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Key Points:
- We show that regional trends in depths of magma storage exist
- Crustal structure and stress settings of volcanic arcs control magma ascent
- Rates of melt generation are independent from rates of magma ascent in the crust

Supporting Information:
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Regional controls on magma ascent and storage in volcanic arcs

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Abstract Understanding the controls for magma ascent and storage depth is important for volcanic hazard assessment. Regional differences in the depths of magma storage between volcanic arcs suggest that the settings of subduction zones and of overriding plates influence how magma ascends through the crust. Here we use a compilation of data for 70 volcanoes in 15 volcanic regions to better understand the geodynamic controls on magma storage. We describe the subduction system, which consists of the subducting slab, the mantle wedge, and the upper plate with 12 parameters encompassing the kinematics of the subduction, the structure and geometry of the slab, the timing of the subduction, the thermal structure of the slab, the upper-plate crustal structure, its stress regimes, and its thermal structure. We find that the magma reservoir depths correlate with the upper-plate crustal structure and with the stress regimes. Shallow reservoirs ($<$5 km depths) are 52% more common in young Tertiary crust than in old Precambrian crust and 42% more common in thin crust ($<$25 km) than in thick crust ($>$45 km). Similarly, shallow magma reservoirs are 33–69% more common in extensional and strike-slip stress regimes that in compressional regimes. This illustrates the effect of buoyancy for magma ascent as well as the importance of stress regime and preexisting structures.

1. Introduction

Most volcanic eruptions are fed by dikes propagating from a magma reservoir, a partially molten body located in the crust. The depth of magma storage is of fundamental importance for volcanic hazards assessment such as the likelihood of a dike to reach the surface and to feed an eruption [*Gudmundsson*, 2012], the size and duration of an eruption [*Galindo and Gudmundsson*, 2012], and the potential for an eruption to form a caldera [*Gregg et al*., 2012]. However, little is known about the geodynamic controls of magma storage depths.

In a subduction zone, at a depth of about 100 km, metamorphism of hydrous minerals contained in the crust of a descending oceanic slab frees water and provokes partial melting of ultramafic rocks in the mantle wedge [*Gill*, 1981], leading to the generation of buoyant melt. The rate of melt generation is to the first order a function of the degree of hydration of the subducting slab (depending on its age), the rate at which the slab descends into the mantle (the subduction kinematics), and the fertility of the mantle (defined as the potential to create basalt, depending on the dip angle and age of the slab, referred to as slab characteristics, the duration of the subduction, and the thickness of the overriding plate) [*Cagnioncle et al*., 2007]. Magma ascends through the mantle wedge by porous flow via reaction infiltration instabilities [*Aharonov et al*., 1995; *Stracke et al*., 2006], or in form of dikes [*Nicolas*, 1990; *Rubin*, 1995; *Kühn and Dahm*, 2004; *Johnson and Jin*, 2009] at rates of tens to hundreds of meters per year [*Turner et al*., 2000; *Turner and Foden*, 2001; *Turner et al*., 2003; *Bourdon and Sims*, 2003].

In the crust of the upper plate, magma transport occurs primarily through dikes. Magma reservoirs form and grow when dikes get deflected into sills [*Clemens and Mawer*, 1992; *Petford et al*., 2000; *Gudmundsson*, 1990], which depends on the balance between forces driving and resisting magma ascent. Such forces include (1) the buoyancy arising from the difference between the density of the magma and that of the surrounding rocks [*Ryan*, 1994; *Scandone et al*., 2007], (2) the magma viscosity, and (3) the stress field and presence of mechanical contrasts [*Takada*, 1999; *Gudmundsson*, 2011a]. The depth of a magma reservoir reflects how easy it is for magma to ascend in the crust. Many volcanic systems develop multiple reservoirs, shallow ones being fed by one or more deeper reservoirs [*Gudmundsson*, 2000; *Kavanagh et al*., 2006], the longevity of which is dictated by the melt supply [*Karlstrom et al*., 2009, 2010; *Annen et al*., 2008].

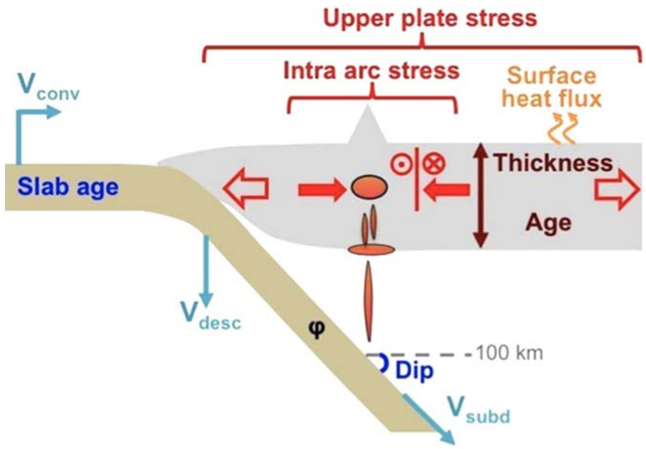

Figure 1. Cartoon illustrating the subduction (blue shades and black) and upper-plate crustal (orange to dark red shades) parameters potentially affecting magma ascent that are tested for correlations with the magma storage depths (the current subduction duration is not shown). We consider the kinematics of the subduction (light blue): convergence (V_{conv}), subduction (V_{subd}), and vertical descent velocities (V_{desc}); the slab characteristics (dark blue): age and dip angle at 100 km from the trench; the thermal structure of the slab (black): thermal parameter φ [*Kirby et al.*, 1996]; the upper-plate crustal structure (dark red): age and thickness; the upper-plate stress settings (red): intra-arc and upper-plate stresses; and the upper-plate thermal structure (orange): surface heat flux.

