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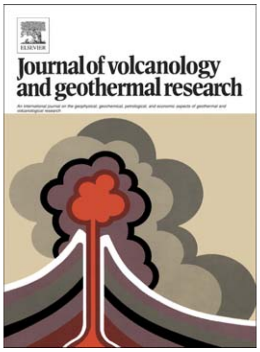

Magma dynamics during the 2007 Stromboli eruption (Aeolian Islands. Italy): Mineralogical, geochemical and isotopic data

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Magma dynamics during the 2007 Stromboli eruption (Aeolian Islands. Italy) : mineralogical, geochemical and isotopic data"

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Abstract

After the 6 month-long effusive event of 2002-2003, a new lava effusion occurred at Stromboli between 27 February and 2 April 2007. Despite the different durations, approximately the same volume of magma was emitted in both eruptions, in the order of 10^7 m^3. A paroxysmal eruption occurred at the summit craters in both the 2002-2003 and 2007 episodes, during which a significant amount of low porphyritic (LP), volatile-rich magma was erupted. In both cases, the paroxysms did not interrupt the lava emission. Here, we present compositional data, including texture, mineralogy, chemistry and Sr and Nd isotope ratios of bulk-rock, groundmass and separated minerals of lavas erupted in 2007, together with chemistry and Sr and Nd isotope composition of the pumices emitted during the 15 March paroxysm. As a whole, the lavas have the same texture and chemistry that characterize the highly porphyritic (HP) products usually erupted at Stromboli during normal Strombolian activity and effusive events. Compared to the previous HP products, the 2007 lavas show minor but systematic mineralogical and isotopic variations which are consistent with a modest increase of the magma supply rate of the volcano. Compositional variations during the entire duration of the event are very modest. Glass chemistry changes in lavas erupted in the second half of March can be explained by the minor mixing between the volatile-rich LP magma rising through the shallow magmatic system during the 15 March paroxysm and the degassed residing HP magma. A first conclusion of this study is that there is no compositional evidence supporting major changes in the magma dynamics of the volcano accompanying the effusive activity, as also suggested for the 2002-2003 event. The activity of Stromboli is controlled by a steady state feeding system in which refilling, mixing, degassing and crystallization at shallow level continuously operate, with modest oscillations in the magma supply rate. Switching between normal Strombolian and effusive activity is related to periods of relatively more vigorous refilling of the shallow system, leading to progressive pressure increase in the upper conduits associated with only minor compositional variations in the erupted products.

Keywords: Stromboli volcano, petrological monitoring, steady-state system, geochemistry, mineralogy, Sr-Nd isotopes.

Introduction

The renewal of the eruptive vigor in basaltic volcanoes in persistent or quasi-persistent state of activity is commonly associated with changes in chemical and/or textural characteristics of the erupted magmas, both correlated with shallow magma dynamics, changes in geochemical parameters and edifice deformation (Garcia et al., 2000; Thornber, 2003; Corsaro and Pompilio, 2004; Vlastelic et al., 2005). Reactivation or increase in the volcanic activity may also occur without any evident variations in the chemistry of the erupted products. However, a careful analytical investigation often highlights trace element and/or isotopic changes that, even if slight, can be a sign of a relevant modification in the magma dynamics (Landi et al., 2006; Schiavi et al., 2006). Several studies reveal that the magmas feeding these kinds of volcanoes usually show short and long-time compositional changes, depending on the structure of the plumbing system, the recharge history of magma reservoir and the interplay between the deeper and the shallow part of the feeding system (Garcia et al., 1988; Garcia et al., 2000; Thornber, 2003; Corsaro and Pompilio, 2004; Vlastelic et al., 2005). Only a prolonged petro-chemical monitoring, with systematic sampling of the erupted products, associated with detailed studies of their texture, chemical and isotopic composition, can reveal chemical trends in time that allow understanding the behaviour of the magmatic plumbing system and forecasting its evolution.

Stromboli (Fig. 1), Aeolian islands, Southern Italy, is one of the most active, best-studied and best-monitored volcanoes in the world. Gas geochemistry and geophysical data have been collected nearly continuously by the staff of the Istituto Nazionale di Geofisica e Vulcanologia (INGV). In addition, previous field, petrologic, geochemical and geophysical studies have established the basic structure of the magmatic plumbing system [this volume and Calvari et al., 2008 and references therein). Thus, many of the basic parameters necessary to understand the magma dynamics which control both the behaviour of the volcano and the occasional changes in its state of activity, are available in the literature.

The last effusive activity started on 27 February 2007 and continued up to 2 April 2007. It occurred 3 years and 7 months after the end of the previous one (December 2002-July 2003) and offered the chance to perform, for the second time in few years, a systematic sampling of the products emitted during the entire eruptive crisis. Here, we present textural, mineralogical, chemical and isotopical data for a set of samples collected during the entire duration of the eruption. Compositional data available in literature on a suite of about 300 samples collected over the past 25 years, represent a robust data set that also enables observing minor compositional variations possibly associated with changes in eruptive stile. Moreover, the comparison of petrological studies with geophysical and geochemical data, collected during the 2002-2003 and the 2007 effusive eruptions, gives the opportunity to learn about the magma feeding system operating during an effusive episode at Stromboli and to make inferences on its future evolution and related volcanic activity.

Background

Stromboli, the northernmost island of the Aeolian archipelago in Italy, is regarded as a typical example of a basaltic volcano with steady behaviour, thanks to the persistence of its Strombolian explosive activity over the past 1400-1800 years (Rosi et al., 2000), and the continuous streaming of gas from the summit craters with an estimated output of 6-12x10^3 tons/day (Allard et al., 1994). The active craters are located in the upper part of the Sciara del Fuoco, a horseshoe depression resulting from several flank collapses which have affected the NE flank of the volcano over the past 13,000 years (Pasquaré et al., 1993; Tibaldi, 2001) (Fig. 1). Typical Strombolian activity (hereafter normal Strombolian activity) consists of intermittent mild explosions, commonly every 10-20 min, throwing scoriaceous bombs, lapilli and ash from ten to hundreds of meters above the craters. This activity is occasionally interrupted by more energetic events (paroxysms) lasting from some tens of seconds (Bertagnini et al. 1999) to several minutes (Rosi et al. 2006, Bertagnini et al. 2008) and throwing pumiceous and scoriaceous bombs, lapilli and ash from several hundred meters to a few kilometres above the craters. Lava effusion represents another type of activity of the volcano, which occasionally produces outpouring of lavas flowing onto the Sciara del Fuoco depression. Overflow from the active craters lasting from hours to days are included in this type of activity. However, the most voluminous lava effusions, with durations of several months, usually originate from vents opened some hundreds of meters below the craters. In recent decades, such events occurred in 1975 (3 months), 1985-86 (6 months) and 2002-2003 (6 months). The estimated volume of the emitted lavas was $7\text{x}10^2$, $6\text{x}10^6$ and $11\text{x}10^6$ m^3, respectively (Capaldi et al., 1978; De Fino et al., 1988; Calvari et al., 2005; Baldi e al., 2008; Marsella et al., 2008). This implies an average mass flux of around 0.2 m^3/sec during the 1985-1986 eruption and of 0.3 m^3/sec during the 2002-2003 effusive event, by assuming a maximum estimate of 50 vol% of bubbles and voids in the deposit. These values are considerably higher than the mass flux estimated for normal Strombolian activity, in the order $0.7*10^{-6}$ - $0.3*10^{-3}$ m^3/sec (Ripepe et al., 2008), assuming a magma density of 2700 Kg/m^3.

Two types of magmas with slightly different bulk composition (high-K and shoshonitic basalts) but with contrasting texture and matrix glass composition, feed the present-day activity at Stromboli: a highly porphyritic (HP), degassed shoshonitic-basalt, with ~50 vol% of phenocrysts (33 vol% of plagioclase An_{60-90}, 12 vol% of clinopyroxene Mg#0.73-0.91 and 5 vol% of olivine Fo_{70-73}, on average), residing in the upper part of the plumbing system and sustaining the normal Strombolian activity and the lava effusions, and a deeper volatile-rich high-K basalt with low content of phenocrysts (LP) (<5 vol% of olivine and clinopyroxene with higher MgO/FeO ratio than that of the crystals in the HP magma), emitted as pumiceous clasts only during the paroxysms (Rosi et al., 200; Métrich et al., 2001, Francalanci et al., 2004; Bertagnini et al., 2008). These two kinds of magma were first recognized thanks to systematic petrologic monitoring, in 1993 (Bonaccorso et al. 1996). Evidence of syn-eruptive mingling between LP and HP magmas in the paroxysms is ubiquitous. Products with intermediate textural and compositional characteristics appear to be exceptionally rare (Corsaro and Miraglia, 2005; Andronico et al., 2008; Landi et al., 2008b).

The origin of the HP shallow magma is mainly attributed to discrete intrusions of deep LP magma into the shallow reservoir(s), and its mixing with the HP residing magma (Francalanci et al., 1999; Landi et al., 2004). This induces mineral phase dissolution followed by crystallization chiefly driven by water loss at low pressure (Métrich et al., 2001; Landi et al., 2004; Francalanci et al., 2005). Actually, continuous mixing between these two magmas is well documented on the basis of textural, mineralogical, chemical and isotopic studies (Francalanci et al. 1999, 2004, 2005; Landi et al., 2004, 2006, 2008a; Armienti et al., 2007; Fornaciai et al., submitted). The shallow magma system is also affected by significant recycling of crystals deriving from old (possibly up to 10 ka ago) cumulus crystal mushes situated just below the volcanic edifice, as suggested by isotopic studies on bulk rocks and *in situ* Sr isotope microanalysis (Francalanci et al., 2005).

The refilling magma batches derive from volatile-rich parental melts, via crystal fractionation, at a lithostatic pressure of 200-300 MPa, corresponding to a depth of ~7.5-11 km, as determined from H_2O and CO_2 contents dissolved in melt inclusions within olivine of LP pumice (Métrich et al., 2001, 2005; Bertagnini et al., 2003). According to Vaggelli et al. (2003) and Francalanci et al. (2004, 2005), the mixing process between HP and LP magmas, concomitant with continuous crystallization of olivine, pyroxene and plagioclase, occurs in an intermediate reservoir at ~3 km depth, likely a remnant of an old Stromboli structure. Continuous refilling from depth of the shallow magma body, together with the continuous magma emission, determines the steady state of the plumbing system. Landi et al. (2004; 2008b) suggest a transitional zone, where processes possibly related to convection phenomena occur in the lower part of the shallow system ($P<50$ MPa) due to sinking of degassed, dense HP magma and its re-equilibration at higher volatile pressure. In this transitional zone, dissolution would play the main role, accompanied by minor crystallization. Following this interpretation, extensive crystallization of volatile rich magmas leading to the formation of the HP magma must be confined inside the volcano.

