Volcanoes: From Mantle to Surface

KEITH D. PUTIRKA and KARI M. COOPER, Guest Editors

Down the Crater: Magma Storage and Eruption
Volcano Monitoring: Deformation
Magma Reservoirs: Crystal’s-Eye View
Volatiles in Volcanic Systems
Forecasting Volcanic Activity
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Volcanoes: From Mantle to Surface

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Mean = 118 ± 150 microns
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Elastic thickness
Mean = 27 ± 12 km
Volcanoes: From Mantle to Surface

Guest Editors: Keith D. Putirka and Kari M. Cooper
The north slope of Mount St. Helens erupted catastrophically at 8:32 a.m. on 18 May 1980 in southern Washington state, about 50 miles northeast of Portland (Oregon, USA). This eruption was preceded by a magnitude 5.1 earthquake and a subsequent landslide that are thought to have triggered the main eruption. Although relatively “minor” compared to other US eruptions (e.g., Yellowstone Supervolcano in Wyoming, USA), Mount St. Helens was the deadliest and most economically destructive eruption in United States’ history (Tilling et al. 1990): it killed 57 people, including U.S. Geological Survey (USGS) volcanologist Dr. David A. Johnston who was monitoring the volcano 6 miles north of Mount St. Helens. It’s somewhat ironic that Dave Johnston was killed “by an unusual eruptive event that was largely unanticipated, in magnitude or style, except perhaps by Dave himself” (Hildreth 1980).

Several months before the May eruption, there were at least four warning signs that major changes were occurring beneath Mount St. Helens (Tilling et al. 1990). These changes included (1) increased seismic activity; (2) increased volcanic activity, including the formation of a bulge on the north flank of Mount St. Helens; (3) phreatic and other minor eruptions; and (4) changes in gas composition. As a result of these warning signals, Johnston and USGS coworkers were able to convince civil authorities to close Mount St. Helens to the public prior to the May eruption, which undoubtedly saved many lives. According to USGS volcanologist Wes Hildreth, Dave Johnston hoped that “systematic monitoring of fumarolic emissions might permit detection of changes characteristically precursory to eruptions” (Hildreth 1980).

I remember the Mount St. Helens eruption vividly for several reasons. One was that I met Dave Johnston several years before the eruption, when he interviewed for a faculty position in the Department of Geology at Stanford University (California, USA). I remember his interview talk, his stage fright, and how enthusiastic he was about his PhD work on the Cimarron Volcano in southwest Colorado (USA). The second reason was that I was teaching an introductory geology class to about 175 Stanford undergraduates (California, USA). I remember his interview talk, the increased volcanic activity, including the formation of a bulge on the north flank of Mount St. Helens; (3) phreatic and other minor eruptions; and (4) changes in gas composition. As a result of these warning signals, Johnston and USGS coworkers were able to convince civil authorities to close Mount St. Helens to the public prior to the May eruption, which undoubtedly saved many lives. According to USGS volcanologist Wes Hildreth, Dave Johnston hoped that “systematic monitoring of fumarolic emissions might permit detection of changes characteristically precursory to eruptions” (Hildreth 1980).

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ABOUT THIS ISSUE

Volcanoes are the powerhouses of nature that can, within minutes, transform a beautiful mountainscape into a desolate landscape devoid of life. Many of us know of singular historic volcanic events because of their impact on society: the 79 AD Mount Vesuvius eruption that resulted in the destruction of Pompeii and Herculaneum (Italy); the deadly 1883 eruption of Krakatoa (Indonesia) that was heard 3,100 miles away; the tragedy of the 1985 Nevada del Ruiz (Columbia) eruption, which resulted in a lahar that killed more than three quarters of the 28,700 inhabitants of Armero; or the costly eruption of Eyjafjallajökull (Iceland) in 2010, which caused more than 10 million air passengers to be stranded and cost the global economy an estimated US$ 4.7 billion. Whether eruptions are mild or catastrophic, volcanoes fascinate and captivate us.

As this issue goes to press (February 2017), there are 33 volcanoes erupting throughout the world, with another 1,500 active volcanoes slumbering until the conditions are right for an eruption. Some of those slumbering volcanoes have nasty histories, such as the supervolcano Campi Flegrei (near Naples, Italy) that is currently making headlines as it has entered a period of seismic unrest. But, as you will read, scientists are making significant progress in uncovering the plumbing systems of volcanoes or what triggers an eruption. Much remains unknown about the origins of such volcanoes and how it is transported to the surface. More is known about the slumbering until the conditions are right for an eruption. Some of those slumbering volcanoes have nasty histories, such as the supervolcano Campi Flegrei (near Naples, Italy) that is currently making headlines as it has entered a period of seismic unrest. But, as you will read, scientists are making significant progress in uncovering the plumbing systems of volcanoes or what triggers an eruption.

The Elements editorial team is delighted that Nancy has accepted our invitation to become a principal editor, and we look forward to working with her. She is already hard at work on our October 2017 issue (“Boron: Light and Lively”).

Gordon Brown, Bernie Wood, Friedhelm von Blanckenburg, Nancy Ross, and Jodi Rosso

INTRODUCING NANCY L. ROSS, PRINCIPAL EDITOR 2017–2019

We are delighted to announce that Nancy L. Ross has joined the Elements team as a principal editor, replacing Gordon Brown (2014–2016), whose three-year term comes to an end with this issue. Nancy is currently Professor of Mineralogy and Head of the Geosciences Department at Virginia Tech (USA).

Nancy has been a pioneer in the study of the crystalline structures, elastic properties, and stability of Earth materials under the extreme pressures and temperatures of Earth’s lower crust and mantle. More recently, she has studied the thermodynamic properties and effect of surface hydration on metal-oxide nanoparticles. She uses a combination of theoretical modeling and experimental techniques (such as X-ray and neutron diffraction; Raman spectroscopy and inelastic neutron scattering) to determine the structure relations of crystals and vibrational properties of minerals that govern their thermodynamic properties.

Nancy is active within our scientific community. She was elected fellow of the Mineralogical Society of America (MSA) (1991), honorary fellow of the Societá di Mineralogia e Petrologia (2014), and fellow of the Geological Society of America (2016). She served as President of MSA (2009–2010) and as MSA’s Distinguished Lecturer (2011–2012). She has served on a number of commissions and councils. She has also been on advisory groups for funding agencies [e.g., the Natural Environment Research Council (UK) and the National Science Foundation (USA)] and government laboratories [e.g., Oak Ridge National Laboratory (Tennessee, USA) and Los Alamos National Laboratory (New Mexico, USA)]. She served on the Elements advisory board 2005–2008.

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THANKS GORDON

With this issue, Gordon Brown (Stanford University, California, USA) completes his three-year term as a principal editor of Elements. Gordon has been a vital part of our editorial team since 2014. During his tenure, he oversaw the following issues: “Kaolin” (v10n3), “Mineralogy of Mars” (v11n1), “Social and Economic Impact of Geochemistry” (v11n4), “Earth Sciences for Cultural Heritage” (v12n1), “Deep-Mined Geological Disposal of Radioactive Waste” (v12n4), and “Volcanoes: From Mantle to Surface” (v13n1). In addition to working closely with our guest editors and handling manuscripts, Gordon actively solicited contributions to our Perspectives column and wrote editorials to give us a historical context for today’s science. Thank you, Gordon, for all your hard work and the time you committed to Elements.

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Meet the Authors

Juliet Biggs is a Reader in the School of Earth Sciences at the University of Bristol (UK) where she works on active volcanic and tectonic processes. Current projects include studying caldera unrest in the East African Rift and long-lived eruptions in Latin America. Her research focuses on using satellite imagery, in conjunction with field observations, to provide new insights into magmatic processes. She was awarded the Bullerwell Prize of the British Geophysical Association in 2016 and the Lloyds of London Science of Risk Prize in 2014.

Katharine V. Cashman is a Professor of Volcanology at the School of Earth Sciences at the University of Bristol (UK). She has worked on volcanoes around the world but is (arguably) best known for her research on Mount St. Helens (Washington, USA) and Kilauea (Hawaii, USA) and addressing the interplay between chemical and physical processes that drive volcanic eruptions. Her studies encompass a wide variety of eruption styles and settings, as well as the written and oral histories of volcanic regions. She is a Fellow of the American Geophysical Union, the American Academy of Arts and Sciences, the Academia Europaea, the Royal Society and the National Academy of Sciences.

Kari M. Cooper is a professor in Earth and Planetary Sciences at the University of California, Davis (USA). Her early interest in volcanoes was cemented by studying active lava flows during a United States Geological Survey—National Association of Geoscience Teachers internship at the Hawaiian Volcano Observatory. Her masters at University of Washington and her doctorate at the University of California, Los Angeles, were followed by postdoctoral work at the California Institute of Technology (USA). Prior to her current appointment, she held a faculty position at the University of Washington (USA). Her research has included structural and metamorphic evolution of the Alaska Range and large-scale recycling of crustal material into the mantle, but has recently focused on U-series dating of volcanic crystals in crustal magma reservoirs.

Marie Edmonds is a Reader in Earth Sciences Department at the University of Cambridge (UK). Prior to her current appointment, she was volcanologist with the British Geological Survey, then a Mendenhall Fellow with the US Geological Survey. She received her PhD in volcanology at the University of Cambridge in 2002. Edmonds’ research concerns the role that volatiles play in magmatic differentiation, eruption processes and styles. She has worked extensively on the Soufrière Hills Volcano (Montserrat). More broadly, she is interested in the role of volcanoes in geochemical cycling and climate.

Matthew E. Pritchard is a geophysicist who measures changes in the shape of the Earth and develops models of the myriad processes that cause these changes, such as earthquakes, volcanic eruptions, groundwater, landslides, and glaciers. He makes these observations in the field and via radar and optical satellites. He was educated at the University of Chicago (BA) (Illinois, USA) and the California Institute of Technology (MS and PhD), and was a Harry Hess Postdoctoral Scholar at Princeton University (New Jersey, USA). He has been a faculty member at Cornell University (New York, USA) since 2005 and spent 7 months as a Visiting Professor at the University of Bristol (UK) in 2016.

Keith D. Putirka grew up in Los Angeles (California, USA) and was inspired to study geology while hiking in the Sierra Nevada, the San Gabriel Mountains and the Mojave Desert in the western USA. His degrees are in geology—a BS from California State University Northridge; MS from California State University, Los Angeles; and PhD from Columbia University (New York, USA). Keith resides in Clovis (California) and is a professor at the California State University, Fresno, where his teaching and research interests include arc volcanoes and plutons, planetary cooling/tectonic histories, the composition of exoplanets, and the history of science. He is the Editor of the American Mineralogist.

R. Stephen J. Sparks FRS CBE is Professorial Research Fellow in the School of Earth Sciences at Bristol University (UK). His research concerns volcanic and igneous processes, and he has made contributions in petrology, physical volcanology, fundamental fluid mechanics, sedimentology, and in hazard and risk assessment methods. Honours include the 2004 Arthur Holmes Medal (European Union of Geoscience), 2000 Arthur Day Medal of the Geological Society of America, the 2008 Thorarinsson Medal (International Association of Volcanology and Chemistry of the Earth’s Interior), 2012 Wollaston Medal (Geological Society of London) and the 2015 Vetlesen Prize (regarded as the equivalent of the Nobel Prize for Earth Sciences).

Paul J. Wallace is Professor in the Department of Earth Sciences at the University of Oregon (USA). He received his PhD in geology from the University of California at Berkeley (USA) in 1991, a postdoctoral research associate at the University of Chicago (Illinois, USA), and was a staff scientist with the Ocean Drilling Program before coming to Oregon in 2001. His research focuses on volatile recycling and magma formation in subduction zones; volatiles in explosive, caldera-forming rhyolitic eruptions; and relationships between shallow degassing processes, crystallization, and eruption styles.

Colin J. N. Wilson is a Professor of Volcanology at the Victoria University of Wellington (New Zealand). He studied at Imperial College, London (UK) with George Walker and has worked extensively in New Zealand, the western United States, and Alaska. He studies large explosive eruptions, particularly those that generate ignimbrites, in order to understand eruption processes on a variety of scales. He also researches the dynamics of magmatic systems at large silicic caldera volcanoes (Taupo Volcanic Zone [New Zealand], and Long Valley and Yellowstone [both USA]), integrating laboratory and analytical information with detailed field studies.

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This perspective is based largely on my study of the Long Valley Caldera (California, USA) over the past 40 years. Here, I’ll examine the “knowns” and the “known unknowns” of the complex tectonic–magmatic system of the Long Valley Caldera volcanic complex. I will also offer a few brief thoughts on the “unknown unknowns” of this system.

THE KNOWN UNKNOWNS


Mammoth Mountain has a magmatic system that is distinct from that of the Long Valley Caldera. But it, too, joined in the regional unrest with a nine-month earthquake swarm in 1989–1990. Mid-way through this sequence, long-period “volcanic” earthquakes began occurring at mid-crustal depths (10–20 km). By early 1990, diffuse emissions of magmatic CO2 began killing trees in several areas around the mountain, and elevated levels of 3He/4He were detected from a fumarole on the upper flank of the mountain. The CO2 emissions have since resulted in four fatalities when skiers fell into CO2-rich snow pits. Swarms of lower-magnitude 6 (M 6) earthquakes. Three were located beneath the Sierra Nevada just south of the caldera and the third was located beneath the southern margin of the caldera. A leveling survey later that summer revealed that the resurgent dome in the center of the caldera had bowed upward by 25 cm since the late 1970s, implying magmatic, rather than tectonic, processes were at work (Savage and Clark 1982).

Attempts by US Geological Survey (USGS) geologists to explain the implications of the ongoing unrest were initially greeted with outrage and denial in the resort community of Mammoth Lakes—a population largely unaware of the long history of volcanism in the area. Antagonism toward Earth scientists gradually waned through the 1980s and early 1990s as the caldera’s unrest continued to produce many locally felt earthquakes. The community began to accept the message presented by scientists through frequent public lectures and geological field trips open to the public. Outreach has included USGS support for civil authorities from Mammoth Lakes and Mono County to attend the 10th anniversary meeting on the eruption of Mount St. Helens.

Seismic unrest of the Long Valley Caldera has continued with recurring earthquake swarms in the south moat seismic zone (SMSZ), accompanied by elevated seismicity in the Sierra Nevada block to the south. Inflation of the resurgent dome has continued at rates as high as 20 cm/y (1980–1982 and 1997–1999), with a relatively stable interval from 2000–2010 (Hill 2006). Uplift resumed in 2011 at a rate of ~2 cm/y, and continues to this day. The center of the resurgent dome currently stands ~80 cm higher than before the onset of inflation in 1979–1980 (Montgomery-Brown et al. 2015).

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by activation of hydrothermal fluids, while the other involves renewed intrusion of magma and associated volatiles into the upper crust. Careful mapping and analysis of the eruptive history of the Long Valley Caldera led Hildreth (2004) to suggest that current inflation is driven by hydrous volatiles from secondary boiling of the final stages of a moribund, 760 ka Bishop magma chamber. Others suggest that inflation is driven by advection of a melt-fraction into the upper crust. The simplest model providing a good fit to the deformation data is a volume increase in a compact magma body centered at a depth of 7 km beneath the center of the resurgent dome (Montgomery-Brown et al. 2015).

The difference between these two views carries important implications for hazard assessment. If the volume of low seismic wave-speeds 10–15 km beneath the caldera inferred by Weiland et al. (1995) and Seccia et al. (2011) holds up to further testing, does it correspond to a zone of secondary boiling in a moribund Bishop magma chamber or to recent (last ~10,000 years) emplacement of a melt fraction at mid-crustal depths resulting from, say, basalt underplating and collapse of a lower-crustal crystal mush?

Geothermal fluids upwelling beneath the Inyo Domes flow eastward down the hydrologic gradient within the postcaldera fill (2–3 km deep). Magmatic CO₂ carried by this thermal water is apparently derived from a basaltic reservoir somewhere beneath the Inyo Domes (Brown et al. 2013). The elevated ³He/⁴He ratios in thermal springs in the east moat have been attributed to fluids ascending from upper-mantle sources along an extension of the Hilton Creek Fault into the caldera (Suemnicht et al. 2015). At issue here is lack of evidence for postcaldera (760 ka) displacement along the Hilton Creek Fault into the caldera (Hildreth 2004; Hill and Montgomery-Brown 2015). This leaves a question of whether the magmatic CO₂ and the elevated ³He/⁴He in the thermal water in the east moat might be, in part, derived from a recent melt intrusion beneath the resurgent dome.

The temporal correlation between the onset of seismicity in the Sierra Nevada south of the caldera and caldera unrest suggests a tectonic–magmatic interaction. A related issue is the possibility of a local tectonic earthquake triggering the onset of eruptive activity in a magmatic system that has reached a tipping point in its evolution. Indeed, Hildreth (2004) points to the possibility that a major earthquake on the Hilton Creek Fault intersects the southeastern margin of the ring radiocarbon and seismicity at Mammoth Mountain, CA, USA. Earth and Planetary Science Letters 390: 52–53.


REFERENCES


Contamination makes aluminum oxide a priceless gem

Aluminum oxide or corundum is a commonly available material. However, trace levels of contaminates in the crystal structure of aluminum oxide can result in priceless gems, such as rubies, sapphires, and emeralds. Rubies are corundum with chromium contaminates. It’s the chromium that produces the deep red color. Next to diamonds, rubies are the most precious gems. Sapphires come in many different colors: yellow, red, pink, and the more traditional color, blue. The blue color is only possible when titanium and iron are both present in the structure. The gem shown in Figure 1 was labeled a ruby at a gem show. However, the X-ray diffraction pattern collected on the Rigaku MiniFlex, shown in Figure 2, matches corundum and the two additional phases that can be found in sapphires, mainly, rutile [TiO₂] and Cronsstedtite [Fe₇⁺Fe³⁺(SiFe³⁺)O₃(OH)₃].

This gem would be more appropriately called a red sapphire.
Maggas are erupted from a wide range of depths. Olivine compositions, for example, indicate magma storage in the lower crust and upper mantle, while clinopyroxene and amphibole record middle to upper crust storage. Pre-eruptive magmas also often cool by 100–300 °C, frequently at middle–upper crust depths, indicating clogged, ephemeral volcanic pathways. These coolings imply that mafic recharge is not a sufficient cause for eruption and that crystallization-induced vapor saturation is a more proximal eruption trigger. But an improved understanding of eruption mechanisms requires precise identifications of what are herein termed “ultimate”, “proximal,” and “immediate” causes of eruption.

Keywords: thermometry, barometry, arc volcanoes, eruption triggers, magma storage, magma transport

INTRODUCTION
Volcanism, and planetary evolution generally, involves the continual release of gravitational potential energy as buoyant materials rise and crystalline materials (or metallic liquids or subducted slabs) sink. Earth’s separation into a core, mantle, and crust, with oceans and an atmosphere, reflects this release, and volcanic eruptions are but a spectacular illustration of the process. However, the buoyant rise of magma (a silicate liquid that may or may not contain crystals or bubbles) does not always culminate in a volcanic eruption. As little as 3%–4% of arc magmas may reach Earth’s surface (Paterson and Ducea 2015), while lava flows comprise 10% of mid-ocean ridge crust. Most magmas apparently don’t erupt. Rather, they form dikes, plutons, and sill complexes. It follows that to understand volcanoes we must understand magma storage, the pathways of magma movement, and the circumstances that countenance magma transport to a planetary surface.

“Mush” Model
The “mush column” of Marsh (1996), conceived to describe the Hawaiian plumbing system, provides an excellent scaffold to describe volcanic sources and pathways and has been adapted to large silicic systems (Bachmann and Bergantz 2004; Hildreth and Wilson 2007). “Mush” was defined by Marsh to describe magma with 25–55 volume % crystals; enough to increase viscosity but less than the 55% that causes a magma to become a rigid body. Later authors (e.g. Bachmann and Bergantz 2004) also used “mush” to describe more rigid magma systems. The mush column concept can, and should, replace earlier concepts of long-lived, liquid-dominated magma chambers. The more modern view is one of crust-wide dikes and sills, which may or may not connect scattered bodies of liquid (e.g. Annen et al. 2015), and mush zones (Bachmann and Bergantz 2004) that segue into completely solid wall rock. It is from such systems that volcanic liquids erupt and plutons form. This mush model, inspired by field observations, is supported by calculated crystallization depths (Putirka 1997; Klugel and Klein 2006), a lack of seismic evidence for large batches of liquid sitting in the crust, and studies of plutons, which reveal that magma batches are assembled in episodic, small increments over millions of years (Paterson et al. 2011; Annen et al. 2015). It is also the model that most accurately connects plutons and volcanoes. Uneruptible mushes appear to be a typical igneous state, often destined to form plutons, while eruptible, liquid-dominated bodies exist ephemerally within such systems, within temporal windows lasting as little as 10^4 years (e.g. Barboni and Schoene 2014).

MASH Hypothesis
Our current view of magma storage builds upon one of the more important models developed in the last century: the MASH hypothesis of Hildreth and Moorbath (1988). The MASH acronym derives from “melting, assimilation, storage, and homogenization.” The “melting” process occurs in the mantle, while the “ASH” processes nominally occur together in a “MASH zone” in the lower crust. “Assimilation” refers to the reaction of basaltic magmas with adjacent wall rock; “storage” implies fractional crystallization; and “homogenization” refers to magma mixing, e.g. basaltic with rhyolitic, to make andesitic magmas. This model frames much volcanologic research, correctly emphasizing assimilation and mixing to form andesites and dacites.

But our understanding of magmatic systems has evolved. Wall-rock assimilation can be trivial (e.g. Putirka et al. 2014), and “ASH” processes can occur separately at quite different crustal levels. As will be shown, the lower crust can be mostly a site of mafic magma fractionation, whereas intermediate magmas are generated at a wide range of depths, often in the middle- and upper crust. We can still speak of MASH, but not necessarily of singular MASH zones. Additionally, other processes are no less crucial to understanding volcanic systems. Mafic “recharge”—the injection of basaltic materials into or beneath a felsic magma/mush—may be essential for revitalizing felsic systems (Wiebe 2016), for amalgamating plutons into batholiths (e.g. Coint et al. 2013), and, perhaps, for initiating eruptions. Additionally, crystallization-induced
volatile saturation may trigger eruptions (Tait et al. 1989) or initiate deep-seated magma transport (e.g. Armienti et al. 2013). We might thus abbreviate our understanding of volcanic systems as “recharge, crystallization + mixing, and eruption (RCME)”, although it may be better to instead recognize that our understanding has evolved beyond acronyms.

**THE DEEPEST ROOTS OF VOLCANIC PLUMBING SYSTEMS**

The mantle—defined here as rocks with densities >3.0–3.25 g/cm$^3$ or P-wave velocities >7.6 km/s—is often considered as no more than a source of heat and melt. But volcanic pathways can extend deep into the mantle. For example, in Hawaii (USA), mantle xenoliths derive from >50 km (Clague 1987), i.e. well below Moho depths of 15–20 km (Hill and Zucca 1987), and similar to maximum depths of magma-induced seismic tremor (Dvorak and Dzurisin 2000).
extend into the mantle. Olivine phenocrysts can contain agents by which the Moho transitions are obscured (e.g. Klein 2006). Geophysical studies further reveal that sill fluid inclusions from the Madeira Archipelago (Klügel and 1993). Sub-Moho pressures have also been recorded in Hawaiian clinopyroxene phenocrysts (Putirka 1997) and fluid inclusions from the Madeira Archipelago (Klügel and Klein 2006). Geophysical studies further reveal that sill complexes—interpreted to be stalled mafic magmas with olivine precipitates—extend well below the Moho at Hawaii (ten Brink and Brocher 1987) and the Izu–Bonin arc (Sato et al. 2009). The crust/mantle transitions in these areas are not clearly defined, and sill complexes are the likely agents by which the Moho transitions are obscured (e.g. Sato et al. 2009). Together, these data provide compelling evidence for subcrustal magma storage.

Olivine compositions further show that volcanic pathways extend into the mantle. Olivine phenocrysts can contain high forsterite (Fo; Mg$_2$SiO$_4$) contents, irrespective of tectonic setting, reaching values of >91% Fo (noted as Fo = 91) both in ocean basin lavas (Putirka et al. 2007) and in continental arc lavas, such as the Cascades (Fig. 2A). Given that host lavas at arcs have up to 8%–9% FeO (Fig. 2B), these olivine compositions require parental liquids with 14%–18% MgO (Putirka et al. 2007; Putirka 2016). These high-MgO magmas are called picrites, and can explain the subcrustal P-wave seismic velocities noted above. Moreover, if completely molten, picrites are as dense as, or even more dense than, the lower crust, and are denser still when carrying crystals (Fig. 3). This high density explains why picrites are common in the submarine portions of oceanic volcanoes (compared to subaerial eruptions) (Garcia 2002) and are rare in continental settings. Most volcanoes appear to be rooted in picritic sill systems in the lower crust and upper mantle.

Magma densities allow us to paint a broader picture of magma stagnation. As Lister and Kerr (1991) show, magmas can only overshoot their level of neutral buoyancy (LNB: where magmas and ambient wall rock have equal densities) by a few kilometers. This is not to say that tectonic forces are unimportant: ten Brink and Brocher (1987) show that regional stresses can profoundly influence volcanic activity. But such stress barriers only inhibit liquids from reaching their LNB—and so we can use calculated densities to estimate the depths to which tectonically uninhibited magmas (no crystals or bubbles) may rise. Silicate liquids form a density continuum, with no density minimum when P–T conditions are used as input (Fig. 3). However, there appears to be a distinct break in density at 10%–12% MgO, where buoyancy gains are more rapid with further fractionation (decreasing in MgO). Dry picrites (14%–18% MgO, no water) are neutrally buoyant in the uppermost mantle and lower crust, but can rise into the middle crust with an addition of 3% H$_2$O (Fig. 3). More evolved dry basaltic magmas (5%–8% MgO) can stall within the middle crust, or, if hydrous, in the upper crust (Fig. 3). Of course, any of these melts can erupt—and do—if vapor saturated. But non-vapor-saturated basalts exhibit a wide range of densities, and so can pond and release heat throughout the crust. Volcanic pathways are “hot columns” with transient intervals of high melt fraction (“hot zones”; Annen et al. 2015), which can vary with depth and time, probably as a function of melt composition.

How fast might basaltic magmas transit the crust? Nickel zoning in olivine yields mantle-to-surface transport speeds of 3.3 m/h (Ruprecht and Plank 2013)—within the 1–10 m/h range obtained by entirely different methods at Mt. Etna (Italy) (Armienti et al. 2013). The Etna study further implicates water saturation as an important accelerant in the middle to lower crust. These calculated magma transport rates probably reflect an average value that smooths over periods of rapid conveyance punctuated by interludes of stagnation. In a pulsed transport system, it may be no surprise that most magmas are unerupted (e.g. Paterson and Ducey 2015)—“interim” stagnation becomes permanent, possibly for lack of water, as magmas cool to the point of becoming uneruptible mush.

**Magma Storage and Transport in the Middle and Upper Crust**

Properly employed, igneous thermobarometers can detect both protracted and transient storage depths. Depth estimates are not necessarily depths of prolonged storage: individual P–T estimates may represent transient crystallization during transport (minor cooling or decompression-driven volatile release). And because silicate minerals have very slow internal diffusion rates, transient P–T conditions can easily be preserved. Yet another challenge for identifying prolonged storage sites is that a single chamber, within a dike-and-sill ladder, can collect crystals formed at many depths, only to be flushed out together in a later
eruptive episode. However, prolonged storage depths might be obtained from P–T estimates in aggregate. For example, while individual clinopyroxene grains from Hawaii record crystal growth from the mantle to the near surface, depth estimates cluster at 11–16 km, and exhibit a low- to high-T pool at 1,200–1,150 °C (Fig. 1B). This depth range matches an interval of high compressional wave velocities, which have been interpreted as gabbro sills (Hill and Zucca 1987). And gabbro xenoliths record crystal growth/reequilibration over this same depth range, but with an additional 200 °C of cooling. The 11–16 km interval thus appears to be a site of prolonged storage. It might also serve as a supply depot for sustained eruptions: a volcanic edifice infiltrates as magmas fill a shallow reservoir, and deflates during eruption. At Hawaii, eruptions continue well after deflation ends (Dvorak and Dzurisin 1987), draining in a top-to-bottom fashion progressively deeper parts of a hydraulically connected conduit that extends into the mantle (Putirka 1997). These postdeflation eruptions account for 80% of erupted volumes (Dvorak and Dzurisin 1987), although still unclear is the fraction of this 80% that is stored at 11–16 km, or below.

