Olivine Exit Interviews—Piecing Together Magmatic Puzzles

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Los Hornitos cinder cones (Chile); site of tephra with skeletal olivine rapidly transiting thick arc crust (Salas et al. 2021). PHOTO: PHILIPP RUPRECHT.

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When magmas erupt at the surface, they may have undergone many changes since their inception. While olivine drives some of these changes through crystallization and fractionation, it also records the magma evolution via mineral chemistry and by trapping mineral and melt inclusions. Olivine is an effective recorder of intensive parameters, such as temperature and melt composition, and provides an outstanding petrological tool for constraining dynamic processes, such as ascent, mixing, and cooling. Olivine sheds light on magmatic puzzles that involve both mafic and more evolved magmas, with protracted and complex magmatic histories that often obscure earlier and deeper processes. This contribution summarizes the current state of how olivine helps reconstruct source-to-surface magma assembly through its chemistry, inclusions, and textures.

KEYWORDS: olivine zoning; crystal records; crystal growth; crystal diffusion

INTRODUCTION

Where do magmas come from? How do they evolve on their transit through the mantle and crust and under what conditions? Where do they stall and mix with other magmas or other crustal components along the way? Crystals carried by the magma are the premier recorders of these events as they retain transient changes more faithfully compared with the carrier melt that averages across all these processes. Previous reviews regarding crystal records have highlighted many general concepts associated with them (e.g., Davidson et al. 2007). Here we want to focus specifically on the information that is extracted from olivine as it grows, hitchhikes along the way, and changes chemically via diffusion in response to changes in melt composition, pressure, and temperature conditions. Many analogies have been proposed for these kinds of records, and one that we find highly effective is the description of crystals as participants in exit interviews, where each crystal participated in the same event, but had a unique vantage point, thus keeping records with a different focus or sensitivity (see BOX 1).

Olivine has played a key role when interpreting crystal records because of its ubiquity in ultramafic to intermediate magmas, and in some cases even in evolved magmas (Welsch et al. 2023 this issue). Moreover, it has received abundant attention in experimental studies (e.g., Jambon et al. 1992; Beattie 1993; Faure et al. 2003; Chakraborty 2010; Coogan et al. 2014), which ensures that partitioning relationships of major and trace elements are well understood, that elemental and isotopic diffusion in olivine has been constrained for many elements, and that robust estimates on its growth dynamics in different thermal and compositional environments are emerging. This wealth of detailed knowledge makes olivine one of the most frequently used minerals to explore processes of magma transport, storage, and assembly. However, it is not only the chemical zoning and growth textures that constrain these processes; olivine is also well-known for its ability to trap surrounding melts during crystal growth in so-called melt inclusions, or as embayments, which partially isolate those carrier melts (Faure and Schiano 2005; FIG. 1). Such melt inclusions and embayments are particularly powerful in their ability to trap volatile elements, which are the primary agents determining the style of volcanic eruptions (Wallace et al. 2021).

Determining Intensive Magma Parameters

Temperature and magma water content are two of the most important intensive parameters as they control magma crystallinity and viscosity and therefore magma rheology and dynamics. For decades, olivine has been used as a sensitive probe to record crystallization temperatures (Roeder and Emslie 1970). The minor volume differences (<5%) of the olivine lattice between the Fe- and Mg-endmembers make Fe-Mg partitioning between melt and olivine a first-order function of temperature (see FIG. 3 in Welsch et al. 2023 this issue). The olivine–melt thermometer is among the best calibrated thermometers (e.g., Beattie 1993). Other temperature-dependent olivine–mineral partitioning relationships (e.g., aluminum partitioning between olivine and spinel, FIG. 1; Coogan et al. 2014) provide additional temperature constraints. Thus, precise temperature conditions of magmas throughout the mantle and the crust can be determined, because olivine is an early crystallizing phase and these well-calibrated thermometers exist. Determining magma water content also uses partitioning between olivine and melt, whether it is directly for hydrogen (e.g., Barth and Plank 2021) or for minor elements like calcium (Gavrilenko et al. 2016). These are examples of the numerous thermodynamic models that have been developed using olivine. Constraining temperature and water content are especially important when piecing together magmatic histories, as these parameters directly impact estimates of process rates within the magma.