Whatever the realistic model, chemical and isotopic evidences together with chemical and textural zoning of the minerals always indicate that after a refilling event, efficient mixing plus crystallisation processes rapidly drive the system to the low pressure equilibrium condition, typical of the HP degassed magma (Francalanci et al., 2004-2005; Landi et al., 2004, 2006).

Chronology of the eruption

On 27 February, an eruptive fissure opened on the NE external flank of the NE-Crater and the emitted lava formed three branches that rapidly reached the sea, flowing on the E margin of the Sciara del Fuoco depression. Late on the first day, the three initial flows stopped and a new vent opened in the eastern sector of the Sciara del Fuoco at about 400 m.a.s.l. (Fig. 2a). In a few days, a lava flow fed by this vent formed a lava bench, several tens of meters wide, which significantly modified the coastline (Fig. 2 b). Between 4 and 9 March, while the lava eruption was continuing, important changes occurred in the summit area, with significant widening of the crater rim due to crater collapses and ash explosions (Fig. 2c, d). Activity at the 400-m vent stopped for a few hours on 9 March, when another vent opened at about 550 m a.s.l. on the northern outer flank of the NE-Crater, almost in the same position as those active during the 2002-2003 eruption. The 550-m-vent was active for less than 24 hours, and when it closed, the 400 m vent again opened issuing lava down to the sea. On 15 March 2007, while the effusion from the 400 m vent was still on-going, a paroxysmal explosion occurred from the NE crater, ejecting ballistic blocks in the NE sector of the islands, towards Stromboli village and producing an eruptive plume which deposited ash and pumiceous lapilli/bombs in the SW sector. This event did not interrupt the lava emission, which progressively formed an extended lava delta at the base of the SdF. The effusive activity ended completely on 2 April 2007.

The onset of the effusive phase led to a drop of magma level in the central conduit and to the cessation of the Strombolian activity from the central crater. From the beginning of March, discontinuous ejections of fine, brownish ash started in the summit crater. Ash emission characterized the activity at the central crater in March and for few months after the end of the effusive event. By early July 2007, the typical Strombolian activity had gradually resumed.

Compared to the previous 2002-2003 flank eruption, the effusion rate during the 2007 event was roughly an order of magnitude greater, whereas the total volume of lava emitted (on the order of 10^7 m^3) was similar. The greater effusion rate in 2007 resulted in a much shorter duration.

Sampling

Sampling collection was undertaken by Istituto Nazionale di Geofisica e Vulcanologia and University researchers, aided by volcanological guides and Civil Protection staff. Sampling of the lava flows was not a simple task because the eruptive vent at 400 m above sea level (a.s.l.), active for almost the length of the eruption, was located on the steep flank of the Sciara the Fuoco, where the danger of landslides proved a constant threat. Most samples therefore come from the moving upper crust, glowing fronts or levees, of thick aa flows which built the lava fan at the bottom of the Sciara del Fuoco, covering the Spiaggia dei Gabbiani, at <20 m a.s.l. A total of 11 lava samples erupted from 27 February to 2 April were collected. Most of the samples were quenched in water. Unfortunately, it was impossible to sample the lava flow emitted on 9 March from the vent at 550 m a.s.l., that was active for just one-day. Three ash samples emitted from the summit craters on 2 (STR020307ASH sampled at 400 m a.s.l.), 17-18 (STR180307ASH sampled at Nel Cannestrà) and 25-26 March (STR260307ASH sampled at Semaforo Nuovo) were also collected. Scoria bombs (STR150307D, F) and lapilli (STR150307B) emplaced in the summit area and lapilli

(STR150307A) floating near Punta Lena, emitted by the 15 March paroxysmal activity, were also sampled.

Analytical methods

Modal and mineral chemistry analyses were performed on the lavas sampled throughout the eruption. Chemical (major and trace elements) and isotopic (Sr and Nd) analyses of whole-rocks and groundmasses were performed on all the samples collected. Sr isotope data were also determined for separated crystals (clinopyroxene and olivine of about 2 mm in size).

Modal analyses were performed using an optical microscope equipped with a point counter, counting minerals >0.1 mm in size. In each sample 1500-2000 points, excluded bubbles, were counted with a grid dimension of 0.5 mm.

Texture and major element composition of the minerals were analyzed with a Philips XL30 scanning electron microprobe equipped with EDAX DX4 at Dipartimento di Scienze della Terra of the University of Pisa, Italy (analytical error: 1% for concentrations higher than 15wt%, 2% for 5-15 wt%, 5% for 1-5 wt%, and 30% for <1 wt%) and an electron microprobe JEOL-JXA-8200, (WD/ED combined microanalyzer) at Istituto Nazionale di Geofisica e Vulcanologia, Rome.

Major elements and trace element contents of bulk rocks were measured at the Centre National de la Recherche Scientifique, Vandoeuvre Les Nancy Cedex, France, respectively by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Analytical uncertainty is: <1% for SiO_2 and Al_2O_3, <2% for Fe_2O_3, MgO, CaO, Na_2O, K_2O, <5% for MnO and TiO_2 and 5-10% for P_2O_5, and <5% for all trace elements except U (<8%).

Matrix glass compositions have been measured on water-quenched lava and ash samples with abundance of microlites less than 10 vol.%. The experience gained during several years of petrologic monitoring taught us that the glassy matrix of rapidly quenched samples, such as ash and small-sized lapilli, generally contains less than 10% microlites. For microlites content up to 10%, we assume that the composition of glass is representative of the composition of magma “frozen” at the moment of its eruption. The choice to measure composition of glass with less than 10% microlites, minimizes the effect of post-eruptive crystallization that is evident in large-sized pyroclasts, such as bombs, and lava flows. The glass analyses were performed at the Istituto Nazionale di Geofisica e Vulcanologia, sezione di Catania by a LEO-1430 scanning electron microscope (SEM), equipped with an Oxford EDS micro-analytical system. Analytical conditions are 20 kV of acceleration tension, 1200 nA of probe current and XPP data reduction routine. To minimize alkalis loss during analysis, a square raster of 10x10 μm is used. Replicate analyses of the international standards VG-2 basaltic Glass, USNM 111240/52 (Jarosewich et al., 1980) ensure an analytical precision, expressed as relative standard deviation, that is less than 1% for SiO_2, Al_2O_3, FeO_t, MgO and CaO and less than 3% for TiO_2, Na_2O, and K_2O (Miraglia, 2006).

Sr isotope ratios were performed at the Department of Earth Sciences of the University of Florence and at the Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Napoli-Osservatorio Vesuviano, where Nd isotope ratios were also determined. Whole-rock powders and the separation of groundmasses and minerals were made separately by the two labs. Isotope ratios were analysed by Thermal Ionization Mass Spectrometry (TIMS) using multicollector ThermoFinnigan Triton®-Ti mass spectrometers equipped with nine movable Faraday cups. At the Florence lab, isotope data were measured using a dynamic mode and the data were corrected for mass fractionation using an exponential law based on $^{86}Sr/^{88}Sr = 0.1194$, according to the procedure reported in Avanzinelli et al. (2005). Replicate measurements of NBS 987 (0.710249, Thirlwall, 1991) standard during the period of these analyses gave mean values of $^{87}Sr/^{86}Sr = 0.710248 \pm 0.000014$ (2σ, n = 27). Long term mean values measured over the years 2003-2005 for NBS 987 Sr standard were $^{87}Sr/^{86}Sr = 0.710250 \pm 0.000012$ (2σ, n = 147). Sr analytical blank measured during the course of this study is 142 pg (average value of four analytical blanks). At the Naples INGV laboratory, Sr and Nd isotope ratios were measured statically. Sr and Nd isotope ratios were corrected for mass fractionation using $^{86}Sr/^{88}Sr=0.1194$ and $^{146}Nd/^{144}Nd=0.7219$. Replicate analysis of NIST NBS 987 and La Jolla Reference (0.511856, Thirlwall, 1991) standards gave average values of 0.710250 ± 0.000014 (2σ, n = 56) and 0.511837 ± 0.000011 (2σ, n = 50), respectively. The external reproducibility 2σ during the period of measurements is calculated according to Goldstein et al. (2003). Sr blank during the period of chemical processing was 250 pg.

Petrography and mineral chemistry of the lavas

Products collected during the 2007 effusive eruption have very similar petrographic and mineralogical characteristics to those of the HP scoria and lavas of the present-day activity of Stromboli (Landi et al., 2004, 2006; Francalanci et al., 2004). They have porphyritic textures with euhedral phenocrysts and micro-phenocrysts of plagioclase (<2.5 mm), clinopyroxene (<5 mm) and olivine (<4 mm). Frequent glomeroporphyritic aggregates (up to 5-6 mm in size), made up of the same minerals occurring as phenocrysts, are also present (Fig. 3a-c). Modal analyses yield 45-51 vol% of crystals, including plagioclase as the dominant phase (29-33 vol%), followed by clinopyroxene (11-14 vol%) and olivine (4-5 vol%) (Table 1). All the minerals are set in a hypocrystalline groundmass. Several samples show sectors with cryptocrystalline groundmass (dark colour in Fig. 3d), which likely represent recycled portions of the chilled borders and/or upper crust of the lava flows.

