The Sub-Volcanic Chamber as a Chemical Filter between Volcanics and Deeper Pluton Sources in a Tilted Continental Margin Arc in Mongolia

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Abstract

Much of Mongolian geology comprises a large collage of collided crustal and oceanic fragments called the Central Asian Orogenic Belt. In the remote southwestern corner of Mongolia, the Gobi Tienshan Intrusive Complex (GTIC), one of these collided fragments, represents a tilted magmatic arc crustal section from the paleo-surface to 12 km depth. I focused on mapping the surface volcanic sequence and sub-volcanic plutons in this section and examined samples collected along transects across their contact believed to be an intrusive relationship along the eastern contact and a gradational relationship in grain size and composition along the southern contact. Two main sub-volcanic rock types are Rapikiiv Porphyries and K-feldspar rich Syenogranites. Both units are compositionally similar, but the Syenogranite unit displayed grain characteristics that implied a faster cooling period which is consistent with their structural concordance with the adjacent volcanics. Similar compositions over a range of grain size suggest similar source magmas of both the sub-volcanics and some volcanics. Whole rock geochemical analyses including major element and isotopic data showed that the volcanic unit has multiple sources over time, including, but not limited to, the currently exposed sub-volcanic chamber. However, rare earth element patterns display similarities between the sub-volcanic and volcanic units, possibly indicating a geochemical filtering process in the sub-volcanic system which may have implications for the conceived impact of sub-volcanic chamber processes on volcanic geochemistry. Isotopic data shows us that crustal sources are tapped throughout the complex including the sub-volcanics and volcanics, providing evidence for a continental margin tectonic setting for the GTIC.

Introduction:

Continental margin arc magmatism has been a major topic of geologic study which has led to a very detailed knowledge of how these systems work and the processes that drive them. In order to understand how active magmatic systems operate we must study extinct continental margin arcs and observe the preserved characteristics of these systems. However, while a large amount of general characteristics have been agreed
upon in the scientific community there continues to be areas of modern debate about the evolution and processes of these systems including melting, fractionation, assimilation, storage and hybridization at all levels of a magmatic arc (Economos, 2008). Each of these processes are important in understanding how magmatic system are built spatio-temporally, whether it is through pulses, intense flare ups or a steady state of magmatism.

An important area of study has developed around discovering the compositional and temporal relationships between a plutonic chambers and volcanic piles. The two igneous environments share a number of similarities as well as a great number of differences which has led them to be viewed in two separate groups. Plutons are able to capture the later stages of magmatic activity in an arc, providing insight only to the concluding period of a system. Meanwhile, volcanic piles offer an instantaneous snapshot of the magmatic activity at the time of extrusion of the magma giving a more substantial time frame for studying the processes of the system. A large amount of work is being done to create a model which includes data from all areas of magmatic activity, both intrusive and extrusive, that better connects these two systems and allows for a greater knowledge of the process of differentiation of the earth and the creation of a silicic continental crust (O’Bachmann et al, 2007).

Magmatic systems become more complicated with vertical depth, both compositionally and thermally, but this is often hard to observe in an active system we must turn to extinct magmatic arcs to gain data about the relationships between all parts of a system. In order to study these characteristics related to the depth in the system we studied a continental arc system where post-magmatic tectonic forces have tilted the region and through faulting and erosion left a vertical to oblique cross-section through the
system. This rare and important feature allows us to relate all of the different sections of a volcanic arc including the host rocks, deep plutons, shallow sub-volcanics and the volcanic pile. This system provides the ability to make important conclusions about processes that drive continental margin arcs and thus the history of the differentiation of the Earth and the origins of the crust.

The Tectonic History in Asia and the Geologic Setting of the GTIC

The tectonic history of the Central Asian Orogenic Belt was characterized by a complex pattern of subduction and subsequent collision relating to the closure of the ocean basin between the North China Craton - Tarim block and Siberian Craton. It includes passive and active margin sedimentary packages, Achaean Proterozoic cratonal blocks, Paleozoic metamorphic terrains of up to amphibolite and granulite facies, ophiolites and accretionary complexes, but it is dominated by magmatic belts of juvenile nature. The geology of Mongolia (Map 1) is completely characterized by this collage of collided and accreted material situated between the North China Craton in the south and the Siberian Craton in the north. The Tarim Block added an east-west component to the tectonic activity creating a curvature to the belts of accreted material. The Gobi Tienshan Intrusive Complex, GTIC, is a member of the southernmost and youngest belt in the Central Asian Orogenic Belt, CAOB, making it a point of interest in obtaining a greater comprehension of the tectonic activity of the region.

