

Editorial

Magmas and their sources: A special issue honoring Frederick A. Frey

This special issue is dedicated to Frederick A. Frey (Fig. 1), a pioneer in the use of trace element geochemistry (especially the rare-earth elements, REE) to interpret the origin and evolution of basalts and andesites, peridotites, granites, meteorites, tektites and even sediments. Fred's remarkable career spans more than 5 decades starting in 1964 with his seminal paper with advisor Larry Haskin entitled "rare earths in oceanic basalts" (Frey and Haskin, 1964). Given that Fred was an Associate Editor of *Geochimica et Cosmochimica Acta* (GCA) for 20 years, GCA is a highly appropriate venue for this collection of twenty-seven new scientific papers in his honor.

Fred's undergraduate training was in chemical engineering. After a year in industry, he decided to seek an advance degree. He was undecided on whether to get a Harvard MBA or Ph.D. in physical chemistry at the University of Wisconsin at Madison. The coin he flipped landed on heads and we have all benefitted greatly from that lucky toss (Haskin and Frey, 1987). It was fortuitous for us that Fred met Larry Haskin, his thesis supervisor, who introduced him to Radiochemical Neutron Activation Analysis (RNAA), and got him started on determining REE abundances in mafic and ultramafic rocks. When Fred started on this journey in 1961, virtually nothing was known about REE abundances in these rocks. The RNAA method was a tedious and painstaking procedure. This early analytical training undoubtedly honed Fred's uncompromising insistence on the importance of the highest quality geochemical data.

After moving to the Massachusetts Institute of Technology (MIT) in 1966 as an assistant professor, Fred, along with others, utilized newly available high resolution Ge(Li) detectors to introduce Instrumental Neutron Activation Analysis (INAA) to the geochemical community. This new method made the previously tricky determination of the apparently not so-

rare-earth elements, more amenable to routine analysis. The 1960's ushered in a veritable revolution in geochemistry as new instrumentation (e.g., INAA, XRF and TIMS isotope dilution) supplanted more tedious and less precise geochemical methods for both major and trace element analyses. Fred was a major contributor to that revolution. The advances in instrumental analyses and the improved data quality made possible the use of quantitative trace element modeling of magmatic processes. Fred and his students contributed to this modeling through ground-breaking studies of trace element partitioning between coexisting minerals and melts.

Far more than a gifted and productive geochemist, Fred realized early in his career that if he was to understand the dynamics of the Earth's mantle and melting processes within it, required two approaches: first, to study mantle rocks and mantle-derived magmas (basalts) in different tectonic environments; and second, to integrate trace element geochemistry with petrology, mineralogy, and isotopic analyses on carefully chosen samples that he helped collect. His extensive and highly cited publications (Supplement 1) show that he has been extremely successful in understanding the petrogenesis of igneous rocks. Knowing the field context, whether on land or at sea, has always been a critical issue for his geochemical studies. Fred set out to become a "real" geologist embracing field studies and in particular the where, why and how of sample collection. Although not formally trained in field geology, Fred enjoys field work and he collaborates with those who are adept in the field including some of the authors in this special issue. His field work has taken him to diverse geological settings from the Chilean Andes to the depths of the Indian Ocean and the wilds of Kerguelen Island. He ranks his time on Kerguelen with Dominique Weis and others as one of the highlights of his career.



Fig. 1. Fred and Julie Frey on Kaua'i, Hawai'i circa 2010.

Among his many honors, Fred was elected a fellow of the Geochemical Society, the European Association of Geochemistry and the American Geophysical Union. He was the recipient of the AGU Bowen Award and the Geological Society of America's Distinguished Career Award in Petrology, Mineralogy and Geochemistry. Fred served as President of the Volcanology, Geochemistry and Petrology (VGP) section of the American Geophysical Union and was a member of the Apollo Lunar Sample Analysis Planning Team.