Plagioclase ranges in composition between An_{60} and An_{90} (Fig. 4a) and shows the typical concentric zoning in which ~10 to ~150 μm layers of labradoritic plagioclase (An_{64}-An_{70}) alternate with small-scale (1-5 μm) oscillatory zoned bytownitic (An_{70}-An_{90}) plagioclase. The latter often grows on dissolution surfaces and shows patchy zoning and sieved textures with abundant melt inclusions (dark colour in Fig. 3c). Clinopyroxene crystals are mainly augite, clustering around Mg# 0.74-0.78 [= molar $Mg^{2+}/(Mg^{2+}+Fe^{2+})$]. Diopsidic compositions (Mg# 0.86-0.91; $Fs_{5\text{-}8}$) are present as corroded cores and/or thin intermediate layers with rounded boundaries (Figs. 3b, 4b). Olivine composition is between Fo_{66} and Fo_{82} with most of the analyses in the range Fo_{70}-Fo_{73} (Fig. 4c). Clinopyroxene and olivine with Fe-richer compositions (Mg# of 0.70-0.72 and $Fo_{66\text{-}69}$, respectively) in the cores of the crystals and/or in narrow layers in the inner part of them, are sporadically found. Rims of the euhedral plagioclase, clinopyroxene and olivine crystals, in textural equilibrium with the groundmass, have $An_{62\text{-}70}$, Mg# 0.74-0.76 ($Fs_{13\text{-}14}$) and $Fo_{71\text{-}74}$ compositions, respectively (Fig. 4 a,b,c). All of these rim compositions are representative of low pressure and low temperature (~1110°C) equilibrium conditions of the shallow, degassed HP magma (Métrich et al., 2001; Landi et al., 2004, 2006; Francalanci et al., 2004).

Despite these general characteristics of the HP scoria and lavas of Stromboli, the sporadic but systematic presence of crystals displaying textural and/or compositional disequilibrium is a notable feature of the lavas erupted during the whole eruptive event, except for that erupted at the beginning of the eruption, on February 27th. This distinguishes the 2007 lavas from the previous HP products, including the 2002-2003 lava samples (Figs. 3e, f, g, h). Some disequilibrium features are well recognizable only using SEM analyses but are not evident under an optical microscope. This makes it difficult to state the modal quantity of the crystals in disequilibrium. We can only estimate that each thin section contains less than 1% in volume of crystals >300 μm in size with disequilibrium textures and/or compositions.

The crystals in disequilibrium have cores with the same texture and composition of minerals of the HP magma, but they show rims with less evolved composition (Fig. 4). Plagioclase show <50 μm thick, patchy-zoned rims with skeletal texture, abundant glass inclusions, rare bubbles and compositions mainly ranging from An_{75} to An_{82} (Fig. 3e, Fig. 5a). Disequilibrium clinopyroxene shows a large textural variability, including: i) rounded crystals with patchy-zoned cores Mg# 0.73-0.80 surrounded by a thick layer Mg# 0.86 (Fs_8) and <20 μm external rims Mg# 0.80 (Fig. 5b); ii) nearly-euhedral to rounded crystal with <10 μm thick rims with average composition of

Mg# 0.81 (Fig. 5c); iii) rare, resorbed crystals Mg#0.78 (darker in thin section) surrounded by <25 μm thick rims with the composition Mg#0.76-0.77 which is supposed to be in equilibrium with the HP, degassed magma (Fig. 3h). Olivine crystals in disequilibrium show, as well, a spectrum of textures consisting of: (i) rounded to euhedral crystals with cores Fo_{70-73} and rims ranging from <30 μm layer Fo_{74-76} (Figs. 3f, 5c, d) to 60 μm-thick, MgO richer corona (Fo_{75-80}), characterized by patched-zoning, abundant glassy inclusions and rare voids (Fig. 5e); (ii) crystals with resorbed cores Fo_{70} surrounded by zones Fo_{79-82} with skeletal texture and final rims, <10 μm thick, Fo_{73} (Fig. 5f); (iii) crystals with cores Fo_{70-73} and rims Fo_{72-73} with abundant glass inclusions (Fig. 3g). According to Bertagnini et al. (2003), the texture of the rims (iii) is most likely the result of resorption phenomena.

Glass matrix composition

Glass matrix compositions (Table 2) were measured on selected lava flows (STR270207 and STR080307), on one bomb (STR150307F) and two lapilli samples (STR150307A, B) erupted during the 15 March paroxysm, and on ash samples sporadically emitted by the summit craters during the eruption (STR020307ASH, STR180307 ASH, STR260307 COA ASH).

Most of the lavas collected during the eruption have shoshonitic matrix glass composition, with SiO_2 ranging 51.75-52.90 wt%, K_2O=3.75-5.14 wt% (Fig. 6) and CaO/Al_2O_3=0.45-0.53. On the whole, they coincide with the compositional field of the matrix glass of HP lavas and scoria erupted during the 2002-2003 eruption (Landi et al., 2006). The glass composition of the LP pumiceous lapilli (STR 150307A) erupted during the 15 March paroxysm (Fig. 6) is significantly different from the previously described HP lavas and scoria matrix glasses. In fact, they are basalts and fall within the compositional field of LP glasses emitted during the 5 April 2003 paroxysm (unpublished data; Métrich at al., 2005). HP scoriaceous lapilli (STR 150307B) and a bomb (STR 150307F) erupted together with the LP pumice during the 15 March paroxysm, have shoshonitic glass composition very similar to matrix glasses of HP lavas and scoria.

Time-related compositional variations (Fig. 7) of HP glass matrix are not particularly evident during the eruption even though HP lapilli erupted on 15 March (STR150307B) and ash emitted immediately after the paroxysm (on 18 March, STR180307) are slightly more primitive than the other products. The latter samples have the highest values of CaO/Al_2O_3 and MgO associated with the lowest K_2O value.

The comparison of our data with literature show that the glasses of 2007 eruption are more variable and slightly less evolved (see their CaO/Al_2O_3 content) than their counterparts emitted during 2002-2003 effusive activity (Landi et al., 2006). A good match is observed between LP basaltic lapilli erupted on 15 March and the LP products emitted during the 5 April 2003 paroxysm (Fig. 7).

Bulk rocks composition

All the products of the 2007 eruption show a basaltic bulk rock composition, like that of volcanics erupted during historical activity (Fig. 6). As in the recent past, LP lapilli and bombs erupted on 15 March belong to the high-K calc-alkaline suite, whereas HP effusive products and bombs emitted on 15 March (STR150307F) belong to the shoshonitic series. HP products plot within the compositional range observed in similar products erupted since 1906 (see the range reported in Landi et al., 2006 and reference therein). LP pumices erupted on 15 March and in the paroxysm of 5 April 2003 have common compositional characteristics. On the whole, bulk rock compositions of 2007 lavas (Table 3) are fairly homogeneous and the observed chemical variations for both major and trace elements are within analytical error. Among the major elements, the largest percentage relative standard deviations (%RSD≈3) are observed for MgO and Na_2O, while the largest variability in trace elements is found for Cr (%RSD≈9) and for Ni (%RSD (≈5).

The compositional variability during the 2007 eruption is appreciably smaller than that observed during the 2002-2003 eruption (Fig. 8). In addition, these small variations do not appear closely correlated with time (Fig. 8) or with relevant eruptive phenomena. Some incompatible trace elements are correlated in binary plots and the resulting trends may be compatible with a liquid line of descent controlled by crystallization or cumulus/dissolution of phenocrysts. In these diagrams (Fig. 9) the LP pumices erupted on March 15 and on 5 April 2003 play the role of parental liquids. It is worth noting that within both 2002-2003 and 2007 products, samples erupted before and after the paroxysms, are identifiable on the basis of the Th concentration. In Fig. 9 all samples erupted before 5 April 2003 and 15 March 2007 are slightly more enriched in Th than the rocks erupted after the paroxysms.

Sr-Nd isotope composition of lavas, scoria and pumice

The Sr isotopic ratios of nine whole-rock lava flow samples are similar within the analytical errors, ranging around 0.70616 (Table 4; Fig. 10). The only exception is the March 10 sample STR100307A, which is significantly more enriched in radiogenic Sr (0.706228 ± 0.000006) with respect to the others (Table 4). The Sr isotope ratios of the groundmasses separated from lavas are generally slightly lower than those of the respective whole-rocks; nonetheless, considering the analytical errors, they are not distinct from whole-rock values. Only the $^{87}Sr/^{86}Sr$ value of the groundmass of sample STR100307A ($^{87}Sr/^{86}Sr = 0.706156 \pm 0.000006$), is appreciably lower than that of the corresponding whole-rock and similar to the other groundmass values.

The Sr isotopic ratios of the 2007 lavas are similar to the lowest values of the scoria erupted during the 1994-2006 period of activity (Fig. 10) and plot in the Sr isotopic range of the whole-rock and groundmass of the 2002-2003 lava flows. In detail, considering that $^{87}Sr/^{86}Sr$ decreased with time in the 2002-2003 effusive events, they particularly match those of the whole-rock of lavas emitted before the 5 April 2003 paroxysm (Francalanci et al., 1999, 2004, this volume and unpublished; Landi et al., 2006).

The Sr isotope composition of the rocks emitted during the paroxysmal event of 15 March 2007 shows a greater variability. The scoria bomb has a whole-rock $^{87}Sr/^{86}Sr$ value (0.706166±0.000006) similar to the whole-rock values of the lava flows, whereas the $^{87}Sr/^{86}Sr$ value of its glassy groundmass is slightly, but significantly less radiogenic, and similar to the lava groundmass values. The whole-rock of pumice lapilli has an appreciably lower $^{87}Sr/^{86}Sr$ value (0.706140±0.000006) than the whole-rock scoria value. The matrix glass separated from the pumice sample is slightly less radiogenic than the pumice whole-rocks ($^{87}Sr/^{86}Sr$ = 0.706128±0.000006) (Table 4, Fig. 10).

Other significant aspects of the isotopic data of these samples are: (1) the LP pumice of the 15 March paroxysm shows higher Sr isotope ratios than those of the previously erupted pumice (during 1996-2003) (Fig. 10; Francalanci et al., 1999, 2004, 2008 and unpublished data); (2) the olivine crystals separated from HP samples are in Sr isotopic equilibrium with the host groundmass, on the contrary, clinopyroxene crystals are highly enriched in radiogenic Sr, with respect to the respective groundmasses (Table 4; Fig. 10); (3) isotope ratios measured in selected whole rocks and separated groundmass show an inverse correlation between $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ (Fig. 11), the less Sr radiogenic LP pumice samples from the paroxysmal event being characterized by higher Nd isotope ratio.