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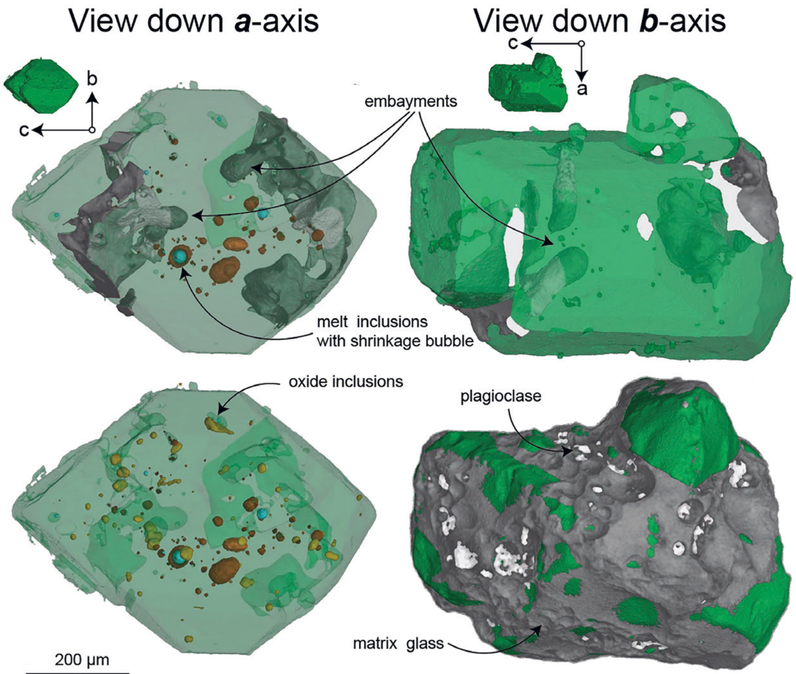

Figure 1 X-ray micro–computed tomography (CT) model for an olivine crystal from the terminal scoria of the 1932 Quizapu eruption, Chile. The micro–CT model distinguishes olivine (green), silicate glass (gray), adhering plagioclase (white), oxide inclusions (yellow), and silicate melt inclusions (red) with shrinkage bubbles (blue) based on density of the imaged phases. The images are specific frames taken from a detailed movie rendered from the micro–CT model (full model in data repository: doi.org/10.5281/zenodo.6812473) that highlights different aspects of the crystal's interior. Views down the *a*-axis are partially transparent to show the melt inclusions and their shrinkage bubbles, as well as the matrix melt penetrating the crystal to form so-called embayments (TOP) and the distribution of oxides (BOTTOM), respectively. The view down the *b*-axis highlights the partial distribution of embayments and how they separate multiple olivine subgrains that form the composite crystal.

Linking Provenance and Process—Major and Trace Elements

While temperature has a strong control on the olivine composition, melt chemistry is equally important, especially as magmas evolve and the Mg/Fe ratio in the melt drastically decreases. Olivine chemistry, and specifically the forsterite content Fo with Fo = Mg/(Mg + Fe) (on a molar basis), is used as a proxy for melt (and magma) chemistry that carries the olivine from source to surface. This is powerful when investigating erupted magmas and how they were assembled (Fig. 2), assuming that olivine compositions reflect the melt composition of the batch in which they spend the majority of their existence (e.g., centuries to millennia, Winslow et al. 2020), and that rim compositions represent the final, surface-bound magma. Identifying the dominant components of a magmatic system hence requires the study of populations conceptually similar to mineral provenance studies at the scale of mountain ranges and watersheds. Distinct olivine populations may be identified in Fo distributions encompassing n > 1000 individual spot analyses (Fig. 2) that can be linked to a specific zone in a magma plumbing system. A large number of analyses is needed to capture the major and subordinate environments of crystallization and storage; just like one needs to conduct a large survey of exit interviews to extract a detailed account of all events beyond the basic scoreline. As a result, we recognize that the crust is only a leaky barrier to mantle-derived magmas and source magmas as well as crustal reservoirs, including crystal cumulates, which can be probed simultaneously (Ruprecht and Plank 2013; Oeser et al. 2018).

Studies that have analyzed a large number of olivine grains (>>100) from either a single eruption or episodic activity show that eruptions often contain a complex crystal cargo that requires tapping chemically distinct magmatic reservoirs, from mid to upper crustal storage regions (Kahl et al. 2015) to the mantle (Ruprecht and Plank 2013). In the latter example, the deeper and significantly more primitive components (>Fo88) demonstrate the composite nature of parts of this basaltic andesitic to andesitic eruption. However, while Fo content distributions highlight subordinate populations, accompanying trace element concentrations (and potentially isotopes), textures, and mineral inclusions delineate the complete crystal origins and histories. In particular, nickel concentrations in olivine have been used to identify different reservoirs in the mantle and crust (Fig. 2), although very different processes may result in similar trace element signatures. Multi-element signatures help distinguish between those processes, where e.g. Ni/Cr ratios prove to be highly sensitive when distinguishing between fractionation and cumulate remobilization. Moreover, those trace element signatures help link peaks in the Fo spectra to different olivine populations of distinct origin.