The geology of Mongolia was initially studied and mapped by Russian geologists in the 1950’s and 1960’s and they created the first geologic and elevation maps of the country. Their knowledge of the locations of contacts and compositions of the main units
were encompass the general knowledge we still believe to be true today, but their interpretations and ages are seen to be unreliable. The next large amount of geologic work done on the area was by the Czech Geological Survey (Hanzl et al. 2008) in their completion of a 1:200,000 map of the Gobi Tienshan Intrusive Complex and its surrounding area. Their work provided key insights and helpful maps to the accurate and effective field work as well as for the completion of this project as a whole.

The Gobi Tienshan Intrusive Complex (Map 2) is located in the Great Gobi Protected Area, along the southern border with China, in the southwest corner of Mongolia. This unique arc exposes the different depths of a volcanic crustal section that has been tilted and eroded so that movement along the surface in a southeast to northwest direction is an increasing depth transect through the volcanic complex. In the northwest corner of the complex lie the granodiorite host rocks, followed by multiple magmatic intrusions which created several igneous bodies throughout the complex, with the largest bodies being the Granite Unit, the Mingling Unit, the Enclave Plume unit and the late dikes which cut through all of the units. The southeast corner of the complex exposes the shallowest part of the volcanic system, the sub-volcanic chamber and the volcanic unit.

By taking samples and studying each of these units in detail, we can obtain a better understanding of how this volcanic system operated and the relationships that existed between coeval subvolcanic and volcanic units. This work can greatly impact the way that we are able to understand currently active magmatic systems. The aim is to better understand the complicated interactions between all of deeper plutons, sub-volcanic chambers, and volcanic rocks in the GTIC, and possibly extrapolate those findings to active analogous modern arcs.
In the field we noted compositional, textural and structural characteristics of sub-volcanic and volcanic rocks and sub-divided units based on these features. Building on the reconnaissance scale field mapping of previous summers, we created a detailed map of the sub-volcanic area and the volcanic-subvolcanic contact in its entirety. Through this field mapping we obtained a broader understanding of the geologic processes that occurred in this area. We also collected samples in order to study the petrography, geochronology and the geochemistry of the volcanic and sub-volcanic rocks to better constrain the chemical and temporal relationships between the units in the system.

My work focused on interpreting the magmatic history of the sub-volcanic and volcanic units. Through the study of field, petrologic and geochemical data, I made some interesting conclusions about the sub-volcanic chamber and its interactions with the other units, including: 1) The contact between the volcanic and sub-volcanic unit differs between in different locations because of the depth from the surface of different areas of the sub-volcanic chamber as well as the geography of the cross section that has been created across the surface through the complex, 2) The Gobi Tienshan Intrusive Complex is a continental margin arc that has been tilted through the tectonic activity of the colliding of the North China and Siberian Cratons in Asia, and 3) Due to geochemical relationships shown between the volcanic and sub-volcanic units and between the volcanic unit and the rest of the units in the complex, the sub-volcanic chamber can be believed to have a chemical filtering process occurring through fractionation of specific minerals in the chamber. My work also contributed to our understanding of the overall tectonic setting of the complex.
**Hypotheses:**

The observed field relationships generated three main working hypotheses for the remainder of the project. First, I believed, from the field observations, that the southern sub-volcanic volcanic contact is gradational in grain size because it is located at the top of a magma body that cooled quickly because of its closer proximity to the surface of the magmatic arc than the contact between the sub-volcanics and volcanics in the eastern section of the field area. In order to further investigate this we looked at the geochemistry to evaluate the similarities and differences in composition between the Syenogranite unit and the volcanic pile. We also looked at the petrography to evaluate the grain characteristics giving clues to the cooling history of the granites and volcanics. Lastly we will look at the geochronology and link the temporal relationship between the Syenogranites and the volcanic pile.

The second focus of the project will involve the relationship between the granite units in the sub-volcanic chamber. I proposed that the red granite body at the top of the sub-volcanic chamber is a product of fractionation of the Rapikivi Porphyry granites and that the transitional lens shaped unit is related to the crystallization during melt fractionation. The geochemistry was the main data source used to inspect this theory. We used the compositional data to gather an understanding of the chemical relationships between the four granite units in the sub-volcanic chamber. The petrography also provided information from the grain characteristics of each unit allowing us to interpret the crystallization history of each unit in the chamber.