A loosely parallel story is told at volcanic arcs (Fig. 1D). For example, in the North American Cascades, clinopyroxene phenocrysts crystallize at depths ranging from near-surface down to 25 km. But most clinopyroxene crystallization in the Cascades occurs in the upper 5–11 km of the crust, suggesting that most basaltic magmas reach clinopyroxene saturation in the middle and upper crust. Amphiboles from Cascade magmas yield similar crystallization depths, recording up to 300 °C of additional cooling. These amphiboles hail from both mafic enclaves (the rock record of mafic recharge) and felsic host lavas, and support a model where clinopyroxene-saturated “recharge” magmas invade an already-shallow, amphibole-saturated felsic magma/mush system, and then become amphibole saturated themselves. Of course, no single magma chamber extends from 5 km to 11 km; rather, a series of dikes, sills and mush bodies permeate this interval (Fig. 1C). The inferred dike–sill–mush system for the Cascades is clearly shallower than at Hawaii, probably reflecting the lower density of the andesitic Cascade magmas (60% SiO$_2$, 2.8% MgO) which help them rise to higher levels in the crust (Fig. 3) compared to Hawaiian basaltic magmas. It is not yet known how the Cascades’ dike-and-sill ladder system is emptied: all in one eruptive episode, or mostly after magmas are collected in a shallow staging area?

**HOW VOLCANIC PLUMBING SYSTEMS EVOLVE**

Plutonic rocks provide a glimpse into the evolution of volcanic pathways and hint at a key role for the middle crust. In one part of the Sierra Nevada (western USA), gabbros fractionate directly to form granite while successive recharge magmas are emplaced above their predecessors but below a growing, convective felsic magma body (Putirka et al. 2014). Coint et al. (2013) found similar patterns in the much larger Wooley Creek Batholith. Volcanic pathways are probably related to crustal evolution, where the middle crust acts as a transfer zone. Basaltic magmas repeatedly invade the middle crust and fractionate; their crystalline residues sink to form cumulates that add to the lower crust, and their felsic differentiates are extracted from a rigid mush to rise upwards (Bachmann and Bergantz 2004) and add to the upper crust.

Phenocrysts from different arc lavas also record crustal thickening. Beneath the Cascades (crust = 35 km), the median clinopyroxene crystallization depth is 5 km. In contrast, beneath the Central Andes (crust = 70 km), half of all clinopyroxene grains crystallize at >34 km (Fig. 1E). This contrast occurs despite Andean liquids being clinopyroxene-saturated at very similar SiO$_2$ contents (59%), albeit higher MgO (4.5%) compared to Cascade lavas (60% SiO$_2$, 1.8% MgO). In both cases, clinopyroxene rarely crystallizes beneath the middle crust (40 km at the Andes; 12 km at the Cascades) (Fig. 1E). This seems to imply that clinopyroxene saturation is mostly a middle–upper crust phenomenon (Fig. 3): if arcs can erupt high-forsterite olivine grains, clearly they should also erupt high-P clinopyroxene grains, if such exist. Another possibility is that picrites only reach clinopyroxene saturation near their solids, at which point they become uneruptible mushes. In either case, picrites, not pyroxenites, should dominate the lowermost mafic crust.

Further insights into magmatic plumbing systems derive from trace element ratios. Volcanic Sr/Y ratios, for example, are a rough measure of magma fractionation depths (Chapman et al. 2015). This is because at high pressures (>15–20 kbar), garnet precipitates from basaltic magma, or is a residual phase during partial melting of the crust, and garnet is a sink for Y but rejects Sr. Garnet fractionation, therefore, drives equilibrium liquids to high Sr/Y (40 to >200). In the middle and upper crust, however, plagioclase and amphibole replace garnet, and liquids equilibrated in these crustal regions have modest or very low Sr/Y (<40). Chapman et al. (2015) found that median Sr/Y ratios are low (<8) for arcs built on thin crust (e.g. the Izu–Bonin arc) and higher (>25) for arcs built on thicker crust (central Andes) (Fig. 4). A better proxy for crust thickness might be modal, rather than median, Sr/Y ratios (Fig. 4). In any case, Sr/Y ratios also record crustal growth: maximum Sr/Y values in the Sierra Nevada Batholith increase steadily with time (Fig. 4E). Importantly, however, low Sr/Y magmas are present at all time periods (Fig. 4E): within mature arcs, no single process (deep vs. shallow fractionalization or melting) monopolizes felsic magma genesis (e.g. Coint et al. 2013). The middle crust also seems to behave as a leaky transfer zone, allowing some basaltic magmas to rise and differentiate at low P (Fig. 3) even when the upper crust is thick.
WHY MAGMAS ERUPT: A MUDDLE AND A SUGGESTION FOR PROGRESS

We have no shortage of working hypotheses regarding eruption triggering. Sparks et al. (1977) and Tait et al. (1989) posit that felsic magmas may be brought to an eruption-ready state by magma mixing, mafic recharge, or in situ partial crystallization. Any or all of these can drive a system to vapor saturation and increase magma buoyancy.

However, the above hypotheses are made more complex by recent advances (for details, see the other articles in this issue). Mineral-scale age dates show that felsic magmas are often \(10^3-10^4\) y older than their eruption ages. Thus, some felsic magmas/mushes lie in wait to be reactivated by mafic recharge magmas. Studies on plutons also reveal that large rigid magma bodies seem to have been formed from innumerable magma recharge events, which apparently rarely, or never, result in eruption (Coint et al. 2013; Putirka et al. 2014). Recharge, then, may be a necessary but still insufficient eruption condition. Perhaps, then, magma mixing is an eruption trigger. Kahl et al. (2011) reported multiple magma mixing events that presaged the 1991–1993 eruptions at Mt. Etna. But which mixing event, if any, pushed the system to a point of eruptive instability? Recharge and mixing events are not singular: perhaps a particular event is crucial; perhaps none are. As an added complication, volcanoes, at least ephemerally, are hydraulically connected from an exhalative vent to a mantle source (e.g. Putirka 1997). We still need to know where along a volcanic pathway eruptible felsic systems lie in wait for a recharge/mixing event, and whether recharge/mixing depths are more important at certain depths compared to others, or whether eruption triggering is a conduit-wide process. A remaining challenge is to untie ourselves from acronyms and unfold these processes into causative sequences, which may vary between volcanoes, or between individual eruptions.

When thinking in terms or causative sequences, we are quite likely to find that eruptions are caused by multiple, cascading, triggers. For progress, we should begin to differentiate between causes that are “ultimate”, “proximal” or “immediate”, accepting that there may be a continuum. To illustrate these three causes, we’ll take the 18 May 1980 eruption of Mt. St. Helens (Washington, USA) as an example. The earthquake-triggered landslide that sparked the event may be its immediate cause; its proximal cause might be emplacement of low-density magma into the upper crust and/or the magma’s approach to vapor saturation; the ultimate cause—not at all clear—might involve partial melting in the mantle or a recharge event initiated by means yet uncertain from a depth unknown. None of these distinctions are easy. Was the landslide triggered by tectonic forces or by increased magma overpressure, driven by a crystallizing, vapor-saturated magma? In the latter case, proximal and immediate causes might be identical. Mantle partial melting might be an important trigger, or perhaps it is a trivial ultimate cause, if mantle melt supply rates are long compared to the timescales of eruptive cycles (e.g. Zellmer and Turner 2007). Perhaps mixing or recharge are more usefully viewed as “ultimate” causes. Can recharge also serve as an immediate cause? Perhaps not, when mafic enclaves (our record of recharge) record post recharge coolings of 100–300°C (Fig. 1), but we have too few data to generalize. In any case, precisely articulated hypotheses on the causes and conditions of eruption are obligatory for progress.

REASONS FOR OPTIMISM

The above-stated problems are tractable. For example, we can test whether crystallization-induced vapor saturation is a proximal or immediate cause of eruption by comparing cooling intervals for various systems, and determining whether magmas approach water saturation at pressure and temperature conditions that precede eruption. Or, if magma mixing is an eruption trigger, then mineral compo-
sitions should be strongly bimodal, reflecting the lack of time for newly created intermediate liquids to precipitate new minerals. We can also test hydraulic connectivity and storage. Clinopyroxene grains from the 2010 Merapi (Indonesia) eruptions record pressures ranging from 1 atm to 4.3 kbar (Putirka 2016b), values that are greater than the barometric 1σ error bounds (±2 kbar). If this $P$ range reflects a magmatic system that is hydraulically connected at the time of eruption, then these crystals should yield snyder ring compositions that reflect a diversity of storage conditions. If, instead, a single chamber has collected crystals from various depths, and was evacuated from a once-but-no-longer-connected pathway, then clinopyroxene grains should have convergent ring compositions, to the extent that such crystals share a late thermal history. No-longer connected pathway, then clinopyroxene grains from various depths, and was evacuated from a once-but-no-longer-connected pathway, then clinopyroxene grains from various depths, and was evacuated from a once-but-no-longer-connected pathway. A further reason for optimism are the myriad opportunities. If, instead, a single chamber has collected crystals from various depths, and was evacuated from a once-but-no-longer-connected pathway, then clinopyroxene grains from various depths, and was evacuated from a once-but-no-longer-connected pathway. That such crystals share a late thermal history.

A further reason for optimism are the myriad opportunities to build on the excellent work of Kahel et al. (2011), to integrate petrological and geophysical data. Their study of a Mt. Etna eruption sequence revealed magma-mixing one year before eruption, edifice inflation a month or two later, then additional mixing events 6 months prior to eruption. We can next examine whether, within such a sequence, any particular event pushes a system beyond a threshold, where an eruption becomes probable, perhaps even inevitable. Numerical models and mineralogical studies of active and ancient volcanic systems can be combined to establish threshold conditions and test our sundry working hypotheses on where magmas are stored and why volcanoes erupt.

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Elements

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Currently, it is only possible to look inside an active volcano using indirect geophysical methods. One such method is to measure surface deformation, which results from subsurface magmatic or hydrothermal processes. Modern satellite data allows deformation to be measured at hundreds of volcanoes without relying on limited ground instrumentation. As a result, the number of known deforming volcanoes has increased from 44 in 1997 to over 220 in 2016. This article reviews the diverse ways by which volcanoes can deform, the typical rates and durations of such deformations, and the processes that drive deformation.

**INTRODUCTION**

Whereas geological mapping allows scientists to see the inner plumbing of old volcanoes that have been exhumed by erosion, it is geophysical methods that allow us to study the internal structure of active volcanoes and the processes that may ultimately lead to eruption. Geophysical techniques make measurements near the surface to image the structure beneath a volcano, recording the stress and strain associated with magmatic processes (e.g. Pritchard and Gregg 2016). A common limitation is that multiple sensors must be placed around the volcano in order to make detailed inferences about the subsurface, and the majority of the world’s 1,400 subaerial volcanoes do not have such networks (e.g. Loughlin et al. 2015). Observations of surface deformation (‘geodesy’) can now be made using satellites and can be made globally (e.g. Fournier et al. 2010; Biggs et al. 2014). The number of known deforming volcanoes has quintupled over the last 20 years as traditional ground-based survey methods have been complemented with satellite technology. The ability to observe how different types of volcanoes deform offers a unique perspective on the behaviour of magmatic systems throughout the eruption cycle.

Despite the explosion of observations, our understanding of the significance of deformation (or the lack of deformation) at volcanoes is still in its infancy. The challenge for 21st century volcanologists is to link the new observations of surface deformation to volcanic processes, within the framework of other geological and geophysical observations of magmatic systems. In the coming decades, much more will be learned about complex magmatic systems, from the generation of melt to its interaction with the surface, atmosphere – or shallow crust – and there will be improved monitoring and forecasting of volcanic hazards.

This article will first review the geodetic methods that allow us to study subsurface processes in active volcanoes, and then summarize the broad range of volcanic behaviour that has been observed geodetically.

**GEODETIC TECHNIQUES**

In 1997, deformation had been reported at 44 volcanoes (Dvorak and Dzurisin 1997); by 2010, there were 118 (Fournier et al. 2010) and; at the writing of this article, there are over 220, which we document in the supplementary table. This rapid increase is not the result of a rise in volcanic activity but is a consequence of improved observation and reporting, particularly in the developing world. Technological advances have been vital: a fleet of international satellites (10 radar satellites in 2017 with more planned; e.g. Pinel et al. 2014) make routine, global observations, and global positioning system (GPS) networks make ground-based geodetic observations routine and affordable. However, the list of deforming volcanoes is still incomplete because some volcanoes have never been studied or have only been studied incompletely due to inadequate data.

This review focuses on interferometric synthetic aperture radar (InSAR), the main satellite-based tool that is used to measure surface deformation at volcanoes. Radar (a name itself that derives from ‘radio detection and ranging’) involves the transmission and reception of microwave electromagnetic radiation (roughly $10^8$–$10^{11}$ Hz, or wavelengths of 1 mm to 1 m) (e.g. Pinel et al. 2014). At these wavelengths, radar systems can see through clouds and most types of precipitation and do not rely on the sun’s illumination, giving them a unique all-weather, day–night capability. Each pixel in a synthetic aperture radar (SAR) image is represented by a complex number, with the amplitude corresponding to the intensity of the returned radar energy and the phase equalling a fraction of the complete wavelength (having a value between 0 and $2\pi$). When the phases from two images are combined to form an interferogram, the phase difference reveals variations in the distance between the ground and the satellite that appear as coloured fringes (Fig. 1). Each fringe corresponds...
to half the radar wavelength. The rate of ground displacement can be measured by taking the observed change in distance divided by the time interval between SAR images – this interval usually varies between a day and a few weeks, with rates of deformation ranging from mm/yr to several m per day (Fig. 2). There are two notable limitations to the InSAR technique. First, decorrelation, which occurs when characteristics of the ground and its ability to reflect radar waves change rapidly, for example in heavily vegetated or agricultural regions. Second, atmospheric delays caused by water vapour in the troposphere. Time-series methods that can combine hundreds or thousands of images are increasingly important in overcoming these limitations (e.g. Dzurisin et al. 2006; Pinel et al. 2014).

The revolution in volcano deformation studies as a result of InSAR comes from the ability to routinely image deformation at nearly all of the world’s volcanoes with an accuracy of a few millimetres to a few centimetres. Even so, volcanoes can deform very rapidly (e.g. Fig. 2) and the repeat time between satellite overpasses may be too long to capture these temporal changes, particularly as the amount of data

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**Figure 1** Seven examples of volcano deformation patterns seen with InSAR. Images are ‘wrapped’, and each coloured ‘fringe’ can be thought of as a contour line – the total displacement can be calculated by counting the number of fringes. (A) Deformation at Lazufre on the Chile/Argentina border. From Fournier et al. (2010). (B) Dyke intrusion in Afar (Ethiopia), showing characteristic two-lobed pattern. From Hamling et al. (2009). (C) Flow subsidence at Reventador (Ecuador); deformation is irregular and restricted to the extent of the deposit. (D) Shallow landslides at Arenal Volcano (Costa Rica). From Ebmeier et al. (2014). (E) Subsidence associated with cooling and crystallization of an intrusion at Medicine Lake Volcano (California, USA). The same pattern is seen in levelling surveys extending back 60 years. From Parker et al. (2014). (F) Broad surface uplift (70 km diameter) surrounded by a ring of subsidence (150 km diameter) centred on Volcán Uturunú (Bolivia). See Pitchard and Bescul (2016). (G) Multiple horizontally separated deformation sources in Hawaii, showing simultaneous subsidence of a magma reservoir under Kilauea caldera and dyke intrusion into the East Rift Zone. From M. Poland (pers. comm.).
available for a given volcano varies widely. In some areas, images are collected during every overpass, while in others, data may never have been acquired by certain satellites. Furthermore, data from some satellites are available at no cost (such as the European Space Agency’s Sentinel mission), whereas imagery from other satellites can cost thousands of dollars. One way to overcome this limitation is to use all available satellites in the international constellation. Although the data from the different missions cannot be directly combined, using more satellites increases the frequency of ground observations and, thus, the ability to detect transient events.

Ground sensors complement InSAR observations and can be used to evaluate or correct uncertainties. The most commonly applied is the continuous global navigation satellite system (GNSS), which uses signals from the GPS and other navigation satellites to measure 3-D changes in co-ordinates. Rather than relying on the transmitted code used by cell phones and other domestic systems, geodetic GNSS receivers use the phase of the transmitted signal to achieve sub-millimetre accuracy (Dzurisin 2006). Other ground-based systems (tiltometers, strainmeters, ground-based radar, levelling and triangulation surveys) (Dzurisin 2006) are useful where available, but their use is limited to a handful of volcanoes, and it is not possible to tell how widespread the observed processes are. Ground observations that are collected continuously are especially valuable because they overcome the gaps between satellite InSAR measurements.

**DIVERSITY OF DEFORMING VOLCANOES**

A variety of processes can cause ground deformation at volcanoes: magma movements, landslides, faults, hydrothermal systems, and thermal or thermodynamic volume changes from heating, cooling, melting or crystallization (e.g. Dzurisin et al. 2006). Nevertheless, certain patterns of ground deformation can, to a limited extent, be diagnostic of specific physical process, e.g. a dyke intrusion, cooling lava/pyroclastic flow, or pressurizing ‘magma reservoir’, all of which have distinct patterns of ground displacement viewed with InSAR (Fig. 1A-E). Complexities arise depending on the direction the satellite is looking relative to the ground displacement (e.g. Dzurisin et al. 2006) and when multiple processes occur at nearly the same time (Fig. 1F, 1G). In this section, we describe some commonalities between deforming volcanoes and global patterns in the types of processes that produce ground deformation.

**The Classic Volcano Deformation Cycle**

Prior to an eruption, according to the classic model of the ‘volcano deformation cycle’, magma gradually inflates a magma chamber directly beneath the volcanic edifice until a threshold is reached at which point the chamber ruptures and an eruption rapidly empties and deflates the chamber (e.g. Dzurisin et al. 2006). The inflation phase causes uplift of the ground surface and large numbers of small earthquakes (volcano-tectonic seismicity), while eruption is accompanied by rapid subsidence (Fig. 3A). To a first approximation, this pattern of co-eruptive subsidence and inter-eruptive uplift has been observed at a number of volcanoes with different characteristic length scales and timescales and has been used to provide eruption forecasting in a number of cases (e.g. references in Dzurisin et al. 2006; Fournier et al. 2010). However, the recent explosion in volcano monitoring data has demonstrated that the classic model is an oversimplification. Many volcanoes just do not behave in this way. Furthermore, a simple, large, liquid-filled magma chamber is not compatible with modern geological or petrological observations. Nonetheless, the classic model of the volcano deformation cycle remains a useful concept from which to start.

Long-lived eruptions and intrusions provide an alternative opportunity to observe repeated cycles of behaviour. For example, the multi-decadal eruptions of Soufrière Hills Volcano (SHV) on Montserrat (an andesitic stratovolcano in the Caribbean) and Kilauea (Hawai’i USA) (a basaltic shield volcano) have served as test-beds for new ideas and new monitoring systems. Global positioning system instruments at SHV observed a simple first-order pattern: when lava is erupting rapidly, the surface subsides; during periods of no extrusion, it inflates (Wadge et al. 2014). Similar patterns have been observed at volcanoes with multiple, distinct eruptions, such as Fernandina in the Galapagos (e.g. Pinel et al. 2014) and Ogmok (Alaska, USA) (e.g. Lu and Dzurisin 2014). However, close inspection of the time series shows that inter-eruptive uplift is interrupted by short reversals that are not associated with any magma output at the surface. At Ogmok, these reversals have been attributed to pulses of gas loss or re-absorption (e.g. Caricchi et al. 2014).

**Intrusions**

Most magma does not reach the surface – but sometimes, the intrusion of dykes and sills and the growth of plutos are visible in the geodetic, as well as the geological, record. Earthquake swarms at Eyjafjallajökull (Iceland) in 1994 and 1999 were associated with tens of centimetres of surface uplift but no eruption (Sigmundsson et al. 2010 and references therein). Similar patterns of seismicity and deformation in 2010 culminated in the eruption that disrupted Europe’s air traffic, causing huge economic losses. Magma is supplied in batches, some of which ‘stall’ and form an intrusive complex at the roots of the volcano, while others, as happened in the 2010 eruption, reach the surface, triggering large eruptions which can tap multiple reservoirs (Sigmundsson et al. 2010). Intrusions also occur within volcanic edifices. The orientation of these intrusions is
Restless Calderas

Caldera systems have long repose periods between very large eruptions, but do not remain quiescent – many calderas have frequent, small eruptions, known as resurgent volcanism. In the case of Santorini (Greece) the volume of erupted lava is directly proportional to the time since the previous eruption, evidence that magma supply from depth is continuous (Parks et al. 2012). However, in 2010, a short period of rapid uplift occurred with an equivalent volume to that anticipated for the next eruption, indicating that the magma supply to the shallow reservoir is pulsed rather than continuous (Parks et al. 2012).

Some caldera systems have been known to deform for decades without erupting. At Campi Flegrei (Italy) gradual subsidence over centuries has caused the Roman market at Pozzuoli to become submerged. The subsidence is occasionally interrupted by pulses of uplift but it remains unclear whether the cause is magmatic or hydrothermal (e.g. Chiiodini et al. 2010). At Yellowstone (USA), deformation has a spatially and temporally variable pattern and is attributed to hydrothermal fluids moving between reservoirs as well as magma intrusion (e.g. Chang et al. 2007).

More recently, satellite observations have shown that deformation is occurring at many caldera systems that are not erupting, that have no record of historical volcanism, and that have no real-time monitoring. This includes many volcanoes along the densely populated East African Rift (e.g. Biggs et al. 2014 and references therein) and raises the question of how to interpret caldera deformation in terms of volcanic hazards. The fastest uplift rate seems to be at Laguna del Maule (Chile), which has been uplifting at a rate of 280 mm/y since 2007 (e.g. Fournier et al. 2010). However, the implications for the shallow magma body underneath remain unclear.

Is the behaviour of restless calderas related to external influences? The passage of seismic waves associated with large earthquakes has been shown to influence hydrothermal systems, probably as a result of interactions with gas bubbles. For example, both the 2010 Maule (Chile) and 2011 Tohoku (Japan) earthquakes caused subsidence at several nearby volcanoes, but the subsidence mechanism could be due either to changes in the hydrothermal system or to stress changes acting on the weaker rheological properties of a pluton (e.g. Pritchard et al. 2013).

During and After an Eruption

While co-eruptive subsidence associated with subsurface magma withdrawal is a common feature of eruptions, in many cases it is masked by local surface changes, including both the destruction and creation of topography. Explosive eruptions typically form new craters and vents, they can
alter the morphology of existing structures, and they may trigger large collapses. Eruptive products include lava flows, pyroclastic flows and lahars and these can fill low topography. A new dome may grow near the vent (e.g. Pinel et al. 2014). Ash fall, while rarely thick enough to dramatically alter topography, can alter the appearance of the ground surface making it incoherent to satellite radar and so reducing the efficiency of ground-based monitoring that relies on solar panels. After an eruption, the new topography is typically oversteep, and processes such as landsliding and gravitational spreading (e.g. Ebmeier et al. 2014) act to restabilise the landscape. Subsidence of cooling and compacting lava flows can last for decades: Paricutin (Mexico) erupted in 1952 and is still subsiding today (e.g. Fournier et al. 2010).

Magmatic systems can respond to eruption in multiple ways. In the classic model of the volcano deformation cycle, the magma chamber begins to refill within days of the eruption (e.g. Ogmok volcano, described in Lu and Dzurisin (2014)). But sometimes the volcano just continues to subside (e.g. Kiska volcano in the Aleutian Islands of Alaska, described in Lu and Dzurisin (2014)). For decades after an intrusion, the subsurface magma body will continue to cool, crystallize and degas: at Medicine Lake Volcano (California, USA), modern geodetic observations were combined with levelling surveys from the 1950s to demonstrate that subsidence has continued at ~10 mm/y for at least the last 65 years (Parker et al. 2014).

Limits of Detectability

Several eruptions appear to have taken place at volcanoes with no known deformation (e.g. Fournier et al. 2010; Lu and Dzurisin 2014). Even when co-eruptive subsidence is observed, the volume is usually less than the dense rock equivalent of the erupted products. The classic model of the volcano deformation cycle assumes that there is a constant volume flux of magma being supplied to the magma chamber, producing a linear rate of uplift between eruptions. Altering the boundary conditions such that magma is supplied from a deeper chamber at constant pressure modifies this model such that eruption is followed by exponentially decaying uplift. This may explain observations of eruptions that occur with negligible uplift prior to eruption and very rapid uplift following eruption, such as was observed at Westdahl (Alaska) (e.g. Lu and Dzurisin 2014).

The simplest explanation for a lack of co-eruptive subsidence is that deformation is occurring at a magnitude or resolution beneath our current ability to observe: too fast or too slow, too shallow or too deep, or obscured by atmospheric effects. Already, new satellites with higher resolution and faster orbital repeats (e.g. TerraSAR-X and CosmoSkyMed) have been used to observe previously undetectable processes (e.g. Salzer et al. 2014). Long-term monitoring missions, such as the European Space Agency’s Sentinel programme, have the potential to revolutionise detection capabilities. An alternative explanation is that we ought to consider mass balance, rather than volume balance, because density is far from constant in a three-phase magmatic system undergoing changes in temperature and pressure. Gas bubbles, after all, do make magmas very compressible (e.g. Caricchi et al. 2014).

GLOBAL SYNTHESIS

The rapid increase in the number of geodetically studied volcanoes means that it is now feasible to treat the observations statistically. Biggs et al. (2014) showed that there is a strong link between deformation and eruption for over 500 systematically studied volcanoes, and also between non-deformation and non-eruption. Further, this relationship varies with volcanic parameters: shield volcanoes have a strong link between deformation and eruption and come closest to the classic volcano deformation cycle, while calderas frequently deform without erupting, suggesting that large volumes of magma are stored in the upper crust and that the deformation is caused by gas or hydrothermal fluids. Stratovolcanoes are the most likely to erupt without observable deformation, perhaps because the mass changes are accommodated in a way not detectable by current observation satellite systems, which have revisit times of weeks.

How do we know when a given deformation event may lead to eruption? One way to answer this question is to compare the duration of deformation events to their magnitude and see whether they led to an eruption (Fig. 2). As expected, deformation events that had large magnitudes usually lasted for a short amount of time and typically led to an eruption (e.g. Fournier et al. 2010). Yet there doesn’t seem to be a simple threshold at which deformation duration and/or magnitude should cause concern. On the other hand, there are many volcanoes that can deform at rates of 1–1,000 mm/y without causing eruption in the short term, and so these types of deformation events are not always hazardous. Figure 2 and the online supplementary table with this article are incomplete in several respects. Some volcanoes have never been studied. At others, the temporal sampling is inadequate to resolve pulses of rapid deformation, the deforming area being too small to resolve or had occurred within a data gap. In some cases, deformation was ongoing at the start or end of the available observations, making the specified duration a minimum estimate. There is a cluster of deformation events with a one day duration that likely correspond to even shorter time periods, but these short events could not be constrained because observations were not sufficiently frequent.

Although deformation has been reported at over 200 volcanoes, there remain several eruption styles that have been observed rarely, or not at all. The only geologically observed rhyolite eruption occurred at Chaitén (Chile) in 2008, with only a few hours of pre-eruptive warning (e.g. Wicks et al. 2011). With a sample size of one, it is impossible to state whether the pattern observed is representative. The latest monogenetic eruption occurred at Paricutin during the period 1943–1953, which was before routine satellite observations. Perhaps most alarming is the lack of observation of the very largest eruptions. The most recent magnitude 7 eruption (i.e. erupting a volume in dense rock equivalent of 10^{11}–10^{12} m^3) occurred at Tambora (Indonesia) in 1815. Even recent magnitude 5–6 eruptions, with erupted volumes of 10^{9}–10^{11} m^3 [such as Mount St. Helens (Washington, USA), and Mount Pinatubo (Philippines)] have limited geodetic observations. The only available example is the relatively small eruption of Campi Flegrei (Italy) in 1538, where historical records suggest that several metres of deformation occurred in the years before the eruption (Guidoboni and Ciucarelli 2011). Calderas have the potential for extremely large eruptions, but could we distinguish between the semi-continuous unrest seen at so many calderas and the precursors to a major eruption?

SUMMARY AND PERSPECTIVES

Satellite techniques are rapidly improving our ability to monitor volcanoes on a global basis and have provided insight into the spatial and temporal changes in the subsurface stress fields around volcanoes and intrusions. The classic model of the volcano deformation cycle – co-eruptive deflation and inter-eruptive inflation – is seen at many volcanoes, but the rapid increase in geodetic
monitoring has demonstrated that such a simple model is not always applicable. Deformation can be attributed to the movement and phase transitions of magma, volatiles and hydrothermal fluids and to the intrusions of dykes, sills and the growth of plutons, each of which have their own characteristic geodetic signatures. Surface processes during and after eruptions, such as the formation of volcanic flows and domes as well as edifice instability, may obscure subsurface processes. Alongside developments in observational ability, modelling capabilities have evolved from analytic solutions for point sources and other simplified geometries, to finite element models that can incorporate more complex rheological and structural information, to physics-based models capable of integrating geophysical monitoring with observations of degassing and petrology (e.g. Masterlark 2007; Anderson and Segall 2011).

