Magmatic Apatite: A Powerful, Yet Deceptive, Mineral

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Durango apatite, from the Cerro de Mercado open-pit mine, on matrix.

Apatite may be a minor constituent in magmatic rocks but it is a powerful research tool because it is ubiquitous and it incorporates magmatic water, halogens, S, C, and trace elements including Sr, U, Th, and the rare earth elements. Recent advances in experimental and analytical methodologies allow geologists to analyze apatite textures and compositions in great detail. This information improves understanding of the behavior of volatiles and trace elements both in terrestrial igneous melts and their related fluids and in extraterrestrial bodies, such as the Moon and Mars. With more research, the petrological power of apatite can only increase with respect to understanding eruptive, pluton-building, and mineralizing magmatic systems.

KEYWORDS: apatite, halogens, trace elements, experiments, modeling, magma

INTRODUCTION

Apatite is Ubiquitous

"Apatite" refers to the three calcium phosphate minerals—fluorapatite, chlorapatite and hydroxylapatite—which are represented by the general formula $Ca_5(PO_4)_3(F,Cl,OH)$. Apatite is the primary phosphate in most igneous systems because of the abundance of its constituent elements and its thermodynamic properties. Phosphorus (P) is the 11th most abundant element in the upper crust (~0.15 wt% P_2O_5). Calcium, the other primary constituent in apatite, is even more abundant. These concentrations correspond to a calculated *theoretical normative value* of 0.3 vol% apatite in the upper continental and oceanic crusts. Within a given suite of rocks, normative (theoretical) apatite abundances are not attained because phosphorus is included in other minor phosphate minerals (e.g. monazite, xenotime), as well as some silicates. For example, theoretical concentrations (norms) of apatite are on the order of half of the volume of apatite actually observed in felsic (granite-like) rocks.

Apatite[3] is a common accessory mineral that is nearly ubiquitous in both silicic and carbonatitic systems. It is generally present in concentrations <1 vol%, but in some igneous rocks it can be the dominant phase exceeding 50 vol% (e.g. nelsonites).

Apatite is deceptive in that it occurs as small and rare crystals, but it is still an extremely powerful tool for unraveling complex magmatic systems. It is unique in the breadth of processes that it can shed light onto: volatile inventories and histories, trace-element distributions, ages of geological events, and uplift rates are attainable due to the presence of apatite in many rocks and the analytical methods available to characterize it. Apatite is a powerful geochemical and petrologic tool because its mineral structure can accommodate many elements (Hughes and Rakovan 2015 this issue). The composition, crystal habits, petrologic relations, and crystallization temperatures of magmatic and magmatic–hydrothermal apatite have been investigated through the study of igneous rocks, experimental research, and thermodynamic modeling. These methods have also been used to determine how volatile components, minor and trace elements, and ore elements are distributed between apatite, melts, and fluids.

Apatite is shedding new light on a wide variety of magmatic systems relevant to eruptive, pluton-building, and mineralizing processes on Earth, as well as extraterrestrial bodies (McCubbin and Jones 2015 this issue). Pushing these applications of apatite further will open even more geological doors, for this important, yet still developing, geochemical tool. The diversity and potential of apatite's petrologic power is, however, offset by a number of challenges inherent to this mineral. It can be difficult to interpret apatite textures in thin section, to accurately analyze the concentrations of F and Cl, and to analyze and interpret compositional zonation in apatite.

Apatite Textural and Chemical Forms

Magmatic apatite exhibits two dominant crystal habits: equant to subequant (slightly elongate) and acicular (very elongate). Equant apatite is generally defined by well-formed crystal faces (FIG. 1), and is often easily recognized by its hexagonal shape. This habit is interpreted to have grown under near-equilibrium conditions. Less commonly, equant apatite occurs with no well-formed crystal faces as an interstitial phase that grew late in a magma's crystallization history. Highly acicular apatite grows under conditions far from equilibrium and is indicative of rapid cooling. Some rocks display more than one morphology in a single sample, suggesting a complex cooling and crystallization history. Apatite is generally small (<1 mm in length), but can grow to a large size (e.g. >5 cm in the El Laco, Chile, magnetite lava flow).

