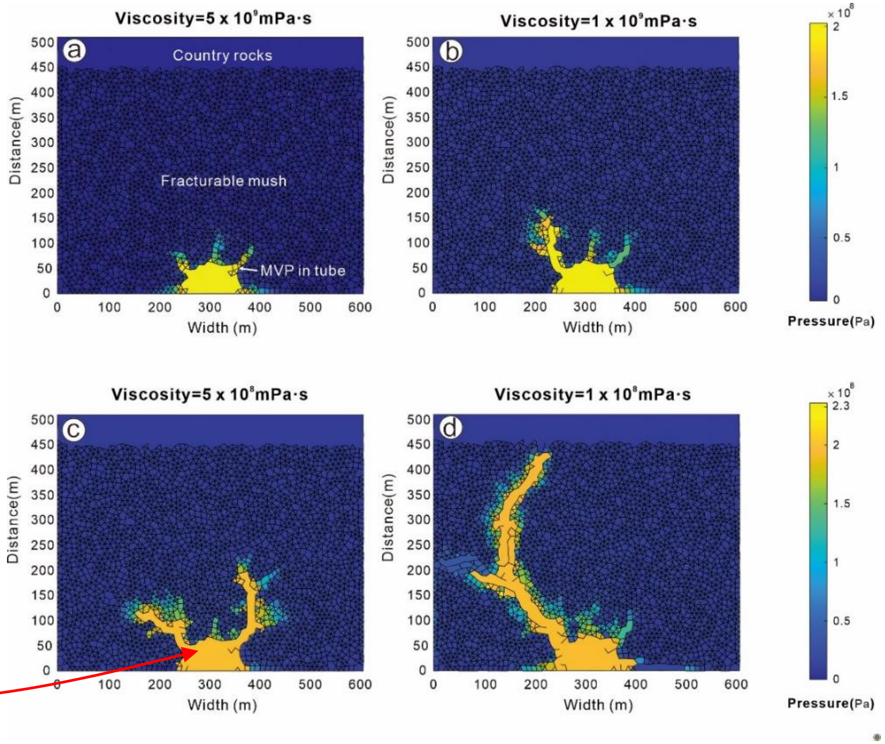
- **From granite to Li-poor pegmatite to Li-rich pegmatite:**
- **“Horn” like evolution curve.**
- **The angle of the “horn” depends on the degree of MVP migration.**
- **Inadequate MVP migration may lend to some Li-rich pegmatites with high δ⁷Li value.**

MVP Viscosity and Li mineralization

- Low viscosity Li-rich fluids (MVP) can migrate further and expand into larger fractures.
- The migration efficiency of MVP is related to the mineralization of Li, Nb, and Ta etc.



