Depths of magma storage in volcanic arcs: testing the influence of regional parameters using a global data compilation

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ABSTRACT

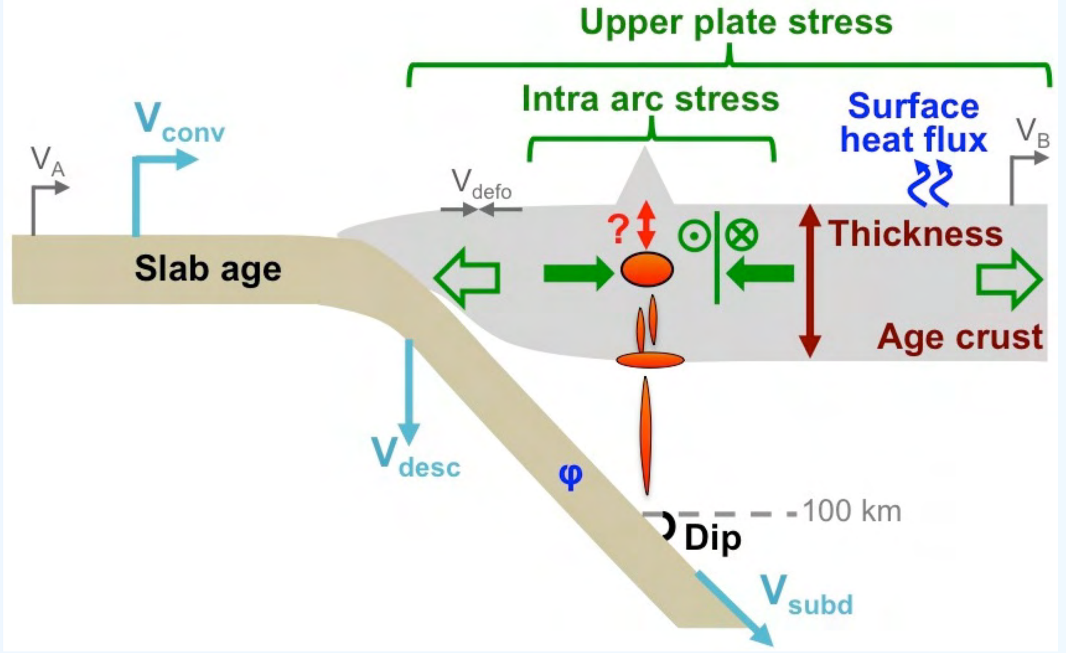
We use a **global data compilation** to test which **regional parameters influence the depths of magma storage** in **volcanic arcs** using data at 70 volcanoes in 8 arcs.

We consider **13 parameters** including the structure of the upper crust, the stress regimes, the kinematic of the subduction, the structure and geometry of the slab, the timing of the subduction, and the thermal structure.

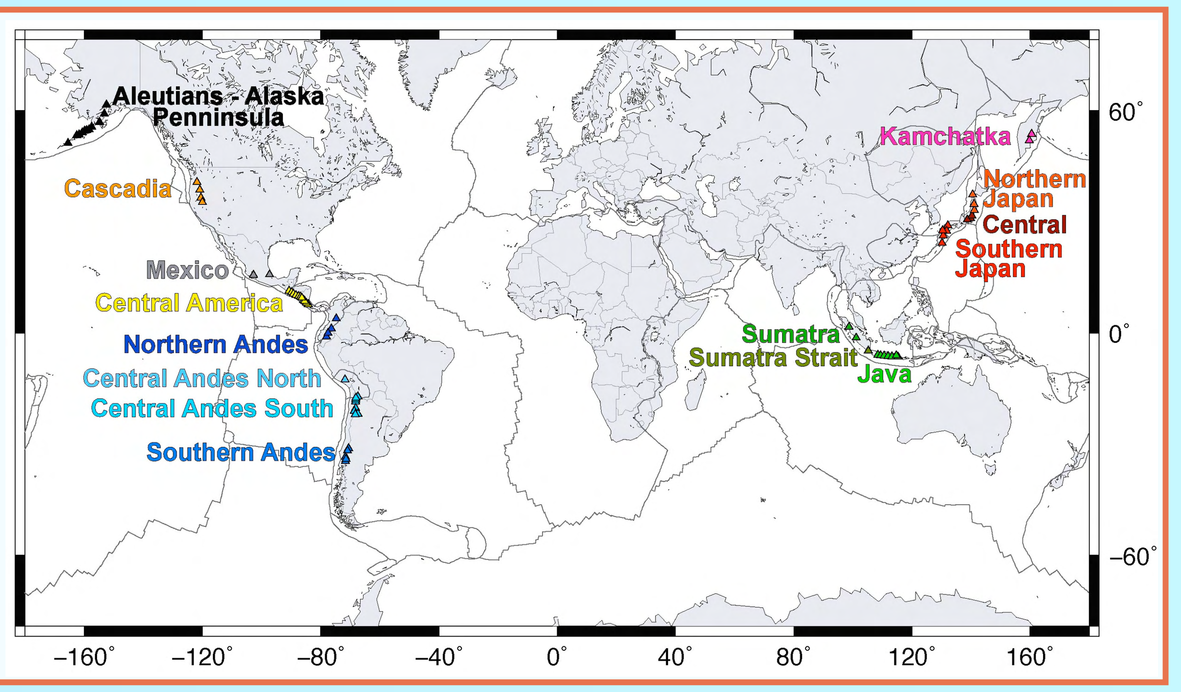
We show that the **depths of magma storage are influenced by the crustal structure and the stress regime**: shallow reservoirs preferentially develop in **young, thin** crusts in **extensive or strike slip stress regimes** suggesting that **buoyancy, stress orientation, and preexisting structures** have a first order effect on magma ascent.

