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Testing the chemical signature of chaotic magma mixing

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Abstract: In this paper recent experimental predictions of the geochemical pattern of rock suites resulting from the mixing of magmas governed by chaotic dynamics are tested. It has been suggested in the past that during chaotic mixing of two magmas, the competition between element diffusion and the stretching and folding of magmas (mixing dynamics), leads to a systematic decrease in correlation between any two elements as the difference in diffusivities between them increases. This hypothesis is tested here using suites of rocks that record magma hybridization and others that record magma fractionation. The prediction is supported by our results, but it is impossible to differentiate between magma suites that have undergone mixing and those that have undergone fractionation.

A recent experiment regarding chaotic magma mixing reported an unexpectedly high level of complexity in the distribution of major elements in systems undergoing mixing. This was also tested during the present work and for that we chose hybrid volcanic glass samples from the 1875 A.D. eruption of Askja Central Volcano, Iceland. A microprobe analysis carried out on samples from the extrusions and the existing published and unpublished data were collated. It was found that the data clustered into two separate groups: a basaltic one with approximately 50% SiO_2 and a rhyolitic one with approximately 70% SiO_2 with a small number of analyses in between. Each of the two end-member groups covers a relatively narrow range of compositions that can be explained by fractionation. The mixing trends are typically linear as is expected in conventional mixing models. We conclude that the typical linear trends between two end-member magmas, typically interpreted in the literature to indicate magma hybridization, are only well-developed for elements with similar diffusivities or for systems where the two end-members were fully mixed in different proportions in different parts of a magma suite, and that the complex trends expected from chaotic mixing are inferred to be relatively rare in nature.

Keywords: Felsic-mafic mixing, Chaotic mixing, magma fractionation, granite, diffusion coefficients, fractionation.

अव्यवस्थित मैग्मा मिश्रण के रासायनिक संकेतों का परीक्षण

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सारांश: प्रस्तुत शोध पत्र में अव्यवस्थित गतिशीलता से नियंत्रित मैग्माज के मिश्रण से उत्पन्न चट्टान वर्गों के भू-रासायनिक स्वरूप की हाल की प्रयोगात्मक भविष्यवाणियों पर परीक्षण किया गया है। पूर्व मे यह सुझाया गया था कि दो प्रकार के मैग्माज के अव्यवस्थित मिश्रण के दौरान तत्वों की विसरणता, तथा मैग्माज के खिंचाव व वलन के बीच स्पर्धा के कारण किन्ही दो तत्वों के सह-संबंधों में विधिवत ह्रास होता है क्योंकि दोनों के बीच विसरणता के अन्तर में वृद्दि होती है। उपरोक्त अवधारणा का परीक्षण उन दो चट्टान वर्गो, पहला जो मैग्मा संकरण दर्ज करते हैं तथा दूसरे जो मैग्मा विघटन को दर्ज करते हैं, के द्वारा किया गया है। यद्यपि निष्कर्ष प्रयोग द्वारा समर्थित है, किन्तु मैग्मा के संकरण व मिश्रण द्वारा निर्मित चट्टान वर्गो मे अन्तर करना असम्भव है।

अव्यवस्थित मैग्मा मिश्रण के बारे में हाल में ही किये गये एक प्रयोग में मिश्रण के दौर से गुजरी प्रणालियों के मुख्य तत्वों में अप्रत्याशित वितरणीय जटिलता प्रदर्शित हुई है। अस्कजा केन्द्रीय ज्वालामुखी, आईसलैन्ड, 1875 ई. के विस्फोट से प्राप्त संकर ज्वालामुखीय काँच के नमूनों के आधार पर यही परीक्षण वर्तमान शोध के दौरान भी किया गया। उत्सारण के नमूनों की सूक्ष्म जाँच विश्लेषण एवं मौजूदा प्रकाशित व अप्रकाशित आंकणों को मिलाकर देखने पर यह पाया गया कि आंकड़े दो विभिन्न समूहों में इकठ्ठे हो गये : पचास प्रतिशत SiO_2 के साथ एक बसाल्टिक तथा लगभग 70 प्रतिशत SiO_2 के साथ एक रायोलेटिक समूह व दोनों के बीच छोटी संख्या में कुछ विश्लेषण आंकड़े। दोनों अंत-सदस्यों के संघटन के अपेक्षाकृत संकीर्ण फैलाव को प्रभाजन से समझाया जा सकता है । मिश्रण के रूझान सामान्यत: रेखीय हैं जैसाकि मिश्रण प्रारूपों से अपेक्षित है। निष्कर्ष यह है कि दो अंत-सदस्यों के बीच प्ररूपी रेखीय रूझान, जिन्हें साहित्य में मैग्मा संकरण का सूचक माना गया है, केवल उन तत्वों के लिये पूर्ण विकसित है जिनकी विसरणता समान है या फिर ऐसी प्रणालियों के लिये जहाँ दोनों अंत-सदस्य मैग्मा समूह के विभिन्न हिस्सों में व विभिन्न अनुपातों में पूरी तरह से मिल गये हों, तथा जटिल रूझान, जोकि अव्यवस्थित मिश्रण से अपेक्षित हैं, प्रकृति में अपेक्षाकृत दुर्लभ हैं।