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3   henceforth, the term apatite signifies magmatic or hydrothermal origin
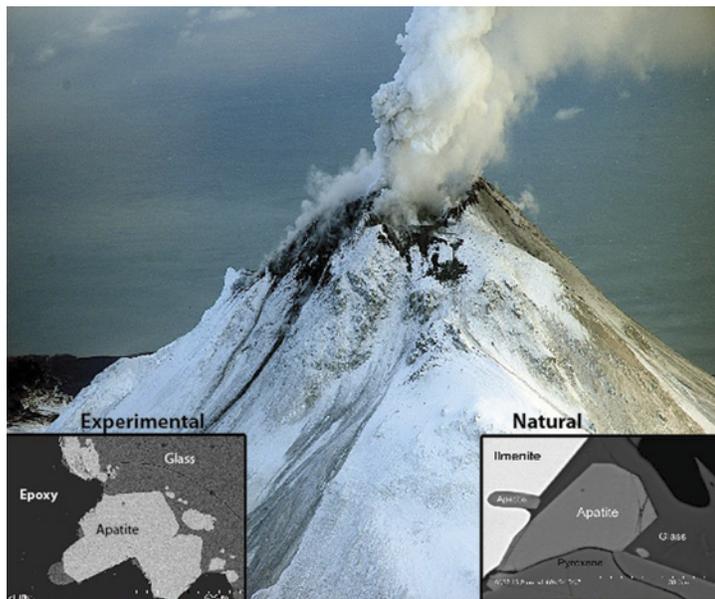
Figure 1 Photograph of Augustine volcano (Cook Inlet, Alaska) degassing in 2006. (**left**) Back-scattered electron/scanning electron micrograph (BSE–SEM) of experimentally grown apatite with run-product glass mounted in epoxy. (**right**) BSE–SEM image of natural apatite with eruptive matrix glass, pyroxene, and ilmenite from an Augustine dacite sample. Augustine image courtesy of the Alaskan Volcano Observatory (URL: www.avo.alaska.edu/images/index.php)

Apatite was long thought to be compositionally unzoned. But, it is a mineral full of surprises. Boyce and Hervig (2009) described apatite from Irazú volcano, Costa Rica, with OH contents ranging from 500 ppm (wt) to 4500 ppm, Cl from 5000 ppm to 20,000 ppm, and F from 24,000 ppm to 37,000 ppm. These variations were interpreted using experimental partitioning data to indicate changing abundances of these volatiles in the melt due to magma mixing and degassing. In a study of apatites from a granodiorite, Farley et al. (2011) found that the apatites were zoned with respect to U and Th, a fact that could lead to potentially large and systematic errors when trying to obtain accurate U–Th/He ages. Recognizing major- and trace-element zoning in apatite is critical to interpreting igneous petrogenesis correctly.

Composition of Natural Apatite

Does the composition of apatite vary as a function of host environment, host-rock composition, or texture? In an effort to better understand these questions, we subdivide the composition of natural apatites into volcanic and plutonic origins (Table 1). Apatites from hydrothermal environments and carbonatites can have volcanic or plutonic parentage and are treated separately here.

The composition of volcanic versus plutonic apatite is not appreciably different (Fig. 2A), but it is highly variable. Excluding apatites from hydrothermal systems, high-Cl apatites (>3.5 wt%) are rare in plutonic systems (but can be extensive in those intrusions where they do occur), and nearly nonexistent in volcanic environments. Taken as a whole, there are no statistical differences in the composition between volcanic and plutonic apatite. This result should not be surprising. Given that apatite generally crystallizes early and at near-liquidus conditions in most

magmatic systems, and given that much of the volume of apatite crystallizes in a small temperature interval means that apatite will record similar processes in the two environments. Volcanic rocks generally have low crystal contents, and hence, a history similar to that of the hypothesized early stages of pluton crystallization. The similarity in apatite compositions suggests that the effects of prolonged crystallization of other halogen-bearing phases in the plutonic environment (in early or late-formed intercumulus apatite), and any subsolidus reequilibration, do not play a pervasive role on compositional zoning in apatite.

