VOLCANOLOGY

Magmatic water content controls the pre-eruptive depth of arc magmas

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Vanguard efforts in forecasting volcanic eruptions are turning to physics-based models, which require quantitative estimates of magma conditions during pre-eruptive storage. Below active arc volcanoes, observed magma storage depths vary widely (~0 to 20 kilometers) and are commonly assumed to represent levels of neutral buoyancy. Here we show that geophysically observed magma depths (6 ± 3 kilometers) are greater than depths of neutral buoyancy, ruling out this commonly assumed control. Observed depths are instead consistent with predicted depths of water degassing. Intrinsically wetter magmas degas water and crystallize deeper than dry magmas, resulting in viscosity increases that lead to deeper stalling of ascending magma. The water–depth relationship provides a critical constraint for forecasting models by connecting depth of eruption initiation to its volatile fuel.

The way we view magmatic plumbing systems beneath active volcanoes has shifted from the notion of singular melt-rich pools (i.e., "magma chambers") toward models that describe complex, multitiered networks of crystal-rich mushes (*1*, *2*). These systems may span the vertical depth of the crust (*3*) and may undergo reorganizations over time scales of volcanic unrest (*4*). In this paradigm, the degree of order in these complex systems is unclear.

Observations show that some sense of order exists in magmatic systems. Despite the resolution limitations, geophysical studies commonly find evidence for discrete regions of magma accumulation that are vertically restricted to a few kilometers (*5*). In contrast to the often-proposed dynamic nature of plumbing systems (*3*, *4*), some geophysical observations are consistent with regions of storage that may persist for years at a particular depth throughout multiple phases of unrest and eruption (*6, 7*). These findings demonstrate our ability to identify favorable regions for magma storage, but we lack a general understanding of the physical controls over depth. This variable is of central importance for historically active arc volcanoes. These systems supply Earth's daily volcanic eruptions and will be a focal point for eruption-forecasting models that use physics-based criteria to predict eruption onset, style, and duration (*8*).

Little is known about the primary controls over the depth of magma storage before eruption. A prevailing notion is that arc magmas are stored at their levels of neutral buoyancy, where the density of the bulk magma is equivalent to that of the host rock (*9*). Although this idea has been rigorously tested at mid-ocean ridges (*10*), the assumption remains largely untested at arcs. Alternatively, magma storage may be controlled by regional stress states or preexisting structures in the crust (*5*, *11*–*13*). An associated idea is that magma storage occurs at crustal rheology boundaries (*14*), the locations of which depend not only on crustal properties but also on strain rate (*15*). Though crustal rheology is an important factor in the long-term survivability of reservoirs (*15*), we lack evidence that differences in crustal rheology alone are responsible for the observed variation in magma storage depths at arcs globally.

A different hypothesis—one that is not consistent with magma storage depth being controlled by extrinsic factors—highlights the potential importance of intrinsic factors such as magmatic water concentration (*15*–*17*). During magma ascent and decompression, water solubility decreases until saturation is reached, at which point water degases progressively (*18*). Melt density, which relates to the buoyant force for magma ascent (*19*), may increase or decrease depending on whether exsolved volatiles remain entrained with the ascending magma (*20*). In all cases, a decrease in magmatic water content leads to an increase in melt viscosity (*20*), which can inhibit magma ascent and dike propagation (*21*, *22*). Magmatic water content is also a strong control on liquidus temperature (*20*). Water degassing is thought to result in undercooling and crystallization (*23*), further increasing magma viscosity. The occurrence of such processes during magma ascent may result in a positive feedback loop in which degassing leads to increased magma viscosity and crystallinity, inhibiting magma ascent and causing magmas to become increasingly subjected to the effects of conductive cooling, thus leading to further melt crystallization and increases in viscosity. An analogous process has been suggested to occur at mid-ocean ridges, where magma ascent is halted as magma reaches a "freezing horizon" (*24*, *25*). At arcs, the process has been described as "viscous death" (*16*). Viscous death may be the ultimate cause of reservoir formation in arcs, and some have found regional evidence for it (*17*). However, its global reach has not been tested.