Discussion

The HP magmas which have fed normal Strombolian activity and lava effusions at Stromboli in the past decades show a general mineralogical and chemical homogeneity (Landi et al. 2004, Francalanci et al. 2004), except for a decrease of the Sr isotope ratios, starting from about 1985 AD (Francalanci et al., 1999). Despite the large outpouring of magma in a short time interval during the 2007 eruption, the lavas erupted throughout the entire effusive event have similar composition, with only minor variations. In the following, we will discuss the implications of the minor compositional variations and make inferences regarding the dynamics of the magma feeding system based on this data.

Inferences from mineralogy

The main petrographic characteristic, which distinguishes the 2007 lavas from previous HP scoria and lavas, is the occurrence of crystals showing evidence of textural and compositional disequilibrium. Most of them have rounded cores with composition similar to those of the minerals of the HP magmas, implying dissolution conditions before the final growth of the less evolved rims (plagioclase An_{75-82}, olivine Fo_{74-82}, clinopyroxene Mg# ~0.80). Crystals with similar textural and compositional characteristics were only found in a few scoriae emitted during the normal Strombolian activity (unpublished data) and in the lava emitted at the end of the 2002-2003 effusive event (on 20 July 2003). Conversely, they are the main petrographic characteristic in highly vesiculate scoriae with an intermediate glass matrix composition between the HP scoria and the LP pumice. These products are emitted from Stromboli during rare explosions classified as intermediate between the normal Strombolian activity and small-scale paroxysms (e.g. explosions of 9 Jan 2005 and 24 Jul 2002; Corsaro and Miraglia, 2005; Andronico et al., 2008; Landi et al., 2008b). A large quantity of minerals inherited from HP magma also occurs within the LP pumice erupted during the paroxysms. They show dissolution surfaces and growth rims with skeletal texture, but the final growth rims have less evolved compositions (plagioclase up to An_{90}, olivine Fo_{82-86} and clinopyroxene Mg# 0.84-0.88; Métrich et al., 2001; Bertagnini et al., 2003; Francalanci et al., 2004) than those observed in the crystals with reverse zoning of the 2007 lavas. These different zoning patterns rule out a direct involvement of LP magmas (H_2O=2.5-3 wt%) in the processes which originate the disequilibrium phenomena observed in the 2007 lavas. The fact that the quantity of the minerals in disequilibrium remains unchanged in lavas erupted before and after the 15 March paroxysm reinforces this suggestion. Hydrothermal experiments carried out on Stromboli HK-basalt at T=1100 ºC and P between 48 and 100 MPa (Di Carlo et al., 2006) indicate that minerals with compositions ~An_{78-82}, ~Fo_{78-82}, ~Mg#0.78-0.8 crystallize from less evolved and more water-rich melts (CaO~9-10 wt%, MgO~4.4-5 wt%; H_2O between 1.2 and 2.4 wt%) than the groundmass of the HP products (CaO~7.5-7.8wt%, MgO~ 3.3-3.5, H_2O<0.5 wt%). Crystals with reverse zoning in the 2007 lavas possibly originated in an intermediate zone of the feeding system dominated by convection and mixing between sinking shallow degassed magma and deep volatile-rich melts. Mixing, degassing, dissolution and minor crystallization would originate melts with intermediate characteristics between HP and LP magmas. Based on the study of the 9 Jan 2005 products, Landi et al. (2008b) suggest that gas phase plays a chief role in the dissolution phenomena and that mineral dissolution is mainly driven by re-hydratation of the recycled degassed magma, via differential gas bubble transfer and to some extent its physical mixing with volatile-rich magma blobs, at pressure likely >50 MPa.

We deduce that the occurrence of these disequilibrium features in 2007 lavas points to the involvement of lesser quantities of hotter and/or magmas with intermediate volatile contents from deeper parts of the shallow feeding system, somehow implying a more vigorous supply rate. The skeletal texture and the Ca-rich plagioclase rims suggest rapid crystal growth rates during the rapid uprising to the surface associated with fast degassing (see detailed discussion in Landi et al., 2004).

Time related variations of major and trace element compositions

Glass chemistry and bulk rock compositions illustrate that 2007 lavas fall within the compositional range of products emitted during the 2002-2003 effusive activity but, on the whole, they are more homogeneous than those of the previous effusive episode. This leads us to confirm that the shallow magmatic system feeding the Stromboli effusive activity is capable of maintaining steady state conditions in which the magma composition does not significantly change in time. Time-related compositional trends in 2007 lavas are not evident, though minor variations of glass chemistry and trace element compositions are observed in products erupted during and after the 15 March paroxysm, up to the end of March. These variations do not correspond to the observed changes in Sr and Nd isotopic ratios for these samples. In detail, glass matrix composition of HP scoriaceous lapilli and ash erupted on 15 and 18 March respectively (Fig. 7) is more primitive than in previous products and the 26 and 29 March lavas have a lower content of some incompatible trace elements (Figs. 8, 9). These compositional features reveal a similar behavior to that observed during the 2002-2003 eruption, when the imprint of the crystal-poor, volatile-rich magma, erupted by the 5 April paroxysm, modified the chemical and isotopical composition of the successive lavas which became more primitive than the pre-5 April samples (Landi et al., 2006). Likewise, we suggest that the HP magma erupted after the 15 March paroxysms was slightly more primitive than pre-15 March magma, because it mixed with the LP magma erupted during 15 March paroxysm. Noteworthy is the fact that the effects of the mixing process were exhausted two weeks after the 15

March paroxysm, since they have not been recorded in the composition of lavas erupted in late April. Glass and bulk rock compositions of the 15 March LP pumice overlap the compositional field of 5 April 2003 products. This observation suggests that the major and trace element chemistry of the parental magma refilling the shallow plumbing system remained unchanged over the five years between the two eruptions.

Inferences from Sr and Nd isotopes

The isotopic values of the 2007 lavas overlap those of the 2002-2003 lavas erupted before the 5 April paroxysm (Landi et al., 2006) and do not show significant variations during the entire duration of the effusive event. However, comparing Nd-Sr isotope data of whole-rock and groundmass in lavas, scoria and pumice, it is evident that two isotopically distinct magmas were involved in the 2007 eruption. As in the past 23 years, the deeper LP magma emitted as pumice is always less radiogenic than the shallow HP magma erupted as scoria and lavas. A third component is further represented by the most radiogenic pyroxene crystals of lavas (Fig. 10). Indeed, the presence of high Sr radiogenic clinopyroxene and plagioclase in the HP magma system of Stromboli, at least since about 1984, has already been noted in recent literature (Francalanci et al., 2005, 2008; Landi et al., 2008a; Nardini et al., 2008). High Sr radiogenic minerals (plagioclase and clinopyroxene ± olivine) in the HP magmas of Stromboli are thought to derive from cumulate crystal mush, remnant of the previous magmatic activity of Stromboli, which was more enriched in radiogenic Sr (Francalanci et al., 1989; 2005). The crystal mush zone is sited at a depth between the HP and LP magma systems, probably closer to the shallow HP magma body. Some cumulate crystals are thought to be crystallized about 10 ka ago, based on Sr isotope ratios of resorbed plagioclase cores found in 2002 lava samples (Francalanci et al., 2005; Nardini et al., 2008). These xenocrysts were trapped in the LP refilling magma during its uprising and brought into the shallow system. Several Sr isotope disequilibrium stages have been highlighted by detailed micro-Sr analyses in minerals. Different Sr radiogenic values to those of the bulk rock are either limited to the core of the crystals or extended throughout the whole crystal. This depends on the time interval during which the xenocrysts remained in the shallow system and/or on the diffusion rate of Sr in the different minerals (Francalanci et al., 2005; Nardini et al., 2008). The olivine crystals showing Sr isotopic equilibrium with their host liquids are possibly phenocrysts crystallized in the HP magma. Alternatively, they are xenocrysts which were isotopically re-equilibrated.

The presence of highly Sr-radiogenic xenocrysts can explain the slightly lower Sr isotope ratios of groundmasses with respect to the whole-rock values of lavas and scoriae. However, they do not entirely explain the high ^{87}Sr/^{86}Sr value of the STR100307 sample (Fig. 10). We conclude that the sample powder was not statistically homogenized during its preparation in lab, probably as a consequence of the small size of the sample. Indeed, it is necessary to add to the groundmass of the STR100307 sample an unrealistic amount of 20-25 wt% of clinopyroxene + plagioclase xenocrysts (average Sr content of 500 ppm) with quite high ^{87}Sr/^{86}Sr values (e.g., 0.7065; Fig. 10). Sr isotope analyses of plagioclase are not available for the 2007 lavas, but the presence of highly Sr radiogenic plagioclase can be surmised on the bases of literature data on the previously erupted products, including the 2002-2003 lavas (Francalanci et al., 2005, 2008; Landi et al., 2008a; Nardini et al., 2008). The significantly higher Sr isotope ratio of STR100307 sample is probably better explained as resulting from the accidental inclusion of xenoliths represented by older rocks, as a new vent opened in that period.

The differences of Sr isotope ratios between groundmass and matrix glass of pumice could be due to syn-eruptive mingling between HP and LP magmas during the paroxysm, associated with an incomplete cleansing of pumice from the scoriaceous portions and/or the xenocrysts inherited from the HP magma. The slightly higher Sr isotope ratio of the 15 March pumice compared to those of 5 April 2003, is likely related to long-time isotopic variations of the deeper feeding system.

Insights into magma dynamics leading to changes in the eruptive style

From a volcanological viewpoint, the lava effusion at Stromboli volcano should be considered a perturbation of the volcano’s steady course of activity. These events, as pointed out by studies made on the 1985, 2002-2003 and 2007 lava samples, are not associated with major variations in the composition of the erupted magmas. Indeed, the change in the eruptive style from Strombolian to effusive at Stromboli is not accompanied by notable modifications in texture, mineral and glassy matrix chemistry and isotopic values of the erupted products (De Fino et al, 1988; Landi et al., 2006; Fornaciai et al., submitted; Calvari et al., 2008). On the other hand, a systematic sampling of an effusive eruption at Stromboli was carried out only during the 2002-2003 event. Based on the compositional features of the 2002-2003 lavas, Landi et al. (2006) proposed two possible triggering mechanisms: i) the arrival of a larger volume than normal of fresh volatile-rich magma in the shallower system, some months before the onset of the eruption, as suggested by isotopic evidence and geochemical data (Carapezza et al., 2004; Aiuppa and Federico, 2004); ii) a long-term, gradual pressure increase in the conduit, beginning years before the eruption and eventually triggering a sudden lava outpouring. The absence of variations in the seismic activity and/or changes in edifice deformation before the onset of an effusive eruption (Ripepe et al., 2005, 2007;

Bonaccorso et al., 2003; Calvari et al, 2007; Bonaccorso et al., 2008), as well as the similarity between the chemical and isotopic composition of the 2007 lavas, the scoria erupted during the normal Strombolian activity of the past years and the 2002-2003 lavas, all indicate that major variations in the refilling mechanisms of the shallow magma did not occur immediately before the 2002-2003 effusive eruption.