The variability in apatite composition as a function of host-rock composition yields interesting trends (Fig. 2B–D). Apatite is typically dominated by the F-rich component, but rare Cl-rich apatite occurs in mafic rocks and, to a lesser extent, in silica-rich igneous rocks. Boudreau (1995 and references therein) described the composition, textures, and stratigraphic association of apatite throughout several mafic-layered intrusive suites (Fig. 2C). Intercumulus, near Cl-end-member apatite was described from just below the platinum group element–mineralized J-M Reef in the Stillwater Igneous Complex (a Neoarchean intrusion in southern Montana, USA) and the Bushveld Igneous Complex (a Paleoproterozoic intrusion in South Africa) (Boudreau 1995). The Cl-rich apatite is significant given that experimental work shows that Cl may be chemically associated with Pt in mineralizing hydrothermal fluids. Hydrous Bushveld apatites contain up to 50% OH component in the hydroxyl site; whereas, relatively OH-free apatites range from the nearly pure F- to pure Cl-end-member compositions. The apatite compositions vary systematically with stratigraphic height within the Stillwater and Bushveld intrusions. Higher up in the Stillwater sequence, F- and OH-rich apatite predominates (Fig. 2C), suggesting that the apatite story can be complex. However, the proportion of Cl-rich apatites in both intru-
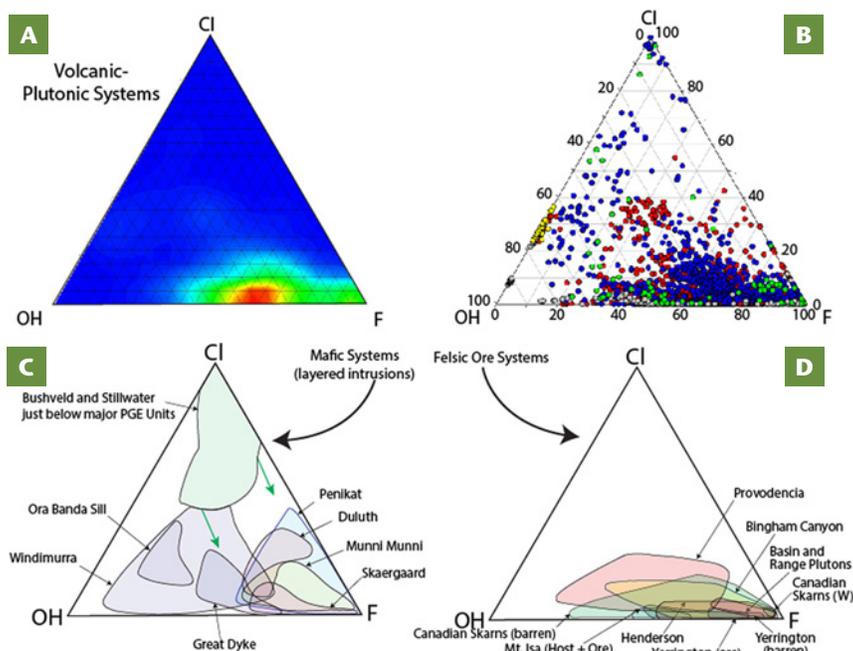

Figure 2 Plots of the halogen content in apatite (in molar proportions) as a function of four different parameters. (**A**) Host environment, where hotter colors indicate more analyses. (**B**) Host rock composition: red is felsic, blue is mafic, gray is carbonatites, green is hydrothermal, yellow is sedimentary. (**C**) Mafic layered intrusion (modified from Boudreau 1995). (**D**) Felsic ore systems. Data are primarily from the GEOROC database, Belousova (2000), Piccoli and Candela (2002), and references therein.

sions is small. High-Cl apatites (>6 wt%) also occur in parts of the enigmatic apatite–magnetite deposits of Chile, possibly from late-stage Fe-rich magmas.

Analytical Challenges

The composition of apatite is determined using a variety of techniques with electron probe microanalysis (EPMA) being the most common. Analysis by EPMA was considered reliable until Stormer et al. (1993) made a troubling observation: the measured X-ray flux from apatite is affected by crystal orientation. As a result, apparent F concentrations can change by as much as 100%—less so for Cl, Ca and P, or grains with oblique orientations—when the electron beam is parallel to the *c* axis of the apatite. Stormer et al. (1993) suggested that accurate analysis of apatite requires multiple analyses at the same spot and extrapolation of the count rates back to time zero. Others have found that highly accurate analyses of F and Cl can be made using low electron beam densities, large beams, and by analyzing grains with the electron beam perpendicular to apatite's *c* axis (Goldoff et al. 2012). The OH content of apatite can be estimated indirectly from EPMA measurements of F and Cl by charge balance, and assuming that the halogen site is full (Piccoli and Candela 2002). Alternatively, the OH content can be measured directly by secondary ion mass spectrometry or by Fourier-transform infrared spectroscopy.