Satellite imagery has proved a remarkable reconnaissance tool to discover new phenomena. As new satellites and constellations of satellites are launched in the coming years (e.g. Pinel et al. 2014), even more new discoveries will be made. Yet, the biggest questions remain: “Which of the deforming volcanoes are a threat?” and, “Under what circumstances does deformation lead to eruption?”

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INTRODUCTION

Magmas are generated deep within the Earth, and only a fraction of them eventually make it to the surface to produce eruptions. In between magma generation and eruption, all magmas must transit the crust, during which time they may stall and be stored within crustal magma reservoirs at various depths. But what do these magma reservoirs look like? What kind of conceptual model is most accurate? The most common popular conception is of a single, simple “magma chamber”: a large, homogeneous, body of completely molten magma surrounded by country rocks, with a sharp transition between the two (Fig. 1A). However, the scientific consensus has shifted in recent decades to a more complex picture of a “magma reservoir,” consisting largely of crystal mush (a mixture of crystals and liquid where the crystals make up more than ~40%–50% of the volume), grading to solid material (country rock plus solidified magmas) at the margins. In this model, only a relatively small proportion of the magma is liquid at any given time (Fig. 1B, 1C). The magma reservoir concept fits with a wide variety of observations, but it brings up additional questions. How big are these reservoirs? How long do they survive in the crust, and how much input of mass and heat is necessary to sustain them? How does their physical state (e.g. temperature, percentage of melt) vary over space and time within the reservoir? When, where, and for how long are largely liquid bodies of magma present? And what processes and timescales are necessary to accumulate the volumes of largely liquid magma that are erupted?

Four broad categories of methods can provide information about the state and evolution of magma reservoirs: geophysical imaging and remote sensing (Lees 2007; Kiser et al. 2016); theoretical or computational models (Huber et al. 2012; Annen et al. 2015; Bergantz et al. 2015); observations of plutonic rocks representing former magma reservoirs (e.g. Coleman et al. 2016); observations of volcanic rocks. Each of these four methodologies captures a different slice of a reservoir’s history and answers different parts of the question (see other articles in this issue for further discussion).

This paper focuses on crystals in volcanic rocks as an archive of the conditions and processes operating within magma reservoirs. This sample is biased, both because the magmas that have been erupted are a minority of the magmas generated in the Earth’s interior, and because each erupted magma is probably not representative of the reservoir as a whole. However, this sample bias can, in fact, be useful. The crystals directly sample the part of the reservoir that produces eruptions, providing information about the active part of the reservoir. For example, the crystals that grow within a subsurface magma can be slow to equilibrate chemically after compositional changes in the local environment and can, therefore, contain detailed, long-term records of such changes. Furthermore, these crystals provide a unique perspective on active reservoir processes because they capture the long-term (tens to hundreds of thousands of years) history of the region feeding eruptions. This then provides an important complement to other methods of studying active volcanoes.

The crystals within volcanic rocks can be broadly divided into two categories: major phases and accessory phases. The major phases are the major rock-forming minerals (e.g. olivine, feldspars, pyroxenes, amphiboles) that would make up the bulk of the solidified rock were it to crystallize to completion. The proportions of these major phases present are functions of variables such as the major-element composition of the bulk magma, pressure–temperature conditions of crystallization, and volatile contents of the magma. In contrast, accessory phases are present in abundances of much less than 1% of the total volume of the rock, and their presence in the magma often reflects (at least in part) the abundances of trace elements in the melt, in addition to those variables controlling the major-element composition. For example, zircon saturation in magmas is sensitive to the zirconium concentration in the melt as well as the
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liquid-rich magmatic mush

A

B

C

Figure 1 (A) Artist’s conception of the magma chamber beneath Yellowstone Caldera (USA), illustrating the popular conception that a magma chamber is a \textit{“big tank”} of magma. Image Credit: US National Parks Service. (B) Schematic diagram illustrating a crystal-mush dominated reservoir beneath Long Valley Caldera (California, USA). Modified from Hildreth and Wilson (2007). (C) Schematic model for the Yellowstone magma system based on seismic data. Blue and yellow regions near the surface indicate basaltic and rhyolitic eruptive deposits, respectively. Reprinted with permission of AAAS from Huang et al. (2015).

LONGEVITY OF MAGMA RESERVOIRS

The longevity of a magma reservoir depends on how it is defined. Life spans of volcanic systems (i.e., multiple volcanoes or vents active over time in a broad area) are similar to the total duration of magmatism recorded in plutonic systems (~10 My) (Grunder et al. 2006; Coleman et al. 2016). However, the duration of activity at any given volcanic edifice is shorter, typically ~1 My (Grunder et al. 2006). Taking one further step down in scale, individual volcanic eruptions contain crystals with ages that typically span tens to hundreds of thousands of years (Reid 2003; Zellmer et al. 2005; Turner and Costa 2007; Schmitt 2011; Cooper 2015) (Fig. 2). Thus, the life span of activity at a given magmatic system seems to be on the order of millions to ~10 million years, of which a “moving window” of tens to hundreds of thousands of years of activity is sampled by any given eruption. But the residence time of eruptible magma itself seems much shorter—decades or centuries up to a few millennia. These apparently contradictory estimates of storage timescale can, however, be reconciled if the conditions and timescales of long-term storage within the “background” state of the reservoir are different from the conditions and timescales of accumulation and storage of magma bodies just before eruption.

PHYSICAL STATE OF MAGMA RESERVOIRS

The replacement of the “big tank” model of a magma chamber with a “crystal mush” model (e.g., Hildreth and Wilson 2007; Bachmann and Bergantz 2008) has been driven by the following observations:

1. Seismic imaging of magma reservoirs is, typically, consistent with the presence of a few tens of percent of melt at most (Lees 2007; Huang et al. 2015; Kiser et al. 2016).

2. Crystals within volcanic rocks typically show considerable diversity in composition (ranging from major- and trace-element zoning to differences in isotopic composition both within and between crystals) and in age, inconsistent with a simple cooling and crystallization
Accessory phase ages – spot analyses

Major phase ages – bulk mineral separates

Figure 2: Compilation of U-series crystal age data for accessory and major phases from a wide variety of erupted magmas. (A) Compilation of model $^{238}$U–$^{230}$Th ages for individual spots (40 μm in diameter) on zircon and other accessory phase grains from volcanic rocks. Ages are expressed as preeruptive crystal residence (i.e. crystal age minus the eruption age). Each vertical array shows data for a single sample (or a group of closely related samples), where lines indicate the range of ages for individual spot analyses; solid lines for interior analyses and dashed lines for unpolished surface analyses. The mean ages, or the dominant peaks on probability density functions (pdf), are shown as solid circles; secondary pdf peaks are indicated by open circles. Upward-pointing arrowheads indicate analyses within error of secular equilibrium (older than 400 ka); downward-pointing arrowheads indicate analyses within error of eruption age. ‘CA’ is California. Modified from Cooper (2015). (B) Compilation of $^{238}$U–$^{230}$Th (light blue circles) and $^{230}$Th–$^{226}$Ra (dark blue diamonds) ages of bulk mineral separates of major phases, expressed as preeruptive residence age. Vertical lines show maximum and minimum residence ages calculated by combining the 2σ uncertainties on the eruption age and the crystal age. Arrows on the error bars represent samples with ages within error of eruption age (downward-pointing arrowheads) or secular equilibrium (upward-pointing arrows). Mean or best estimate ages are shown by the symbols; lines without symbols indicate samples for which only a maximum and minimum age estimate were available. ‘OVC’ is Okataina Volcanic Center. Modified from Cooper and Kent (2014) and Cooper (2015).

Some important observations can be drawn from the age data alone. For example, compiled age data for zircons (and other accessory minerals) in volcanic rocks show a large range of ages in single eruptions, within a single hand sample, and even, in some cases, within a single crystal (e.g. Reid 2003; Schmitt 2011; Storm et al. 2014; Cooper 2015; Steltten et al. 2015). Numerical models of periodic injection of magma recharge into a reservoir are consistent with maintaining some melt-dominated zones within a larger, partially molten region over long periods of time (e.g. Huber et al. 2012; Annen et al. 2015). Furthermore, liquid-dominated bodies of magma demonstrably exist, because they are erupted. But for how long are eruptible magma bodies stored in the reservoir prior to eruption, and how are they produced within an overall mushy reservoir? The question of what a magma reservoir looks like becomes dependent on its size and on the timescales being considered. For example, records from volcanic crystals can provide a much more detailed picture than the reservoir-scale averaging inherent in most numerical models or geophysical imaging. Critically, the ability to date individual crystals (or, in the case of major phases, crystal populations) and to compare ages to crystal-scale chemical information provides constraints on the temporal evolution of the chemical environment within the reservoir.
In addition to providing information about a magma reservoir’s longevity, crystals also act as archives for how a magma reservoir’s composition may have changed. Variations in trace-element and isotopic composition of crystals, especially when combined with age data for the same crystals, can provide information about the degree to which different parts of a reservoir demonstrate coherent compositional evolution. A comparison of combined age and trace-element data for zircon surfaces (white symbols in Fig. 3A) with age and trace-element data for zircon interiors (orange symbols in Fig. 3A) in a recent study of post-caldera volcanic activity at Yellowstone Caldera (USA) (Stelten et al. 2015), shows that the zircon surfaces are relatively compositionally restricted at any given time but that surfaces and interiors both show systematic variations in composition over time (Fig. 3B). This pattern of data indicates that the zircon crystals began growing in a long-lived, compositionally diverse part of the reservoir, then moved to a region that was more restricted in composition where the final stages of zircon growth (the surfaces) occurred. At the same time, the average compositions of zircon interiors and surfaces mimic temporal changes in glass composition (Fig. 3B), suggesting a coherent change in the average chemical composition of the reservoir over time. Sanidine ages (Fig. 3C) and lead isotopic compositions (not shown) from the same Yellowstone samples (purple symbols in Fig. 3C) document that the sanidine also crystallized shortly prior to eruption from a compositionally restricted part of the reservoir. Because sanidine would be expected to crystallize from rhyolitic magma during the entire interval of zircon crystallization, this suggests that the sanidine that crystallized coevally with the zircon interiors was not erupted. Considering all this information together produces a model of the magma reservoir below Yellowstone (Fig. 3D) where melt plus zircon interiors are extracted from a long-lived, compositionally diverse, crystal mush, leaving behind the sanidine and, presumably, other major phases. The melt plus zircon is then transported to a different, melt-dominated, region of the reservoir where it is stored for a comparatively short time (less than a few thousand years) during which time zircon surfaces and additional sanidine crystallize from the melt prior to eruption (Stelten et al. 2015).

The concept that much of a magma reservoir exists as a crystal mush (or even near-solidus) for much of the time is supported by constraints on the thermal history of crystals from within magma reservoirs. Trace-element concentration variations within crystals are a natural consequence of crystal growth within a compositionally evolving magma reservoir and/or of crystals being transported from one region of a compositionally diverse reservoir to another. Trace-element variations are commonly observed in crystals from arc volcanoes, such as Mount Hood (Oregon, USA) (Cooper and Kent 2014) (see red line in Fig. 4A).

Frequently, these changing environments during growth lead to different zones within a crystal that are not in chemical equilibrium with each other, or with the host liquid (compare purple line with red line in Fig. 4A). As a consequence, the trace elements will diffuse between zones within the crystal, moving towards equilibrium. The rate of this diffusive reequilibration within a crystal is exponentially dependent on temperature. If initial conditions and diffusion rates for a particular element in a given crystal are known or can be estimated, trace-element profiles can be modelled to constrain the duration of crystal residence at a particular temperature (Costa et al. 2008). Even if all of these parameters are not fully constrained, the time over which disequilibrium between crystal and host liquid can be preserved is a strong function of temperature. This means that some order-of-magnitude information about storage durations can be obtained even in the absence of complete information. By combining the crystal ages (blue line at the top of Fig. 4B) with diffusion modelling, assuming a particular temperature (T_d in Fig. 4B), it is possible to constrain the maximum percentage of the total crystal lifetime that could have been spent at that temperature (red line segments and areas in Fig. 4B).

In the context of the mush model of magma reservoirs, one temperature that is of particular interest is the
“rheological lock-up” temperature—the temperature at which a particular magma composition reaches a crystallinity of ~40%–50%, causing a transition from crystals suspended in a liquid to liquid existing within a locked crystal network—a crystal mush. In the case of Mount Hood, preservation of Sr disequilibria within plagioclase crystals limits the time spent at 750 °C (the lock-up temperature for this magma composition) to a few centuries up to 2,800 years, corresponding to a maximum of 12% of the minimum age of the crystal cores (21 ka), and <<1% of the average crystal age (126 ka) (Cooper and Kent 2014). Of course, more complex thermal histories than storage of the average crystal age (126 ka) (Cooper and Kent 2014). The concept of rapid remobilization of a mush is supported by numerical models that explore the conditions required for remobilization, although different models have widely varying predictions about reactivation times (Burgisser and Bergantz 2011; Huber et al. 2012; Parmigiani et al. 2014; Bergantz et al. 2015). In addition, numerical models that track individual crystals during reactivation support the idea that crystals from chemically diverse layers can be intimately mixed during the process of remobilization (Bergantz et al. 2015). Finally, there is growing evidence that eruptions (even very large ones) can be fed by multiple smaller bodies that may be distributed within a crystal mush (Allan et al. 2013; Storm et al. 2014). In some cases, it appears that multiple magma bodies were tapped during the course of a single eruption without having been assembled into a larger body prior to eruption (e.g. Eyjafjallajökull volcano in Iceland; see Cashman and Giordano 2014 and references therein). Thus, the emerging picture of what a magma reservoir looks like is highly dependent on when you are looking. Reservoirs appear to spend most of their existence in a quiescent, largely crystalline state (where the magma is entirely liquid; T_m), solidus (the temperature below which the magma is entirely solid; T_s), and an arbitrary modeled diffusion temperature (T_d) are shown as dashed lines. Modified from Cooper and Kent (2014).

**Figure 4** How to constrain a magma’s thermal history. (A) Trace-element concentrations measured in a profile across a crystal. In this example, measured Sr concentrations (red line) across a plagioclase crystal (Inset) are far from concentrations expected for equilibrium with host liquid (purple line). Thin dashed lines show modelled evolution of the Sr concentration profile from initial concentrations toward equilibrium, calculated at 850 °C. (B) Diagram illustrating how a crystal’s thermal history can be constrained using modelled diffusion durations combined with absolute crystal ages. The blue line shows a schematic temperature–time history of crystals within a magma reservoir, where high temperatures could be related to recharge events (or other heat input events to the reservoir), followed by cooling. The arrowed blue line indicates the total time recorded by the crystals, as captured by the U-series crystallization ages. The red regions (and red segments in top section) indicate the maximum duration of storage at or above a specified temperature that could preserve the measured profile. Temperatures of liquidus (the temperature above which the magma is entirely liquid; T_lq), solidus (the temperature below which the magma is entirely solid; T_s) and an arbitrary modeled diffusion temperature (T_d) are shown as dashed lines. Modified from Cooper and Kent (2014).

**HOW LONG DOES IT TAKE TO “PRIME” A RESERVOIR FOR ERUPTION?**

The mush model of magma reservoirs does present something of a paradox: in order to erupt, magmas must be above the rheological lock-up temperature, yet much of a reservoir likely exists for most of the time as a crystal mush below the rheological lock-up temperature. Therefore, an important implication of the thermal history data is that all of the “action” in terms of rejuvenation of a crystal mush, accumulation of erupted bodies of magma, mixing between resident and recharge magmas, growth of crystals or rims of crystals that are in equilibrium with the erupted melt composition, must take place within a comparatively short period of time. Indeed, the Yellowstone study discussed above is but one example of a growing body of evidence suggesting that erupted magma bodies are assembled rapidly—within decades to centuries of eruption, or at most a few millennia—from compositionally diverse and long-lived magma reservoirs (e.g. Costa et al. 2008; Druitt et al. 2012, 2013). Further evidence for this idea comes from timescales of diffusion of trace elements across compositional boundaries within crystals (Costa et al. 2008), and from the kinetics of growing crystal faces from initially rounded melt inclusions (Pamukcu et al. 2015).

The concept of rapid remobilization of a mush is supported by numerical models that explore the conditions required for remobilization, although different models have widely varying predictions about reactivation times (Burgisser and Bergantz 2011; Huber et al. 2012; Parmigiani et al. 2014; Bergantz et al. 2015). In addition, numerical models that track individual crystals during reactivation support the idea that crystals from chemically diverse layers can be intimately mixed during the process of remobilization (Bergantz et al. 2015). Finally, there is growing evidence that eruptions (even very large ones) can be fed by multiple smaller bodies that may be distributed within a crystal mush (Allan et al. 2013; Storm et al. 2014). In some cases, it appears that multiple magma bodies were tapped during the course of a single eruption without having been assembled into a larger body prior to eruption (e.g. Eyjafjallajökull volcano in Iceland; see Cashman and Giordano 2014 and references therein). Thus, the emerging picture of what a magma reservoir looks like is highly dependent on when you are looking. Reservoirs appear to spend most of their existence in a quiescent, largely crystalline state (where crystallization, diffusion, and compositional evolution operate slowly) that is punctuated by brief periods of intense activity during which diverse crystals are gathered together and are mixed along with their host liquids, crystallization occurs rapidly, and the magmas become primed for eruption.

**FUTURE DIRECTIONS**

A growing body of evidence supports the idea of dominantly cool and mushy storage conditions and the rapid assembly of erupted magma bodies. Yet, much remains to be explored. Are storage conditions different for the magmas that feed
eruptions of different sizes? Do different compositions of magmas have different storage histories? What are the conditions required to maintain a magma reservoir as a relatively cold crystal mush for long periods of time, and how do these conditions change when “priming” the system for eruption? Are the liquid and crystal components of erupted magmas stored separately and only combined immediately before eruptions? What geophysical or other observational signals should we expect to see when a reservoir is in a “normal” background state compared to being in an active state that may precede eruption?

Three themes of ongoing research encourage optimism that we are poised to make progress toward answering these questions. First, efforts to directly constrain the thermal histories of magma storage are increasing in number. The fruitful theoretical efforts will provide much-needed observational evidence about how thermal conditions of magma storage evolve over space and time. Having this kind of data for eruptions for a range of sizes and compositions will allow us to look for commonalities or differences in behavior that will be key to understanding the variables that drive storage and eruption. Second, modelling of processes in magma reservoirs has been rapidly advancing in the sophistication of situations that can be simulated. This increasingly provides modelling output that can be directly compared to the observational records, which should allow us to explore the physical processes of storage and mobilization. Third, there is an increasing ability to compare petrologic data to geophysical data in order to better understand the deformation signals (Kahl et al. 2013).

In short, there is closer communication than ever between petrological, geophysical, and modelling approaches to understand magma storage and mobilization, with enormous potential to make fundamental advances in our understanding of magma storage systems and eruptions.

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Volatile and Exsolved Vapor in Volcanic Systems

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INTRODUCTION

Volcanic eruptions, in all their diverse forms, are driven by overpressure, buoyancy, and degassing. Subaerial eruptions produce vast clouds of volcanic gases, a process that has shaped our hydrosphere over Earth’s history. Many rocks produced by volcanic eruptions, particularly explosive eruptions, are dominated by vesicles—bubbles frozen in place during eruption (Fig. 1). There can be no doubt that to understand volcanic processes, the mechanisms and consequences of magmatic volatile degassing are paramount.

Magmatic volatiles are chemical constituents in silicate melts that partition into a magmatic vapor phase at low (crustal) pressures. The primary magmatic volatiles that drive volcanic eruptions are water (H2O) and carbon dioxide (CO2). Volatiles are only present in small amounts in magmas (a few wt%), but their influence belies their weight. The presence of dissolved volatiles in silicate melts controls the abundance and composition of crystal phases that grow in the magma during cooling and decompression, as well as the density of silicate melts (Ochs and Lange 1999). This has consequences for buoyant magma ascent through the crust, as well as for convection in magma reservoirs.

Within a few kilometers of the Earth’s surface, silicate melts typically reach saturation with respect to a magmatic vapor phase, which is disseminated as bubbles. Volatile exsolution can occur as a result of isobaric cooling and crystallization in magma reservoirs, and this can lead to an increase in reservoir pressure (because the surrounding country rocks are relatively incompressible) that can trigger eruptions (Tait et al. 1989). Volatile exsolution also occurs during decompression and eruption of magma, causing tremendous expansion of bubbly magma and its acceleration up the conduit. The rate and efficiency of exsolution and vapor loss during ascent, as well as the rheological properties of the magma, largely control eruption style.

The magmatic vapor phase in crustal magma reservoirs is predominantly CO2 at depth, becoming more H2O-rich at lower pressures (Fig. 2A). Volcanic gases (a term used to describe the vapor phase when discharged at the surface through a vent or fumarole) contain a myriad of other chemical species, chief of which are sulfur (Fig. 2B) and halogens. Sulfur partitions strongly into the vapor phase at low pressures (Scaillet et al. 1998; Fig. 2C). In relatively oxidised and low temperature magmas in the upper crust, most of the sulfur is likely to exist in the vapor phase rather than being dissolved in the melt (Fig. 2D). A consequence of this is that explosive volcanic eruptions typically release far more sulfur (as sulfur dioxide) than can be accounted for by the amount dissolved in melt inclusions (tiny aliquots of melt trapped in crystals) (Wallace 2001). Chlorine, which also partitions into the vapor, forms complexes with metals, a key part of the process of forming porphyry Cu deposits and epithermal Au deposits in the shallow plumbing systems of some volcanic systems. For highly saline magmas, a high-density magmatic vapor phase at depth separates into a lower density vapor and a brine, causing metals to partition between the two phases and helping to enrich the concentrations of these metals.

The presence of vapor bubbles changes a magma’s bulk physical and rheological properties. Bubbles make magma compressible. Compressible magma responds to injections or evacuations of magma (e.g. during eruption) by contracting or expanding, like a “magma sponge” (Voight et al. 2010), and this property has consequences for eruption magnitude and duration (Huppert and Woods 2002) and volcano monitoring. The exsolution of H2O from silicate melts removes a “network modifier”, resulting in the lengthening of chains of corner-sharing silicate tetrahedra in the melt, thereby increasing melt viscosity. The interplay between exsolution, viscosity change, and outgassing during magma ascent is, therefore, critical in determining eruption style.

The behavior of the exsolved vapor phase in long-lived, vertically extensive, mush-dominated magmatic systems beneath volcanoes remains poorly understood and is the
The reconstruction of volatile budgets in magsmas that feed volcanic eruptions has received much attention from the perspective of understanding climate impacts, mantle volatile systematics, magma storage, and volcanic processes. Various tools exist to determine volatile concentrations and speciation in silicate melts and their exsolation history, including melt inclusion geochemistry (Lowenstern 1995), phase equilibria experiments, and thermodynamic models. More challenging is the evaluation of how exsolved vapor is generated and distributed in magma reservoirs. Owing to buoyancy, vapor bubbles may segregate from their source magma. Long-lived reservoirs, which are subject to sporadic recharge and mingling of magmas, may develop complex reservoir architectures over time, with segregated regions of melts, mushes, and exsolved vapor (Christopher et al. 2015).

This article reviews the evidence for the formation, distribution, and form of exsolved vapor in magma reservoirs and the consequences for volcanic processes.

ABUNDANCE AND DISTRIBUTION OF EXSOLVED VAPOR IN MAGMA RESERVOIRS

Vapor saturation of silicate melts occurs when the sum of the partial pressures of the dissolved volatiles in a silicate melt is equal to the confining pressure, at which point a multicomponent vapor phase will be in equilibrium with the magma. The solubility of the volatiles CO₂ and H₂O is mainly controlled by pressure (Fig. 2A). The much lower solubility of CO₂ compared to H₂O causes vapor at higher pressures to be more CO₂ rich, and at lower pressures, more H₂O rich. Bubbles are the consequence of vapor-saturation of magmas, and their nucleation and growth in silicate melts accommodates the exsolving vapor phase. Bubble nucleation may be homogeneous (in melt) or heterogeneous (on crystals) and requires volatile supersaturation to overcome surface tension. The extent of supersaturation is usually small and easily achieved in decompressing or crystallizing a magma, except in the case of homogeneous nucleation of bubbles in crystal-free rhyolitic magma, where strong melt supersaturations may develop.

Other volatiles, such as sulfur and halogens, partition into the exsolved vapor phase to varying extents. Sulfur and chlorine partition behavior is well understood for a wide range of oxidation states and silicate melt compositions (Zajacz et al. 2012). In general, experiments indicate that sulfur will partition strongly into the vapor phase, particularly for more reducing conditions below the sulfate–sulfide transition [at an oxygen fugacity of –fayalite–magnetite–quartz (FMQ) + 1 log unit] (Fig. 2B, 2C), caused by the lower solubility of sulfur when it exists as sulfide (S²⁻) than when it occurs, under more oxidising conditions, as sulfate (S⁶⁺). Saturation of the silicate melt with sulfide melt or with anhydrite (at more oxidising conditions) limits the sulfur concentration in the coexisting vapor phase. Sulfur partitioning into the vapor phase is much more pronounced for more silica-rich compositions (Fig. 2C) (Zajacz et al. 2012). Chlorine partitions less strongly into a vapor phase at magma chamber conditions than sulfur. Chlorine-rich vapor is important for transporting metals to the sites of hydrothermal ore deposits. Experimental data are consistent with the idea that for long-lived magmatic systems in which evolved magmas are recharged by underplating mafic magmas, the vapor phase coexisting with the evolved magma will be more chlorine-rich, whilst the vapor phase supplied by the mafic magmas will be sulfur-rich, to a degree that depends on oxidation state and whether saturation with respect to a sulfur-bearing phase has been reached.

focus of much recent research. Vapor bubbles may be retained in crystal-rich magmas by capillary forces at low gas fractions, or the bubbles may be transported through quasi-brittle fractures at high vapor mass fractions and might modify the bulk rheological properties of crystal mushes, rendering them able to respond to magma recharge (by mingling and reorganization) on relatively fast timescales (Huber et al. 2011).
Observations Constraining Vapor Saturation of Silicate Melts in the Crust

Primitive mafic magmas in arc settings have an average H₂O content of ~4 wt% (Plank et al. 2013), whereas mid-ocean ridge basalts have 0.3–0.5 wt% H₂O and ocean island basalts associated with hotspots have 0.5–1.5 wt% H₂O (Dixon et al. 2002). Concentrations of CO₂ in different types of basaltic magma are more difficult to constrain using melt inclusions and submarine pillow basalts because low solubility causes deep degassing during ascent, but initial values are likely to be ~2,000 ppm CO₂ for primary mid-ocean ridge basalt magmas (Michael and Graham 2015), up to several wt% for more trace-element-enriched oceanic and hotspot magmas, and possibly up to 1 wt% in primary arc magmas. In arc systems, the deep magmatic vapor phase released by magma intrusion into the crust has been linked to flux melting and assimilation of lower crustal rocks and the generation of intermediate magmas, as well as to the linked processes of lower crustal dehydration (by extraction of water-rich partial melts) and the formation of granulite terrains.

There is strong evidence that magmas stored in the mid to upper crust prior to eruption are commonly vapor-saturated as a consequence of magma differentiation, prolonged storage, and recharge or underplating by CO₂-rich mafic magma (Wallace 2001). The geochemistry of melt inclusions hosted by quartz in the Bishop Tuff (Long Valley, California, USA) have been used to reconstruct the distribution and abundance of the exsolved vapor phase (Wallace et al. 1999) within the Long Valley Caldera magma body. Volatiles and trace element concentrations are consistent with vapor-saturated crystallization in a magma chamber zoned with respect to exsolved vapor, varying from ~1 wt% exsolved vapor near the bottom of the body (at ~250 MPa) to ~6 wt% near the top (at ~150 MPa) (Wallace et al. 1999).

Another approach to quantifying the abundance of exsolved vapor in magma reservoirs is to compare the mass flux of volcanic gases with the flux of magma erupted. At the Soufrière Hills Volcano (Montserrat), measurements of the gas composition and flux during the eruption (1995–2011) permitted estimates to be made of 2–8 wt% exsolved vapor in the magma prior to eruption (Edmonds et al. 2014), similar to estimates for the Bishop Tuff. This amount of exsolved vapor would impart significant compressibility to the magma, which would cause the magma to behave like a sponge, easily compressed or expanded (Voight et al. 2010), thus buffering magma reservoir volume changes. A muted ground deformation signal was in fact observed during eruption of the Soufrière Hills Volcano: the observed volume decrease (deflation) during periods of eruption was only around one tenth of the volume erupted (Voight et al. 2010) (Fig. 3). The presence of exsolved vapor also has the effect of greatly increasing eruption longevity owing to the greater compressibility, leading to eruption of a larger mass to relieve the same overpressure (Huppert and Woods 2002).