Timescales from Diffusion Studies

As noted in the previous section, olivine major and trace element and isotope records are subject to diffusion on timescales of magma storage and transport. Both major and trace element diffusivities have been determined to good precision, enabling studies that explore degassing phenomena during magma ascent (e.g., Li, H) and mixing between chemically distinct magma batches (e.g., Mg-Fe, Ca, Ni, Cr). In fact, olivine is probably by far the most frequently used mineral phase to use for diffusion studies in magmatic systems (Ruprecht and Plank 2013; Kahl et al. 2015; Costa 2021; see also Jollands et al. 2023 this issue for the general concepts). These studies have revealed unprecedented details about rates of magmatic processes. Olivine is sensitive to track ascent on the order of minutes from crystal storage regions using fast-diffusing hydrogen and lithium as well as track month- to year-long episodes of magma unrest and reorganization using slower diffusing elements such as Fe-Mg, Ca, Ni, and Cr (Jollands et al. 2023 this issue). Many reviews have provided a detailed summary of the different applications and tools that are beyond the scope of this overview, with Costa (2021) being an excellent start to dive deeper into the continuously growing field. Thanks to these developments, forward modeling of mineral zoning is now a routine approach to determining timescales of magmatic processes. Moreover, while the precision of these diffusion-based methods suggests that linking mineral zoning records with seismicity, deformation, or gas emissions can be achieved in some simple eruption scenarios, such comparisons remain limited by an incomplete knowledge of the thermal histories during periods of volcanic unrest