So, how prevalent are problematic analyses in the literature? Consider the apatite analyses recorded in the Geochemistry of Rocks of the Oceans and Continents (GEOROC4) database. It contains over 1400 apatite analyses, of which greater than 10% exceed the maximum F concentration that can occur in end-member fluorapatite (3.77 wt% F).

MAGMATIC AND MAGMATIC–HYDROTHERMAL APATITE

Apatite's remarkable usefulness provides vital geochemical and isotopic information on the partial melting of rocks at elevated metamorphic conditions and on magma evolution. The P and REE concentrations of granites and basalts reflect the mineralogy of the metamorphic rocks that were involved in their genesis and the processes of rock melting and magma generation. Apatite crystallization controls P concentrations in evolving melts. Basaltic rocks may contain up to 1 wt% P_2O_5, whereas silica-enriched granitic and rhyolitic rocks may contain as little as 0.02 wt% P_2O_5.

TABLE 1	TABLE OF MAGMATIC APATITE COMPOSITIONS (WT%) See FIGURE 2 for data sources.		
	Silicate Magmas	**Carbonatites**	**Hydrothermal Systems**
SiO₂	0.448	0.980	0.297
FeO	0.281	0.160	0.135
MnO	0.262	0.087	0.027
MgO	0.104	0.161	0.050
CaO	54.155	53.635	54.343
SrO	0.228	1.079	0.226
Na₂O	0.130	0.432	0.222
P₂O₅	41.056	39.612	41.606
SO₃	0.167	0.239	0.304
F	2.522	2.322	2.445
Cl	0.462	0.316	0.827
Total	99.814	99.023	100.484
Light REE	0.835	1.670	0.925
Middle REE	0.310	0.211	0.223
Heavy REE	0.041	0.016	0.022
Total	101.001	100.917	101.654
−O=F,Cl	−1.17	−1.05	−1.22
Total	99.83	99.87	100.44

Apatite and Phosphorus Solubility Relations

The stability of apatite and its solubility in silicate melts have been the subject of hydrothermal experiments across a range of pressures, temperatures, and melt compositions, including mafic to felsic, and alkaline [i.e. moles of (Na + K) > Al)] to aluminous [moles of Al > (Na + K)] systems. Such research has determined that apatite solubility in silicate melts varies strongly with temperature, the SiO_2 and CaO concentrations, and the aluminosity [moles of Al_2O_3/ $(Na_2O + K_2O + CaO)$] of the melts. Phosphorus is much more soluble in hot mafic melts than in cooler felsic melts, and aluminous and alkaline melts may dissolve significantly more P than metaluminous melts [i.e. melts with moles of $Al_2O_3 = (Na_2O + K_2O + CaO)$]. Some apatite-saturated mafic melts dissolve more than 12 wt% P_2O_5 at magmatic temperatures and pressures.
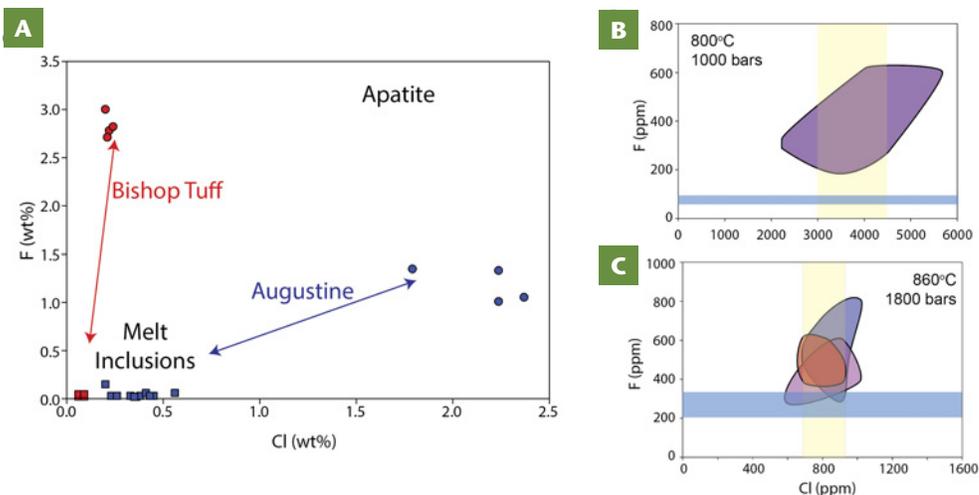
FIGURE 3 (**A**) Plot of F and Cl in apatite and coexisting melt inclusions (MI) from the Plinian phase of the Pleistocene Bishop Tuff eruption (in red) and the 2006 Augustine volcano eruption (in blue). (**B, C**) Diagrams representing the calculated Cl and F concentrations in coexisting apatite and melts at the *P–T* conditions estimated for the two eruptions. The method of calculation, and the assumptions therein, are described in Piccoli and Candela (1994) and summarized in the text. The Augustine apatite and melt inclusion data are from Webster et al. (2010) and Doherty et al. (2014, reference therein). The yellow and blue fields represent the range in estimated melt Cl and F concentrations, respectively, based on published apatite compositions.