संकेत शब्द : फेल्सिक-मैफिक मिश्रण, अव्यवस्थित मिश्रण, मैग्मा विघटन, ग्रेनाइट, विसरणता गुणांक, विघटन।

INTRODUCTION

The classical model of magma mixing is based on the simple view that two volumes of different magmas mix to completion within the volume of a typical hand sample. From this view it follows that the compositions of the mixtures represented by different samples should plot along a straight line linking the two end-members in binary element plots. Where each mixed sample plots on the mixing line depends only on the volume proportion of the two end-members involved in the mix. However, this is true only if the two magma batches mix to completion (complete hybridization) at least at the scale of a sample. If mixing results from stretching and folding, a small magma volume is exposed to ever changing surroundings and its composition is constantly in the process of adapting to this change. Because different elements have different diffusion coefficients in silicate melts the degree of hybridization of this magma volume varies, and depends on the exact path that this particular volume travels during mixing (Perugini *et al.* 2006). This process implies that a chaotically mixed suite should not plot along a linear trend, as currently expected.

Chaotic dynamics controls the mixing between fluids and stretching and folding is the basic process of chaotic dynamics (Ottino 1989; Perugini *et al.* 2006; De Campos *et al.* 2011). During mechanical stretching and folding of fluids, filaments are generated and generation of these filaments at several length scales is necessary for efficient mixing (De Campos *et al.* 2011). Among many experiments that have been developed to study the chaotic mixing processes, the mechanical journal bearing system (JBS) has received particular attention because it enables the study of fluid mixing under careful control of the structure of flow fields (Ottino 1989).

Perugini *et al.* (2006) postulated that during chaotic mixing, elements with similar diffusivity would behave in a similar way and would, therefore, define well-correlated trends. Conversely, elements with different diffusivity would become increasingly dissociated and correlation coefficients would become increasingly weak. So the authors postulated that the correlation coefficient between elements with similar diffusivities would be high in a suite of chaotically mixed rocks, and those with different diffusivities would have low correlation coefficients.

Perugini *et al.* (2006) studied chaotic mixing using both numerical models and natural samples from a lava flow erupted during the magmatic activity of Lesvos Island, Greece. The Lesvos lava flow was generated by mixing dynamics involving both chaotic flow fields and chemical diffusion between rhyolitic and Qtz-trachytic magmas. Results of mixing models and geochemical analyses of the volcanic rocks were presented in diagrams plotting correlation coefficient between two elements versus their diffusivity differences. As predicted, trace elements with similar values of diffusion coefficient yielded good correlation in inter-elemental plots. As the difference between diffusion coefficients increased the correlation was progressively lost (Perugini *et al.* 2006). These authors explored a binary plot in which the correlation coefficient between La and other REEs and Sr and Rb were plotted against the difference in diffusivity between La and the other elements. In such a plot, La has high correlation coefficients with other LREE, which have similar diffusivities, and this decreases towards HREE and Rb and Sr. Numerical simulations of chaotic mixing reproduce with very good approximation the geochemical features observed in the natural samples of Lesvos, including positive and negative Eu anomalies over very short distances.

De Campos *et al.* (2011) studied magma mixing in a JBS apparatus using two silicate melts: a haplogranite and a haplobasalt (viscosity contrast of 10^3) that correspond to the 1 atm eutectic composition of the Anorthite-Diopside binary system. Chaotic mixing was imposed by the journal rotation. The experiment revealed that mixing can occur even when the two magmas have high viscosity contrasts. Most significantly, chaotic mixing did not lead to linear chemical trends in binary variation diagrams, but produced rather unexpectedly complex, curvilinear trends. The mixing of magmas is a process that can occur at any stage in the life span of a magmatic system and it does not necessarily require the presence of magmas generated from different sources, i.e. mantle and crustal derived melts. So any petrological processes such as fractional crystallisation, assimilation and partial melting that can cause both chemical and temperature gradients across a magma body can produce end-members that may then undergo chaotic mixing processes should the differentiated magma be forced to flow and co-mingle.

The findings of both Perugini *et al.* (2006) and De Campos *et al.* (2011) are based on laboratory studies. In this paper we test whether or not these findings are applicable in the field. We test whether Perugini *et al.'s* (2006) approach allows for distinction between igneous bodies that have undergone magma mixing from those undergoing crystal fractionation. We note at the outset that elements with similar diffusivities, such as La and Ce, also have a number of other similar properties, such as ionic radii and charges, and therefore they should also behave similarly during the crystal fractionation and other differentiation processes. If so Perugini *et al.*'s (2006) approach would not allow differentiation between them. For this purpose we use: a) mingled samples of the Tynong North quarry, Tynong pluton, Australia, and b) the Gyamsa and Leh plutons, part of the Ladakh Batholith, India (Weinberg & Dunlap 2000). We also attempted to test the De Campos *et al.'s* (2011) findings for natural samples. For this we used glass samples from the Askja 1875 A.D. eruption as they record magma hybridization processes (Sigurdsson & Sparks 1981).