Overpressure of the magmatic system leading to the 2007 eruption is likely related to the occurrence of VT seismicity recorded at depths of about 5-6 km between April and November 2006 (INGV, Sezione di Catania Reports; http://www.ct.ingv.it; D'Auria et al., 2006). This unusual seismic activity has been interpreted as a possible indicator of volcanic unrest (Patané et al., 2007). According to Bonaccorso et al., (2008), after the beginning of the effusive activity, a release of pressure related to the rapid emptying of the shallow plumbing system was detected by GPS and tilt stations installed on the island. Based on the deflation feature, the authors infer a depressurizing vertically elongated source with centre under the volcano edifice about 2.8 km below sea level. Geochemical data show large variations of the plume CO_2/SO_2 ratio since December 2007, likely reflecting an important increase of deeply-derived CO_2-rich gas bubbles. It promoted an overall decrease of the magma density and fast convection resulting in the increase of the explosive activity at the craters from December 2006 to the beginning of the eruption in February 2007. The measured CO_2/SO_2 ratio requires gas-melt separation at pressure of about 40-100 MPa, corresponding to a depth of 1-3 Km. In this model the increase of the CO_2 degassing could be linked to the feeding of an intermediate magma storage body by deeper volatile-rich LP magmas (Aiuppa et al., this volume). It is noteworthy that the presence of an intermediate magma reservoir, at depth of about 3 km, was already proposed in the recent literature on the bases of fluid inclusions and Sr isotope data (Vaggelli et al., 2003; Francalanci et al., 2004; 2005).

Increase of CO2 flux and fast convection would facilitate the admission into the shallow HP magma body of minor portions of melts carrying few resorbed crystals coming from an intermediate magma system, without significantly affecting temperature and composition that usually control the equilibrium in the HP magma. Finally, we propose that the feeding system of Stromboli remains in steady state conditions through time by means of continuous intrusion of volatile-rich magmas, their degassing, crystallisation and mixing at shallow level with the degassed resident shallow magma, and extrusion of the resulting HP magmas. Episodic increases in the feeding rate determine pressure increase in the conduit, leading to a more intensive activity at the craters and eventually to an effusive event, with minor disturbances in the chemical and physical equilibrium of the shallow magma system. What is important is that the nearly constant characteristics of the HP magmas also require low volumetric proportions of the deep magmas feeding the HP magma body during the periods of more intense activity. The large volume of nearly homogeneous magma emitted in a short time span during the 2007 effusive activity and the constant mineralogy and isotopic values in lavas erupted after the 15 March paroxysm, also suggest that the petrogenetic processes (degassing, crystallization and mixing), restoring the chemical-physical equilibrium at low pressure, seem to be fairly rapid, in the order of weeks or days. Ultimately, these processes are strictly related to the volume ratio between the refilling fresh magma from higher depth and the upper HP magma. Unfortunately, there are not enough adequate data to give a satisfactory estimate of the magma volumes operating in the feeding system of Stromboli.

The volume of the shallow magma reservoir is a key issue also for understanding the relationship between lava effusion and paroxysm. It is worth noting that both during the 2002-2003 and the 2007 eruptive crises a paroxysmal explosion occurred after 3 months and after 16 days of lava effusion, respectively. Although the relationship between lava effusion and the triggering of the paroxysm is not the point of this paper, some general observations can be made. In detail : i) the occurrence of paroxysms during effusive activity does not belong to the usual behaviour of the volcano, as deduced from historical records of activity over the past 100 years (Barberi et al, 1992; Bertagnini et al., 2008 and references therein). In fact, only one case is reported (in 1915) in which two paroxysms took place during a 6-month-long effusive crisis with lava flows inside the SdF; ii) Métrich et al. (2005), based on H_2O and CO_2 dissolved content in olivine melt inclusions, proposed that the ‘‘perturbation’’ inducing the 5 April 2003 explosion was initiated at pressure $\geq$240 MPa, corresponding to a depth >8 km (by assuming a rock density of 2700 kg m^{-3}). The above observations suggest that there are no simple relationships between lava emission and paroxysm and that triggering mechanisms of the paroxysm are rather related to a deep source such as the bubble-driven ascent of magma blobs from depth. How and if the rapid emptying of the conduits, with removal of a volume of magma in the order of 10^6-10^7 m^3, can lead to the destabilization of the deeper system, remains an open question and is strongly related to the volume of the upper HP magma reservoir. In this framework the hypothesis of Bonaccorso et al. (2008), that consider the rapid magmastatic pressure decay due to the lava effusion as a trigger for the paroxysm, should be further discussed by also taking into account the correct volume of magma involved in this process.

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Figure and table captions

Fig. 1 – View of the NW flank of Stromboli island. The picture shows the Sciara del Fuoco depression (SdF) with the active craters (SC) in its upper part, and the two villages on the coast. The lavas erupted in the 2007 effusive event (L) occupy the NE flank of the Sciara del Fuoco. (Photo by A. Amantia-INGV Catania).

Fig. 2 – Images of the volcano showing the 2007 lava field and the morphology of the crater terrace. a) view of the active vent within the Sciara del Fuoco at 400 m a.s.l. (photo by L. Lodato-INGV Catania); b) view of the 2007 lava field from N (photo by A. Amantia-INGV Catania); c) morphology of the crater terrace after the end of the 2007 effusive episode; d) the morphology of the crater terrace in June 2005 is also shown for comparison. Photos c and d were taken from Pizzo Sopra la Fossa, located SE of the craters (Photo by P. Landi).

Fig. 3 - Photomicrographs of the 2007 lavas. (a), (b) pictures showing the typical porphyritic texture of the lavas with abundant plagioclase and larger clinopyroxene and olivine and crystal aggregates; (c) plagioclase crystals showing the typical textural zoning consisting of alternating layers free of inclusions and sieve-textured layers rich in melt inclusions; (d) picture showing cryptocrystalline, black zones (likely recycled portions of the chilled borders and/or upper crust of the lava flow) hosted in a rock with hypocrystalline groundmass; (e-h) crystals showing

disequilibrium textures; (e) plagioclase showing a black rim with sieve-texture and rich in melt inclusions.; (f) round shaped olivine; (g) olivine rimmed by a layer rich in melt inclusions, likely due to dissolution; (h) clinopyroxene with skeletal rim (see text for details).

Fig. 4 – Plagioclase (a), clinopyroxene (b) and olivine (c) composition in the 2007 lavas as An mol%, Mg# [molar $Mg^{2+}/(Mg^{2+}+Fe^{2+})$] and Fo mol%, respectively. Open symbols: rims <20 μm; filled symbols: inner part of the crystals. Grey area: composition of the rims <20 μm of the mineral phases in the 2002-2003 lavas (from Landi et al., 2006).

Fig. 5 - Back-scattered electron images of crystals showing disequilibrium textures and compositions. (a) Plagioclase phenocryst showing reversed zoning with a rim <50μm thick, bytownitic in composition (An_{80-82}); (b) clinopyroxene with rounded core and reversed zoning. (c), (d): olivine and clinopyroxene with reversed zoning; (e), (f): olivine with reversed zoning and deeply resorbed cores.

Fig. 6 – SiO_2–K_2O classification diagram (modified from Peccerillo and Taylor, 1976) for bulk rocks and glass matrix compositions of lavas, scoriae, ash and pumices of 2007 eruption. Compositional fields of glass matrices of 2002-2003 lavas (area bounded by a thick-lined box) are from Landi et al. (2006). Also plotted for comparison are: bulk rock compositions of 2002-2003 HP lavas (from Landi et al., 2006), bulk rocks and glass matrix compositions of 5 April 2003 LP pumices (from Métrich at al., 2005; Francalanci et al., 2008; unpublished data) and 1906-2000 HP scoria and lavas (from Landi et al., 2006).

Fig. 7 - Temporal variations of average (±σ) K_2O wt%, MgO wt% and CaO/Al_2O_3, in glass matrix compositions of lavas and pyroclastites of 2007 eruption. The compositional range of 2002–2003 HP lavas (light grey band) and 5 April LP paroxysm pumices (dark grey band), are plotted for comparison. Literature data from Landi et al. (2006), Métrich at al. (2005) and unpublished data.

Fig. 8 - Time vs. selected major and trace elements for 2007 bulk rock compositions. (grey area: compositional range of the 2002-2003 lavas). For symbols, see Figure 6.

Fig. 9 - Th versus selected incompatible elements for bulk rock compositions of the samples erupted during the 2007 effusive event. For symbols, see Figure 6. Striped and dotted areas represent the composition of HP lavas erupted before and after the 5 April 2003 paroxysm,

respectively; grey area shows the composition of LP rocks erupted on 5 April 2003 paroxysm. Literature data from Landi et al. (2006), Métrich at al. (2005), unpublished data.

Fig. 10 – Variation of Sr isotope ratio with time in the juvenile products (HP lava and scoria, LP pumice) outpoured during the 2007 effusive event. Full symbols: whole-rock, open symbols: separated groundmass, cross: separated single crystals of olivine and clinopyroxene. HP: Highly porphyritic; LP: Low porphyritic. 2σ error bars on $^{87}Sr/^{86}Sr$ are also plotted. Dates report day/month of 2007 year. Fields show the compositional variations of HP scoria and LP pumice erupted since 1994 (Francalanci et al., 1999, 2004, 2008, this volume and unpublished). The Sr isotope variation of the 2002-2003 HP lavas and scoria (whole-rock and groundmass) is reported between the two lines (data from Landi et al., 2006). The $^{87}Sr/^{86}Sr$ values of the earlier erupted HP scoria and lavas are higher than the grey field.

