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Soputan Volcano, Indonesia: Petrological Systematics of Volatiles and Magmas
and Their Bearing on Explosive Eruptions of a Basalt Volcano

by

Syegi Lenarahmi Kunrat

A thesis submitted in partial fulfillment of the
requirements for the degree of

Master of Science
In
Geology

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Portland State University
2017

ABSTRACT

Soputan volcano is one of the few basaltic volcanoes among 127 active volcanoes in Indonesia. It is part of the Sempu-Soputan volcanic complex located south of Tondano Caldera, North Sulawesi and commonly produces both explosive eruptions with VEI 2-3 and effusive lava dome and flow eruptions. Over the last two decades, Soputan had thirteen eruptions, the most recent in 2016. Most eruptions started explosively, followed by dome growth and in some cases pyroclastic flows. Our study focuses on understanding the magmatic system of Soputan and what processes are responsible for its highly explosive eruptions, which are typically uncommon for a basaltic magma composition. Our study includes tephra samples predating the 1911 eruptions, lava flow samples from the 2015 eruption, and ash from a 2015 fallout deposit.

Our whole rock major and trace element composition are virtually identical to lava flow and select pyroclastic deposit compositions of Kushendratno et al. (2012) for the 1911–1912 and 1991–2007 eruptions. Bulk rocks contain 49 to 51 wt.% SiO_2 , whereas 2015 ash samples are slightly more silicic with 53 wt.% SiO_2 , consistent with segregation of groundmass from phenocrysts in the eruption cloud. Mantle normalized incompatible trace elements indicate strongly depleted HFSE (High Field Strength Elements) and REE (Rare Earth Elements) signatures but with spikes at Pb and Sr and mild enrichment of Rb and Ba.

In comparison of data of this study with what was reported by Kushendratno et al. (2012), Fo_{68-79} olivine-hosted melt inclusions range from basaltic (48–52 wt.% SiO_2) to basaltic andesite (54–55 wt.%) as compared to 54 - 65 wt.% SiO_2 glass in Fo_{68-74} olivines.

The compositional range of melt inclusions is consistent with 50% fractionation of multiple minerals including observed phenocrysts of olivine, plagioclase, pyroxene and oxides. Compositional trends with an inflection point likely reflect a change in the crystallizing assemblage, where early crystallization includes clinopyroxene and plagioclase, while later crystallization is dominated by plagioclase. New volatile concentration data from melt inclusions (S max. 0.35 wt.%, Cl max. 0.17%, H₂O max. 5.3 wt.% from FTIR analyses) are higher than previously reported from younger samples (S max. ~0.07 wt.%, Cl max. 0.2%, H₂O max. ~1 wt.%). H₂O is relatively constant (~1-4 wt.%) for individual tephra samples (data by FTIR and water by difference method). Our inclusion data suggest that more volatile-rich magmas exist at depth and this is consistent with a model whereby recharge of deep, volatile-rich magmas into a more degassed and crystal-rich magma initiates a new, highly explosive eruption.

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Introduction

Indonesia is an archipelago that lies on the triple junction of three major tectonic plates, the Indo-Australian, Eurasian, and Pacific plates. Indonesia is volcanically very active and has approximately 127 active volcanoes, 69 of which are monitored continuously (Figure 1), stretching from Sumatra island in the west to Halmahera island in the east (Badan Geologi, 2011; Gertisser and Keller, 2002). These active volcanoes are associated with volcanic arcs above subduction zones. The arc systems include the Sunda, Flores, Sangihe and Halmahera arc (Figure 1a). Most volcanoes are basaltic-andesite/andesite and fewer are basalt volcanoes, as expected from their geotectonic context.

Figure 1. a) Map of Indonesia with its subduction system (black lines with arrows show the direction of plate movement) and the active volcanoes (white circles). Area highlighted by red shown in b). b) Location map of Soputan volcano (grey square) in North Sulawesi Province and other active volcanoes on the island (base map retrieved from <http://www.geomapapp.org>).

Nine active volcanoes are associated with the Sangihe arc system, eight volcanoes in North Sulawesi and one volcano in Central Sulawesi, Sulawesi Island. The three most active volcanoes in Sulawesi (from south to north) are Soputan, Lokon and Karangetang volcanoes (Figure 1b). These volcanoes have been continuously active from mid-1900 until today (Badan Geologi, 2011; CVGHM, 2017). Among these three volcanoes, Soputan is the focus of this study.

Soputan is a crystal-rich, basalt volcano. Eruptive episodes begin with explosive eruptions that are followed by lava flow emplacement and/or dome growth. Activity since 2011 has been dominated by dome growth, occasionally interrupted by explosive eruptions with VEI (Volcanic Explosivity Index) 2-3 (Kushendratno et al., 2012; Zaennudin et al., 2013). A VEI of 3 is quite uncommon for a basalt volcano. Previous preliminary studies attribute the explosivity of this basaltic system to the high crystallinity of magma and presence of excess vapor (Kushendratno et al., 2012).

This study used petrologic indicators of magma storage and ascent in order to better understand the causes of the explosive eruptions of Soputan volcano. Focus was placed on understanding the systematics of volatiles using a petrologic approach. The hypothesis tested in this research was that the explosive nature of Soputan eruptions was the result of gas-rich basalt magmas intruded into a crystal-rich shallow reservoir, followed by crystallization and volatile transfer into shallow magma, where pressurization of excess gas is aided by the presence of high viscosity crystal-rich resident magma.

Background

2.1. Geological settings

Soputan (01.108333° N, 124.733333° E) is the youngest and most active stratovolcano of the Sempu-Soputan volcanic complex, which lies on the neck of North Sulawesi-Indonesia (Figure 1b), close to the south margin of Tondano Caldera. The summit height is 1809 meters above sea level with a 600 m by 450 m wide crater that is now filled by a lava dome from recent eruptions (Center for Volcanology and Geological Hazard Mitigation-Indonesia [hereinafter referred to as CVGHM, unpublished data]; Kushendratno et al., 2012; Suratman et al., 1990; Zaennudin et al., 2013) Soputan has several parasitic cones from which flank eruptions took place. Some have specific names, such as Aesopot and Aesopot Weru.

In addition to Soputan, other volcanoes in the complex have been extinct. Inactive volcanoes in the vicinity are Mount Rindengan (the oldest), Mount Maniporok, Mount Kelelondei, and Mount Temboan (the youngest) (Irawan et al., 1993; Suratman et al., 1990). Based on the published geological map (Kartadinata et al., 1998), volcanic activity of Sempu-Soputan volcanic complex prior to formation of the Soputan cone consisted of: Mount Manimporok (as the oldest), Mount Sempu, Mount Watukolok, Mount Rindengan and Mount Temboan, Mount Kelelondei, Mount Masem and Mount Toure (the youngest), which formed after collapse of the Tondano Caldera (~250kya) (Figure 2; Harpel et al., 2016; Zaennudin et al., 2013). A recent unpublished study (Prambada et al., 2012) revealed that Mount Manimporok and Mount Temboan, along with Mount Simarayar, Mount Toure, Masem crater and Soputan overlie Sempu caldera (Fig. 2; Prambada et al., 2012).

Figure 2. Map of Sempu-Soputan volcanic complex. Black dash lines represent the inactive volcanoes in the complex, whereas the red circles represent Soputan volcano and its parasitic vents. Base map retrieved from <http://www.geomapapp.org>.

2.2. Eruptive history

Soputan is one of the most active volcanoes in Indonesia. Its first recorded eruption occurred around 1450 CE (Global Volcanism Program, 2013). After a few hundred years, Soputan began to erupt again in 1785 CE (Kusumadinata et al., 1979) and has been active ever since. Excluding the 1450 CE event, its repose period has been between 1 and 45 years (Table 2, Figure 3). Eruptions that occurred from 1450 to 1890 were derived from Soputan's summit crater, including explosions with VEI 2-3 (Table 1).

The first flank eruption occurred on February 4, 1901. It began with an explosive eruption, followed by lava flows from a parasitic vent called Aesoput. Between 1901 and 1913, there were six explosive eruptions that were sourced from Aesoput (Global

Volcanism Program, 2013; Kushendratno et al., 2012; Suratman et al., 1990), all with VEI 2. The Aesoput parasitic vent of Soputan has produced ~60 million m³ of lava between 1906 and 1923.

Table 1. Description of Soputan's eruption sequence from first activity until present.

Time	Description	Sequence
1450	The first recorded eruption at Soputan.	Explosion. VEI 3
1785 - 1890	Soputan summit's eruptions.	Explosions. VEI 2
1901 - 1913	Flank eruption and first parasite vent (Aesoput) formed	Explosions – Lava. VEI 2
1915	Flank eruption and second dome (Aesoput Weru) formed.	Explosions – Lava. VEI 2
1917 - 1953	Eruptions source at Aesoput.	Explosions – Lava. VEI 2.
1966-present	Eruption activities at Soputan main crater	Explosions – Lava - Dome. VEI 1 - 3.

Another flank eruption that took place on different location, northeast of Soputan in 1915 formed a new dome named Aesoput Weru. Eruptive activity from the Aesoput Weru vent location was dominated by lava flows. It was followed by another period of eruption sourced at Aesoput from 1917 until 1953. All four VEI 2 eruptions from Aesoput were accompanied by lava flows.

In 1966, the eruption has shifted back to Soputan main crater, and since then until present, the activity of Soputan has been restricted to its summit crater. It always started with an explosion (mostly VEI 2-3), was followed by emission of lava flows and/or dome growth, and was occasionally interspersed with production of pyroclastic flows (Table 1 & 2; Figure 3).

Figure 3. Soputan eruption events from 1450 to present based on VEI (Volcanic Explosivity Index). All different circles represent eruptions that occurred at Soputan summit. Light grey and dark grey diamond represent the eruptions that occurred at Soputan parasitic vents. Different sizes represent different scale of VEI. (adapted from Wright et al., 2016).

Table 2. Historic eruptions of Soputan volcano **.

Date	Repose time (year)	Eruptive vent	Description
1450 ± 10 y.	335	Soputan	First reported activity of Soputan, VEI 3
1785 - 1786	34	Soputan	Eruptions from the main crater. VEI 2
1819	14	Soputan	VEI 2
1833	12	Soputan	VEI 2
1845	45	Soputan	VEI 2
1890	11	Soputan	VEI 2
1901	5	Aesoput	Flank eruption that created a crater on the northeast flank of Soputan. VEI 2.
September 17, 1906	1	Aesoput	Another flank eruption at the same location as the previous one, followed by lava flows, and formed a parasite cone called Aseoput. VEI 2.
June 5–23, 1907	2	Aesoput	More frequent gas emissions and incandescence were observed at 3 pm, June 5. Explosive eruption on June 7 with the same intensity as previous eruption. VEI 2
June 1908-June 1909	2	Aesoput	Several eruptions occurred in the parasitic cone, accompanied by lava flows that lasted for 1 year. VEI 2.
November 1911-April 1912	1	Aesoput	Eruption accompanied by lava flows for 5 months. VEI 2.
April-July 1913	2	Aesoput	More eruptions at the parasitic cone. VEI 2.
April-June 1915	2	Aesoput Weru	A new dome, 'Aesoput Weru' located south of Aesoput and northeast of Soputan was formed. Lava flows with 4,000-5,000 m runout length to the southeast. VEI 2.
November 1917	7	Aesoput	An eruption occurred at Aesoput. VEI 2.

Date	Repose time (year)	Eruptive vent	Description
November 27, 1923-Januari 18, 1924	23	Aesoput	Several eruptions occurred during this period of time. VEI 2.
August 22-27, 1947	6	Aesoput	VEI 2.
November, 1953	13	Aesoput	VEI 2. The eruptions that occurred during this period also marked the last activity at Aesoput cone
May 21, 1966	2	Soputan	Eruption began with an explosive eruption from the northern part of the crater. A lava dome formed inside the crater and lava flows descended down the west flank. VEI 3.
July 16, 1968	2	Soputan	VEI 1.
February 16, 1970	1	Soputan	VEI 2
May 19, 1971	2	Soputan	VEI 1.
Jan 6, 1973	9	Soputan	VEI 2.
August-November 1982	2	Soputan	August 26-27, explosive eruptions with thick black eruption columns to 2,000 – 3,000 m height above the summit. Ash falls covered ~12 villages located to the southeast and south with 12-13 cm thick ash. The ash reached as far as Kotamubagu (~60km from the volcano) and 850 people were evacuated. September 17-18. Vulcanian and strombolian eruptions occurred with 300 – 3,000 m column heights. November 9 – 10. A vulcanian eruption on November 9 produced a 4,000 m high eruption column that went to the west and ashfalls reached Tomohon (~30 km from the summit), subsequent eruptions continued until November 10. VEI 3.
May 25-26, 1984	1	Soputan	Several explosive eruptions occurred from 9.44 pm on May 25 until May 26, at 11.35 am. The highest eruption column was 5,000 m and was accompanied by lightning and incandescent volcanic bombs. Two airports (~50 km northeast and ~200 km southwest from the summit) were closed during the eruption period. VEI 3.
May 19, 1985	4	Soputan	An explosive phase occurred for ~7 hours producing ash clouds that went east of the summit. The thickness of the ash at several villages to the southwest and southeast (~9–12 km from the summit) was 1-1.5 cm. VEI 2.
April-July 1989	2	Soputan	Several eruptions that occurred during this time period were from the main crater, with plume height range between 1,000-1,500 m and were accompanied by the dome growth. In May, the volume of the lava dome was approximately 2.5 million m ³ . VEI 2.
1991-1995	5	Soputan	Several explosive eruptions at the main crater occurred between October-December 1991. The lava dome grew continuously from 1991-1995. On November 1992, the lava dome filled up the main crater with estimated volume was 19.6 million m ³ . In July 1995, the lava dome collapsed and in later years the crater was again filled by a new dome. VEI 2.

Date	Repose time (year)	Eruptive vent	Description
May- August 2000	4	Soputan	<p>An explosive eruption phase began May 13 with a thick, black ash cloud that rose to 1,000 m above the summit. It was followed by collapse of the 1999-2000 dome (a rapidly emplaced dome compared to the 1995 lava dome). 2 cm thick of the ash falls covered villages located ~9km from the volcano.</p> <p>July-August. Several explosive and strombolian eruptions occurred. Several were not observed but were heard at Maluku observatory (~12 km east of the summit). The eruption cloud rose to ~3,500 m with a brown to brown-black color. Occasionally, pyroclastic flows travelled to 700 m runout distance and a lava avalanche travelled westward to a maximum of 2,000 m runout. The dome growth, lava flows and rock falls continued for entire eruption phase. VEI 2.</p>
October- December 2004	1	Soputan	<p>October 18 explosions ejected a 600 m thick white-grey eruption column. The rumbling sound was heard until the Post observatory (~12 km from the summit). Darwin Volcanic Ash Advisory Center (VAAC) reported based on satellite observations, the altitude of the plume probably rose up to 5,000-6,000 m. height.</p> <p>On December 24, another eruption occurred with an ash cloud height of 500-1,000 m to the north-northeast direction and was accompanied by a lava avalanche to the south reaching approximately 150-200 m length. VEI 3.</p>
April- December 2005	1	Soputan	<p>The first eruption phase in 2005 began from April 20 to April 24, with eruption columns ~1,000 m height. Lava fountains rose between 75-200 m above the summit. A lava dome grew rapidly during this period.</p> <p>On July 18, a bigger explosive eruption occurred and the dome collapsed, which yielded a large pyroclastic flow.</p> <p>The last eruption phase in 2005 started with a phreatic eruption on December 26, followed by a strombolian eruption the next day. VAAC reported that the plume height was approximately 5,800 m above the summit and traveled in a southeast direction. Another strombolian eruption occurred on December 28, with ash plume ~1,000 m height above the summit, followed by pyroclastic avalanche approximately 500 m to east and southwest direction. VEI 1-2.</p>
December 14, 2006	1	Soputan	VEI 1.
October 25, 2007	1	Soputan	<p>An explosive eruption ejected an eruption column to above 1,000 m height followed by production of pyroclastic flows that travelled ~500 m to the southwest and lava flows to the west with a distance of 100-150 m. Incandescence at ~30-50 m height was observed on the summit at night. Strong booming and rumbling sounds were heard at Lokon observatory (~30 km from the Soputan). VEI 3.</p>

Date	Repose time (year)	Eruptive vent	Description
June-October 2008	1	Soputan	<p>June 6. An eruption which yielded a dome collapse and pyroclastic flow occurred at 11.07 am (GMT +8). The biggest pyroclastic flows had approximately 6,500 km runout lengths to the west and widths ranging between 0.5-2 km. A subsequent eruption column to above 2,000 m above the summit also went to the west and the ash fall reached as far as Kotamubagu (a town located ~60km from the volcano). Incandescence was observed at night and rock falls continued until the next day. The estimated volume of pyroclastic flow and surge deposits was 17,423,500 m³.</p> <p>October 6. There were seven explosive eruptions with maximum column height to 1,500 m above the summit. The observed pyroclastic flow (produced by rock falls) went west-southwest with ~500 m length. Incandescence around the summit reached 50-150 m height and was seen during the night. VEI 3.</p>
July-August 2011	3	Soputan	<p>July 3. Explosive eruptions occurred with column heights circa 5,000-6,000 m above the summit, followed by pyroclastic flows that reached 4,000 m runout distance. Few villages on the east of the volcano were covered by 2-14 cm thick ashfall.</p> <p>August 14. An eruption with column height of 1,000 m above the summit occurred and lava flows reached up to 1,200 m flow distance. VEI 3.</p>
August 26-27, 2012	1	Soputan	<p>August 26-27. Three eruptions occurred in two days, followed by lava flows reaching 1 km to the southwest. Eruption column heights were between 1 – 4 km above the summit. The ash falls moved westward reaching Motoling village ~30 km from the summit. The eruption lasted approximately 11 hours.</p> <p>September 18. The second eruption of 2012 occurred midday. A thick grey ash column with height ca. 1.5 km above the summit moved northward. A Strombolian eruption followed the main eruption and lasted for few hours. A lava flow was seen during the night approximately 1.5 km length. VEI 3.</p>
January-March 2015	3	Soputan	<p>January 6. Two eruptions occurred with column heights between 1,500 and 6,500 m above the summit. The thick dark grey color of eruption column moved to the east-southeast direction. The lava flow travelled southwest to ca. 2 km distance. Incandescence of ~400 m length was observed (probably lava flow). Lava flows continued to occurred for several weeks.</p> <p>March 7-9. The eruption occurred at 5.09 pm (GMT +8) with greyish white thick plume and 4,500 m column height above the summit, moving southeast, followed by pyroclastic flows to the west that reached 2,500 m distance. The strombolian eruptions continued until March 9, with column heights of approximately 150-700 m. The lava flow (accompanied by rock falls) was seen during the strombolian eruption reaching 1.5km northward. VEI 3.</p>

Date	Repose time (year)	Eruptive vent	Description
January- February 2016	1	Soputan	<p>January 4-6. Several vulcanian and strombolian eruptions occurred with column heights between 2,000 and 6,500 m for vulcanian eruptions and 200-250m for strombolian. The lava flows went northeast.</p> <p>The January 2015 eruption had a column height of 6,500 m that drifted southwest and was followed by a pyroclastic flow that reached 2.5 km to the southeast.</p> <p>February 6-7. The explosive eruptions produced thick grey eruption clouds reaching 2,500 – 3,000 m above the summit toward east and southeast direction. Lava flows moved to the north and east direction. The February 7 eruption was followed by pyroclastic flows triggered by the rock falls toward the east with ~2km runout distances. VEI 3.</p>

** Sources: Badan Geologi, 2011; Global Volcanism Program, 2013; Kusumadinata et al., 1979; unpublished fieldwork reports of CVGHM

There are changes in Soputan eruption's style. The eruptions that occurred between 1450 and 1965, both at Soputan summit and its flank vent, consisted of VEI 2 explosive events without any record of dome formation or lava extrusion. Since 1966, an initial explosive eruption of VEI 1-3 was followed by lava extrusion (Figure 3, Figure 4). Furthermore, Soputan has become more frequently active in the last 20 years, with 13 VEI 1-3 explosive eruptions (CVGHM unpublished data; Kushendratno et al., 2012; Zaennudin et al., 2013).

Figure 4. Evolution of Soputan a) Soputan volcano on January 5, 2016. b) Aesoput eruption on January 14, 1924, c) Soputan (left) and Aesoput (center) in 1921, d) Soputan crater in 1933, no dome in the crater, e) Soputan summit observed in 2014 with the dome overtopping its rim. (All the images are copyright of Center for Volcanology and Geological Hazard Mitigation (CVGHM)).

The most recent eruption occurred on January 5, 2016. The eruption began with an explosive eruption with a magnitude of VEI 3, an eruption column height of 6.5 km and pyroclastic flows that travelled up to 2.5 km down the east flank (CVGHM, 2016). Since

then, a dome has continued to grow within the crater and has been accompanied by lava flow advance and rock falls.

2.3. Eruptive products

Kushendratno et al. (2012) and Zaennudin (2013) described the eruptive products of Soputan. They found that eruptive products of the last ~100 years are compositionally relatively homogenous low-Mg high-alumina basalts. The products are rich (40-50%) in plagioclase, olivine, pigeonite and titanomagnetite phenocrysts with sizes up to ~0.8 mm (800 μm) (Kushendratno et al., 2012). The olivine phenocrysts of Soputan demonstrate a range of textural and compositional characteristics. Olivine phenocrysts range in texture from strongly resorbed and rimmed by pyroxene to being euhedral, pristine phenocrysts. Resorbed olivine crystals have a Fo_{60} (Fo or forsterite is the Mg-bearing end member or component of the olivine solid solution; herein after refer as Fo) composition and reaction rims of pigeonite. The euhedral-subhedral olivine crystals have Fo_{70} composition without reaction rims (Kushendratno et al., 2012).