In addition to being a distinguished scientist, Fred is also a highly successful educator. As a professor at MIT, Fred graduated 21 Ph.D. and 10 master's students from around the world including Chile, China, Czech Republic, France, Hong Kong, Japan and Taiwan. These students have gone on to careers of leadership in geoscience both in academia and industry (see [Supplement 2](#)).

The papers of this special issue reflect Fred's diverse geological interests. They include studies of mantle xenoliths and processes as well as ultramafic to silicic igneous rocks from many tectonic settings (mantle plumes, volcanic arcs, mid-ocean ridges and continents). Several of the papers are authored by Fred's former students, who were motivated and inspired by his scientific work. Several other papers are authored by scientists who did research while visiting MIT or cases of collaboration arising from Fred's sabbatical visits.

This special issue is subdivided into five theme areas reflecting Fred's main areas of research. They include: mantle geochemistry, Hawaiian and other plume-related lavas, volcanic arc magmatism, mid-ocean ridge and Iceland geochemistry, and continental basaltic to silicic magmatism.

1. MANTLE GEOCHEMISTRY

One of Fred's major research interests is to figure out the compositional variations within the Earth's mantle, and the origins of such heterogeneity. Fred established a long-term, highly productive collaborative relationship with Dave Green at The Australian National University to study the geochemical variations in mantle peridotite. In their stellar paper [Frey and Green, \(1974\)](#) and a series of later papers, they convincingly showed that mantle metasomatism is an important mechanism generating geochemical and isotopic heterogeneity within the mantle. Papers published in this special issue include experimental, analytical and model simulation approaches to document and understand the geochemical variations within the mantle.

[Hart and Gaetani, \(2016\)](#) report experimentally determined Pb partition coefficients between FeS melt and basalt melt under P–T conditions that are applicable to mantle melting. They find that the Pb partition coefficient is strongly dependent on pressure and the melt FeO content. Using the newly determined Pb partition coefficient data, they show that the third Pb paradox, constant Nd/Pb ratio in oceanic basalts ([Hart and Gaetani, 2006](#)), can be solved by involving sulfide minerals during mantle melting.

[Jackson et al. \(2016\)](#) provide new Os and He isotopic data on xenoliths, mostly peridotitic, recovered from Samoa and Tubuai in the Pacific Ocean. Based on the low $^{187}\text{Os}/^{188}\text{Os}$ in these peridotitic xenoliths, they interpret them as in-situ Pacific lithosphere brought up by plume-derived lavas. The authors also discuss the survival of ancient depletion signatures in

different isotopic systems: elements that are not efficiently recycled back to the mantle via subduction zones are more likely to preserve their ancient isotopic signatures in the convecting mantle.

Milidragovic and Francis, (2016) review the volumetrically minor, but ubiquitous, ferropicrites of Neoproterozoic age, in Archean cratons. Based on their unusual major (Fe-rich) and trace element data, the authors argue that these Fe-rich rocks imply an Fe-rich mantle, which may have formed by late meteoritic addition after core formation.

Gaetani, (2016) discusses the behavior of Fe during mantle melting. Using model calculations, he shows that $\text{Fe}^{3+}/\text{total Fe}$ in partial melt is controlled by both source oxygen fugacity and partial melting conditions. Consequently, he cautions against using $\text{Fe}^{3+}/\text{total Fe}$ in oceanic basalts to infer their mantle source oxygen fugacity.

Wang et al. (2016) report Mg isotopic data on high $^{206}\text{Pb}/^{204}\text{Pb}$ (>20) peridotites and lavas from New Zealand, with the aim of understanding the petrogenesis of the HIMU endmember. They find that peridotites have $\delta^{26}\text{Mg}$ typical of global mantle peridotites, but lavas have lower $\delta^{26}\text{Mg}$. The low $\delta^{26}\text{Mg}$ signature is attributed to a recycled carbonated eclogite signature in the mantle source of these New Zealand HIMU lavas.