DIFFERENTIATING BETWEEN MIXING AND FRACTIONATION: Testing Perugini *et al.* (2006)

Mixed magmatic suite: Tynong Province

The Tynong Batholith comprises five plutons: Baw Baw, Toorongo, Tanjil Bren, Tynong, and Lysterfield. It is characterized by multiple hybridization events between mantle and crustal magmas. In this section, we investigated their geochemistry and tested Perugini *et al.*'s (2006) hypothesis with particular focus on samples from the Tynong North quarry. The Tynong pluton is characterized by the presence of zones of mingling between small bodies of mafic-intermediate magma and dominant felsic magma which are best exposed in the Tynong North quarry. Here rocks of dioritic composition appear as large mingled masses within granitic rocks, producing simple and composite dykes, pods and enclaves. Hybrid rocks with quartz and plagioclase surrounded by hornblende in the form of ocelli, and granitoids with rapakivi and antirapakivi textures, are also exposed in this quarry. Long prismatic to acicular apatite crystals are common in the mafic microgranular enclaves (MME) and some larger mafic bodies in the quarry.

Representative Harker diagrams of the Tynong Province granitoids are shown in figure 1. The trends defined in each of these diagrams vary from linear (for Fe_2O_3 and CaO) to curved (for Al_2O_3), to ill-defined (for Na_2O). However, table 1 shows that the linear best fit can be poor even for Na_2O, such as in the case of the Toorongo pluton. The correlation coefficient values for different oxides with respect to SiO_2 for the Tynong pluton only are listed in table 2, and selected Harker diagrams are depicted in figure 2. Most of the oxides have linear trends with respect to SiO_2 as shown by a high value of r^2 (Table 2, Fig. 2). As is typical for many suites, due to higher mobility during incipient weathering, K_2O and particularly Na_2O, have poorly defined trends (Table 2).

In order to test the approach of Perugini *et al.* (2006) we plotted the correlation coefficients between La and different REE and the other selected trace elements against the difference in diffusivity between La and these elements (Fig. 3). This was done by plotting, for example, La against Ce (Fig. 2), and determining the r^2 value. This value was then plotted against the difference in diffusivity between the two, which in this case is $0.17*10^{-9}$ (Nakamura & Kushiro 1998). Our 10 samples from the Tynong North quarry define a similar pattern to that predicted by Perugini *et al.* (2006) for mixed magmatic bodies (Fig. 3).

For samples from the Tynong North quarry La is strongly correlated with Ce (Fig. 2) and other LREE, and correlation decreases towards the HREE as expected (Fig. 3). When La is plotted against other trace elements such as U, Rb, Sr, Eu and Ba for which the diffusion coefficient difference is high, the correlation coefficient is very low (Fig. 3). In summary, the plots in figure 3 show that elements with similar diffusivities have high correlation coefficients and those elements with different values become increasingly uncorrelated. The results imply that linear trends between the two end-member magmas would only be well-developed for elements with similar diffusivities, and not for others.

Fractionated systems: Gyamsa-Leh plutons, Ladakh, India

The Ladakh batholith around the city of Leh is composed of two plutons (Weinberg & Dunlap 2000): the older, ~60 Ma Gyamsa and the younger, ~50 Ma Leh pluton. At the contact between the two, the granitic rocks and diorites of the Leh pluton intrude the Gyamsa pluton. The Gyamsa pluton is divided into two parts: a felsic tonalite, granodiorite, and granite mass to the east and amphibolitic migmatite within the same plutonic rocks to the west. The igneous origin of the amphibolite is inferred from the presence of zoned plagioclase phenocrysts.

The Leh pluton grades from mafic enclave-rich quartz-diorite in the south to an enclave-free granite at the N70°W-trending and steep contact with the Gyamsa pluton (Weinberg & Dunlap 2000). Change in composition is broadly parallel to this contact and can be seen in the gradual change in colour of the mountains. This change was interpreted to result from the settling of crystals and enclaves, and this interpretation was further supported by the presence of a 20 X 10 m body of layered cumulates within the granodiorite layer (Fig. 4) (Weinberg & Dunlap 2000). This is a layered sequence with repetition of cumulate layers with up to 90% modal content of euhedral, 0.5 cm long hornblende, grading to plagioclase-rich tonalite layers at the ~50 cm scale.

The origin of the mafic enclaves in the Leh pluton is not established, and it could be either through an early event of magma mingling, or through remobilisation of an earlier magma chamber by a new magma intrusion. From the perspective of this paper, we follow the view in Weinberg & Dunlap (2000) based on field relationships, that the main process controlling the lithological variation is crystal fractionation. However, Santosh (2010) interpreted the mafic enclaves in Ladakh Batholith as formed by multiple events of mafic and felsic magma mingling.

The origin of lithological variations in the Gyamsa pluton is less clear. A possible interpretation is that the granitic rocks are derived directly from melting of the amphibolites (Weinberg, unpublished data). However, from the point of view of this paper, the granitic rocks of this pluton have locally partly digested amphibolitic xenoliths, but lack the mafic enclaves found in the Leh pluton, and lack any evidence that magma mixing played a key role in its origin.