Based on the petrological findings of Kushendratno et al. (2012), the following can be inferred. The Fo_{70} composition indicates that the melt from which euhedral olivine grew was low in magnesium. This is consistent with the idea that basalt magma feeding into the shallow magma reservoir of Soputan had already undergone some differentiation at depth. Lower Fo content (~60) of resorbed olivine indicates even lower Mg in the melt. This combined with the resorption texture (as compared to euhedral-subhedral olivine) suggests that resorbed olivines probably originated from resident magma at shallower depth that was undergoing passive degassing, crystallization, and melt evolution, thereby destabilizing olivine and crystallizing pyroxene instead. Lower Fo content was possibly

caused by diffusional reequilibration of the olivines as the interstitial melt became more evolved during continued crystallization. On the other hand, the euhedral olivines are probably derived from deeper mafic recharge magma that did not undergo much more crystallization but instead mixed with shallow resident magma followed by eruption.

2.4. Melt Inclusion and volatiles

The intensity of an eruption is controlled mainly by the abundance of volatiles in the magma at the time of eruption, which is itself controlled by original volatile content, magma ascent rate, and viscosity of the melt (Myers et al., 2014; Wallace et al., 2015). When magma moves towards the surface, the pressure drops and the solubility of dissolved volatiles decreases, causing exsolution of volatiles. In response to continued pressure decrease, the resultant gas bubbles then expand and segregate from the melt to cause an explosive eruption. To understand the character of an eruption of a volcano, we must understand the volatile content and degassing behavior leading up to the eruption. Unfortunately, when an eruption occurs, almost all volatile constituents are lost to the atmosphere, except for small bits of trapped melt within crystals called melt inclusions (Métrich and Wallace, 2008; Wallace et al., 2015). These melts are trapped during crystallization, sealed within the crystals, and quenched to form glass/melt inclusions in the crystals. The melt inclusions, therefore, preserve the melt composition at various points during crystallization of the magmatic system underneath the volcano (Métrich and Wallace, 2008; Myers et al., 2014; Wallace et al., 2015).

Major volatiles in the magma are H₂O, CO₂, S, Cl and F. The most abundant volatiles in magmas are H₂O and CO₂, followed by sulfur, chlorine and fluorine. These

major volatiles have different degrees of solubility in silicate melts, where H₂O solubility is greatest followed by CO₂. The solubility of both H₂O and CO₂ decreases as pressure decreases, making H₂O and CO₂ concentration in melt inclusions a useful proxy for pressure (depth) of melt entrapment if it assumed that the melt was volatile-saturated during crystallization. The solubility of S, Cl and F are more complex because the presence of both solid and liquid phases in the melt influences their saturation (Métrich and Wallace, 2008; Wallace et al., 2015).

Methods

3.1. Sample collection

Pyroclastic fall and lava flow samples were collected from three sites located west and north-west of the volcano (Figure 5). Fall deposit tephra samples predating 1911 eruptions are the main subject of this study; tephra phenocrysts with melt inclusions are rapidly quenched in fallout deposits and most closely preserve the original volatiles as entrapped during crystal growth. The tephra sample site is a quarry exposure where 8 distinct tephra units could be distinguished (Figure 6). Two additional ash samples of the 2015 eruption were collected from the Soputan Observatory. Finally, a 2015 lava flow was sampled (Figure 5).

Figure 5. Map of Soputan volcano (open square) and surroundings showing sample collection sites; the tephra site (red circle) (Figure 6), ash fall collection site/Soputan observatory (green circle) and the 2015 lava flow site (blue circle) (base map retrieved from <http://www.geomapapp.org>).

The 8 tephra units were sampled and named based on relative stratigraphic position (Figure 6). Unit 1 is the lowermost tephra layer and is considered to be the oldest deposit of this study, whereas unit 8 represents the youngest deposit within this entire column.

Figure 6. Stratigraphic column of pyroclastic deposits of Soputan volcano. Scale is in cm.

The timing of the eruptions that generated these deposits is unknown. However, the eruptive history of Soputan (Kartadinata et al., 1998) includes production of frequent lapilli-producing explosive eruption columns over the past several hundred years (Figure 3; Badan Geologi, 2011; Kusumadinata et al.; 1979; unpublished data of CVGHM), based

on prevailing wind direction that commonly blows both westward or eastward (unpublished data of CVGHM), these are unequivocally Soputan tephra deposit.

From the eight tephra units preserved in the tephra section (Figure 6), I selected five different units for further compositional and textural study. Tephra samples from units 1, 2, 6, and 8, and the 2015 ash samples were analyzed using XRF and ICP-MS instruments to generate whole rock major and trace element compositions. In addition, olivine crystals and glass inclusion compositions were analyzed from units 1, 4, 6, and 8 (Table 3). All figures and tables in the following chapters will use the sample codes as shown in Table 3. Subsample naming is based on the type of samples and analysis.

Table 3. Sample codes based on the type of eruption product and analyses.

Samples		Analysis			Sample ID's			Symbols
Type	Unit*	XRF-ICPMS	EMPA	FTIR	XRF-ICPMS	EMPA	FTIR	
Tephra	1	✓	✓	✓	SOPT-01	SOP01, SOPF-01xx, SOP-01-xxx	SOPF01, SOPF-01xx	closed pink, closed and open orange circle
	2	✓			SOPT-02			maroon square
	3							
	4		✓	✓		SOP04, SOPF-04xx, SOP-04-xxx	SOPF04, SOPF-04xx	Close pink, closed and open green diamond
	5							
	6	✓	✓	✓	SOPT-06	SOP06, SOPF-06xx, SOP-06-xxx	SOPF06, SOPF-06xx	Closed pink, closed and open purple star
	7							
	8	✓	✓	✓	SOPT-08	SOP08, SOPF-08xx, SOP-08-xxx	SOPF08, SOPF-08xx	Closed pink, closed and open blue triangle
Groundmass	4		✓			GM-4		
Lava	Year 2015	✓			SOPL-15			Pink & yellow cross
Ash	Year 2015	✓			SOPA-15			Pink & gray cross

3.2. X-Ray Fluorescence (XRF) & Inductively Coupled Plasma–Mass Spectrometry (ICPMS)

Major element and some trace element compositions of tephra, ash and lava flow samples were obtained using XRF analyses, whereas higher accuracy trace elements compositions were generated through ICP-MS analysis. Samples were collected, weighed, ground into a powder, heated to 800-1000 °C, and cooled into beads. The beads were then reground into a powder and separated for XRF and ICP-MS analysis. The analysis was conducted at GeoAnalytical Lab, Washington State University, Washington (Johnson et al., 1999; School of the Environment, 2017).

3.3. Mineral sample preparation

In order to analyze the mineral and melt inclusion, further preparation was carried out on the tephra samples. Individual tephra units were sieved into 4 different (991, 600, 250 and 125 µm) grain size bins, and olivine and plagioclase phenocrysts were hand-picked from the 600-991 µm fraction. Picked olivine crystals that contain pristine melt inclusions (glassy without abundant mineral inclusions or evidence of devitrification) were separated, mounted on glass slides, polished and carbon coated.

3.4. Electron Microprobe Analysis (EMPA)

The samples were analyzed using the Cameca SX-100 Electron Microprobe at Oregon State University, Oregon, and operated remotely from Portland State University, Oregon. The EMPA operating conditions for spot analyses include 15 kV accelerating

voltage, beam current of 8 nA and a beam diameter of 5 μm . The calibration standards that were used are natural standard glass and minerals: VG-2, Fo83, Fo90, MAGT, BHVO-2G (Streck, 2015, unpublished). Loss of Na during analysis was minimized by low beam current and larger beam size as well as by counting Na first and for a short during (10 sec). Finally, a zero-intercept correction was applied to obtained analysis data of Na and K.

The analysis routine included major elements (SiO_2 , TiO_2 , Al_2O_3 , MnO , FeO , MgO , CaO , Na_2O , K_2O and P_2O_5) and volatile elements (S and C). Individual melt inclusions were analyzed at 2-3 points and 1-2 points were analyzed on each olivine host next to the inclusion but far enough to avoid any olivine that might have grown during post-entrapment crystallization along inclusion walls. H_2O concentrations were estimated using the by-difference method.

3.5. Fourier Transform Infrared Spectroscopy (FTIR)

FTIR spectroscopic analysis was conducted at the University of Oregon to obtain H_2O and CO_2 concentrations in melt inclusions. FTIR analyses were performed prior to EPMA analyses to prevent beam damage that might affect FTIR results. The glass inclusion were doubly polished to 20-60 μm thicknesses. Thickness measurements were made using two methods (Johnson et al., 2010; Myers et al., 2014); the reflectance fringe method using FTIR software and physical measurement using a micrometer. The reflectance method generated higher accuracy results. Therefore, this method was the preferred method used here. The aperture dimension was adjusted according to the glass inclusion sizes.

H₂O and CO₂ concentrations were calculated using distinct peaks in the FTIR absorption spectrum. The peaks of interest used here include the O-H peak at 3550 cm⁻¹ and doublet carbonate peaks at 1515 and 1430 cm⁻¹. The H₂O and CO₂ values were calculated using Beer's law (Dixon & Pan, 1995):

$$C = \frac{Abs \times Mw}{\epsilon \times \rho \times d} \quad (\text{equation 1})$$

where C is the concentration of H₂O (wt.%) and CO₂ (ppm), Abs is absorbance height of the vibration band, Mw (g/mol) is the molecular weight of the volatile species, ϵ (L/mol.cm) is the absorbance coefficient, ρ (g/L) is the sample density, and d (micron) is glass thickness. The absorbance coefficient and glass density are composition-dependent for basalts. Therefore, individual values for each melt inclusion were calculated, except for absorbance coefficient of H₂O (63 L/mol.cm), which was applied to all samples (Dixon & Pan, 1995; Johnson et al., 2008; Myers et al., 2014).

The biggest uncertainty was derived from the thickness measurement. The thickness range between 20-60 microns was considered to be the ideal thickness to produce a sufficient absorption peak without saturating the signal. If the glass is too thick then the peak height approaches that of total absorption. Whereas, if it's too thin, reflectance fringe peak heights approach the total peak height, disturbing the carbonate peaks measurement (Myers et al., 2014; personal communication with Paul Wallace and Madison Myer). As mentioned previously, the reflectance method were most likely be used to minimize the uncertainty.

3.6. Scanning Electron Microscope (SEM)

BSE (Backscattered Electron) images of olivine crystals were taken in order to document olivine zoning and textural context of melt inclusions using the Scanning Electron Microscope at the Cascades Volcano Observatory (CVO) – US Geological Survey. These olivines were the same samples as the one used for EMPA analysis only. The samples were mounted, and carbon coated prior to imaging at an emission current of 41.8 μA .

Results

4.1. Whole rock composition

All analyzed Soputan samples are basaltic in composition, except for the ash fallout sample that has basaltic andesite composition (Figure 7). The silica content of tephra samples is between 49.1 and 49.4 wt.%, whereas the lava flow is 50.8 wt.% SiO₂ and the 2015 ash sample is 52.6 wt.% SiO₂. The more evolved composition of the ash sample is consistent with segregation/removal of phenocrysts from the eruption cloud prior to deposition of ash from the sample site.

Figure 7. Total alkali silica diagram of the whole rocks of Soputan tephra samples and 2015 lava and ash fallout samples. Color codes and symbols as in Table 3.

The other major element composition of Soputan basalt samples includes: Al_2O_3 is between 19.3 and 21 wt.%, total FeO between 9.5 and 10.5 wt.%, MgO from 5.4 to 6.9 wt.%, CaO 10.2 to 11.1 wt.%, Na_2O 2.3 to 2.6 wt.%, K_2O 0.24 to 0.3 wt.%, TiO_2 between

0.8 and 0.9 wt.%, MnO between 0.19 and 0.2 wt.% and P_2O_5 between 0.09 and 0.11 wt.% (Appendix A). Conversely, basaltic andesite ash fall has Al_2O_3 content of 18.7 wt.%, FeO 9.8 wt.%, MgO 4.7 wt.%, CaO is 9.4 wt.%, Na_2O 3.1 wt.%, K_2O 0.4 wt.%, TiO_2 is 0.9 wt.%, MnO is 0.2 wt.% and P_2O_5 is 0.1 wt.%.

Figure 8. Harker diagram of Soputan whole rocks. Other volcanoes (for comparison) are Lokon (dark blue open triangle), Barren Island (brown open circle) and Merapi (dark blue open diamond). 2007 Soputan data (red diamond) also included. Data of Lokon from Elburg & Foden (1998), Barren Island from Streck et al. (2011), Soputan 2007 from Kushendratno (2012), and Merapi from Gertisser & Keller (2003). The color codes and symbols as in Table 3.

All analyzed tephra units are similar in composition with the exception of the fallout ash sample (Figure 8), and there is no clear temporal trend with any major element variations. This pattern holds true for the trace element compositions. All tephra samples have very similar trace element compositions; however, the 2015 ash has slightly elevated trace element concentrations (Appendix A, Figure 9 & 10).

For comparison, compositions of Soputan samples are plotted along with basalts of Lokon, Merapi, and Barren Island volcanoes. Lokon is a currently active volcano ~30 km north of Soputan; whereas Merapi is the most active volcano in Indonesia with basalt to basaltic-andesite composition that is also produce an explosive eruption. Barren Island located very close to north of Indonesian border and compositionally range from basalt to andesite.

Figure 9. Incompatible normalized trace element diagram of samples of Soputan and other volcanoes in Indonesia and Barren Islands, which is north from Indonesia border. Data are normalized to primitive mantle compositions (Sun & McDonough, 1989). Color codes and symbols as in Table 3.

Soputan samples are more depleted in incompatible elements than samples from other Indonesian volcanoes plotted here, with the exception of lower Nb and Ta values of Barren Island basalts. Furthermore, Soputan eruptive products are slightly more mafic and higher in Ca and Al than other recent mafic Indonesian eruptive products. The tephra deposits, 2007 and 2015 deposits have similarity in major and trace elements composition. It is consistent with Kushendratno et al. (2012) report that stated the whole rock of Soputan is relatively homogenous throughout time.

Figure 10. Rare Earth Element (REE) diagram of Soputan whole rock, other volcanoes in Indonesia and Barren Islands. Data normalized to chondrite (Sun & McDonough, 1989). Color codes and symbols as in Table 3.

4.2. Olivine-host and melt inclusions

The most abundant mineral phase in tephra deposits is plagioclase, followed by olivine and pyroxene. However, very few plagioclase-hosted melt inclusions are pristine; many more olivine crystals host pristine melt inclusions. Therefore, our study focused on trapped melt inclusions in olivine.

Olivine compositions in all tephra units have a very similar range. Forsterite content largely varies between Fo₇₀ and Fo₇₉; only tephra unit 8 has olivine with a lower Fo content (Fo₆₈). These values are higher than the Fo₆₂ – Fo₇₀ olivine compositions reported in Kushendratno et al. (2012). The CaO and MnO content of olivine range from 0.11 to 0.24 wt.% for CaO and 0.25 to 0.52 wt.% for MnO. Few olivine grains have CaO and MnO above or below this range (Figure 11). Olivine microphenocrysts (<0.1mm) in the groundmass have an Fo content of 73.

Figure 11. Variation diagram of olivine compositions from 4 different tephra units (1, 4, 6 and 8) and the groundmass. CaO and MnO versus Fo content. Color codes and symbols as in Table 3.

The correlation between olivine major elements and Fo content reveals CaO compositional data do not show a correlation with Fo content. On the other hand, MnO content decreases with increasing Fo content (Figure 11). A small number of olivine grains display more Mg-rich cores (Figure 12), signified by darker colors in the backscattered electron (BSE) images, that represent lower average atomic number (Z) and with higher average Z in the rims. Olivine zoning cannot be precisely identified because the BSE images that were taken (Figure 12) were derived from individual partial olivine crystals.

Figure 12. Backscattered electron images of several olivine-hosted melt inclusions. Grayscale shade correlates with the average atomic number of the analyzed material, such that black is empty space, light gray is olivine, and dark gray is a melt inclusion (black arrows).

Table 4. Major element and volatile composition of melt inclusions hosted by olivine.

Inclusions	Sample ID	Wt. %	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂
	SOPF-0101	<i>n</i> = 2	51.89	0.92	19.84	9.54	0.17	4.58	9.84	3.02	0.34	0.16	0.00	981	982	46.10	3.05	292.87
		<i>St.dev.</i>	0.12	0.01	0.04	0.00	0.04	0.03	0.14	0.19	0.05	0.01	0.00	51.62	89.10	0.17		
	SOPF-0102	<i>n</i> = 2	49.21	1.23	19.12	9.80	0.14	5.92	11.85	2.73	0.33	0.28	0.01	2370	c.d.	51.87	4.35	625.12
		<i>St.dev.</i>	0.42	0.09	0.37	0.42	0.07	0.27	0.34	0.23	0.03	0.01	0.01	14.14	c.d.	0.08		
	SOPF-0104	<i>n</i> = 2	48.21	0.91	20.19	9.81	0.17	6.35	12.20	2.35	0.22	0.09	0.03	1815	885	53.58	4.42	793.73
		<i>St.dev.</i>	0.01	0.05	0.17	0.07	0.02	0.04	0.08	0.07	0.08	0.01	0.04	255.27	79.90	0.01		
	SOPF-0109	<i>n</i> = 2	55.50	1.32	17.00	9.83	0.21	4.28	8.17	3.30	0.49	0.18	0.02	649	1237	43.71	3.47	<50
		<i>St.dev.</i>	0.15	0.02	0.09	0.14	0.08	0.12	0.15	0.25	0.03	0.01	0.03	24.75	193.75	0.32		
	SOPF-0111	<i>n</i> = 2	52.03	0.58	18.41	11.85	0.22	5.23	8.67	3.01	0.30	0.09	0.02	1471	c.d.	44.01	4.04	1233.86
		<i>St.dev.</i>	0.41	0.08	0.84	0.08	0.02	0.03	0.29	0.01	0.03	0.00	0.01	27.58	c.d.	0.01		
	SOPF-0114	<i>n</i> = 2	54.90	1.31	17.28	9.52	0.17	4.71	8.01	3.53	0.58	0.18	0.04	545	c.d.	46.85	3.29	c.d.
		<i>St.dev.</i>	0.31	0.01	0.05	0.07	0.13	0.03	0.10	0.04	0.02	0.01	0.05	44.55	c.d.	0.04		
	SOPF-0402a	<i>n</i> = 2	52.65	0.77	18.33	10.88	0.23	4.69	8.72	3.45	0.41	0.18	0.05	1108	c.d.	43.44	3.75	917.98
		<i>St.dev.</i>	0.21	0.26	0.40	0.12	0.08	0.11	0.51	0.08	0.11	0.03	0.07	6.36	c.d.	0.30		
	SOPF-0402b	<i>n</i> = 2	51.50	1.13	17.14	12.18	0.25	5.36	9.67	2.65	0.27	0.15	0.02	989	861	43.98	0.80	c.d.
		<i>St.dev.</i>	0.74	0.05	0.48	0.13	0.00	0.02	0.17	0.02	0.06	0.02	0.00	88.39	159.81	0.14		
	SOPF-0406	<i>n</i> = 2	48.38	0.88	18.95	11.32	0.17	5.47	11.86	2.92	0.27	0.11	0.06	1339	c.d.	46.26	1.50	525.22
		<i>St.dev.</i>	0.33	0.01	0.25	0.19	0.06	0.13	0.35	0.13	0.12	0.02	0.07	14.14	c.d.	0.17		
	SOPF-0407	<i>n</i> = 2	48.68	0.99	18.18	11.84	0.23	5.75	11.58	2.84	0.29	0.17	0.06	1947	855	46.39	1.15	c.d.
		<i>St.dev.</i>	0.48	0.02	0.12	0.32	0.13	0.10	0.07	0.03	0.10	0.04	0.02	60.81	110.31	0.25		
	SOPF-0408	<i>n</i> = 2	50.05	0.74	18.63	11.75	0.23	6.02	10.35	2.34	0.19	0.10	0.00	1730	c.d.	47.73	3.00	450.83
		<i>St.dev.</i>	0.36	0.07	0.05	0.10	0.04	0.00	0.02	0.19	0.05	0.04	0.00	45.25	c.d.	0.20		
	SOPF-0409	<i>n</i> = 2	52.76	1.31	18.07	10.72	0.25	4.30	8.52	3.67	0.51	0.13	0.01	623	1043	41.67	1.16	83.62
		<i>St.dev.</i>	0.45	0.05	0.18	0.37	0.11	0.13	0.10	0.04	0.12	0.01	0.02	144.25	180.31	0.11		
	SOPF-0410	<i>n</i> = 2	52.96	0.93	18.86	10.13	0.18	4.63	8.94	3.22	0.32	0.16	0.02	1342	c.d.	44.90	2.60	<50
		<i>St.dev.</i>	1.21	0.03	0.10	1.20	0.07	0.55	0.28	0.18	0.06	0.01	0.03	81.32	c.d.	0.01		
	SOPF-0411	<i>n</i> = 2	52.12	1.36	16.65	12.03	0.17	4.91	9.21	3.19	0.44	0.15	0.00	847	c.d.	42.11	0.60	<50
		<i>St.dev.</i>	0.38	0.06	0.56	0.62	0.01	0.21	0.12	0.07	0.04	0.00	0.00	8.49	c.d.	0.20		
	SOPF-0412	<i>n</i> = 2	53.09	0.78	18.56	10.36	0.18	5.10	9.03	2.77	0.29	0.15	0.00	1243	c.d.	46.76	3.99	<50
		<i>St.dev.</i>	0.47	0.09	0.07	0.24	0.01	0.09	0.09	0.02	0.03	0.00	0.00	135.06	c.d.	0.12		