Rheology and rigidity contrasts likely control the depths of magma stagnation at shallow levels, close or within the volcanic edifice where local crustal heterogeneities are common [*Mazzarini et al.*, 2010; *Menand*, 2011; *Gudmundsson*, 2011a], but are not believed to have a significant effect at deeper levels, where host-rock alteration and layering is limited [*Gudmundsson*, 2006].

Zellmer [2008] suggested that the melt production rates in the mantle influence the speed at which magma migrates through the crust. However, recent petrological and geophysical observations suggest that magma ascends in pulses of durations and volumes changing in time [*Druitt et al.*, 2012; *Parks et al.*, 2012; *John et al.*, 2012], implying that ascent rates may be independent from production rates both in the crust and mantle.

Acocella and Funiciello [2010] suggested that crustal magma ascent is mostly influenced by the upper-plate stress regime, and that magma ascent is facilitated in extensional and strike-slip settings. This is in agreement with the observations that, while the main path of a dike is formed by its magmatic overpressure, many dikes use faults as pathways [*Gudmundsson*, 2007]. A number of other studies have also shown that faults and stress fields influence magma ascent [*Hutton*, 1988; *Guineberteau et al.*, 1987; *D'lemos et al.*, 1992; *De Saint Blanquat et al.*, 1998; *Brown and Solar*, 1998; *Benn et al.*, 1998; *Román-Berdiel et al.*, 2000; *Kalakay et al.*, 2001; *Corti et al.*, 2003, 2005; *Galland et al.*, 2003, 2007a, 2007b; *Musumeci et al.*, 2005].

Variation in buoyancy due to differences in the crustal density structure may influence the levels of magma storage [*Ryan*, 1994; *Pinel and Jaupart*, 2004], but have also been shown to exert only little control on dikes, i.e., basaltic dikes would never reach the surface by buoyancy effects alone as the upper crustal density is less than that of a basaltic magma [*Vigneresse et al.*, 1999; *Zellmer*, 2008; *Gudmundsson*, 2012]. Similarly, because geothermal gradients must be overcome to avoid freezing, they have been suggested to play a role in magma ascent [*Rubin*, 1995; *Jellinek and DePaolo*, 2003], but it has also been proposed that ascending magmas are the thermally active systems influencing the geothermal gradients [*Marsh*, 1989; *Zellmer*, 2008].

To investigate what exerts the strongest control on magma ascent, we compile the depths at which magma accumulates below arc volcanoes, referred to as the magma reservoir depths, and evaluate how they correlate with the parameters describing the settings of the subduction zones and of the upper plate. This paper is organized as follow. First, we summarize the parameters potentially affecting magma ascent and storage that are considered in this study. Second, we present the data set of magma reservoirs depths compiled. Third, we discuss the observed relationships between subduction and upper-plate crustal parameters and the depths of magma storage. Finally, we address the implications of our results in term of processes influencing crustal magma ascent and storage depths.

2. Geodynamic Parameters Tested for Control on Magma Ascent and Storage Depths

Here we summarize the parameters potentially affecting magma ascent that are tested for correlations with the depths of magma storage (Figure 1 shows 11 of the 12 tested parameters). We organize these parameters in two classes: related to the subduction settings or to the crust of the upper plate.

2.1. Subduction Parameters

The subduction parameters describe the slab and mantle wedge and influence the melt production rates, as described in section 1. Four categories are considered:

1. The kinematics of subduction, which determines the rate at which the slab descends into the mantle and thus the rate at which fluids enter the subduction (light blue on Figure 1): the convergence velocity (relative normal velocity between the subducting and the upper plate), the subduction velocity (sum of the convergence and the deformation velocity in the upper plate), and the vertical descent velocity (convergence velocity times the sine of the dip angle).

2. The slab characteristics, which influence the degree of hydration of the slab and the fertility of the mantle (dark blue on Figure 1): the age and the dip angle at 100 km from the trench (also controlling the size of the mantle wedge).

3. The current subduction duration, which corresponds to the longevity of the arc in its current location and characterize the fertility of the mantle. The total subduction duration, which corresponds to the longevity of arc volcanism in a region, is not considered because (1) it suffers from sampling bias, arcs with short total durations ($<$100 Myr) being 2.7 times more common than arcs with long durations, and (2) it is linked to other parameters such as the crustal age and thickness [*Kay*, 1980].

4. The thermal structure of the slab, which influences its degree of hydration (black in Figure 1): thermal parameter φ of the slab, a warm slab being characterized by low φ values, and a cold slab by high φ values [*Kirby et al*., 1996].

2.2. Upper-Plate Crustal Parameters

The upper-plate crustal parameters influence the buoyancy of the magma and the resistance it faces to ascend (stress). Three categories are considered:

1. The crustal structure, which influences the density structure and affects the magma buoyancy (dark red in Figure 1). We consider the age and thickness of the upper plate. The density structure is also largely influenced by the crustal composition, which varies according to the type of crust: volcanic arcs exist on oceanic, transitional, and continental crust, oceanic crust differing significantly from the two others. To limit this variability, we consider only continental and transitional arcs, which have similar crustal compositions.

2. The stress settings, which influence the resistance against magma ascent (red on Figure 1): intra-arc (local) stress, which consider the stress in the vicinity of the arc (within $\sim$100 km distance of the volcano) and includes faults, and upper-plate stress, which is an average over the entire upper plate and does not include tectonic structures (also referred to as regional stress).