Figure 5 shows how La for the Leh pluton and Gyamsa pluton correlates with other elements. The results are similar to those for the Tynong pluton (Fig. 3) in that the correlation is progressively lost as the diffusivity difference increases. Figure 6 shows that the Leh pluton has the strongest correlations and smoothest trend with much higher correlation coefficients than either the Gyamsa or the Tynong plutons although these trends are quite similar but steeper. The flat trend and high correlation for the Leh pluton can be explained on the basis of duration or intensity the fractionation process

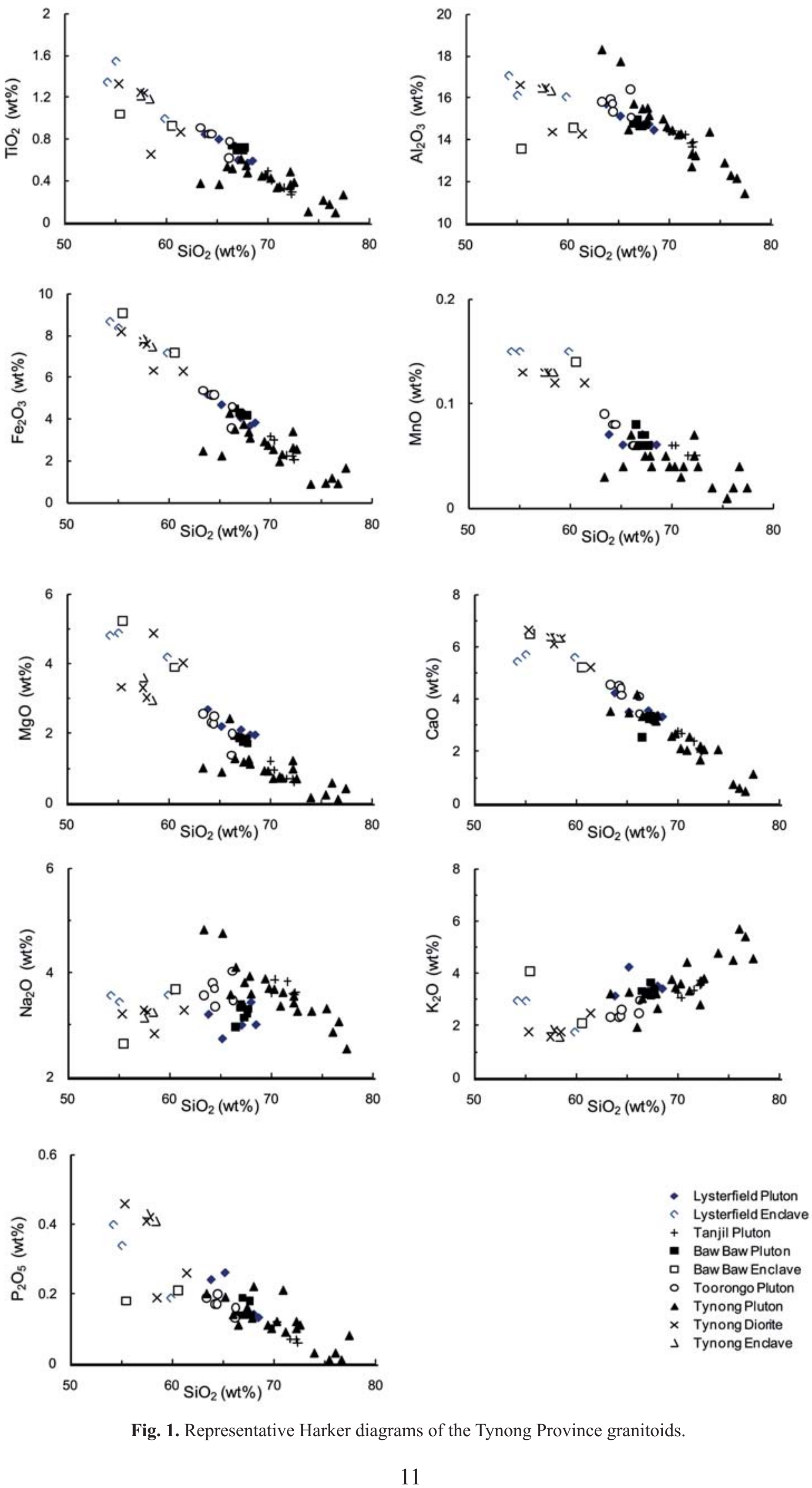

Fig. 1. Representative Harker diagrams of the Tynong Province granitoids.