4 The GEOROC database can be found at georoc.mpch-mainz. gwdg.de/georoc/.

Apatite Saturation Temperature

The temperature at which a silicate melt first saturates and crystallizes apatite (the apatite saturation temperature, or AST) is required for some petrologic and geochemical studies and can be easily calculated for most magma compositions. For example, the distribution or partitioning, of volatile components and REEs between apatite and melt varies significantly with temperature. Efforts to calculate magmatic REE and volatile concentrations via the application of apatite compositions and the relevant experimental constraints on component partitioning between apatite and melt require accurate ASTs. By volume, most apatite crystallizes over a small temperature interval below the AST (Piccoli and Candela 2002).

Thermodynamic Relations and Modeling of Apatite–Melt–Fluid(s) Systems

What is the relationship between F, Cl, and OH in apatite and the volatile contents of the melt from which it crystallized? Does the presence of high-Cl apatite indicate that it crystallized from a high-Cl system? Not necessarily. Apatite with a given composition can crystallize from melts with highly variable F, Cl and OH concentrations depending on the effects of pressure, temperature, and system composition.

Explaining the behavior of magmatic halogens using theoretical models takes one of two forms. One form, e.g. Nernst partition coefficients, D_i, represents the distribution of an element (i) between two phases in equilibrium. For the case in which D_F represents the concentration of F in apatite relative to its concentration in the melt, the F concentration in magmatic apatite generally greatly exceeds the F content of the coexisting melt: F shows compatible behavior. The same is true for Cl in apatite and melt, though to a lesser extent. The Nernst coefficients can be integrated with simple Rayleigh fractionation calculations to evaluate how halogen concentrations in apatite should change with melt crystallization. For reasonable modal abundances of apatite and relevant values of D_F and D_{Cl}, the concentrations of F and Cl increase in the melt as crystallization progresses.

Models that use simple Nernst coefficients and the Rayleigh fractionation equation, however, suffer from problems, especially those due to host-phase stoichiometry. Nernst evaluations are useful for qualitative assessments of halogen behavior in magmatic systems, though more detailed models may be required to obtain more accurate estimates of magmatic halogens. For example, these potential pitfalls were eloquently pointed out by Boyce et al. (2014) in evaluating magmatic lunar water contents from apatite compositions (McCubbin and Jones 2015).

A second way to investigate the behavior of magmatic halogens using apatite is a more rigorous modeling approach that employs a detailed assessment of the thermodynamic properties of apatite. This involves determining the activity or fugacity of halogens and water in either the fluid or the melt when in equilibrium with apatite. Activity, $a_i = \gamma_i X_i$, is a measure of the availability of a chemical component for reaction in a system, and contains terms for mole fraction (X_i) and a coefficient which takes into account the nonideal mixing in the melt (γ_i). Fugacity, $f_i = \Gamma_i a_i P = \Gamma_i \gamma_i X_i P$, represents a relative "escaping tendency" of volatiles from a melt. It contains a term for intermolecular distances (Γ_i), an activity term (a_i), and is corrected for pressure (P). Activities and fugacities can be used appropriately for fluid-undersaturated and fluid-saturated magmas.