No correlations with kinematic parameters of subductions are observed suggesting that the rates of melt generation have less effect on crustal magma ascent than the crustal parameters themselves.

1/ CONCEPT AND METHOD



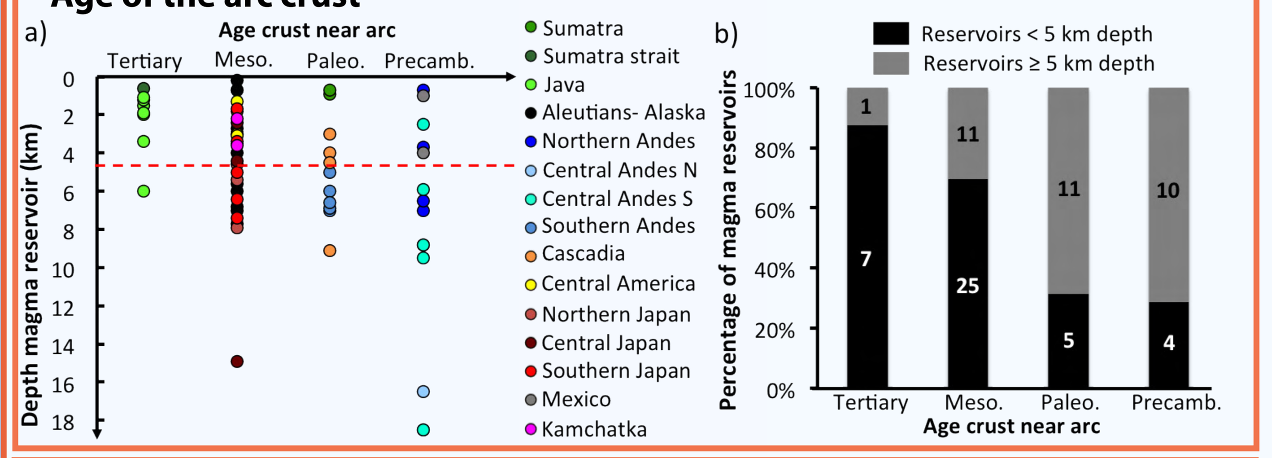
- **CONCEPT**: *Chaussard and Amelung (2012)* **detected regional trends in depths of magma storage using space geodesy** along complete volcanic arcs.
- **GOAL**: Test which **regional parameters correlate with the depths of magma reservoirs** to better constrain **what influences magma ascent in volcanic arcs**.
- **METHOD**: **Global data compilation**: data collected at 70 andesitic volcanoes in 8 continental and transitional arcs.
- Figure 1, left: cartoon of the **different parameters tested** as potentially influencing the depths of magma storage: **upper plate age and thickness** (dark red), the **intra-arc and upper plate stress regimes** (green), the **convergence rate, the subduction rate, and the vertical descent rate** (light blue), the **slab age and dip angle** (black), the **total duration of the subduction and the duration of the current subduction** (not represented), and the **surface heat flux and slab temperature** (thermal parameter φ)(dark blue).
- Figure 2, right: **location of the volcanoes** and color-code used to refer at each volcanic region.
- **LIMITS**: **availability of data on a global scale**. Do not consider volcano-dependent parameters: magma properties (density, viscosity, volatile content), volcanic structure (volcano volume, spacing), which may influence the depths of magma storage but are not available on a global basis.
  -> focus on **continental and transitional volcanic arcs** to limit the crustal structure variability.
  -> focus on **andesitic volcanoes** or with an andesitic component (basaltic-andesitic to andesitic-dacitic volcanoes) to limit the magma variability (density and viscosity).