Hu et al. (2016) present the Mg isotopic compositions in pyroxenites and two lherzolites, as well as their mineral separates, from the Cenozoic Hannuoba basalts, China. This detailed, systematic Mg isotopic investigation of pyroxenites is important in applying non-traditional stable isotopes to study the role of garnet pyroxenite in the petrogenesis of oceanic basalts. This paper also extends the work of Fred and others on xenoliths from Hannuoba basalts (Song et al., 1990; Zhi et al., 1990).

2. MID-OCEAN RIDGE AND ICELAND

Fred's wonderful scientific journey started with measuring the REE abundances in mid-ocean ridge basalts (MORB). When selecting his PhD project with advisor Larry Haskin, Fred was offered a choice between Apollo lunar rocks and basalts from the ocean bottom. He selected the terrestrial project because there were many more MORBs available. After Fred obtained the REE data, he realized that although MORB are melts, they have depleted REE patterns similar to melting residues (Frey and Haskin, 1964; Haskin and Frey, 1966). This, and other geochemical and isotopic evidence led to the two-stage melting model for the MORB generation (e.g., Hofmann, 1988). The new papers in this special issue continue Fred's interest in MORB petrogenesis.

Husen et al. (2016) report major and trace element data on whole rocks, melt inclusions and minerals from Macquarie Island ophiolites, SW Pacific Ocean. They discovered large compositional variations in these lavas, ranging from ultra enriched to ultra depleted. They conclude that the observed compositional variation reflects fractional dynamic melting of a homogeneous mantle peridotite, rather than mantle heterogeneity.

Turner et al. (2016) report new $^{231}\text{Pa}/^{235}\text{U}$ disequilibrium data on 26 well-characterized Icelandic lavas. Combined with published ^{238}U – ^{230}Th – ^{226}Ra data, as well as trace element and radiogenic isotopic data, they discuss the relative roles of partial melting of garnet peridotite and garnet pyroxenite in producing these Icelandic lavas. Specifically, they show that the combination of ($^{231}\text{Pa}/^{235}\text{U}$) and ($^{230}\text{Th}/^{238}\text{U}$) may be used to identify the role of garnet pyroxenite in generating oceanic basalts.

Herbrich et al. (2016) report geochemical data (major and trace elements, and Sr–Nd–Pb isotopes) for samples dredged during the R/V Sonne 208 Cruise at several sites to the north of the western Galapagos spreading center. Samples within 30 km of the ridge axis do not show systematic correlation between isotopic compositions and sample locations. However, samples further away from the axis do show a correlation toward more radiogenic Sr and Pb isotopes and less radiogenic Nd isotopes. The authors attribute this geochemical–geographic relationship to a zoned plume structure.

3. HAWAIIAN AND OTHER MANTLE PLUME LAVAS

Mantle plume magmatism caught Fred's interest long before mantle plumes became a household word in geochemistry (Zielinski and Frey, 1970, on the Atlantic Ocean island Gough). For the next ten years, Fred worked on several topics including mantle xenoliths, and mid-ocean ridge and arc lavas (see Supplement 1). The allure of Hawai'i led Fred to attend a 1979 conference celebrating the 75th anniversary of the Hawaiian Volcano Observatory. There he met two of the guest editors for this volume (Rhodes and Garcia). These serendipitous meetings led to an explosion of papers (30) on Hawaiian volcanism in the 1980's and 1990's by Fred with his students and others. This research spanned nearly the entire length of the Hawaiian–Emperor chain extending from an older volcano in the chain (e.g., Suiko; Clague and Frey, 1980) to the youngest (Lō'ihi; Frey and Clague, 1983). The papers in this issue extend Frey's pioneer efforts to understand the origin and evolution of plume-related lavas (e.g., Chen and Frey, 1983; Frey et al., 1990; Frey and Rhodes, 1993; Yang

et al., 2003; Huang and Frey, 2005; Xu et al., 2014). The new papers in this issue use major and trace elements, and isotopic geochemistry of shield lavas (which comprise 90+% of Hawaiian volcanoes) for some of the recently active volcanoes (Kīlauea, Mauna Loa and Mauna Kea), and the petrology and geochemistry of rejuvenated lavas, which form after a significant hiatus in volcanism.