Lastly I believe that the volcanic pile is chemically related to the sub-volcanic chamber as well as each of the large plutonic bodies of the complex because each of these
plutonic units were part of the extruded material of the arc over the time period of the magmatic system. The geochemistry was the most direct way of accomplishing this, as we compared the trends in many geochemical plots to determine the patterns and relationships between the volcanics, sub-volcanics and the deeper complex units such as the granites, enclaves, mingling granites, granodiorites and the late intruding dikes. The geochronology also provided insight on the temporal relationships between each of the units in the Gobi Tienshan Intrusive Complex allowing us to interpret the period in which they were each contributing to the magmatism in the complex.

Data

Mapping and Field Observations

Map C – This map shows the sub-volcanic and volcanic field area in the southeastern corner of the GTIC with the units, structures and station locations.
The sub-volcanic chamber and volcanic unit are located in the southeast corner of the Gobi Tienshan Intrusive Complex. The sub-volcanic chamber is exposed on the surface with an arcuate contact with the volcanic pile along the southern and eastern boarders of the chamber. Minor post-magmatic strike-slip displacement is observed in the northwest corner of the field area.

We sub-divided the sub-volcanic chamber into four different main granite units. The largest of the units is the Rapikivi Porphyry and it is located in the northern part of the sub-volcanic chamber. This unit consists of approximately 38% K-feldspar, 30% plagioclase, 20% quartz, 7% hornblende and 5% biotite with +/- 1% epidote. Hornblende grains have an elongate or acicular shape. The groundmass crystals throughout this unit have graphic textures. Rapikivi porphyroclasts (crystals of K-feldspar with a ring of plagioclase grown completely around them) are the defining characteristic of this unit and were found in populations of about 4-5 crystals per 100 cm² area, ranging in size from 0.5 – 1 cm (Photo 1). The Rapikivi Porphyry unit also contained epidote observable in hand specimen. Some areas had millimeter size crystals while epidote was also seen growing in a fibrous, radiating habit in clusters up to 1.5 cm in size. We also found apalite dikes running through the unit, with epidote present in these veins as well as pegmatites with varying grain sizes.

The next unit in the sub-volcanic area is the K-feldspar Porphyry. This unit is situated in the center of the sub-volcanic chamber and is much smaller in map area than the Rapakivi Porphyry. This unit is composed of 55% K-feldspar, 30% quartz, 8% plagioclase and 7% biotite with a small amount of epidote dispersed through the rock. The dominant mineral is K-feldspar with some quartz crystals which occurs both in
clusters of larger grains and as small grains in the groundmass. There were very few mafic minerals, mostly biotite with little to no hornblende. Plagioclase crystals were found in patches of higher concentration while there were other patches where plagioclase was absent. We observed multiple apalitic dikes, which included pegmatitic quartz pools. The unit had a slightly identifiable magmatic fabric of about 72° strike and 75° dip.

In the southern most part of the sub-volcanic chamber is the Syenogranite unit. This unit is K-feldspar rich with an approximate composition of 50% K-feldspar, 35% quartz, 5% plagioclase, 5% biotite and 5% hornblende. The groundmass of the unit is a fine grained K-feldspar and quartz mix, with grain size about 1/8 mm and smaller. The mafics were difficult to determine but are assumed to be equal amounts of biotite and hornblende. There are also quartz pools and vugs of quartz, fluorite, and other minerals grown from gas pockets. The unit also had apalite dikes and epidote growths with signs of albitionization along the margins of these dikes.

In the southeastern corner of the sub-volcanic chamber lies the Transitional Granite unit. This unit is intermediate between the Feldspar Porphyry and the Syenogranite units from the sub-volcanic chamber. The Transitional Granite unit is found in contact with a small section of Feldspar Porphyry which was observed to have a K-feldspar groundmass with plagioclase porphyroclasts about 1-3 mm in size. This portion of the unit had much less quartz than the rest of the Transitional Granite unit and had acicular hornblende and a small amount of biotite. The Transitional Granite was also seen in contact with a small section similar to the Syenogranite which had a mixed matrix of K-feldspar and quartz like the rest of the unit, but there was no evidence of
plagioclase, instead there were porphyroclasts of quartz and K-feldspar. The overall groundmass in the transition granite unit is a quartz and K-feldspar equigranular matrix, with crystals smaller than 0.5 mm. There were porphyroclasts of both quartz and plagioclase ranging in size from 1-2 mm, with all of the porphyroclasts being less than 5 mm in size. Hornblendes are aligned parallel to a magmatic fabric striking 59° and dipping 84°. Apalite dikes were observed aligned with this magmatic fabric as well.