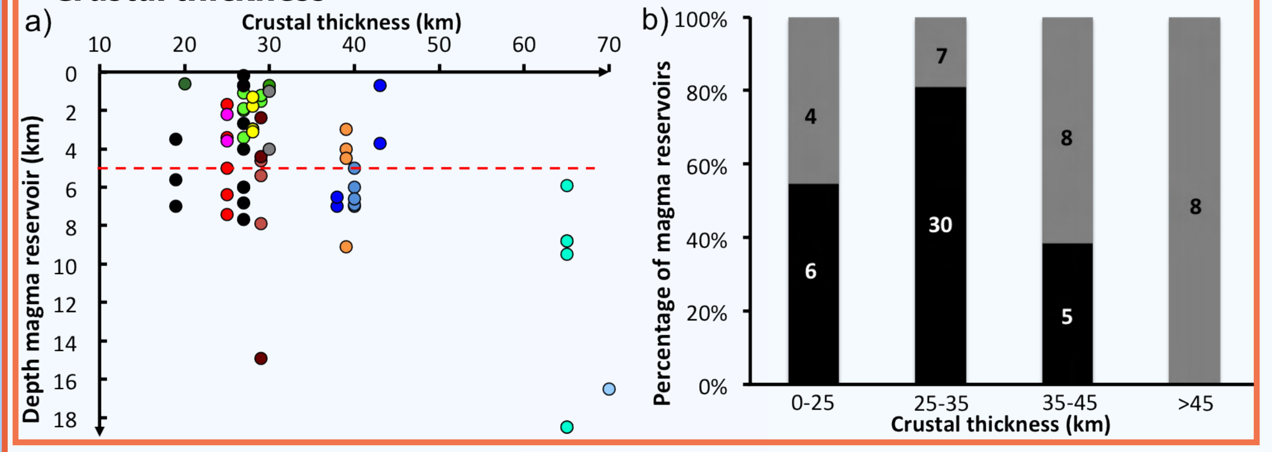
2/ DEPTHS OF MAGMA STORAGE VS REGIONAL PARAMETERS

a) Depths of the shallowest identified magma reservoir at each considered volcano against the tested regional parameters (volcanic regions are color-coded following Figure 2)
b) Cumulative histograms normalize to 100% of the proportions of shallow (<5 km, black) and deep (>5 km, grey) reservoirs for a given range of the tested parameters.
Red frames indicate correlations