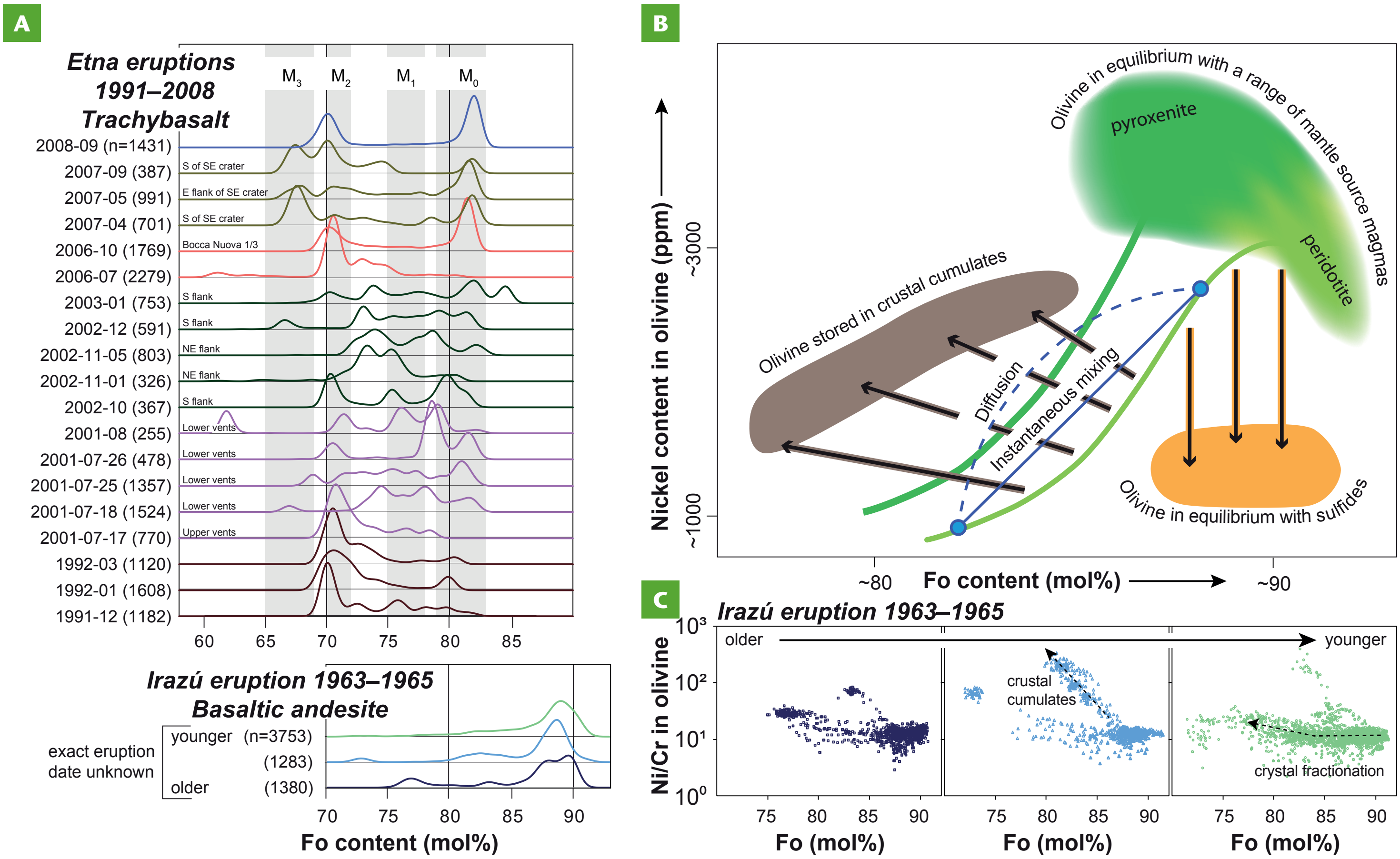

FIGURE 2 (**A**) Kernel density distributions of olivine analyses for two well-studied volcanic systems (Etna, Italy with n_{total} = 18,692 analyses; Irazú, Costa Rica with n_{total} = 6416 analyses). Etna analyses are individual microprobe spot analyses (FROM KAHL ET AL. 2015), while Irazú analyses are individual segments of l76 line scans collected by laser-ablation inductively-coupled plasma mass spectrometry (FROM RUPRECHT AND PLANK (2013), underlying data in data repository: doi.org/10.26022/IEDA/112499). Compositional spectra show the compositional range and which compositions dominate the olivine populations. For Etna, the compositional populations M_0–M_3 are dominant. Note that some episodes have more complex mixing histories than others. (**B**) Schematic Ni versus Fo diagram showing how different processes affect trace element compositions: green curves represent olivine fractionation trends (FROM HERZBERG 2011 AND SOBOLEV ET AL. 2005) for magmas derived from peridotite (light green) and pyroxenite (dark green). Shifts from these curves may be related to reequilibration 1) in a crustal cumulate in the presence of pyroxene (brown, OESER ET AL. 2018) or 2) in the presence of sulfides (orange, BARNES ET AL. 2013) or incomplete diffusive equilibration with faster diffusive response for Ni compared with Fe-Mg (blue curves, GORDEYCHIK ET AL. 2020). (**C**) Ni/Cr variations versus Fo content in 1963–1965 Irazú olivine crystals show two distinct trends (note the logarithmic scale) with high Ni/Cr indicative of olivine storage in, and remobilization from, crustal cumulates, and relatively constant low Ni/Cr associated with crystal fractionation. Note that the crustal cumulate population waxes and wanes throughout the eruption.

prior to eruptions, as well as complications associated with zoning potentially representing crystal growth instead of diffusion processes. Robust temperature–time histories during crystal growth and diffusion remain a challenge, while competition between growth and diffusion can be explored, combining multiple elements with different diffusivities (e.g., Costa and Dungan 2005) or combined major and minor elemental and isotope zoning (e.g., Oeser et al. 2018). Major advances in this field will undoubtedly come from ongoing improvements of experimental data and increasing spatial resolution of diffusion profiles to capture even faster processes; however, another important direction is the need to expand on the concept of populations, which Kahl et al. (2015) and other studies have demonstrated elegantly.

How are Magmatic Processes Actually Recorded During Crystal Growth?

If the goal is to link zoning information to processes in the magma chamber, it is essential that growth and zoning histories be understood so that spatial information can be placed into a temporal context. However, in recent years, olivine has been at the center of a major paradigm shift where studies of trace element zoning and crystal growth textures have increasingly pointed toward complex growth histories that deviate from simple linear and concentric crystallization (Milman-Barris et al. 2008; Welsch et al. 2013; Salas et al. 2021; FIG. 3). Evidence is mounting that the olivine we see as a final product (a nice polyhedral crystal) may not be the norm during growth. Instead, a much more complex growth history with an early framework of rapidly growing branches may precede the final polyhedral shape (FIG. 4), all during which olivine captures variable amounts of trace elements. Phosphorus and its zoning in olivine have been particularly useful and well documented across a wide range of samples because its slow diffusion rate gives it the unique advantage to retain original growth histories (Milman-Barris et al. 2008). Thus, elemental P maps (such as those shown in FIG. 3) have revealed complex growth histories where a simple concentric and linear growth model fails. There, narrow zones enriched in P are the fingerprint of early rapid growth. In contrast, the interstitial spaces and large domains filled with P-poor olivine form subsequently when the growth conditions seek to re-approach equilibrium (FIG. 3). The geometry of skeletal and dendritic olivine has funda-