The geochemical distinctions between lavas from sub-parallel Loa and Kea trend Hawaiian volcanoes and their origins is the focus of the new paper by Frey et al. (2016). Abundance ratios of incompatible elements and isotopic ratios of Sr, Nd, Hf and Pb in Hawaiian shield lavas are used to characterize the Loa component, which is interpreted to arise from multiple components. One component is a gabbro adcumulate (i.e. no trapped melt) with abundant cumulus plagioclase, which is recognized by high Sr/Nd and La/Nb, and relatively low $^{206}\text{Pb}/^{204}\text{Pb}$ and high $^{208}\text{Pb}/^{204}\text{Pb}$ at a given $^{206}\text{Pb}/^{204}\text{Pb}$, consistent with their low U/Pb and Th. The distinctive Pb isotope ratios of Loa lavas require a long-time interval, ~ 3 Ga, to develop. Adcumulate rocks with abundant cumulus plagioclase are common in the lower crust of continents, oceans and arc ratios. A second component recognized from Hf and Nd isotopes requires an ancient material with high Lu/Hf, which may have been derived from pelagic sediment or ancient depleted lithosphere. A third component is characterized by relatively high $^{87}\text{Sr}/^{86}\text{Sr}$, although a relatively recent event lowered its Rb/Sr.

The highly successful Hawaiian Scientific Drilling Project (HSDP) cored ~ 3.3 km into Mauna Kea Volcano providing a detailed stratigraphic sequence that has been extensively geochemically studied (e.g., Rhodes et al., 2012). Two new papers by Huang utilize these cores to address fundamental geochemical issues. Huang et al. (2016) analyzed major and trace elements in four, thick (9.3–98.4 m) HSDP flow units and found the major element abundances in three submarine flow units are controlled by olivine abundance. A subaerial flow shows post-magmatic alteration that mostly affected K and Rb, and to a lesser degree Ba, Sr and U. Therefore, ratios involving these elements are potentially unreliable for inferring source geochemistry. However, Huang et al. found some normally immobile elements are potentially mobile under some conditions, including P, HREE and Y.

Huang and Humayun, (2016) evaluate the role of a mafic source component in the petrogenesis of Hawaiian lavas using major and trace element abundances in HSDP high-CaO glasses and lavas. These results are compared to HSDP high- and low-SiO₂ lavas. The high-CaO lavas have a U-shaped trace element pattern, enriched in both the most incompatible

(Nb, Th) and the least incompatible (Sc, V) elements when normalized to the low-SiO₂ lavas. The high-CaO parental magma is interpreted to represent a mixture of a low degree partial melt of the low-SiO₂ mantle source with a high degree ($>80\%$) partial melt derived from a clinopyroxene-rich cumulate source. The mafic cumulate may have formed beneath a volcanic arc during continent formation, in the lower continental crust, or as high pressure cumulates from a magma chamber.

We have learned over the last decade about the striking differences between Hawaiian shield lavas in their Pb isotopes, trace elements and even major elements (e.g., Weis et al., 2011; Jackson et al., 2012). Rhodes, (2016) shows that the Al₂O₃ content of Hawaiian shield lavas is remarkably uniform at a given MgO content within and between volcanoes, including Kea and Loa type volcanoes. This observation is at odds with models for melt production in a heterogeneous, thermally zoned, mantle plume. Rhodes, (2016) argues this aluminum “conundrum” can be explained if Hawaiian shield lavas result from melts of garnet peridotite that reacted with a depleted harzburgite residue as the magma ascended through the upper regions of the plume.

The paper by Tuohy et al. (2016) uses the geochemistry (with emphasis on volatiles) of natural and rehomogenized glass inclusions in olivine from two historical eruptions of Kīlauea to infer crystallization history and the magma emplacement dynamics within Kīlauea’s East Rift. Melt inclusions in olivine from a summit and distal rift zone eruption show similar wide ranges in Nb/Y ratio suggesting the olivine population represents a mix of phenocrysts and xenocrysts. The rift zone inclusions have CO₂ contents that require crystallization over a much wider range of depths (~ 1 –16 km) than the summit inclusions implying the rift zone magma was supplied from a deeper source prior to eruption.