Large sulfur dioxide clouds accompanying explosive eruptions require a preeruptive vapor phase containing sulfur in the magma reservoir (Wallace 2001). Notably, the eruptions associated with the largest sulfur clouds per erupted unit volume of magma appear to be intermediate arc magmas (andesites and dacites) (Wallace 2001). An example of this is the eruption cloud shown in Figure 3A, from Okmok Volcano (Alaska, USA) in 2008. Sulfur partitioning into the vapor phase is maximized when the magma is relatively cool, silica- and H₂O-rich, and alkali-poor, conditions met by the vast majority of explosive arc eruptions. The opportunity to observe a contrast to this sulfur-rich case may have presented itself recently: the Plinian eruption of Chaitén Volcano (Chile) in 2008 was associated with a remarkably sulfur-poor cloud (Carn et al. 2009) that accompanied the eruption of crystal-poor rhyolite. This low abundance of gaseous sulfur may have been due to the lack of crystals, which may have played a role in restricting vapor storage prior to eruption. Understanding the spatial and temporal controls on the amount, composition, and mobility of exsolved vapor...
Dynamics of Vapor-Rich Magma in the Crust and Eruption Triggering

The role of bubbles in magma mixing, eruption triggering, and the dynamics of magma reservoirs has been studied using analog materials and modelling. Mafic magmas underplating more silicic, viscous magmas can produce a range of behaviors. If the mafic magma is vapor-saturated, bubbles may accumulate at the interface between the mafic and the felsic magmas, lowering the bulk density of the mafic magma, which then may induce overturn, mafic enclave formation, or bubble rise through the interface, depending on the viscosity contrast between the two magmas (Thomas and Tait 1997). Heating and remobilization of crystal-rich magma in the crust may take place by “gas sparging”, a process of mafic underplating, quenching, and outgassing of vapor that advects heat through the pore spaces of the crystal-rich magma, causing it to partially melt and perhaps trigger an eruption (10s of km² in size) (Bachmann and Bergantz 2006).

A great deal of attention has been devoted to the microphysics of multiphase crystal mushes. The presence of an exsolved vapor phase has implications for bulk mush rheological properties: only a few weight per cent of exsolved vapor is needed to substantially reduce the effective bulk viscosity of a crystal-rich magma (e.g. by four orders of magnitude for the addition of 9 vol% vapor in a 70% crystallinity magma) and to induce shear-thinning behavior, where the viscosity decreases with increasing strain rate (Pistone et al. 2013). Vapor bubbles could make mushes more mobile in response to magma recharge events, potentially allowing larger volumes of magma to be erupted, whereas the removal of such a vapor phase (through outgassing) could result in “viscous death” and the formation of plutonic bodies. Injection of vapor bubbles into crystal-rich suspensions in analogue materials shows that mushes may also behave in a brittle way with a yield strength, allowing the magmatic vapor phase to migrate relatively rapidly through them (Fig. 4) (Oppenheimer et al. 2015).

EXSOULATION OF VOLATILES DURING ERUPTION

Eruptions may be triggered when overpressures exceed the tensile strength of the country rocks, allowing magma to ascend along fractures towards the surface. These overpressures may be caused by magma recharge or by isobaric vesiculation during crystallization. As magma ascends, preexisting bubbles grow, or a new population of bubbles may nucleate, owing to the continued lowering of H₂O and CO₂ solubilities in silicate melts at low pressures (Fig. 2A). Bubble growth during magma decompression is limited by the rate of diffusion of volatiles into bubbles, by the rate of viscous deformation of melt as bubbles expand, and by the decompression rate.

The growth of vapor bubbles driven by H₂O exsolution has multiple immediate consequences: a rise in both the melt viscosity (Dingwell et al. 1996) and the solidus temperature, inducing a rapid burst of crystallization; and lowering physical and chemical consequences of gas-rich magmas, including:

1. **Viscosity Reduction**: Exsolved vapor reduces the effective viscosity of a crystal-rich magma (e.g., by four orders of magnitude for the addition of 9 vol% vapor in a 70% crystallinity magma).

2. **Shear-Thinning Behavior**: The viscosity decreases with increasing strain rate, allowing magma to become more mobile.

3. **Mush Compressibility**: The presence of vapor bubbles makes mushes more compressible and mobile in response to magma recharge.

4. **Outgassing**: Exsolved gas causes magma to be more compressible, which results in only muted deformation being observed at the surface prior to and after eruptions. Sulfur, present in the melt as dissolved ions S²⁻ and SO₄²⁻, partitions into the gas to form a mixture of SO₂ and H₂S, which is a function of temperature, pressure, melt composition, and oxygen fugacity (fO₂).

5. **Buffering Effect**: The buffer effect of the compressible gas phase on volume change of the magma reservoirs.

Influence of Volatile Exsolution and Outgassing on Volcanic Eruption Styles

For basaltic eruptions, which involve relatively low viscosity melt, eruption style is governed by ascent rate and the dynamics of two-phase flow (Houghton et al. 2016). At low ascent rates, bubbles rise through melts in the conduit, yielding an eruptive spectrum from quiescent degas-
The effects of outgassing and magma ascent rate on volcanic eruption style. Images show a representative range of volcanic eruption styles, with styles associated with rapid magma decompression at the top and slow magma decompression at the bottom. Viscosity increases from left to right. For central diagrams, yellow is liquid, light grey is gas, medium grey is solids (e.g., crystals).

For high viscosity magmas (crystal-rich andesites, dacites, and rhyolites), magma decompression rate and the rheological properties of the magma control the style of eruption. Here, the viscous retardation of bubble growth generates bubble overpressure. Magma fragmentation is driven by overpressure overcoming the tensile strength of the surrounding melt. For the case of Vulcanian eruptions, the high bulk viscosity of the magma precludes conduit refilling on the timescale of the eruption, rendering the eruption discrete in duration and limited in magnitude. For slightly lower bulk viscosity magmas (e.g. crystal-free rhyolites) and large magma chamber overpressures, Plinian eruptions, with magma column heights of 10s of km that often penetrate the stratosphere, are driven by continuous magma fragmentation and magma flow, refilling the conduit on timescales of eruption (Fig. 5). The primary mode of magma fragmentation here might be brittle failure caused by rapid strain rates experienced by the rapidly vesiculating and expanding magma (Papale 1999).

At low magma ascent rates, when relaxation of viscous stresses in the silicate melt can keep pace with bubble growth, permeable bubble networks develop as the melt vesiculates, allowing the magma to effectively outgas volatiles both upward into the atmosphere and laterally into shear-fractured conduit margins and country rocks, thus preventing magma fragmentation and explosive eruptions. Effective magma permeabilities for outgassing may develop at porosities of around 30%, but perhaps at much lower porosities for sheared magmas (Rust and Cashman 2004). Under conditions of high magma porosity and efficient gas loss, magmas erupt effusively in the form of steep-sided lava flows or domes.
FUTURE PERSPECTIVES

Werner Gilgenbach (1937–1997, German-born New Zealand-based chemist and volcanologist) proposed that andesitic volcanoes are "ventholes" that allow excess subducted volatiles to be recycled to the surface, where the term "venthole" implies the rise of a free volatile phase to the surface from a zone of arc magma generation. While this may be an extreme view, the observations suggest that, in most cases, magma bodies in the crust not only are vapor-saturated but also need to be charged with a magmatic vapor phase before they can erupt. Indeed, vapor saturation in crustal magma bodies may be an inevitable consequence of the high CO₂ contents of most mantle-derived mafic magmas, causing continuous fluxing of overlying silicic magma by CO₂-rich vapor to occur. Within this framework, long periods of relatively small-scale eruptions and unrest at volcanoes such as Montserrat or Popocatépetl (Mexico) may be viewed as essentially intrusive events in which the mass of erupted magma, while potentially devastating locally, is small in comparison to the likely masses of both stored, differentiated magma and mafic, recently intruded magma at depth. Explosive eruptions of much larger magma bodies, however, contain within them the exsolved gases released from underlying mush zones and recharging mafic magmas (Parmigiani et al. 2016): these might reflect thousands or even tens of thousands of years of vapor-phase accumulation (Christopher et al. 2015).

The next key step in understanding volcanic systems is to develop methods for tracking the movement of the magmatic vapor phase independently of magma movement. Four potential methods are here proposed: (1) tracking of the concentrations and fluxes of volatile components of different solubilities, using the composition and density of melt inclusions and fluid inclusions to reconstruct equilibration depths, and using volcanic emissions to estimate total depth-averaged volatile fluxes; (2) phase equilibrium experiments and textural studies that can reveal processes such as gas fluxing; (3) seismic, ground deformation, and other geophysical methods to track mass and density changes that might be linked to outgassing; and (4) use of volatile isotopes such as ²¹⁰Po that can reveal information about the volumes and timescales of degassing magma bodies.

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REFERENCES


**Dynamic Magma Systems: Implications for Forecasting Volcanic Activity**

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Magma systems that supply volcanoes can extend throughout the crust and consist of mush (melt within a crystalline framework) together with ephemeral magma accumulations. Within a crystal-rich mush, slow processes of melt segregation and heat loss alternate with fast processes of destabilisation and magma transport. Magma chambers form by two mechanisms: incremental magma intrusion into sub-solidus rocks or the segregation and rapid merging of melt-rich layers within mush regions. Three volcanic states reflect alternations of slow and fast processes: dormancy, unrest and eruption. Monitoring needs to detect processes of melt and fluid movements in the lower and middle crust during destabilisation to improve forecasting.

**INTRODUCTION**

A major societal application of volcanology is giving an early warning of volcanic activity to reduce risks to communities. Forecasting is enabled by monitoring geophysical signals and volcanic emissions, and by observing volcanic phenomena. Forecasts are informed by historical records, geological studies and empirical knowledge about past patterns of activity. Underpinning these endeavours are ideas about the igneous processes that control volcanism, which are often viewed through the concept of an upper crustal magma chamber. Ideas are changing, however, about how the magmatic systems beneath volcanoes work. Here, we summarise emerging concepts and explore what they mean for monitoring and forecasting.

**OBSERVATIONS OF MAGMA SYSTEMS BENEATH ACTIVE VOLCANOES**

The concept of an upper crustal (typically 3–10 km) magma chamber explains many phenomena associated with volcanic unrest and eruptions, such as shallow earthquakes, ground deformation and gas emissions. These three phenomena can be attributed to the internal processes within a magma chamber, to the movement of magma and magmatic fluids (supercritical exsolved volatiles) from the chamber to the surface, and to the transfer of heat and magmatic fluids to hydrothermal systems (Fig. 1). Many petrological and geochemical characteristics of volcanic products can also be explained by processes within a magma chamber that as itself at least transiently connected to a magma supply at depth. For example, replenishment by new magmas is widely postulated to trigger eruptions and explain various petrological characteristics of volcanic materials.

Increasingly, however, more than one magma chamber is invoked to explain geochemical and petrological observations of magmatic systems. The replenishment model implies a deeper magma source, while geochemical, petrological, and geophysical observations suggest that eruptions can tap multiple magma bodies that might be either vertically or laterally distributed. As examples, the eruption of the Soufrière Hills volcano (Montserrat) tapped four different magma bodies extending from 5 km to at least 15 km depth (Christopher et al. 2014); eruptions of Mount St Helens (Washington, USA) involved a magmatic system extending from about 5 km to at least 30 km depth (Blundy et al. 2008); eruptions from the Taupo Volcanic Zone (New Zealand), tapped at least two different magma bodies from vents 25–30 km apart (Cooper et al. 2012); and eruptions of Eyjafjallajökull (Iceland), tapped melt bodies throughout the crust (Tarasewicz et al. 2012). Geobarometry on phenocrysts indicates magma depths of origin extending into the middle and lower crust (e.g. Putirka 2017 this issue). These findings lead to the concept of a transcrustal magmatic system in which the shallow magma chamber may be only a volumetrically minor part of the entire volcanic plumbing and volcanic behaviour is governed by the whole system.

“Magma” is here defined specifically as “eruptible melt with or without suspended crystals and volatiles”. Magmatic mush has enough crystals to form a touching framework, and is synonymous with a partially molten (super-solidus) rock. The transition from magma to mush occurs over a narrow crystal content (typically between 55% and 65%), with many orders of magnitude increase in viscosity (Fig. 2). Magma chambers are regions of magma embedded within mush and, commonly, fully solidified plutons. Magma chambers can supply volcanic eruptions. A transcrustal magmatic system refers to the entire network of magma and mush and sub-solidus plutons embedded in older crustal rocks: it is the integrated result of magmatism in a given location. Within an active magmatic system, there can be multiple regions of mush and magma at different levels. The term “magma reservoir” was originally synonymous with the term “magma chamber”, but is increasingly used to describe the entire transcrustal magmatic system. Bachmann and Huber (2016) review these notions in detail for silicic systems and provide their historical roots.

Seismic tomography supports the concept that magmatic systems extend throughout the crust below many volcanoes (e.g. Huang et al. 2015). Importantly, these studies fail to find large coherent regions of magma, and seismic velocity anomalies are commonly interpreted as near-solidus mush
(<10% melt). This suggests that either large magma bodies are not present or are too small to be resolved seismically, except where discrete melt-rich lenses are recognised from strong seismic reflections (e.g. Sinton and Detrick 1992).

Mush-dominated sub-volcanic systems are also indicated by geochemical and geochronological analysis of igneous rocks and their constituent minerals, which add key information on timescales. A first-order observation relates to the complex growth histories and diverse crystal origins of minerals. Importantly, widespread disequilibrium textures and diverse crystal compositions record mixing of different magmas, disruption of mush, entrainment of refractory plutonic materials, and xenocrysts incorporated from surrounding country rock (Davidson et al. 2007). Trace element zoning patterns in crystals commonly indicate short magma residence times (years to centuries) in upper crustal chambers (Morgan and Costa 2010). In contrast, U-series studies of zircon indicate very long residence times (>10^3–10^6 years) for fractionation and storage of melts (Hawkesworth et al. 2004). Reconciling these timescales requires long residence of fractionated melts (slow processes) and rapid crystallization when magmas are transported and assembled in the upper crust (fast processes). From this perspective, the long times represent the timescales of chemical evolution, while the short times record rapid physical rearrangement of magmatic systems that can lead to volcanic eruptions.

**TRANSCRUSTAL MAGMA PLUMBING: DYNAMICAL CONSIDERATIONS**

We now discuss the dynamic processes that form transcrustal magma systems. We define the base of the crust as the petrological Mohorovičić discontinuity (Moho), or true boundary between the crust and mantle. This is distinct from the seismically defined Moho, which may lie above crust-derived ultramafic cumulate rocks. The crust acts as a physical barrier to magma ascent, and primitive basaltic magmas rarely erupt at the Earth’s surface. Instead, most magmas stall and cool, de-gas, crystallize and evolve to lower density and chemically evolved melts. Heat transfer with, and volatile (notably water) fluxes into, surrounding crust can cause partial melting and produce magma from older rocks or remobilise earlier intrusions (Bachmann and Huber 2016). Within transcrustal magma systems, we distinguish three types of igneous processes: first, vertical (upward) transport of magma; second, stalling in the crust (intrusion); third, internal (super-solidus) magma and mush processes.

**Magma Transport**

Vertical magma transport can occur by fast or slow mechanisms. Flow of magma and magmatic fluids along fractures enables fast transport (Rubin 1995). The transporting fracture system is preserved in solidified rocks as dykes (magma) or veins (fluids) in brittle cold crust and is manifested in active volcanic systems as earthquakes, tremor and deformation. In more ductile environments, especially mush systems, magma and fluids likely ascend through ephemeral fractures that may not be preserved in the geological record and need not be associated with measurable geophysical signals. Propagation speeds for transient fractures are commonly ~10^2–10^4 m/s, so timescales for flow and emplacement are relatively short (minutes to years).

Slower transport mechanisms relate to ductile processes on different scales. At small scales, buoyant melt or fluid can segregate from partially molten rock to form melt-rich layers by compaction (Solano et al. 2012) or shear
strain (Holtzman et al. 2003). Compaction-driven segregation is both rapid (10^3–10^5 years) and efficient for low viscosity melts (basalt to andesite) and their associated fluids. Segregation creates evolved melt lenses and refractory mafic and ultramafic cumulate rocks. Segregated fluids can also separate easily from their parent melts. For high viscosity melts (e.g. rhyolitic magma), segregation timescales are much longer (10^4 to >10^5 years) and segregation is correspondingly less efficient.

**Stalling Magma Movement: Intrusion Formation**

 Interruption of magma ascent is necessary to form igneous intrusions and magma chambers. Horizontal intrusions (sills) can form because of density contrasts, rigidity contrasts, or changes in stress state (Menand 2008). The density control hypothesis postulates that magmatic dykes cannot penetrate far through rocks that have lower density than the penetrating melt and that stably stratified density interfaces promote intrusion (Taisne et al. 2011). In a density-stratified crust, this hypothesis favours a depth-dependence of magma composition, with denser basaltic magmas intruding deeper than intermediate and silicic magmas (Putirka 2017 this issue). Major density interfaces, such as the geophysical Moho and Conrad discontinuities, could be preferred locations for intrusion. Sill formation is also favoured at interfaces where high-rigidity rocks overlie low-rigidity rocks. In this way, intrusions can localise around major geological discontinuities such as the brittle–ductile transitions in the mid crust. Finally, a vertical minimum stress (σ2), as is common in compressional tectonic settings, favours sill formation.

Predicting conditions that promote substantial intrusions requires consideration of both the thermal evolution and the “room problem”. Thermal models of growth by incremental intrusion (Annen et al. 2015) find that magma chambers can form when a magma flux threshold is exceeded and when there are high surrounding temperatures. The condition of high ambient temperature suggests that magma bodies should form most readily in the lower crust, leading to models of lower crustal mixing and assimilation (Hildreth and Moorbath 1988) and of deep crustal hot zones where regions of partial melt can be sustained for long times and where extensive magma differentiation may occur (Annen et al. 2006). In the colder upper crust, formation of magma chambers and associated crystal mush requires magma fluxes that greatly exceed estimated time-averaged fluxes, implying that magma chambers are transient and episodic features. This analysis further suggests that the proportion of plutonic rock relative to surrounding crust by viscous flow. Second, components of intruding magma can become denser by crystalization and physical segregation of basal mafic-rich cumulates, which cause the intrusion floor to sag (Roman and Jaupart 2016). In this mechanism, downward migration of dense cumulates balances upward migration of more buoyant magma (Paterson et al. 2011). With typical viscosities of 10^17–10^18 Pa s and reasonable magma flux rates, intrinsically slow ductile deformation of hot, but sub-solidus, rocks is expected for magma transport in the middle and lower crust.

**Magma and Mush Processes**

Within a vertically extensive magmatic system, the room problem is minimised and a new mechanism of forming magma chambers can be invoked. Melt-bearing mush accumulations are highly susceptible to segregation of melt-rich layers by compaction and shear. This creates a magma–mush system that is inherently unstable. We suggest that within such a system, melt layers will episodically move upwards, amalgamate and mix together; at the same time, the surrounding mush will subside (Fig. 3). Importantly, there is no volume change associated with the vertical re-organisation of incompressible phases (melts and crystals). Two timescales underpin magma accumulation by internal mush processes. First, long timescales are associated with melt segregation and are typically 10^3–10^6 years (Solano et al. 2012). Second, short timescales are associated with instability, re-organisation and amalgamation and are governed by the relatively low viscosity of mush (10^13–10^14 Pa s for 40% melt) (Costa et al. 2009). To address timescales of instability for growing buoyant melt-rich layers within a melt-rich mush we can apply Equation 26 in de Bremond d’Ars et al. (1998). An assumed wavelength of 5 km yields approximate timescales of destabilisation of months to several years. These are the timescales of volcanic eruptions.

**DYNAMIC STATES OF MAGMATIC SYSTEMS: DORMANCY, UNREST, ERUPTION**

Above, we identified two different ways of forming magma chambers: (1) incremental intrusion into sub-solidus rocks, distinguishing between brittle and ductile environments and (2) involved the segregation of melts (and fluids) from mush and the amalgamation of these melts during periods of instability (Fig. 3). Although individual volcanic systems can be dominated by either or both mechanisms, low rates of magma supply, as would be expected during the early stages of volcanism, will favour intrusive processes, while in mature long-lived systems mush processes can dominate. In this section, we focus on mush system dynamics in mature systems.

Herein, we identify three dynamical volcanic regimes that are, or have been, supplied by mature transcrustal magmatic systems: the dormant state, the state of unrest, and the eruptive state (Fig. 3).

- **The dormant state** is characterised by slow melt (and fluid) segregation from the mush and growth of multiple melt-rich layers. This regime is driven by an influx of mantle magmas, and likely involves development of melt or fluid layers. The volcano itself will appear dormant, with no surface activity beyond fumaroles and hydrothermal activity.

- **In a state of unrest** there is significant instability over short timescales; melt and/or fluid layers amalgamate and ascend as the residual mush moves downward. Increases in pressure that accompany the decompression of fluids and fluid-saturated melts should generate
detectable changes in the near surface, such as surface deformation, enhanced seismicity and magmatic fluid release. However, in the state of unrest, no eruption takes place and the unrest dies down as the system stabilises.

- In the eruptive state the system is so perturbed that magma and fluids break through to the surface. The two regimes of unrest and eruption involve fast processes that enable shallow bodies of eruptible magma to accumulate and sometimes erupt. Qualitatively, episodic volcanism can be explained as the alternation of long repose intervals (centuries, millennia or longer) and short periods of unrest and eruptions (days to decades), reflecting the coupling of slow and fast processes.

An important question for forecasting is whether periods of unrest will develop into eruptions. We envisage no fundamental difference between the processes that cause unrest leading to eruption and processes that cause unrest but no eruption. In fact, unrest is widely acknowledged as much more frequent than eruptions at many volcanoes (Moran et al. 2011). Multiple episodes of unrest without eruption may record progressive development of a shallow magma chamber of increasing volume on a pathway to eventual eruption. In this case, eruptions are triggered by reaching a critical overpressure sufficient to form magma pathways to the surface and are treated as either time- or volume predictable. That these simple models do not always apply provides evidence of other important factors, including processes acting throughout the transcrustal magmatic systems.

**MONITORING VOLCANOES**

A major challenge in volcano monitoring is how to use signals collected from instruments at the Earth’s surface to infer movement of magma and fluids at depth. Historically, seismic signals have provided the first warnings of volcanic unrest, signals that have improved with new instruments and denser networks. Volcano-related earthquakes record rock breakage and reflect changes in stress caused by pressure changes within magmatic systems, by movement of fluids within hydrothermal systems, by discharges of fluid from magmatic systems, and by intrusion and magma flow along conduits to the surface. Changes within the magmatic system may activate far-field crustal faults and fractures; conversely, tectonic stresses may trigger changes in the magmatic system.

Deformation can be measured by geodetic measurements on the ground (global positioning system, electronic distance metres, tiltmeters), satellite-based interferometric synthetic aperture radar (InSAR) and strain meters in bore-holes. Patterns of deformation are typically interpreted by applying Mogi models for elastic deformation from changing source pressure. Although usually attributed to magma intrusion into a shallow chamber, pressure changes inferred from deformation can also reflect volatile processes (exsolution or degassing) or changes in shallow hydrothermal systems. As shown below, in unstable and vertically extensive magmatic systems upward magma transport in itself does not cause large volume changes because the upward flux of magma is compensated by the downward transport of mush. Under these circumstances, volatile exsolution and decompression may be the primary cause of volume changes, pressurisation and deformation (e.g. Chang et al. 2010; Christopher et al. 2015).

Gas emissions can be directly sampled at fumaroles, and indirectly sampled by remote sensing from satellites and ground instruments. Routine gas monitoring focuses on \( \text{SO}_2 \) because its low atmospheric abundance allows routine and accurate monitoring. Instruments to investigate other gases, such as halogens, \( \text{CO}_2 \) and water, are typically deployed in campaign research projects and are not currently part of real-time monitoring systems. Increases in \( \text{SO}_2 \) can provide robust evidence of magmatic gas release in some volcanoes (e.g. Christopher et al. 2015). Implications of gas data for eruption potential are, however, commonly ambiguous. A decline in \( \text{SO}_2 \) might imply a decrease in eruption potential or it might mean that gas has become trapped and the volcano is preparing to explode.

**IMPLICATIONS FOR MONITORING AND FORECASTING DIFFERENT VOLCANIC STATES**

**Dormant State**

A dormant volcano is one that shows no detectable signs that can be construed to indicate an impending eruption: there is either no geophysical activity whatsoever or there is a low-level state of background activity (e.g. earthquakes, minor deformation and active fumaroles). Background activity includes long-established hydrothermal systems on some dormant volcanoes can cause pronounced seismic activity, as well as deformation and discharge of fluids, experience may suggest that they do not indicate a pathway to magmatic eruptions.

While there may be no upper crustal unrest in a dormant volcano, the deeper magmatic system can be active, as manifested by slow processes of melt and volatile segregation in mush and by crystallization and gas exsolution in slowly cooling magma. During compaction, melts slowly move upwards, decompress, and, if the melt is volatile-saturated, exsolve fluids. For this reason, volatile compositions in transcrustal magmatic systems will continually exsolve and percolate towards the surface (Fig. 3 top). Volatile compositions are strongly dependent such that low-solubility volatiles (notably \( \text{CO}_2 \)) exsolve at relatively deep level whereas high-solubility volatiles (notably water and sulphur species) exsolve at relatively shallow levels. The dramatic density and viscosity contrast between melts and fluids causes them to decouple (Christopher et al. 2015). Thus, large volumes of fluids can be generated, separated from their parent magmas and then accumulate as discrete layers within magmatic systems. This fluid may leak directly to the surface as fumaroles and regions of diffuse degassing or may add magmatic fluid components to near-surface hydrothermal systems. However, magmatic fluids can also be stored for long periods of time within the magmatic system, to be released much later, perhaps in association with eruptions.

The above “slow” processes occur in hot ductile environments at low strain rates. They may be largely aseismic, although transient movements of magmas and fluids may be monitored by tracking long-period earthquakes in the lower and middle crust (Nichols et al. 2011). Even in dormant volcanoes, slow exsolution and upward migration of compressible volatiles can cause positive volume changes and deformation, as well as feeding fumaroles and diffuse surface gas emissions and contaminating hydrothermal systems. An example is the 1978–2004 period of unrest at the Long Valley caldera in California (USA) (Hill 2006), where more than three decades of non-eruptive unrest has been attributed in part to fluid fluxes from a transcrustal magmatic system.

**State of Volcanic Unrest**

Unrest is common at volcanoes around the world. Although signs of unrest may precede volcanic eruptions, unrest in volcanic regions neither implies nor requires eruption (Moran et al. 2011). Unrest that is not immediately related to eruption can be triggered by changes in hydrothermal systems that are unrelated to magmatic disturbances such as unrest triggered by tectonic activity. As outlined above, non-eruptive unrest may also record input of fluids from fast processes deep within magmatic systems that
accompany destabilisation, upward movement of magma and fluids, and general rearrangement of magma, fluid, and mush (Fig. 3 middle). In this scenario, the deep processes may be difficult or impossible to detect if related to ductile processes or if resulting from earthquakes that are either too small to detect or that are dissipated by the mush itself. Exceptions include deep (mid-crustal) long-period earthquakes, which are commonly interpreted as movement of either magma or fluid (Nicholls et al. 2011). In the shallow crust, pressure changes associated with rapid decompression of fluids can be large enough to deform the crust elastically. The result can be earthquakes, surface deformation and enhanced fumarole emissions.

Exsolved volatiles can become strongly decoupled from their parent magmas. Implicit in this concept is the notion that large volumes of “old” magmatic volatiles could separate into volumetrically significant accumulations within dormant systems, only to be released during periods of destabilisation (e.g. Hill 2006; Christopher et al. 2015). Thus, volcanic unrest could arise by destabilisation of magma layers, by volatile accumulations or, indeed, both together. Purely volatile-driven unrest should be considered as, for example, sources of pressure for ground deformation.

**Eruptive State**

We suggest that many eruptions are the end result of major and rapid destabilisation and reorganisation of transcrustal magmatic systems. The transcrustal model stands in contrast to models of incremental magma chamber growth. Nevertheless, both end-member models clearly represent points along a spectrum of possible behaviours. One important consequence of the rapid destabilisation model is that multiple layers of melts, magmas and volatiles could combine to form larger eruptible magma bodies (Fig. 3 bottom). If pressure changes caused by destabilisation are large enough, then the magmas and fluids break to the surface and erupt. Instability can also continue during an eruption if eruption-related pressure fluctuations control the evolution of activity. The question then becomes one of recognizing the signs of magmatic unrest that indicate large-scale destabilisation. Here, we frame this problem by considering, in particular, timescales of likely processes and the critical role of volatiles.

Short timescales are anticipated for internal re-organisation of transcrustal magmatic systems in a ductile dynamic regime. An approximate timescale for the brittle-ductile transition is the ratio of viscosity (μ) to the elastic modulus (E). Mush systems have approximate viscosities between $10^{13}$ Pa s (high melt fractions) and $10^{17}$ Pa s (low melt fractions), so for $E \sim 10^{10}$ Pa, the timescales above which ductile behaviour can be expected are tens of minutes to a few months. Similar short timescales can be anticipated for volatile exsolution in response to upward migration. These processes have potentially major implications on how to interpret ground deformation signals.