Inclusions	Sample ID	Wt. %	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂
	SOPF-0603	<i>n</i> = 3	51.59	1.20	19.57	9.87	0.22	3.98	9.26	3.87	0.48	0.14	0.01	677	c.d.	41.83	1.33	c.d.
		<i>St.dev.</i>	0.06	0.06	0.29	0.04	0.01	0.03	0.23	0.09	0.08	0.03	0.01	45.54	c.d.	0.12		
	SOPF-0605	<i>n</i> = 3	50.44	0.78	18.48	12.06	0.15	5.74	9.72	2.89	0.45	0.13	0.08	1564	c.d.	45.86	1.29	c.d.
		<i>St.dev.</i>	1.15	0.01	0.84	2.87	0.05	1.42	1.36	0.30	0.06	0.06	0.04	255.27	c.d.	0.23		
	SOPF-0606	<i>n</i> = 3	49.10	0.88	20.10	9.80	0.14	5.62	12.39	2.17	0.25	0.10	0.03	1944.67	c.d.	50.54	3.60	c.d.
		<i>St.dev.</i>	0.06	0.06	0.23	0.06	0.07	0.01	0.09	0.14	0.05	0.04	0.03	87.90	c.d.	0.17		
	SOPF-0612	<i>n</i> = 3	49.95	0.84	19.34	10.95	0.18	5.87	11.21	2.22	0.24	0.10	0.01	2046.67	c.d.	48.86	2.74	106.93
		<i>St.dev.</i>	0.41	0.08	0.12	0.35	0.06	0.18	0.26	0.12	0.06	0.02	0.01	169.05	c.d.	0.20		
	SOPF-0613	<i>n</i> = 3	51.61	0.81	19.43	9.89	0.13	5.95	9.77	3.65	0.38	0.20	0.01	1712.00	c.d.	51.72	2.11	<50
		<i>St.dev.</i>	0.44	0.09	0.24	0.12	0.01	0.13	0.31	0.28	0.09	0.04	0.02	71.97	c.d.	0.44		
	SOPF-0615	<i>n</i> = 3	48.97	0.88	20.08	10.66	0.22	6.19	11.94	2.41	0.22	0.10	0.07	1853.33	c.d.	50.87	4.05	72.72
		<i>St.dev.</i>	0.73	0.05	0.56	0.31	0.13	0.14	0.11	0.11	0.02	0.02	0.06	56.30	c.d.	0.17		
	SOPF-0801	<i>n</i> = 3	49.88	0.59	19.12	11.65	0.24	5.69	10.68	2.24	0.26	0.10	0.02	1872.67	c.d.	46.55	4.04	516.96
		<i>St.dev.</i>	0.41	0.04	0.41	0.61	0.05	0.30	0.09	0.16	0.06	0.03	0.03	132.30	c.d.	0.02		
	SOPF-0802	<i>n</i> = 3	50.32	0.61	20.21	11.08	0.17	5.58	10.18	2.29	0.21	0.10	0.05	1800.67	c.d.	47.32	2.60	608.53
		<i>St.dev.</i>	0.08	0.05	0.60	0.20	0.04	0.14	0.04	0.16	0.02	0.02	0.05	135.63	c.d.	0.16		
	SOPF-0803	<i>n</i> = 3	49.24	1.13	18.87	10.48	0.12	5.43	11.24	3.17	0.42	0.15	0.01	798.00	c.d.	48.02	0.84	c.d.
		<i>St.dev.</i>	0.14	0.03	0.22	0.01	0.04	0.04	0.09	0.08	0.12	0.01	0.01	105.65	c.d.	0.19		
	SOPF-0805	<i>n</i> = 3	53.97	0.76	16.29	11.43	0.24	5.34	8.64	2.94	0.48	0.18	0.03	634.33	c.d.	45.42	0.68	183.03
		<i>St.dev.</i>	0.39	0.66	0.26	0.12	0.08	0.12	0.04	0.07	0.08	0.06	0.03	29.26	c.d.	0.35		
	SOPF-0806	<i>n</i> = 3	53.62	0.83	16.82	11.86	0.20	4.91	8.49	3.02	0.39	0.21	0.03	1145.00	c.d.	42.45	4.19	<50
		<i>St.dev.</i>	0.24	0.07	0.26	0.02	0.05	0.02	0.28	0.04	0.11	0.04	0.06	168.77	c.d.	0.14		
	SOPF-0812	<i>n</i> = 3	54.46	0.86	16.86	10.97	0.28	4.63	8.39	3.19	0.36	0.19	0.00	558.67	c.d.	42.96	1.10	6.92
		<i>St.dev.</i>	1.28	0.45	0.38	0.88	0.02	0.31	0.33	0.11	0.04	0.00	0.00	158.51	c.d.	0.36		

Groundmass	Sample ID	Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	S (ppm)	Cl (ppm)	Total	Mg#
Olivine	GM-4	<i>n</i> = 3	56.62	1.53	12.83	12.36	0.29	5.78	6.96	3.09	0.62	0.26	47	c.d	100	45.42
		<i>St.dev.</i>	0.53	0.28	0.66	0.85	0.03	0.59	0.15	0.64	0.13	0.06	38			0.90

Standard	Sample ID	Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	S (ppm)	Cl (ppm)
	VG-2	<i>n</i> = 2	51.44	1.96	14.31	11.48	0.19	6.79	10.72	2.62	0.24	0.26	100	1178	183
		<i>St.dev.</i>	0.03	0.06	0.12	0.08	0.08	0.02	0.18	0.01	0.05	0.02		93.34	106.07
	FO83		39.82	0.00	0.04	17.33	0.37	42.38	0.02	0.02	0.01	0.02	100	0	0
	FO90		41.78	0.00	0.03	9.64	0.08	48.33	0.11	0.01	0.00	0.02	100	10	0
	MAGT		0.00	0.21	0.10	99.54	0.03	0.08	0.00	0.03	0.00	0.02	100	154	416
	BHVO-2G		50.56	2.77	13.81	11.36	0.14	7.13	11.30	2.12	0.45	0.35	100	0	61

*Major elements, S and Cl composition were analyzed using EMPA

H₂O and CO₂ composition by FTIR

c.d. means cannot be determined

Major element and volatile compositions for 27 representative melt inclusions are shown in Table 4 above. Cl concentrations could not be determined for most inclusions due to low concentrations and relatively high detection limits. CO₂ concentrations (by FTIR) were also not determined for several inclusions due to the presence of reflectance fringes that obscured the CO₃ peak heights and/or olivine wafer thicknesses below 20 microns.

Figure 13. K₂O and SiO₂ concentration of the melt inclusions. Grey circles are the melt inclusions, the diagonal grey lines separate the low-K, calc-alkaline and high-K series, and the vertical grey line is a boundary between basalt and basaltic-andesite composition after Ewart,(1982).

In total, 74 melt inclusions were analyzed for their major element compositions. Composition of melt inclusions range from low-K basaltic to basaltic-andesite (Figure 13). More specifically, the following elemental ranges were observed for melt inclusions: SiO₂: 48.0 – 55.5 wt.%, Al₂O₃: 13.5 – 21.4 wt.%, MgO: 4.0 – 6.4 wt.%, FeO: 9.2 – 12.9 wt.%, CaO: 6.6 – 12.8 wt.%, Na₂O: 2.2 – 4.2 wt.%, K₂O: 0.17 – 0.96 wt.%, and TiO₂: 0.3 – 1.8 wt.% (Figure 14).

Tephra units have very similar ranges of melt inclusion compositions. MgO and Al₂O₃ show negative trends relative to SiO₂ and are relatively scattered compared to CaO, which shows a distinct negative trend. The FeO and TiO₂ data are scattered and do not show a correlation with SiO₂. The Na₂O and K₂O data vary positively with SiO₂, although Na₂O data are more scattered than K₂O. The groundmass glass has the most silicic composition, with higher FeO, Na₂O, K₂O and TiO₂, and lower MgO, Al₂O₃ and CaO than the melt inclusions.

The olivine-hosted melt inclusions are more mafic (SiO₂ 48-55 wt.%) than the data that were reported in a previous study (SiO₂ 54 wt.%) (Kushendratno et al., 2012). The matrix glass composition, on the other hand, has a very similar composition, that is 57 wt.% (Kushendratno et al., 2012).

4.3. Volatiles in melt inclusions

Our volatile data of Soputan melt inclusions consist of S, Cl, H₂O and CO₂. The range in S concentration in the trapped melt inclusions of all tephra units is between 300 and 2,400 ppm. The exception is one higher value in unit 6 (3,466 ppm) and one lower value in unit 8 (120 ppm). The tephra also have similar concentrations of Cl, from 702 to 1,714 ppm, with one melt inclusion from unit 6 that has no detectable Cl. The H₂O compositions of tephra unit 1 range from 2.0 to 4.4 wt.%, whereas units 4, 6 and 8 have similar compositions, which are within a range of 0.6 to 5.3 wt.% (Table 4, Figure 15). The CO₂ compositional range is different for each tephra unit. These are: unit 1: 293 to 1,234 ppm, unit 4: 84 to 918 ppm, unit 6: 73 to 439, and unit 8: 7 to 609 ppm (Table 4).

Figure 15. S, Cl and H_2O versus SiO_2 of the trapped melt inclusions. For the H_2O vs. SiO_2 diagram, the colored symbols are the H_2O data generated by FTIR analyses and black symbols are values derived with the “by difference” method. Color codes and symbols as in Table 3.

Discussion

The following section evaluates whole rock, mineral and melt inclusion data and the evidence they provide for petrogenetic processes that occurred at Soputan magmatic system. The data correction will be described at the beginning of this chapter, followed by discussing magmatic processes occurring beneath Soputan, which will then be used to create a magmatic plumbing system model of Soputan. A comparison of Soputan with other basalt to basaltic andesite volcanoes is also included.

5.1. Correction for post-entrapment crystallization

The composition of the melt inclusions may have changed due to several post-entrapment modification processes, particularly olivine post-entrapment crystallization (PEC) and Fe diffusive loss. In order to account for those effects and determine the actual initial compositions, the melt inclusion data were corrected using the Petrolog program of Danyushevsky et al. (2011). Figure 16a shows the Fo content of the host olivine crystals and the uncorrected Mg# of trapped melt inclusion glass compositions. Solid lines delineate lines of equal partition coefficient (between 0.2 and 0.3) for these compositions.

The correction program is based on the assumption that the olivine compositions have not changed, but melt compositions may have changed due to crystallization after the melt inclusion was trapped and sealed. Melt compositions are corrected by accounting for Fe-Mg exchange from the melt in order to achieve olivine-melt partition coefficients of $K_d = 0.3$. Corrected inclusion compositions are shown in Figure 16b. The uncorrected melt

inclusions are more scattered and out of equilibrium with their olivine-hosts as far as a single K_d value is concerned.

Figure 16. a) Mg# of melt inclusions vs. Fo content of olivine-host of the uncorrected composition; b) Mg# of melt inclusions vs. Fo content of olivine-host of the uncorrected composition. Symbols as in Table 3.

Other post-entrapment process that could have influenced the composition of melt inclusions is boundary layer enrichment. Analogous to plotting $\text{Al}_2\text{O}_3/\text{CaO}$ ratios (Johnson et al., 2010), CaO/MgO against the size of the melt inclusion was used to evaluate boundary layer enrichment in these olivine-hosted melt inclusions. Figure 17 shows that CaO/MgO ratio does not correlate with size of melt inclusions, as would be expected if boundary layer effects were prevalent. Although at the small end the ratios are scattered, overall the CaO/MgO ratio is nearly the same for all sizes. This indicates that boundary layer enrichment effects do not control the composition of melt inclusions. In other words, the present melt inclusion compositions closely resemble the melt composition at entrapment.

Figure 17. Ratio CaO/MgO versus melt inclusion size. The area between two solid black lines is the whole rock composition of all tephra deposits. The graph format is after Johnson et al. (2010). Color codes and symbols as in Table 3.

Hereafter discussion and interpretation are based on these corrected melt inclusion compositions. As mentioned before, whole rock compositions of Soputan eruptive products, as represented with the tephra units of this study, are homogenous since pre-1911 eruptive events. However within each eruptive unit, olivine-hosted melt inclusions indicate a range in pre-eruptive melt composition (Figure 18).

Each sampled tephra deposit of this study comprises a distinct eruptive event (Figure 6). Therefore each eruptive event has sampled a similar range in melt compositions that were trapped during crystallization (Figure 18). Melts range from basalt to basaltic-andesite with notable ranges in concentrations of Mg, Ca and H₂O. Observed ranges largely overlap for all studied eruptive units. The wide range of melt compositions is paralleled by variation in Fo content of olivine hosts (Figure 16, 18). The compositional similarity to whole rock, melt inclusion, and olivine between eruptive units implies uniformity to magma evolution processes at Soputan for many years, with similar parental melt compositions through time (Figure 9).

Figure 18. Stratigraphic position of analyzed tephra units against SiO₂, MgO, CaO and H₂O concentrations. Large symbol for bulk rock data of each unit all other data are from melt inclusion.

5.2. Fractional crystallization and mixing processes

All data described in the results section can be integrated and used as indicators of magma evolution processes as well as possible eruption triggers. Magmatic processes that could influence the melt inclusion and volatile composition include fractional crystallization, assimilation of country rock, and magma mixing. When crystallization occurs, some elements were incorporated in the crystallizing minerals and thus are proportionally depleted in the melt (compatible elements); others are excluded from the crystals and enriched in the melt (incompatible elements). Volatiles generally behave incompatibly and so are enriched in the melt during crystallization in a volatile-undersaturated magma. Once a magma is volatile-saturated, continued crystallization will

cause exsolution of volatiles from the melt (second boiling). In some cases, depletion of volatiles could also be caused by crystallization of minerals in which volatiles are compatible, such as Cl in apatite and S in sulfides (Johnson et al., 2010). Assimilation and mixing processes change the composition of the melt by changing the bulk composition of the system.

Figure 19. a) K₂O versus MgO and b) ratio of K₂O/P₂O₅ versus TiO₂/P₂O₅ of the melt inclusions. The graph format follows Johnson et al. (2010). Color codes and symbols as in Table 3.

In order to evaluate the possibility of a fractional crystallization as the driver of compositional variability, MgO, a compatible element in olivine, is plotted against K₂O, an incompatible element (Figure 19a). The observed increase in K₂O accompanied by a decrease of MgO is consistent with fractional crystallization (e.g. olivine fractionation).

Furthermore, incompatible element ratios of K₂O/P₂O₅ were plotted against TiO₂/P₂O₅ for the melt inclusion and whole rock data to test for distinct evolutionary processes (Figure 19b). P₂O₅ was used as the denominator in this comparison, because in basaltic magma this element is very slow to diffuse and, therefore, can be enriched in the melt boundary layer near crystals (Métrich and Wallace, 2008). Variation in compatible

vs. incompatible element ratios among inclusions or between inclusions and whole rock can be due to boundary layer effects, assimilation, mixing of crystals that formed from different melt compositions, and fractional crystallization that includes titanomagnetite or apatite (i.e. Ti-bearing and P-bearing phases).

There is a wide compositional spread to the K_2O/P_2O_5 vs TiO_2/P_2O_5 melt inclusion ratios (Figure 19b). However, the groundmass ratios are very similar to whole rock ratios, such that melt inclusion ratios include both higher and lower ratios than both whole rock and groundmass compositions. A lower ratio of TiO_2/P_2O_5 may indicate the fractionation of titanomagnetite or other Ti-bearing oxide phase. In contrast, the widely scattering TiO_2/P_2O_5 and K_2O/P_2O_5 ratio values of most melt inclusions might be explained by assimilation or mixing processes (Johnson et al., 2010).

Olivine-incompatible elements Al_2O_3 and CaO were used to shed more light on possible boundary layer enrichment effects and to demonstrate chemical effects of fractional crystallization. Because Al and Ca are found only in minimal quantities in olivine, these elements will not have been affected by boundary layer enrichment processes. Melt inclusion compositions should show similar ratios of Al_2O_3 to CaO as the whole rock compositions, so those that lie along the dashed line in Figure 20a have not experienced boundary layer enrichment. Around 70% of corrected melt inclusion compositions follow the trend lines defined by the whole rock Al_2O_3 to CaO ratio, whereas ~30 % of the melt inclusions have compositions that differ from the whole rock ratio. Most of these compositions lie at the high CaO concentration end and have lower Al_2O_3/CaO ratios (Figure 20a, b). If all melt inclusions are genetically related to the whole rock

composition, this suggests that most inclusions did not experience boundary layer enrichment.

Figure 20. a, b) Al_2O_3 versus CaO of melt inclusions and whole rocks. The dashed lines represent area of melt inclusion with same Al_2O_3 and CaO ratio as the whole rock, black arrows show plagioclase and clinopyroxene fractionations. Dark grey arrow indicated the unusual trend of the melts. The graph format is after Johnson et al. (2010). Color codes and symbols as in Table 3.

These compositional data also inform the interpretation of crystallization processes. In order to evaluate the role of fractional crystallization on the melt inclusion compositions, the composition of plagioclase (upper right point on Figure 20b) and clinopyroxene (lower right point on Figure 20b) are plotted with melt inclusion data. Melt inclusion compositions form an unusual linear trend in CaO – Al_2O_3 space, due to the crystallization of both phases. This caused the melt composition to decrease in CaO content without a correlating change in Al_2O_3 (horizontal arrow on Figure 20b). Later crystallization of dominantly plagioclase would have caused both CaO and Al_2O_3 to decrease in the melt (declining arrow in Figure 20b). In contrast, olivine fractionation dominates the evolutionary signature from Jorullo (Johnson et al., 2010) and Colima volcanoes (Métrich and Wallace, 2008), where melt inclusion compositions increase in both CaO and Al_2O_3 contents from bulk rock. It is clear that multiple phases are crystallizing from the melt at Soputan.

If the whole rock compositions represent the parental melt from which all crystals formed (i.e. there was no assimilation or mixing), then the whole rock composition should be more mafic than all melt inclusions. Whole rock compositions do not plot at the most mafic end of the compositional spectrum. Instead, whole rock compositions plot near the inflection point in the compositional trend.

How can we interpret the presence of melt inclusions that are more mafic than the whole rock data? Kushendratno et al. (2012) suggest that subhedral augite (clinopyroxene) is a xenocryst based on textural characteristics, which means it would not have crystallized from Soputan magmas. More specifically, both plagioclase and clinopyroxene could be antecrysts (i.e. phenocrysts that crystallized from different melts but are from the same system) rather than xenocrysts. This would explain both the compositional variation from the olivine-hosted inclusions and the textural context to augite described by Kushendratno et al.

To further explore which minerals needed to crystallize in order to explain observed compositional trends recorded by melt inclusions, a simplified fractional crystallization model was performed. Individual minerals included in this model were: Fo₈₀ olivine, high-Ca plagioclase (An₉₄), augite and Ti-bearing spinel. The bulk mineral composition was generated by combining these minerals in various proportions.

Figure 21. Simple model of fractional crystallization involving olivine, plagioclase, clinopyroxene and titanomagnetite. Grey line is high-Ca plagioclase fractionation, brown line is olivine (Fo80) fractionation, green line is clinopyroxene crystallization, black line is titanomagnetite crystallization and red line is bulk mineral crystallization. All plots are created using the mineral proportion from a least square model. The circle symbols on the lines represent 5% increment of mineral removal. High-Ca plagioclase and clinopyroxene composition were taken from Kushendratno et al. (2012), titanomagnetite from Streck et al. (2004), and the olivine was from this study. Color codes and symbols as in Table 3.

In this model, the goal was to produce a liquid line of descent that is consistent with the compositional trends given by melt inclusions (Figure 21).. The best-fit bulk mineral assemblage is composed of 21% olivine, 74.1% plagioclase, 0.6% clinopyroxene and 4.3% titanomagnetite. Although the bulk assemblage evolutionary trend is less of a fit for Al₂O₃ and CaO, it fits the melt inclusion data better than crystallization of any single phase. The misfit could be due to using a single composition and a fixed proportion of minerals.. In conclusion, the result suggests that magmas of Soputan have crystallized olivine in conjunction with plagioclase, clinopyroxene and titanomagnetite.

Matrix glass of Soputan basalt samples has a composition of ~58 wt.% SiO₂. Using the least square model to estimate the crystal contents of the bulk rock yields 49.7%. Based on these calculations, plagioclase is the most abundant mineral in the system consistent with petrographic observation. This corroborates that at least 50% crystallization is needed to compositionally evolve a basalt liquid with ~12 wt.% CaO and 48 wt.% SiO₂ to a melt with 7 wt.% CaO at 55 wt.% SiO₂, as is consistent with the matrix glass composition.

5.3. Volatiles, degassing and crystallization

The tephra samples of this study have volatile composition higher than the pyroclastic flow deposit of 2007 eruption that was reported by Kushendratno et al. (2012). The maximum concentration of S (4,366 ppm) of the tephra units is much higher than the ~700 ppm of the recent deposit. The Cl concentration has maximum value of 1,714 ppm, while the previous study indicated 2,000 ppm. The maximum concentration of water is 5.2 wt.%, whereas Kushendratno et al. (2012) reported ~4 wt.% as determined by the difference method (Table 4).

Figure 22 shows that S decreases with increasing silica content and Cl has slightly positive trend with silica. S is less soluble in the melt or exsolves faster than Cl. Therefore, melt with low S will have higher Cl. H₂O on the other hand does not vary consistently with SiO₂, and does not show any trend across the units.

Figure 22. a-c) Ratio of S, Cl, H₂O, normalized by K₂O versus K₂O and d) ratio of S/K₂O against Cl/K₂O. The graph format is after Johnson et al. (2010) and Myers et al. (2014). The color codes and symbols as in Table 3.

Here, we evaluate the relationship between degassing and crystallization of the Soputan magmatic plumbing system. S, Cl and H₂O volatile concentrations normalized to K₂O and plotted against K₂O (Figure 22). These plots can be used to distinguish between degassing and crystallization processes. A vertical trend represents degassing processes only, a horizontal trend indicates a pure crystallization, and a diagonal trend indicates simultaneous degassing and crystallization (Figure 22).