Hawaiian rejuvenated volcanism was an area of early and continuing interest of Fred (Clague and Frey, 1982; Yang et al., 2003). The new paper by Clague et al. (2016), examines Fred’s long-term fascination with the causes of compositional diversity within some Honolulu alkalic lavas. This paper, done in collaboration with Fred, documents the mineralogical and compositional variations within one thick flow, presents a new $^{40}\text{Ar}/^{39}\text{Ar}$ age for it and offers a physical model to explain these variations. The model invokes the slow advance and cooling of this 15-m thick ‘a’ flow, which promoted the segregation of pegmatoids, the formation of light and dark bands with differing proportions of melilite and clinopyroxene, and induced volatile-enhanced mobility of incompatible elements.

The tiny island of Ka‘ula at the northwest end of the main Hawaiian Islands was another locale previously investigated by Fred. [Garcia et al. \(2016\)](#) present geochemical and geochronology results on new submarine samples from Ka‘ula to better understand the cause of the extensive rejuvenated volcanism on and around this island as well as around the other main northern Hawaiian Islands. They show the northern Hawaiian rejuvenated lavas have a significant Loa source component unlike the less voluminous rejuvenated lavas from the southern Hawaiian Islands.

Oceanic plateaus, especially Kerguelan in the southern Indian Ocean, are of special interest to Fred. Thus, the paper by [Tejada et al. \(2016\)](#) on the Shatsky Rise in the Northwest Pacific is an appropriate part of this volume. The Shatsky Rise is arguably considered the best example of an oceanic plateau. Tejada et al. present new $^{40}\text{Ar}/^{39}\text{Ar}$ ages and trace element and Nd, Pb, and Hf isotopic data for dredged rocks from Shatsky, and new trace element and isotopic data for a few drill core samples from the Hess Rise. The two plateaus, though located ~ 1200 km apart, are thought to be genetically related. The chemistry and isotopic composition of the Shatsky and Hess seamounts are similar to ocean island basalt in contrast with other plateaus that formed by deformation-related, shallow mantle-derived volcanism. The new ages indicate that Shatsky Rise may have been formed in multiple-stages, over a longer duration than previously thought.

4. ARC MAGMATISM

Fred’s interest in subduction zone magmatism was a natural complement to his work on mantle xenoliths, and the mantle sources of MORB’s and oceanic island basalts. Unlike basalts from these tectonic settings, arc basalts are rarely primitive and do not contain mantle xenoliths. Their absence creates special challenges for interpretation of arc magmatism. Through collaboration with Dave Green in the late 1970’s, Fred acquired a suite of island arc high-Mg andesites or “boninites” which were unlike typical arc basalts, but matched the composition of primary melts of water-saturated peridotite. Trace element analysis revealed that boninites typically have “U-shaped” REE patterns, similar to those of mantle harzburgites. The U-shaped patterns in harzburgite were interpreted to reflect a two stage process of depletion via melt extraction followed by enrichment from metasomatism ([Frey, 1984](#)). [Hickey and Frey \(1982\)](#) interpreted the U-shaped patterns in boninites to represent hydrous fluid-induced melting of depleted harzburgite in a subduction setting. Fred then shifted his work to the Horoman complex in Japan, one of the few peridotite complexes

worldwide within a present day subduction zone (e.g., [Takazawa et al., 1992](#); [Saal et al., 2001](#)), for insights into the sub-arc mantle. Fred’s interest in continental arc rocks was inspired by Chilean MIT student Leopoldo Lopez Escobar. With Leo, Fred collected and analyzed rocks from volcanoes of the Andean Southern Volcanic Zone (SVZ). Their goal was to define along and across-strike changes in rock composition ([Lopez-Escobar et al., 1977](#)). This laid the groundwork for a long-term research program that addressed the influence of differing crustal properties, and mantle and subduction zone parameters on magma geochemistry (e.g., [Tormey et al., 1991](#); and 19 other papers on the Chilean SVZ). Fred’s most important contribution to understanding arc magmatism was his perspective that everything from initial mantle heterogeneity and subduction zone metasomatism, through interaction with lower and upper crust, were likely to affect the composition of arc magmas, and that strategic thinking was needed to unravel these effects. In the three papers featured in the arc magmatism section of this special issue, authors use differing strategies to understand the origin and evolution of arc magmas.