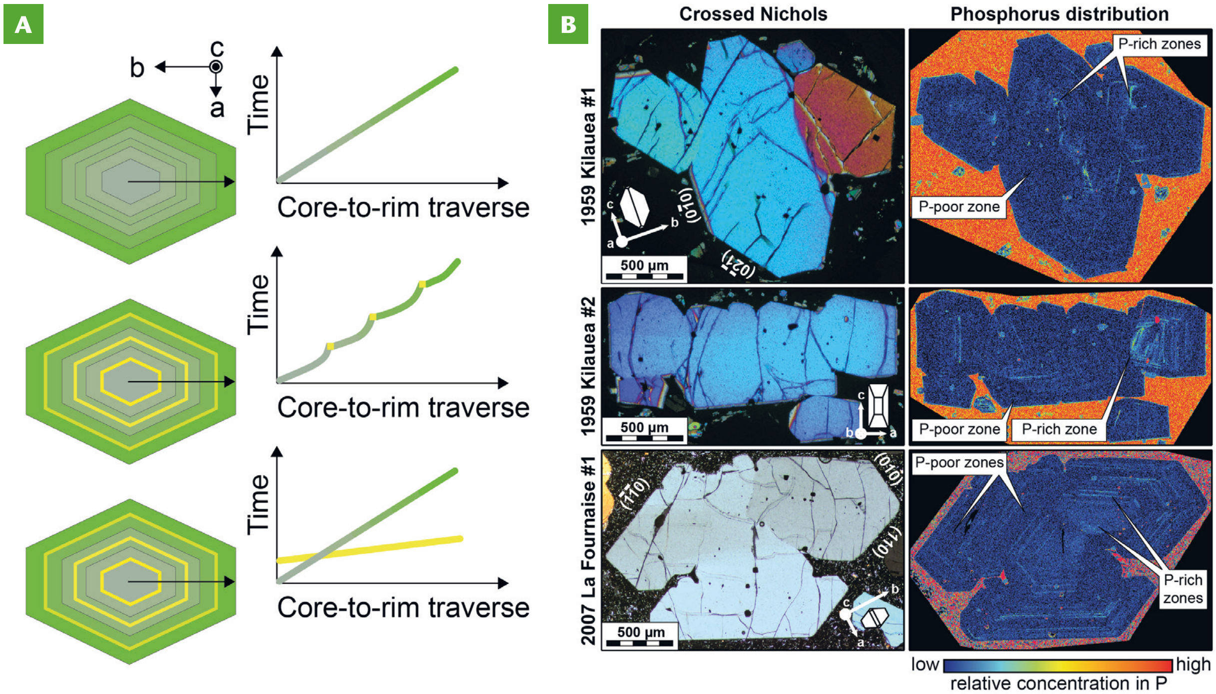

Figure 3 (**A**) Schematic zoning in olivine with a conventional growth history (top). High phosphorous zones (yellow bands) are interpreted as boundary layer enrichments during episodic slowing of growth (**middle**) and rapidly growing skeletal and dendritic structures that advance the crystal framework much more quickly than framework-filling equilibrium growth (**bottom**). Note that dendritic P-rich zones in some crystal planes still occur as quasi-concentric features. These are three potential growth models; combinations of these and other alternative models may exist. (**B**) Examples of olivine growth and associated P zoning, showing skeletal features as well as creating melt channels/embayments. X-ray distribution maps in (**B**) were obtained with the JEOL JXA-8500F electron microprobe of the University of Hawai'i at Mānoa, USA.

mental implications for diffusion calculations, where time may not always be represented in concentric continuous growth rings. While resorption has been recognized for a long time to alter core-to-rim temporal records, complex growth histories can cause space–time inversion with old near-rim zones (fast advancing dendritic and skeletal structures) and younger interior zones (Fig. 3). Diffusion calculations may therefore need to consider whether length scales of equilibration may be significantly shorter during the presence of an open framework, especially for zoning found in crystal interiors.