To elucidate the role of water in the formation depth of magma reservoirs, we compare new and existing observations of magmatic water contents with corresponding geophysical observations of magma storage depth (*26*) (tables S1 to S3). Arcs are the best setting for our study because initial magmatic water contents are variable (*27*), and arc volcanoes are common targets for geophysical studies of magmatic plumbing systems (*5*). Our focus is on improving understanding of the observed reservoir depths rather than their long-term evolution. Therefore, our results are less relevant for long-lived silicic systems, which have been well studied elsewhere (*15, 28*).

Estimates of magmatic water content come from melt inclusion data, which include additional data for the central-eastern Aleutian arc and compiled data from arcs globally (table S2). Our dataset includes 3856 naturally glassy melt inclusions from which we derive estimates of magmatic water content for 62 volcanoes. We restrict our dataset to mafic-intermediate melt compositions (<63 wt % SiO_2, <7 wt % total alkalis), which are less likely to have experienced water enrichment during melt evolution in the middle to upper crust. We assume that these melt compositions represent the melt feeding the reservoir. We use the maximum observed water concentration as the estimate of water content of the magma in the middle to upper crust before degassing. We take this approach to minimize the influence of processes that decrease water, such as degassing and post-entrapment diffusive loss of water (*26*).

We compiled magma storage depth estimates from geophysical studies, particularly those based on geodetic or seismic observations (table S3). Our compilation includes 331 depth estimates for 168 distinct magma reservoirs. The depths we consider are referenced to the land surface (not sea level, as commonly reported). The depth below the surface relates closely to the overburden pressure, which can then be linked to the depth of magma degassing through volatile solubility relationships. Many geochemical approaches for determining magma storage depth are highly dependent on magmatic water content. Therefore, to avoid circular logic in comparing magmatic water content to storage depth, we restrict our estimates of magma storage depth to those determined using geophysical data.

Water contents of mafic-intermediate magmas from arc volcanoes vary from ~1 to 7 wt % (average: 4.0 ± 1.3 wt %) on the basis of our compilation, consistent with earlier work (*27*).

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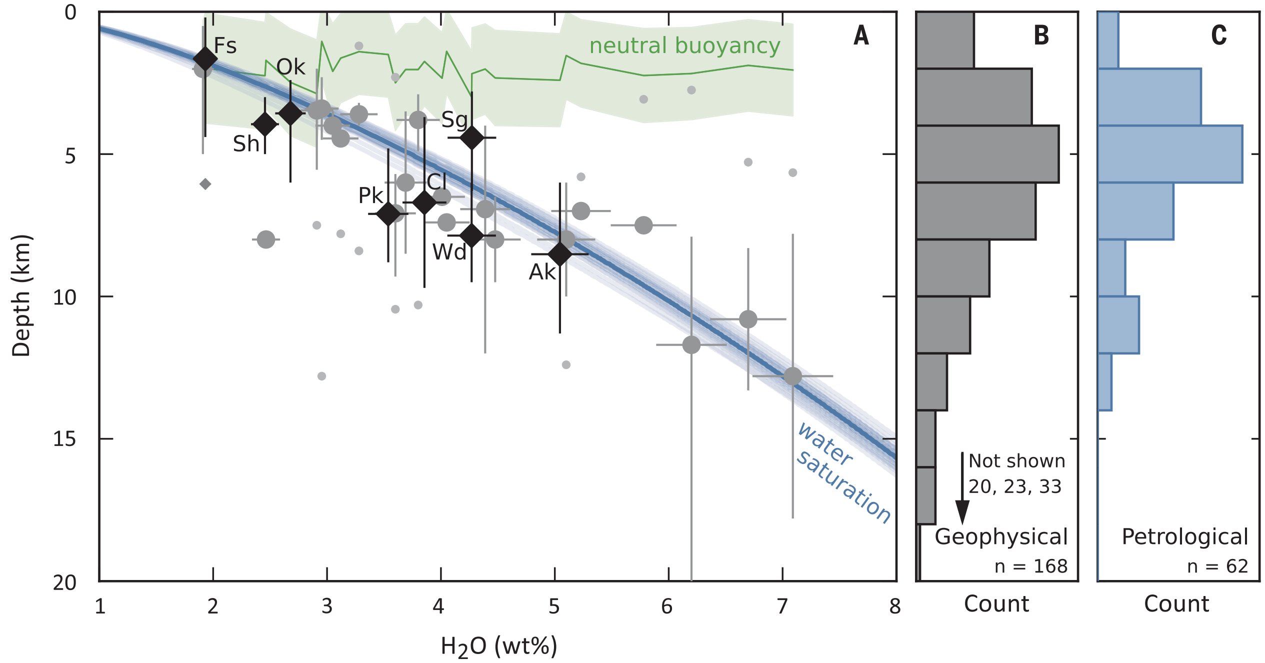