The S/K₂O, Cl/K₂O and H₂O/K₂O diagrams (Figure 22) show similar diagonal trends, indicating degassing and crystallization. This diagonal trend reflects degassing and crystallization, as commonly occurs in response to decompression/ascent. The second trend modifies compositions horizontally in the S/K₂O and H₂O/K₂O plots (Figure 22a, c) and is

due to isobaric differentiation at different depths, as caused either by cooling or by crystallization. Based on repeat analyses of the same inclusion, the observed variation in K_2O content among inclusions is greater than its analytical error. The ratio of S/ K_2O against Cl/ K_2O (Figure 22d) shows a strong positive trend, which is evidence for higher degassing of S compared to Cl throughout the process. This is consistent with a stronger partitioning of S over Cl or F into the degassed phase than was found by others (Métrich and Wallace, 2008)

5.4. H_2O - CO_2 solubility model

H_2O - CO_2 solubility models can be used to estimate the minimum melt inclusion entrapment pressures if we assume that the system was H_2O - CO_2 saturated. There are two solubility models that applicable for basaltic magma, which are Volatile-Calc (Newman and Lowenstern, 2001) and the Papale (2006) models. The Volatile-Calc model can give more precise estimation of solubility parameters for tholeiitic and alkali-rich basalts but yields a poor estimation for calcic or calc-alkaline basalts (Moore, 2008). On the other hand, the Papale model can estimate the parameter for calcic or calc-alkaline basalts more precisely (Johnson et al., 2010). For this study, we used the Papale model to estimate saturation pressures and degassing paths.

Figure 23 shows that measured H_2O and CO_2 contents preserve saturation pressures ranging from below 50 MPa to above 200 MPa. In addition, isobars and isopleths were calculated using the Papale model and are shown for reference on Figure 23. Isobars represent constant pressure, whereas isopleths represent lines of constant vapor composition (Newman and Lowenstern, 2001). The closed-system degassing path was

generated starting with 5.3 wt. % H₂O and 1299 ppm CO₂. This degassing path indicates that within the magmatic system of Soputan, gas bubbles remained in equilibrium with the melt from which they exsolved during ascent to the surface (Métrich and Wallace, 2008). The H₂O-CO₂ melt inclusions from Soputan contain more CO₂ than can be explained by a single closed system degassing path.

Figure 23. H₂O-CO₂ solubility model of melt inclusions follow Papale model (2006). The model was run at 1100°C. Symbols are as listed in Table 1. Isobars are represented by the solid lines, isopleths as the dash lines, and the degassing path as the grey line. 100 Megapascal (MPa) = 1 kbars, and 1 kbars = ~3.5 km depth (after Wilson, 2007).

The higher concentration of CO₂ in most melt inclusions can be explained by flux of a CO₂-rich vapor through the system. As the CO₂-rich vapor segregates from melt at depth, it can rise through and re-equilibrate with the overlying magma column (Métrich and Wallace, 2008). This process causes the volatile composition to move along a single isobar in the direction of higher CO₂ content until it reaches the CO₂/H₂O ratio indicated by isopleth lines of constant vapor composition (Métrich and Wallace, 2008).

Some Soputan melt inclusions reached between 40 to 75 mol.% CO₂ (refer to isopleth lines on Figure 23), however many of melt inclusion were grouped closer to 40

mol.% isopleth. Evidence for this gas fluxing process is found at other arc basaltic volcanoes, where CO₂-rich flux is indicated by melt inclusions that were in equilibrium with exsolved gas containing 40 to 75 mol.% CO₂ (Johnson et al., 2010; Wallace, 2004).

An alternative interpretation that I cannot exclude to explain low H₂O and high CO₂ contents is the possibility of water diffusion from the trapped melt inclusions. Water diffusion may relatively enrich the CO₂ concentration on the melt and, in many cases, causes crystallization of the melt inclusion and formation of a shrinkage bubble (Johnson et al. 2008). Many of my inclusions do contain bubbles (Table 4), but I cannot differentiate between primary entrapment of vapor bubbles with melt (as at Pinatubo, Wallace and Gerlach, 1994) or post-entrapment diffusive water loss causing shrinkage bubbles.

The combination of H₂O – CO₂ data, saturation pressures, and melt compositions reveals additional information (Figure 24). Evidence for batch decompression during crystallization would suggest that mafic melts were trapped at greater depth than more evolved melt. However, the correlation between the minimum saturation pressure and SiO₂ contents is more complex.

Compositional variation of SiO₂ and other elements were found at a wide range of pressures and depths (Figure 24). The most mafic melt inclusions record entrapment pressures between 1500 and 200 bars. Similarly, evolved melt compositions were entrapped over a broad range of pressures, extending up to >2000 bars. This diversity of melt compositions at all pressures is consistent with mixing occurring in the system and melt that was not necessarily from a single batch of magma. The relative position of melt inclusions within the olivine mineral hosts would provide more information on the

progression of crystallization and/or mixing for single crystals. However, I do not have melt inclusion position information since the samples in this study are partial crystals.

Figure 24. Minimum saturation pressure of trapped melt inclusion against SiO₂ concentration. The color codes and symbols as in Table 3.

5.5. Magmatic plumbing system model

In order to create a model of the Soputan magmatic plumbing system, I will compare a simple magma evolution scenario involving one batch of decompressing and crystallizing magma with the compositional data in this study. For the simple magma evolution scenario, I assumed that only one batch of magma is involved (Figure 25).

When a mafic magma intrudes at a certain depth, fractional crystallization can occur at that pressure. As magma ascends toward the surface, the change in pressure induces

degassing that can induce crystallization in turn (Figure 25). The melt will progressively evolve causing a decrease in concentrations of MgO, CaO and Al₂O₃ and increase of SiO₂ and K₂O during crystallization (Figure 25a). Ideally, olivine fractionation will occur first at greater depths followed by pyroxene and plagioclase at shallower depths (Wilson, 2007). During the degassing process, CO₂ will exsolve first due to its low solubility in the melt followed by H₂O (Figure 25b) and other volatiles. Mixing between mafic magma and the resident magma could also occur. Trapped melt at greater depths may have generally more mafic compositions with higher CO₂ and H₂O than melt that was trapped at the shallowest level.

Figure 25. a) CaO vs. SiO₂ diagram and b) H₂O-CO₂ solubility model of an oversimplified magma evolution that involved single batch magma. The samples were taken from this study (grey circles). b) the gray line represents the closed degassing system, isobars and isopleths were included.

The findings in this study show a more complex system, as supported by the following petrologic lines of evidence:

- S/K₂O, H₂O/K₂O, and Cl/K₂O ratios versus K₂O plots show trends consistent with degassing during crystallization (Figure 22), in part due to decompression.

Figure 26. The melt inclusions that were trapped at estimated pressure according to H₂O-CO₂ solubility model (Figure 23). Solid black lines are isobars, and black dash lines are isopleths. Grey lines show the degassing path of 4.0 and 5.2 wt.% of H₂O at 1299 ppm CO₂ and at 1100°C.

- Melt inclusions with a range of SiO₂ between 48 and 54 wt.% were trapped at a range in pressures (0-200MPa) and depths (0-7km) (Figure 23). Melt inclusions of group A (SiO₂ 48-53 wt.%, Al₂O₃ 18-20 wt.% and CaO 9-12 wt.%) were trapped at pressures of 125 to >200 MPa (4.4- >7 km); group B (SiO₂ 48-52 wt.%, Al₂O₃ 18-20 wt.% and CaO 10-12 wt.%) at pressures of between 50 and 100 MPa (~1.4 – 3.2 km); and Group C at pressures <50 MPa (<1.4 km) (Figure 26). These pressure groups suggest multiple magma storage depths in the Soputan plumbing system.

Figure 27. A simplified conceptual model of the Soputan magmatic plumbing system. The number codes represent the processes involved: 1. Recharge of CO₂-rich mafic magma; 2. Trapped melt inclusions, degassing, crystallization and mixing processes; 3. Gas streaming; 4. Eruption. The format is after Myers et al. (2014).

- Compositional variation of melts that were trapped at similar pressure and depth support an interpretation of mixing. (Figure 24)
- The difference in composition between melt inclusions and whole rocks can be explained by fractional crystallization of plagioclase, olivine, clinopyroxene and titanomagnetite. The difference that cannot be explained by crystallization may be related to a mixing process (Figure 19 and Figure 20).
- Relatively high CO₂ concentrations at a wide range of H₂O values (0.6 – 5.3 wt.%) and pressures are consistent with CO₂-rich fluxing (Figure 23).
- Repeated patterns of compositional diversity of study units suggest that these processes repeat through time as could occur due to episodic recharge (Figure 6 and Figure 24).

According to the evidence that was stated above, the general processes that likely occurred in the Soputan system are as follows: episodic recharge of CO₂-rich mafic magma from a deeper source to the system (~7 km) (1). Fractional crystallization, degassing, and possibly mixing processes then took place throughout the system (2). Exsolved CO₂-rich vapor from deep recharge will flux through the overlying magma column. Gas fluxing contributes to an increase of gas volume and pressurization close to the surface (3). Overpressure conditions at shallower depths leads to an explosive eruption. As pressure decreases, explosive phases are then followed by lava flows (4).

The complex combination of all of these processes suggests that the episodic recharge of magma involves the same major elements and volatile compositions. Compositional similarity through time suggests that the processes involved in the system have not changed for more than a century.

5.6. Comparison with other mafic volcanic eruptions

The combination of magmatic processes described above contribute to Soputan's eruptive behavior, including production of high explosivity eruptions. However, this behavior is not unusual, as many mafic volcanoes also exhibit highly explosive behavior, e.g. Jorullo, Cerro Negro, Telica and Etna volcanoes (Table 5).

The ten volcanoes in Table 5 have basaltic to basaltic andesite compositions. The compositional variation of erupted melt inclusions indicates melt evolution in the subvolcanic reservoir. Previous workers have inferred a combination of fractional crystallization, degassing and in several cases, gas-rich flux at these volcanoes. Several volcanoes also experienced mixing or assimilation prior to eruption, such as at Arenal, Parícutin and Cerro Negro volcanoes (Luhr, 2011; Portnyagin et al., 2014; Streck et al., 2002). The high explosivity of these eruptions has commonly been attributed to fast ascent rates (e.g., Sable et al. 2006). In addition, as is clear from Table 5, several other factors likely contribute to highly explosive behavior. For example, these systems all contain abundant crystals and many contain evidence for gas input from unerupted magma (Table 5). Crystals in these systems include both phenocrysts (large crystals) and microlites (small crystals); the relative effect of each population is suggested for further study and is not further discussed here. High crystallinity will lead to an increase in magma viscosity, increasing the ability for mafic magma to retain its gas. The presence of a gas flux will increase the volume of the gas phase in the shallow system, potentially contributing to shallow overpressure. The combination of high viscosity with elevated gas flux and faster ascent rates can then produce high explosivity mafic eruptions.

Interestingly, Soputan has a distinct character that makes it different from other volcanoes, which is bulk homogeneity that remains unchanged for hundreds of years (Figure 18). This homogeneity is also observed in its eruption style, where eruption sequences commonly begin with an explosive event, followed by lava effusion, despite changes in vent location through time. The homogeneity of composition and eruptive behavior through time may be controlled by consistent deep magma input from below. The nature of this recharge composition and its input rate requires further study.

Table 5. Chemical and mineralogic characteristics of Soputan and other basaltic to basaltic andesite volcanic eruptions.

Volcanoes	Eruption styles	Whole rock composition	Mineral hosts	Melt inclusion composition	Phenocryst (P) and/or total (T) crystallinity	Max. H ₂ O (wt.%)	Max. CO ₂ (ppm)	Gas-rich flux	References
Soputan, Indonesia (pre-1911 & 2007)	Strombolian-vulcanian	Basalt (SiO ₂ : 49 wt.%)	olivine	Basalt to basaltic andesite (SiO ₂ : 48-56 wt.%)	~50% (P) – 80% (T)	5.3	1299	yes	this study; Kushendratnoo et al., 2012
			olivine	Basalt to basaltic andesite (SiO ₂ : 45-54 wt.%)					
Galunggung, Indonesia (1982-1983)	Plinian	Basalt to andesite (SiO ₂ : 48-56 wt.%)	plagioclase	Basaltic-andesite to dacite (SiO ₂ : 54-64 wt.%)	20-40% (P)	0.38	750	yes	de Hoog et al., 2001; Sisson & Bronto, 1998
			pyroxene	Basaltic-andesite to dacite (SiO ₂ : 56-70 wt.%)					
Jorullo, Mexico (1759-1774)	Plinian	Basalt (SiO ₂ : 49 wt.%)	olivine	Basalt to basaltic andesite (SiO ₂ : 50-55 wt.%)	50-59% (T)	5.3	1000	yes	Johnson et al., 2008
Paricutin, Mexico (1943-1952)	Plinian	Basaltic andesite to andesite (SiO ₂ : 55-59 wt.%)	olivine	Basalt to andesite (SiO ₂ : 51-60.5 wt.%)	3% (P) 43-50% (T)	4	296	no	Luhr, 2001; Erlund et al., 2010
			plagioclase	Basaltic-andesite to dacite (SiO ₂ : 56-67 wt.%)					
Arenal, Costa Rica (1968-1996)	Vulcanian	Basaltic andesite (SiO ₂ : 54-56 wt.%)	pyroxene	Andesite to dacite (SiO ₂ : 64-69 wt.%)	~25-40% (P)	>6	n.a.	-	Streck et al., 2002; Streck & Wacaster, 2006

Volcanoes	Eruption styles	Whole rock composition	Mineral hosts	Melt inclusion composition	Phenocryst (P) and/or total (T) crystallinity	Max. H ₂ O (wt.%)	Max. CO ₂ (ppm)	Gas-rich flux	References
Volcan Llaima, Chile (~1850AD, 1957, 2008)	Vulcanian	Basalt to basaltic andesite (SiO ₂ : 51-54 wt.%)	olivine	Basalt to andesite (SiO ₂ : 49-57 wt.%)	20-35% (P)	4.4	511	yes	Bouvet de Maisonneuve et al., 2012
Telica, Nicaragua (2300 y. BP, 1982, 2011)	Violent-Strombolian	Basaltic to andesite (SiO ₂ : 50-59 wt.%)	olivine	Basalt (SiO ₂ : 47-52 wt.%)	6-45% (P)	5.2	1642	yes	Robidoux et al., 2017
			pyroxene	Basaltic-andesite to dacite (SiO ₂ : 55-66 wt.%)		0.46	309		
Cerro Negro, Nicaragua (1867-1995)	Strombolian-vulcanian	Basalt (SiO ₂ : 48-51 wt.%)	olivine	Basalt to basaltic-andesite (SiO ₂ : 45-56 wt.%)	~36-50% (P)	6.08	1039	yes	Portnyagin et al., 2014; Roggensack et al., 1997
Cinder Cone, Lassen, USA, (pre-1915)	Vulcanian	Basaltic-andesite to andesite (SiO ₂ : 53-60 wt.%)	olivine	Basalt to basaltic-andesite (SiO ₂ : 51-53 wt.%)	-	3.5	1500	no	Walowski, 2015
Etna, Italy (122 B.C.)	Plinian	Trachybasalt (SiO ₂ : 51 wt.%)	olivine	Basalt to basaltic-andesite (SiO ₂ : 50-53 wt.%)	1-10% (P) 38-82% (T)	3.12	880	no	Carlo& Pampilio, 2004; Goepfert&Gardner, 2010; Sable et al., 2006

Gas-rich flux refers to evidence for external vapor streaming through the magmatic system.

Conclusions

Soputan is a crystal-rich basaltic volcano that produces frequent explosive eruptions accompanied by lava flows and/or dome growth and occasionally produces pyroclastic flows. The whole rock data indicate compositional homogeneity while melt inclusion and volatile compositions indicate comparable compositional ranges, producing basalt to basaltic andesite melt compositions over more than a hundred years of activity. Each eruptive event preserves petrologic evidence for complex shallow magma evolution involving fractional crystallization, mixing, degassing, and gas fluxing processes.

The high explosivity of this basaltic system is due to high viscosities and volatile concentrations. Melt inclusions preserve evidence for CO₂ fluxing through the shallow magma storage system and reequilibration with shallow melt. The presence of an excess gas phase is consistent with previous work (Kushendratno et al., 2012), which documented presence of excess sulfur in previous eruptions. Pressurization of this gas is made possible by the high viscosities produced by a high crystal content of magma. Furthermore, the chemical diversity of melt inclusions across the range of pressures recorded by volatile contents is consistent with magma differentiation at variable depth and mixing in the shallow magma reservoir.

The complex magmatic system produced homogenous volcanic products through time indicating that magmatic processes beneath Soputan have not undergone significant changes for hundreds of years.

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Appendix A

Table A.1. Major and trace element composition of whole rocks of Soputan tephra samples.

Sample ID	Tephra				2015 Ash fall	2015 Lava flow
	SOP01T	SOP02T	SOP06T	SOP08T	SOPA-15	SOPL-15
XRF data	Normalized Major Elements (Weight %):					
SiO₂	49.38	49.41	49.14	49.41	52.61	50.80
TiO₂	0.808	0.869	0.773	0.755	0.912	0.818
Al₂O₃	21.04	19.41	20.58	19.33	18.66	19.71
FeO*	9.52	10.45	9.69	10.44	9.83	9.89
MnO	0.186	0.202	0.185	0.195	0.207	0.197
MgO	5.46	6.18	5.73	6.86	4.72	5.36
CaO	11.00	10.66	11.14	10.41	9.42	10.18
Na₂O	2.28	2.46	2.41	2.26	3.10	2.63
K₂O	0.24	0.27	0.25	0.25	0.40	0.31
P₂O₅	0.091	0.098	0.092	0.090	0.139	0.110
Pre-norm. total	100.00	100.01	99.99	100.00	99.99	100.01
XRF data (ppm)						
Ni	15	16	16	22	12	11
Cr	5	7	7	6	1	2
Sc	28	34	30	28	30	26
V	256	281	259	256	242	252
Ba	46	50	49	50	72	61
Rb	6	6	5	6	7	6
Sr	317	297	314	293	295	307
Zr	29	31	28	31	43	36
Y	15	15	15	14	20	16
Nb	0.0	0.0	0.3	1.0	0.6	0.1
Ga	16	16	15	15	17	16
Cu	94	97	86	69	179	86
Zn	66	68	63	68	83	68
Pb	3	3	3	2	16	3
La	5	7	3	1	3	4
Ce	9	4	6	10	10	11
Th	0	1	0	0	0	1
Nd	7	3	6	7	7	9
U	1	1	0	1	1	0

Sample ID	Tephra				2015 Ash fall	2015 Lava flow
	SOP01T	SOP02T	SOP06T	SOP08T	SOPA-15	SOPL-15
ICP-MS (ppm)						
La	2.40	2.51	2.37	2.52	3.70	3.50
Ce	6.22	6.61	6.09	6.32	9.41	8.14
Pr	1.02	1.09	0.98	1.03	1.52	1.33
Nd	5.37	5.69	5.11	5.30	7.98	6.76
Sm	1.87	2.00	1.78	1.77	2.57	2.20
Eu	0.78	0.82	0.76	0.76	1.05	0.88
Gd	2.39	2.57	2.33	2.27	3.29	2.74
Tb	0.43	0.47	0.41	0.41	0.60	0.49
Dy	2.83	3.07	2.66	2.69	3.83	3.21
Ho	0.59	0.66	0.57	0.56	0.82	0.67
Er	1.65	1.77	1.57	1.58	2.23	1.85
Tm	0.25	0.26	0.23	0.23	0.33	0.27
Yb	1.48	1.61	1.39	1.40	1.98	1.67
Lu	0.23	0.24	0.23	0.22	0.31	0.26
Ba	46.62	47.52	45.18	47.41	70.52	57.84
Th	0.35	0.37	0.33	0.34	0.51	0.44
Nb	0.64	0.68	0.64	0.67	0.97	0.89
Y	14.43	15.57	13.87	13.78	19.66	16.35
Hf	0.82	0.90	0.81	0.85	1.28	1.05
Ta	0.07	0.08	0.08	0.07	0.10	0.09
U	0.10	0.10	0.09	0.10	0.13	0.12
Pb	2.53	2.62	2.49	2.45	14.28	2.93
Rb	4.13	4.19	4.00	4.14	6.62	5.20
Cs	0.33	0.31	0.32	0.31	0.50	0.37
Sr	314.93	293.40	311.39	290.18	294.01	304.92
Sc	27.63	32.83	29.22	27.30	29.47	25.70
Zr	26.32	27.84	25.75	27.26	40.61	33.86

Table A.2. Whole rocks composition of Soputan 2007, Lokon, Merapi and Barren Island volcanoes