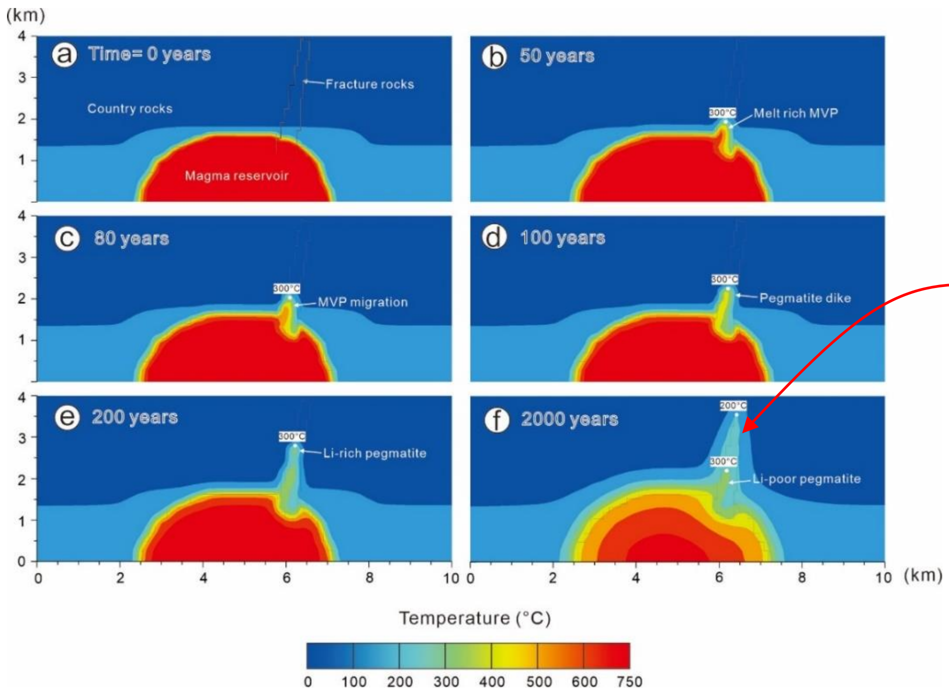
Lamy-Chappuis et al., 2020



Discrete element simulation

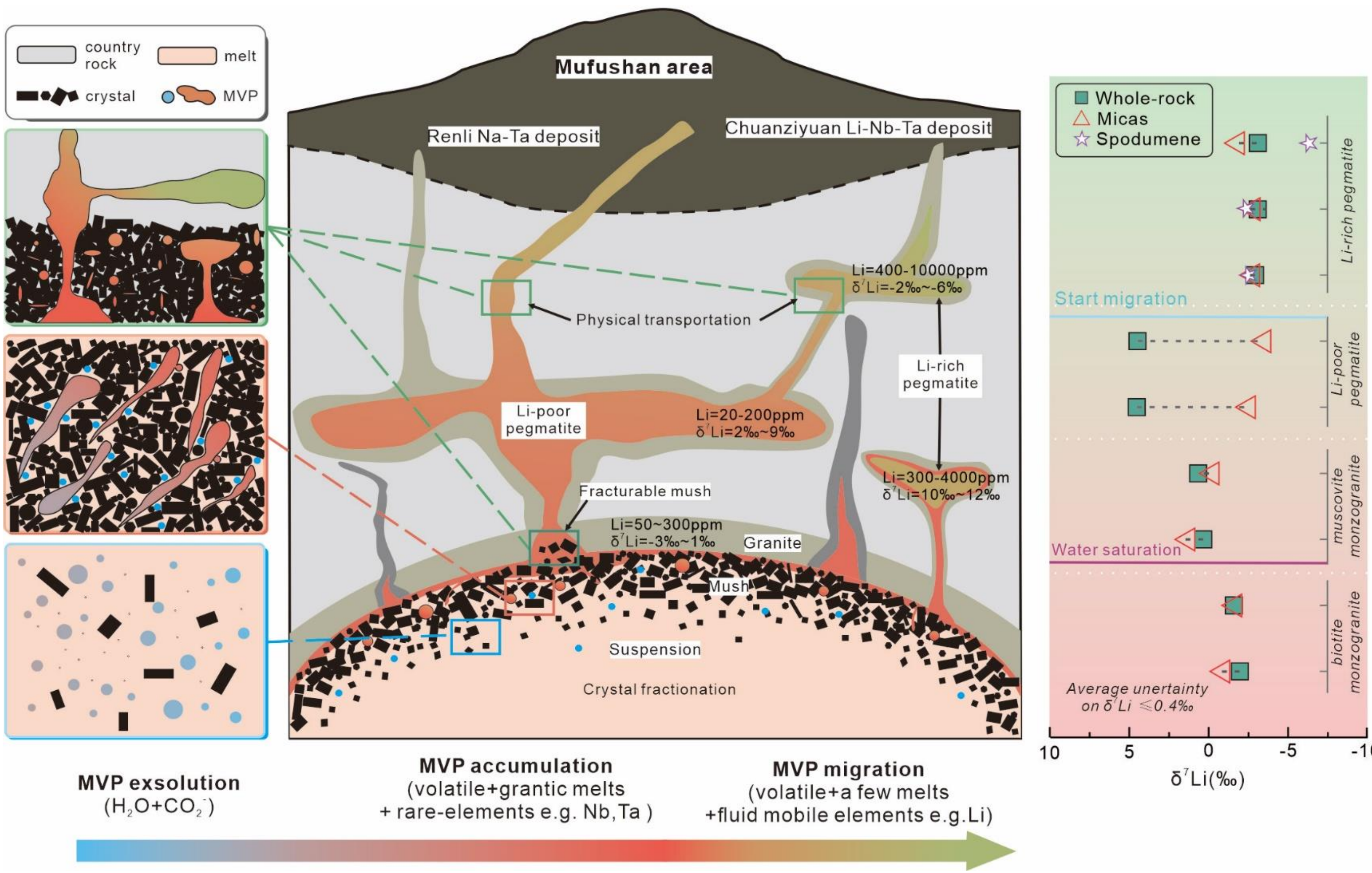
Migration distance and cooling time

- **The Li-rich pegmatite can migrate about 3km away from the magma reservoir.**
- **Li-rich pegmatite crystallizes rapidly in decades, but Li-poor pegmatite takes thousands of years to cool.**



The crystallization temperature of pegmatite is generally **300 - 400 ℃**, and fluxing components could lower the temperature.

Implications



Implications

- **The findings of this study are as follows, though some of them need to be confirmed by further work:**
  - **MVP exsolution is not the direct reason for making coarser crystal particles.**
  - **MVP accumulation might have an impact on both pegmatite formation and element enrichment.**
  - **MVP migration or physical transportation has the potential to cause the diversity of rare-metal mineralization.**

Unlabelled images and content are from:

Ye, X.Y., Li, B.*, Chen, X.D., Lu, A.H., Lei, J., Zhao, L.,Tan, D.B., Xiao, Y.L.*, 2023, Lithium isotopic systematics and numerical simulation for highly-fractionated granite-pegmatite system: Implications for the pegmatite-type rare-metal mineralization, *Ore Geology Reviews.* (Accept)

Ye, X.Y., Li, B.*, Tan, D.B., Zhu, Z.Y., Xiao, Y.L., 2023, A critical review of lithium isotope analytical methods, with implications for rare-element mineralization in granite-pegmatite systems. (Major revision)