Fig. 11 – Sr versus Nd isotope ratios for the juvenile products (HP lava and scoria, LP pumice) outpoured during the 2007 effusive event. Full symbols: whole-rock, open symbols: separated groundmass. HP: Highly porphyritic; LP: Low porphyritic. 2σ error bars are also plotted. Fields show the compositional variations of HP scoria, HP lavas and LP pumice erupted since 1994 (data from Francalanci et al., 1999, 2004, 2008 and unpublished; Landi et al., 2006). For comparison, all data are normalised to La Jolla reference standard value of 0.511856 reported by Thirlwall (1991) (La Jolla standard value obtained in the Florence lab is 0.511845 ± 0.000007, n = 57).

Table 1 - Modal analyses of selected lava samples of the 2007 effusive eruption.

Table 2 - Average (+σ) glass matrix composition of selected samples from the 2007 eruption.

Table 3 – Major (wt%) and trace (ppm) element bulk rocks of selected samples from the 2007 eruption.

Table 4 - Sr and Nd isotope ratios on the products erupted in the 2007 effusive eruption. *Footnotes:* Data from the Florence lab: in larger type and not in bold, data from the Naples lab: in smaller type and in bold; 2σ =internal error.

Fig 1

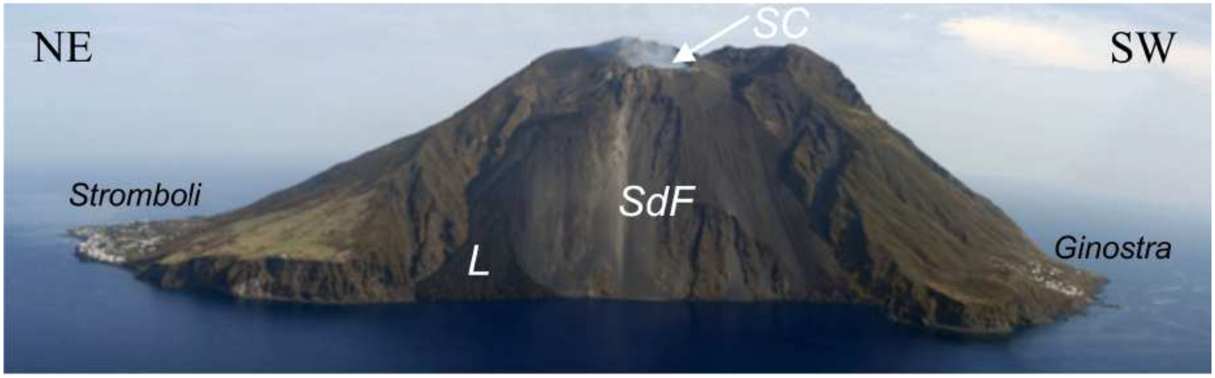

Fig 2

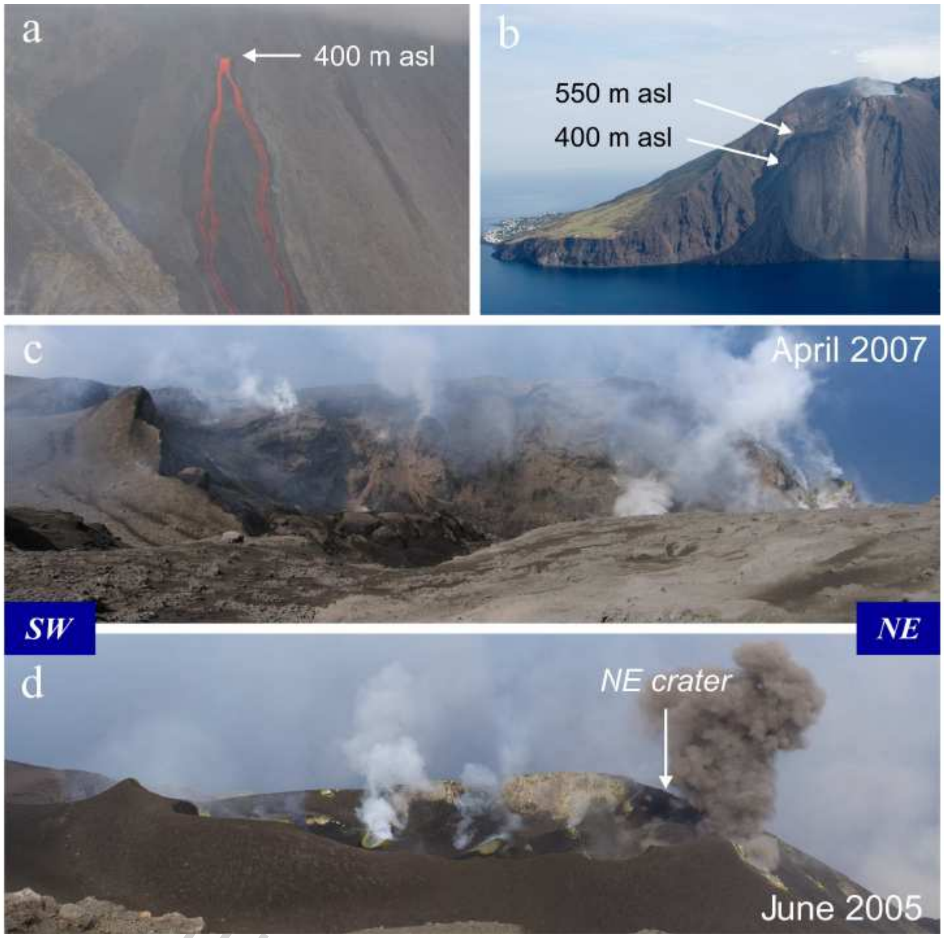
a
400 m asl
b
550 m asl
400 m asl
c
April 2007
SW
NE
d
NE crater
June 2005

Fig 3

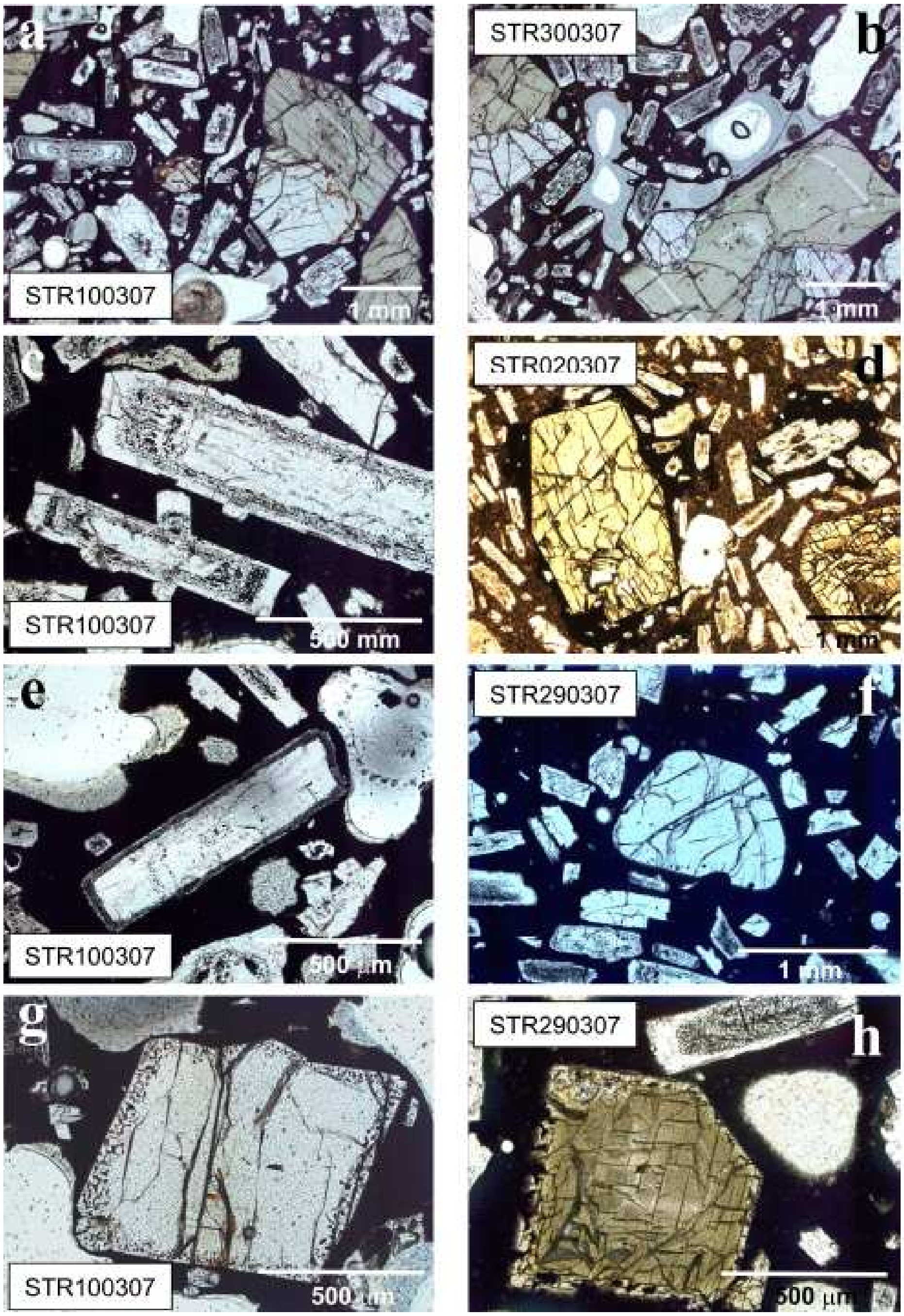
a
STR100307
1 mm
STR300307
b
1 mm
c
STR100307
500 mm
STR020307
d
1 mm
e
STR100307
500 μm
STR290307
f
1 mm
g
STR100307
500 μm
STR290307
h
500 μm