3. The thermal structure, characterized by the crustal geotherm influencing the surface heat flux (orange on Figure 1), which may affect the speed at which an ascending magma is cooling.

For the subduction parameters, we use the convergence velocity data from *Hughes and Mahood* [2011] completed by *Zellmer* [2008]; the subduction velocity, vertical descent velocity, and slabs' thermal parameter data from *Lallemand et al*. [2005]; and the slab age, dip, and subduction duration data from *Hughes and Mahood* [2011]. For the upper-plate crustal parameters, we use the age data from *Hughes and Mahood* [2011]; the crustal thicknesses data from *Hughes and Mahood* [2011] completed by *Zellmer* [2008]; the surface heat flux data form *Zellmer* [2008]; the upper-plate stress regime from *Acocella and Funiciello* [2010]; and the intra-arc stress regime from *Chaussard and Amelung* [2012].

The ascent of magma is also influenced by its density [e.g., *Ryan*, 1994; *Scandone et al*., 2007; *Menand and Tait*, 2002; *Nishimura*, 2009] but because magma densities values are rarely constrained they are not included in this data compilation. To limit the density variability, we consider only volcanoes with an andesitic component (basaltic-andesitic to andesitic-dacitic). This way we can test for the effect of the buoyancy, which depends mostly on the crustal density distribution and is accounted for in crustal age and thickness.

Volcano-dependent parameters, such as magma viscosity and volatile content, are poorly constrained and were not included. These parameters strongly influence magma ascent at very shallow depths (in the

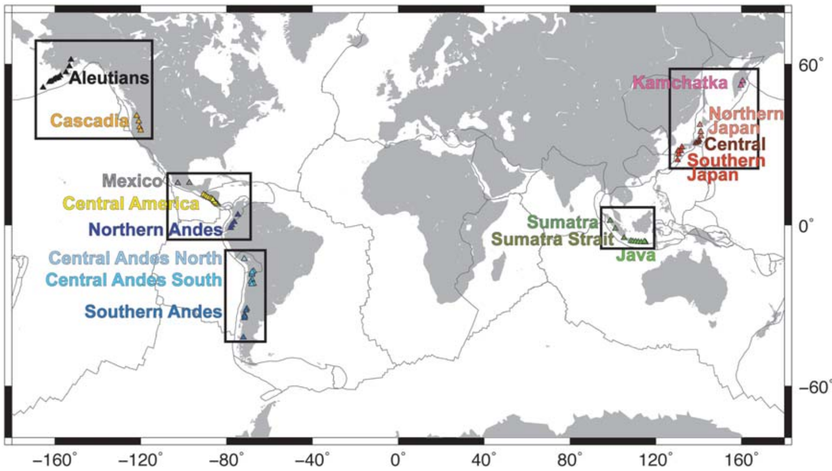

Figure 2. Map showing the 15 volcanic regions considered, introducing the color used to characterize the different arcs in Figures 4–8 and supporting information Figures S1–S8. The black thin lines show the contours of the main tectonic plates. The black rectangles locate the maps presented in Figure 3.

conduit) [*Gonnermann and Manga*, 2013], but have little effect on magma ascent at greater depths [*Tait and Taisne*, 2013].

3. Depths of Magma Storage

The depths of magma storage are estimated using geophysical [e.g., *Dzurisin*, 2003; *Londono and Sudo*, 2003; *Battaglia et al*., 2008; *Kagiyama et al*., 1999] or petrological measurements [e.g., *Samaniego et al*., 2011]. These depth estimates depend on assumptions about the crustal structure and source geometry, and are limited by trade-offs between source depth, overpressure, and size [*Dzurisin*, 2003; *Battaglia and Hill*, 2009].

We have compiled a data set of reservoir depths consisting of published geodetic estimates (interferometric synthetic aperture radar (InSAR), Global Positioning System (GPS), leveling, and tilt), other geophysical estimates (seismology, gravity, and resistivity), and petrological estimates (Table S1), used in this order of preference when multiple sources are available. In case multiple estimates based on the same data type were published in the same year, we average them. We do not consider sources within the volcanic edifices, which often represent the hydrothermal or conduit system. We use the depth of the shallowest detected magma reservoir at each volcano, i.e., the top of the plumbing systems. The magma reservoir depths are converted into depths below the average regional elevation of the area to enable comparison among regions.

Our data set includes 70 andesitic volcanoes in eight continental and transitional arcs: Sunda (western part only), Aleutians (eastern part only), Andes, Cascadia, Central America, Japan, Mexico, and Kamchatka. We have subdivided the arcs into a total of 15 volcanic regions due to along-arc variations in subduction and tectonic settings (Table S1). Figure 2 shows the locations of the volcanoes and the color code, which identifies the different volcanic regions in Figures 4–8 and supporting information Figures S1–S8. The following volcanic arcs are not included in our data set because they are island arcs developed on oceanic crust: east Sunda and Banda, Kurile, Ryukyu, Izu-Bonin, Mariana, Solomon, Vanuatu, Tonga-Kermadec, western Aleutians, Panama, Lesser Antilles, and South Sandwich [*Hughes and Mahood*, 2011]. Arcs on continental or transitional crust not included because of the lack of reservoir depth data are the Aegean, Philippines, New Britain, Vanuatu, and New Zealand arcs.

The reservoir depths are shown in Figure 3. The top of the plumbing system is mostly shallow (red to brown colors) in the Cascadian, Mexican, Central American, and Indonesian arcs and in the North-Andean region. A larger variability is observed in the Aleutian and Japan arcs where the top of the plumbing systems varies from shallow to deep, while in the Southern Andes and in the Central Andes shallow reservoirs are absent (no red colors).