Apatite–Melt ± Fluid Equilibria

Studies of magmatic fluids are hampered by the fugitive nature of those fluids. Evidence has been destroyed, is lacking, is altered, or can't easily be interpreted due to the changing composition of the fluids with magma evolution. Estimates of fluid composition are most commonly calculated as ratios of activity (a_{HCl}/a_{HF}) or fugacity (f_{HCl}/f_{HF}). Calculation of fugacity ratios of halogens from the apatite composition is quite straightforward. In the case of HCl and H_2O:

$$f_{HCl}^{aq} / f_{H_2O}^{aq} = \left(X_{CAp}^{Ap} / X_{HAp}^{Ap} \right) \left(1/10^K \right),$$

where $X_{CAp}^{Ap} / X_{HAp}^{Ap}$ is the mole fraction ratio of Cl/OH in apatite, and K is an equilibrium constant defined as $K = 0.04661 + (2535.8/T) - ((0.0303(P-1))/T)$, where T and P are in Kelvin and bars, respectively. This assumes that ideal mixing (i.e. $a_i = X_i$) of F, Cl, and OH occurs in apatite at magmatic temperatures (Piccoli and Candela 1994).

Hovis and Harlov (2010) found that mixing between fluorapatites and chlorapatites is nonideal and asymmetric with respect to composition. Data on F–OH mixing relationships also exhibit some nonideality (Hovis et al. 2014). Similar information on the Cl–OH join and F–Cl–OH ternary currently don't exist and are sorely needed for the study of rocks that contain apatite of these compositions.

Estimates of fluid, as well as melt, Cl contents can be made. Piccoli and Candela (1994) used apatite compositions to predict the Cl in the melts that formed the Plinian phase of the Bishop Tuff (a vast volcanic ash deposit resulting from a massive mid-Pleistocene eruption in western North America). The Plinian phase resulted from one of the more spectacular caldera-forming eruptions in North America (Fig. 3), and the explosive nature of this eruption was controlled largely by magmatic volatile behavior. Calculations were performed for 860°C (AST) and 1800 bars and were compared to volatile data from silicate melt inclusions (minute quantities of silicate melt trapped in minerals and quenched to glass). The apatite compositions suggest 700–960 ppm Cl and 160–300 ppm F in the initial melt, given reasonable estimates of the melt/fluid partitioning of Cl and F. These estimates compare favorably with published compositional data on Bishop Tuff melt inclusions, thus adding confidence to the calculation method.

A second example involves apatite-saturated lavas of the 2006 eruption of Augustine volcano, Alaska (Fig. 1), where some apatites contain 1.2 wt% Cl and 2.2 wt% F. The relevant Nernst partition coefficients imply equilibrium Cl and F concentrations of ~3650 and 40 ppm, respectively, in the melt at 1000 bars and 800°C. Melt inclusions from the 2006 eruptions have Cl and F concentrations of 3300–3800 ppm and ~200–300 ppm, respectively. If the melt inclusions represent the melt composition at the time of apatite crystallization then the apatite compositions accurately predict the amount of Cl in the Augustine melt but underestimate F.

VOLATILE PARTITIONING BETWEEN MELTS, FLUIDS, AND MAGMATIC–HYDROTHERMAL APATITE

Apatite acts as a monitor of volatile behavior during magma evolution. Apatite compositions reveal how volatiles partition between apatite, fluids, and melts as magmas ascend through the crust, cool, and crystallize (Fig. 3). For example, the OH content of apatite provides crucial constraints on magmatic H_2O concentrations. Furthermore, the other magmatic volatiles S, Cl, and F are often of sufficient abundance in magmas and their associated volcanic gases

that they influence the acidity of precipitation and desta-bilize the radiation-absorbing ozone when ejected into the atmosphere. Apatite is a powerful tool for understanding the evolution of these hazardous volatiles.