Fig. 1. Link between magmatic water content and storage depth. (**A**) Magma storage occurs primarily where water degassing becomes important, not at the levels of neutral buoyancy. Data are for central-eastern Aleutian volcanoes (diamonds) and other locations (circles). Large symbols denote the reservoirs closest to the water saturation curve at each volcano, which fall on or near the curve in 27 of 28 cases (RMSE: 1.6 km). About half of the volcanoes have one or more other reservoirs (small markers) that are plotted off of the curve. Markers show the average centroid depth. Vertical error bars indicate the range of observed depths, and horizontal error bars denote assumed 5% measurement errors. Water degassing is approximated to start at the water saturation curve (blue lines), which was calculated with MagmaSat (*29*) and 27 density models. The same density models were used to calculate average (green line) and 1σ SD (green shaded area) levels of neutral buoyancy for open-system ascent. Closed-system models (not shown) indicate that magma is buoyant throughout the crust. Central-eastern Aleutian volcanoes are labeled (Ak, Akutan; Cl, Cleveland; Fs, Fisher; Pk, Pakushin; Ok, Okmok; Sg, Seguam; Sh, Shishaldin; Wd, Westdahl). (**B**) Histogram of 168 magma storage regions at 112 volcanoes estimated using geophysical methods. Three depth estimates (20, 23, and 33 km) are not shown. (**C**) Histogram of the water-saturation depth for 62 volcanoes. The similarity in the distributions in (B) and (C) supports the observation from (A) that storage depth relates to magmatic water content.

Geophysical observations of magma storage are mostly constrained to the upper ~20 km of crust. A distinctive mode in observed storage depths occurs at 4 to 6 km below the surface with a long tail to greater depths (6.4 ± 2.8 km, 10%-trimmed average, 6.0-km median; Fig. 1B). These observations are likely biased to shallow depths because many of the geophysical techniques employed have better resolution at shallower depths. However, our results show substantial shallow (~3 to 9 km depth) storage of magmas at arcs.

We can investigate the control of magmatic water content on magma storage depth by comparing the geochemical and geophysical datasets (Fig. 1A). Water and depth estimates increase concurrently in 27 of the 28 volcanic systems (the exception being Semisopochnoi). Not only do pre-eruptive storage regions form a strong water–depth trend, the trend also coincides with the water-saturation curve [1.6-km root mean square error (RMSE) for large symbols in Fig. 1A]. This provides strong evidence for a link between observed water content and depth. For half of the studied systems, this is the only known region of magma storage. For the other half, two or more discrete regions of magma storage have been identified (table S1). The other regions of magma storage (small symbols in Fig. 1A) are plotted off of the water-saturation curve. Therefore, although we observe magma storage along the water-saturation curve in nearly all of the volcanic systems we analyzed, this is not the only storage depth. Degassing of water will initiate at depths greater than that of water saturation if a vapor phase containing CO_2 is present, perhaps explaining the general tendency for storage to occur slightly below the water-saturation curve (Fig. 1A), but the effect of this is generally minor (*29*).