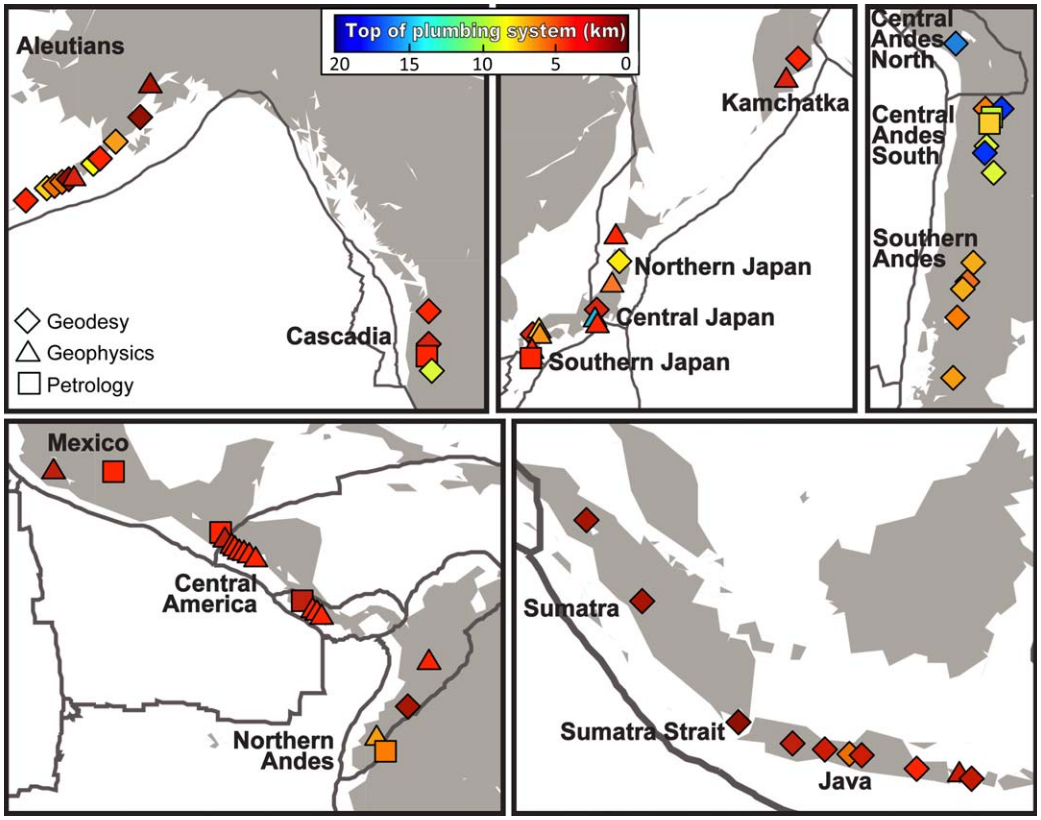

Figure 3. Maps of the top of the volcanic plumbing system for 70 volcanoes. The symbol color indicates the depth of the shallowest magma reservoir. The symbol type identifies the data source. Diamonds: geodesy (InSAR, GPS, leveling, and tilt), triangles: other geophysical techniques (seismic, gravity, and resistivity), squares: petrology.

The regional variability of the reservoirs depths is summarized in Figure 4 (at (a) individual volcanoes and (b) using cumulative histograms). The ratio of shallow reservoirs (depth $<$ 5 km) to deep reservoirs (depth $>$ 5 km) is shown using a $\pm$ 1 km range to associate uncertainties to the cumulative histograms (errors bars on Figure 4b). The histograms show that shallow reservoirs are dominant in some volcanic regions (Sumatra, the Sumatra Strait, Java, Central America, Mexico, and Kamchatka) but lack in others (Northern, Central, and Southern Andes; Figure 4b). This confirms that regional trends in the depths of magma storage exist, suggesting that the subduction or the upper-plate settings influence the level of magma storage.

4. Correlation Between Magma Storage Depths and Subduction or Upper-Plate Crustal Parameters

We use the following approach to assess which parameters may influence the magma reservoir depths. For each of the 12 parameters, we produce two diagrams. The first one shows the depths of magma storage against the tested parameter at each volcano (Figures 5–8a and supporting information Figures S1–S8a), the second is a cumulative histogram showing the ratio of shallow to deep reservoirs for given ranges of values of the parameter (Figures 5–8b and supporting information Figures S1–S8b). The errors bars represent how the proportion of shallow to deep reservoirs changes when the depth separating shallow from deep reservoirs is 4, 5, or 6 km (Figures 5–8b and S1–S8b). In average for all the parameters and all the ranges of values considered, the choice of this transition depth results in a change of proportion of 11%. We evaluate the cumulative histograms for variations in ratios of shallow to deep reservoirs in function of the ranges of parameters and consider variations significant when larger than 15% both between the first and last range of parameter values and between neighboring ranges. Nonhorizontal orange boxes highlight significant variations, whereas horizontal boxes denote a lack of variation. To limit the length of the paper, only the diagrams showing correlations are included, the others are available in the supporting information.