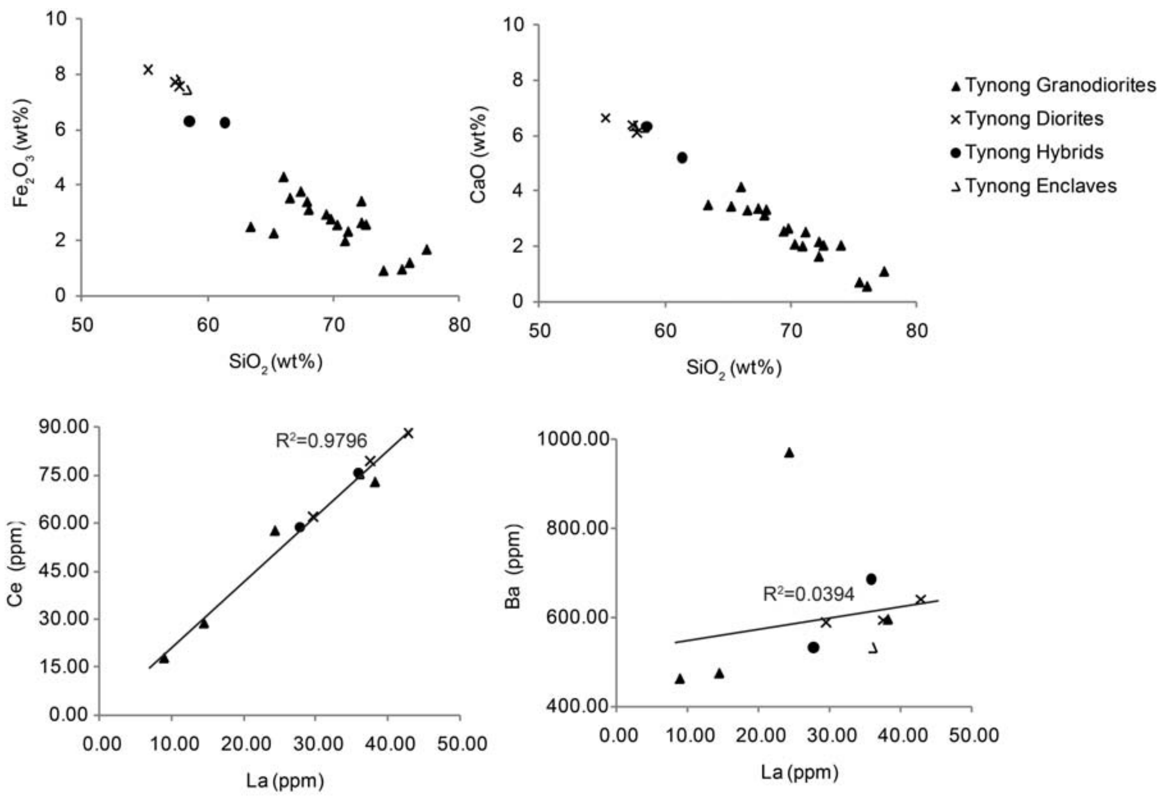

Fig. 2. Selected Harker diagrams, and Ce and Ba vs. La for samples of the Tynong pluton. Note linear trends of major elements, and a well-defined linear trend between Ce vs. La, and a very poor relationship between La vs. Ba.

Table 1. *Correlation coefficient values, r^2, of the linear best fit line for Fe_2O_3 with SiO_2 for the Tynong Province granitoids.*

Pluton	No of samples	r^2
Tanjil	6	0.9741
Lysterfield	10	0.9901
Baw Baw	9	0.9965
Toorongo	6	0.7068
Tynong	26	0.8565

Table 2. *Correlation coefficient values, r^2 of the linear best fit line for different oxides with SiO_2 for the Tynong pluton.*

Oxides	r^2
TiO_2	0.8019
Al_2O_3	0.5569
Fe_2O_3	0.8565
MnO	0.8091
MgO	0.7618
CaO	0.9615
Na_2O	0.003
K_2O	0.7951
P_2O_5	0.809

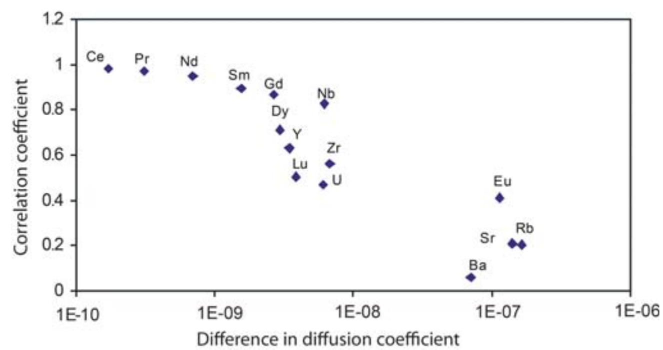

Fig. 3. Correlation coefficient (r^2) between La and other elements plotted against the absolute value of the difference in diffusion coefficient (ΔD) between La and those elements for samples from the Tynong North quarry. The diagram shows high correlation coefficients for elements of similar diffusivities to that of La, decreasing sharply as the diffusivity difference increases. Correlation coefficients were derived from best fit lines to data in binary plots of La versus each element (n=10, silica content between 55.3% and 70.9%). Diffusion coefficients are after Nakamura & Kushiro (1998).

involved. The more strongly fractionated a magma body becomes, the stronger the correlations between all elements. The Leh pluton yields high correlation all the way to Lu with