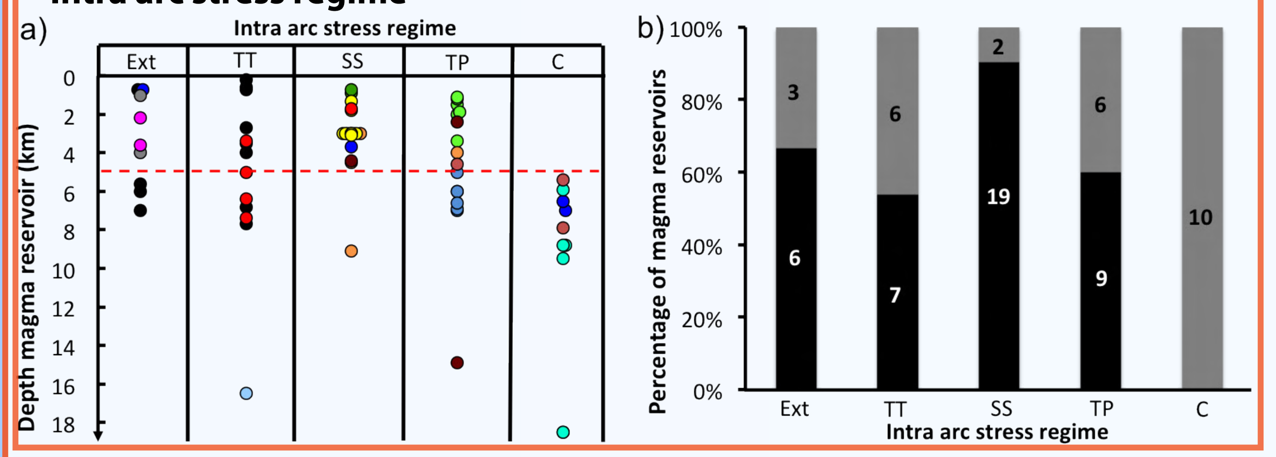
- **Age of the arc crust**



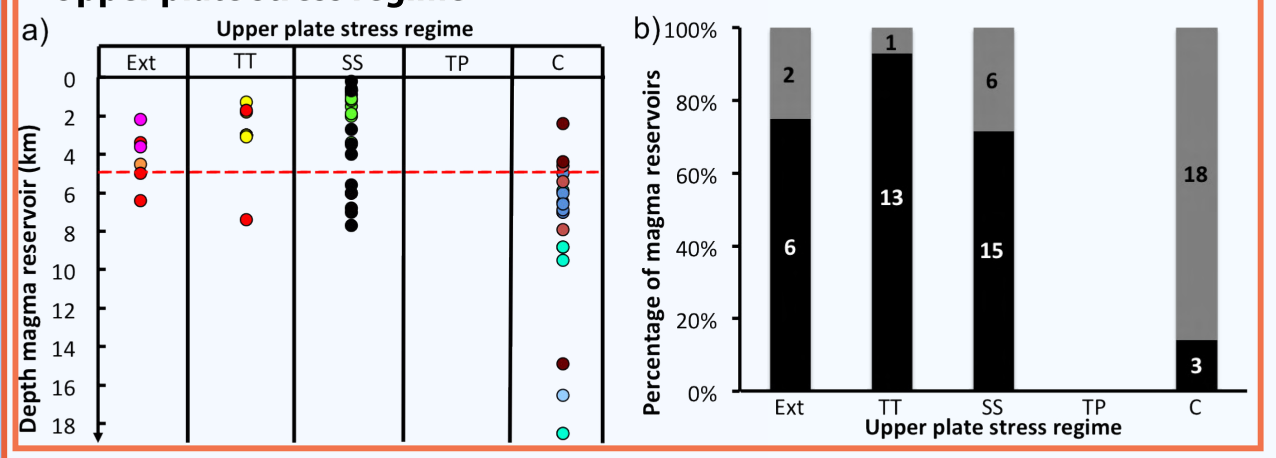
- **Crustal thickness**



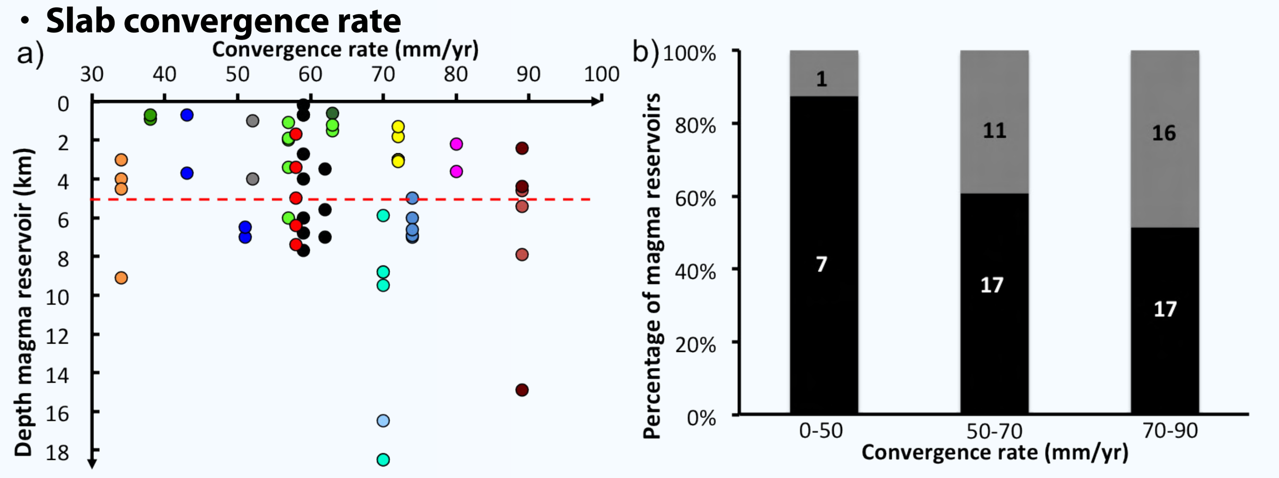
- **Intra arc stress regime**



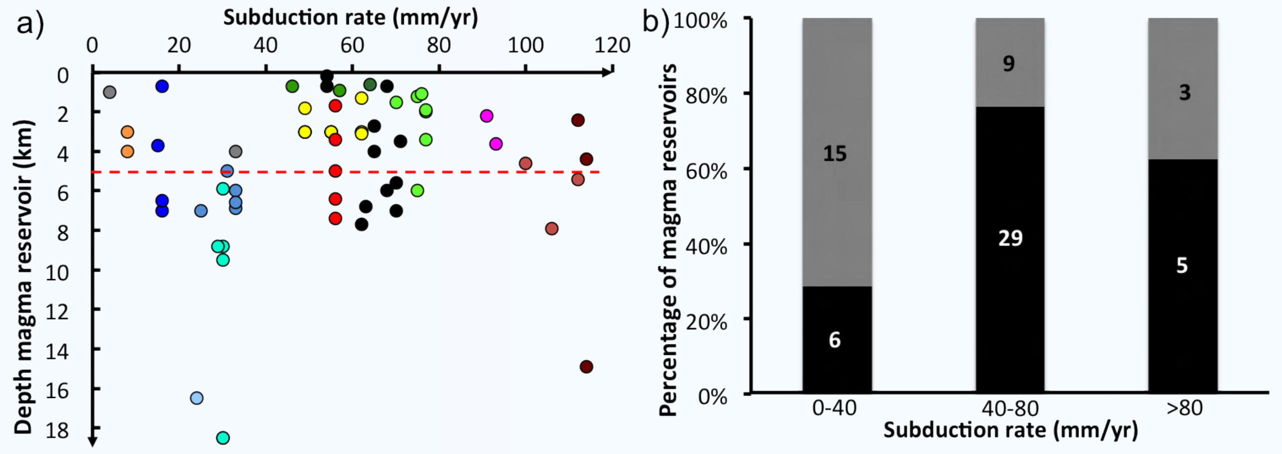
- **Upper plate stress regime**