Commonly, surface deformation signals are attributed to magma intrusion (replenishment) into shallow magma chambers, although usually no explanation is given for that replenishment. The volume changes observed from deformation are then used to estimate volumes of new (intruded) magma. However, the resupply of a shallow magma chamber by destabilisation of a transcrustal magma system (Fig. 3) provides an alternative interpretation: that ground inflation is caused primarily by volatile exsolution and expansion (or, conversely, that ground deflation may record degassing), and that the rearrangement of incompressible melt and crystal components plays little to no role. The implications of volatile-generated, rather than magma-generated, pressures as an explanation for measured surface deformation are hugely different from those of traditional (recharge) models. Consider the volumes of magma implied. If shallow magma chambers are supplied by a destabilisation and amalgamation event, but volume change is created by exsolution of only a small mass fraction of volatiles, then the implied volume of magma addition may be one to two orders of magnitude larger than if it were assumed to reflect magma alone. From this, we suggest that replenishment models that do not fully consider the role of volatiles may both over- and under-estimate the amount of magma responsible for the observed deformation. Over-estimates can result if the exsolved volatiles segregate from the magmatic system, or if they recharge the shallow magma chamber and eventually leak from the system. Alternatively, eruptible magma volumes may be greatly under-estimated if exsolved (and compressible) volatiles are retained within the recharge magma.

Although we have emphasised the role of internal processes in transcrustal magmatic systems, volcanic activity can also be modulated by tectonic conditions (e.g. Wilson and Rowland 2016). A given destabilisation scenario will only lead to eruption if the stress regime is suitable for developing dyke systems to the surface, and this in turn depends both on the strain rate and the stress state of the crust. For this reason, development of truly comprehensive...
volcano forecasting models also requires the incorporation of processes that account for the interplay between internal igneous processes, strain rates and stress systems that can be developed by both tectonic and magmatic processes. As an example of how these new concepts impact on forecasting in real cases, we briefly discuss the 1995 to 2010 eruption of the Soufrière Hills Volcano (Montserrat) drawing principially from Christopher et al. (2015). Since the last phase of dome extrusion in 2010, the volcano has continued to inflate and emit an average of about 370 tons of SO$_2$ per day. Key questions on Montserrat for management and planning are whether the dome extrusion and associated hazardous activity will restart or if, in fact, the eruption has ceased. While the new concepts cannot provide a definitive answer to these questions, they do inform long-term probabilistic assessments. For example, if the inflation and continued high SO$_2$ emissions are interpreted to represent magma rechange, then the observations are more ominous than if the activity reflects the release of volatiles from a previously insulated magma system within an unstable transcrustal magmatic system. Such admittedly qualitative notions can be fed into expert elicitation methods for prognosis and advice. The point is that changing concepts of how volcanoes work feed directly into interpretation and forecasting. And, developing and testing new conceptual models are critical for improving volcanic hazard assessment.

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Volcanoes: Characteristics, Tipping Points, and those Pesky Unknown Unknowns

Colin J.N. Wilson

INTRODUCTION

“Reports that say that something hasn’t happened are always interesting to me, because as we know, there are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns – the ones we don’t know we don’t know.” (Rumsfeld 2002)

This quotation from the former US Secretary of Defense Donald Rumsfeld, echoing numerous earlier sources, has served for many as a polarising statement attached to a sequence of controversial political decisions (e.g. Morris 2014). I use this quotation here as a basis for considering selected aspects of volcano behaviour and our present understanding of progress towards forecasting volcanic eruptions. In the last few decades, enormous advances have been made in volcanic monitoring and forecasting techniques and their application for many of the world’s volcanoes. This overview, however, considers the case of volcanoes that erupt infrequently (or have been inactive in historic times) and/or that discharge evolved magmas in explosive eruptions, accompanied in the largest examples by caldera collapse. Here, I consider some aspects of what we know about such volcanoes, what we do not know but still are aware of (“known unknowns”), and whether there are likely to be aspects of these volcanoes and their behaviour about which we are unaware (the “unknown unknowns”).

Modern studies (over the last ~60 years) have discovered and quantified many aspects of volcanoes and volcano systems within the Earth’s crust. By system I include the subsurface reservoir (potentially occupying tens of thousands of km³) in which magma (molten rock) is generated and stored, the melt-dominant bodies that represent the eruptible magma, the plumbing systems that feed magma to the surface, and the physical processes that operate prior to and during eruptions to control the eruption style. There are two main threads involved in volcano studies: first, a dominantly geological thread concerned with the products of past events; and second, a dominantly geophysical thread that, fundamentally, can only be applied to live systems. Of course, geochemical studies are also essential and are common to both approaches. But my aim here is to compare studies on what has happened, as witnessed by eye or evidenced in the rock record, versus studies concerned with the real-time behaviour of volcanic systems.

With the geological thread, the processes that generate and accumulate magma at depth can be followed by studying the mineralogy and chemistry of eruption products and/or by performing laboratory experiments on natural or simplified rock compositions and/or by running numerical or analogue models. By ‘past events’ I mean things that have happened such that there is something to measure or analyse in the form of volcanic products (solids, liquids or gases), although these may have only just been erupted (e.g. Pankhurst et al. 2014). A particularly fruitful area of research is to take eruptions for which there are eyewitness controls and then study them geologically so as to compare eruption products with the observational constraints (e.g. Newhall and Punongbayan 1996; Hildreth and Fierstein 2012). The geophysical thread uses geophysical and geochemical techniques in real-time to follow the movement of magma during volcano unrest, the rise of magma to the surface prior to and during eruptions, and the release of mobile components in advance of the magma itself (e.g. Pallister and McNutt 2015).

A primary aim of both of the above geological and geophysical threads is to understand and forecast the behaviour of volcanoes in a way that is useful to society: to be able to forecast future activity in ways that reduce risk and minimise impacts on people and infrastructure. In frequently (historically) active volcanoes, especially those erupting fluid mafic magmas, such an aim is, in principle,
achievable (e.g. Aki 2004). This is because there is knowledge from multiple observed events and because of the scope and range of sizes of the volcanic activity, i.e. such activity has not been large or violent enough to pose a serious hazard, or it can be successfully mitigated against because it falls within clear boundaries of behaviour. However, with volcanoes that erupt more viscous, intermediate to felsic magmas, historic eruptions and those represented in the geological record sometimes display features that are seemingly not forecastable or that are unique to single events (see next section). Yet, these unanticipated features have a strong influence on eruption styles (and associated hazards and risks) and the timescales over which such hazards develop and are prolonged. Observations suggest that we are still not able to accurately forecast or predict the timing and styles of future eruptions at many of the world's volcanoes, particularly those capable of large-scale explosive eruptions.

VOLCANO CHARACTERISTICS

Volcanoes worldwide have distinctive shapes (e.g. shield, cone, caldera), settings (e.g. arc or intraplate; subaerial or submarine) and eruption products and sequences. As such, many volcanoes are instantly recognisable in an image. The past histories of many volcanoes can allow patterns of past behaviour to be deduced. However, as we are constantly reminded is the case with investment funds, past performance is not necessarily a guide to future performance: the past geological history of a volcano is not an infallible guide to what will happen in the next eruption. Consequently, the world’s volcano observatories typically utilize probabilistic forecasts that incorporate not only the particular volcano’s history but also global databases, conceptual and physical models, and geophysical monitoring to forecast eruptions.

However, to illustrate the issues that I am raising here, consider the natures of three recent eruptions from three New Zealand volcanoes (Fig. 1).

- On 10 June 1886, the latest eruption occurred from Tarawera (a dome complex that is part of the rhyolitic Okataina caldera volcano). This eruption was basaltic, short-lived (4.5 hours), and deadly (Thomas 1888). Although minor volumes of basalt had previously been erupted at the onset of other rhyolite eruptions at Okataina, the 1886 eruption represents the largest basaltic event known in the ~2 Ma history of the Taupo Volcanic Zone. There has, to date, been no associated rhyolite eruption, however.

- Rangitoto is the youngest and largest (0.7 km³) of 53 eruptive centres in the basaltic Auckland Volcanic Field. This centre alone represents 40%–50% of the magma erupted in the field over its >190 ky lifespan, yet was erupted in two short pulses only ~550–500 years ago (Needham et al. 2011). Both the volume of this centre and its two periods of activity are unprecedented in the geological history of the field.

- The 232 CE eruption of Taupo was the largest event at that volcano for over 23 ky, and culminated in emplacement of a ~30 km³ ignimbrite (Wilson 1985). The parental pyroclastic flow to this ignimbrite was disgorged as a blast-like event in only ~400 seconds, and travelled radially to 80 ± 10 km from vent at speeds exceeding 200 m/s, devastating ~20,000 km² of uninhabited landscape, including pristine forest that had remained undisturbed by volcanism for thousands of years.

**Figure 1** Three illustrative examples from the recent New Zealand volcanological record of unique events. (A) View looking northeast along the line of craters that formed in the 10 June 1886 eruption of Tarawera. The red-brown thick scoria beds visible in the crater walls represent 4.5 hours of vigorously explosive activity. (B) Distant view of Rangitoto, the youngest of 53 basaltic centres in the Auckland Volcanic Field. (C) Pale grey Taupo ignimbrite, formed at the climax of the 232 CE eruption of Taupo volcano, with numerous incorporated black, charred logs and branches. This location is about 50 km from source, the flow having climbed about 700 m to reach this site.
None of these events could realistically have been forecast or foreseen from the preceding historical or geological records for the volcanoes concerned. How can one forecast the unique?

In addition, there are three points about volcano behaviour that arise from consideration of historic events. First, the largest eruption, globally, in the past 2,000 years is of the Indonesian volcano of Tambora (1815). Yet, despite its size and impact on contemporary society, the Tambora eruption is accepted to be roughly two orders of magnitude smaller than the largest Quaternary eruption, that of the Indonesian volcano of Toba, which occurred at ~74 ka (Petraglia et al. 2012). Historic activity at volcanoes worldwide thus covers only a fraction of the potential scale of volcanic activity under ‘normal’ circumstances (i.e. excluding flood basalt events). Second, perceptions of what a volcano will produce in its next eruption are often skewed by the rarest, largest events. The classic case of this is the Yellowstone volcano (USA), around which the term ‘supervolcano’ is so intertwined, where its activity is generally linked to its largest eruptions, not the most frequent eruptive size or style, nor the most probable next event. Indeed, for some people, a major supereruption at Yellowstone is seemingly imminent (see Klemetti 2016). Third, there is for many volcanoes an inescapable obstacle to the forecasting of future behaviour. If you take a long enough time period in the eruptive history of a volcano to get a sound statistical approach to forecasting (e.g. through magnitude–frequency relationships), the analysis is quite likely to be misleading (e.g. Aki 2004). This is because during that time period the parental magma system feeding and controlling the eruptive behaviour of the volcano may have changed in its characteristics, or become wholly changed into a new system, or become moribund (e.g. Hildreth 2004). Although viable from a purely statistical perspective, a probabilistic approach to the timing and size of the next eruption at a volcano cannot utilise data from a defunct magma system. Furthermore, there is no possibility of an eruption from a volcano with no live magma system, regardless of its past behaviour. Ngaruhoe volcano in New Zealand (Hobden et al. 2002) may be an example of the latter situation: frequent eruptive activity (recorded from 1840 onwards) ceased in 1975, and any future activity will be from a system that may be wholly new in its characteristics.

Even if the parental magma system is assumed to have stayed active and relatively uniform in its characteristics, a given sequence of eruptions does not necessarily provide a clear means of forecasting the timing or size of the next event. At Taupo volcano (New Zealand), for example, eruption sizes and their repose periods considered separately are not normally distributed, and plots of the eruption sizes versus repose periods show no clear relationships (Wilson 1993) (Fig. 2). Forecasts of future eruption size at that volcano have to resort to a probabilistic approach. This approach, however, then has to consider a recent (post-25.4 ka) geological history which encompasses eruptions that have varied by three orders of magnitude in size and includes repose periods lasting anything from a decade to several thousand years (Fig. 2).

ERUPTION CHARACTERISTICS

Within single eruptions, wide differences in their nature and timings present great challenges. Some historic eruptions started vigorously [e.g. Rabaul volcano (Papua New Guinea) 1994: Global Volcanism Program 1994] and prehistoric examples like the Bishop Tuff (~767 ka, California, USA) show an abrupt onset and no geological evidence for significant time breaks (Wilson and Hildreth 1997). In contrast, other eruptions have started and stopped multiple times: Montserrat is a notable recent example (Global Volcanism Program 2013), and the ~25.4 ka Oruanui eruption (New Zealand) a prehistoric example (Allan et al. 2012). There is a huge gap in our knowledge of the deposits of prehistoric eruptions that would allow us to infer the presence of short time breaks (hours to decades). These time breaks are not always geologically significant or obvious and present challenges to quantify with better than order-of-magnitude outline. Although such time breaks are of human interest, they may be unpredictable for volcanologists charged with forecasting or predicting the course of an imminent or ongoing eruption. Breaks between activity of hours to years are difficult to document in the geological record but may cover time periods during which eruption styles or conditions (e.g. ash plume dispersal directions) have changed drastically. I would argue that the recognition of periods of inactivity is of equal significance to that of recognising the processes and products of activity in the study of past eruptions. Civil authorities need sound advice on the future progress of an ongoing eruption, and such advice may be problematic to supply.

Coupled with this (possible) spectrum of eruptive timings is the fundamental issue of deciding when an eruption has actually finished so that recovery operations (whether social, infrastructural, ecological, or magmatic) can begin. What time period after significant activity has to pass before an eruption can be considered to have finished? This is often challenging to determine because of the contrast between the timescales of geological processes and human activity (political and fiscal). For example, should the 2004–2008 activity at Mount St. Helens (Washington, USA) be considered as a natural extension of the 1980–1986...
events, or as a separate eruption? And how would the products be judged as part of the prehistoric geological record some thousands of years from now?

**TIPPING POINTS**

As mentioned above, with the present state of volcano studies, there are two major sources of information that can be applied. First, there is the geological study of past events, supplemented in the historical record with eyewitness information (e.g. Hildreth and Fierstein 2012), but mostly undertaken in the prehistoric record through studies of eruption products. Our knowledge is, thus, limited to processes and events that leave a tangible marker in the geological record. For example, an earthquake that leaves no surface evidence in the form of, for example, a surface fault rupture or landslides over a large area cannot be discerned in the prehistoric record. The influence of earthquakes on the behaviour of volcanoes is, therefore, largely unknown: cause and effect cannot be demonstrated for virtually all eruptions in the geological record. Second, there is presently an ever-increasing array of geophysical and geochemical techniques that can directly detect signals of sub-surface activity, but these signals cannot necessarily be translated, with confidence, to specific volcanic processes, let alone used to predict what eruptive activity will follow.

In an active eruption, the two approaches (the past record and the real-time observations) converge, in some cases with great success (e.g. Mount Pinatubo (Philippines): Newhall and Punongbayan 1996). But there are inevitable gaps. One gap is that we can only assess the composition and state of the magma involved once it has reached the surface, although there are possibilities arising of gaining information on the properties of newly erupted materials rapidly enough to make forecasts within the lifetime of an eruption (e.g. Pankhurst et al. 2014). A second gap is that whereas we can reconstruct magmatic processes from historic eruption products and plausibly link these processes to geophysical signals recorded at the time (e.g. Kilgour et al. 2014), the reverse cannot yet be done with confidence in many cases. For example, signals of uplift at caldera volcanoes are often linked to magmatic inflation; but, other causes (such as changes in the state of a hydrothermal system) may contribute to the surface signals and so lead to ambiguity (Acocella et al. 2015). Signals of unrest may, in turn, be no guide to the likelihood or imminence of eruptive activity. At Long Valley Caldera (California, USA), magma is proposed to underlie the resurgent dome complex and be contributing to present-day unrest (Seccia et al. 2011). Yet geological evidence implies that the magmatic system in that particular area is moribund and that no eruption has occurred for ~100 ka (Hildreth 2004).

A key concept that arises from the points made above is that of a tipping point in volcano behaviour, marking the point when unrest [which may run for decades to centuries, such as at Campi Flegrei (Italy) (Acocella et al. 2015)] irrevocably leads to an eruption. However, the time gaps between (i) the tipping point and the onset of eruption, (ii) the eruption onset and when hazardous conditions begin, and (iii) the onset and eruption climax have been exceedingly variable in observed eruptions and have ranged from a day or so in the case of Chaitén volcano (Chile) (Major and Lara 2013) to decades in the case of Rabaul volcano (Robertson and Kilburn 2016). If a volcano is escalating rapidly towards eruptive activity, such as happened for Pinatubo in 1991 (Newhall and Punongbayan 1996), the symptoms can be identified and made use of in valuable forecasting and mitigation efforts on societally useful timescales (e.g. Voight 1988). However, such methods still cannot always identify the tipping point. A key example of the problem is Rabaul, where a major seismic crisis occurred in 1983–1985 yet the eruption occurred in 1994 with only about 27 hours warning, following a regional earthquake (Global Volcanism Program 1994). The tipping point for a particular eruption may, thus, be an external agent, invisible in the geological record and unanticipated in real time. The precise timing of the 18 May 1980 cone collapse at Mount St. Helens, for example, was controlled by a separate earthquake, which in and of itself will have left absolutely no trace in the geological record.

Thus, at one end of the spectrum, in the monitoring of long-dormant, large caldera volcanoes, and especially those with geological records of large explosive eruptions and reputations to uphold [e.g. Taupo, Yellowstone, Toba, Long Valley, Laguna del Maule (Chile/Argentina), Campi Flegrei], how could one recognise the tipping point? The amounts of deformation involved at caldera centres are often large, occurring on geologically rapid timescales and often leading to perceptions of imminent eruption (e.g. Singer et al. 2014; Acocella et al. 2015). Yet, comparisons of the timescales of unrest (years to decades or centuries) versus studies of the geological record of eruption frequencies (at intervals typically of centuries to tens of thousands of years) show that unrest events at such volcanoes are one to three orders of magnitude more frequent than eruptions. The current states of unrest at large caldera volcanoes (e.g. Acocella et al. 2015) are, thus, no guide to which of them will erupt first or what will turn unrest into activity. If the specific timing of any particular eruption is controlled by external factors, such as the regional stress state (Allan et al. 2012) or a linked or independent seismic event (Manga and Brodsky 2006), then there may be insoluble challenges in eruptive forecasting because of the possibility of random events that are wholly independent of the volcanic system but that force the volcano past its tipping point at short notice.

**VOLCANO ‘KNOWN UNKNOWNS’ AND ‘UNKNOWN UNKNOWNS’**

Observations and conceptual models of volcanic products have built a remarkably detailed picture of the subsurface magmatic systems, but all have the inescapable limitation that they are built on what is known. For models, boundary conditions have to be set, and these are based on what we know or on what we know that we don’t know, such as the temperature structure in the crust. Therefore, models tend to be self-limiting. Models are also problematic because they need to be ground-truthed and hence are not necessarily predictive. For example, at the Taupo and Yellowstone caldera volcanoes (Fig. 3), studies of past eruptions (e.g. Barker et al. 2015; Stelten et al. 2015) imply that there are currently large volumes (hundreds to thousands of cubic kilometres) of partially molten rock (geophysically imaged at Yellowstone) that are fuelling the modern geothermal heat fluxes. Yet, however sophisticated the models are made for these and other volcanoes, the amount of magma released in the next eruption, and the timing of that release are not forecastable except in probabilistic terms (Fig. 2). But probabilities are in themselves problematic. In the event of volcano unrest that might lead to an eruption, does one, for example, advise civil authorities to prepare for the smallest, the median, or the potentially largest event? What if, for sake of argument, the next eruption turns out to be unprecedented in the history of the volcano (Fig. 1)?

The continuing arrival of new technologies – drones for ‘cheap’ observations in hazardous conditions, satellite sensing systems for monitoring and surveillance, rapid
Two of the world’s largest and most active supervolcanoes in repose. Both volcanoes represent great challenges to forecast. (A) Yellowstone volcano (Wyoming, USA), looking northwest from the north side of the Red Mountains. Lewis (nearer) and Shoshone (farther) lakes are surrounded by the large flat-topped rhyolite lavas of the Central Plateau Member (erupted from ~170-70 ka; see Stelten et al. 2015). The Red Mountains are an uplifted block of ~1 km thick Huckleberry Ridge Tuff, eroded by glacial activity. The mountains in the far distance are the Madison, Gallatin and Absaroka ranges, north of the Yellowstone caldera. (B) Taupo volcano (New Zealand), looking north-northeast from the summit of Pihanga volcano, an extinct stratovolcano rising ~1 km above its surroundings. Lake Taupo infills a collapse caldera mostly created in a major eruption at 25.4 ka. It has seen 28 eruptions since 25.4 ka, most of them from vents down the eastern (right-hand in this view) side of the lake and now concealed beneath its waters (see Barker et al. 2015).

Conclusions

There are several questions that can be applied to any volcano that is not currently in eruption, but are especially applicable to caldera volcanoes that have geological records of large eruptions of felsic magma.

1. When will it next erupt?
2. How big will the eruption be?
3. What eruption products will result and what are their consequent hazards and impacts?
4. What will be the timescale of the total eruption, and will there be breaks in activity?
5. What determines the timing of markers, such as the tipping point at which an eruption is inevitable (although not necessarily imminent), the onset of an eruption when material reaches the surface, and the climactic event or events during an eruption?
6. How does one determine the end of the eruption so that recovery can begin?

Although some of these questions can be answered in outline or as probabilistic assessments based on knowledge of past activity, the major issue is whether confident answers can be given to all of these questions for future events. Any probabilistic assessment of the range of options at a volcano like Taupo, with its greatly diverse range of eruption sizes and styles (Wilson 1993), still means that forecasts or predictions of future events are problematic – even in today’s data-rich environment. Does one plan for the most likely event or the worst event, if the change from one to the other scenario may occur rapidly? How then does one plan for events that have no precedents (Fig. 1)? At long dormant volcanoes, does the possible presence of magma and symptoms of unrest necessarily indicate that any eruption is likely or even possible (e.g. Seccia et al. 2011)? In any case, the biggest impacts associated with volcanic eruptions not only include the loss of human life and direct destruction of property and infrastructure but also significant downstream economic effects due to the interconnected nature of modern society (e.g. Budd et al. 2011). The more we uncover and document the timing and dynamics of prehistoric eruptions, the greater diversity we see. In returning to the opening quotation from Rumsfeld (2002), modern volcanology has made enormous progress in characterising volcanic systems (admitting that much remains to be done, especially in arc environments). We now know a lot, and have a good grasp on the ‘known unknowns’ that may be made accessible through improved technology and be applied to volcanoes erupting in today’s world. The success of volcanic monitoring and the societal responses to many eruptions over the past few decades is strong evidence that the behaviour of many historically active or reawakening volcanoes can be dealt with (e.g. Newhall and Punongbayan 1996). What remains are the ‘unknown unknowns’. These natural factors seem best (and most worryingly) to apply to volcanoes that erupt felsic magmas and that have or will have the potential to generate eruptions large enough to form calderas. The proportion of such volcanoes that will ever be forecastable or predictable in useful ways remains the greatest challenge to modern volcanology simply because we do not know what we do not know.

Acknowledgments

I thank the editors for the opportunity to contribute to this issue and thank Wes Hildreth, Jake Lowenstern, John Pallister and Keith Putirka for contrasting perspectives and comments on these topics and the manuscript.
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ALL CHANGE FOR MINSOC JOURNALS

With effect from 2017, the two journals published by the Mineralogical Society of Great Britain and Ireland (Mineralogical Magazine and Clay Minerals) will become effectively 'online only'. We have reduced the price of the journal to reflect the change in our costs. Devotees of the printed copy can still purchase the paper versions of the journals with an additional payment. The response from our readers and members since our initial announcement in 2016, has been overwhelmingly positive. Relieved librarians no longer need to find homes for papers journals!

We are ready to help any reader who has difficulty in making the transition to online only. Please contact us at admin@minersoc.org. To help streamline the transition, a single annual payment of membership dues to the society now also covers access to the journals. Members simply go to www.minersoc.org, click on “Member login” (you’ll need to register the first time you use it) and from there you’ll be able to access all of Clay Minerals, Mineralogical Magazine and indeed, Elements, online, without further barrier. And don't forget – our journal archives (from the 1876 to 1999) are available free of charge to all readers.

Now more than ever, it is important to keep the mineral community informed about new content published in our journals. We’ll be doing this via social media, list-serves and by means of our E-Bulletin. We will also be encouraging authors to do likewise, i.e. promote their own published work. With on-line access now generally the norm, the mineralogical community has a huge choice in terms of what to read. Let’s make sure they read an MSGBI article!

We welcome your feedback. Please email kevin@minersoc.org or any of the Principal Editors.

CLAY MINERALS

Clay Minerals is the official journal of the European Clay Groups Association. The journal has recently been undergoing significant change: we have remodelled our Editorial Board and appointed some new representatives of the national societies. We have appointed a new ‘Management Committee’, which will include representatives of the European societies. First to occupy the editorial hot seats are Bruno Lanson (France), Reiner Dohrmann (Germany), Chris Greenwell (UK) and Javier Huertas (Spain). They will meet regularly with the Principal Editor, George Christidis, and the Executive Director of the Mineralogical Society, Kevin Murphy.

In addition, we now have in place a system for securing and publishing timely, high-quality review papers. And we have deployed a new manuscript tracking system with the intention of completing peer review for the vast bulk of manuscripts in not more than 10 weeks. We will couple this with online pre-publication of accepted papers within 1 or 2 days of acceptance and with short acceptance to formal publication times.

The remit of our journal has moved more towards applied clay science, especially in the area of clay chemistry, and our new editorial board reflects this change (http://www.minersoc.org/cm-editors.html).

Most importantly of all, we aim to make the published content available to as wide an audience as possible. From 2017 onwards, all members of the national European Clay Groups will be able to subscribe to Clay Minerals direct (at www.minersoc.org – click on “join”) or via the national group for a fee of just £30 or €35.

WEBSITE

Websites seem to go through a life cycle of about five years. At first, they feel very fresh and new, then they go a little bit stale, and finally you can’t wait to change them! The Mineralogical Society has arrived at that final stage. So... it is with great pleasure that we have launched our revised website, still at www.minersoc.org. I’m sure you’ll agree that it looks fresh and modern. In addition to the good looks, we are afforded a more robust security system; we can embed more readily the burgeoning social media presence of the society and our special interest groups; and we can create more sub-sites with inherent architecture, which is useful for building pages for conferences, etc. (Aideen Murphy is acknowledged for her help in creating the new pages and moving and updating the content from the old site.) Feedback is always welcome.

DHZ

Sales of An Introduction to the Rock-Forming Minerals (3rd edition by Deer, Howie and Zussman, 2013, Mineralogical Society) published about four years ago, continue to go very well. Please note that an updated version (ver. 9) of the online supplement (Crystalviewer) has been uploaded at http://crystalmaker.com/dhz. This is available for free, for anyone to download: give yourself a colourful crystallochemical treat and take a look.

An Introduction to the Rock-Forming Minerals

A warm welcome to CrystaMaker Software Ltd, the author of CrystalViewer™, a professional software, and download CrystalViewer for DHZ.

Our flagship “CrystaMaker” program lets you build, display, and manipulate all kinds of crystal & molecular structures.

Elements February 2017
SOCIETY AWARDS


Hey Medal

“To recognize existing and ongoing research of excellence carried out by young workers, within the fields of either Mineralogy, Crystallography, Petrology or Geochemistry. Evidence of excellence should be in the form of work published in highly regarded, international scientific journals. Nominated candidates do not necessarily need to be Members of the Mineralogical Society. On the closing date for nominations, candidates must be within 15 years of the award of their first degree, except where there has been a career break, detailed in the nomination, in which case the committee chair may agree to accept nominations from candidates for whom the first degree was awarded more than 15 years previously.”

Collins Medal

“The Collins Medal will be awarded annually to a scientist who, during a long and active career, has made an outstanding contribution to pure or applied aspects of Mineral Sciences and associated studies. Publications, teaching, outreach and other activities leading to the promotion of mineral sciences, in the broadest sense, will be taken into account in making the award. Nominees do not have to be Members of the Mineralogical Society or nationals of Great Britain and Ireland.”

Mineralogical Society-Schlumberger Award

“To recognize scientific excellence in mineralogy and its applications; mineralogy being broadly defined and reflecting the diverse and worldwide interests and membership of the Society with its various specialist groups. Evidence of such excellence should be in the form of published work by a currently active scientist. Nominations on behalf of both younger scientists and well-established workers would be welcomed. Nominees do not have to be Members of the Mineralogical Society.”

Howie Best Paper Award

At the same time, please consider a nomination for the Howie Award.

An award will be made annually to “the lead author of the ‘best paper’ published (in English) in a mineralogical journal (sensu lato) within three years of award of his/her PhD”. Details of the nomination process are given at: http://www.minersoc.org/best-paper1.html.