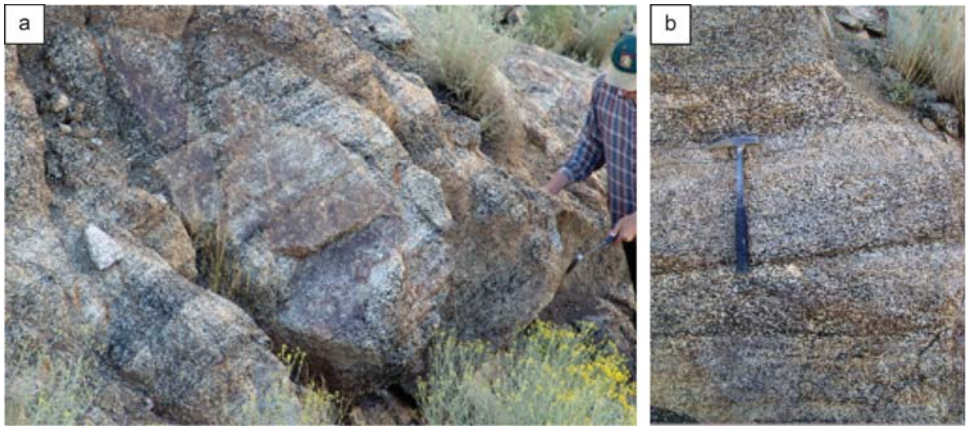

Fig. 4. a) The cumulate zone, Leh pluton, Ladakh, b) layering within cumulates, Leh pluton, Ladakh (Photos by R. Weinberg, users.monash.edu.au/~weinberg/).

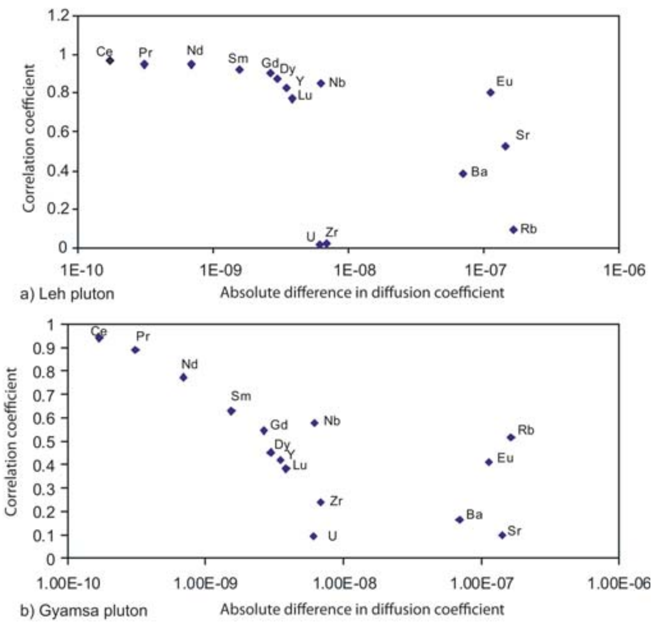

Fig. 5. Correlation coefficient (r^2) against the absolute value of the difference in diffusion coefficient (ΔD) between La and other trace elements for samples from the Ladakh Batholith. a) Leh pluton (n=8, silica content between 51.87% and 75.17%), b) Gyamsa pluton (n=10, silica content between 57.17% and 76.20%). The diagram shows high correlation coefficients for elements of similar diffusivities to that of La, decreasing sharply as diffusivity increase. Nb is somewhat anomalous and plots up from the main decreasing trend. Correlation coefficients were derived from the best fit lines to the data in binary plots of La versus each element. Data from Roberto Weinberg (unpublished). Diffusion coefficients are after Nakamura & Kushiro (1998).

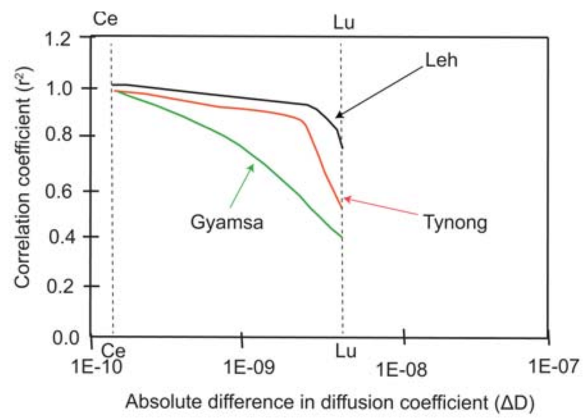

Fig. 6. Comparison of variation of degree of correlation (r^2) and their diffusion coefficients (ΔD) between La and other trace elements for samples from the Leh, Gyamsa and Tynong plutons , for REE only (also see Figs. 3 and 5).

r^2=0.8, compared to r^2=0.4 for the Gyamsa pluton. The Leh pluton is also much better behaved than the Tynong, which has a lower r^2=0.5 for Lu (Figs. 3, 5 and 6). On the other hand, if several processes are in play contemporaneously, such as several mixing and fractionation events partly overprinting one another, the noisier the element correlations will become, leading to a steeper slope due to dissociation of elements with different properties. Most significantly, the slopes of curves from LREE and HREE, indicating worsening correlations, increase from Leh to Tynong to Gyamsa plutons (Fig. 6). This could be interpreted as a measure of internal complexity of magmatic processes.