	Soputan 2007	Lokon	Barren Island	Merapi	
XRF data	Normalized Major Elements (Weight %):				
SiO₂	50.73	50.92	51.62	52.88	51.85
TiO₂	0.84	0.88	0.83	0.80	0.87
Al₂O₃	19.68	18.23	21.48	18.61	18.53
FeO*	9.61	9.66	7.10	9.32	9.65
MnO	0.20	0.19	0.15	0.20	0.21
MgO	5.50	5.76	4.02	3.50	3.90
CaO	10.32	10.53	11.35	9.39	9.58
Na₂O	2.60	2.93	2.96	3.30	3.20
K₂O	0.30	0.54	0.40	2.00	1.98
P₂O₅	0.11	0.19	0.10	0.29	0.29
Pre-norm. total	99.89	99.83	100.01	100.29	100.06
Trace Elements (ppm)					
La	2.67	5.83	4.63	17.20	17.30
Ce	7.25	14.30	11.12	34.50	34.60
Pr	1.16	2.03	1.59	4.18	4.28
Nd	6.13	9.52	8.00	17.80	18.00
Sm	2.05	2.63	2.67	4.34	4.33
Eu	0.85	0.94	0.99	1.34	1.36
Gd	2.54	2.91	3.27	4.13	3.65
Tb	0.47	0.49	0.61	0.59	0.63
Dy	3.03	3.09	4.02	3.46	3.45
Ho	0.64	0.67	0.87	0.71	0.72
Er	1.76	1.93	2.44	2.11	1.93
Tm	0.26	0.29	0.36	0.31	0.32
Yb	1.60	1.85	2.30	2.22	2.01
Lu	0.26	0.29	0.37	0.33	0.33
Ba	57.40	111.00	76.00	439.00	431.00
Th	0.38	1.12	1.32	7.23	6.16
Nb	0.73	1.82	0.53	3.30	2.94
Y	16.00	19.57	23.28	23.00	22.80
Hf	1.01	1.19	1.72	2.15	2.14
Ta	0.05	n.a.	0.04	0.23	0.21
U	0.10	0.24	0.20	1.29	1.02
Pb	2.50	2.85	1.97	15.70	14.80
Rb	5.01	11.40	10.20	46.80	45.70
Cs	0.37	0.45	0.26	n.a.	n.a.
Sr	301.00	411.90	217.43	600.00	603.00
Sc	25.80	32.20	30.74	n.a.	n.a.
Zr	29.90	44.90	58.00	86.00	83.00

n.a. is not analyzed

Appendix B

Table B.1. Major element compositions of olivines

Olivines	Sample ID	Wt. %	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	NiO	Fo
	SOPF-0101		38.61	0.00	0.02	23.62	0.43	37.19	0.12	0.01	0.00	0.00	100.00	0.09	74
	SOPF-0102		39.98	0.06	0.05	19.29	0.32	40.07	0.15	0.01	0.03	0.05	100.00	0.00	79
	SOPF-0104		39.32	0.00	0.03	18.83	0.32	41.23	0.21	0.04	0.02	0.00	100.00	0.04	80
	SOPF-0109		38.03	0.00	0.03	25.35	0.29	36.09	0.15	0.05	0.01	0.00	100.00	0.00	72
	SOPF-0111		38.11	0.03	0.00	24.81	0.44	36.40	0.12	0.05	0.02	0.02	100.00	0.10	72
	SOPF-0114		39.05	0.00	0.02	22.64	0.34	37.78	0.14	0.00	0.02	0.01	100.00	0.03	75
	SOPF-0402a		37.65	0.00	0.00	25.05	0.50	36.57	0.15	0.04	0.00	0.05	100.00	0.00	72
	SOPF-0402b		37.79	0.00	0.03	25.05	0.48	36.49	0.16	0.00	0.00	0.00	100.00	0.10	72
	SOPF-0406		38.37	0.04	0.02	22.76	0.36	38.21	0.15	0.03	0.05	0.02	100.00	0.06	75
	SOPF-0407		38.56	0.01	0.00	22.92	0.30	37.99	0.17	0.00	0.04	0.01	100.00	0.14	75
	SOPF-0408		39.39	0.03	0.00	22.40	0.29	37.72	0.11	0.00	0.05	0.00	100.00	0.13	75
	SOPF-0409		38.83	0.00	0.00	25.52	0.48	34.94	0.21	0.01	0.00	0.00	100.00	0.04	71
	SOPF-0410		37.94	0.06	0.02	24.48	0.32	36.98	0.17	0.02	0.00	0.00	100.00	0.10	73
	SOPF-0411		36.94	0.00	0.04	26.08	0.59	36.06	0.18	0.08	0.04	0.00	100.00	0.00	71
	SOPF-0412		38.34	0.00	0.00	23.59	0.39	37.46	0.18	0.04	0.00	0.00	100.00	0.00	74
	SOPF-0603		37.64	0.03	0.01	26.24	0.42	35.44	0.16	0.05	0.00	0.00	100.00	0.00	71
	SOPF-0603		38.15	0.00	0.03	25.37	0.39	36.03	0.00	0.02	0.00	0.01	100.00	0.16	72
	SOPF-0605		38.32	0.02	0.05	23.43	0.36	37.52	0.24	0.00	0.05	0.00	100.00	0.09	74
	SOPF-0605		38.36	0.00	0.05	23.85	0.31	37.40	0.00	0.02	0.00	0.01	100.00	0.06	74
	SOPF-0606		39.24	0.00	0.03	20.55	0.27	39.71	0.15	0.02	0.03	0.00	100.00	0.00	77
	SOPF-0606		39.17	0.02	0.03	20.39	0.30	39.97	0.08	0.00	0.00	0.04	100.00	0.03	78
	SOPF-0607		38.98	0.00	0.00	19.73	0.40	40.78	0.09	0.00	0.00	0.02	100.00	0.14	79

Olivines	Sample ID	Wt. %	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	NiO	Fo
	SOPF-0607		39.67	0.00	0.03	19.52	0.23	40.26	0.17	0.05	0.06	0.00	100.00	0.10	79
	SOPF-0612		39.22	0.05	0.03	21.36	0.23	38.88	0.22	0.00	0.00	0.00	100.00	0.12	76
	SOPF-0612		39.55	0.00	0.05	21.72	0.21	38.44	0.00	0.01	0.00	0.00	100.00	0.02	76
	SOPF-0613		39.51	0.00	0.06	19.28	0.31	40.67	0.15	0.02	0.00	0.00	100.00	0.08	79
	SOPF-0613		39.25	0.00	0.06	19.28	0.33	40.83	0.18	0.06	0.01	0.01	100.00	0.12	79
	SOPF-0615		39.03	0.00	0.00	20.15	0.33	40.30	0.17	0.02	0.00	0.00	100.00	0.09	78
	SOPF-0615		39.62	0.02	0.00	20.22	0.29	39.64	0.15	0.00	0.05	0.00	100.00	0.14	78
	SOPF-0801		38.93	0.00	0.02	22.35	0.38	38.09	0.13	0.00	0.10	0.00	100.00	0.08	75
	SOPF-0801		38.63	0.00	0.04	23.81	0.56	36.72	0.14	0.07	0.00	0.02	100.00	0.05	73
	SOPF-0802		38.35	0.00	0.00	23.66	0.31	37.44	0.19	0.05	0.00	0.00	100.00	0.00	74
	SOPF-0802		39.68	0.00	0.00	22.38	0.31	37.26	0.33	0.02	0.02	0.00	100.00	0.02	75
	SOPF-0803		38.33	0.00	0.05	22.65	0.32	38.62	0.00	0.01	0.00	0.01	100.00	0.08	75
	SOPF-0803		38.81	0.00	0.02	19.93	0.24	38.65	2.31	0.00	0.01	0.02	100.00	0.04	78
	SOPF-0805		38.75	0.00	0.06	23.37	0.44	37.26	0.10	0.02	0.00	0.00	100.00	0.00	74
	SOPF-0805		37.63	0.01	0.02	25.05	0.50	36.58	0.13	0.06	0.02	0.00	100.00	0.06	72
	SOPF-0806		37.65	0.00	0.05	26.60	0.59	34.93	0.13	0.02	0.00	0.04	100.00	0.02	70
	SOPF-0806		38.01	0.00	0.00	25.90	0.41	35.41	0.10	0.04	0.14	0.00	100.00	0.00	71
	SOPF-0812		38.68	0.00	0.03	25.28	0.51	35.30	0.18	0.00	0.00	0.02	100.00	0.00	71
	SOPF-0812		37.67	0.02	0.05	25.97	0.47	35.61	0.17	0.03	0.00	0.00	100.00	0.02	71
	SOPF-0108		39.70	0.00	0.06	20.16	0.25	39.81	0.00	0.00	0.01	0.01	100.00	0.00	78
	SOP-01-210		39.06	0.06	0.04	22.76	0.33	37.59	0.16	0.00	0.00	0.01	100.00	n.a.	75
	SOP-01-215		38.49	0.00	0.03	24.14	0.40	36.73	0.10	0.04	0.07	0.00	100.00	n.a.	73
	SOP-01-319		39.10	0.20	0.00	20.50	0.31	39.59	0.23	0.03	0.00	0.04	100.00	n.a.	77
	SOP-01-320		38.83	0.03	0.00	23.67	0.36	36.86	0.15	0.03	0.08	0.00	100.00	n.a.	74

Olivines	Sample ID	Wt. %	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	NiO	Fo
	SOP-01-323		37.45	0.01	0.02	27.07	0.52	34.77	0.11	0.00	0.00	0.05	100.00	n.a.	70
	SOP-01-327		38.50	0.01	0.05	23.98	0.39	36.89	0.17	0.00	0.00	0.00	100.00	n.a.	73
	SOP-01-433		37.88	0.00	0.08	25.09	0.50	36.29	0.14	0.00	0.01	0.00	100.00	n.a.	72
	SOP-01-501		39.22	0.01	0.01	20.13	0.33	40.09	0.15	0.01	0.03	0.01	100.00	0.19	78
	SOP-01-501		39.75	0.00	0.01	19.53	0.36	40.14	0.15	0.01	0.05	0.00	100.00	0.01	79
	SOP-04-101		39.17	0.00	0.05	19.92	0.25	40.42	0.18	0.01	0.00	0.00	100.00	n.a.	78
	SOP-04-214		38.45	0.00	0.02	21.42	0.28	39.63	0.19	0.00	0.01	0.00	100.00	n.a.	77
	SOP-04-501		39.03	0.00	0.02	21.75	0.34	38.65	0.20	0.00	0.00	0.00	100.00	0.02	76
	SOP-04-501		39.13	0.00	0.04	22.02	0.34	38.34	0.13	0.00	0.01	0.01	100.00	0.14	76
	SOP-04-502		37.22	0.00	0.02	25.70	0.42	36.64	0.00	0.00	0.00	0.00	100.00	0.05	72
	SOP-04-502		37.57	0.04	0.05	25.11	0.39	36.58	0.17	0.01	0.06	0.00	100.00	0.00	72
	SOP-04-502		37.44	0.02	0.07	24.71	0.56	36.99	0.11	0.02	0.06	0.02	100.00	0.08	73
	SOP-04-502		38.27	0.04	0.02	25.08	0.39	36.07	0.13	0.00	0.00	0.00	100.00	0.02	72
	SOP-04-503		38.57	0.00	0.05	23.20	0.42	37.53	0.17	0.04	0.00	0.02	100.00	0.02	74
	SOP-04-503		38.03	0.31	0.00	22.78	0.42	37.94	0.42	0.05	0.03	0.03	100.00	0.06	75
	SOP-04-504		38.29	0.00	0.01	23.44	0.48	37.74	0.00	0.00	0.00	0.04	100.00	0.01	74
	SOP-04-504		38.57	0.00	0.00	22.54	0.49	38.26	0.13	0.00	0.01	0.00	100.00	0.00	75
	SOP-04-506		38.89	0.00	0.03	21.77	0.45	38.79	0.03	0.04	0.00	0.01	100.00	0.04	76
	SOP-04-506		39.70	0.00	0.04	21.25	0.31	38.66	0.00	0.01	0.00	0.03	100.00	0.05	76
	SOP-04-507		38.39	0.00	0.04	24.75	0.39	36.24	0.17	0.00	0.02	0.00	100.00	0.00	72
	SOP-04-507		37.84	0.00	0.09	25.04	0.37	36.61	0.03	0.02	0.00	0.00	100.00	0.05	72
	SOP-04-508		38.64	0.00	0.00	25.01	0.41	35.76	0.16	0.02	0.01	0.00	100.00	0.00	72
	SOP-04-508		38.31	0.00	0.03	25.46	0.46	35.46	0.29	0.00	0.01	0.00	100.00	0.01	71
	SOP-04-509		39.10	0.01	0.02	20.05	0.22	40.39	0.18	0.00	0.00	0.02	100.00	0.10	78

Olivines	Sample ID	Wt. %	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	NiO	Fo
	SOP-04-509		39.16	0.07	0.01	19.59	0.40	40.57	0.16	0.03	0.00	0.00	100.00	0.11	79
	SOPF-0614		38.74	0.06	0.05	23.21	0.39	37.55	0.00	0.00	0.00	0.00	100.00	0.00	74
	SOPF-0614		38.32	0.00	0.00	22.84	0.34	38.25	0.19	0.02	0.03	0.02	100.00	0.04	75
	SOP-06-212		38.93	0.09	0.06	22.49	0.34	37.92	0.17	0.00	0.00	0.00	100.00	n.a.	75
	SOP-06-217		38.30	0.03	0.05	23.74	0.41	37.32	0.13	0.00	0.00	0.03	100.00	n.a.	74
	SOP-06-320		38.47	0.00	0.02	23.74	0.45	37.11	0.16	0.03	0.00	0.02	100.00	n.a.	74
	SOP-06-321		39.08	0.00	0.04	19.32	0.33	40.99	0.17	0.02	0.03	0.02	100.00	n.a.	79
	SOP-06-431		39.10	0.03	0.05	20.47	0.42	39.63	0.17	0.07	0.05	0.01	100.00	n.a.	78
	SOP-06-503		38.84	0.07	0.03	21.23	0.41	39.18	0.21	0.02	0.00	0.01	100.00	0.05	77
	SOP-06-503		38.82	0.04	0.01	20.78	0.43	39.77	0.13	0.00	0.01	0.01	100.00	0.00	77
	SOP-06-503		38.47	0.00	0.06	21.34	0.34	39.76	0.00	0.00	0.02	0.02	100.00	0.09	77
	SOP-06-503		38.58	0.00	0.03	21.35	0.31	39.49	0.16	0.06	0.02	0.00	100.00	0.00	77
	SOP-06-506		39.78	0.05	0.01	18.69	0.34	40.96	0.16	0.00	0.02	0.00	100.00	0.00	80
	SOP-06-506		39.64	0.00	0.06	19.74	0.22	40.13	0.18	0.00	0.02	0.01	100.00	0.06	78
	SOP-06-507		38.66	0.22	0.02	23.84	0.30	36.94	0.00	0.00	0.00	0.03	100.00	0.00	73
	SOP-06-507		38.47	0.00	0.02	23.84	0.30	37.13	0.20	0.00	0.00	0.05	100.00	0.14	74
	SOP-06-508		38.89	0.00	0.00	20.05	0.34	40.42	0.26	0.00	0.04	0.00	100.00	0.08	78
	SOP-06-508		39.38	0.00	0.05	19.94	0.40	40.06	0.14	0.04	0.00	0.00	100.00	0.00	78
	SOP-06-509		38.65	0.00	0.04	23.01	0.40	37.90	0.00	0.00	0.00	0.00	100.00	0.16	75
	SOP-06-509		38.89	0.02	0.05	23.19	0.40	37.22	0.15	0.03	0.02	0.02	100.00	0.00	74
	SOPF-0813		39.04	0.01	0.00	19.67	0.38	40.72	0.14	0.01	0.03	0.00	100.00	0.02	79
	SOPF-0813		39.14	0.00	0.02	20.24	0.19	40.26	0.11	0.03	0.00	0.01	100.00	0.02	78
	SOP-08-104		39.10	0.00	0.05	20.91	0.25	39.53	0.14	0.00	0.02	0.00	100.00	n.a.	77
	SOP-08-107		38.95	0.00	0.05	23.39	0.34	37.09	0.16	0.02	0.00	0.00	100.00	n.a.	74

Olivines	Sample ID	Wt. %	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	NiO	Fo
	SOP-08-212		40.15	0.03	0.03	19.38	0.36	39.94	0.11	0.00	0.01	0.00	100.00	n.a.	79
	SOP-08-212		39.09	0.00	0.01	19.90	0.43	40.33	0.22	0.00	0.02	0.00	100.00	n.a.	78
	SOP-08-213		38.26	0.09	0.05	25.00	0.26	36.07	0.22	0.05	0.00	0.00	100.00	n.a.	72
	SOP-08-213		37.43	0.00	0.01	24.85	0.37	37.02	0.29	0.00	0.02	0.01	100.00	n.a.	73
	SOP-08-213		38.20	0.00	0.06	24.77	0.38	36.30	0.29	0.00	0.00	0.01	100.00	n.a.	72
	SOP-08-213		37.79	0.00	0.01	25.10	0.50	36.31	0.25	0.04	0.00	0.00	100.00	n.a.	72
	SOP-08-214		37.76	0.01	0.01	25.00	0.47	36.42	0.29	0.04	0.00	0.00	100.00	n.a.	72
	SOP-08-214		38.24	0.00	0.00	24.89	0.42	36.28	0.13	0.00	0.04	0.00	100.00	n.a.	72
	SOP-08-216		36.29	0.00	0.07	30.18	0.57	32.61	0.19	0.00	0.06	0.02	100.00	n.a.	66
	SOP-08-216		37.36	0.00	0.03	27.15	0.47	34.79	0.20	0.00	0.00	0.00	100.00	n.a.	70
	SOP-08-217		38.08	0.00	0.00	25.93	0.53	35.25	0.21	0.00	0.00	0.00	100.00	n.a.	71
	SOP-08-217		37.94	0.02	0.04	25.87	0.44	35.37	0.26	0.01	0.03	0.01	100.00	n.a.	71
	SOP-08-428		38.04	0.00	0.01	25.38	0.42	35.97	0.11	0.05	0.00	0.01	100.00	n.a.	72
	SOP-08-429		38.76	0.00	0.00	20.98	0.29	39.79	0.17	0.00	0.00	0.01	100.00	n.a.	77
	SOP-08-610		39.29	0.00	0.10	20.25	0.24	40.05	0.00	0.05	0.00	0.02	100.00	0.00	78
	SOP-08-610		39.11	0.00	0.00	20.44	0.37	39.87	0.20	0.00	0.00	0.00	100.00	0.00	78
	SOP-08-611		39.21	0.00	0.00	21.12	0.20	39.20	0.14	0.08	0.00	0.05	100.00	0.00	77
	SOP-08-611		39.49	0.00	0.01	21.34	0.26	38.68	0.18	0.04	0.00	0.00	100.00	0.00	76
	SOP-08-612		39.10	0.00	0.01	21.14	0.22	39.52	0.00	0.00	0.00	0.00	100.00	0.04	77
	SOP-08-612		38.84	0.00	0.06	21.61	0.27	38.98	0.17	0.03	0.00	0.03	100.00	0.10	76
	SOP-08-614		38.96	0.01	0.00	19.97	0.21	40.62	0.20	0.04	0.00	0.00	100.00	0.09	78
	SOP-08-614		38.35	0.05	0.05	20.74	0.39	40.26	0.10	0.00	0.04	0.03	100.00	0.08	78
	SOP-08-615		39.24	0.00	0.08	21.54	0.41	38.45	0.27	0.00	0.02	0.00	100.00	0.10	76
	SOP-08-615		38.84	0.00	0.02	22.61	0.26	38.10	0.16	0.00	0.00	0.01	100.00	0.00	75

Olivines	Sample ID	Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	NiO	Fo
	SOP-08-616		37.88	0.00	0.07	25.24	0.46	36.16	0.14	0.00	0.04	0.02	100.00	0.00	72
	SOP-08-616		37.22	0.03	0.03	25.31	0.51	36.79	0.11	0.00	0.00	0.00	100.00	0.02	72
	SOP-08-618		38.93	0.00	0.00	20.26	0.25	40.40	0.11	0.00	0.03	0.02	100.00	0.04	78
	SOP-08-618		39.19	0.06	0.08	20.63	0.26	39.61	0.13	0.00	0.04	0.00	100.00	0.02	77
Groundmass	Sample ID	Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	NiO	Fo
Olivine	GM-4		37.82	0.02	0.00	25.48	0.52	35.85	0.20	0.03	0.03	0.05	100.00	0.06	71
	GM-4		38.86	0.08	0.00	24.45	0.51	35.83	0.22	0.03	0.02	0.01	100.00	0.00	72
	GM-4		38.76	0.04	0.05	22.45	0.31	38.24	0.12	0.00	0.01	0.00	100.00	0.00	75
	GM-4		38.45	0.00	0.04	25.14	0.26	35.82	0.24	0.04	0.02	0.00	100.00	0.13	72

Table B.2. The average values of major element composition of the olivines

SOP-01-210

	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO
n = 1	39.06	0.06	0.04	22.76	0.33	37.59
<i>St.dev.</i>	0.78			1.59	0.16	
CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	NiO	Fo
0.16	0.00	0.00	0.01	100.00	0.00	74.65
0.10						

SOP-01-215

	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO
n = 1	38.49	0.00	0.03	24.14	0.40	36.73
<i>St.dev.</i>	0.77			1.69	0.20	
CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	NiO	Fo
0.10	0.04	0.07	0.00	100.00	0.00	73.06
0.06						

SOP-01-319

	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO
n = 1	39.10	0.20	0.00	20.50	0.31	39.59
<i>St.dev.</i>	0.78			1.43	0.15	
CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	NiO	Fo
0.23	0.03	0.00	0.04	100.00	0.00	77.49
0.14						

SOP-01-320

	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO
n = 1	38.83	0.03	0.00	23.67	0.36	36.86
<i>St.dev.</i>	0.78			1.66	0.18	
CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	NiO	Fo
0.15	0.03	0.08	0.00	100.00	0.00	73.51
0.09						

SOP-01-323

	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO
n = 1	37.45	0.01	0.02	27.07	0.52	34.77
<i>St.dev.</i>	0.75			1.89	0.26	
CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	NiO	Fo
0.11	0.00	0.00	0.05	100.00	0.00	69.60
0.07						

SOP-01-327

	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO
n = 1	38.50	0.01	0.05	23.98	0.39	36.89
<i>St.dev.</i>	0.77			1.68	0.19	
CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	NiO	Fo
0.17	0.00	0.00	0.00	100.00	0.00	73.27
0.10						

SOP-01-433

	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO
n = 1	37.88	0.00	0.08	25.09	0.50	36.29
<i>St.dev.</i>	0.76			1.76	0.24	
CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	NiO	Fo
0.14	0.00	0.01	0.00	100.00	0.00	72.06
0.08						

SOP-04-101

	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO
n = 1	39.17	0.00	0.05	19.92	0.25	40.42
<i>St.dev.</i>	0.78			1.39	0.12	
CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	NiO	Fo
0.18	0.01	0.00	0.00	100.00	0.00	78.35
0.11						

SOP-04-214

	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO
n = 1	38.45	0.00	0.02	21.42	0.28	39.63
<i>St.dev.</i>	0.77			1.50	0.14	
CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	NiO	Fo
0.19	0.00	0.01	0.00	100.00	0.00	76.74
0.11						

SOP-06-212

	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO
n = 1	38.93	0.09	0.06	22.49	0.34	37.92
<i>St.dev.</i>	0.78			1.57	0.17	
CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	NiO	Fo
0.17	0.00	0.00	0.00	100.00	0.00	75.03
0.10						

SOP-06-217

	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO
n = 1	38.30	0.03	0.05	23.74	0.41	37.32
<i>St.dev.</i>	0.77			1.66	0.20	
CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	NiO	Fo
0.13	0.00	0.00	0.03	100.00	0.00	73.70
0.08						

SOP-06-320

	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO
n = 1	38.47	0.00	0.02	23.74	0.45	37.11
<i>St.dev.</i>	0.77			1.66	0.22	
CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	NiO	Fo
0.16	0.03	0.00	0.02	100.00	0.00	73.59
0.10						