While decoding growth histories has become essential for understanding olivine zoning and piecing together magmatic puzzles, the growth morphologies of olivine also provide insight into the dynamics of the systems and can constrain thermal histories, especially cooling rates, degrees of undercooling, and even crystallization timescales (Fig. 4). These characteristic shapes, termed crystal habits, depend on both the crystallographic structure and the growth conditions. The dynamic crystallization experiments of Faure et al. (2003) in a simple system have shown that olivine has four main crystal habits: polyhedral, tabular, skeletal, and dendritic (Fig. 4). Because each habit crystallizes in a defined domain of cooling conditions, they can each be used as a probe of the amount of cooling experienced by the parental magma. Following the in situ experiments of Jambon et al. (1992) with a tholeiitic melt, each habit forms also at different growth rates, with polyhedral and tabular olivine crystallizing at slow growth rates (about 10^{-10} to 10^{-8} m/s in a tholeiitic melt), and skeletal and dendritic olivine at fast growth rates (in the range 10^{-8} to 10^{-6} m/s). From these experiments, first-order crystallization timescales of minutes to weeks of sustained crystal growth can be estimated from the habit and grain size of natural crystals. The difference between the initiation of cooling under the liquidus of the melt and the olivine crystallization would be minimal as crystallization experiments have constrained the nucleation delay to be of the order of 6 to 60 min (Donaldson 1979). In all cases, the reduction of the Gibbs free energy drives crystal growth; however, kinetic effects (diffusion) also impact growth textures as the local energy balance may include volume (mass fraction) and surface effects. Skeletal and dendritic crystals form when growth becomes diffusion-limited at large undercooling and fast cooling, because the major elements of olivine (Fe, Mg, Si) cannot be delivered to and other elements cannot move away from the crystallizing interface fast enough. Such habits reduce the diffusive length scale at the expense of minimizing the surface energy rapidly (i.e., complex crystal shapes are energetically unfavorable compared with polyhedral shapes), while still lowering the system's Gibbs free energy. Thus, olivine habits constrain the dynamic history as well as potentially the size and architecture of terrestrial magma systems (e.g., Albert et al. 2020) and beyond (First et al. 2023 this issue).

With the recognition that olivine growth histories may involve different growth regimes and potentially the assembly of larger crystals from multiple smaller subgrains (Welsch et al. 2013; Figs. 1 and 3), new models for the formation of melt inclusions and embayments have emerged. Facilitated by the hosting geometry of skeletal and dendritic crystals (Fig. 4), melt inclusions and embayments can be preserved either because of imperfect completion of crystallization or because infilling is arrested during eruption (Faure and Schiano 2005; Fig. 1). Such formation mechanisms highlight that any melt trapped in these structures may record a different stage of the magma system's evolution than the surrounding olivine. Only with time may the host olivine and enclosed melt re-equilibrate diffusively (Jollands et al. 2023 this issue). These effects may be important considering that melt inclusions and embayments are some of the prime targets to constrain the magma pre-eruptive volatile element contents and magmas' ascent rates; the latter being constrained by the systematic diffusive loss of volatile elements from the melt as magmas ascend, decompress, and degas (Wallace et al. 2021).

Adding Volatile Stories to the Puzzle Through Melt Inclusions and Embayments

Although a nominally anhydrous mineral itself, olivine plays an outsized role when exploring volatile budgets in volcanic systems and when using decompression-driven degassing signatures to address magma transport rates (Lloyd et al. 2014; Barth and Plank 2021; Wallace et al. 2021). Melt inclusions are among the best tools to constrain magma storage depth because of the strong pressure dependence of melt to dissolve volatile elements (most importantly H_2O and CO_2) and therefore place compositional and zoning records extracted from olivine crystals into a spatial framework. However, the fast diffusion of hydrogen through the olivine lattice (Jollands et al. 2023 this issue) limits any extrapolation of the water budget in magmas stored and generated deeper in the Earth. This is typically highlighted by olivine hosted–melt inclusions being zoned in hydrogen, and melt inclusion populations for individual volcanoes spanning a range of minimum entrapment pressures (Wallace et al. 2021). While magma ascent rates can be extracted from melt inclusions and their olivine hosts (Barth and Plank 2021), such rate estimates are only based on hydrogen diffusion, which is fast enough in olivine to be sensitive to the relevant timescale. Alternatively, melt embayments take advantage of the range of diffusivities of multiple volatile elements (H, C, S; Lloyd et al. 2014) that provide independent constraints on ascent rates and therefore potentially resolve ascent rate histories that are more complex than linear ascent. The use of melt embayments is hence a growing research direction. While embayments are common in olivine because of their frequent assembly from skeletal subgrains, recent ascent rate studies have only analyzed a small number (<10) of diffusion profiles. Thus, advances to test whether such small datasets are representative or whether a larger population approach is needed are the next steps to develop robust olivine-based ascent rate models.