The award will take the form of a bursary (£1,000) to attend an international conference (to be agreed with the society) to present a paper which will be entitled the “R.A. Howie Memorial Lecture”. The money will be paid on receipt of an official confirmation of registration for the conference.

The “R.A. Howie Memorial Lecture” Award is named in honour of Prof. R.A. Howie (1923–2012) who was a distinguished professor of mineralogy at Kings College London and Royal Holloway University, London (both UK).

The 2015 winner of the Howie Award was Jessica J. Barnes

The winning paper was:


Jessica used the prize fund to attend and speak at the Microscopy and Microanalysis 2016 meeting hosted by the Microscopy Society of America in Columbus (Ohio, USA).

NEW SOCIETY TRUSTEES

With effect from 2017, the MSGBI welcomes the following new officers and trustees:

<table>
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<tr>
<th>General Secretary (2017–2022)</th>
<th>Jana Horák</th>
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<td>Public Relations Officer (2017–2022)</td>
<td>Philip Pogge von Strandmann</td>
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<td>Three Ordinary members of Council (2017–2019)</td>
<td>Clare Warren, Chiara Petrone, Sam Broom-Fendley</td>
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<td>Two Custodian Trustees</td>
<td>David Wray, John Bowles</td>
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<tr>
<td>Distinguished Lecturer Coordinator</td>
<td>David Pyle</td>
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<tr>
<td>Awards Committee Chair</td>
<td>Kathryn Goodenough</td>
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Welcome and thanks to them all for their service to the society.
Combination of lake-sediment geochemical results from Labrador and northeastern Québec is complicated by the differing analytical protocols applied in the two regions. While the Québec samples were digested with aqua regia prior to analysis, certain elements in the Labrador samples had previously only been analyzed either after a near-total digestion or by the total-element method of neutron-activation. In order to create a more harmonious regional data set, 5,510 Labrador samples were re-analyzed after aqua regia digestion.

Rocks of the Labrador Trough (New Québec Orogen) have given rise to the most extensive and distinctive patterns, particularly of chalcophile and siderophile elements. For some (e.g. Cu and Pb), the most strongly elevated values extend only 300 km from 54° 45’ N to about 57° 30’ N, whereas the highest values of As and Sb define a curvilinear feature that extends over the trough’s entire 600 km strike length (Fig. 1). The well-documented glacial dispersion train associated with the Strange Lake/Lac Brisson rare earth element and rare metal deposit is also defined by elements such as Sn, and appears to extend at least 25 km westwards into Quebec. The distribution of S closely follows that of loss-on-ignition (LOI), and, in Labrador and the adjacent part of Québec, S values fall sharply at approximately latitude 57°N. Further west, however, elevated S and LOI values persist as far north as Ungava Bay in the catchment basin of the Koksoak River. This work has been successful in eliminating the discontinuity at the provincial border for most elements and in creating lucid geochemical maps covering an area of 300,000 km².

The full article can be viewed at: www.appliedgeochemists.org/index.php/publications/explore-newsletter

**RECENT ARTICLE PUBLISHED IN EXPLORE**

**“Allogamated Lake-Sediment Data from Quebec and Labrador, Canada”**  
Stephen Amor1, Martin McCurdy2, Robert Garrett5, David Corrigan2 and Fabien Solgadi1

**PROPOSED SESSIONS FOR RFG2018**

The Association for Applied Geochemists has proposed 14 sessions for the Resources for Future Generations 2018 conference (RFG2018), which will be held 16–21 June 2018 in Vancouver (Canada) (see www.rfg2018.org). Anyone interested in participating in the sessions should contact the AAG organising committee chair, Peter Winterburn (pwinterburn@eos.ubc.ca), who will direct you to the appropriate session chairs. The organising committee is also open to further suggestions for additional sessions, as well as proposals for workshops and field trips to be run in association with RFG2018. Please note that the deadline for session proposal is 1 May 2017.

- “Footprints of Giant Orebodies – Mineralogical, Spectral and Geochemical”
- “Mineral Exploration in Extreme Environments”
- “Hydrogeochemistry: Environment and Exploration”
- “Acid Rock Drainage in Mining and Civil Construction”
- “Analytical Technology in the Search for Minerals: Space to the Lab to the Field”
- “Macro- to Micro-Biogeochemistry: Exploration, Processing, Remediation and the Environment”
- “Hydrocarbons in the Exploration for Metalliferous and Non-Metalliferous Deposits”
- “Stable and Radiogenic Isotope Systems: Applications in Exploration and the Environment”
- “Economic Redevelopment of Brownfields: New Uses for Old Mines”
- “Groundwater and Mineral Resources”
- “Geometallurgy: Exploration-Evaluation-Exploitation-Environment”
- “Exploration Case Studies – Out of the Box Concepts, Methodologies, and Practices”

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1 Geological Survey of Newfoundland and Labrador  
P.O. Box 8700, St. John’s NL, Canada A1B 4J6  
e-mail: stephenaamor@gov.nl.ca

2 Natural Resources Canada, Geological Survey of Canada  
601 Booth Street, Ottawa ON, Canada K1A 0E8

3 Ministère de l’Energie et des Ressources naturelles  
Direction générale de géologie Québec  
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Val-d’Or QC, Canada J9P 3L4
FROM THE PRESIDENT

On 1 October 2016, the Japan Association of Mineralogical Sciences (JAMS) transformed from a private association into a general incorporated association. JAMS was established in 2007 as the result of a merger between the Mineralogical Society of Japan (established in 1955 as an independent mineralogy working group of the Geological Society of Japan) and the Japanese Association of Mineralogists, Petrologists and Economic Geologists (originally established in 1928). Thus, JAMS, with its 88-year history, has started a new phase as an incorporated association.

This means that it will have legal compliance and obligations through (1) improved reliability in both its academic and societal functions, (2) legal stability through clarification of responsibilities, and (3) holding of properties. As the first president of this incorporated association, I am happy to make a contribution to JAMS and the Earth and planetary science community.

Part of the JAMS mission is outreach. So, to mark its transformation to an incorporated association, JAMS has selected jadeite (hisui in Japanese) as the national stone of Japan. Prior to this, American mineralogist George F. Kunz proposed “rock crystal” as the national stone of Japan in his 1913 book, The Curious Lore of Precious Stones. However, based on new knowledge and understanding of the importance of the rocks that form Japan, not only in terms of natural science but also of social science, culture, and art, the national stone was replaced with something more appropriate (see the accompanying article).

Moving to a topic in my own research field, the Japanese spacecraft Hayabusa2 was launched in 2014 and should arrive at asteroid Ryugu in mid-2018. Samples of this C-type asteroid (carbonaceous chondrite or related material) will be returned to Earth late of 2020. A call for nomination of sub-team leaders for the Initial Analysis Team for samples returned by Hayabusa2 was recently announced. The sub-teams cover chemistry, petrology and mineralogy, volatiles, and organics. We expect that JAMS members will be selected as some of the sub-team leaders and will contribute to the initial analysis.

Our next annual meeting will be held at Ehime University (Japan) in September 2017. Some members of JAMS will be conveners of the international sessions of the Japan Geoscience Union Meeting 2017, to be held in May at Makuhari (Chiba Prefecture). It is a great honor to meet fellow researchers from all over the world at such conferences.

Prof. Akira Tsuchiyama, JAMS President

JADEITE: THE NATIONAL STONE OF JAPAN

In 2016, the JAMS selected jadeite as the national stone of Japan. In making this decision, we did not distinguish between minerals and rocks, and we decided to select a stone that is a basic and familiar geological constituent of Japan. We set up the following criteria for the national stone:

(1) A beautiful stone that occurs naturally in Japan and is known to the Japanese.
(2) A stone that has global significance, not only in mineral sciences and Earth sciences, but also in other fields.

Additional recommended criteria were as follows:

(3) A stone that has been used for a long period of time and in a wide variety of ways in Japanese life.
(4) A stone that is still produced today and can be observed in the field.
(5) Field observations of the stone can be done in a sustainable way according to conservation law.

We made the selection through a ballot of the society members at the JAMS Annual Meeting on 24 September 2016. Five candidates for the national stone were chosen according to public comments and the recommendations of the JAMS Working Group: these were granite (granitic rocks and their pegmatites), stibnite, native gold, rock crystal (quartz; including Japanese twin, agate, chalcedony and jasper), and jadeite (including jadeitite).

“Jadeite” (hisui in Japanese) is a comprehensive term that includes the mineral jadeite and the rock jadeitite. Fine-grained and slightly transparent forms are known as the jewel “jadeite jade” (also hisui in Japanese). It is accepted that jadeite forms only in divergent plate boundaries, such as the Japanese islands which have cold thermal gradients (Harlow et al. 2015). The occurrence of jadeitite is restricted to associated areas of serpentinites, which are younger than 550 million years. Thus, jadeite is one of the rocks that indicate a cooling of the Earth. Jadeite (hisui) was used for stoneware in the Upper Paleolithic age and as magatama (comma-shaped beads) until the 8th century in Japan. The occurrence of jadeite in Japan faded into obscurity after that time, but it was rediscovered in 1938 in Itoigawa (Kohno 1939). At present, we can observe jadeite in the field at sites all over Japan, and some of these localities are protected by law.

Prof. Akira Tsuchiyama, JAMS President


Original Articles

Internal textures and U-Pb geochronology of zircons in metamorphic rocks from the Southwestern Highland Complex, Sri Lanka – D. Nuwan Sanjaya WANNIARACHCHI, Masahide AKASAKA, Yasutaka HAYASAKA and L.R.K. PERERA

Cation ordering of (110) and (211) sectors in granitoid garnet from Mali – Yurie NAKAMURA, Takahiro KURIBAYASHI and Toshiro NAGASE

Thermal structure of the Kebara Formation and its proximal areas in the western Kii Peninsula, SW Japan: Application of the carbonaceous material Raman geothermometry – Kenta YOSHIDA, Naoki AYOJAGI, Ryoji KATO and Takao HIDAJIMA

Evidence for partial melting of eclogite from the Moldanubian Zone of the Bohemian Massif, Czech Republic – Takahiro MIYAZAKI, Daisuke NAKAMURA, Akihiko TAMURA, Martin SVOJTKA, Shoji ARAI and Takao HIDAJIMA

Letters

Pressure-volume-temperature equation of state of e-FeO(OH) to 11 GPa and 700 K – Akio SUZUKI

Hydrogen distribution in chondrodite: a first-principles calculation – Masami KANZAKI

INVITATION TO THE JPGU-AGU JOINT MEETING 2017

We are pleased to inform you that the first joint meeting between the JpGU (Japan Geoscience Union) and the AGU (American Geophysical Union) will be held 20–25 May 2017 at Makuhari Messe (Chiba Prefecture, Japan). More than 100 international sessions have been proposed. Detailed information is available at http://www.jpgu.org/meeting_e2017.
DMG
German Mineralogical Society

FROM THE PRESIDENT

Dear Members of the DMG,

In this ever-changing world, it is a comfort to know that, after 106 years, the German Mineralogical Society (DMG) is still thriving. It has a constant membership of about 1,630, with more than 20% of which are students, thereby keeping the society dynamic and alive for years to come. This is important because the DMG provides a unified umbrella under which different mineral-related subdisciplines – petrology, crystallography, economic geology, ore petrology, technical mineralogy, geochemistry, and biomineralogy – blend their home harbour. Financially, the DMG continues to be in safe financial waters, despite the present low interest rate clearly affecting our reserves.

On behalf of all members, I want to thank the outgoing president, François Holtz, who served the society for the last two years with everlasting optimism and enthusiasm. François, I want to warmly thank you for all your efforts in building international bridges for DMG members and for your seeming omnipresence for the society! Special thanks are also due to Paul Keller, who retired from the International Mineralogical Association’s Commission on New Minerals, Nomenclature and Classification as DMG representative. His position was taken over by Thomas Witzke. Furthermore, I welcome the new section chairmen within the DMG: Timm John (petrology and petrophysics), Ronny Schönberg (geochemistry), Helmut Klein (chemistry, physics and crystallography of minerals) and Christoph Berthold (applied and environmental mineralogy), who respectively replace Wolfgang Bach, Stefan Weyer, Christoph Berthold and Stefan Stöber.

After a short membership, Cristina de Campos retired from the board and Karen Appel, who will be replaced by Catherine McCammon in 2017 and Susanne Greiff thankfully took over at short notice. Student member Insa Cassens will hand over her duties to Thomas Rose. I would like to express my sincere thanks to all active members of the DMG, as well as to all members of the boards, sections, commissions and working groups. The continued active engagement of our members is crucial for the successful survival of our society.

After the DMG’s participation in the very successful 2nd European Mineralogical Conference (emc2016) held last September in Rimini (Italy), the society will be involved in one major international meeting in 2017 – that of GeoBremen 2017. This joint meeting of the DGGV and the Deutsche Mineralogische Gesellschaft (DMG) and the Deutsche Geologische Gesellschaft – Geologische Vereinigung (DGGV) will provide a multidisciplinary platform to share the exciting themes and topics of the Earth and material sciences of the 21st century.

From seafloor to summit, from the Harz Mountains (Germany) to the Himalayas, from geology to oceanography, from petrology to mineralogy, from inorganic geochemistry to geobiology, from low- to high temperatures and pressures, from the crust to the core, from the field to the lab, and from the Earth to the stars, we expect exciting scientific contributions, animated discussions and new ideas.

Scientific themes:

- “Dynamic Earth – from the Interior to the Surface”
- “Rates and Processes in Magmatic and Metamorphic Systems”
- “Geosphere–Biosphere Interactions”
- “Solid–Liquid Interface Reactions”
- “Earth History and Global Change”
- “Early Earth and Evolution of Planets”
- “Sedimentary Systems”
- “Applied Geosciences”
- “Energy, Materials, Resources”
- “Education and Museums”
- “Open Session”

Important Dates

1 June 2017: Deadline for abstract submission
Before 15 August 2017: Normal registration
After 15 August 2017: Late registration

For more information please visit: www.GeoBremen17.de

All the best,

Reiner Klemd (DMG President)
NEW HONORARY MEMBERS

In recognition of distinguished service to our society and of outstanding contributions to the mineralogical sciences, DMG has appointed two honorary members in 2016: Herbert Kroll (Münster), and Herbert Palme (Senckenberg Frankfurt, formerly Cologne). Congratulations to both!

Herbert Palme

Herbert Palme was born in 1943, studied physics and mathematics at the University of Vienna (Austria) and received his PhD in nuclear physics at the Institute for Radium Research and Nuclear Physics, also in Vienna. After his doctorate, he continued his academic career at the Max Planck Institute for Chemistry, Department of Cosmochemistry, in Mainz (Germany). He defended his habilitation in mineralogy at the Johannes Gutenberg University Mainz in 1985 and was a visiting scientist at various prestigious research institutions in the United States: the Enrico Fermi Institute of the University of Chicago, the Lunar and Planetary Laboratory at the University of Arizona in Tucson, and the California Institute of Technology in Pasadena. From 1994 to 2008, he held a professorship of mineralogy and geochemistry at the Institute of Mineralogy and Geochemistry of the University of Cologne (Germany). Since 2008, he has been an honorary member of the Senckenberg Research Institute and Natural History Museum in Frankfurt am Main.

Herbert Palme's research interests are broad. When he was in Mainz, his main focus was on the origin of the lunar crust and of refractory inclusions in chondrites. His work on meteorites was groundbreaking: he discovered new meteorite groups, such as the acapulcoites. He was also interested in the siderophile signatures of large terrestrial impactors and on the composition and formation of the Earth's mantle and core. In the early 1990s, he expanded his field of research to laboratory studies of certain equilibrium processes that might aid in understanding the formation processes of meteorites, planets, and the Moon.

Overall, Herbert Palme has contributed significantly to our understanding of the formation of the Solar System.

Herbert Palme received numerous awards for his scientific achievements. Amongst others, he is a Fellow of the Meteoritical Society, a Fellow of the Geochemical Society, and a corresponding member of the Austrian Academy of Sciences. The Meteoritical Society awarded him its Leonard Medal in 2003. In 2006, he received the Urey Medal from the Geochemical Society and the European Association of Geochemistry. In 2010, he became an honorary member of the Senckenberg Research Institute and Natural History Museum in Frankfurt am Main.

Herbert Kroll

Herbert Kroll was born in 1940 and began studying geology in 1962 at the University of Mainz, where he was supported by an award from the prestigious German Academic Scholarship Foundation. In 1964, he moved on to the ETH Zürich (Switzerland) and finally to the University of Münster, where he was awarded a Diploma in Mineralogy in 1967. He became a member of the German Mineralogical Society (DMG) in 1968. Kroll submitted his dissertation thesis to the Faculty of Chemistry in 1971, and received a University Award for exceptional excellence. In 1981, he received the venia legendi (the authorization to teach in a German university) in the Faculty of Chemistry with his pioneering thesis, “Structure and Metrics of Feldspars”. A year later he was appointed Professor (C2), and in 1991 was offered the Chair (C4) in Structure and Dynamics of Earth Materials at the Bavarian Research Institute of Experimental Geochemistry and Geophysics (BGI) of the University of Bayreuth, which he declined for personal reasons. In 2007, the DMG awarded Herbert Kroll its highest award, the Abraham Gottlob Werner Medal, for scientific eminence during his career.

Herbert Kroll served the DMG as secretary from 1988 to 1994. On 1 August 1988, the presidents of the French, Italian and German Mineralogical Societies signed an “Agreement upon the publication of the European Journal of Mineralogy”, and Herbert Kroll was one of the German members of the small group of functionaries finalizing this historic accord.

Herbert Kroll has published 71 scientifically outstanding articles (some with co-authors), including contributions in books and countless abstracts, that deal primarily with polymorphism, solid solution and unmixing in “model minerals” (and their synthetic equivalents) in the feldspar, orthopyroxene, olivine and garnet groups. These studies were augmented by additional research on Rietveld methods, computer simulation of crystal structures, least-squares procedures, mathematical fundamentals of indexing powder diffraction patterns, Landau theory and (Al,Si) distribution in framework silicates.

Herbert Kroll is specifically interested in ordered/disordered/anti-ordered states as a function of external parameters. His clarification of the historically controversial phase relationships of albite–anablitemonalbite was spectacular. His studies have also resulted in a number of practical applications, such as an improved two-feldspar thermometer and the simultaneous determination by X-ray methods of Al,Si order [Tr(110) method] and chemical composition of feldspar. His methods, not only intended for experts, have been successfully implemented in several regions characterized by extensive terranes of metamorphic rocks, such as in Sri Lanka, the Scottish Highlands and the central Swiss Alps.

Herbert Kroll has provided an elegant bridge from crystallography to petrology, as reflected in the comparatively broad spectrum of 15 international scientific journals in which his contributions have been published. Needless to say, the European Journal of Mineralogy played an increasingly important role after 1991.

Herbert Kroll has acquired an international reputation at the highest level. He has been asked to co-author monographs of international significance and has received many invitations for research visits to the USA. He became a Fellow of the Mineralogical Society of America in 1995. Last but not least, it can be said that today, twelve years after mandatory retirement in the German university system, Herbert Kroll is a scientist as active in research as ever.

Astrid Holzheid (Kiel)

Hans Ulrich Bambauer (Münster), Walter Maresch (Bochum)
SAMPLE CERTIFICATION WORKSHOP

The International Association of Geoanalysts (IAG) sponsored its second sample certification workshop, which was held 24–26 October 2016 at Horwood House, a rural estate near Milton Keynes (UK). This two-and-a-half-day meeting followed on from the first such workshop held in 2014 (see IAG society news item in June 2014 issue of Elements). The 2016 workshop agenda was packed full of presentations by top leaders in the field of analytical geochemistry, including representatives from major national metrology institutes. The rural setting of Horwood House provided a highly productive setting for discussions devoted to emerging topics in analytical metrology. One of the key themes addressed during the workshop was whether it is appropriate to integrate results from a proficiency testing scheme for the subsequent certification of a material. Previous work by Potts et al. (2015), which followed on from the IAG’s first sample certification workshop, have shown that the results from the GeoPT whole-rock proficiency testing programme are in very good to excellent agreement with the concentration values produced during ISO [International Organization for Standardization]-compliant certification rounds independently conducted by the IAG’s sample certification committee. Although such work is highly technical in nature, it is essential that current practices be subjected to ongoing review to ensure that such work remains compliant with ongoing revisions to ISO guidelines on the production of certified reference materials.

Another topic of rapidly growing interest is the production of certified reference materials for microanalytical methods, such as electron probe microanalyzer, laser ablation, and secondary ion mass spectrometry (SIMS). Currently, no ISO-compliant certified reference material exists for the calibration of major element abundance, trace element abundance or isotope ratio values when operating at the nanogram or smaller sampling size. In order to help overcome this situation, the IAG has now established a working group which will focus on strategies for identifying and characterizing materials suitable for calibrating or validating in situ analytical methods.

IAG AUTUMN COUNCIL MEETING

Following the October 2016 sample certification workshop, the IAG Council held its autumn meeting, which was attended by eleven council members. As has become the norm over recent years, the agenda for this council meeting was long, requiring many topics to be addressed in rapid succession. Reports to the council confirm that IAG continues to thrive both in terms of a growing membership and a high level of interest in IAG programmes from the broader geochemical community. The demand for reference materials continues to be strong, as documented by sales through IAGeo Limited, the trading arm of the International Association of Geoanalysts. Particularly heartening has been the rapid uptake of the SdAR (‘Sediment Animus River’) suite of blended stream sediments, which has proven very popular for the calibration of portable X-ray fluorescence devices. Manuscript submissions to Geostandards and Geoanalytical Research, the official journal of our association, continue at a high level. Council has now begun to address how best to expand its support for this key activity, including discussions about expanded page allocations and the production of single themed issues. For the Geoanalysis 2018 meeting in Sydney (Australia) also continues on schedule, including ongoing updates to the conference’s official web site, 2018. geoanalysis.info/.

SIMS SHORT COURSE

In 2016, the IAG provided support for the short course “Introduction to Secondary Ion Mass Spectrometry in the Earth Sciences”. This annual course, targeting graduate students and early career researchers, has been held at the Helmholtz Zentrum Potsdam (Germany) since 2002. In 2016, the course attracted 26 participants from across Europe and beyond, each of whom were provided with a basic training in microanalytical geochemistry, as well as a broad foundation in the use of SIMS as a tool for isotope ratio and trace element determinations. As always, the course strongly emphasized both the calibration of SIMS quantitative results and the necessary sample preparation requirements needed to ensure optimal data quality. New in 2016 was a post-course visit to the accelerator-SIMS facility at the Helmholtz Zentrum in Dresden and the NanoSIMS and ToF [Time of Flight]-SIMS facility at the Helmholtz Centre for Environmental Research in Leipzig. This optional addition to the course provided those participating with a glimpse of the new technologies now being used for the quantification of ultra-trace level abundances on nanogram sample masses (i.e. the accelerator-SIMS in Dresden) and what is required to prepare biological specimens and the new classes of peripheral instrumentation needed for visualizing structures at the nanometer scale (Nano-SIMS and ToF-SIMS in Leipzig).

CITATION

Potts PJ, Thompson M, Webb PC (2015) The reliability of assigned values from the GeoPT proficiency testing programme from an evaluation of data for six test materials that have been characterised as certified reference materials. Geostandards and Geoanalytical Research 39: 407-417

Michel Wiedenbeck (michael.wiedenbeck@gfz-potsdam.de)
the success of the Goldschmidt conference is the enthusiasm and energy of the delegates and the volunteers who set the themes and run the sessions. Though certain regions are still under-represented, geochemists now come from all corners of the globe, reflecting the importance of geochemistry in today’s world. The success of the Goldschmidt conference(s) testifies to the vigor of our field.

I find the vibrancy of today’s geochemical community to be particularly heartening because we live in a time when scientific logic, and even scientific reality, is often called into question. I think what most attracted me, and I suspect many others, to science is that its goal is to uncover a physical reality that actually exists. The Earth is round; it is not flat. Water freezes at 0 °C; if salt is added, it freezes at a lower temperature. These are facts, not points of debate. Likewise, we cannot vote to overturn the laws of thermodynamics. The facts provided by careful observations, analyses and experiments form the basis for our understanding of the world. Geochemistry has a particularly important role to play here, because the facts that we provide have a bearing on so many of the challenges facing the world today, including the search for resources, environmental pollution, and, of course, climate change. But geochemistry is not solely of practical importance. We geochemists also provide factual information that can be used to help answer intrinsically fascinating questions related to how the Earth formed and evolved or to how life emerged. Ideologies come and go, but the information provided by geochemists and other Earth scientists gives us a solid basis for understanding how our planet functions. In today’s context, the health and diversity of our increasingly international geochemical community is very encouraging.

Have an excellent new year.

Laurie Reisberg
President, Geochemical Society

GS INTRODUCTORY STUDENT MEMBERSHIPS

To increase student participation, the GS grants free memberships to students in countries that are under-represented in the society. This includes most countries in Africa, Asia (excluding China, Japan, and South Korea), and South America. Introductory Student Memberships offer benefits that include print and online subscriptions to Elements, the weekly Geochemical News e-mail, and discounted registration rates for the Goldschmidt Conference and other scientific meetings. More information is available at www.geochemsoc.org/programs/ism/.

Current Introductory Student Members come from Colombia, Ghana, India, Indonesia, Mexico and Nigeria. We want to expand this list to many more countries, so if you know students studying geochemistry, encourage them to join!

For students from countries not included in this program, membership is just $15 for one year or $25 for two years. Joining a professional society is a great way for students to expand their professional networks and learn about the latest happenings in the field.

MEETING ASSISTANCE PROGRAM

The Geochemical Society’s Meeting Assistance Program (MAP) provides support for symposia or conferences related to geochemistry. All GS members are eligible to apply. Sponsorships provide $2,000, and the society may award up to five per year. The GS Program Committee reviews applications twice a year, and the next deadline is 31 March 2017. For more information, visit: tinyurl.com/GeoChemMAP.

2016 MAP Sponsorships

Pan American Current Research on Fluid Inclusions (PACROFI) XIII Conference; 24-26 May 2016; Columbia, MO, USA
4th International Workshop on Highly Siderophile Element Geochemistry; 11-15 July 2016; Durham, UK
Meeting of Ethiopian Geochemistry Professionals to Establish a National Association; November 2016, Addis Ababa, Ethiopia
RiMG: Measurements, Theories and Applications of Non-Traditional Stable Isotopes; 11-12 December 2016; San Francisco, CA, USA
**European Association of Geochemistry**

**PRESIDENT’S CORNER**

It is an honour, and a great pleasure, to become President of the European Association of Geochemistry (EAG). My first task is to thank Liane Benning for the fantastic job she has been doing over the last two years. Under her leadership, EAG has flourished as never before. The 2015 Goldschmidt conference in Prague (Czech Republic) was one of the most attended, and certainly one of the most exciting, geochemistry events of the last decade. Liane has also been central to developing EAG publications.

*Geochemical Perspectives (GP)*, founded by Liane, Eric Oelkers, Susan Stipp and Tim Elliott, and later on, Janne Blihert-Toft, recently achieved the remarkable impact factor of 8.8. *Geochemical Perspectives Letters (GPL)* was launched two years ago, and this new publication is already a highly praised letters journal. The business model is unique: GPL and GP are produced by geochemists for geochemists, without any interference from commercial publishers. The publications are run, fed and evaluated by our community. EAG’s decision to invest into this new publication endeavour allows us to offer open access to GP and GPL to anyone in the world, without subscription. Authors are not required to pay publication fees to publish in GPL, although we strongly encourage some financial contribution from those who can afford to do so.

I would also like to extend my sincere thanks to Marie-Aude Huishoff, EAG Business Office Manager. Marie-Aude is pivotal in keeping the EAG boat sailing at full power. Many thanks as well to Karim Benzerara, who agreed to take on the ungrateful task of treasurer. The EAG is a vibrant community that relies on unselfish individuals. These are the councillors and committee members, a list of whom can be found at www.eag.eu.com/about. Special mention to Rizlan Bernier-Latmani, Carsten Münker and Emily Pope, who joined us recently. We are also very grateful to outgoing councillor Ruben Kretzschmar for several years of generous help and effort.

I would like to recognize the lasting and substantive contributions of Chris Ballentine and Eric Oelkers, both of whom recently finished their terms on the council. Chris Ballentine served the EAG Council for nearly 10 years, as Goldschmidt Officer then as Vice-President/President/Past-President. Chris’ steady leadership and diplomacy have been inspiring. His initiatives are innumerable, including playing key roles in the successful establishment of an agreement between the EAG and the Geochemical Society and in initiating partnerships with numerous other national and international societies. Eric Oelkers has been the longest serving councillor ever: 13 years of devoted service, assuming in turn all the responsibilities within the council, including Goldschmidt Officer and Vice-President/President/Past-President. Eric has also been a co-founding editor of GP and GPL. His dedication and the vision he’s always had for EAG have allowed our society to grow tremendously, to the benefit of the geochemistry community as a whole.