Fig 4

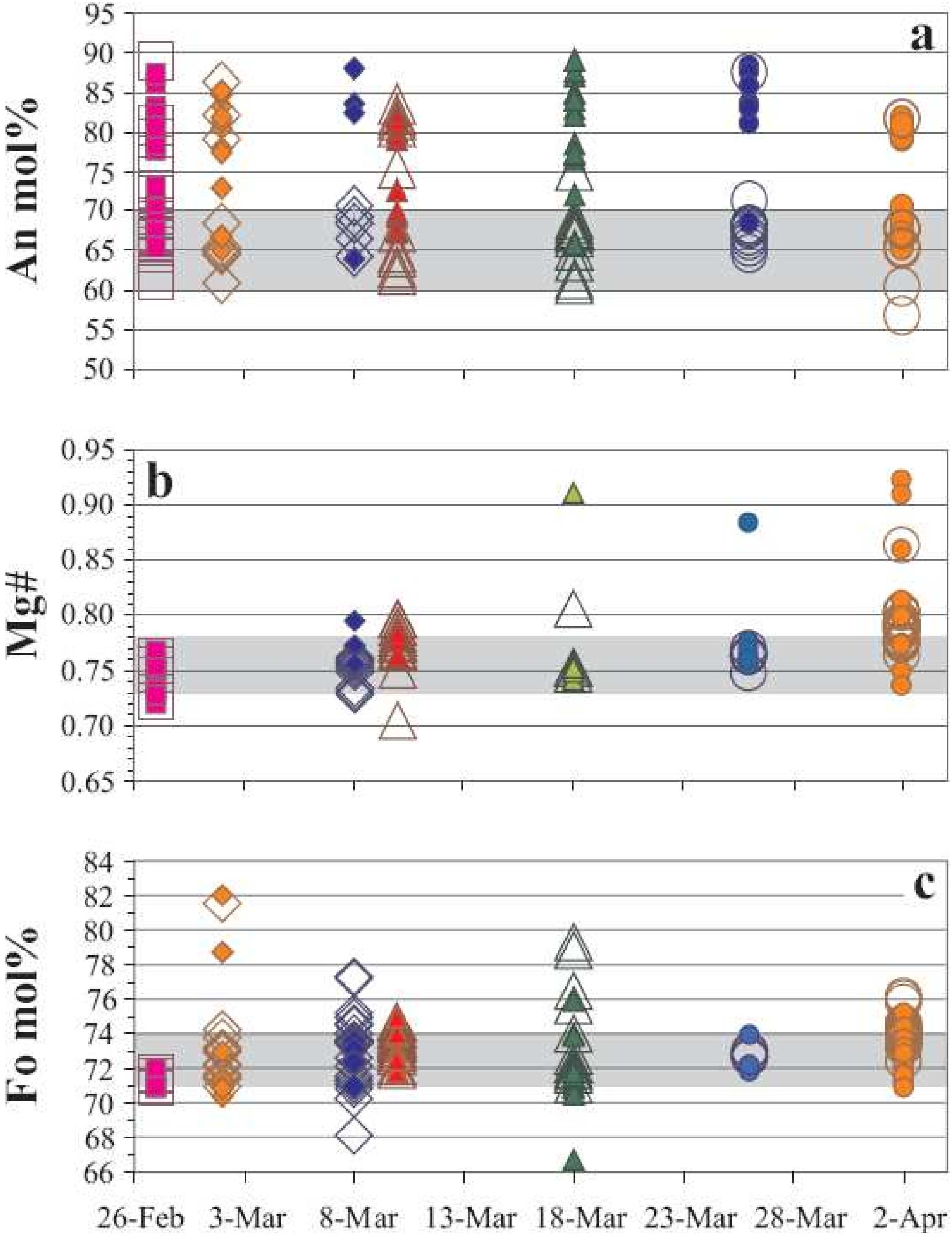
a
An mol%
95
90
85
80
75
70
65
60
55
50
b
Mg#
0.95
0.90
0.85
0.80
0.75
0.70
0.65
c
Fo mol%
84
82
80
78
76
74
72
70
68
66
26-Feb
3-Mar
8-Mar
13-Mar
18-Mar
23-Mar
28-Mar
2-Apr

Fig 5

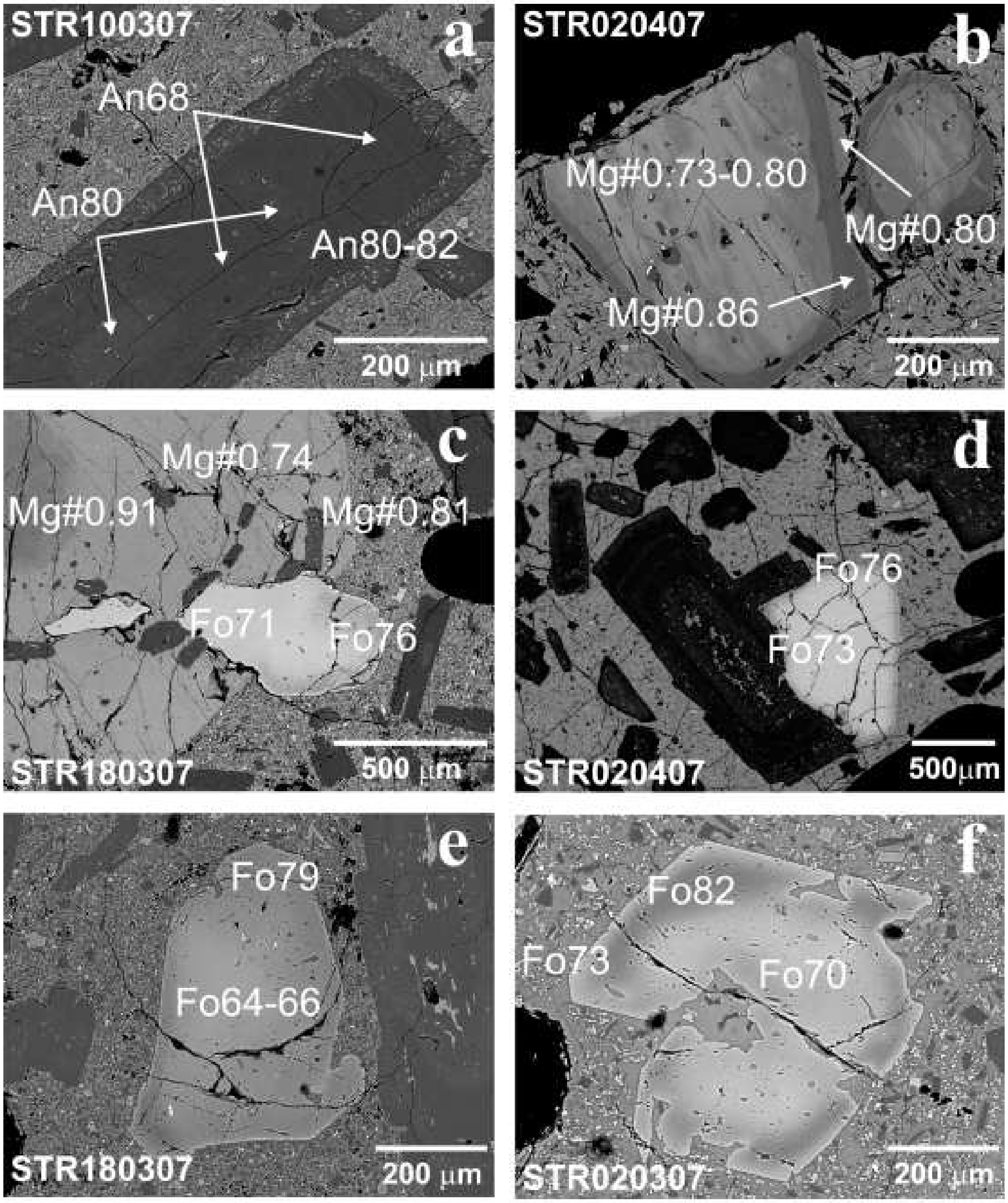
STR100307
a
An68
An80
An80-82
200 μm
STR020407
b
Mg#0.73-0.80
Mg#0.80
Mg#0.86
200 μm
c
Mg#0.74
Mg#0.91
Mg#0.81
Fo71
Fo76
STR180307
500 μm
d
Fo76
Fo73
STR020407
500μm
e
Fo79
Fo64-66
STR180307
200 μm
f
Fo82
Fo73
Fo70
STR020307
200 μm

Fig 6

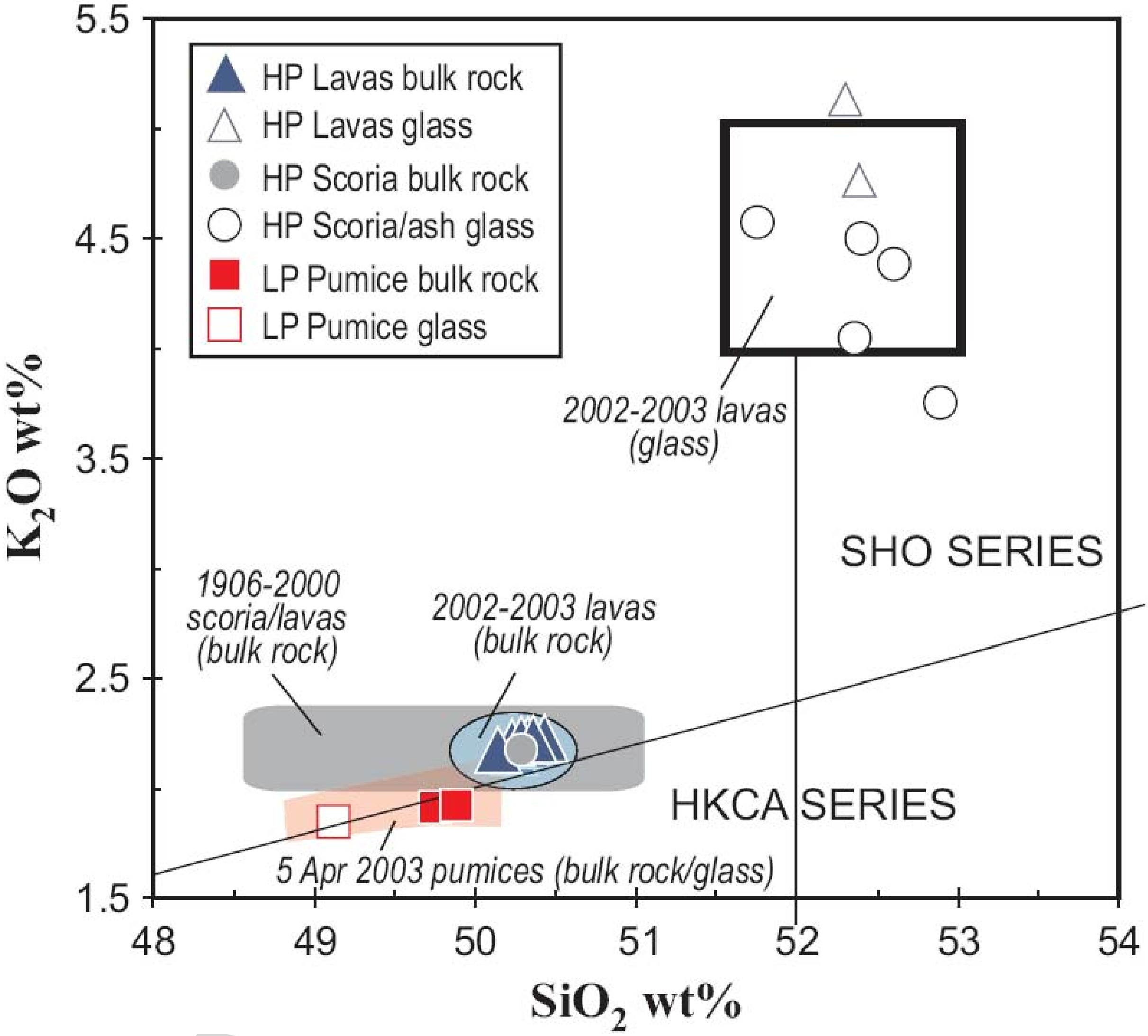
5.5
4.5
3.5
2.5
1.5
K_2O wt%
48
49
50
51
52
53
54
SiO_2 wt%
▲ HP Lavas bulk rock
△ HP Lavas glass
● HP Scoria bulk rock
○ HP Scoria/ash glass
■ LP Pumice bulk rock
□ LP Pumice glass
2002-2003 lavas (glass)
SHO SERIES
1906-2000 scoria/lavas (bulk rock)
2002-2003 lavas (bulk rock)
HKCA SERIES
5 Apr 2003 pumices (bulk rock/glass)