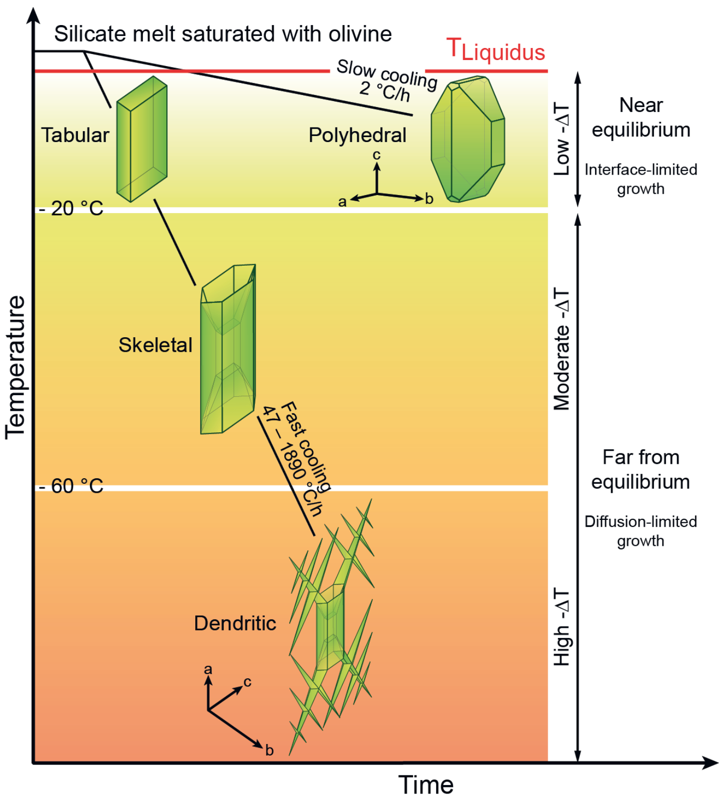

FIGURE 4 Olivine growth habits as a function of cooling rate and undercooling in a simple system (CaO-MgO-Al_2O_3-SiO_2). MODIFIED FROM FAURE ET AL. (2003). Crystals were modeled using the same parameters and methods as given in Welsch et al. (2013, 2023 this issue). Large cooling rates and increasing undercooling in the melt produce a sequence of tabular, skeletal, and dendritic textures elongated in the direction [10*w*]. In contrast, low cooling rates produce polyhedral textures elongated along the *c*-axis (direction [001]) regardless of undercooling. Based on this nomenclature, the texture of natural crystals in basalts can be described as "hybrids" by combining a skeletal/dendritic framework with polyhedral overgrowths as a result of a growth history initiated at moderate to high undercooling diminishing over time (Welsch et al. 2013; Salas et al. 2021; see also FIG. 3).

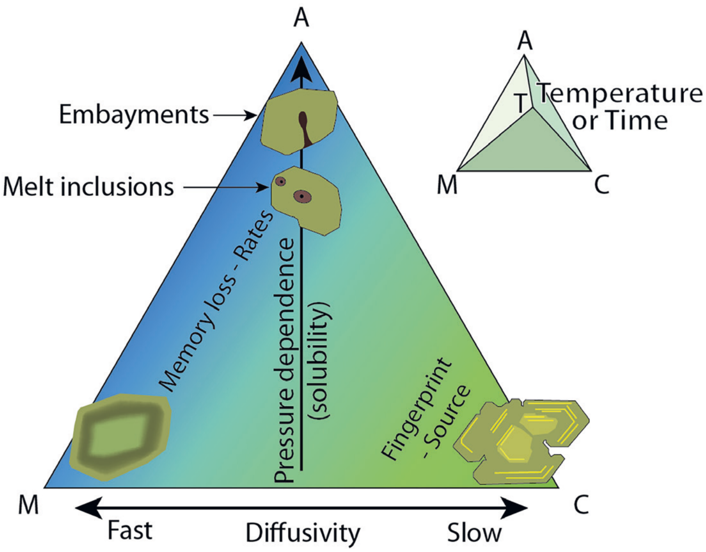

FIGURE 5 Classification of magmatic processes and how they are interrogated with olivine-based tools (INSPIRED BY DAVIDSON ET AL. 2007). Most magmatic processes can be separated into ascent (A), mixing (M), and crystallization (C) processes. Mineral-scale zoning can either be used to fingerprint initial crystallization conditions (slow-diffusing elements) or to extract rates of mixing and ascent processes (fast-diffusing elements). Specifically, embayments and melt inclusions track ascent processes because of the strong pressure dependence of volatile elements' solubility. Temperature and time are added here as a fourth dimension as they modulate through the diffusive length scale the sensitivity of crystal records to fingerprinting the source conditions or changes since initial crystallization.

CONCLUDING REMARKS

When olivine exits from volcanic systems, it is one of the most versatile mineral phases to reconstruct the events from the kick-off (magma genesis in the mantle) to the final whistle (eruption). Numerous techniques have been developed for olivine to trace the main processes from the source regions to Earth's surface and only a small cross section is presented here; olivine has many more stories to tell.