SOP-06-321

	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO
n = 1	39.08	0.00	0.04	19.32	0.33	40.99
<i>St.dev.</i>	0.78			1.35	0.16	
CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	NiO	Fo
0.17	0.02	0.03	0.02	100.00	0.00	79.08
0.11						

SOP-06-431

	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO
n = 1	39.10	0.03	0.05	20.47	0.42	39.63
<i>St.dev.</i>	0.78			1.43	0.21	
CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	NiO	Fo
0.17	0.07	0.05	0.01	100.00	0.00	77.53
0.10						

SOP-08-104

	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO
n = 1	39.10	0.00	0.05	20.91	0.25	39.53
<i>St.dev.</i>	0.78			1.46	0.12	
CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	NiO	Fo
0.14	0.00	0.02	0.00	100.00	0.00	77.11
0.09						

SOP-08-107

	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO
n = 1	38.95	0.00	0.05	23.39	0.34	37.09
<i>St.dev.</i>	0.78			1.64	0.17	
CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	NiO	Fo
0.16	0.02	0.00	0.00	100.00	0.00	73.86
0.10						

SOP-08-212

	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO
n = 2	39.62	0.01	0.02	19.64	0.40	40.13
<i>St.dev.</i>	0.74			0.37	0.05	
CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	NiO	Fo
0.16	0.00	0.02	0.00	100.00	0.00	78.46
0.08						

SOP-08-213

	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO
n = 4	37.92	0.02	0.03	24.93	0.38	36.42
<i>St.dev.</i>	0.39			0.15	0.10	
CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	NiO	Fo
0.26	0.02	0.01	0.00	100.00	0.00	72.25
0.03						

SOP-08-214

	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO
n = 2	38.00	0.01	0.01	24.94	0.45	36.35
<i>St.dev.</i>	0.34			0.08	0.03	
CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	NiO	Fo
0.21	0.02	0.02	0.00	100.00	0.00	72.21
0.11						

SOP-08-216

	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO
n = 2	36.83	0.00	0.05	28.67	0.52	33.70
<i>St.dev.</i>	0.75			2.14	0.07	
CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	NiO	Fo
0.19	0.00	0.03	0.01	100.00	0.00	67.69
0.01						

SOP-08-217

	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO
n = 2	38.01	0.01	0.02	25.90	0.48	35.31
<i>St.dev.</i>	0.10			0.04	0.06	
CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	NiO	Fo
0.23	0.01	0.02	0.00	100.00	0.00	70.85
0.03						

SOP-08-428

	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO
n = 1	38.04	0.00	0.01	25.38	0.42	35.97
<i>St.dev.</i>	0.76			1.78	0.20	
CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	NiO	Fo
0.11	0.05	0.00	0.01	100.00	0.00	71.64
0.07						

SOP-08-429

	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO
n = 1	38.76	0.00	0.00	20.98	0.29	39.79
<i>St.dev.</i>	0.78			1.47	0.14	
CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	NiO	Fo
0.17	0.00	0.00	0.01	100.00	0.00	77.18
0.10						

Table B.3. Major element and volatile compositions of melt inclusions

Inclusions	Sample ID	Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	"H ₂ O"	Mg#
Olivine	SOPF-0101		51.80	0.92	19.86	9.54	0.20	4.60	9.94	2.88	0.38	0.17	0.00	1017	919	0.10	46.23
	SOPF-0101		51.97	0.91	19.81	9.54	0.14	4.56	9.74	3.16	0.30	0.16	0.00	944	1045	0.10	45.98
	SOPF-0102		48.91	1.17	18.85	10.09	0.19	6.12	12.09	2.57	0.35	0.28	0.00	2360	1611	0.10	51.92
	SOPF-0102		49.50	1.30	19.38	9.50	0.09	5.73	11.61	2.89	0.31	0.27	0.01	2380	991	0.10	51.81
	SOPF-0104		48.20	0.88	20.31	9.85	0.15	6.38	12.14	2.40	0.16	0.08	0.06	1995	941	0.09	53.58
	SOPF-0104		48.21	0.95	20.07	9.76	0.18	6.32	12.25	2.30	0.28	0.10	0.00	1634	828	0.09	53.57
	SOPF-0109		55.61	1.33	17.06	9.73	0.15	4.20	8.07	3.47	0.47	0.18	0.00	631	1374	0.12	43.49
	SOPF-0109		55.39	1.30	16.94	9.93	0.26	4.37	8.28	3.12	0.51	0.19	0.04	666	1100	0.11	43.93
	SOPF-0111		51.73	0.53	19.00	11.80	0.21	5.20	8.46	3.01	0.28	0.09	0.03	1451	0	0.12	44.01
	SOPF-0111		52.32	0.63	17.81	11.90	0.23	5.25	8.87	3.01	0.32	0.09	0.02	1490	1248	0.13	44.00
	SOPF-0114		55.12	1.32	17.25	9.48	0.07	4.69	7.94	3.51	0.56	0.17	0.00	576	0	0.11	46.88
	SOPF-0114		54.68	1.30	17.32	9.57	0.26	4.73	8.09	3.56	0.59	0.18	0.07	513	1092	0.11	46.82
	SOPF-0402a		52.50	0.96	18.62	10.80	0.28	4.61	8.36	3.51	0.49	0.20	0.00	1103	1019	0.13	43.22
	SOPF-0402a		52.80	0.59	18.05	10.97	0.17	4.77	9.08	3.39	0.33	0.16	0.09	1112	0	0.12	43.65
	SOPF-0402b		52.03	1.10	16.80	12.09	0.25	5.35	9.55	2.66	0.32	0.17	0.02	926	974	0.14	44.08
	SOPF-0402b		50.98	1.17	17.48	12.27	0.25	5.38	9.79	2.63	0.23	0.14	0.03	1051	748	0.14	43.88
	SOPF-0406		48.15	0.88	19.13	11.19	0.21	5.38	12.11	3.01	0.18	0.13	0.11	1329	0	0.13	46.14
	SOPF-0406		48.61	0.87	18.77	11.46	0.13	5.56	11.61	2.83	0.35	0.10	0.01	1349	99	0.13	46.39
	SOPF-0407		49.02	1.00	18.10	11.62	0.32	5.68	11.53	2.86	0.22	0.20	0.08	1904	777	0.13	46.57
	SOPF-0407		48.34	0.97	18.26	12.07	0.14	5.82	11.62	2.82	0.36	0.14	0.05	1990	933	0.14	46.21
	SOPF-0408		50.30	0.78	18.60	11.68	0.20	6.02	10.37	2.20	0.22	0.07	0.00	1762	890	0.12	47.87
	SOPF-0408		49.80	0.69	18.67	11.82	0.26	6.02	10.34	2.47	0.16	0.13	0.01	1698	0	0.12	47.59
	SOPF-0409		52.44	1.35	17.94	10.98	0.33	4.38	8.45	3.64	0.60	0.14	0.02	521	1170	0.14	41.59
	SOPF-0409		53.08	1.28	18.19	10.46	0.17	4.21	8.59	3.70	0.43	0.12	0.00	725	915	0.13	41.74
	SOPF-0410		53.81	0.91	18.79	9.29	0.23	4.25	9.14	3.34	0.37	0.17	0.04	1284	0	0.10	44.90
	SOPF-0410		52.10	0.95	18.93	10.98	0.13	5.02	8.74	3.10	0.28	0.15	0.00	1399	922	0.12	44.91

Inclusions	Sample ID	Wt. %	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	"H ₂ O"	Mg#
	SOPF-0411		52.40	1.32	17.04	11.59	0.18	4.76	9.30	3.14	0.41	0.15	0.00	841	1203	0.14	42.26
	SOPF-0411		51.85	1.41	16.25	12.46	0.16	5.06	9.13	3.24	0.47	0.15	0.00	853	0	0.16	41.97
	SOPF-0412		52.75	0.84	18.61	10.53	0.18	5.17	8.97	2.75	0.31	0.15	0.00	1338	0	0.11	46.68
	SOPF-0412		53.42	0.72	18.51	10.19	0.17	5.04	9.10	2.78	0.27	0.16	0.01	1147	1037	0.10	46.85
	SOPF-0603		51.61	1.27	19.37	9.88	0.21	3.97	9.41	3.84	0.57	0.17	0.02	646	1477	0.12	41.75
	SOPF-0603		51.52	1.18	19.90	9.84	0.24	3.96	9.00	3.97	0.42	0.11	0.00	729	0	0.12	41.76
	SOPF-0603		51.64	1.15	19.44	9.91	0.23	4.02	9.38	3.81	0.45	0.13	0.02	655	112	0.12	41.97
	SOPF-0605		51.25	0.79	19.07	10.02	0.18	4.73	10.68	3.11	0.50	0.17	0.05	1744	1089	0.11	45.69
	SOPF-0605		49.63	0.77	17.89	14.09	0.11	6.74	8.75	2.68	0.41	0.09	0.11	1383	7601	0.15	46.03
	SOPF-0606		49.03	0.89	20.01	9.86	0.06	5.61	12.32	2.33	0.23	0.14	0.07	2046	0	0.09	50.37
	SOPF-0606		49.10	0.82	20.36	9.78	0.16	5.61	12.37	2.14	0.31	0.06	0.03	1889	2987	0.09	50.55
	SOPF-0606		49.16	0.94	19.92	9.75	0.20	5.63	12.49	2.05	0.21	0.11	0.01	1899	727	0.09	50.71
	SOPF-0607		48.50	0.72	19.11	9.89	0.17	5.98	12.91	2.61	0.31	0.19	0.00	1884	0	0.10	51.85
	SOPF-0607		48.78	1.05	19.46	9.78	0.20	5.91	12.11	2.67	0.33	0.09	0.00	1900	0	0.10	51.84
	SOPF-0607		52.69	0.23	21.11	9.76	0.27	6.28	6.77	2.91	0.26	0.10	0.00	1924	0	0.08	53.41
	SOPF-0612		49.49	0.78	19.35	10.83	0.23	5.76	11.40	2.29	0.29	0.10	0.02	2094	859	0.11	48.68
	SOPF-0612		50.23	0.80	19.45	10.67	0.12	5.77	11.31	2.08	0.26	0.08	0.02	2187	3095	0.10	49.07
	SOPF-0612		50.15	0.92	19.22	11.35	0.20	6.08	10.91	2.30	0.17	0.11	0.00	1859	10149	0.11	48.84
	SOPF-0613		51.95	0.91	19.71	10.02	0.12	6.01	10.02	3.67	0.39	0.25	0.00	1757	26045	0.10	51.65
	SOPF-0613		51.78	0.73	19.31	9.86	0.13	6.04	9.87	3.37	0.28	0.16	0.00	1750	11560	0.10	52.20
	SOPF-0613		51.11	0.81	19.27	9.79	0.15	5.79	9.43	3.92	0.46	0.18	0.03	1629	5338	0.11	51.32
	SOPF-0615		48.13	0.93	19.75	10.75	0.08	6.21	11.97	2.32	0.20	0.11	0.00	1794	828	0.11	50.75
	SOPF-0615		49.44	0.82	20.73	10.31	0.25	6.03	12.03	2.37	0.21	0.07	0.11	1906	17262	0.09	51.06
	SOPF-0615		49.34	0.90	19.77	10.91	0.33	6.32	11.82	2.53	0.24	0.12	0.10	1860	17437	0.11	50.79
	SOPF-0801		50.34	0.59	19.58	10.96	0.22	5.36	10.69	2.42	0.20	0.13	0.05	1731	813	0.11	46.56
	SOPF-0801		49.77	0.64	18.90	11.87	0.20	5.80	10.77	2.13	0.32	0.08	0.00	1993	771	0.12	46.53
	SOPF-0801		49.53	0.55	18.86	12.12	0.29	5.92	10.58	2.17	0.27	0.08	0.00	1894	0	0.12	46.54

Inclusions	Sample ID	Wt. %	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	"H ₂ O"	Mg#
	SOPF-0802		50.41	0.60	20.83	10.90	0.18	5.46	10.14	2.46	0.19	0.09	0.07	1773	8230	0.10	47.16
	SOPF-0802		50.28	0.65	19.62	11.30	0.20	5.73	10.19	2.14	0.22	0.10	0.00	1681	752	0.11	47.47
	SOPF-0802		50.26	0.56	20.16	11.03	0.12	5.56	10.22	2.28	0.23	0.12	0.10	1948	630	0.10	47.33
	SOPF-0803		49.17	1.10	18.70	10.49	0.16	5.39	11.30	3.25	0.56	0.16	0.01	877	965	0.12	47.81
	SOPF-0803		49.16	1.15	19.11	10.48	0.09	5.44	11.14	3.17	0.35	0.14	0.02	839	375	0.12	48.05
	SOPF-0803		49.40	1.14	18.79	10.49	0.10	5.47	11.28	3.09	0.35	0.14	0.00	678	1124	0.12	48.19
	SOPF-0805		54.37	0.00	16.28	11.54	0.31	5.47	8.65	3.02	0.40	0.12	0.03	668	0	0.12	45.82
	SOPF-0805		53.92	1.18	16.04	11.44	0.15	5.29	8.59	2.91	0.57	0.23	0.06	615	1218	0.13	45.17
	SOPF-0805		53.60	1.11	16.55	11.31	0.27	5.25	8.67	2.89	0.47	0.18	0.00	620	1716	0.13	45.27
	SOPF-0806		53.83	0.85	16.69	11.83	0.14	4.93	8.60	2.98	0.27	0.23	0.00	1319	863	0.13	42.59
	SOPF-0806		53.37	0.88	17.11	11.88	0.24	4.89	8.17	3.06	0.47	0.23	0.10	982	0	0.14	42.31
	SOPF-0806		53.67	0.74	16.65	11.86	0.22	4.91	8.70	3.00	0.44	0.17	0.00	1134	1380	0.14	42.45
	SOPF-0812		54.10	1.18	16.59	11.06	0.27	4.65	8.74	3.06	0.40	0.19	0.00	660	1240	0.13	42.83
	SOPF-0812		53.40	1.03	16.70	11.80	0.25	4.93	8.35	3.21	0.37	0.19	0.01	640	977	0.14	42.67
	SOPF-0812		55.88	0.35	17.30	10.05	0.30	4.32	8.09	3.29	0.31	0.19	0.00	376	0	0.10	43.37
	SOPF-0108		49.25	1.52	19.95	10.20	0.23	5.88	10.26	2.73	0.27	0.15	0.03	1591	913	0.11	50.67
	SOPF-0108		49.00	1.34	19.67	10.68	0.18	6.09	10.10	2.99	0.23	0.17	0.03	1476	1133	0.11	50.42
	SOP-01-210		50.77	0.95	19.08	11.31	0.20	5.80	9.34	2.49	0.27	0.16	n.a	1508	665	0.11	47.75
	SOP-01-210		50.58	0.83	19.62	10.81	0.31	5.53	9.63	2.55	0.31	0.18	n.a	1339	717	0.11	47.70
	SOP-01-210		51.32	0.66	19.56	10.49	0.21	5.43	9.80	2.50	0.23	0.17	n.a	1457	757	0.10	48.01
	SOP-01-215		53.16	0.71	19.34	9.95	0.18	4.73	9.21	2.66	0.13	0.25	n.a	1048	1139	0.09	45.91
	SOP-01-215		52.38	0.36	19.33	10.42	0.20	4.92	9.42	2.64	0.38	0.20	n.a	901	846	0.10	45.72
	SOP-01-215		51.79	0.86	19.11	10.96	0.26	5.21	9.31	2.29	0.27	0.22	n.a	1045	812	0.11	45.88
	SOP-01-319		48.58	1.08	20.17	9.55	0.20	5.19	12.65	2.61	0.23	0.11	n.a	1283	1053	0.10	49.21
	SOP-01-319		48.61	1.14	20.14	9.52	0.20	5.23	12.73	2.25	0.38	0.14	n.a	1275	827	0.10	49.48
	SOP-01-319		48.89	1.09	20.02	9.55	0.20	5.31	12.64	2.24	0.20	0.20	n.a	1207	1002	0.09	49.78
	SOP-01-320		51.95	1.10	16.96	11.82	0.27	5.77	9.32	2.50	0.46	0.17	n.a	1237	760	0.13	46.55

Inclusions	Sample ID	Wt. %	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	"H ₂ O"	Mg#
	SOP-01-320		51.65	1.06	17.40	11.58	0.22	5.62	9.66	2.68	0.28	0.15	n.a	959	983	0.13	46.37
	SOP-01-320		52.48	1.13	17.39	11.40	0.11	5.59	9.08	2.60	0.30	0.18	n.a	902	886	0.12	46.64
	SOP-01-323		54.25	1.00	16.44	12.78	0.29	5.15	6.54	3.14	0.58	0.16	n.a	1037	1335	0.15	41.80
	SOP-01-323		53.56	0.86	17.14	12.62	0.26	4.97	6.74	3.68	0.38	0.16	n.a	1378	1023	0.15	41.24
	SOP-01-323		53.63	0.84	16.76	13.04	0.35	5.19	6.50	3.46	0.48	0.14	n.a	1362	1023	0.16	41.53
	SOP-01-327		49.88	0.53	18.56	12.47	0.14	5.79	10.47	2.27	0.24	0.05	n.a	1430	1099	0.13	45.31
	SOP-01-327		49.04	0.57	18.47	13.29	0.18	6.21	10.32	2.06	0.14	0.12	n.a	1597	776	0.13	45.44
	SOP-01-327		49.38	0.29	18.55	12.85	0.28	5.96	10.29	2.39	0.23	0.10	n.a	1266	700	0.13	45.26
	SOP-01-433		50.82	1.14	17.43	11.78	0.34	5.07	10.29	2.85	0.41	0.14	n.a	904	888	0.14	43.42
	SOP-01-433		50.48	0.92	18.08	11.79	0.35	5.07	10.16	3.00	0.32	0.17	n.a	1208	1100	0.14	43.40
	SOP-01-433		50.57	1.22	17.12	12.66	0.28	5.51	9.87	2.61	0.34	0.17	n.a	1050	1456	0.15	43.69
	SOP-01-433		52.81	1.13	17.30	11.45	0.21	5.10	9.13	2.66	0.33	0.15	n.a	862	987	0.13	44.23
	SOP-01-501		50.58	0.99	20.52	9.70	0.12	5.20	11.99	2.38	0.08	0.10	0.01	1975	12251	0.09	48.85
	SOP-01-501		50.79	0.70	22.19	9.69	0.16	5.18	10.09	2.70	0.27	0.09	0.06	2776	12158	0.08	48.78
	SOP-04-101		47.86	1.10	19.43	10.41	0.19	5.87	12.65	2.63	0.26	0.13	n.a	2066	1040	0.11	50.13
	SOP-04-101		48.34	1.06	20.11	9.40	0.21	5.37	13.01	2.53	0.33	0.13	n.a	1897	1101	0.10	50.44
	SOP-04-101		48.31	1.08	20.07	9.78	0.11	5.60	12.66	2.41	0.33	0.13	n.a	1716	1222	0.10	50.54
	SOP-04-214		49.99	0.98	19.42	10.35	0.22	5.72	10.43	2.75	0.35	0.10	n.a	1219	763	0.11	49.62
	SOP-04-214		49.03	0.97	19.50	10.91	0.13	5.87	10.29	3.14	0.35	0.15	n.a	1224	1116	0.12	48.93
	SOP-04-501		52.78	0.92	18.63	9.28	0.09	5.71	8.86	3.33	0.49	0.17	0.00	724	1113	0.10	52.32
	SOP-04-501		52.69	0.89	18.67	9.51	0.17	5.93	8.59	3.14	0.44	0.18	0.00	701	662	0.09	52.64
	SOP-04-501		54.59	0.18	19.31	8.85	0.12	5.59	7.59	3.52	0.25	0.20	0.06	695	0	0.08	52.93
	SOP-04-502		53.05	0.94	18.01	10.97	0.30	4.90	8.92	2.75	0.33	0.15	0.00	1281	751	0.12	44.33
	SOP-04-502		52.66	0.90	18.51	10.91	0.18	4.91	9.37	2.63	0.13	0.18	0.00	1541	731	0.11	44.52
	SOP-04-502		51.62	0.81	17.97	12.11	0.23	5.42	9.27	2.57	0.21	0.14	0.00	1398	320	0.13	44.36
	SOP-04-502		51.24	0.46	17.73	12.42	0.26	5.57	9.70	2.52	0.25	0.13	0.00	1517	0	0.13	44.41
	SOP-04-502		51.62	0.96	18.50	11.68	0.48	5.16	8.67	2.88	0.23	0.14	0.02	1456	0	0.13	44.07