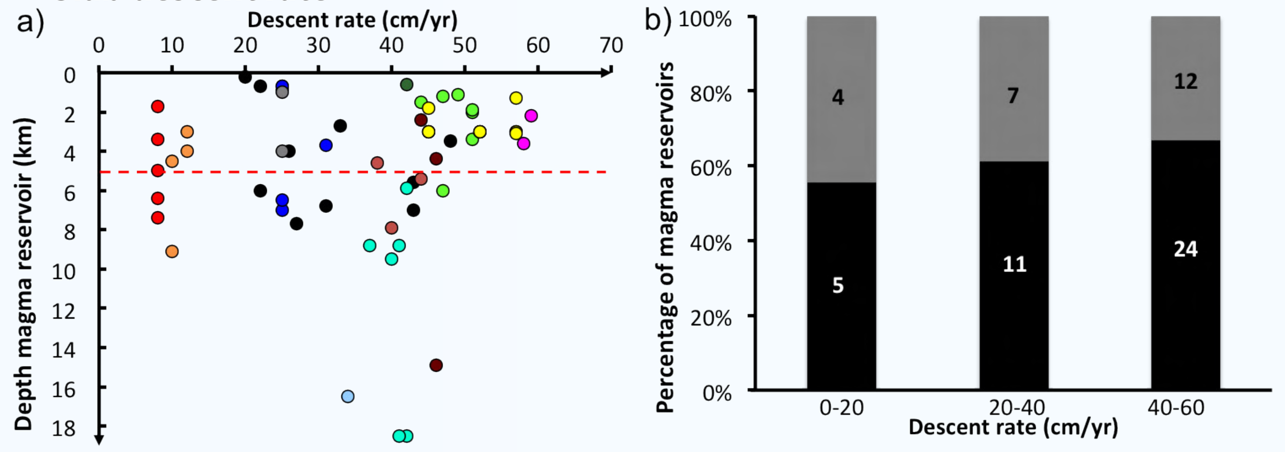
- **Slab convergence rate**



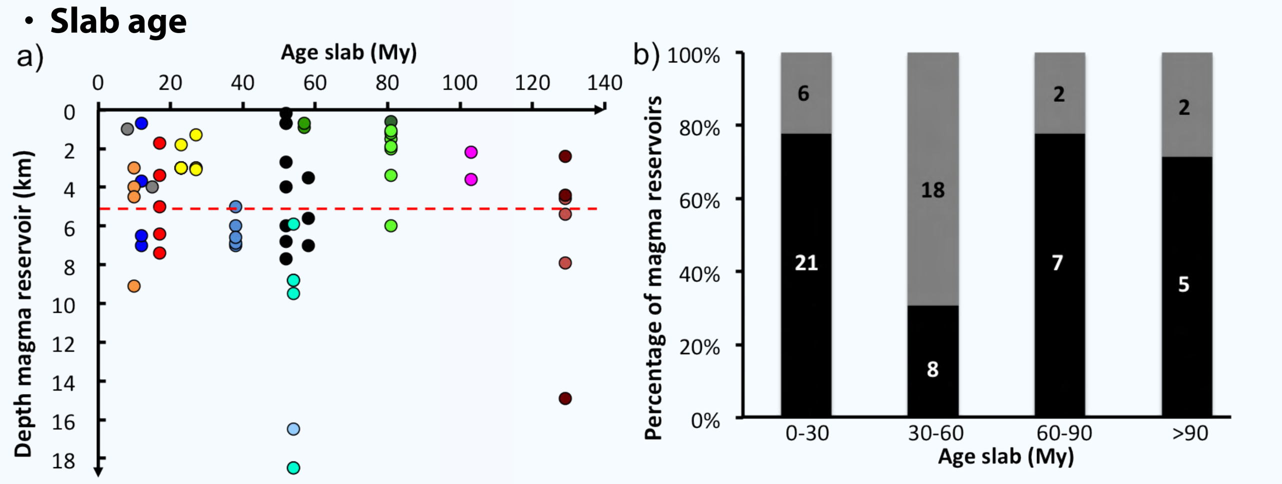
- **Slab subduction rate**



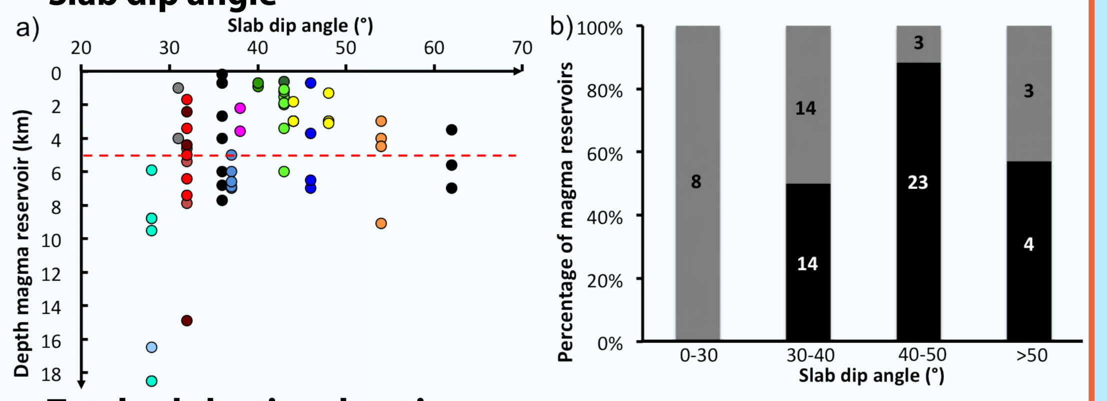
- **Slab descent rate**



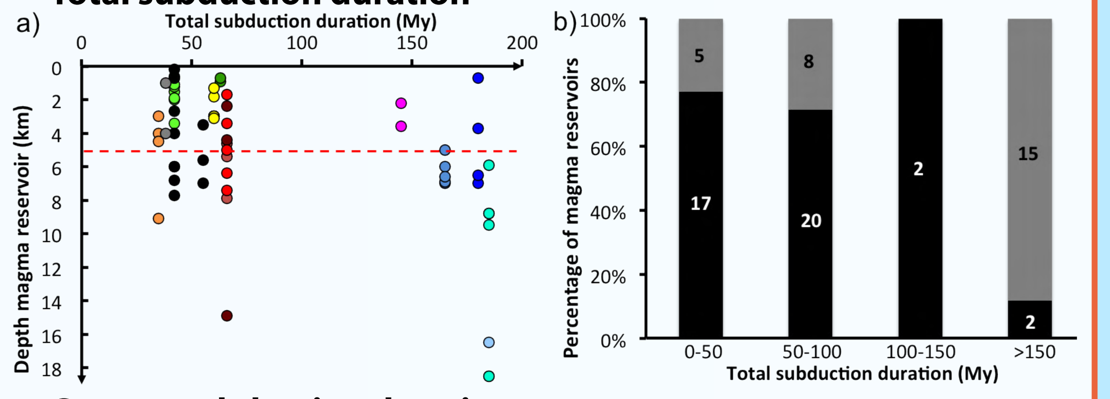
- **Slab age**



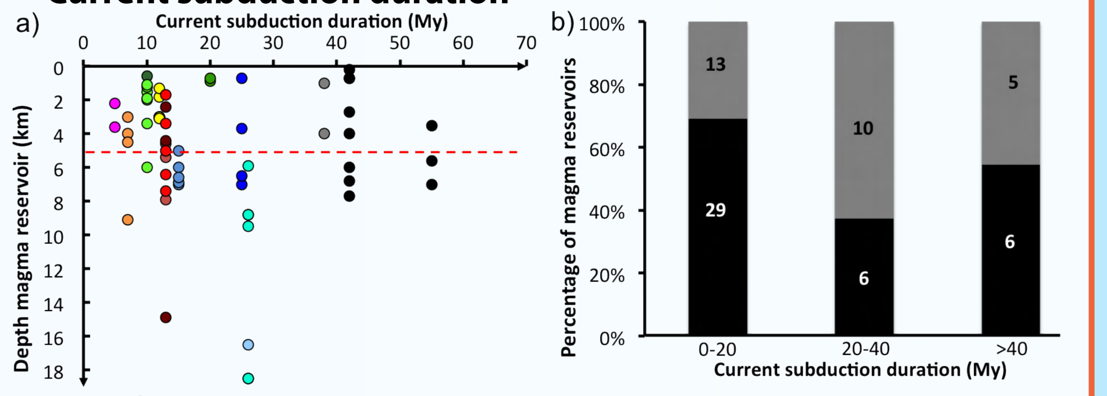