We can also compare all of the geophysically identified magma storage regions at arcs (n = 168) with the predicted depths at which arc magmas begin degassing water (water-saturation depth) at all arc volcanoes with water constraints (n = 62). Water-saturation depths form a distinct mode at 4 to 6 km (5.5 ± 1.8 km, 10%-trimmed average, 4.9-km median; Fig. 1C), which coincides closely with geophysical estimates of magma depth (Fig. 1B). The water-saturation depth is determined by calculating the pressure at which melt would saturate with a pure-water vapor (*29*) and converting pressure to depth by using a summary density model based on data from 27 volcanoes (table S4). Additionally, our calculated water-saturation depths are influenced by our choice of solubility model, but different models yield similar results (*26*) except for one (*30*), which yields lower pressure (depth) estimates.

Although the empirical link between magmatic water content and storage depth is clear (Fig. 1), the interpretation requires further consideration. Two plausible explanations exist: (i) Magmatic water contents control magma stalling [mantle control (*27*)], or (ii) the storage depth of magmas dictates the water contents of the observed melt inclusions [crust control (*27*)]. Therefore, we need to know whether melt inclusions accurately record magmatic water contents. If the mantle control is dominant, then the water content of melt inclusions should correlate with other nonvolatile tracers of slab- and mantle-melting processes (e.g., Nb/Ce and Ba/La). If instead the water contents of melt inclusions are the result of a crustal control, melt should degas or melt inclusions should diffusively equilibrate to reflect their stalling depth. Any correlations that existed in the parental magma between water and nonvolatile tracers would be destroyed during these processes. Such correlations can be difficult to identify because they require a sufficiently large sampling of an arc segment where a relationship is expected. However, the central-eastern Aleutian volcanoes show systematic relationships between water and trace elements (Fig. 2) (*27*), and other melt inclusion studies have found similar correlations at other arcs, such as the Cascade (*31*) and Central American (*32*) arcs. Such systematics support a mantle control in which intrinsically wetter magmas, with distinct trace element compositions, degas and crystallize deeper than dry magmas, resulting in deeper storage before eruption. This trend exists globally despite substantial differences in magmatic flux and crustal properties between volcanoes, demonstrating the global importance of water content to the depth of reservoir formation. Whether a reservoir formed in this way would grow upward or downward with subsequent magmatic additions is unclear, which may cause some of the observed scatter (Fig. 1A). The longevity of such reservoirs is a separate question, which is best approached by means of thermomechanical modeling (*15*). Additionally, though water saturation can explain the presence of the observed storage reservoirs, their formation is not required. For example, cinder cones can erupt water-saturated magma with primitive compositions that are inconsistent with storage in the middle to upper crust.

Neutral buoyancy has long been invoked as a control over magma storage. We estimated the level of neutral buoyancy (LNB) for volcanoes in Fig. 1A by comparing our 27 compiled crustal-density models (table S4) with models of ascent, degassing, and crystallization conducted using rhyolite-MELTS (*29*, *33*) (tables S5 to S7). For each volcanic system, we performed two models of adiabatic magma ascent: (i) an open-system model in which crystals and vapor were fractionated from the melt upon formation and (ii) a closed-system model in which crystals and vapor remain in equilibrium with the ascending magma. The results of our open-system models have consistent LNBs at ~2 km depth. Closed-system models universally show that magmas are buoyant throughout the crust, owing to the strong influence of a vapor phase on magma buoyancy (table S5). Although there are a small number of reservoirs at depths equivalent to the LNB assuming open-system melt evolution (Fig. 1A), most reservoirs occur at greater depth. Therefore, we reject neutral buoyancy as a primary control over magma storage depths. This result is consistent with findings at mid-ocean ridges (*10*); however, perhaps owing to differences in crustal density and stress state between arcs and ridges, neutral buoyancy has remained a fixture in arc-volcano literature for decades (*15*).