TESTING DE CAMPOS ET AL. (2011): ASKJA SAMPLES

The Askja central volcano is one of the largest and most active volcanoes in Iceland and is located in the northern part of the Eastern Volcanic Zone (Sigurdsson & Sparks 1981). It belongs to the Dyngjufjoll fissure system of the Northern Rift Zone, central Iceland (Kuritani *et al.* 2011). Icelandic central volcanoes are characterized by the repeated eruption of fractionated mafic, intermediate and felsic lavas and the formation of calderas (Sigurdsson & Sparks 1981). Withdrawal of magma from reservoirs beneath the central volcano causes caldera collapse (Sigurdsson & Sparks 1981). A petrologic model of the Askja magma chamber based on the eruptive products consists of a density-stratified magma chamber with an upper part of rhyolite and a lower part of ferrobasalt and an intervening layer of icelandite (Kuritani *et al.* 2011; Sigurdsson & Sparks 1981). Model calculations show that the icelandite can be derived from ferrobasalt by 50% fractional crystallization, but single-stage fractional crystallization models cannot account for the generation of the observed acid magma (Sigurdsson & Sparks 1981). Instead, a more complex fusion, hybridization and fractional crystallization model was presented that was consistent with the available petrologic evidence (Sigurdsson & Sparks 1981).

Kuritani *et al.* (2011) studied the major and trace elements and Sr, Nd and Pb isotopic data together with ^{238}U-^{230}Th-^{206}Ra systematics. The lavas show compositional variation from magnesian basalt to ferrobasalt and rhyolite (Kuritani *et al.* 2011). The magnesian basalt and ferrobasalt suite consists of lavas older than 1875 A.D. In this suite there is a trend of increasing $^{87}Sr/^{86}Sr$ with increasing SiO_2 and according to Kuritani *et al.* (2011) this suite evolved through assimilation and fractional crystallisation. But in the ferrobasalt-rhyolite suite $^{87}Sr/^{86}Sr$ decreases slightly with increasing SiO_2. The icelandite and rhyolite magmas are considered to have been formed by extraction of the interstitial melt from a mushy boundary layer along the wall of the ferrobasalt magma chamber, which was followed by accumulation of the melt to form separate magma chambers (Kuritani *et al.* 2011).

For this study we used microprobe glass analysis data from Dr. Sheila Seaman (University of Massachusetts, personal communication), from Kuritani *et al.* (2011) and also our own data obtained by EPMA. The sample used for this study was provided by Seaman and was taken from the 1875 A.D. Askja eruption and is the same sample set and the same mount that Seaman analysed. As the 1875 A.D. Askja eruption is an example of incomplete mixing between rhyolitic and basaltic magmas (Sparks *et al.* 1977) we used the sample from this eruption to test the findings of De Campos *et al.* (2011) in natural samples.

As explained above if 50% of sample A mixes with 50% of sample B and if they mix completely then the resulting samples must plot midway between A and B. But stretching and folding of filaments, and incomplete mixing is expected to produce scattered data points, and it is not necessary for them to plot on a simple mixing line. The resulting plot of all available microprobe glass analysis for the 1875 A.D. Askja eruption is shown in figure 7. First, the data obtained define two main groups, one silica-rich and the other silica-poor, with only a few analyses plotting in between and providing a faint link between the two. All of these intermediate points are from Kuritani *et al.*'s (2011) data set. The MgO data also has a number of intermediate values indicating hybridization. The MgO, CaO and FeO vs. SiO_2 plots show trends compatible with fractionation of ferroaugite for the mafic compositions as indicated by the plotted lines, and the Al_2O_3 vs. SiO_2 plot is compatible with fractionation of bytownite. The P_2O_5 vs. SiO_2 plot suggests fractionation of apatite while the Na_2O vs. SiO_2 diagram for the rhyolitic part of the plot suggests a possible fractionation trend of Na-rich plagioclase. Hence, the observed trends for 1875 A.D. Askja eruption are compatible with fractionation within the two end member felsic and mafic magmas, and a few intermediate samples suggest limited hybridization between the end members.

DISCUSSION

The geochemical patterns for the hybridized rocks of the Tynong North quarry (Fig. 3) show similar patterns to the mixed magmas of Perugini *et al*. (2006) with La strongly correlated with Ce and other LREE, and worsening correlation towards the HREE. When La is plotted against other trace elements such as U, Rb, Sr, Eu and Ba for which the diffusion coefficient difference is high, the correlation coefficient is very low (Fig. 3). However, the same approach yields similar patterns for suites that have undergone crystal fractionation (the Leh and Gyamsa plutons) and therefore does not alone allow distinction between the different processes (Figs. 3, 5 and 6).

The results for the analyses of glass samples from the fractionated and hybridized 1875 A.D. Askja eruption samples (n=324) were plotted in Harker diagrams to test De Campos *et al.*'s (2011) findings. The hybrids seem to follow a straight line of mixing as would be expected from the traditional mixing literature, and seem to trend towards some of the more fractionated end-members of the mafic group. We therefore interpret the results to indicate that the eruption tapped two magma batches that were undergoing separate fractionation: a mafic body dominated by fractionation of ferroaugite, and a felsic body controlled by the fractionation of Na-rich plagioclase. The two underwent a small degree of mixing and the linear trends suggest between them that stable bulk mixing was the dominant process. However, the variability of the relationships between the apparent mixing lines and the basalt array may indicate limited decoupling of elements, as expected, if mixing played a role.