Olivine studies constrain both sources and processes of magmatic systems (FIG. 5). Slow-diffusing elements retain the fingerprints of different reservoirs that may contribute to the final magma. They also retain details about the crystallization history itself and therefore describe the growth sequence. In this case, olivine is like the spectator that remembers—exactly—the beginning of the game and the events that followed. Faster-diffusing elements tend to equilibrate too quickly to reliably retain source information and instead experience memory loss (e.g., flat Fe-Mg olivine that re-equilibrates with continuous crystallization and ensuing melt chemistry change; Winslow et al. 2020). However, such elements are sensitive to a variety of mixing processes and partial re-equilibration can constrain the timescales of mixing-to-eruption. Volatile elements and their presence in olivine-hosted melt inclusions and embayments represent a separate tool. Their fast diffusivity combined with the pressure dependence of the volatile element solubility in silicate melts makes them sensitive to ascent processes. Here, memory loss of deeper records may also occur as melt inclusions and embayments re-equilibrate in regions of prolonged storage. The result is that volatile element records in olivine and hosted inclusions and embayments are likely faithful recorders of crustal magma assembly and the ascent rate associated with the eruption. Whether they can retain maximum volatile element contents strongly depends on the time it takes from the moment and depth at which they start to lose volatile elements. Therefore, where exactly an olivine–element pair falls in terms of its sensitivity for a specific magmatic process is strongly temperature and/or time dependent as those variables control the diffusive length scales, i.e., the length scale over which memory loss occurs.

Olivine is a generous interviewee that shares information about many events (i.e., magmatic processes) during magma petrogenesis. However, to extract a full picture of the magmatic history, it is imperative to study large populations with their geochemical signatures (major, minor, trace elements, and isotope signatures) and their textural variations. With the continued improvement of analytical techniques and their efficiencies to automate and reduce the duration of analyses, the limitations for large population studies should fade.

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BOX 1: THE EXIT INTERVIEW ANALOGY FOR MINERAL ZONING RECORDS

Imagine you are a journalist outside a stadium full of spectators, but you are not attending the game inside the stadium. You only hear the noise (e.g., seismicity). You don't even know what game is being played, how big the stadium is, or what else may be going on in the stadium. However, you want to understand what happened inside the stadium with all its important nuances and details. To learn about the events, you conduct a series of interviews after the game is over. How many interviews do you need? What level of detail do you want to capture? How representative is an individual interview? Are some spectators more faithful in their answers than others? Some of the spectators may have arrived early to not miss anything, while others may have arrived late, left the action, or roamed the stadium intermittently. Some may have forgotten the first half of the event by the time they leave the stadium. Others may tell the events in a nonlinear way, jumping from one exciting event to another.

This is a complex problem and the same applies when studying magmatic systems using crystal "exit interviews." Analogous to the examples above, olivine may arrive earlier than other mineral phases, but some olivine may also be picked up later on ascent, or be removed during magma differentiation and later remobilized. Olivine may "forget" some information as diffusion erases older records. The timeline of olivine growth may deviate from a core-to-rim traverse.

Moreover, some crystals may experience the action in close proximity, e.g., the arrival of new magma and the mixing of different batches (think seats near the exits), while others record such processes only gradually and in a significantly muted way (spectators that only realize slowly that the stadium has filled up over time). Some crystals may move around and refocus on a different set of processes (spectators may see some free seats in the stadium and move). Many more analogies could be drawn and mineral phases other than olivine may have traits comparable to some populations of spectators in the stadium. One important final analogy is, when all is done, crystals erupt at the surface, potentially being gathered from a range of environments with unique records. Similarly, the spectators leave the stadium together; however, not in a very orderly manner. On the way out of the stadium, people mix and mingle. Thus, the events that individual spectators recorded need to be placed into this context.

To reconstruct the detailed story of the events that are hidden from direct sight requires many interviews so that individual stories are backed up and localized or specific stories are captured. From this analogy, the following fundamental underlying concepts should be incorporated to interpret mineral zoning records.

1. Memory is local: Mineral zoning is linked to physical and chemical changes in the melt from which the minerals grow and in which they reside.
2. Chemical and physical changes in the melt can occur on a range of scales, everything from boundary layers at the crystal scale and local fronts associated with recharge or chamber wall cooling to wholesale events that affect the entire magma body.
3. Crystals are mobile: The dynamic nature of most magmatic systems causes crystals to experience differential movements to neighboring crystals that lead to divergence of mineral records (unlike, e.g., for tree ring records where two adjacent trees are assumed to always have an identical record).
4. Crystals reside in magmatic systems on various time scales; some crystals experience many events while others have a much more restricted timescale on which they record.
5. Memory loss: Not all information in a crystal is retained indefinitely. Some information is lost very quickly while other information may be retained for the entire "lifetime" of the crystal.
6. Nonlinear memory: Not all records are retained linearly; crystal growth may not always be concentric and continuous from core to rim.

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