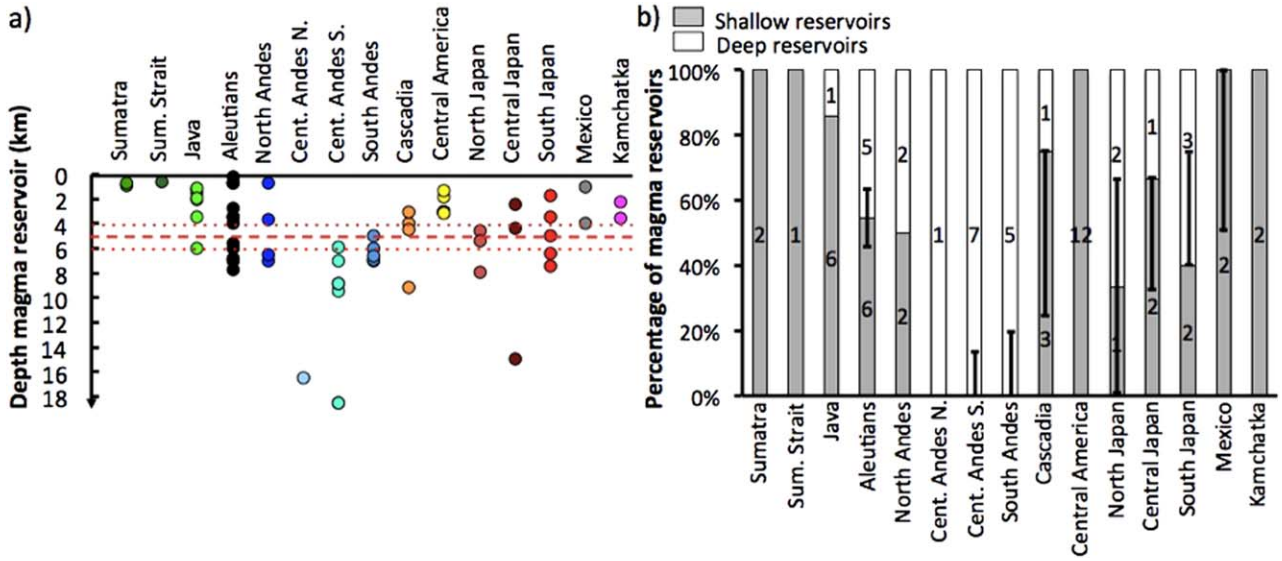

Figure 4. Regional variability of the magma reservoir depths. (a) Reservoirs depths per regions for the 70 volcanoes. The dashed and dotted lines at 5 ± 1 km depth mark the transition between shallow and deep reservoirs. (b) Normalized cumulative histograms showing the proportions of shallow (grey rectangles) and deep (white rectangles) reservoirs. The number of reservoirs is shown in the columns of the histogram, which are normalized to 100% to avoid sampling biases. The errors bars represent the effect of the depth chosen to separate shallow and deep reservoirs (5 km is used as a default, the error bars represent how the cumulative distribution changes if the limit between shallow and deep reservoirs was taken as 4 and 6 km depth).

4.1. Subduction Parameters

4.1.1. The Subduction Kinematics

Supporting information Figures S1–S3 show the depths of magma reservoirs versus the convergence velocity, the subduction velocity, and the vertical descent velocity. These three parameters describe the subduction kinematics, a proxy for the amount of fluids released into the mantle wedge. The proportion of shallow magma reservoirs in regions with low convergence velocities (<50 mm/yr) is 75–88%, 61–68% in regions with medium convergence velocities (50–70 mm/yr), and 74–61% in regions with high convergence velocities (>70 mm/yr), when considering the uncertainties. Thus, the differences in proportion of shallow magma reservoir is 14% between the first and last range of values, and 7 and 0% between neighboring ranges (Figure S1a). Because the variations in the proportion of shallow to deep reservoirs between the first and last range of values and between neighboring ranges are all below 15%, we consider that there is no significant correlation between magma storage depths and descent velocities. Similarly, no correlations are identified between the depths of magma reservoirs and the subduction velocities, the difference in proportion of shallow reservoirs in subduction with slow (0–40 mm/yr) and rapid (>80 mm/yr) velocities being of 0% (Figure S2). Descent velocities produce similar results, the proportion of shallow magma reservoirs is increasing by only 10 and 3% for descent velocities increasing from 0–20 to 20–40 mm/yr and from 20–40 to >40 mm/yr, respectively (Figure S3). Thus, the depths of magma storage do not correlate with the kinematic settings of subductions.

4.1.2. The Slab Characteristics

Supporting information Figures S4 and S5 show the depths of magma reservoirs versus the slab age and dip angle, respectively. Shallow magma reservoirs are observed in similar proportions for all slab ages (0% variation between slab of 0–30 and >90 Ma) and dip angles (3% variation between slab dip of 0–30° and >55°), suggesting that these parameters do not exert a strong influence on magma ascent or storage depths.

4.1.3. The Subduction Duration

Supporting information Figures S6 shows the depths of magma reservoirs versus the current duration of the subductions. No correlation is observed, shallow magma reservoirs existing in similar proportions in recent and old subduction settings (0% variation between subductions younger than 20 Ma or older than 40 Ma).