Degassing of water upon magma ascent causes increases in magma viscosity and liquidus temperatures (*20*), which can explain

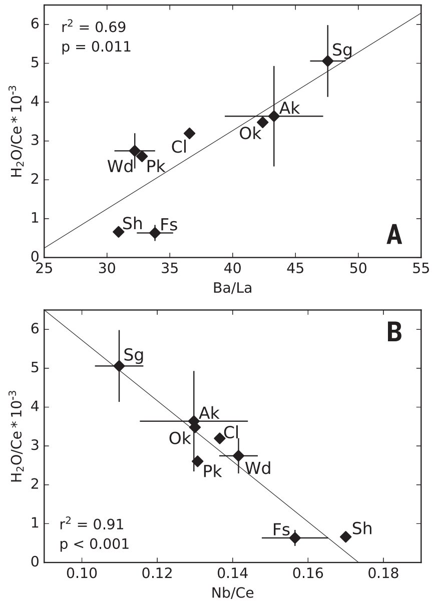

Fig. 2. Melt inclusion data for the central-eastern Aleutians. (**A** and **B**) The correlations indicate that degassing and diffusive water exchange have not substantially affected the water contents of the melt inclusions. Trace element data do not exist for most (five of eight) melt inclusions with maximum water content. For these melt inclusions, we use average trace element compositions of bulk rock samples with similar (i.e., within 0.25 wt %) K_2O concentrations. Bulk rock data at Cleveland do not extend to a sufficiently low K_2O concentration, so we extrapolated the bulk rock trend (table S8). Markers represent the mean ratios, and error bars denote SDs.