Prior research on volatiles has been based, largely, on analyses of melt inclusions, but these samples of melt are susceptible to changes in composition that magmatic apatite is not. Hence, apatite is better at retaining accurate information on magmatic volatiles. Moreover, melt inclusions are rare in apatite-bearing plutonic rocks. Hence, apatite in these rocks serves as a better source of information on magmatic volatiles in plutons.

Hydrothermal Experiments on Apatite and Their Application to Magmatic Processes

Interpreting magmatic processes requires information on volatile distribution between melts, fluids, and apatite, which is determined experimentally (TABLE 2). Experimental studies establish how H_2O, Cl, F, and S partition between apatite and fluids and/or melts as a function of melt composition, temperature, and pressure. Experiments also determine the rates of volatile diffusion through apatite as a function of the crystallographic orientation and pressure (Brenan 1994), and how trace elements partition between apatite and various melts and fluids (TABLE 2).

Fluorine and Cl are important to processes of magmatic ore formation, and experiments show that Cl partitioning between apatite and melt varies with the Cl concentration of coexisting fluids and with pressure (FIG. 4). However, as observed by Boyce et al. (2014), the presence of three essential volatile components (e.g. F, Cl, and OH) occupying a single ion site in apatite complicates the application of Nernst partition coefficients to magmatic systems. In rhyolitic melts, Cl partitions more strongly in favor of apatite as pressure decreases from 2000 to 275 bars at 850 to 950°C. It follows that the application of experimental partition coefficients for Cl involving equilibrium between apatite, melt, and fluids to natural systems requires accurate knowledge of the pressure of final equilibration between apatite, melt, and fluid.

Sulfur partitioning between apatite and rhyolitic and trachyandesitic melts has been determined experimentally. Sulfur partitions preferentially into apatite relative to
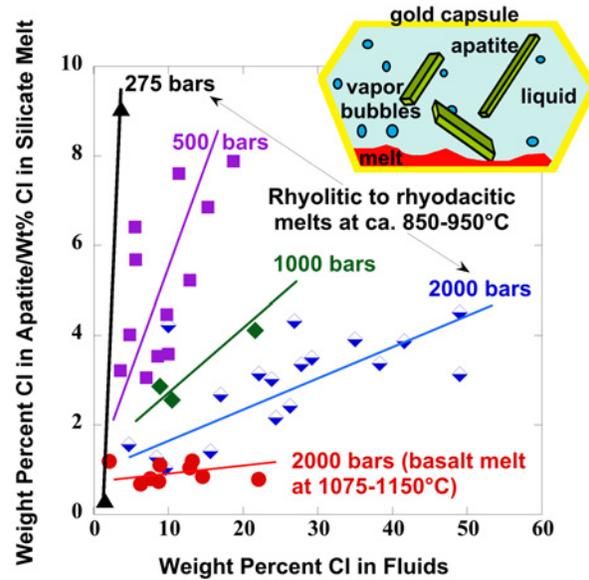
these two melts and more strongly in favor of apatite with decreasing concentrations of S in the melt (Parat and Holtz 2005). These experimental data can be applied to apatites from evolving, subduction-related volcanoes to estimate pre-eruptive, magmatic S contents and better understand degassing of SO_2 to the atmosphere.

Interpreting apatite compositions with experimental data, and/or modeling, provides estimated abundances of magmatic S, H_2O, Cl, and F. Example systems for which this is useful include granite- and rhyolite-forming magmas; subduction-related eruptive magmas, some of which are mineralized with Cu, Au, and Mo; igneous–hydrothermal

TABLE 2 SUMMARY OF EXPERIMENTAL CONDITIONS FOR COMPONENT PARTITIONING RUNS INVOLVING APATITE ± MINERALS ± SILICATE MELT ± SALT MELTS ± AQUEOUS FLUID(S) (REEs = RARE EARTH ELEMENTS).