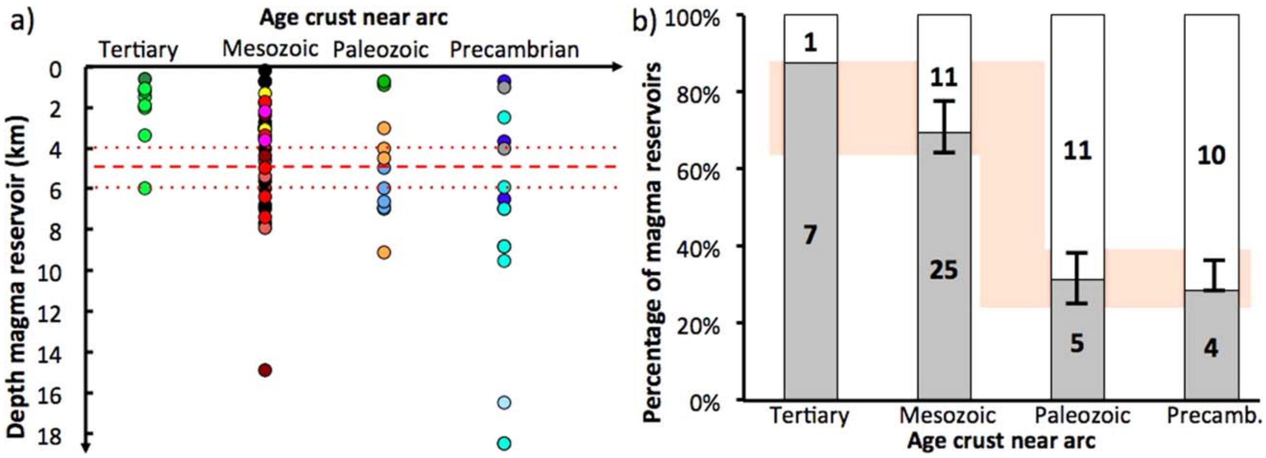

Figure 5. Depths of magma storage in function of the age of the upper crust (same legend as Figure 4). (a) At the 70 volcanoes individually, the volcanic regions being color-coded similarly to Figure 2. (b) Cumulative histograms of the proportion of shallow and deep reservoirs in function of ranges of upper crust ages. In this and in the following figures, nonhorizontal boxes highlight a correlation.

4.1.4. The Thermal Structure

Supporting information Figure S7 shows the depths of magma reservoirs versus the slab thermal parameter φ representative of its temperature. Shallow reservoirs are observed in similar proportions in subduction with hot and cold slabs (0% variation between slabs with φ of 0–2000 or $>$4000 km).

4.2. Upper-Plate Crustal Parameters

4.2.1. The Crustal Structure

Figures 5 and 6 show the depths of magma storage versus the age of the upper-plate's crust and its thickness, respectively. More shallow magma reservoirs are observed in arcs with young crust (88% and 64–78% in Tertiary and Mesozoic crust, respectively) than in arcs with older crust (25–38% and 29–36% in Paleozoic and Precambrian crust, respectively). Shallow magma reservoirs are thus 50% and 52% more common in Tertiary crust than in Paleozoic and Precambrian crust, respectively, and 28% and 26% more common in Mesozoic crust than in Paleozoic and Precambrian crust, respectively. Shallow magma reservoirs are also more common in arcs with thin crust than in arcs with thick crust. Shallow magma reservoirs are 18%, 63%, and 42% less common in arcs with crust $>$45 km than in 35–45, 25–35, and 0–25 km thick crust, respectively. These observations suggest that arcs with young and thin crusts are more favorable to the development of shallow magma reservoirs than arcs with old and thick crusts.

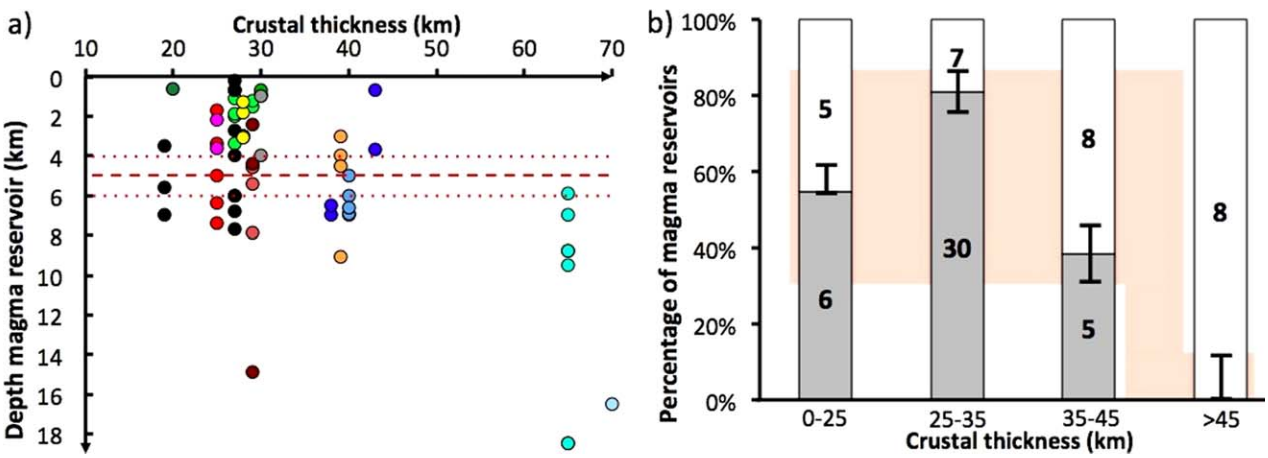

Figure 6. Same as Figure 5 but in function of the crustal thickness.