[Price et al. \(2016\)](#) report and interpret geochemical data for 4 groups of mafic and ultramafic xenoliths from andesitic Egmont Volcano, New Zealand. They infer different evolutionary pathways of arc magmas from Egmont and Ruapehu volcanoes. Mantle derived primary arc magmas underplate and intrude the lower crust, and undergo fractional crystallization and assimilation there and in dispersed magma storage systems on the way to the surface.

[Hickey-Vargas et al. \(2016\)](#) explore mantle melting processes beneath the Andean Southern Volcanic Zone, using the geochemistry of unusually primitive, MgO-rich basalts from a cluster of fault-controlled small eruptive centers (SEC). They present trace element and isotopic evidence that magma formed by active flux melting of the subarc asthenosphere is, in some cases, overprinted by melting of pyroxenite, which was formed and stored in the mantle lithosphere over the duration of arc magmatism at this convergent margin.

[Zellmer et al. \(2016\)](#) interpret the mechanics of the reaction of forsterite plus silica to form enstatite during arc magma evolution. They used an ion microprobe equipped with Stacked, Complementary Metal-oxide Semiconductor Active Pixel Sensor (SCAPS) imaging to examine reacting olivines at sub-micron level in natural andesitic tephra from North Island, New Zealand. They use this information to model olivine dissolution and pyroxene growth rates, and infer the timescales between olivine entrainment in magma and eruption.

5. CONTINENTAL MAGMATISM

Fred's reputation and influence on the geochemical/ petrological and volcanological community undoubtedly rests on his enormous contribution to our understanding of the composition of mantle rocks, oceanic basalts, including those from spreading ridges, oceanic plateaus and oceanic mantle hotspots, as well as subduction-related arc volcanism. It may come as a surprise, though, that throughout his career he has also contributed significantly (18 publications) to an understanding of continental magmatism. Most of these are directed towards basalts and included xenoliths: from Australia, in collaboration with such colleagues as David Green and Dick Price, and from China, in collaboration with Yi-Gang Xu, Martin Menzies, Yan Song and others. Granites have not been neglected either! Fred's work on granites started with New England granites, in collaboration with Dave Wones and Grant Buma, extending westwards to granites of the Sierra Nevada batholith, with Bruce Chappell, Dave Wones and others. Somewhere in the mid 1980's, Fred abandoned granites altogether, recognizing that they were not liquids, and much more difficult to understand than basalts and arc magmas. Modern studies have proved him correct (e.g., [Bachmann and Bergantz, 2008](#)). Silicic magma bodies are crystal-liquid mushes as is clearly illustrated by [Hertogen and Mareeis, \(2016\)](#).

This issue contains seven papers on continental magmatism, mirroring Fred's contribution in this area. Five papers discuss basaltic magmas, or hybrids formed by mixing of basaltic and silicic magmas, and two focus on granites.

[Fodor and Johnson, \(2016\)](#) discuss the possible origins of intermediate andesites and dacites that are associated with voluminous silicic ash-flow tuffs and lavas and minor alkalic basalts in the Goldfield – Superstition volcanic province of Arizona. Using petrographic, mineralogical and whole-rock major and trace element data they eliminate crystal fractionation of basalt and dehydration melting of crustal rocks. They conclude that the characteristic inverse correlation of REE and high field-strength (HFSE) elements with SiO₂ results from numerous episodes of magma mixing as basaltic magma invaded the rhyolite magma reservoir.