Inclusions	Sample ID	Wt. %	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	"H ₂ O"	Mg#
	SOP-04-503		51.32	0.19	18.49	11.92	0.25	6.11	9.09	2.40	0.25	0.16	0.00	893	0	0.11	47.76
	SOP-04-503		50.53	1.00	19.01	10.93	0.18	5.38	10.07	2.68	0.30	0.18	0.00	860	800	0.11	46.74
	SOP-04-503		50.72	0.93	18.85	10.70	0.25	5.18	10.07	3.01	0.45	0.19	0.06	1003	749	0.12	46.33
	SOP-04-504		50.17	0.42	18.64	11.89	0.21	6.04	10.58	2.08	0.20	0.12	0.00	1829	0	0.12	47.52
	SOP-04-504		50.43	0.56	18.66	11.47	0.31	5.80	10.70	2.20	0.21	0.11	0.00	1889	829	0.11	47.40
	SOP-04-504		50.35	0.47	18.86	11.33	0.29	5.72	10.90	2.25	0.15	0.14	0.02	1787	840	0.11	47.39
	SOP-04-506		50.98	0.87	19.75	10.95	0.16	5.87	10.80	2.42	0.23	0.07	0.02	1825	16638	0.10	48.87
	SOP-04-506		51.58	1.03	20.18	11.31	0.23	6.21	7.12	2.44	0.24	0.07	0.00	1978	0	0.10	49.46
	SOP-04-506		49.83	0.83	18.93	11.57	0.21	6.24	10.24	2.27	0.18	0.12	0.04	1549	918	0.11	49.00
	SOP-04-507		53.52	0.17	17.24	11.66	0.23	5.34	9.18	2.68	0.17	0.10	0.00	1453	0	0.12	44.93
	SOP-04-507		52.31	0.49	18.05	11.77	0.32	5.31	9.10	2.70	0.20	0.13	0.02	1354	782	0.12	44.55
	SOP-04-507		52.90	0.53	17.07	12.15	0.23	5.42	9.01	2.93	0.27	0.13	0.01	1313	3634	0.13	44.29
	SOP-04-508		52.73	0.33	19.54	10.36	0.25	4.52	9.36	2.93	0.36	0.13	0.00	2052	872	0.10	43.74
	SOP-04-508		52.95	0.22	19.77	10.63	0.26	4.68	9.17	2.85	0.28	0.16	0.00	2382	4951	0.10	43.98
	SOP-04-508		53.23	0.28	19.53	10.49	0.23	4.68	9.68	2.59	0.18	0.10	0.03	2052	5537	0.09	44.32
	SOPF-0614		49.47	0.53	19.22	9.91	0.20	4.78	13.03	2.82	0.25	0.17	0.06	1601	0	0.10	46.24
	SOPF-0614		49.90	1.01	19.55	9.91	0.14	4.71	11.95	3.11	0.30	0.13	0.00	1268	4316	0.11	45.85
	SOPF-0614		50.75	1.07	20.22	10.06	0.27	4.70	12.57	3.33	0.47	0.15	0.05	1318	31537	0.11	45.44
	SOP-06-212		54.09	0.74	19.00	9.73	0.14	4.74	7.14	4.04	0.42	0.18	n.a	390	1466	0.11	46.47
	SOP-06-212		53.60	0.67	19.08	9.93	0.06	4.77	7.23	4.26	0.46	0.21	n.a	506	1705	0.11	46.12
	SOP-06-212		53.57	0.48	19.16	9.75	0.10	4.65	7.40	4.40	0.56	0.20	n.a	397	1971	0.11	45.96
	SOP-06-217		52.54	0.84	19.39	9.77	0.21	4.88	9.88	2.39	0.25	0.22	n.a	1486	787	0.09	47.10
	SOP-06-217		51.88	0.91	19.02	10.30	0.19	5.12	10.32	2.14	0.39	0.13	n.a	1484	932	0.10	46.99
	SOP-06-217		52.64	0.75	19.31	9.67	0.20	4.90	10.19	2.14	0.29	0.30	n.a	1364	989	0.09	47.44
	SOP-06-320		50.78	0.80	18.87	11.31	0.31	5.60	10.20	2.19	0.17	0.10	n.a	1371	629	0.11	46.90
	SOP-06-320		50.16	0.68	18.74	11.80	0.25	5.73	10.19	2.34	0.42	0.10	n.a	1660	709	0.12	46.42
	SOP-06-320		50.37	0.80	18.29	12.01	0.17	5.86	10.09	2.29	0.36	0.13	n.a	1491	767	0.12	46.51

Inclusions	Sample ID	Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	"H ₂ O"	Mg#
	SOP-06-321		49.64	0.65	19.87	9.75	0.18	6.17	11.73	2.11	0.25	0.14	n.a	2029	893	0.09	53.01
	SOP-06-321		49.99	0.46	19.89	9.76	0.19	6.18	11.36	2.31	0.23	0.12	n.a	1963	823	0.09	53.04
	SOP-06-321		49.55	0.71	19.97	9.75	0.10	6.10	11.74	2.30	0.24	0.07	n.a	2169	942	0.09	52.70
	SOP-06-431		49.63	1.01	20.17	9.69	0.12	5.77	11.39	2.22	0.24	0.17	n.a	1619	795	0.09	51.46
	SOP-06-431		49.64	1.10	19.80	9.75	0.27	5.76	11.33	2.25	0.38	0.14	n.a	1679	821	0.09	51.31
	SOP-06-431		49.33	0.92	20.43	9.74	0.19	5.83	11.56	2.11	0.15	0.19	n.a	1787	963	0.09	51.62
	SOP-06-503		51.54	0.95	19.07	10.59	0.16	6.04	10.59	2.35	0.21	0.10	0.00	4856	6074	0.10	50.41
	SOP-06-503		50.37	1.08	19.22	10.78	0.27	5.98	10.86	2.61	0.32	0.18	0.02	2077	12164	0.11	49.72
	SOP-06-506		49.73	1.08	19.66	9.89	0.12	6.08	11.38	2.55	0.27	0.07	0.05	1691	4370	0.10	52.30
	SOP-06-506		49.39	1.13	19.83	9.75	0.19	5.98	11.19	2.64	0.27	0.12	0.04	1657	931	0.10	52.22
	SOP-06-506		49.62	1.06	19.41	9.87	0.15	6.07	11.37	2.65	0.22	0.12	0.08	1637	1163	0.10	52.27
	SOP-06-507		51.42	1.32	19.93	9.90	0.16	4.38	10.32	3.82	0.38	0.23	0.00	252	17675	0.12	44.10
	SOP-06-507		51.54	1.40	20.24	10.00	0.24	4.36	10.46	4.08	0.38	0.22	0.02	316	27305	0.12	43.73
	SOP-06-507		50.39	1.33	19.63	9.74	0.14	4.28	10.27	3.79	0.44	0.21	0.00	340	1517	0.12	43.92
	SOP-06-508		48.47	1.09	18.69	10.31	0.21	5.76	12.67	2.93	0.31	0.10	0.09	1681	918	0.12	49.90
	SOP-06-508		48.57	0.94	18.55	10.60	0.11	5.98	12.51	2.69	0.42	0.13	0.09	1641	927	0.11	50.16
	SOP-06-508		48.58	1.06	19.47	10.18	0.17	5.76	12.90	2.74	0.20	0.13	0.09	1853	7056	0.11	50.20
	SOP-06-509		57.14	0.00	21.40	9.83	0.13	4.55	2.29	4.00	0.57	0.28	0.00	917	0	0.09	45.24
	SOP-06-509		50.96	1.22	19.05	10.40	0.12	4.82	9.27	3.95	0.36	0.21	0.04	926	1278	0.13	45.23
	SOP-06-509		50.79	1.33	18.77	10.90	0.16	5.07	8.79	3.75	0.48	0.18	0.02	1005	0	0.13	45.33
	SOPF-0813		49.66	1.18	19.58	10.48	0.18	6.26	9.71	2.78	0.33	0.15	0.00	1514	0	0.10	51.57
	SOPF-0813		48.98	1.17	20.17	10.49	0.16	6.30	10.16	2.50	0.32	0.18	0.06	1720	0	0.10	51.69
	SOPF-0813		49.21	1.28	19.62	10.49	0.23	6.29	10.26	2.62	0.22	0.21	0.07	1349	709	0.10	51.65
	SOP-08-104		48.26	0.92	18.45	11.00	0.17	5.83	12.41	3.00	0.24	0.16	n.a	1620	1207	0.12	48.57
	SOP-08-104		48.04	1.05	18.52	11.13	0.15	5.93	12.52	2.73	0.22	0.15	n.a	1783	904	0.12	48.73
	SOP-08-104		47.63	1.12	18.72	11.00	0.16	5.79	12.71	2.76	0.37	0.19	n.a	1775	990	0.13	48.42
	SOP-08-107		50.12	1.28	18.67	11.47	0.12	5.41	9.88	2.77	0.41	0.13	n.a	774	1284	0.13	45.66

Inclusions	Sample ID	Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	"H ₂ O"	Mg#
	SOP-08-107		50.14	1.15	18.51	11.48	0.25	5.43	9.93	2.92	0.26	0.20	n.a	833	1062	0.13	45.74
	SOP-08-212		48.75	1.06	18.49	10.53	0.13	6.11	11.98	2.87	0.32	0.11	n.a	1263	942	0.12	50.82
	SOP-08-212		48.74	0.89	18.68	10.50	0.10	6.10	12.15	2.77	0.40	0.09	n.a	1419	1295	0.11	50.90
	SOP-08-212		48.13	1.07	18.83	10.54	0.17	6.06	12.26	2.91	0.29	0.10	n.a	1370	935	0.12	50.59
	SOP-08-213		49.21	0.93	19.15	11.93	0.18	5.12	10.71	2.76	0.23	0.13	n.a	1301	891	0.13	43.31
	SOP-08-213		48.19	1.18	19.07	12.21	0.18	5.12	11.12	2.76	0.32	0.19	n.a	1138	1199	0.15	42.77
	SOP-08-213		48.88	0.87	19.38	11.73	0.23	4.97	10.92	2.87	0.35	0.13	n.a	1082	1103	0.13	43.02
	SOP-08-213		48.47	1.05	19.01	12.18	0.26	5.12	10.82	2.84	0.37	0.17	n.a	1093	779	0.14	42.85
	SOP-08-213		48.89	0.85	19.24	12.04	0.11	5.13	10.82	2.70	0.39	0.10	n.a	1009	816	0.14	43.15
	SOP-08-213		49.54	0.70	18.93	11.92	0.11	5.12	10.73	2.79	0.33	0.16	n.a	1213	871	0.13	43.38
	SOP-08-214		49.24	0.83	18.90	11.71	0.22	5.06	11.53	2.44	0.32	0.10	n.a	1230	901	0.13	43.51
	SOP-08-214		48.93	1.03	18.71	12.06	0.18	5.22	11.40	2.23	0.34	0.18	n.a	1182	545	0.14	43.57
	SOP-08-214		48.73	1.03	19.06	11.87	0.27	5.10	11.42	2.34	0.39	0.12	n.a	1240	850	0.13	43.37
	SOP-08-216		54.07	1.81	13.28	13.04	0.21	4.57	7.86	3.58	0.98	0.77	n.a	166	1252	0.21	38.44
	SOP-08-216		54.44	1.81	13.36	12.84	0.31	4.60	7.76	3.19	1.07	0.85	n.a	258	1762	0.20	38.95
	SOP-08-216		54.33	1.87	13.50	13.08	0.21	4.75	7.60	3.11	0.79	0.93	n.a	0	1599	0.20	39.30
	SOP-08-216		55.21	1.50	13.66	12.47	0.28	4.56	7.64	3.05	0.98	0.81	n.a	54	1579	0.18	39.47
	SOP-08-217		49.41	0.61	18.59	12.62	0.28	5.16	10.27	2.95	0.31	0.09	n.a	919	1102	0.14	42.15
	SOP-08-217		49.90	0.63	18.77	12.22	0.17	5.01	10.05	3.01	0.37	0.19	n.a	1006	1089	0.14	42.21
	SOP-08-217		49.93	0.71	18.39	12.45	0.11	5.10	10.32	2.94	0.30	0.08	n.a	1068	1217	0.14	42.19
	SOP-08-428		52.19	0.86	17.75	12.21	0.29	5.51	8.47	2.49	0.33	0.19	n.a	978	1018	0.13	44.58
	SOP-08-428		51.64	0.94	17.68	12.26	0.34	5.42	8.59	2.56	0.66	0.17	n.a	881	974	0.14	44.08
	SOP-08-429		50.56	0.87	19.36	10.51	0.24	5.96	10.00	2.50	0.28	0.21	n.a	1879	990	0.10	50.24
	SOP-08-429		50.63	1.00	19.24	10.55	0.16	5.94	9.80	2.61	0.31	0.24	n.a	1954	1029	0.10	50.07
	SOP-08-429		51.19	1.01	18.83	10.52	0.24	5.99	9.65	2.41	0.39	0.24	n.a	1847	1105	0.10	50.39
	SOP-08-610		49.98	1.12	18.57	10.49	0.13	5.99	10.43	2.99	0.50	0.17	0.00	426	2763	0.11	50.46
	SOP-08-610		49.99	1.11	18.91	10.49	0.07	6.04	10.10	2.95	0.40	0.17	0.00	450	1320	0.11	50.65

Inclusions	Sample ID	Wt. %	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	"H ₂ O"	Mg#
	SOP-08-610		50.96	0.00	18.74	10.64	0.16	6.22	10.53	3.13	0.41	0.14	0.05	417	7837	0.10	51.05
	SOP-08-611		50.32	0.83	19.79	10.51	0.11	5.70	10.12	2.73	0.31	0.10	0.00	1993	1201	0.10	49.17
	SOP-08-611		50.44	0.63	19.89	10.55	0.09	5.88	10.25	2.33	0.21	0.14	0.00	2024	0	0.10	49.83
	SOP-08-611		50.10	0.88	19.72	10.58	0.20	5.87	10.58	2.17	0.31	0.12	0.00	2222	772	0.10	49.70
	SOP-08-612		52.46	0.88	18.00	10.49	0.18	5.81	9.01	2.80	0.39	0.27	0.04	749	983	0.11	49.66
	SOP-08-612		53.10	0.00	18.57	10.59	0.11	5.96	8.30	2.99	0.28	0.26	0.02	771	0	0.10	50.09
	SOP-08-612		52.34	1.09	18.06	10.49	0.15	5.68	8.82	3.13	0.38	0.19	0.00	908	1418	0.11	49.14
	SOP-08-614		49.55	0.92	19.24	10.68	0.24	6.23	11.55	2.55	0.18	0.11	0.00	2255	7882	0.10	50.96
	SOP-08-614		51.91	0.00	20.78	10.53	0.19	6.56	7.76	2.33	0.28	0.12	0.02	2254	0	0.08	52.64
	SOP-08-614		49.32	0.89	19.15	10.66	0.16	6.27	11.49	2.30	0.23	0.09	0.00	2292	1052	0.10	51.18
	SOP-08-615		52.07	0.75	17.32	11.88	0.22	6.10	8.12	3.37	0.37	0.12	0.06	784	926	0.13	47.78
	SOP-08-615		52.93	0.85	17.42	10.96	0.24	5.71	8.56	3.10	0.36	0.11	0.00	665	1088	0.12	48.15
	SOP-08-615		52.17	0.80	18.15	10.99	0.23	5.72	8.64	3.01	0.41	0.17	0.03	590	1351	0.12	48.11
	SOP-08-616		53.23	0.99	18.26	10.51	0.27	4.58	8.70	3.22	0.40	0.18	0.00	1078	1137	0.12	43.73
	SOP-08-616		53.09	1.10	18.18	10.50	0.16	4.58	9.09	3.09	0.37	0.12	0.00	946	1029	0.12	43.74
	SOP-08-616		53.39	0.90	18.19	10.51	0.10	4.63	9.12	3.02	0.33	0.12	0.00	811	1351	0.11	44.00
	SOP-08-618		49.13	0.89	19.33	10.65	0.18	6.10	11.47	2.36	0.17	0.20	0.02	1712	1249	0.10	50.51
	SOP-08-618		48.80	0.98	19.20	10.60	0.09	6.00	12.06	2.35	0.17	0.12	0.00	1660	576	0.11	50.23
	SOP-08-618		49.45	1.00	19.29	10.51	0.17	6.05	11.47	2.20	0.24	0.10	0.00	1889	890	0.10	50.64

Grondmass	Sample ID	Wt. %	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	S (ppm)	Cl (ppm)	Total	Mg#
	GM-4		56.08	1.78	12.65	12.91	0.26	6.21	6.78	2.54	0.48	0.32	11	0	100	46.15
			57.15	1.58	13.56	11.38	0.33	5.10	7.07	3.80	0.66	0.26	87	7819	101	44.42
			56.64	1.22	12.27	12.78	0.30	6.03	7.03	2.93	0.73	0.21	43	1455	100	45.70

Stabdard	Sample ID	Wt. %	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	S (ppm)	Cl (ppm)
	VG-2		51.44	1.96	14.31	11.48	0.19	6.79	10.72	2.62	0.24	0.26	100	1178	183
	VG-2		51.49	1.88	14.14	11.36	0.30	6.82	10.97	2.63	0.17	0.23	100	1310	333
	FO83		39.82	0.00	0.04	17.33	0.37	42.38	0.02	0.02	0.01	0.02	100	0	0
	FO90		41.78	0.00	0.03	9.64	0.08	48.33	0.11	0.01	0.00	0.02	100	10	0
	MAGT		0.00	0.21	0.10	99.54	0.03	0.08	0.00	0.03	0.00	0.02	100	154	416
	BHVO-2G		50.56	2.77	13.81	11.36	0.14	7.13	11.30	2.12	0.45	0.35	100	0	61

Table B.4. The average values of each melt inclusion's major element and volatile compositions

SOPF-0101

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O
<i>n</i> = 2	51.89	0.92	19.84	9.54	0.17	4.58	9.84	3.02	0.34
<i>St.dev.</i>	0.12	0.01	0.04	0.00	0.04	0.03	0.14	0.19	0.05
P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s		
0.16	0.00	981	982	46.10	3.05	292.87	yes		
0.01	0.00	51.62	89.10	0.17	0.31	122.84			

SOPF-0102

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O
<i>n</i> = 2	49.21	1.23	19.12	9.80	0.14	5.92	11.85	2.73	0.33
<i>St.dev.</i>	0.42	0.09	0.37	0.42	0.07	0.27	0.34	0.23	0.03
P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s		
0.28	0.01	2370	n.d	51.87	4.35	625.12	yes		
0.01	0.01	14.14	n.d	0.08	0.05	19.94			

SOPF-0104

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O
n = 2	48.21	0.91	20.19	9.81	0.17	6.35	12.20	2.35	0.22
<i>St.dev.</i>	0.01	0.05	0.17	0.07	0.02	0.04	0.08	0.07	0.08
P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s		
0.09	0.03	1815	885	53.58	4.42	793.73	no		
0.01	0.04	255.27	79.90	0.01	0.15	39.98			

SOPF-0109

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O
n = 2	55.50	1.32	17.00	9.83	0.21	4.28	8.17	3.30	0.49
<i>St.dev.</i>	0.15	0.02	0.09	0.14	0.08	0.12	0.15	0.25	0.03
P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s		
0.18	0.02	649	1237	43.71	3.47	50<	yes		
0.01	0.03	24.75	193.75	0.32	0.03				

SOPF-0111

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O
<i>n</i> = 2	52.03	0.58	18.41	11.85	0.22	5.23	8.67	3.01	0.30
<i>St.dev.</i>	0.41	0.08	0.84	0.08	0.02	0.03	0.29	0.01	0.03
P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s		
0.09	0.02	1471	n.d	44.01	4.04	1233.86	yes		
0.00	0.01	27.58	n.d	0.01	0.03	9.47			

SOPF-0114

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O
<i>n</i> = 2	54.90	1.31	17.28	9.52	0.17	4.71	8.01	3.53	0.58
<i>St.dev.</i>	0.31	0.01	0.05	0.07	0.13	0.03	0.10	0.04	0.02
P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s		
0.18	0.04	545	n.d	46.85	3.29	c.d.	yes		
0.01	0.05	44.55	n.d	0.04	0.06				

SOPF-0402a

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O
<i>n</i> = 2	52.65	0.77	18.33	10.88	0.23	4.69	8.72	3.45	0.41
<i>St.dev.</i>	0.21	0.26	0.40	0.12	0.08	0.11	0.51	0.08	0.11
P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s		
0.18	0.05	1108	n.d	43.44	3.75	917.98	yes		
0.03	0.07	6.36	n.d	0.30	0.10	68.32			

SOPF-0402b

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O
<i>n</i> = 2	51.50	1.13	17.14	12.18	0.25	5.36	9.67	2.65	0.27
<i>St.dev.</i>	0.74	0.05	0.48	0.13	0.00	0.02	0.17	0.02	0.06
P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s		
0.15	0.02	989	861	43.98	0.80	c.d.	no		
0.02	0.00	88.39	159.81	0.14	0.01				

SOPF-0406

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O
<i>n</i> = 2	48.38	0.88	18.95	11.32	0.17	5.47	11.86	2.92	0.27
<i>St.dev.</i>	0.33	0.01	0.25	0.19	0.06	0.13	0.35	0.13	0.12
P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s		
0.11	0.06	1339	n.d	46.26	1.50	525.22	yes		
0.02	0.07	14.14	n.d	0.17	0.03	116.60			

SOPF-0407

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O
<i>n</i> = 2	48.68	0.99	18.18	11.84	0.23	5.75	11.58	2.84	0.29
<i>St.dev.</i>	0.48	0.02	0.12	0.32	0.13	0.10	0.07	0.03	0.10
P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s		
0.17	0.06	1947	855	46.39	1.15	c.d.	yes		
0.04	0.02	60.81	110.31	0.25	0.01				

SOPF-0408

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O
<i>n</i> = 2	50.05	0.74	18.63	11.75	0.23	6.02	10.35	2.34	0.19
<i>St.dev.</i>	0.36	0.07	0.05	0.10	0.04	0.00	0.02	0.19	0.05
P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s		
0.10	0.00	1730	n.d	47.73	3.00	450.83	yes		
0.04	0.00	45.25	n.d	0.20	0.03	24.29			

SOPF-0409

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O
<i>n</i> = 2	52.76	1.31	18.07	10.72	0.25	4.30	8.52	3.67	0.51
<i>St.dev.</i>	0.45	0.05	0.18	0.37	0.11	0.13	0.10	0.04	0.12
P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s		
0.13	0.01	623	1043	41.67	1.16	83.62	yes		
0.01	0.02	144.25	180.31	0.11	0.00	7.51			

SOPF-0410

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O
<i>n</i> = 2	52.96	0.93	18.86	10.13	0.18	4.63	8.94	3.22	0.32
<i>St.dev.</i>	1.21	0.03	0.10	1.20	0.07	0.55	0.28	0.18	0.06
P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s		
0.16	0.02	1342	n.d	44.90	2.60	50<	yes		
0.01	0.03	81.32	n.d	0.01	0.10				

SOPF-0411

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O
<i>n</i> = 2	52.12	1.36	16.65	12.03	0.17	4.91	9.21	3.19	0.44
<i>St.dev.</i>	0.38	0.06	0.56	0.62	0.01	0.21	0.12	0.07	0.04
P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s		
0.15	0.00	847	n.d	42.11	0.60	50<	yes		
0.00	0.00	8.49	n.d	0.20	0.02				