Volcanic rocks were observed in the south and the eastern part of the field area. The volcanic pile in the south was characterized by a dark matrix, too fine grained to determine composition with a variety of porphyroclasts, including plagioclase and quartz, about 1-2 mm in size and rectangular and circular in shape respectively. There were multiple volcanic characteristics observed in the southern volcanic pile including columnar jointing, pepperite sandstones and volcanic banding that strikes about 122° and dips about 66° (Photo 2). Alteration was found in abundance in the volcanic pile in veins of epidote, usually found around slicken lines showing that a fault is the source of the alteration fluid. The volcanic pile in the east was dark blue with only a few, small porphyroclasts of plagioclase and quartz. The color change observed on the ground and in the satellite image did not correspond to any noticeable compositional change in the volcanic rocks. The volcanic pile had characteristics including volcanic banding striking 118° and dipping 88°.

The last of the major units in the shallowest section of the Gobi Tienshan Intrusive Complex are the late intrusive dikes. The dikes were observed to have a variety of compositions, from quartz diorite to dacite and range in size from as wide as 5 meters to under a meter. The dikes had chilled margins (Photo 3) with more resistant fine
grained edge and the center material had a fine grained dark matrix, with porphyroclasts
of plagioclase quartz and hornblende, about 1-3 mm in size. The dikes were oriented in
the northwest to southeast direction through the field area striking about 148° and dipping
70°. The dikes were seen to intrude the volcanic pile and carried pieces of the granite
from the sub-volcanic chamber (Photo 4). In the southern part of the region the dikes
were not seen cutting into the volcanic pile and were not observed intruding into the
Syenogranite unit in the southern part of the sub-volcanic chamber. Therefore, the dikes
running through the field area are known to be younger in age because of their
crosscutting relationship across the different units and into the volcanic pile.

We also observed structural relationships in the sub-volcanic chamber and
volcanic unit. The contacts between the four different granite units in the sub-volcanic
chamber were inferred based on outcrop locations as many contacts themselves were
obscured by alluvial material. The observed contact between the volcanic and sub-
volcanic chamber was observed to be gradational in the southern part of the field area
(Photo 5). As you walked along the contact there was an observed color change and the
grain size of the granite unit gradually decreased but it was difficult to tell where the unit
became volcanic. The contact in the eastern part of the field area between the Rapikivi
Porphyry and the volcanic pile was observed to be intrusive. The Rapikivi Porphyry was
observed to be intruding the volcanic unit (Photo 6) with a dike of granite material
cutting into the volcanic pile.

Petrography

Sub-volcanic Syenogranite
The sub-volcanic Syenogranite unit along the southern contact with the volcanic pile displayed rapid cooling grain characteristics. Two thin sections of this unit along the contact were examined; the first sample, 4808, showed a break down of chemical components as 45% K-feldspar, 38% quartz, 10% plagioclase, 5% epidote and 2% biotite much like the assumed content from field observations of the unit. The overall groundmass of quartz and K-feldspar was still crystalline. The K-feldspar crystals throughout the section were slightly larger and phenocrysts of plagioclase. This sample also displayed a considerable amount of secondary alteration with a fair amount of secondary epidote scattered throughout the sample as well as plagioclase crystals being broken down into seracite.

The second sample, 5008, examined showed a slightly abnormal mineral content with 45% quartz, 30% plagioclase, 18% K-feldspar, 5% epidote and 5% opaque minerals. Overall the groundmass of this sample was also still crystallized with the quartz crystals displaying a graphitic texture (Photo 7) which forms in grains that have a rapid cooling history. This sample also showed considerable secondary alteration in the presence of epidote throughout the sample as well as the plagioclase crystals breaking down into seracite.

**Southern Volcanic Pile**

Volcanic sample petrography was done on samples collected in both the southern and eastern volcanic piles. In the southern volcanic pile the samples showed consistently high amounts of plagioclase and a high degree of secondary alteration. Sample 5108 contained 35% plagioclase, 30% epidote, 20% K-feldspar, 8% opaques and 7% quartz. Overall, the plagioclase crystals could be observed in hand sample and the grain
characteristics displayed evidence of extrusion through patterns of volcanic flow with the alignment of the thin needlelike plagioclase crystals in a flowing arrangement (Photo 8).