Geochemistry is blossoming in Asia, with the formidable rise of the geochemistry community of Japan. We seek to improve relations between our respective communities and with others around the world. As an example, EAG has launched such initiatives as sponsoring distinguished lecturers on tours of Eastern European and African capitals. We are thinking about several actions to enhance opportunities for young researchers from developing countries, including ways to improve student participation in workshops and conferences. Your suggestions are, as always, most welcome.

The next few years could be potentially challenging. Populism is gaining momentum, raising concerns about what this might imply in terms of denying science and promoting belief rather than facts. Geochemistry is a privileged discipline in which to observe and understand how the world functions in time and space. We are continuously observing, building stories and developing models that can be tested and corrected at any moment when new data arise. I am always amazed to see what can be said using trace elements in a microphase or with isotopic ratios at extreme precision about processes that occurred billions of years ago, or that will take place in the future (sadly, in some cases, the all-too-near future). We are fortunate to be paid for doing a creative, non-profit job, and it is time to give back to society what society has given to us. We need to stand up and inform decision makers. More modestly, but equally importantly, talk to our neighbours around the corner.

We are now just a few months away from the next Goldschmidt conference, to be held in Paris (France), and we look forward to welcoming you to the *Ville-Lumière*. Antje Boetius and Marc Chaussidon are efficiently sharing the task of organizing this exciting event in one of the most beautiful cities in the world. The conference will take place 13–18 August 2017 and will be a great opportunity to relax in the country of culture, food and wine, where radioactivity and the carbon cycle, among others, were first discovered. I look forward to seeing you all very soon!

*Bernard Marty, EAG President*

**CHANGES IN THE EAG COUNCIL**

**Sigurður (Siggi) Gíslason** has recently been elected Vice-President of the EAG. He is a Research Professor at the Institute of Earth Sciences, University of Iceland, and chairman of the CarbFix Project (www.carbfix.com), an initiative to store carbon in basaltic rocks. Siggi’s major scientific interests are as follows: 1) measuring the chemical and physical erosion rates of basaltic terrains and determining the role of basalt erosion in the global carbon cycle; 2) quantifying the carbon storage potential of basaltic rocks; 3) measuring the dissolution rates and dissolution mechanisms of volcanic glasses and minerals as a function of glass composition, aqueous solution composition and temperature; 4) assessing the environmental pressure from volcanic eruptions.

Following the council elections last fall, EAG members have also elected three new councilors (see below), each of whom will serve for three years, participate in council discussions, decisions and initiatives and act as ambassadors for the society.

**Rizlan Bernier-Latmani** is Associate Professor of Environmental Microbiology at École Polytechnique Fédérale de Lausanne (EPFL, Switzerland). Her research focus is geomicrobiology, specifically, how microbes interact with the geosphere with respect to metal contaminants and investigating microbe mobility in the environment.

**Carsten Münker** is, since 2009, professor for geochemistry and cosmochemistry at the University of Cologne (Germany). His research focuses on the application of novel isotope and trace element tools to problems in geochemistry and cosmochemistry, with an emphasis on high-temperature processes.
Emily Pope is Assistant Professor at the Natural History Museum of Denmark, an institution that is within the University of Copenhagen. Emily is interested in the role of fluids in high-temperature geological processes and has used oxygen and hydrogen stable isotopes to better understand active geothermal systems, ore-forming processes and fluid flux between the Earth’s surface and mantle.

2017 EAG COUNCIL

**PRESIDENT** Bernard Marty (CRPG Nancy, France)

**VICE-PRESIDENT** Sigurður Gíslason (University of Iceland)

**PAST-PRESIDENT** Liane G. Benning (German Research Center for Geosciences GFZ and University of Leeds, UK)

**TREASURER** Karim Benzerara (Pierre and Marie Curie University, France)

**SECRETARY** Andreas Kappler (University of Tübingen, Germany)

**GOLDSCHMIDT OFFICER** Antje Boetius (University of Bremen, AWI Helmholtz and MPG, Germany)

**GOLDSCHMIDT OFFICER** Helen Williams (University of Cambridge, UK)

**COUNCILORS**

Rizlan Bernier-Latmani (EPFL, Switzerland)

Janne Blichert-Toft (ENS Lyon, France)

Don Canfield (University of Southern Denmark)

Vinciane Debaille (University of Brussels, Belgium)

Kirsten Küsel (Friedrich Schiller University Jena, Germany)

**Early Career Councilor** Stefanie Lutz (German Research Center for Geosciences GFZ, Germany)

Carsten Münker (University of Cologne, Germany)

Andreas Pack (University of Göttingen, Germany)

Emily Pope (University of Copenhagen, Denmark)

Dominik Weiss (Imperial College London, UK)

GOLDSCHMIDT® 2017

13–18 August 2017

Paris, France

Abstract deadline: 1 April

Early registration deadline: 13 June

goldschmidt.info/2017
A Tribute to Frank Christopher Hawthorne (volume 54, part 1, January 2016)
The latest thematic issue of The Canadian Mineralogist is in honour of Prof. Frank C. Hawthorne (University of Manitoba, Canada) and his extraordinary contributions to mineralogy and crystallography. The issue is appropriately huge – 372 pages – and includes sixteen articles on a variety of topics as diverse as Frank’s own career.

The cover shows the crystal structure of frankhawthorneite, Cu$_2$Te$_6$$^+$O$_4$(OH)$_2$. The preface describes Frank’s accomplishments and impact. His early interest in amphiboles is well represented by articles concerning the crystal chemistry of synthetic amphiboles, partitioning of chlorine into ferro-paragiste, synthetic potassic-ferro richterite, and magnesio-hastingsite. His work on the crystal chemistry of rock-forming minerals is represented by papers on Cs-bearing beryl and fibrous tourmaline. A lengthy article revising and expanding the structure hierarchy of natural and synthetic hexavalent uranium compounds constitutes a major contribution to the field of structure hierarchies, where Frank was an early leader, developing hierarchies for several other classes of minerals. Frank’s work interpreting the topological aspects of crystal structures is honoured by two papers on the titanium–silicate (TS) block minerals. Of course, the fundamental work of describing and revising the structures of new minerals is also represented by five articles. In recognition of the broad impact of Frank’s work, the issue also includes papers on the evolution of structural complexity in boron minerals and surface precipitates and adsorption complexes in remediated soils.

These articles constitute a worthy tribute to Frank’s accomplishments and impact, and we hope that our readers enjoy the “Frank Hawthorne Issue”.

A Tribute to John Leslie Jambor (volume 53, part 5, September 2015)
The September 2015 issue is a thematic one, dedicated to John Leslie Jambor (1936–2008), second editor of The Canadian Mineralogist. The issue is a fitting tribute, as it contains thirteen articles on themes central to John’s interests during his career. In the first contribution, Luca Bindi (University of Florence, Italy) and his team re-establish the validity of jamborite as a mineral species. They show that jamborite contains sulfate groups, a finding that is very fitting, as John maintained a fondness for sulfates even since he defined gunningite, a sulfate of zinc. Jamborite was the first of 34 new species that John proposed to the International Mineralogical Association (IMA) during his career. There are additional articles on minerals and mineral structures, including ore minerals, always a focus in John’s work. The article on owyheeite recalls John’s membership in what might be called “the sulfosalt club”. John carried out the early characterization of ore assemblages in the Strange Lake peralkaline granite in Quebec–Labrador (Canada) and his findings are reviewed in this issue. The issue also contains an article on an anomalous distribution of Cr in clinopyroxene from Mont Royal (Montréal, Quebec, Canada) and another on interstratified nickeliferous lizardite – clinohlore. Finally, there are three articles on the theme of mineralogy applied to mine wastes, which held so much of John’s attention late in his career.

UPCOMING ISSUES
- A thematic issue to accompany the 12th International Platinum Symposium (March 2016)
- A pegmatites-themed issue, based on presentations made at the PEGS 2015 conference, Ksiaz, Poland (July 2016)

Check the complete list of articles that are coming up in future issues at http://www.mineralogicalassociation.ca/doc/Upcoming_Issues.pdf.

THE 2017 PINCH MEDAL AWARDED TO DR. PETER TARASSOFF
The 2017 Pinch Medal has been awarded to Dr. Peter Tarassoff who was born in Montréal, Canada, in 1934. He holds a bachelor degree in metallurgical engineering from McGill University (Canada) and a doctorate in chemical metallurgy from the Massachusetts Institute of Technology (MIT) (USA).

He first became interested in minerals at the age of 10 and took an introductory course in geology at the young age of 12. His interest was encouraged by his parents, teachers, and a Boy Scout leader. He soon discovered the mineral collection at the Redpath Museum at McGill University which further developed his interest and knowledge in systematic mineralogy. It is at this time that Peter began to amass what is now a large, systematic collection with an emphasis on minerals from alkaline rocks. As an undergraduate student in 1953, Peter had the opportunity to work for the Geological Survey of Canada in the Yukon Territory which resulted in a mineralogical term paper and a dynamite-box of mineral specimens. Peter was further introduced to the New England pegmatites by members of the Boston Mineral Club while he was a graduate student at MIT.

Peter’s professional career was in research and development in Canada’s mining and metallurgical industry. He worked as a research engineer with the Québec Iron and Titanium Corporation (Sorel, Québec), for two years, and spent the rest of his career with the Noranda Research Centre, of Noranda Inc., a major Canadian mining and natural resource company. At the time of his retirement in 1991, he was Vice President and Chief Scientist.

Peter explored and collected at some of Canada’s most important localities. In 1962, he discovered the Saint-Amable alkaline sill (Demix-Varennes quarry, Québec, Canada), first visited the now world-famous site of Mont Saint-Hilaire (MSH) (Québec, Canada) in 1963 and has been collecting there continuously until the present day. After his retirement, Peter turned his energies towards mineralogy and ornithology.

Peter has made it his life-long goal to document the geology and mineralogy of Mont Saint-Hilaire: committing the last 50 years of his life to this endeavour, longer than that of any known collector. Of the >400 mineral species found at MSH, Peter has been the first person to identify at least 35 of these species. In addition, his collecting and subsequent examinations have resulted in him discovering 12 new species from not only MSH but other alkaline localities. Considered to be “the dean” of Mont Saint-Hilaire mineral collectors for his long and sustained contributions to Mont Saint-Hilaire mineralogy, Peter was honoured with having the new species, petarasite, named after him in 1980 by George Y. Chao, T. T. Chen, and J. Baker.
Peter’s dedication to systematic collecting, curating of his own collection, and keeping and maintaining an archive of accurate, detailed historical and scientific information has been of great benefit to the mineral sciences community in Canada and world-wide. Researchers have benefitted from his generosity in providing specimens and information for their studies. Peter has also authored or co-authored many articles in scientific and popular mineralogical publications. Peter has been a member of the Mineralogical Association of Canada since 1964, and was a member of the Mineralogical Society of America for more than 30 years.

Fourteen years ago Peter returned to his roots to work as a volunteer at the Redpath Museum where he has helped to completely renew the mineral exhibits, reorganize the mineral collection, and has written a scientific guide to the mineral gallery. He is an associate at the museum with the title of Honorary Curator of Mineralogy. Peter knows where his passion for the minerals sciences began and he is doing his utmost to ensure that the next generation has the same opportunities that he did.

The Pinch Medal recognizes major and sustained contributions to the advancement of mineralogy by members of the collector-dealer community. The Mineralogical Association of Canada is honoured to present Dr. Peter Tarassoff with this award: he is the true embodiment of what it means to be a professional amateur in the mineral sciences. His legacy, spanning more than five decades, will serve as inspiration for future generations. The Pinch Medal is given out on a bi-annual basis and will be presented at the Tucson Gem & Mineral Show Banquet on 11 February 2017.

$5000 Scholarships

The Mineralogical Association of Canada Foundation will award two $5000 scholarships to graduate students, one to a student enrolled in an MSc program and one to a student in a PhD program. The applicable fields of study are:

- Mineralogy
- Crystallography
- Geochemistry
- Mineral Deposits
- Petrology

Deadline to apply: May 1, 2017

Eligibility

1. Students entering the second year of an MSc program or the second or third year of a PhD program at a Canadian university in September 2017.
2. Canadian citizens enrolled in the above or equivalent programs at any university.

For more information, contact the business office:
Mineralogical Association of Canada
490 de la Couronne
Québec, QC G1K 9A5, Canada
office@mineralogicalassociation.ca

Application form available at www.mineralogicalassociation.ca

Serpentine Days 2016

The 4th international Serpentine Days workshop was held 25–29 September 2016 at the Lazaret resort in Sète (France). Workshop sponsors included the Société Française de Minéralogie et de Cristallographie (SFMC), Géosciences Montpellier, the CNRS, the Université de Montpellier, the Institut des Origines and the Université de Lyon, the Région Occitanie Pyrénées–Méditerranée, and the Deep Carbon Observatory. The workshop convened more than 85 scientists from 13 countries with broad expertise in the geological, physical, chemical and microbiological processes of serpentinization to share new findings in this exciting field of research. Sète’s strategic location enabled the group to spend the first mild days of Autumn immersed in a deep discussion on the side products of serpentinization, such as methane and that intriguing, but evasive, mineral, brucite.

The program was divided into several sessions including:

- serpentines and tectonics, serpentinites and subduction, experimental petrology, serpentinization, redox and carbon cycle, serpentinization and life, ophiolites as field laboratories, and serpentinization in extra-terrestrial systems.

Two poster sessions complemented the oral discussions. Outstanding keynote speakers introduced each session, leading to passionate discussions that continued during coffee breaks and poster sessions. The participation of colleagues from NASA expanded our views on possible serpentinization on Mars.

To complete the workshop, Yves Lagabrielle (University of Rennes, France) and Michel de Saint-Blanquat (University Paul Sabatier, Toulouse, France) led a two-day field trip to the Pyrénées. More than 40 participants joined the field trip, where they explored field evidence of mantle denudation associated with a Cretaceous rifting event in the North Pyrenean Zone (Étang de Lers and Bestiac).

See the full Serpentine Days 2016 workshop report at http://serpentine2016.gm.univ-montp2.fr/

Award Presentation

Camille Cartier, co-winner of the 2015 Haüy–Lacroix award of the SFMC, gave a lecture in Paris (14 November 2016) on the behaviour of the rare earth elements and high field-strength elements at low oxygen fugacity during the early differentiation of the Earth. After a sabbatical year, Camille received her medal from Bertrand Devouard, President of the SFMC.
2017 INCOMING PRESIDENT’S ADDRESS

It is a great honour and a privilege to become President of the Meteoritical Society. I thank Past-President Mike Zolensky for his term and for allowing me to pick up where he left off. Thankfully, Mike will be there for the next two years to help us figure out what he has done. I am also looking forward to working with Meenakshi Wadhwa, newly elected Vice President, whom I am sure will sort out both Mike and myself.

I was introduced to meteorites by Paul Sipiera (Planetary Studies Foundation) when we were both students at Otago University in New Zealand. It was my intention to study isotopic anomalies in meteorites with William Compston on the then newly commissioned SHRIMP at the Australian National University (ANU). Paul introduced me to these awful looking rocks called carbonaceous chondrites. After learning igneous and metamorphic petrology as an undergraduate, these rocks were the weirdest things I had ever seen.

Still, I persevered and was then introduced to the strange mineral hibonite by Ernst K. Zinner (1937–2015). I had been working at ANU to try and resolve the +1‰ 50Ti anomaly in Allende CV3 calcium–hibonite by Ernst K. Zinner (1937–2015). I had been working at ANU and after learning igneous and metamorphic petrology as an undergraduate, these rocks were the weirdest things I had ever seen.

The scale of the isotopic anomalies in hibonites is similar to that found in pre-solar grains, yet these objects were formed in our Solar System. It is simply the chemical memory of the precursors of these grains that were heated to extreme levels in our Solar System some 4.57 billion years ago. Meteorites are samples of the Solar System that have largely escaped much of the planetary homogenisation evident on Earth. With the discovery of more and more exoplanets, meteorites also provide the only ground truth of what an evolving planetary system must have looked like and what processes were active. Unfortunately, meteorites lack context. We must infer location within the current Solar System from where they are now, and then the early Solar System from whence the components came.

Two major developments are helping us out. Fireball networks, such as the Desert Fireball Network being run in Australia by my colleague Phil Bland, allow the placement of meteors back into their Solar System neighbourhoods. Recovering the meteorite also allows a compositional fix to be made. Compositional and locational data provide essential context for our current meteorite collections.

The other major development for meteoritics is the operation of asteroid sample return missions. I have been proud to participate in the Japan's JAXA Hayabusa sample-return mission from the S-type rubble-pile asteroid of Itokawa. This was an outstanding mission, driving out into the Solar System to visit a small asteroid, and then coming back to Earth, with a few interesting adventures along the way. Over a thousand grains of LL chondrite were recovered from Itokawa. But, they have a surprisingly young age. Some chronometry indicates ages of less than a thousand years from this body. How did this happen, or rather, what is happening now? New missions Hayabusa 2 (JAXA), and Osiris REx (NASA) are now flying to the more common C-type asteroids of Ryugu and Bennu, respectively. Will they find that these really are parent bodies of carbonaceous chondrites? During my presidency, we will go a long way towards finding out answers to that question. And, shortly thereafter, we will have more samples of our Solar System back on Earth.

Trevor Ireland
President 2017–2018

OFFICERS AND COUNCIL MEMBERS

The Meteoritical Society will consist of a number of new officers this year. Trevor Ireland (Australian National University, see above) will be transitioning from Vice President to President, and Meenakshi Wadhwa (Arizona State University, USA) will be the incoming Vice President. Mike Weisberg (City University of New York, USA) will continue as our Secretary for a second term, and Candace Kohl (University of California at San Diego, USA) will also stay on for a second term as our Treasurer. Mike Zolensky (NASA, Johnson Space Center, USA) will continue to serve, albeit in his new capacity as Past President. We thank this new slate of officers in advance for their efforts to lead the Meteoritical Society through the next two years.

The Meteoritical Society Council will consist of Cari Corrigan (Smithsonian Institution, NMNH, Washington DC, USA), Christine Floss (Washington University, St. Louis, Missouri, USA), Keiko Nakamura-Messinger (NASA Johnson Space Center, Houston, Texas, USA), François Robert (Muséum National d’Histoire Naturelle, Paris, France), Pierre Rochette (Aix-Marseille University, Marseille, France), Caroline Smith (Natural History Museum London, UK), Mario Tricoff (Heidelberg University, Germany), and Maria Eugenia Varela (Instituto de Ciencias Astronómicas, de la Tierra y del Espacio, Buenos Aires, Argentina).

We would like to take this opportunity to sincerely thank Monica Grady, who is rotating off the council as an officer, and Sasha Krot, Jay Melosh, Larry Nittler, Kevin Righter, Maria Schönbachler, and Hisayoshi Yurimoto who are rotating off as councilors, for their years of dedicated service to keeping the Meteoritical Society operating smoothly!

The 23rd Session of the Petrology Group of the Mineralogical Society of Poland was held 20–23 October 2016 in Stara Morawa (Poland). The meeting was devoted to recent studies on the subduction systems in the Sudetes (northeastern Bohemian Massif, Central Europe) and related areas, examining both ancient and current analogues. The aim of the session was to bring together a wide spectrum of Polish petrologists, including senior researchers, early career scientists, graduates and undergraduate students. The meeting was attended by ~80 participants from Poland and abroad. Invited lectures on the Cadomian and Variscan subduction systems in the Bohemian Massif, as well as on high-pressure mineralogy and fluids activity in the high-pressure rocks, were given by Reiner Klemd (GeoZentrum Nordbayern, Germany), Jana Kotková (Czech Geological Survey), Ulf Linnemann (Senckenberg Natural History Collections of Dresden, Germany) and Hans-Joachim Massonne (Universität Stuttgart, Germany).

An integral part of the proceedings was to award students for the best oral and poster presentations. This year, the best oral presentation award went to Iwona Klonowska (Uppsala University, Sweden) for, “Diamond-bearing Gneisses in the Seve Nappe Complex, Scandinavian Caledonides – What is Known about their P–T–t Evolution?”; the best poster presentation award went to Marcin Goleti (University of Wrocław, Poland) for, “Prograde Metamorphic History Preserved in Mica Schists from the Kamieniec Metamorphic Belt (Bohemian Massif, Fore-Sudetic Block) based on Quantitative Pressure–Temperature Path from Garnet Zoning”. The meeting was also an occasion to commemorate the former President of the Mineralogical Society of Poland, Ryszard Kryza, who passed away in 2016. Kryza’s excellent research on the subduction systems in the Sudetes had been highlighted by several speakers. Oral and poster sessions were followed by the field trip that focused on the metamorphic rocks of the Śnieżnik Massif. Animated discussions at the outcrops made the field trip very stimulating.

In conclusion, the 23rd Session of the Petrology Group was a scientific and social success. Official and unofficial parts of the meeting resulted in many fruitful discussions, including plans for future scientific activities. The organizing team led by researchers from the AGH (University of Science and Technology in Kraków, Poland) would like to thank all the participants for this great experience.

**Jarosław Majka**
PRESIDENT’S LETTER

Publishing Mineral Descriptions and Crystal Structures

The mineral research community has become concerned about the problem of timely publication of descriptions of new minerals and new crystal structures. There is a great backlog of manuscripts at some journals that are traditional outlets for such work. This has not been a problem at the American Mineralogist, which has taken many steps to make the publication process more efficient. However, there have been concerns among authors that the American Mineralogist has stepped back from its tradition of publishing these fundamental contributions to mineralogy. I have taken this concern very seriously in discussions with council members of the Mineralogical Society of America (MSA).

The American Mineralogist editor has strived to raise the citation index of the journal. Some suspect that descriptive papers don’t engage an adequately broad readership to meet the changed criteria to achieve this goal. Some manuscripts may do a good job of describing a new mineral or its structure but lack details about the species’ geological context or its implications for the mineral forming environment. Likewise, the significance of a new structure type or topology may not be explained in terms of its implications, such as how it is novel or revolutionary, the implications for its thermodynamic properties, its possible phase transitions, or some other important characteristic. Resistance by some authors to include this added information has led to rejection of their manuscripts. I have received assurances that American Mineralogist will continue to perform its role of publishing fundamental mineralogical manuscripts. Nonetheless, the journal faces financial limits on the amount of material it can publish, which results in either increased rejection rates or requests to shorten papers and so help keep the MSA solvent. After all, publishing is MSA’s main game, so keeping our publications viable is critical to the mineralogical sciences. So, I urge authors to address these challenges when submitting to American Mineralogist.

On the horizon is a new outlet for mineralogical data that should improve the situation: the creation of an MSA data journal, which has been talked about for some time and is the pet project of Past President Becky Lange. The publishing emphasis will be presentation of data, rather than implications. This will not necessarily address all problems of publishing mineral descriptions, new occurrences, or structures, but it will lead to a greater spectrum of mineralogical data becoming available in a more timely and less costly manner. One interesting problem it will likely address is the difficulty of, hence seldom seen, publishing mineral descriptions, new occurrences, or structures, but rather than implications. This will not necessarily address all problems of publishing mineral descriptions, new occurrences, or structures, but rather than implications. This will not necessarily address all problems of publishing these fundamental contributions to mineralogy. I have taken this concern very seriously in discussions with council members of the Mineralogical Society of America (MSA).

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George Harlow
2017 MSA President

Notes from Chantilly

- MSA will have electronic balloting for its 2017 election of 2018 MSA officers and councilors. The slate of candidates, all from the USA except where indicated - President: Michael Brown (University of Maryland); Vice President (one to be selected); Lukas P. Baumgartner (University of Lausanne, Switzerland) and Mickey E. Gunter (University of Idaho). Secretary: Bryan C. Chakoumakos (Oak Ridge National Laboratory). Councilors (two to be selected): Martin Kunz (Lawrence Berkeley National Laboratory), Vincent J. Van Hinsberg (McGill University, Canada), Jay J. Ague (Yale University), and Donna L. Whitney (University of Minnesota). Thomas S. Duffy (Princeton University) continues in office as Treasurer. Continuing councilors will be Rajdeep Dasgupta (Rice University); Peter I. Nabelek (University of Missouri-Columbia); Sarah K. Carmichael (Appalachian State University); and Sarah C. Penniston-Dorland (University of Maryland).

- All 2015 and 2016 MSA members have been contacted by mail, electronically, or both about renewing their membership for 2017. If you have not renewed your MSA membership, please do so. If you have not received a notice by the time you read this, please contact the MSA Business Office. You can also renew online at anytime.

J. Alex Speer
MSA Executive Director
jaspeer@minsocam.org

THE MSA COUNCIL

Depending on how they are counted, there have been 159 meetings of the MSA Council, with the first in 1920. As far as I know, there are no pictures of a council meeting until this one in the Fall of 2016. Seated at the table is your hard-working 2016–2017 Council, counterclockwise starting at the right are:

Rebecca Lange, President; Bryan Chakoumakos, Secretary; Wendy Panero, Councilor; Edward Grew, Councilor; Sarah C. Penniston-Dorland, Councilor; Sarah K. Carmichael, Councilor; Matt Kohn, Councilor; Thomas S. Duffy, incoming Treasurer; Michael Brown, incoming Vice-President; Rachel Russell, Managing Editor; Steve Shirey, Past-President; Howard Day, outgoing Treasurer; Peter Nabelek, Councilor; George Harlow, Vice-President & incoming President; J. Alex Speer, Executive Director. Not present: Rajdeep Dasgupta and Abby Kavner, Councilors.
MSA CENTENNIAL HISTORY

In February 1917, one hundred years ago this month, Edward H. Kraus, a faculty member at the University of Michigan, circulated the typeset flyer (below) to 51 mineralogists in the USA and Canada. He invited them to join as charter members the organization to be called the Mineralogical Society of America. At the same time, Prof. Kraus circulated a draft constitution among those he felt were most interested. By the end of the summer, 35 replies were received, 29 being favorable. Much of the discussion in those original reply letters concerned including the terms “petrographical” and “crystallographical,” both as subject matter and in the name of the society; a possible society publication; meetings; whether there were a sufficient number of mineralogists to form a viable and specialized society – might it better to be a branch of a larger society because there were so many other societies; and the $10 cost of membership (= $203.90 in 2016 dollars).


For several years past, none of those attending the annual meetings of the Geological Society of America have discussed the advisability of organizing a separate society composed of persons whose interests be more especially in the field of Mineralogy. The feeling has been growing that the founding of a Mineralogical Society would do much to stimulate greater interest in the subject and also give wider recognition to the work being done in this field in America. Accordingly, the undersigned, who were in attendance upon the meetings of the Geological Society of America, at Atlantic City, in December, 1916, discussed this question very thoroughly, and it was agreed that the time has come when an organization which might be called “The Mineralogical Society of America” should be formed at as early a date as possible.

While many of the advantages resulting from such an organization are apparent to all interested, the undersigned felt that perhaps the greatest benefit to be derived would be from the founding of the society of a Journal to be devoted exclusively to the publishing of mineralogical papers. As is well known, there is great need for a disilled medium of publication for the increasing volume of mineralogical investigations which are being carried on in America. Naturally, such a publication must be a modest basis, and appear perhaps as at first as a quarterly. Members of the society would of course receive the Journal free of charge.

With respect to organization and means of publication, mineralogists in America are far behind their colleagues in Europe, but we feel confident that you will respond promptly and favorably to our appeal to write with us as a charter member in perfecting the organization of this society, the standards of which are to be on a par with those of the Geological Society of America. In order to secure the publication of a Journal, which would naturally have a somewhat limited circulation, it was thought advisable that the annual dues be placed at $10.00.

This letter is being addressed to a selected list of mineralogists in the United States and Canada, and if a sufficient number of favorable replies is received, it is planned to complete the organization sometime during the current year.

Professor Edward H. Kraus, Ann Arbor, Michigan, has been designated to conduct the correspondence looking toward the organization of the society. He will be glad to hear from you at your earliest convenience.

Very sincerely yours,

Edward H. Kraus
Alexander H. Phillips
Frank R. Van Horn

Thomas L. Walker
Edgar T. Wherry
Herbert P. Whittlesey

AWARD NOMINATIONS

Nominations Sought for 2018/2019 Awards
Nominations must be received by 1 June 2017

The Roebling Medal (2018) is MSA’s highest award and is given for eminence as represented by outstanding published original research in mineralogy.

The Dana Medal (2018) is intended to recognize continued outstanding scientific contributions through original research in the mineralogical sciences by an individual in the midst of their career.

Mineralogical Society of America Award (2018) is given for outstanding published contribution(s) prior to 35th birthday or within 7 years of the PhD.

The Distinguished Public Service Medal (2019) is presented to an individual who has provided outstanding contributions to public policy and awareness about mineralogical topics through science.

Society Fellowship is the recognition of a member’s significant scientific contributions. Nomination is undertaken by one member with two members acting as cosponsors. Form required, contact committee chair or MSA home page.