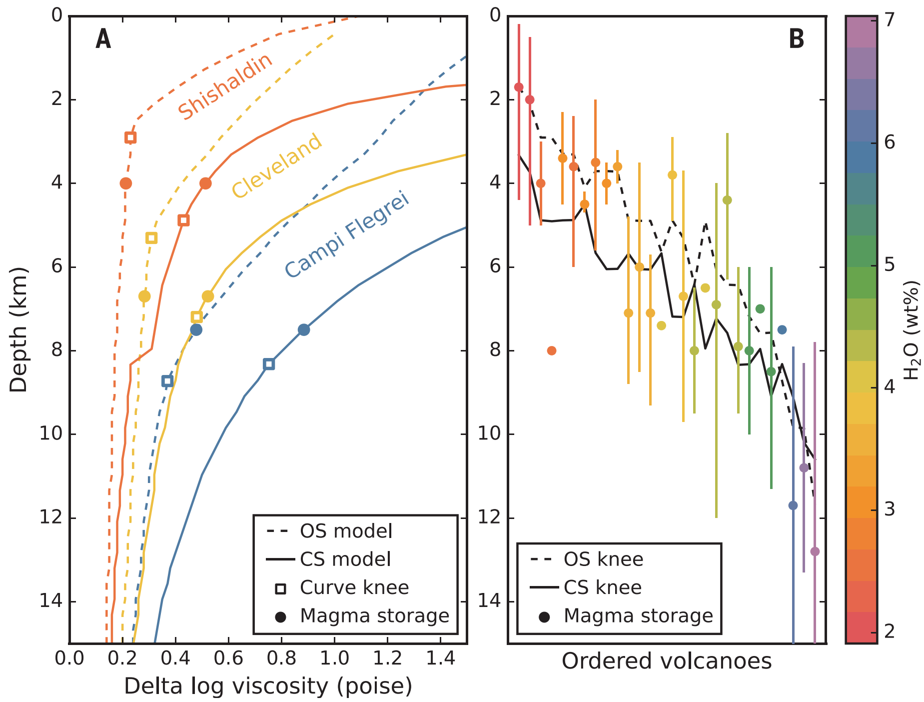

Fig. 3. Relationship between magma storage depth and magma viscosity. Pressure was converted to depth using our summary density model. (**A**) Change in magma viscosity during adiabatic magma ascent for three example volcanoes calculated using rhyolite-MELTS (*29*, *33*) for cases of open-system (OS) and closed-system (CS) crystallization and volatile exsolution. For each volcanic system, the model (curve), the calculated viscosity knee (i.e., point of maximum convexity; square marker), and the average centroid depth of magma reservoirs determined geophysically (circle marker) are shown. Information on the MELTS modeling and calculation of the viscosity knee can be found in (*26*). (**B**) Comparison of the depth of the viscosity knee for OS and CS models (dashed and solid lines, respectively) with the geophysically observed depths of magma storage for volcanic systems in Fig. 1A. The volcanic systems are ordered along the *x* axis by the average depth of the OS and CS knees. In most cases, magma storage occurs at either the OS or CS knee, supporting viscosity change as a control on magma storage depth. Error bars indicate the range of observed depths.

the observed depths of magma storage (Fig. 3 and table S6). We demonstrate this in the results of the MELTS models. We consider the change of the viscosity of the magma during ascent that we calculated with MELTS rather than the absolute viscosity. We make this our focus because our model assumes that magma ascent is occurring, which means that any barrier to initial ascent imposed by the absolute melt viscosity has been overcome. This must be true of the natural systems we studied because their magmas escaped the lower crust to form reservoirs in the middle to upper crust. Alternatively, the change of viscosity during magma ascent may influence dike propagation (*21*, *22*). Our results show that magma viscosity increases during magma ascent (Fig. 3A). Open-system ascent typically leads to smaller increases in melt viscosity during ascent. The "knee" in the depth-viscosity curve (*26*) indicates the point of maximum convexity. Physically, it represents the depth at which viscosity increases during ascent become substantial. We find that most observed magma storage depths occur at either the open- or closed-system viscosity knees (Fig. 3B), supporting the idea that changes in magma viscosity during magma ascent control magma storage depth.

The magmatic systems we studied can generally be considered eruptible. Most of the systems in this study have been historically active. Geophysical data used to constrain magma depth commonly include coeruptive data (*7*), and we used erupted melt inclusions. Our results demonstrate that magmas are buoyant at their storage depth, providing a driving force for ascent and eruption. These systems have clearly experienced viscous stalling, not viscous death, consistent with noneruptive episodes of stalled intrusions that are commonly observed years to decades before many eruptions (*34*). Whether a magma body in the crust ultimately erupts, cools to form a pluton, or grows depends critically on crustal rheology and magma injection rate (*15*). Exsolved volatiles also play a role, as they would exist in a compressible vapor phase that dampens pressure increases due to injection of new magma, enabling reservoir growth (*35*). We investigated initial reservoir formation in the middle to upper crust and show that intrinsically wetter magmas degas water and crystallize deeper, leading to increases in magma viscosity and the formation of reservoirs at greater depths. These results will contribute to models of eruption triggering that depend critically on the conditions of the magma storage region (*8*).

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SUPPLEMENTARY MATERIALS

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Materials and Methods
Supplementary Text
Figs. S1 to S29
Tables S1 to S11
References (*40*–*202*)

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Water-controlled magma depth
Magma is stored deep underground until something triggers an eruption or it cools into a pluton. One traditional view of why the magma stays where it does is the assumption that it has the same density as the surrounding rock, keeping it from ascending upward. Rasmussen *et al*. found that the amount of water that arc magmas have in them determines their depth. Degassing water changes the viscosity, allowing it to stall out at a depth where it is still buoyant. This situation may provide some additional buoyancy to get the magma to the surface during an eruption. —BG