The second sample, 5208, had a composition of 30% plagioclase, 30% quartz, 20% K-feldspar, 10% chlorite, 5% epidote and 5% opaques. Overall, the groundmass of this sample was no longer crystalline, making the composition difficult to determine accurately, but the thin needlelike crystals were also arranged in a volcanic flow pattern in this sample, giving evidence of the extrusion of this sample to the surface. The sample also experienced alteration shown through the presence of epidote and chlorite.

8108 was a southern pile volcanic taken farther from the contact with the sub-volcanic chamber in the southeast corner of the complex. The mineral content of the sample was 50% plagioclase, 15% quartz, 15% epidote, 10% chlorite, 5% seracite with about 5% of the material too altered to determine the composition. Overall this was a very plagioclase rich rock, which was evident in hand sample where large rectangular phenocrysts could be observed growing in clusters as well in the matrix around the phenocrysts. The plagioclase crystals also display original igneous zoning where the crystal has higher albite content in the middle while the outer edges have higher anorthite content creating a change in extinction angles in the crystal along the rim of the crystal.

Even farther from the sub-volcanic contact in the volcanic unit sample 8308 was collected. This sample had a mineral content of 40% K-feldspar, 30% plagioclase, 15% epidote, and 10% quartz. Overall the groundmass consisted of small round crystals that did not have the time to grow very large; their grain shape is indicative to an ash deposit depositional environment. The K-feldspar crystals in the sample were also observed to
have embayments of crystallized melt captured while the K-feldspar was still growing (Photo 9). This grain characteristic is indicative of a rapid cooling history.

The last southern volcanic sample, 8408, which displayed a mineral content of 25% sericite, 20% plagioclase, 20% epidote, 15% opaques, 10% quartz, and 10% chlorite. Overall the hand sample displayed light and dark porphyroclasts determined to be plagioclase, quartz and opaque minerals. The plagioclase had mostly been broken down into sericite making the cooling history of the rock difficult to determine through the high level of alteration occurring.

**Eastern Volcanic Pile**

The eastern volcanic pile displayed different chemistry and a more centralized deposition environment throughout the pile. The first sample, 7208, had a mineral content of 55% quartz, 35% plagioclase and 10% opaques. Overall this rock appeared spotted with small round shaped porphyrys of quartz and plagioclase and a very fine grained matrix. The size and shape of the porphyrys as well as the fine grained matrix is evidence of an ash deposit.

The second sample, 7808, had a mineral content of 30% quartz, 30% plagioclase, 30% epidote, 7% K-feldspar and 3% opaques. The groundmass was difficult to determine content of due to its fine grained nature, but the grains appeared spotted and round in shape with no pattern or alignment, indicative of an ash deposit. The sample also had stripes observed in hand sample, under closer observation these stripes were determined to be veins of higher levels of alteration where the concentration of epidote was noticeably higher.
The last sample from the eastern volcanic pile was 8008 and had a mineral content of 45% quartz, 30% plagioclase, 20% epidote and 5% opaques. Overall the grain texture of this sample was crystals with sharp edges and no alignment of crystals. This sample also displayed characteristics of an ash deposit depositional environment. Overall the eastern volcanic pile appears to have been predominantly an ash deposit with high levels of both quartz and plagioclase and low K-feldspar content.

**Geochronology**

Geochronology data was collected from samples from each of the sections throughout the Gobi Tienshan Intrusive Complex using zircon U-Pb crystal dating. The three main units in the center of the complex all displayed similar ages with the exemption of the granite unit which had a high error most likely explained by standardization problems with the calibration of the instrument. The central Syenitic unit was dated at 293 +/- 13 Ma, the central Granodiorite unit dated at 292 +/- 6 Ma and the Granite unit dated at 311 +/- 19 Ma. The volcanic Rhyolites sampled dated to 292 +/- 15 Ma, this puts them in the same temporal scheme as the central units leading to believe that a link does exists between the deep plutons and the extruded volcanic pile. And lastly the Andesite dike swarm was dated at 299 +/- 6 Ma leaving it the youngest of the units in the complex which further supports the dikes cross cutting relationships through almost all of the units in the complex.