Mineralogical Society of America

Submission requirements and procedures are on MSA’s home page: http://www.minsocam.org/

New title: REVIEWS in MINERALOGY and GEOCHEMISTRY


Since the publication of Geochemistry of Non-Traditional Stable Isotopes in 2004 (volume 55 of the RiMG series), analytical techniques have significantly improved and new research directions have emerged in non-traditional stable isotope geochemistry. This volume reviews the status of non-traditional isotope geochemistry from analytical, theoretical, and experimental approaches to the analysis of natural samples. In particular, applications to cosmochemistry, high-temperature geochemistry, low-temperature geochemistry, and geobiology are discussed. The aim of this volume is to provide the most comprehensive review on non-traditional isotope geochemistry for students and researchers who are interested in both the theory and applications of non-traditional stable isotope geochemistry.

Description and ordering online at www.minsocam.org or contact Mineralogical Society of America, 3635 Concorde Pkwy Ste 300, Chantilly, VA 20151-1110 USA phone: +1 (703) 652-9950 fax: +1 (703) 652-9953 e-mail: business@minsocam.org. Cost is $45 ($33.75 members MSA, GS, CMS).
diffraction (XRD); X-ray fluorescence (XRF); BET (Brunauer, Emmett and Teller) surface area analysis; and X-ray photoelectron spectroscopy (XPS). In addition, cyclic voltammetry assesses the redox behavior of the antimicrobial metal agents encapsulated within the zeolite. This work should make possible the development of zeolite clays as carrier support materials having antimicrobial properties.

Nathan Rabideaux uses the mineralogical and geochemical analysis of terrestrial sediments to reconstruct high-resolution records of Quaternary environmental change near rift lake basins in East Africa. He is particularly interested in how authigenic minerals reflect evolving lake water and soil geochemistry in response to climatic and tectonic forcing. His research is part of a collaborative drilling, coring, and outcrop study that aims to understand climate and environmental change during the Pliocene–Pleistocene in East Africa and how that change relates to hominin evolution and cultural adaptations.
CLAY MINERAL SOCIETY ANNUAL MEETING

The 54th Annual Clay Minerals Society Conference (www.cms2017.com) will be held 5–8 June 2017 in Edmonton, Alberta (Canada) in conjunction with the Oil Sands Clay Conference. The conference is being organized by the Centre for Oil Sands Sustainability and the Clay Minerals Society and will be supported by BUKSA Associates. The program will include the 10th Canadian Powder Diffraction Workshop (Friday to Sunday, June 2–4), a “Dinosaur Hunting in Drumheller” field trip (Saturday, June 3), and Introduction to Oil Sands Clays (Sunday, June 4) prior to the meeting; trade show and tours of the Northern Alberta Institute of Technology and University of Alberta during the conference; and an oil sands tour on Wednesday afternoon and Thursday (June 7–8).

Session titles and topics include:

- “Structure and Properties of Clays”— clay structure, clay modeling, clay nomenclature.
- “Clay Minerals and Health”— use of clay minerals in medicine and beauty products/treatments.
- “Clays and Genomics/Microbiology”— clay interactions with microorganisms/proto-microorganisms.
- “Clays in Oil and Gas”— drilling, fracking, shale gas, tight gas, enhanced oil recovery, and exploration geochemistry.
- “Clays in Mining”— methods for improving selectivity of mining, impacts of clay in non-clay mining processes, and hydrometallurgy/pyrometallurgy.
- “Clay/Organic Interaction and Clay/Polymer Interaction”— fundamentals of the interaction of clays with various organic compounds, including polymers, solvents and proteins.
- “Clays in Water/Solid Separation Processes”— how clays impact solid/liquid separation processes including sedimentation, thickening, centrifuging, and filtering.
- “Clays in Rheology”— this session will focus on the rheological properties of clay slurries.
- “Clays in Geotechnical Engineering”— dam foundations, consolidation, development of strength, and impact on freeze–thaw cycling/frost heave.
- “Clays and Soil Formation”— nutrient cycling and weathering, carbon capture.
- “Clay and Environmental Quality”— clay remediation and contaminant migration.
- Any other topic related to the conference theme.

Abstracts should be submitted by Monday, 20 March 2017 (11:59 PM MT).

CMS MEMBERSHIP RENEWAL

Please renew your membership for 2017!

Dear colleagues,

Registration to the 2017 European Mineralogical Union (EMU) school is now open! Please spread the news!

The 2017 EMU school on Mineral Fibres: Crystal Chemistry, Chemical-Physical Properties, Biological Interaction and Toxicity will be held 19–23 June 2017 in Modena (Italy). The related EMU Notes volume will be also released during the school.

The school welcomes advanced graduate and PhD students, as well as young and experienced researchers with an interest in mineral fibres. The school will cover different multidisciplinary aspects related to the study of natural fibres. It is, thus, aimed at students with a background in biology, chemistry, geology, material science, medicine, and physics. This course is designed for those who strive to work in the field of mineral fibre and asbestos and for those who want to acquire a strong background in this specific area of environmental protection and a multidisciplinary open vision of the asbestos related problems.

For detailed information and REGISTRATION (ON-LINE) go to the web site: emu2017.unimore.it

Travel grants will be issued by EMU and IUCr (International Union for Crystallography) for young scientists participating at the school (see the web site for the details). Selection will be made by the school organizers. SIMP will support attendance (travel and accommodation) of Italian students. A call for applications will be issued by SIMP in the near future. Looking forward to seeing you in Modena!

The Chair of the EMU 2017 school
FINAL THOUGHTS FROM THE PRESIDENT

Well, this is my last contribution as President of IAGC. After a very brief two years, I am passing the baton into the capable hands of Philippe Negrel (French Geological Survey) who will take over the role of IAGC President for the next two years. Neus Otero (University of Barcelona, Spain) is the new vice-president, and she will be profiled in the next issue of *Elements*. I would like to thank everyone on the committee who has helped me to keep some semblance of organisation over the last couple of years, especially Chris Gardner, who has made sure that myself and the rest of the committee have met deadlines and carried out the tasks that we said we would.

I have had the pleasure of attending two of the working group meetings whilst being president and of meeting many members of the IAGC. I would have ideally attended more of the meetings but distances from Australia and an academic calendar that is out of sync with those in the northern hemisphere makes that somewhat of a challenge. I appreciate the considerable work that the IAGC working groups do to organise these popular and productive meetings on a regular basis. The working group meetings allow for considerable networking opportunities and provide for a relaxed atmosphere in which to discuss science. I would certainly recommend them.

Having been involved in geochemistry for over 30 years, I am always heartened by the degree to which it continues to progress as a discipline. When I started, radiogenic and stable isotope techniques were at the cutting edge of research. Over the last few decades, we have seen great advances in understanding the interaction between the biosphere and the lithosphere or hydrosphere, and fields such as biogeochemistry and geomicrobiology are becoming more prominent. We have also seen great advances in technology: portable stable isotope analysers allow real-time geochemical data to be collected in dynamic environments; we can directly determine the geochemistry of other planets; and we can use synchrotron techniques to explore the details of materials and reactions. In the future, I look forward to the new understanding of processes that comes from the new opportunities arising from cross-disciplinary collaboration and the further development of technology that will open up fresh research directions.

As I always do, I’ll finish with an encouragement to be involved in IAGC. If you can help with a working group or contribute to the committee when vacancies arise, please do so; it isn’t a large time commitment, and your contribution is an immeasurable benefit to the society and its members. If you have suggestions of how the society can do things better, or if there are things that we should be doing, then please let us know. So, whether you are looking forward to summer or bracing for winter, I hope that your geochemical endeavours over the next few months are fruitful, and I look forward to seeing you at an IAGC working group meeting in the future.

Ian Cartwright

PROFESSOR JANE PLANT (CBE), 1945–2016

It is with great sadness to report that Jane A. Plant, a leading geochemist who was awarded the Commander of the British Empire (CBE), passed away 4 March 2016. She will be remembered vividly by many of her former research colleagues across the world. A leading geochemist of high international standing, Jane made a lasting impression on those who had the privilege of working with her because of her passion and creativity and exceptional gift for meaningful research. She leaves a substantial legacy: a baseline-geochemical dataset for the United Kingdom (UK) and methods that have been adopted/adopted around the globe as standard for geochemical surveying. Further, Jane developed prolific research outputs in metallogenesis, crustal evolution and medical geochemistry. She became one of the UK’s most senior female scientists in an era when this was rare and when women faced many barriers to progression. She was the author of over 200 publications, and her scientific reputation was recognised throughout her career. Her offices included being on the Royal Commission on Environmental Pollution (1999–2005); President of the Institute of Mining and Metallurgy (2001–2002); Fellow of the Royal Academy of Engineering (2012). In 1997, she was awarded Commander of the British Empire (CBE) for her contribution to science and industry. Jane joined the British Geological Survey (BGS) in 1967 with a first-class geology degree from the University of Liverpool (UK). Her career progressed rapidly, developing geochemical surveying methods, for which she was awarded, in 1977, a PhD from the University of Leicester (UK). By 1983 Jane had achieved Individual Merit Promotion in recognition of her scientific achievements. Following a sabbatical as vice-president of a Canadian exploration company, she became the first female Assistant Director of the BGS before her appointment as BGS Chief Scientist in 2002. Jane retired from the BGS in 2005, but her career continued with publication of *Your Life in Your Hands: Understand, Prevent and Overcome Breast and Ovarian Cancer* (updated 2007 edition, Virgin Books Ltd), the first of several books she wrote on diet and health, following her experiences with cancer. Jane was Emeritus Professor of Geochemistry at Imperial College, London (UK) until her death.

This is a version of the obituary originally published by the British Geological Survey on their website: http://www.bgs.ac.uk/news/item.cfm?id=7318

BIOGEOMON 2017: 9th INTERNATIONAL SYMPOSIUM ON ECOSYSTEM BEHAVIOUR

20–24 August 2017
Litomyšl château (Czech Republic)
www.biogeomon.cz

Registration Deadline: 10 March 2017

The BIOGEOMON 2017 symposium will focus on biogeochemistry in an era of global change. Important themes will include long-term trends in ecosystem functioning, the stoichiometry of biochemical processes in upland and wetland soils, catchment monitoring/modeling, nutrient movements, micronutrients and trace metals in forest ecosystems, grasslands, and extreme environments. Please do not miss the 10 March 2017 abstract deadline. We look forward to seeing you in the lovingly restored 16th century town of Litomyšl.

Specific topics will include:
- Catchment monitoring and modelling
- Process-level studies in upland and wetland soils
- Interactions between biogeochemical cycles of C, N, P, S, Ca and Mg
- Micronutrients and trace metals in ecosystems
- Biogeochemistry in an era of global change
- Linking microbial communities with element pools and fluxes
- Traditional and novel isotope systems in the environment
- Ecosystem restoration/rehabilitation/management

Ian Cartwright
REPORT OF EMU ACTIVITIES 2012–2016

The European Mineralogical Union (EMU) Executive Committee met in September 2017 at emc2016 (Rimini, Italy). Here follows a short summary of the major points and conclusions from that EMU meeting.

The main achievements of 2012–2016 were EMU’s publishing activities (the EMU Notes in Mineralogy series), the organization of EMU ‘Schools’, the organization of conferences (the European Mineralogical Conference and the Goldschmidt Conference), and awarding scientists who have shown exceptional contributions to their field either with an EMU Research Excellence Medal, an EMU poster prize, or with an EMU grant.

The EMU Notes in Mineralogy series continues to grow. Previously published volumes have now been digitized and are available through GeoScienceWorld. During 2012–2016, five volumes were issued. Among them, EMU12 Raman Spectroscopy Applied to Earth Sciences and Cultural Heritage achieved the greatest interest. The next four volumes will be released in accordance with the latest trends in our science. To enhance commissioning, production, and marketing, a new agreement has been signed with the Mineralogical Society of Great Britain and Ireland (MSGB). The production of the Notes is currently a major expense, but that expense has been counterbalanced by improved sales. Income is steadily growing, reaching a record high in 2016. Collaboration with the Mineralogical Society of America (MSA) on educational and publishing projects resulted in EMU Notes being advertised and sold on MSA’s website.

The EMU has, since the very beginning, supported the European Mineralogical Journal. The EMU participates in that journal’s managing committee meetings, nominates one of the chief editors, and helps to solve problems related to the choice of associate editors and to editorial policy.

After the success of Goldschmidt 2013 (Florence, Italy), where mineralogy played a more important role than usual, the European Association of Geochemistry (EAG) provided various slots for EMU activities at Goldschmidt 2015 (Prague, Czech Republic). The same is planned for Goldschmidt 2017 (Paris, France).

The most important award given each year is the EMU Research Excellence Medal. During 2012–2016, Richard Harrison, Diego Gatta, Razvan Caracas, Encarnación Ruiz-Agudo, István Kovács, and Sylvie Demouchy were honoured with this prestigious distinction. Also important are the conference-related EMU prizes. In 2012–2016, EMU awarded 14 poster prizes and awarded grants to dozens of young scientists.

Another very important area of EMU activity is school organization. One occurred in Vienna (Austria) shortly after emc2016, MKR2016 - Mineral Reaction Kinetics: Microstructures, Textures, Chemical and Isotopic Signatures. The next school will be called Mineral Fibres: Mineral Reaction Kinetics: Microstructures, Textures, Chemical and Toxicity, and will take place 19–23 June 2017 in Modena (Italy).

The committee also discussed the importance of cooperation with other international organizations. Cooperation enhances development and promotes the mineralogical sciences. It is very important to have a forum for discussion and a fast way to communicate news of mineralogical interest in Europe. It seems to be necessary to build and maintain an EMU talk list that can include scientists, students, and mineral collectors. This report shows not only the measures and activities undertaken by the EMU Executive Committee but also shows their positive role. For these activities, the outgoing committee deserves the highest appreciation.
CARBONACEOUS CHONDRITE IMPACT MELTS

Nicole G. Lunning1,2 and Catherine M. Corrigan2

1811-5209/17/0013-0068$0.00 DOI: 10.2113/gselements.13.1.68

Collisions between planetary bodies (such as asteroids colliding with one another or with planets) have played a role in the geologic evolution of our Solar System since the formation of planetesimals, the earliest kilometer-scale bodies. Shock damage from collisional impacts leaves evidence on surviving planetary materials that range in scale from kilometer-sized craters to nanometer-sized mineral structural defects. Impact shock-induced melting is thought to be a common consequence of collisions throughout the Solar System. While ordinary chondrites, martian, and lunar meteorites all exhibit signs of having been melted by impacts, until very recently, no impact melts of primitive carbonaceous chondrites had been recognized (Lunning et al. 2016a).

CARBONACEOUS CHONDRITES

Carbonaceous chondrites include the most primitive known Solar System materials and hold important clues for understanding the origin of the Solar System. Some of their primitive components formed as small objects (≤ cm-scale) in the protoplanetary disk and experienced minimal modification after the accretion of their parent planetesimals (Fig. 1). The primitive nature of carbonaceous chondrites is part of the motivation for the ongoing Hayabusa 2 (JAXA) and OSIRIS-REx (NASA) spacecraft missions, which will return samples from carbonaceous chondrite-like asteroids. The samples carried back to Earth by these spacecraft will be the most pristine (i.e. will have experienced the least amount of terrestrial alteration) primitive Solar System materials ever studied by scientists on Earth.

Carbonaceous chondrites are a class of meteorites defined by their similarity in volatile elemental abundance and refractory lithophile elemental abundance. The shared elemental and isotopic signatures of this meteorite class suggest they originated from the same or similar geochemical reservoirs in the protoplanetary disk. However, the 8 known groups (CI, CM, CV, CR, CO, CK, CB, CH) within the carbonaceous chondrite class originated from separate parent bodies.

MISSING IMPACT MELTS

Scott et al. (1992) called attention to the dearth of impact melted carbonaceous chondrite material. The lack of carbonaceous chondrite impact melts might be explained by the meteorites higher volatile concentrations which may prevent the formation of cohesive melts. Many researchers have been searching for these melt features to little avail.

CARBONACEOUS CHONDRITE IMPACT MELTS – FOUND!

Recently, in three separate meteorites, five objects have been identified that appear to be carbonaceous chondrite impact melts. These objects were found by the systematic petrographic examination of the CV chondrites in the Smithsonian Institution’s (USA) thin section library and through the petrological characterization of howardites found in the Grosvenor Mountains (GRO) field area in Antarctica in 1995 (Lunning et al. 2016a,b).

The objects all contain signs that they had rapidly cooled from melts. For example, they contain >60% olivine microphenocrysts, which are strongly zoned with Mg-rich cores and comparatively Fe-rich rims (Fig. 2).

The term “carbonaceous” in their name is a bit of a misnomer. Although a few groups within this meteorite class are somewhat carbon-rich (e.g. CI and CM chondrites contain up to wt% quantities of elemental carbon), carbonaceous chondrites do not consistently contain more carbon than other stony meteorite classes (Krot et al. 2003; Scott and Krot 2003).

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FIGURE 1 NASA image of the Robert Massif (RBT) 04143 carbonaceous chondrite (CV3) found in Antarctica by the U.S. Antarctic Search for Meteorites (ANSMET) program. The cube pictured is 1 cm along each edge and the ruler is in cm. The light-colored object in the piece below the * is an impact melt pocket that formed by in situ melting of this carbonaceous chondrite.

FIGURE 2 Schematic illustrating a generalized scenario for impact melt formation. (A) Impact-induced bulk melting. Only very Mg-rich relict olivine (dark green) is not melted. Immiscible silicate (grey) and FeNiS (yellow) liquids are formed. (B) Olivine rapidly crystallizes from the silicate liquid and FeNiS liquid globules and coalesce into larger globules. (C) Olivine continues to crystallize. The five objects referred to in the main text were arrested around this point, thereby quenching the silicate liquid into glass and trapping vesicles (if present). Images of the slight variations on the texture between separate objects are illustrated in Lunning et al. (2016a).
ORIGIN OF THE CM CHONDRITE MELT DROPLET

Measurements of all three stable isotopes of oxygen ($^{16}$O, $^{17}$O, $^{18}$O) obtained through secondary ion mass spectrometry analyses are a powerful tool for assessing the distinct provenance of planetary materials (e.g. Greenwood et al. 2016). The oxygen three-isotopic signature of olivine in the melt object found in the howardite howardite provided evidence that the object is a CM chondrite impact melt. The nonrelict olivines in this melt object have oxygen three-isotope signatures that overlap the bulk CM chondrite range and do not overlap the ranges of any other known Solar System materials. The relict olivine core in this object has an oxygen three-isotope signature that falls slightly above the carbonaceous chondrite-anhydrous mineral (CCAM) line (Fig. 3) and coincides with the primitive chondrule mineral (PCM) line (Ushikubo et al. 2012). These results further support that this object did not form by impact melting of its howardite host or another member of the howardite, diogenite, diogenite (HED) meteorite clan (generally thought to originate from the asteroid 4 Vesta). Rather, the melt object is composed of CM chondrite impactor material. A CM chondrite was melted upon impact with the parent HED body, ejected a melt droplet, which was solidified in-flight. It was subsequently incorporated into the HED regolithic sediments, which were later collectively lithified to form its host breccia. This CM chondrite melt droplet bears some textural similarity to impact derived crystal-bearing spherules/droplets identified in lunar and martian regolithic samples (Symes et al. 1998; Ruzicka et al. 2000; Udry et al. 2014).

RELEVANCE TO CURRENT ASTEROID EXPLORATION

The newly discovered carbonaceous chondrite impact melts have olivine-dominated mineral assemblages, which are notably different from their unmelted precursors. Thus, impact melt-rich regions on carbonaceous chondrite-like asteroidal surfaces may be identifiable using high-resolution mapping during spacecraft missions. JAXA’s Hayabusa 2 spacecraft and NASA’s OSIRIS-Rex spacecraft are currently heading toward asteroids that are thought to be composed of carbonaceous chondrite material. These recently discovered carbonaceous chondrite impact melts may inform site selection for these spacecraft to collect samples and aid in distinguishing impact-modified material from other regolith components in future samples returned via spacecraft missions to these and other Solar System bodies.

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Figure 3 Oxygen three-isotope plot of olivine in Clast mIM in the regolithic howardite GRO 95574.17. The composition of the olivine relict core (yellow circle) falls slightly above the carbonaceous chondrite–anhydrous mineral (CCAM) line. Oxygen three-isotope compositions of common meteorite groups are from Krot et al. (2003) and references therein. Known achondrite groups plot close to the howardites/eucrites/diogenites or on the terrestrial fractionation line (lunar rocks) or above (martian rocks). Modified from Lunning et al. (2016a).
Proficiency testing (PT) is a cornerstone of good analytical practice, providing one of the few means of really testing the quality of a lab’s analytical output. Participation in a routine PT scheme can form part of lab accreditation, and for many industrial applications (e.g. ore grade determinations for the mining industry) it is often expected that mineral assay laboratories track their PT results. As an example, National Instrument 43-101, which is Canada’s “Standards of Disclosure for Mineral Projects”, requires the written disclosure of the methods used to verify quantitative data related to new mineral prospects seeking public funding. Hence, proficiency testing has become a de facto component of ore grade assessment whenever a mining company applies for listing on the Toronto stock exchange. Clearly, proficiency testing is not only of research importance but also plays a central role in the world’s mining industry.

So what exactly is a proficiency test? A laboratory will receive a material for analysis and it will submit its results to the PT organizers, who will, in turn, evaluate the submitted result against some benchmark believed to represent the true concentration of the analyte of interest. The critical point about a proficiency testing scheme is that the participating laboratories are required to perform their analyses using routine procedures – no special sample preparation methods, no special efforts towards improved data quality, no extra steps in the quality assurance process are allowed. Thus, if a laboratory’s results closely match the benchmark values then one can have confidence that the analytical methods being used on a routine basis are trustworthy. However, if the report from the PT organizers shows significant discrepancies from the set benchmark then the given laboratory needs to take steps to investigate a so-called “out of control” situation.

The International Association of Geoanalysts (IAG) has operated a whole-rock PT programme since 1996, the first of which involved 49 laboratories reporting concentration results on 51 elements from the Threlkeld microgranite of Cumbria (UK) (Thompson et al. 1996). This round of PT testing involved the dispatch of packets of milled whole-rock powders (Fig. 1) where the participating labs were given three months to report their results. Over the following 20 years, the number of participating labs has now grown to over 100. Likewise, over the years the analytical methods used for such analyses have evolved, such that today’s datasets are dominated by solution inductively coupled plasma (ICP) and X-ray fluorescence (XRF) methods – largely gone are the days of neutron activation, wet chemical determinations and atomic absorption analyses. The evaluation of PT data often relies on the experience of the programme organizers, with target benchmarks often based on either the robust mean or the median values of the submitted dataset. So how do we know that these target values are close to the true concentration values of the many various elements? This topic was addressed by Potts et al. (2015) who compared the target values derived from the IAG’s GeoPT dataset to those derived for the same materials based on painstaking certification projects: few significant differences were found between six such datasets.

Now I would like to present several interesting data sets that reveal the presence of analytical problems which might, were it not for the participation in a proficiency testing programme, have gone unnoticed.

First, I present an example of what might be called a well-behaved dataset for iron in a sediment powder (Fig. 2), which is the norm for such work. The data are plotted in ascending order in terms of the reported Fe2O3 (total) concentration. What one sees from this plot is that the data closely approximate a Gaussian distribution (Fig. 2 inset). However, this dataset also shows a few obvious outliers at both the high and the low ends of the mass fraction spectrum. In this dataset, the robust mean of 6.46 g/100 g and the median value of 6.45 g/100 g are in excellent agreement, indicating that there is no significant skewing. Two things are noteworthy: 1) There were a large number of analytical techniques used to obtain the 79 values contained in this report; 2) There appears to be a slight bias of the ICP results towards higher concentrations compared to the XRF data, albeit with the two lowest reported concentration values being from ICP laboratories. Obviously, those dozen or so laboratories that produced results at the extremes of this data spectrum need to investigate their measurement procedures. Nonetheless, the overall distribution of results for iron in this sediment powder looks satisfactory.

In contrast to the dataset shown in Figure 2, I present a dataset for strontium concentrations in the Separation Lake pegmatite (Ontario, Canada) that were reported during the August 2008 round of GeoPT (Fig. 3). Not only do the data show an obvious non-Gaussian data distribution, but there are two distinct plateaus, with the low abundance plateau value of ~8 mg/kg being exclusively populated by laboratories using ICP technology. Furthermore, nearly all members of this group of laboratories used a mass spectrometer as their signal detection system. The second clustering of data around ~35 mg/kg total Sr is dominated by XRF data, but this group also contains a number of analysts reporting results based on ICP technology, the majority of whom recorded their data using an emission spectograph. The explanation here is easy to understand, in that a common approach for determining total Sr mass.

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**Figure 1** Sample sachets from earlier rounds of the IAG’s GeoPT proficiency testing programme. Each unit contains around 50 g of whole-rock powder.
fraction using mass spectrometry relies on the determination only of the $^{87}$Sr content in conjunction with the supposedly known isotopic composition of natural strontium. The Separation Lake pegmatite has an age of 2.64 Ga (Tindle et al. 1998) and a bulk rock rubidium concentration of 2,501 ± 22 mg/kg as defined by the robust mean of the proficiency testing data from 64 laboratories. Considering such a high Rb/Sr ratio, a late Archean age and that the half-life of $^{87}$Rb is 48 Ga, one can understand that this material's strontium budget is dominated by radiogenic $^{87}$Sr. This enrichment in $^{87}$Sr will go undetected if the one can understand that this material's strontium budget is dominated by radiogenic $^{87}$Sr. This enrichment in $^{87}$Sr will go undetected if the analytical method assesses only the $^{88}$Sr in the sample. This dataset should have been a wake-up call for many ICP–MS analysts who might otherwise have continued to make this oversight were it not for their participation in a proficiency testing programme.

A second interesting example involves the MRH-1 rhyolite reference material. The XRF data for zirconium showed a very well-defined mode of 0.15 mg/kg, whereas the ICP results showed a broad spectrum of results with a range of ~200–500 mg/kg. Clearly, there is a method-dependent analytical problem influencing the Ni dataset, and here a bit of knowledge about the sample preparation method, with acid digestion revealing by far the largest scatter in the results. This may come as a bit of a surprise because one would think that a “rhyolitic glass” is one of the less challenging silicate matrices to convert to a solution. A further clue is the strong correlation found between the reported hafnium and zirconium results (Fig. 4). The slope of the best-fit line of Zr/Hf = 31.8 is within the range that is common for zircon (e.g. Hoskin and Schaltegger 2003). Hence, the MRH-1 data clearly point towards some of the participating labs having unsuspected problems getting complete sample dissolution, and, in particular, being unable to fully digest zircon. Those laboratories that reported low Zr (as well as low Hf) abundances should investigate their sample preparation procedure for this suspected problem.

As a final example, I would like to share data from the most recently completed round of the GeoPT programme. The data come from nickel concentrations reported for the SyMP-1 syenite. The results are clearly non-Gaussian in their distribution, with a lower concentration plateau of around 160 mg/kg populated nearly exclusively by XRF data (Fig. 5). Significantly, this group of data consist almost exclusively of laboratories using pressed powder (PP) sample preparation. In contrast, most of the data based on ICP, along with numerous XRF results based on fused disc (FD) sample preparation, cluster around the significantly higher value of ~230 mg/kg. Clearly, there is a method-dependent analytical problem influencing the Ni dataset, and here a bit of knowledge about this syenite’s mineralogy is key to understanding this rather perplexing observation. This syenite contains a significant concentration of 1.01 g/100 g of sulfur, much of this in the form of iron sulfides. It turns out that much of the Ni contained in this material is also housed within these sulfide grains. The XRF measurements need to be corrected for X-ray self-absorption by the sample material, yet the absorption coefficients are routinely based on the bulk composition of the material. In other words, one might suspect that the correction made by many of the XRF laboratories for determining Ni would have been based on a silicate composition, whereas a more appropriate self-absorption correction for Ni measurements on pressed powder pellet samples would use the iron sulfide matrix that is believed to house the nickel (Webb et al. 2016). According to this model, many of the XRF facilities would have under-corrected for self-absorption, resulting in the determination of values for the bulk Ni content of this material that are too low.

Cont’d on page 72
I hope these few case studies help illustrate some intriguing pitfalls in the analysis of bulk rock samples. Certainly, I think these examples put a spotlight on the power of a proficiency testing programme for revealing shortcomings in a laboratory’s methods. I would like to end by thanking Peter Webb (Milton Keynes, UK), who has been a long-term member of the GeoPT steering committee, Thomas Meisel (Leoben, Austria), who is President of the International Association of Geoanalysts, and Marcus Burnham (Sudbury, Canada) of the Ontario Geological Survey, all of whom provided invaluable assistance in preparing this toolkit contribution.

To learn more about this 12-month position, please contact the search committee chair, Dr. Claudia Cenedese, by phone (508-289-2696) or e-mail (ccenedese@whoi.edu). To view the more about WHOI and the position and to apply, please go online at http://jobs.whoi.edu under ‘Administrative Positions’. The review of applications will begin March 1, 2017.

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![Graph showing sulfur isotope signature](image1)

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