- **Slab dip angle**



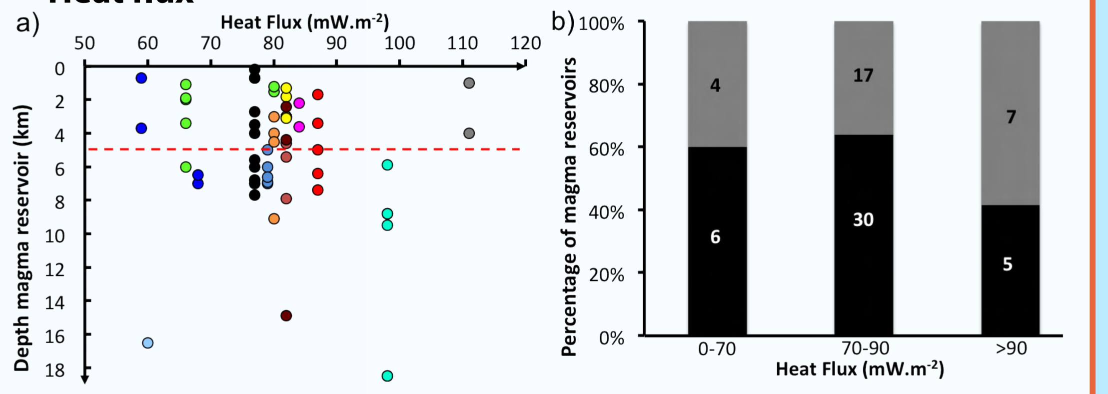
- **Total subduction duration**



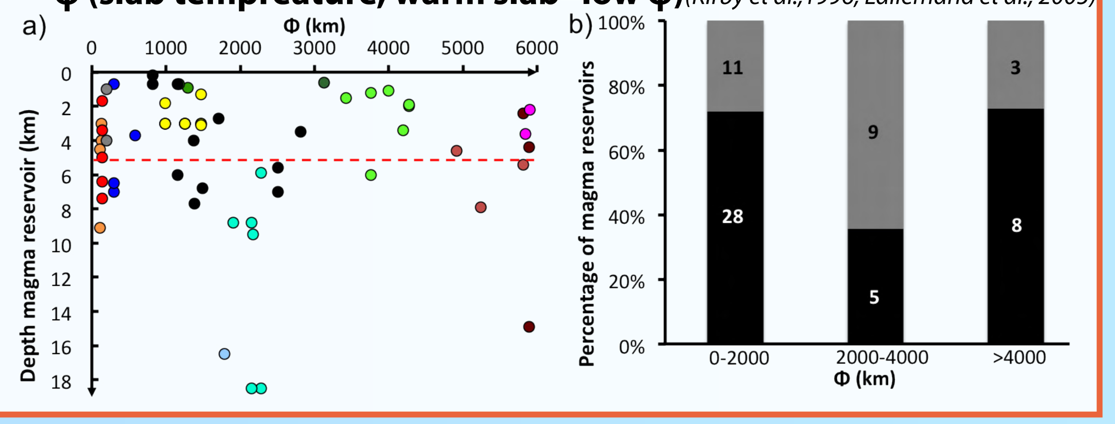
- **Current subduction duration**



- **Heat flux**



- **φ (slab tempreature, warm slab=low φ)** *(Kirby et al., 1996; Lallemand et al., 2005)*