**Geochemistry**

**Major Element Chemistry**

The Sub-volcanics were determined to be all containing silica contents of over 58%, making 10% of them Andesites (SiO$_2$ 58-62%), 20% Dacites (SiO$_2$ 62-75%), and
80% Rhyollites (SiO$_2$ >75%) (Fig. 1). When plotted on the SHAND diagram, they were all decisively Metaluminous (Fig. 2). The SiO$_2$ vs. K$_2$O plot displayed almost all of the sub-volcanic samples to be of the High-K Alkaline series (Fig. 3). In the majors oxides plotting against SiO$_2$ (Fig.4) each of the plots displayed a positive or negative trend except for the Na$_2$O vs. SiO$_2$ plot which displayed no trend line at all.

The Volcanic rock types were determined to be approximately 10% Andesite (SiO$_2$ 58-62%), 40% Dacite (SiO$_2$ 62-75%) and 50% Rhyollite (SiO$_2$ >75%) (Fig. 1). When plotted on the SHAND diagram 70% were considered Metaluminous while 30% were determined to be Peraluminous (Fig.2). The SiO$_2$ vs. K$_2$O plot determined that almost all of the volcanic samples were in the High-K Alkaline series, with two samples being plotted as Calc-Alkaline (Fig. 3). The major oxides vs. SiO$_2$ (Fig. 4) had all of the plots displaying positive or negative slopes except for the Na$_2$O vs. SiO$_2$ plot which displayed no trend line.

**Rare Earth Elements**

The Rare Earth Element plots of the sub-volcanics, volcanics and deeper plutons displayed interesting trends (Fig. 5 & 6). The sub-volcanic and volcanic samples show incredibly tight patterns in their Rare Earth Element plots proving insight to the complicated connection between these two units. When compared to the Rare Earth Element Data from the rest of the deeper plutons in the Gobi Tienshan Intrusive Complex the rest of the complex shows no direct patterns with either the volcanic or the sub-volcanic samples (Fig. 7). Further, we plotted the sub-volcanic and volcanic Rare Earth Element Data against data from understood tectonic settings such as the Cascades, the Aleutian Arc and the Andean Arc (Fig 8). These data sets displayed similar trends to the
Gobi Tienshan Intrusive Complex sub-volcanic and volcanic sections with a shallow sloping trend of the plot and a negative Europium anomaly.

**Isotopes**

The sub-volcanic and volcanic samples plotted on two distinct areas of the isotope chart (Fig. 9). A majority of the sub-volcanic and volcanic samples plotted along the mantle array. These samples correlated with the samples plotted from the Granites, the Mingling granites, the Granodiorites, and the dikes. The second area that the sub-volcanic and volcanic samples plotted was farther to the right of the mantle array, with higher levels of Sr(i)(292). There were a few other samples that plotted to the right of the mantle array including the host rocks which displayed enormously high levels of Sr(i)(292).

**Discussion**

**Map and Petrography**

The observed and mapped shape of the sub-volcanic chamber has given insight to the cooling history of the chamber as a whole. The shape of these granite units could be a product of crystal fractionation in the chamber during the magmatic activity of the shallowest parts of the complex. The units are seen to have similar chemical compositions observed in the field, in petrography and in geochemistry. These similar compositions can be explained by a gradation between units of varying concentrations of K-feldspar. The lens shaped Syenogranite unit which has higher levels of K-feldspar than the massive Rapikivi Porphyry unit in the north can be explained through the crystal fractionation of K-feldspar which created a dense area of K-feldspar rich granite at one
end of the chamber with a lower concentrated region of K-feldspar at the other end. This also explains the relationship of the transitional granite unit as the section in the sub-volcanic chamber where the two compositions of K-feldspar were still mixed when the system became inactive and the cooling process began.

The examined petrography of the southern and eastern volcanic piles helped to determine the cooling and extrusive history of each side of the volcanic arc. The southern half of the volcanic arc displayed grain characteristics of flow patterns providing evidence that the volcanic activity in the southern end of the arc was extruding lava flows across the region. The eastern volcanic pile samples all displayed grain characteristics of ash deposits, leading to the understanding that the volcanic activity in the eastern part of the volcanic arc to be explosive with ash gathering in a depositional environment.

The sub-volcanic volcanic contact in the south is observed to be gradational in the field observations and in the examination of the petrography of the samples in the area. The field area displayed an obvious color change of the units across the contact but the mineral composition of the rock was only determined in thin section. The petrography of the Syenogranites in contact with the southern volcanic pile was observed to be of similar chemical composition. The grain size change occurred at the observed contact in the field, but the grain characteristics of the Syenogranite unit were indicative of a rapid cooling history. This is most likely related to the geometry of the cross-section of the complex and this southern contact between the sub-volcanic and volcanic units was in close proximity to the surface causing the rapid cooling of the granite chamber.