CONCLUSIONS

The numerical simulations of Perugini *et al.* (2006) predict geochemical relationships that are also observed in our natural samples. However, we found that the relationships between different elements controlled by diffusivities and predicted to occur in magma mixing examples, also occur in magmatic sequences undergoing fractionation (e.g., the Leh pluton) and in a pluton for which lithological variations have an undefined origin (Gyamsa pluton). We used a well-known example of magma hybridization preserved in volcanic glasses of the 1875 A.D. Askja eruption to test the De Campos *et al.* (2011) findings. Our analyses merged with other

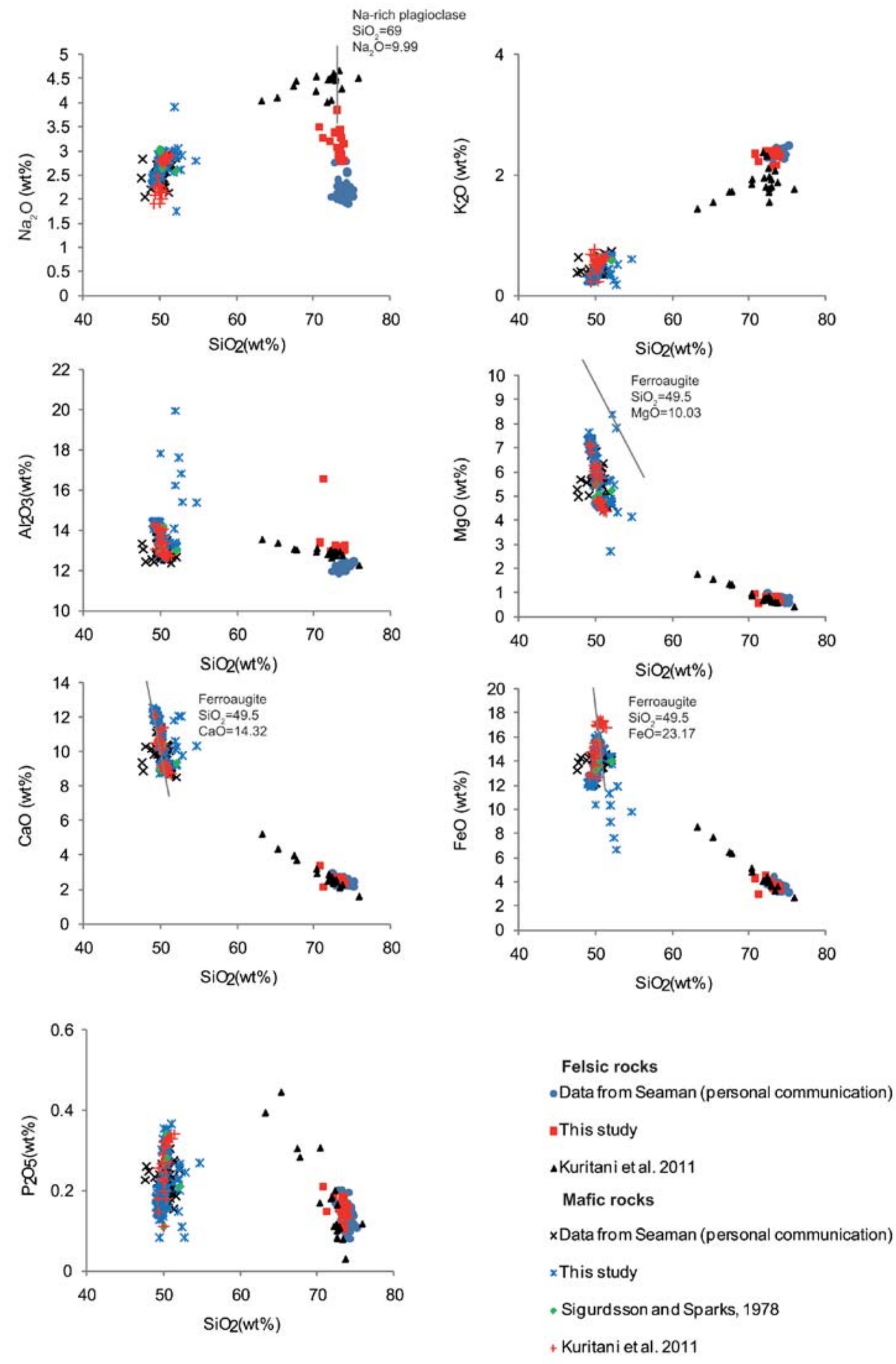

Fig. 7. Harker diagrams for glass from Askja eruption, 1875 A.D. The data defines a basic and an acid group showing a narrow range of silica and a degree of fractionation. A small number of samples have intermediate values. The lines shows fractionation trends of typical (ferroaugite and Na-rich plagioclase) minerals (Deer *et al.* 1963; Deer *et al.* 1992).

available data for the same eruption shows that the samples can be divided into two separate groups, a basaltic one with approximately 50% SiO_2 and a rhyolitic one with approximately 70% SiO_2 with a small number of hybrid samples falling in between the two groups. These hybrids define a linear trend towards the more fractionated mafic samples and indicate that mixing was not chaotic and conform to expectations from the traditional mixing literature.

Nevertheless, merging the conclusions of Perugini *et al.* (2006) and De Campos *et al.* (2011) we conclude that the typical linear trends between the two end-member magmas expected for magma hybridization, is only well-developed for elements with similar diffusivities, or for systems where hybridization between different volumes of two magma end-members achieved full hybridization. However, the Soret effect and chemical convection can play certain role along with diffusivities.

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