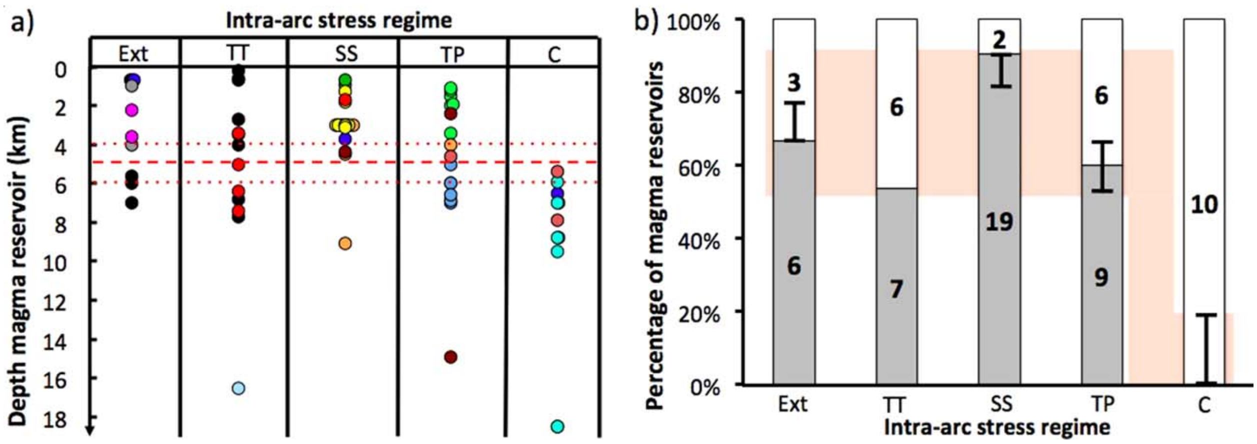

Figure 7. Same as Figure 5 but in function of the intra-arc stress regime. Ext. is for extensive, TT for transtensive, SS for strike slip, TP for transpressive, and C is for compressive intra-arc stress regime.

4.2.2. The Stress Settings

Figures 7 and 8 show the depths of magma storage versus the intra-arc and upper-plate stress regimes, respectively. First, we notice differences between the two, for example, the Aleutians' intra-arc regime is extensive or transtensive, whereas the upper-plate regime is strike slip (black dots). The intra-arc regimes in Indonesia (Sumatra and Java, medium green, dark green dots, respectively) and Japan (red dots) are all transpressive while the upper-plate regimes in the two arcs are strike slip and compressive, respectively. We observe in both figures that shallow magma reservoirs are more frequent in extensive and strike-slip settings (including transtensive and transpressive) than in compressive settings. Considering the intra-arc stress, shallow magma reservoirs are 33% less frequent in compressive regime than in transpressive, 61% less frequent than in strike-slip regime, 34% less frequent than in transtensive regime, and 47% less frequent than in extensive regime (Figure 7). We find similar results with the upper-plate stress regime, even though three volcanoes in a compressive upper plate have shallow reservoirs (Usu, Asama, and Izu-Tobu volcanoes in Japan, red dots in compressive regime above the 5 km dashed line in Figure 8). Shallow magma reservoirs are 47% less frequent in compressive regime than in strike-slip regime, 69% less frequent than in transtensive regime, and 39% less frequent than in extensive regime (Figure 8).

4.2.3. The Thermal Structure

Supporting information Figure S8 shows the depths of magma reservoirs versus the upper-plate's surface heat flux. Shallow reservoirs are observed in arcs with high surface heat flux (Mexico, grey dots) as well as

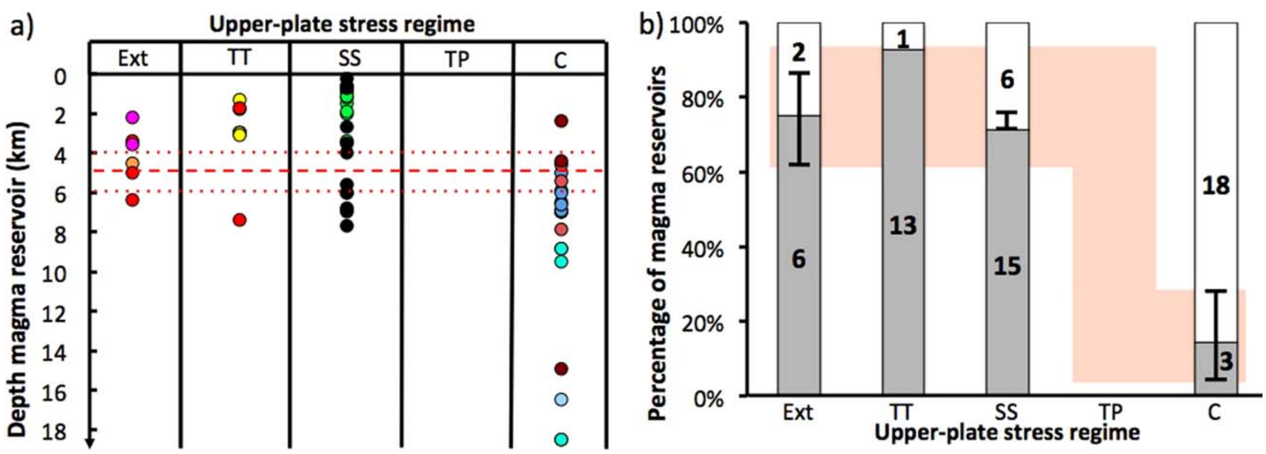

Figure 8. Same as Figure 5 but in function of the upper-plate stress regime.

with low surface heat flux (Northern Andes, Java, dark blue and light green dots, respectively), the variation in their proportion being of only 10%. Thus, we do not detect any correlation between the depths of magma storage and the thermal structure of the upper plate.

5. Discussion

Our analysis shows that the depths of magma storage correlate with the following four parameters: the upper-plate crustal age, the upper-plate crustal thickness, the intra-arc stress regime, and the upper-plate stress regime. All these parameters relate to the upper-plate crust. No correlation was observed with any of the subduction parameters, suggesting that only upper-plate crustal settings control magma ascent and storage depths.

In the next sections, we discuss how crustal structure and crustal stress could affect magma ascent and storage depths, and the lack of correlation between the depths of magma storage and the subduction parameters.