The sub-volcanic volcanic contact in the eastern part of the field area between the Rapikivi Porphyry and the eastern volcanic pile was observed in multiple locations of the
field area to be intrusive. The intrusive relationship between these two units is simply explained through the geometry of the cross section of the complex, while the southern contact was closer to the surface the eastern contact was farther from the surface so the chamber was still hot when it came into contact with the volcanic pile leaving a sharp intrusive history.

The dikes are seen cutting through each unit in the entire Gobi Tienshan Intrusive Complex including the eastern volcanic pile. Their cross-cutting relationships with the units of the complex lead to believe that these dikes are a part of the last surge of magmatism in the complex. The geochronology data supported this notion as most of the complex was dated at about 292 +/- 6 Ma and the dike swarm was dated to be at 299 +/- 6 Ma making it the youngest unit of rocks in the complex.

**Chemistry**

The SiO$_2$ vs. K$_2$O diagram gives an insight into the complicated relationship between the volcanics and their sources from the sub-volcanics and the deeper pluton units. The sub-volcanics over lay the volcanic data on the SiO$_2$ vs. K$_2$O plot in the upper right side of the diagram, with high SiO$_2$ and K$_2$O content. This correlation between the chemistry of the two sections suggests that the sub-volcanic chamber is defiantly a source of the extruded volcanic pile. However, there still remains the lower portion of the volcanic data where there is no overlap of the sub-volcanic samples that must have a different source since it has lower contents of SiO$_2$ and K$_2$O. This source is believed to be the other units of the complex.

The Rare Earth Element plots of the sub-volcanic and volcanic units of the complex give an insight to the tectonic setting of the entire Gobi Tienshan Intrusive
Complex. When compared to the Rare Earth Elemental data from three known continental margin arcs in the Cascades, the Aleutian Arc and the Andean Arc the data was seen to have similar trends. The Gobi desert data directly correlated with the data from the other arcs in that they all had a similar shallow slope and a negative Europium anomaly. This comparison supports the notion that the Gobi Tienshan Intrusive Complex is also a part of a continental margin arc tectonic setting.

The Rare Earth Element data provides another insight to the complex relationship between all of the units in the Gobi Tienshan Intrusive Complex. While the whole rock chemistry between the volcanics and the deeper plutons displays similarities and relations, the Rare Earth Element patterns of the volcanic samples and deeper pluton samples do not show any sort of pattern or trend. However, as discussed earlier, the sub-volcanic and volcanic Rare Earth Element data is observed to be very closely related. This suggests the possibility that the sub-volcanic chamber is acting as a sort of chemical filter between the deeper pluton source magma chambers and the extruded volcanics at the top of the system. Further work on whole rock and single mineral geochemistry is required to test this idea.

The volcanic samples show relatable patterns to the samples from the deeper plutons in the complex. When examining the whole rock chemistry the volcanics and deeper plutons share chemical trends leading to believe that the deeper plutons are a source of the volcanic unit. The isotope data give better insight into the relationship between these units. The volcanic isotopes are plotted along the mantle array overlapping the Granite unit, the Granodiorite unit, the Mingling unit and parts of the dike unit. This overlap in data points is support for the notion that each of the deeper
pluton units was at one point a source of magmatism for the volcanic pile. The volcanic data plotting along the bottom of the mantle array with lower Nd (292) values is support the overall source for each of these units is lower crust. While the dikes with their higher Nd (292) values are more likely from depleted mantle, and the sub-volcanic samples with higher values of Sr(i)(292) are evidence of an upper crustal source.

Conclusions

The differences in contacts between the sub-volcanic chamber and the volcanic pile in the south compared to the contact in the east is due to the chamber depth, compositional differences of each granite body and intrusive and cooling histories of each side of the chamber. This conclusion is supported through the rapid cooling grain characteristics of the syenogranite unit in contact with the volcanic unit in the south, as well as the observed sharp, distinct intrusive contact in the east between the Rapikivi Porphyry and the eastern volcanic unit. The dikes further support this conclusion as they are observed to cut directly through the Rapikvi Porphyry into the volcanic pile in the eastern part of the sub-volcanic chamber, while they did not cut through the Syenogranite unit at all in the south. This supports the notion that the Rapikivi Porphyry and Syenogranite units of the sub-volcanic chamber had different cooling histories.