The Ethiopian-Yemeni flood basalts are widely interpreted to be products of melting of the Afar mantle plume head. [Furman et al. \(2016\)](#) present a more provocative perspective. Using previously published geochemical data, they propose that although most basalts are consistent with peridotite melting in the plume head, others require a substantial contribution from metasomatized subcontinental litho-

sphere. This they attribute to de-lamination of a dynamically unstable lithosphere ([Elkins-Tanton, 2007](#)) that “drips” into the asthenosphere where it melts to produce the primitive high-Ti lavas and picrites, closest to the rift zone.

Foundering and melting of metasomatized subcontinental lithosphere (the “drip” magmatism of [Furman et al. \(2016\)](#)) is also appealed to in the contribution by [Lord et al. \(2016\)](#) to explain the Rio Grande rift-related alkalic dikes and sills at Spanish Peaks, Colorado. These magmas are distinctly bimodal, with both sodic and potassic varieties. The authors suggest that as the lithosphere founders during the initiation of rifting, melting of phlogopite- and/or amphibole-bearing pyroxenite/eclogite veins produced the parental magmas, the more potassic melts being produced at greater depths.

Rifting and melting of metasomatized subcontinental lithosphere is also invoked by [Melluso et al. \(2016\)](#) to account for the wide range of primitive mafic magmas, ranging from olivine leucite nephelinites, through basanites and alkali basalts to tholeiites erupted in the Cenozoic, Ankaratra volcanic complex in central Madagascar. They attribute the wide compositional range to varying degrees of melting, at varying depths (<3–4 GPa), of a source variably metasomatized by a high-Ca, melilitite melt.

[Lustrino et al. \(2016\)](#) addresses the controversial question of whether carbonate inclusions in olivine crystals come from carbonate mantle melts (the prevailing opinion), or are secondary and of crustal origin. The study is based on lavas from a small alkalic volcano in the Calatrava Volcanic Field of central Spain. First, they use morphology, compositional zoning and trace element abundances in the olivine to argue that they are magmatic, not mantle xenocrysts: a necessary requirement if the crystals are crustal in origin. Next, they use major, trace element, C and O isotopic data for the carbonate inclusions, together with experimental constraints, to argue that the carbonate inclusions are of crustal origin.

[Hertogen and Mareeis, \(2016\)](#) present a useful and timely modeling program called SilMush that rapidly simulates the crystallization and solidification of silicic mushes to produce granitic plutons. They test their model by applying it to three plutons (a monzogranite, a syenogranite and an alkali feldspar granite) from the Variscan Northern Vosges Massif of France. In all cases, actual major and trace element variations in the plutons are well reproduced by the model.

[Frost et al. \(2016\)](#) use a combination of field relations, petrology, geochronology and thermobarometry to discuss the origins of two, essentially coeval, leucocratic trondhjemitic gneiss bodies that

were emplaced during an Archean collisional orogeny and are now exposed in the Teton range of Wyoming. They infer that one of the trondhjemites was produced by de-hydration melting, and the other by water-excess melting during the same collisional orogeny. They contrast these Archean trondhjemite gneiss with the two-mica leucogranites, so characteristic of young collisional orogens (e.g., Himalayas), attributing the difference to melting of a geochemically immature continental crust in the Archean.

We hope you will all enjoy this special issue (which Fred co-edited) and use the list of his papers (Supplement 1) to explore Fred's previous publications.

APPENDIX A. SUPPLEMENTARY DATA

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.gca.2016.05.018>.

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Michael O. Garcia

Department of Geology & Geophysics, University of
Hawai'i, Honolulu, HI 96822, USA
E-mail address: mogarcia@hawaii.edu

J. Michael Rhodes

Department of Geosciences, University of
Massachusetts Amherst, Amherst, MA 01003, USA

Shichun Huang

Department of Geoscience, University of Nevada, Las
Vegas, Las Vegas, NV 89154, USA

Rosemary Hickey-Vargas

Department of Earth & Environment, Florida
International University, Miami, FL 33199, USA

Associate editor: Marc Norman

Available online 18 May 2016