5.1. Influence of the Upper-Plate Crustal Structure on Magma Ascent and Storage Depths

The dependence on the age and thickness of the upper plate suggests that the density structure and/or the thermal structure of the crust influences magma ascent. However, the lack of a correlation with the surface heat flux argues against a thermal control, consistent with the concept that the thermal fields are dominated by the ascending magma itself [*Marsh*, 1989]. Thus, the crustal density structure appears to be the main parameter influencing magma storage.

Precise density profiles to quantitatively evaluate how the age and thickness influence the density structure are not systematically available. Thus, we only qualitatively discuss the effect of the density structure on magma ascent and storage depths. Buoyancy, the main force recognized to drive magma ascent [*Spence and Turcotte* 1985; *Gudmundsson*, 2011b], is due to differences in density between the ascending magma and the surrounding rock. If the density of an ascending magma is considered constant, differences in buoyancy between volcanic regions result from depth differences in crustal density contrasts. For example, in a thickened crust in which a density contrast (i.e., transition between 2.9 and 2.7 g/cm^3 density layers) occurs at a deeper level compared to a "normal" crust, an ascending magma of density 2.7 g/cm^3 will lose its buoyancy at this deeper level. Additional effects of magma ascent through a thicker crust also include increased heat loss and prolonged contact with the surroundings, further decreasing the magma buoyancy. In summary, the correlation between magma storage depths and the crustal structure likely illustrates the importance of buoyancy for magma ascent and the storage levels.

5.2. Influence of the Upper-Plate Crustal Stress Regimes on Magma Ascent and Storage Depths

Shallow magma reservoirs preferentially develop in extensive and strike-slip stress regimes, illustrating the importance of tectonic stresses and preexisting structures on magma ascent and the level of magma storage, in agreement with previous studies [e.g., *Walker et al*., 1993; *Watanabe et al*., 1999; *Corazzato and Tibaldi*, 2006; *Acocella et al*., 2008; *Moran et al*., 2011; *Chaussard and Amelung*, 2012]. Differences in intra-arc and upper-plate stress regimes are due to the fact that the intra-arc stress is affected by the presence of crustal faults while the upper-plate stress is a regional average over the entire plate. We found that no shallow magma reservoirs are observed in compressive intra-arc stress, while a few are observed in compressive upper plates. Shallow reservoirs developed in compressive upper plates may be located close to preexisting structures that locally modify the stress or act as pathways, supporting that the preexisting structures significantly influence magma ascent, in agreement with findings from analog modeling and structural observations in all tectonic settings. See *Hutton* [1988] for extensional settings, *Guineberteau et al*. [1987] for transtensional settings, *Corti et al*. [2005] for strike-slip settings, *D'lemos et al*. [1992] or *De Saint Blanquat et al*. [1998] for transpressive settings, and *Brown and Solar* [1998], *Kalakay et al*. [2001], and *Galland et al*. [2003] for compressive settings.

It is likely that the effect of the stress regime on magma migration is dominant at intermediate crustal depths. At deeper crustal levels faults may not be present and the lithostatic stress and viscoelastic behavior decrease the relative effect of tectonic stresses on dike propagation (magma ascends via vertical dikes even in compressive regimes) [*McGarr and Gay*, 1978]. At very shallow depths (1–3 km below the surface) local effects related to heterogeneities, such as sediments layering, dominate the stress field and likely control the depths of magma storage [*Menand*, 2011; *Gudmundsson*, 2006].

5.3. Lack of Correlation With Subduction Parameters

Our analysis does not show any correlation between the reservoir depths and the subduction kinematics, the slab's characteristics, the duration of the current subduction, and the slab's temperature. All these parameters influence the degree of hydration of the slab and the speed or amount of fluids released in the mantle [*Cagnioncle et al*., 2007]. The lack of a correlation suggests that the generation and the ascent of magma are controlled by different processes, similarly to the conclusions reached by *Acocella and Funiciello* [2010]. This concept is also in agreement with observations that melts are mobilized in short-lived fluid-flow events in the mantle [*John et al*., 2012] and that crustal magma ascent is characterize by pulses, the frequency and magnitude of which vary through time, while melt production rates are constant [*Druitt et al*., 2012; *Parks et al*., 2012], supporting that magma ascent is decoupled from magma production.

This is in contrast to the conclusion reached by *Zellmer* [2008], who suggested that melt production rates control ascent rates. *Zellmer* [2008) used lava viscosity as a proxy for magma ascent rate, which may however be influenced by processes occurring in the magma reservoirs. An alternate explanation for the correlation between lava viscosity and subduction kinematics is that melting processes in the mantle influence magma properties, for example faster subducting slabs may result in melts with higher water content and thus a lower viscosity.

Our analysis does not show any correlation between the dip of the slab and the magma reservoirs depth. The slab dip influences the distance between the melting region in the mantle and the surface [*Syracuse and Abers*, 2006], but this distance is also influenced by the crustal thickness. The correlation between the depth of magma storage and the crustal thickness but not with the slab dip confirms that parameters intrinsic to the crust have more influence on crustal magma ascent than subduction parameters.

6. Conclusion

Our study shows that magma ascent and storage in volcanic arcs is influenced by the upper-plate crustal structure (age and thickness) and by the stress regime. The absence of correlation between magma storage depths and the kinematics, structure, and timing of the subduction suggest that magma production rates are independent from magma ascent rates.

The implications in terms of volcanic hazards are that arcs developed in young and thin crusts undergoing extensional or strike-slip stress regimes are more likely to develop shallow magma reservoirs, which are associated with a higher risk of eruption.

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