The overall tectonic setting for the Gobi Tienshan Intrusive Complex is a continental margin arc. The compared patterns of Rare Earth Elemental data between the sub-volcanic and volcanic samples in the Gobi with the data from the Cascades, Aleutian Arc and Andean Arc produced very similar plots, with shallow trends and a negative Europium anomaly. This conclusion supports the field observations and general
assumptions that the complex was a part of a continental margin arc associated with the opening and closing of oceans and basins between the North China and Siberian Cratons in Asia. As the two plates collided hundreds of continental margin arcs that were created from the heat from the collision of the plates became trapped between the two cratons and subsequently accreted to the continent. With this understanding of the tectonic setting we can properly evaluate the complex with a better knowledge of the processes that helped to create it.

The last main conclusion is that the sub-volcanic chamber in this continental margin arc complex acts as a chemical filter between the deeper pluton sources and the extruded volcanics. The whole rock and isotope data compared between the volcanic and deeper pluton units displays similarities including a lower crustal source through the isotope data. But the Rare Earth Element data of the deeper plutons shows no patterns or trends with the volcanic data while the sub-volcanic Rare Earth Element Data is very closely related to the volcanics. This change in patterns in chemical data supports the conclusion that the sub-volcanic chamber has a chemical filtering process that is altering the overall chemistry of the deeper pluton source material before it is extruded as volcanic material. This conclusion of chemical filtering is further supported by the conclusion that the different units in the sub-volcanic chamber are the product of crystal fractionation of K-Feldspar in the chamber. The concentration of K-feldspar ranges between the units with the higher concentrations being in the Syenogranite unit of the south and lower concentrations in the Rapikivi Porphyry in the north. The lens shape of the Syenogranite unit also supports the conclusion of crystal fractionation of K-feldspar as the chemical filtering process that altered the deeper pluton source material before it
was extruded into the volcanic pile. The conclusion of the sub-volcanic chamber as a chemical filtering process has an important impact on the way that volcanoes and volcanic activity can be understood now. By studying the chemical relationships of extinct volcanic arcs we are able to obtain a greater understanding of the chemical processes driving the magmatism in active volcanic systems today.

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Cited Works


Appendix A – Maps

Map 1 – This map shows the complex geological patterns in the North Asian continent. The state boundaries of the country of Mongolia are outlined, encompassing the stripes of accreted material over the region between the North China – Tarim Block and Siberian Craton.
Map 2 – This map shows the entire Gobi Tienshan Intrusive Complex as it has been mapped from field work and with the assistance of satellite images.

Map C – This map shows the sub-volcanic and volcanic field area with the units, structures and station locations.

**Appendix B – Photos**

Photo 1 – Rapikivi Porphyry unit with close up of Rapikivi grain.
Photo 2 – Volcanic Banding observed on weathered rock.

Photo 3 – Chilled margins of late intrusive dikes in the sub-volcanic field area.

Photo 4 – Small clasts of sub-volcanic chamber granite in the dike intruding into the volcanic pile in the eastern part of the field area with ruler for scale.
Photo 5 – The observed color change across the sub-volcanic volcanic contact in the southern part of the field area.

Photo 6 – Intrusive contact between the eastern volcanic pile and Rapikivi Porphyry unit with Granite dike intruding volcanic pile.

Photo 7 – Graphitic texture of quartz crystals in sub-volcanic chamber syenogranite. This grain characteristic is indicative of rapid cooling of the quartz crystals.
Appendix C – Figures

Figure 1 – TAS diagram for Sub-volcanic and Volcanic data
Figure 2 – SHAND diagram for Sub-volcanic and Volcanic data

Figure 3 – SiO$_2$ vs. K$_2$O for Sub-volcanic and Volcanic data
Figure 4 – Major Oxides vs. SiO$_2$ for Sub-volcanic and Volcanic data.

Figure 5 – Rare Earth Elements for Sub-volcanic and Volcanic data.
Figure 6 – Gobi Tien Shan Intrusive Complex Rare Earth Element data.

Figure 7 – Rare Earth Element data Sub-volcanic and Volcanic data compared to GTIC.

Figure 8 – Rare Earth Element GTIC Sub-volcanic and Volcanic data compared to the Andean Arc, Cascades and Aleutians data.
Figure 9 – Isotopic data for the GTIC, displaying the source of the sub-volcanic and volcanic units from the Lower Crust (Mingling, Enclaves, and Granite units) and the Upper Crust.

Figure 10 – K$_2$O vs. SiO$_2$ plot for Sub-volcanics and volcanics, displaying the source relationship of the sub-volcanics to the volcanics in the GTIC.