SOPF-0412

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O
<i>n</i> = 2	53.09	0.78	18.56	10.36	0.18	5.10	9.03	2.77	0.29
<i>St.dev.</i>	0.47	0.09	0.07	0.24	0.01	0.09	0.09	0.02	0.03
P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s		
0.15	0.00	1243	n.d	46.76	3.99	50<	yes		
0.00	0.00	135.06	n.d	0.12	0.08				

SOPF-0603

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O
<i>n</i> = 3	51.59	1.20	19.57	9.87	0.22	3.98	9.26	3.87	0.48
<i>St.dev.</i>	0.06	0.06	0.29	0.04	0.01	0.03	0.23	0.09	0.08
P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s		
0.14	0.01	677	n.d	41.83	1.33	c.d.	yes		
0.03	0.01	45.54	n.d	0.12	0.03				

SOPF-0605

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O
<i>n</i> = 3	50.44	0.78	18.48	12.06	0.15	5.74	9.72	2.89	0.45
<i>St.dev.</i>	1.15	0.01	0.84	2.87	0.05	1.42	1.36	0.30	0.06
P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s		
0.13	0.08	1564	n.d	45.86	1.29	c.d.	no		
0.06	0.04	255.27	n.d	0.23	0.04				

SOPF-0606

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O
<i>n</i> = 3	49.10	0.88	20.10	9.80	0.14	5.62	12.39	2.17	0.25
<i>St.dev.</i>	0.06	0.06	0.23	0.06	0.07	0.01	0.09	0.14	0.05
P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s		
0.10	0.03	1945	n.d	50.54	3.60	c.d.	yes		
0.04	0.03	87.90	n.d	0.17	0.03				

SOPF-0607

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O
<i>n</i> = 3	49.99	0.66	19.89	9.81	0.22	6.05	10.60	2.73	0.30
<i>St.dev.</i>	2.34	0.41	1.07	0.07	0.05	0.20	3.33	0.16	0.03
P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s		
0.13	0.00	1903	0	52.37	2.41	438.05	yes		
0.05	0.00	20.13	0.00	0.91	0.03	22.01			

SOPF-0612

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O
<i>n</i> = 3	49.95	0.84	19.34	10.95	0.18	5.87	11.21	2.22	0.24
<i>St.dev.</i>	0.41	0.08	0.12	0.35	0.06	0.18	0.26	0.12	0.06
P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s		
0.10	0.01	2047	n.d	48.86	2.74	106.93	yes		
0.02	0.01	169.05	n.d	0.20	0.43	12.04			

SOPF-0613

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O
<i>n</i> = 3	51.61	0.81	19.43	9.89	0.13	5.95	9.77	3.65	0.38
<i>St.dev.</i>	0.44	0.09	0.24	0.12	0.01	0.13	0.31	0.28	0.09
P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s		
0.20	0.01	1712	n.d	51.72	2.11	50<	yes		
0.04	0.02	71.97	n.d	0.44	0.01				

SOPF-0615

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O
<i>n</i> = 3	48.97	0.88	20.08	10.66	0.22	6.19	11.94	2.41	0.22
<i>St.dev.</i>	0.73	0.05	0.56	0.31	0.13	0.14	0.11	0.11	0.02
P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s		
0.10	0.07	1853	n.d	50.87	4.05	72.72	yes		
0.02	0.06	56.30	n.d	0.17	0.04	2.37			

SOPF-0801

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O
<i>n</i> = 3	49.88	0.59	19.12	11.65	0.24	5.69	10.68	2.24	0.26
<i>St.dev.</i>	0.41	0.04	0.41	0.61	0.05	0.30	0.09	0.16	0.06
P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s		
0.10	0.02	1873	n.d	46.55	4.04	516.96	yes		
0.03	0.03	132.30	n.d	0.02	0.01	13.37			

SOPF-0802

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O
<i>n</i> = 3	50.32	0.61	20.21	11.08	0.17	5.58	10.18	2.29	0.21
<i>St.dev.</i>	0.08	0.05	0.60	0.20	0.04	0.14	0.04	0.16	0.02
P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s		
0.10	0.05	1801	n.d	47.32	2.60	608.53	yes		
0.02	0.05	135.63	n.d	0.16	0.14	16.85			

SOPF-0803

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O
<i>n</i> = 3	49.24	1.13	18.87	10.48	0.12	5.43	11.24	3.17	0.42
<i>St.dev.</i>	0.14	0.03	0.22	0.01	0.04	0.04	0.09	0.08	0.12
P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s		
0.15	0.01	798	n.d	48.02	0.84	c.d.	yes		
0.01	0.01	105.65	n.d	0.19	0.02				

SOPF-0805

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O
<i>n</i> = 3	53.97	0.76	16.29	11.43	0.24	5.34	8.64	2.94	0.48
<i>St.dev.</i>	0.39	0.66	0.26	0.12	0.08	0.12	0.04	0.07	0.08
P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s		
0.18	0.03	634	n.d	45.42	0.68	183.03	yes		
0.06	0.03	29.26	n.d	0.35	0.01	25.46			

SOPF-0806

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O
<i>n</i> = 3	53.62	0.83	16.82	11.86	0.20	4.91	8.49	3.02	0.39
<i>St.dev.</i>	0.24	0.07	0.26	0.02	0.05	0.02	0.28	0.04	0.11
P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s		
0.21	0.03	1145	n.d	42.45	4.19	50<	yes		
0.04	0.06	168.77	n.d	0.14	0.10				

SOPF-0812

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O
<i>n</i> = 3	54.46	0.86	16.86	10.97	0.28	4.63	8.39	3.19	0.36
<i>St.dev.</i>	1.28	0.45	0.38	0.88	0.02	0.31	0.33	0.11	0.04
P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s		
0.19	0.00	559	n.d	42.96	1.10	6.92	yes		
0.00	0.00	158.51	n.d	0.36	0.02	0.75			

SOPF-0108									SOP-01-210

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O
<i>n</i> = 2	49.12	1.43	19.81	10.44	0.21	5.98	10.18	2.86	<i>n</i> = 3	50.89	0.81	19.42	10.87	0.24	5.59	9.59	2.51
<i>St.dev.</i>	0.18	0.13	0.20	0.34	0.04	0.15	0.12	0.18	<i>St.dev.</i>	0.38	0.14	0.30	0.41	0.06	0.19	0.23	0.03
K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s
0.25	0.16	0.03	1534	n.d	50.55	0.11	n.a.	no	0.27	0.17	0.00	1435	713	47.82	0.11	n.a.	yes
0.03	0.01	0.00	81.32	n.d	0.18				0.04	0.01	0.00	86.69	46	0.17			
SOP-01-215									SOP-01-319

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O
<i>n</i> = 3	52.44	0.64	19.26	10.44	0.22	4.96	9.31	2.53	<i>n</i> = 3	48.69	1.10	20.11	9.54	0.20	5.24	12.67	2.37
<i>St.dev.</i>	0.68	0.26	0.13	0.51	0.04	0.24	0.10	0.21	<i>St.dev.</i>	0.17	0.03	0.08	0.02	0.00	0.06	0.05	0.21
K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s
0.26	0.22	0.00	998	932	45.83	0.10	n.a.	yes	0.27	0.15	0.00	1255	961	49.49	0.10	n.a.	yes
0.13	0.02	0.00	84.02	180	0.10				0.10	0.05	0.00	41.76	119	0.28			

SOP-01-320									SOP-01-323
Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O
n = 3	52.03	1.10	17.25	11.60	0.20	5.66	9.35	2.59	n = 3	53.81	0.90	16.78	12.82	0.30	5.11	6.60	3.42
St.dev.	0.42	0.04	0.25	0.21	0.08	0.10	0.29	0.09	St.dev.	0.38	0.09	0.35	0.21	0.04	0.12	0.13	0.27
K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s
0.35	0.17	0.00	1033	876.33	46.52	0.13	n.a.	no	0.48	0.15	0.00	1259	1127	41.52	0.15	n.a.	yes
0.10	0.02	0.00	179.24	112	0.14				0.10	0.01	0.00	192.42	180	0.28			
SOP-01-327									SOP-01-433
Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O
n = 3	49.43	0.46	18.53	12.87	0.20	5.99	10.36	2.24	n = 3	51.17	1.10	17.48	11.92	0.29	5.19	9.86	2.78
St.dev.	0.42	0.15	0.05	0.41	0.07	0.21	0.10	0.17	St.dev.	1.10	0.13	0.42	0.52	0.06	0.22	0.52	0.18
K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s
0.20	0.09	0.00	1431	858	45.34	0.13	n.a.	yes	0.35	0.16	0.00	1006	1108	43.68	0.14	n.a.	yes
0.06	0.04	0.00	165.50	212	0.10				0.04	0.02	0.00	156.93	248	0.39			

SOP-01-501									SOP-04-101

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O
n = 2	50.69	0.85	21.36	9.69	0.14	5.19	11.04	2.54	n = 3	48.17	1.08	19.87	9.86	0.17	5.61	12.77	2.52
St.dev.	0.15	0.20	1.18	0.00	0.03	0.01	1.35	0.22	St.dev.	0.27	0.02	0.38	0.51	0.05	0.25	0.21	0.11
K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s
0.17	0.10	0.03	2376	n.d	48.81	0.09	n.a.	yes	0.31	0.13	0.00	1893	1121	50.37	0.10	n.a.	no
0.13	0.01	0.04	566.39	n.d	0.05				0.04	0.00	0.00	175.03	93	0.21			
SOP-04-214									SOP-04-501

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O
n = 2	49.51	0.97	19.46	10.63	0.18	5.79	10.36	2.95	n = 3	53.36	0.66	18.87	9.21	0.13	5.74	8.35	3.33
St.dev.	0.68	0.01	0.06	0.40	0.06	0.10	0.10	0.28	St.dev.	1.07	0.42	0.38	0.33	0.04	0.17	0.67	0.19
K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s
0.35	0.13	0.00	1222	940	49.28	0.11	n.a.	yes	0.39	0.18	0.02	707	n.d	52.63	0.09	n.a.	yes
0.00	0.03	0.00	3.54	250	0.49				0.13	0.01	0.03	15.31	n.d	0.31			

SOP-04-502									SOP-04-503

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O
n = 5	52.04	0.81	18.14	11.62	0.29	5.19	9.19	2.67	n = 3	50.86	0.71	18.79	11.18	0.23	5.56	9.74	2.70
St.dev.	0.78	0.21	0.35	0.67	0.11	0.30	0.40	0.14	St.dev.	0.41	0.45	0.27	0.65	0.04	0.49	0.57	0.30
K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s
0.23	0.15	0.00	1439	n.d	44.34	0.12	n.a.	yes	0.33	0.17	0.02	919	n.d	46.94	0.11	n.a.	no
0.07	0.02	0.01	104.19	n.d	0.17				0.10	0.02	0.04	74.88	n.d	0.73			
SOP-04-504									SOP-04-506

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O
n = 3	50.32	0.48	18.72	11.56	0.27	5.85	10.73	2.18	n = 3	50.80	0.91	19.62	11.28	0.20	6.11	9.39	2.38
St.dev.	0.13	0.07	0.12	0.29	0.05	0.16	0.16	0.09	St.dev.	0.89	0.10	0.63	0.31	0.04	0.20	1.98	0.09
K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s
0.19	0.13	0.01	1835	n.d	47.44	0.11	n.a.	yes	0.22	0.08	0.02	1784	n.d	49.11	0.11	n.a.	no
0.03	0.01	0.01	51.26	n.d	0.07				0.03	0.03	0.02	217.42	n.d	0.31			

SOP-04-507									SOP-04-508

Wt. %	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	Wt. %	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O
n = 3	52.91	0.40	17.45	11.86	0.26	5.35	9.10	2.77	n = 3	52.97	0.28	19.61	10.49	0.25	4.63	9.41	2.79
St.dev.	0.60	0.19	0.52	0.26	0.05	0.06	0.09	0.14	St.dev.	0.25	0.06	0.14	0.14	0.02	0.10	0.26	0.18
K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s
0.21	0.12	0.01	1373	n.d	44.59	0.12	n.a.	yes	0.27	0.13	0.01	2162	n.d	44.01	0.10	n.a.	yes
0.05	0.01	0.01	71.97	n.d	0.32				0.09	0.03	0.02	190.53	n.d	0.29			
SOP-06-212									SOPF-0614

Wt. %	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	Wt. %	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O
n = 3	53.75	0.63	19.08	9.80	0.10	4.72	7.25	4.23	n = 3	50.04	0.87	19.66	9.96	0.20	4.73	12.52	3.09
St.dev.	0.29	0.14	0.08	0.11	0.04	0.06	0.13	0.18	St.dev.	0.65	0.30	0.51	0.09	0.07	0.05	0.54	0.26
K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s
0.48	0.20	0.00	431	1714	46.19	0.11	n.a.	yes	0.34	0.15	0.04	1396	n.d	45.85	0.11	n.a.	yes
0.07	0.01	0.00	65.05	253	0.26				0.12	0.02	0.03	179.57	n.d	0.40			

SOP-06-217									SOP-06-320

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O
n = 3	52.35	0.83	19.24	9.91	0.20	4.97	10.13	2.22	n = 3	50.44	0.76	18.63	11.70	0.25	5.73	10.16	2.27
St.dev.	0.41	0.08	0.19	0.34	0.01	0.14	0.22	0.14	St.dev.	0.32	0.06	0.30	0.36	0.07	0.13	0.06	0.07
K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s
0.31	0.21	0.00	1445	902.67	47.18	0.09	n.a.	yes	0.32	0.11	0.00	1507	701.67	46.61	0.12	n.a.	no
0.07	0.08	0.00	69.87	104	0.24				0.13	0.02	0.00	145.19	69	0.26			
SOP-06-321									SOP-06-431

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O
n = 3	49.73	0.61	19.91	9.75	0.16	6.15	11.61	2.24	n = 3	49.53	1.01	20.13	9.73	0.19	5.79	11.43	2.19
St.dev.	0.23	0.13	0.05	0.00	0.05	0.05	0.22	0.11	St.dev.	0.17	0.09	0.32	0.03	0.08	0.04	0.12	0.07
K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s
0.24	0.11	0.00	2054	886.00	52.92	0.09	n.a.	yes	0.25	0.17	0.00	1695	859.67	51.46	0.09	n.a.	no
0.01	0.04	0.00	105.19	60	0.19				0.12	0.03	0.00	85.14	90	0.16			

SOP-06-503									SOP-06-506

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O
n = 2	50.95	1.01	19.15	10.69	0.21	6.01	10.73	2.48	n = 3	49.58	1.09	19.63	9.84	0.15	6.04	11.31	2.61
St.dev.	0.82	0.09	0.11	0.13	0.07	0.04	0.20	0.18	St.dev.	0.18	0.04	0.21	0.08	0.03	0.06	0.11	0.05
K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s
0.26	0.14	0.01	3467	n.d	50.07	0.10	n.a.	no	0.25	0.10	0.05	1662	n.d	52.27	0.10	n.a.	yes
0.08	0.05	0.01	1965	n.d	0.49				0.03	0.03	0.02	27.30	n.d	0.04			
SOP-06-507									SOP-06-508

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O
n = 3	51.12	1.35	19.93	9.88	0.18	4.34	10.35	3.90	n = 3	48.54	1.03	18.90	10.36	0.16	5.83	12.69	2.79
St.dev.	0.63	0.04	0.30	0.13	0.05	0.05	0.10	0.16	St.dev.	0.06	0.08	0.49	0.21	0.05	0.13	0.19	0.13
K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s
0.40	0.22	0.01	303	n.d	43.92	0.12	n.a.	yes	0.31	0.12	0.09	1725	n.d	50.08	0.11	n.a.	yes
0.03	0.01	0.01	45.49	n.d	0.18				0.11	0.02	0.00	112.64	n.d	0.16			

SOP-06-509									SOPF-0813
Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O
n = 3	52.96	0.85	19.74	10.38	0.13	4.81	6.78	3.90	n = 3	49.28	1.21	19.79	10.49	0.19	6.28	10.04	2.63
St.dev.	3.62	0.74	1.45	0.54	0.02	0.26	3.90	0.13	St.dev.	0.34	0.06	0.33	0.01	0.04	0.02	0.29	0.14
K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s
0.47	0.22	0.02	949	n.d	45.27	0.12	n.a.	yes	0.29	0.18	0.05	1528	n.d	51.63	0.10	n.a.	yes
0.10	0.05	0.02	48.42	n.d	0.06				0.06	0.03	0.04	185.88	n.d	0.06			
SOP-08-104									SOP-08-107
Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O
n = 3	47.98	1.03	18.57	11.04	0.16	5.85	12.55	2.83	n = 2	50.13	1.22	18.59	11.48	0.19	5.42	9.91	2.85
St.dev.	0.32	0.10	0.14	0.08	0.01	0.07	0.15	0.15	St.dev.	0.01	0.09	0.11	0.00	0.09	0.01	0.03	0.10
K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s
0.27	0.17	0.00	1726	1034	48.57	0.12	n.a.	yes	0.34	0.16	0.00	804	1173	45.70	0.13	n.a.	yes
0.08	0.02	0.00		156	0.15				0.10	0.05	0.00	41.72	157	0.05			

SOP-08-212									SOP-08-213

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O
n = 3	48.54	1.01	18.67	10.52	0.13	6.09	12.13	2.85	n = 6	48.86	0.93	19.13	12.00	0.18	5.10	10.85	2.79
St.dev.	0.36	0.10	0.17	0.02	0.04	0.03	0.14	0.07	St.dev.	0.49	0.17	0.16	0.18	0.06	0.06	0.15	0.06
K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s
0.34	0.10	0.00	1351	1057	50.77	0.11	n.a.	yes	0.33	0.14	0.00	1139	943	43.08	0.14	n.a.	no
0.06	0.01	0.00	79.78	206	0.16				0.06	0.03	0.00	103.91	169	0.24			
SOP-08-214									SOP-08-216

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O
n = 3	48.97	0.96	18.89	11.88	0.22	5.13	11.45	2.34	n = 4	54.51	1.75	13.45	12.86	0.25	4.62	7.71	3.23
St.dev.	0.25	0.12	0.17	0.18	0.04	0.09	0.07	0.10	St.dev.	0.49	0.17	0.17	0.28	0.05	0.09	0.12	0.24
K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s
0.35	0.13	0.00	1217	765	43.48	0.13	n.a.	yes	0.96	0.84	0.00	120	1548	39.04	0.20	n.a.	no
0.04	0.04	0.00	31.01	193	0.11				0.12	0.07	0.00	115.35	214	0.46			

SOP-08-217									SOP-08-428
Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O
n = 3	49.75	0.65	18.58	12.43	0.19	5.09	10.21	2.97	n = 2	51.92	0.90	17.72	12.24	0.31	5.47	8.53	2.53
St.dev.	0.29	0.05	0.19	0.20	0.09	0.08	0.14	0.04	St.dev.	0.39	0.05	0.05	0.04	0.04	0.06	0.08	0.05
K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s
0.33	0.12	0.00	998	1136	42.18	0.14	n.a.	yes	0.49	0.18	0.00	930	996	44.33	0.13	n.a.	no
0.04	0.06	0.00	74.85	70	0.03				0.24	0.01	0.00	68.59	31	0.35			
SOP-08-429									SOP-08-610
Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O
n = 3	50.79	0.96	19.14	10.53	0.21	5.96	9.82	2.51	n = 3	50.31	0.74	18.74	10.54	0.12	6.09	10.35	3.02
St.dev.	0.35	0.08	0.27	0.02	0.04	0.03	0.18	0.10	St.dev.	0.56	0.64	0.17	0.09	0.05	0.12	0.23	0.09
K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s
0.33	0.23	0.00	1893	1041.33	50.23	0.10	n.a.	no	0.44	0.16	0.02	431	n.d	50.72	0.11	n.a.	yes
0.06	0.02	0.00		58	0.16				0.06	0.02	0.03	17.06	n.d	0.30			

SOP-08-611									SOP-08-612

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O
n = 3	50.29	0.78	19.80	10.55	0.13	5.82	10.32	2.41	n = 3	52.63	0.66	18.21	10.52	0.15	5.82	8.71	2.97
St.dev.	0.17	0.13	0.09	0.03	0.06	0.10	0.24	0.29	St.dev.	0.41	0.58	0.32	0.06	0.04	0.14	0.37	0.16
K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s
0.27	0.12	0.00	2080	n.d	49.57	0.10	n.a.	yes	0.35	0.24	0.02	809	n.d	49.63	0.11	n.a.	yes
0.05	0.02	0.00	124.23	n.d	0.35				0.06	0.04	0.02	86.15	n.d	0.48			
SOP-08-614									SOP-08-615

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O
n = 3	50.26	0.60	19.73	10.62	0.20	6.35	10.27	2.40	n = 3	52.39	0.80	17.63	11.27	0.23	5.84	8.44	3.16
St.dev.	1.43	0.52	0.92	0.08	0.04	0.18	2.17	0.13	St.dev.	0.47	0.05	0.45	0.52	0.01	0.22	0.28	0.19
K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s
0.23	0.11	0.01	2267	n.d	51.59	0.10	n.a.	yes	0.38	0.13	0.03	680	1122	48.01	0.12	n.a.	no
0.05	0.01	0.01	21.66	n.d	0.91				0.03	0.03	0.03	97.83	214	0.21			

SOP-08-616

SOP-08-618

Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	Wt.%	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O
n = 3	53.24	1.00	18.21	10.50	0.18	4.60	8.97	3.11	n = 3	49.13	0.96	19.28	10.59	0.15	6.05	11.67	2.30
St.dev.	0.15	0.10	0.04	0.00	0.08	0.03	0.24	0.10	St.dev.	0.32	0.06	0.06	0.07	0.05	0.05	0.34	0.09
K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s	K ₂ O	P ₂ O ₅	NiO	S (ppm)	Cl (ppm)	Mg#	H ₂ O	CO ₂	Bubble/s
0.36	0.14	0.00	945	1172	43.82	0.12	n.a.	yes	0.19	0.14	0.01	1754	n.d	50.46	0.10	n.a.	yes
0.04	0.04	0.00	133.50	164	0.15				0.04	0.05	0.01	120	n.d	0.21			