System/Pseudosystem	Pressure (bars)	Temperature (°C)	Partitioning Data	Source
$Ca_5(PO_4)_3(F,Cl,OH)$–CaF_2–$CaCl_2$–NaBr salt melt	1	1120–1400	Halogens, OH	[1]*
$Ca_5(PO_4)_3(F,Cl,OH)$–rhyolitic melt–vapor ± brine	500	850–950	Halogens, OH	[2]
$Ca_5(PO_4)_3(Cl)$–H_2O–chloride–phosphate melt	1000 and 1400	735	REEs	[3]
$Ca_5(PO_4)_3(F,Cl,OH)$–basalt melt–vapor ± brine	2000	1066–1150	Halogens, OH	[4]
$Ca_5(PO_4)_3(F,Cl,OH)$–rhyolitic melt–vapor ± brine	2000	900–924	Halogens, OH	[5]
$Ca_5(PO_4)_3(F,Cl,OH)$–S–rhyolite melt	2000	800–1100	Sulfur, F, OH, major elements	[6]
$Ca_5(PO_4)_3(F,Cl,OH)$–S–rhyolite melt	2000 and 4000	900 and 1000	Sulfur, F, OH, major elements	[7]
$Ca_5(PO_4)_3(F,Cl,OH)$–S–trachyandesite melt	2000 and 4000	800–950	Sulfur (involves variable f_{O_2})	[8]
$Ca_5(PO_4)_3(F,Cl,OH)$–rhyolitic to basaltic melts	10,000	1250	Major, minor, trace elements (REEs), OH, halogens	[9]*
$Ca_5(PO_4)_3(F,Cl,OH)$–carbonatite melt	10,000	1250	Major, minor, trace elements (REEs), OH, halogens	[10]*
$Ca_5(PO_4)_3(F,Cl,OH)$–basalt melt	10,000	950–1000	Halogens, OH	[11]
$Ca_5(PO_4)_3(F,Cl,OH)$–H_2O fluid ± albite	10,000	1000	Sr, REEs	[12]
$Ca_5(PO_4)_3(F,Cl,OH)$–HCl–NaCl fluid	10,000 and 20,000	950 and 1050	Halogens, OH	[13]
$Ca_5(PO_4)_3(F,OH)$–phlogopite–H_2O fluid	20,000	1150–1450	F, OH	[14]
$Ca_5(PO_4)_3(F,OH)$–amphibole–phlogopite + K-richterite	25,000–87,000	900–1050	Cl, OH	[15]

* F exceeds maximum for anion site

Sources: [1] Dong (2005); [2] Doherty et al. (2014); [3] Fleet et al. (2000); [4] Mathez and Webster (2005); [5] Webster et al. (2009); [6] Parat and Holtz (2004); [7] Parat and Holtz (2005); [8] Peng et al. (1997); [9] Prowatke and Klemme (2006); [10] Klemme and Dalpé (2003); [11] McCubbin et al. (2014); [12] Ayers and Watson (1993); [13] Brenan (1993); [14] Vukadinovic and Edgar (1993); [15] Konzett et al. (2012)

deposits of Fe- and apatite-rich rocks; oceanic cumulates; ophiolites; and layered mafic intrusions. This exceptional range of systems once again testifies to the petrogenetic power of apatite.

REE AND OTHER TRACE-ELEMENT PARTITIONING IN MAGMATIC APATITE

Because apatite can contain a large range of trace and minor elements (Hughes and Rakovan 2015) it may exert a dominant control on the geochemical behavior of trace components like the REEs, Sr, U, and Th in melts and magmatic fluids. These trace elements partition in favor of silicate melts relative to apatite and in apatite relative to carbonate melts (Prowatke and Klemme 2006; Table 2). With both systems, apatite preferentially incorporates the middle REEs relative to the lighter and heavier REEs, and this relationship is used to identify the presence and role of apatite in magma evolution. In silicate melts, the REEs partition increasingly in favor of apatite as melts evolve to higher SiO_2 contents (Prowatke and Klemme 2006).

CLOSING THOUGHTS

Volatile and nonvolatile elements, including trace elements, are key indicators of magmatic and magmatic–hydrothermal processes during magma genesis and evolution (Table 2) and during magmatic–hydrothermal ore formation. Igneous apatites provide information on protolith composition, the behavior of volatile components in magmas, and weathering effects. Trace elements in apatite also serve as a unique magmatic fingerprint providing important information on igneous provenance and volcanic tephrachronology as well as for the exploration for mineral deposits. This little accessory phase really is a little miracle!

ACKNOWLEDGMENTS

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