3/ SUMMARY OF OBSERVATIONS & DISCUSSION

Correlations observed between the depths of magma storage in volcanic arcs and 4 regional parameters:

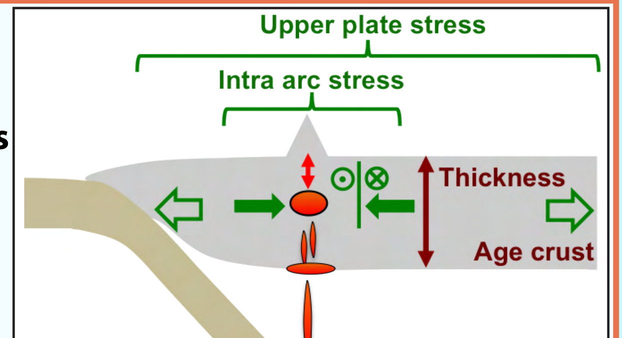
- **Age** of the arc's crust (shallow reservoirs in younger crust)
- **Thickness** of the curst (no shallow reservoirs in thick upper plates)

} **Crustal structure** -> importance of **buoyancy** in magma ascent

- **Intra arc stress** (shallow reservoirs in extension and strike slip)
- **Upper plate stress** (ditto)

} **Crustal stress** -> importance of **stress orientation and preexisting structures**

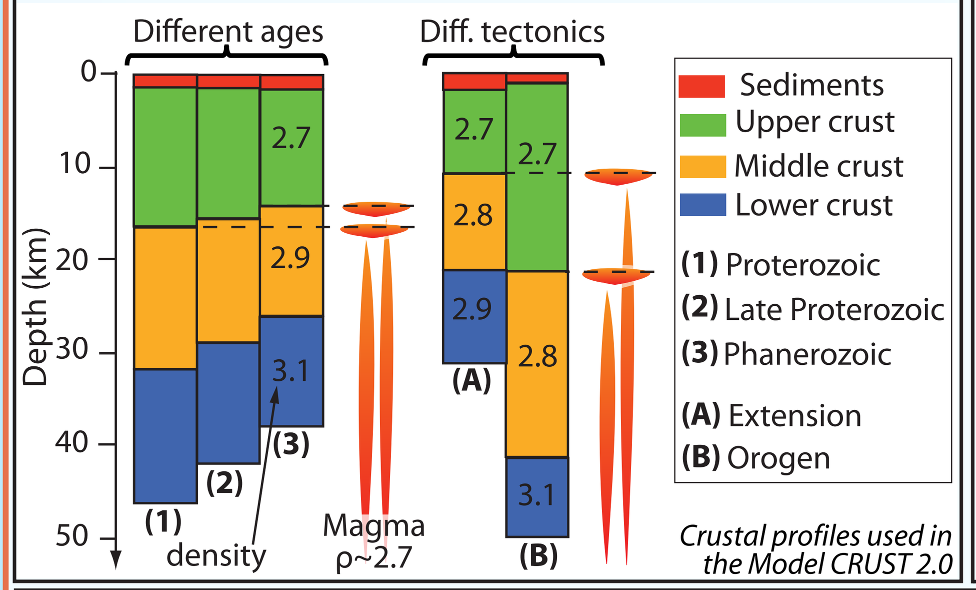
Crustal parameters have a first order effect on the depths of storage



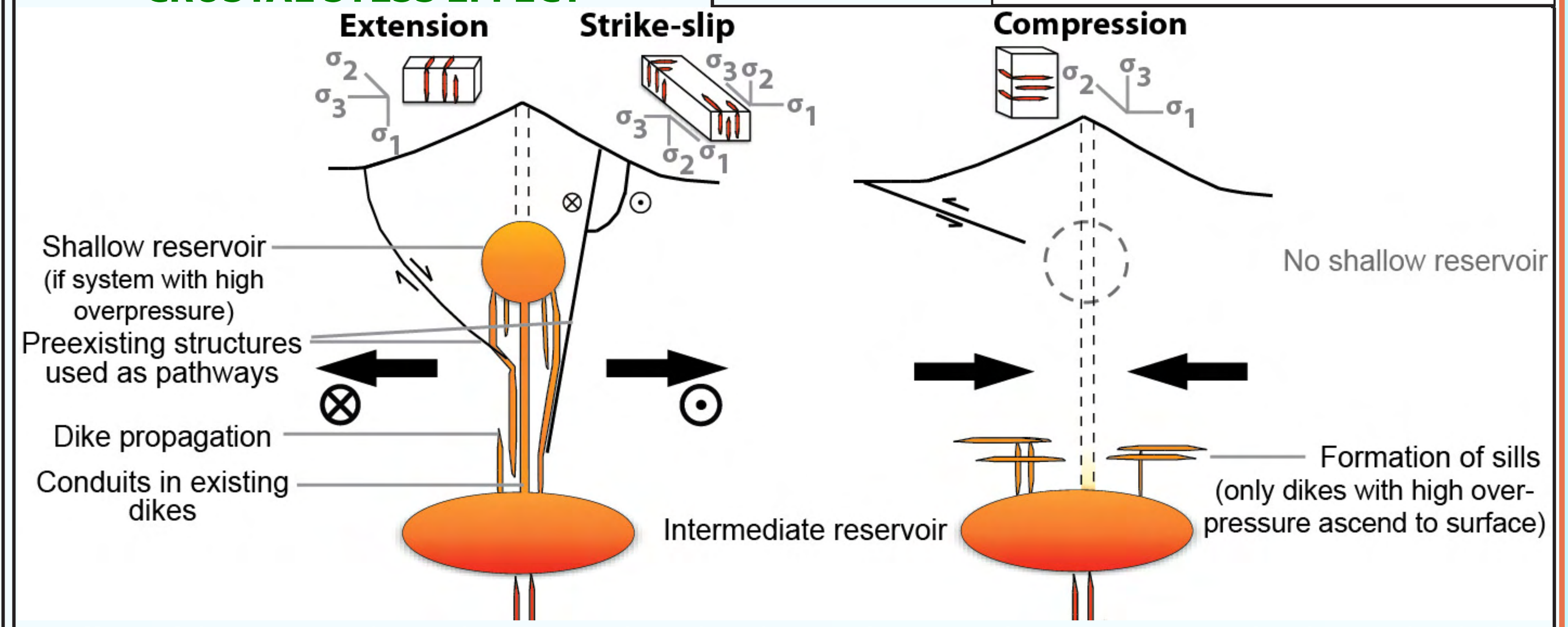
CRUSTAL STRUCTURE EFFECT

Crustal age and thickness influence **density** (constrained from seismic velocities, shown below) and the **temperature structure** (constrained from the heat flux), but no correlation was detected between storage depths and heat flux.

-> Effect of the **density distribution** and resulting **buoyancy** on magma ascent. Illustrated below by different depths of **levels of neutral buoyancy** for different density profiles.



CRUSTAL STRESS EFFECT



Effect of the **stress orientation** (vertical cracks when σ3 horizontal: extension & strike slip) and **existing structures** (steep normal faults and near-vertical strike-slip faults facilitate ascent).

Intra arc stress more influent than upper plate stress: shallow reservoirs in compressive upper plate may be located close to existing structures: modify the stress or act as pathways.

Tectonic stress influent only at **intermediate crustal depths**: at deep crustal levels lithostatic stress and viscoelastic behavior decreases its relative effect and at shallow depths local heterogeneities dominate.

ABSENCE OF CORRELATION WITH OTHER PARAMETERS

- Suggest that magma ascent and storage in the crust is **not directly influenced by the mantle melt production rates.**
- Surprising since *Zellmer (2008)* suggested that the plate convergence rate, proxy for the rates of melt generation, correlates with lava viscosity, reflecting a faster ascent.
- However, **melts production rates may not be representative of melts ascent rates** because melts are mobilized in short-lived fluid-flow events *(John et al. 2012)*.

CONCLUSIONS

- We **integer the depths of magma storage** in a global data compilation, previous works relied only on surface data *(Zellmer, 2008; Acocella & Funiciello, 2010)*.
- The **crustal structure (age and thickness)** and associated **density distribution,** and the **stress settings** have a **first order effect on the depths of magma storage in volcanic arcs,** in agreement with results from *Acocella & Funiciello (2010)*.
- **Magma production rates** have **no direct effect** on magma ascent in volcanic arcs. This result is partly inconsistent with previous studies *(Zellmer, 2008)* and suggests that **different processes control generation and rise of magmas**: **production rates are independent from ascent rates**.
- These observations have **major implications for volcanic hazard assessment**: volcanic arcs developed in **young and thin** crusts undergoing **extensive or strike slip stress** regimes are more likely to present **shallow magma reservoirs** which are associated with a higher risk of significant eruptions.

REFERENCES

(1) Acocella, V., & Funiciello, F. (2010). Kinematic setting and structural control of arc volcanism. Earth and Planetary Science Letters, 289(1-2), 43–53. **(2)** Chaussard, E., & Amelung, F. (2012). Precursory inflation of shallow magma reservoirs at west Sunda volcanoes detected by InSAR. Geophysical Research Letters, 39(21), L21311. **(3)** John, T., Gussone, N., Podladchikov, Y. Y., Bebout, G. E., Dohmen, R., Halama, R., et al. (2012). Volcanic arcs fed by rapid pulsed fluid flow through subducting slabs. Nature Geoscience, 5(7), 489–492. **(4)** Kirby, S. H., Stein, S., Okal, E. A., & Rubie, D. C. (1996). Metastable mantle phase transformations and deep earthquakes in subducting oceanic lithosphere. Reviews of Geophysics, 34(2), 261–306. **(5)** Lallemand, S., Heuret, A., & Boutelier, D. (2005). On the relationships between slab dip, back-arc stress, upper plate absolute motion, and crustal nature in subduction zones. Geochemistry Geophysics Geosystems, 6(9), Q09006. **(6)** Zellmer, G. F. (2008). Some first-order observations on magma transfer from mantle wedge to upper crust at volcanic arcs. Geological Society, London, Special Publications, 304(1), 15–31.