Fig 7

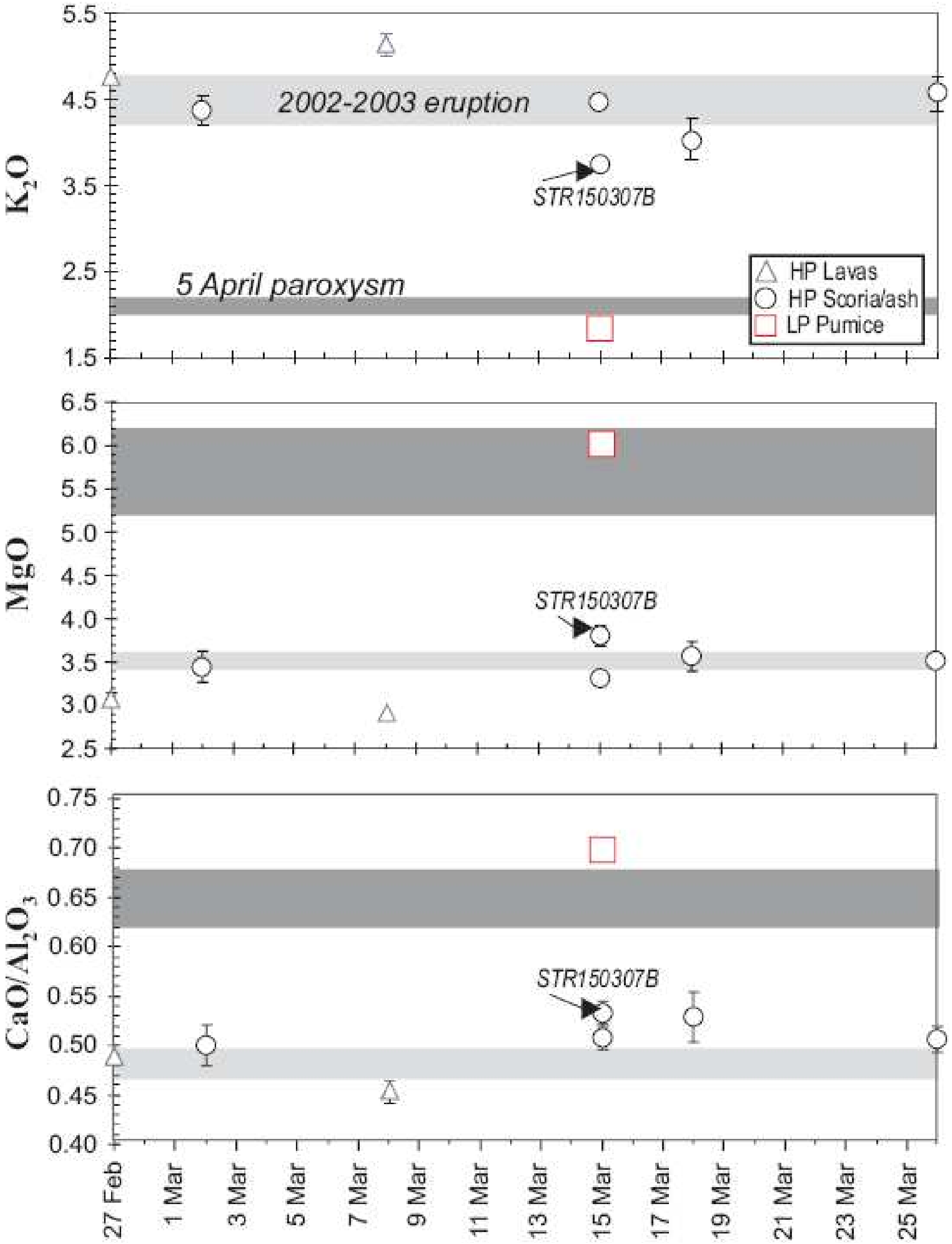
5.5
4.5
3.5
2.5
1.5
K_2O
2002-2003 eruption
STR150307B
5 April paroxysm
△ HP Lavas
○ HP Scoria/ash
□ LP Pumice
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
MgO
STR150307B
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
CaO/Al_2O_3
STR150307B
27 Feb
1 Mar
3 Mar
5 Mar
7 Mar
9 Mar
11 Mar
13 Mar
15 Mar
17 Mar
19 Mar
21 Mar
23 Mar
25 Mar

Fig 8

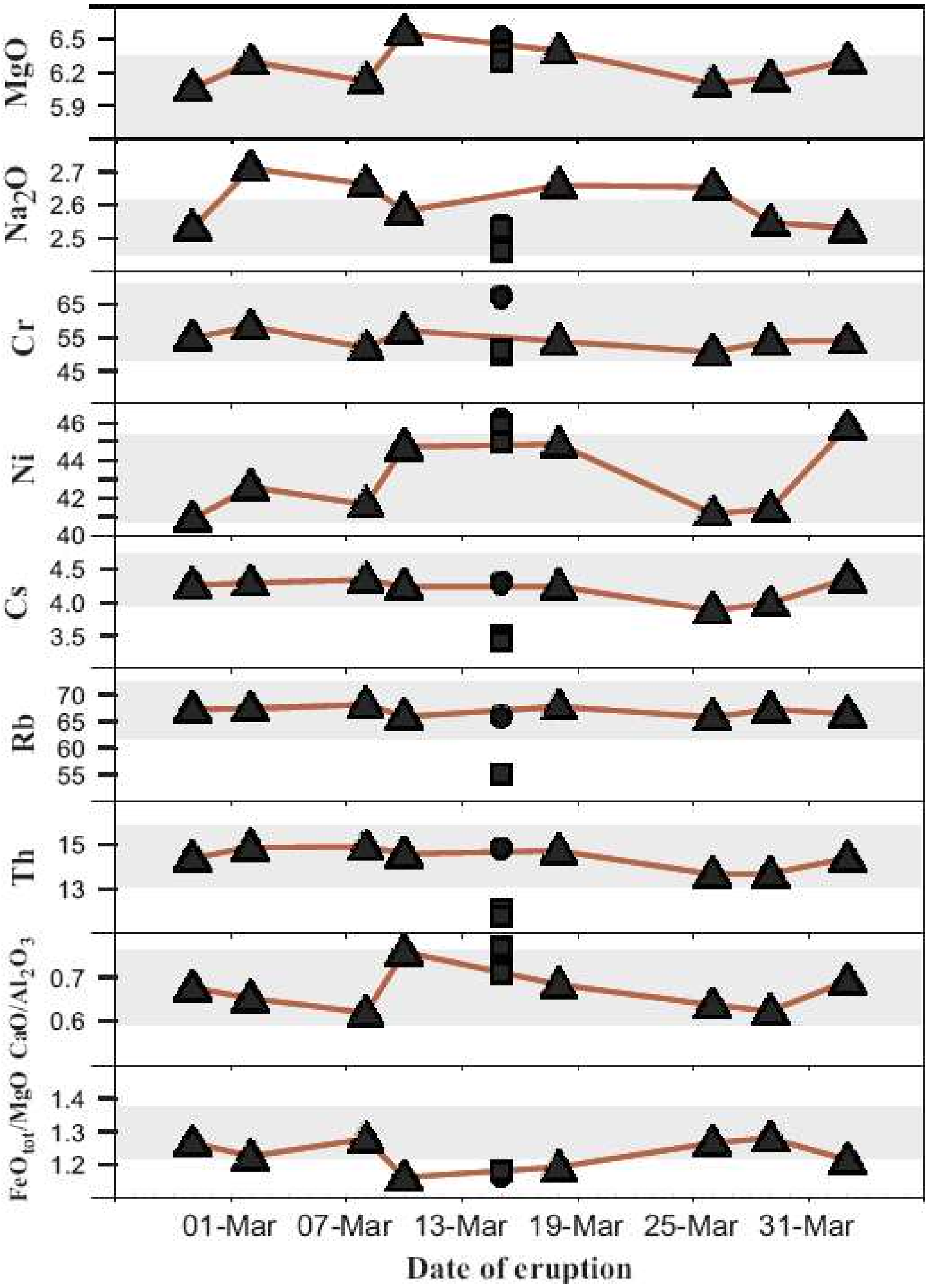
MgO
6.5
6.2
5.9
Na_2O
2.7
2.6
2.5
Cr
65
55
45
Ni
46
44
42
40
Cs
4.5
4.0
3.5
Rb
70
65
60
55
Th
15
13
CaO/Al_2O_3
0.7
0.6
FeO_{tot}/MgO
1.4
1.3
1.2
01-Mar
07-Mar
13-Mar
19-Mar
25-Mar
31-Mar
Date of eruption

Fig 9

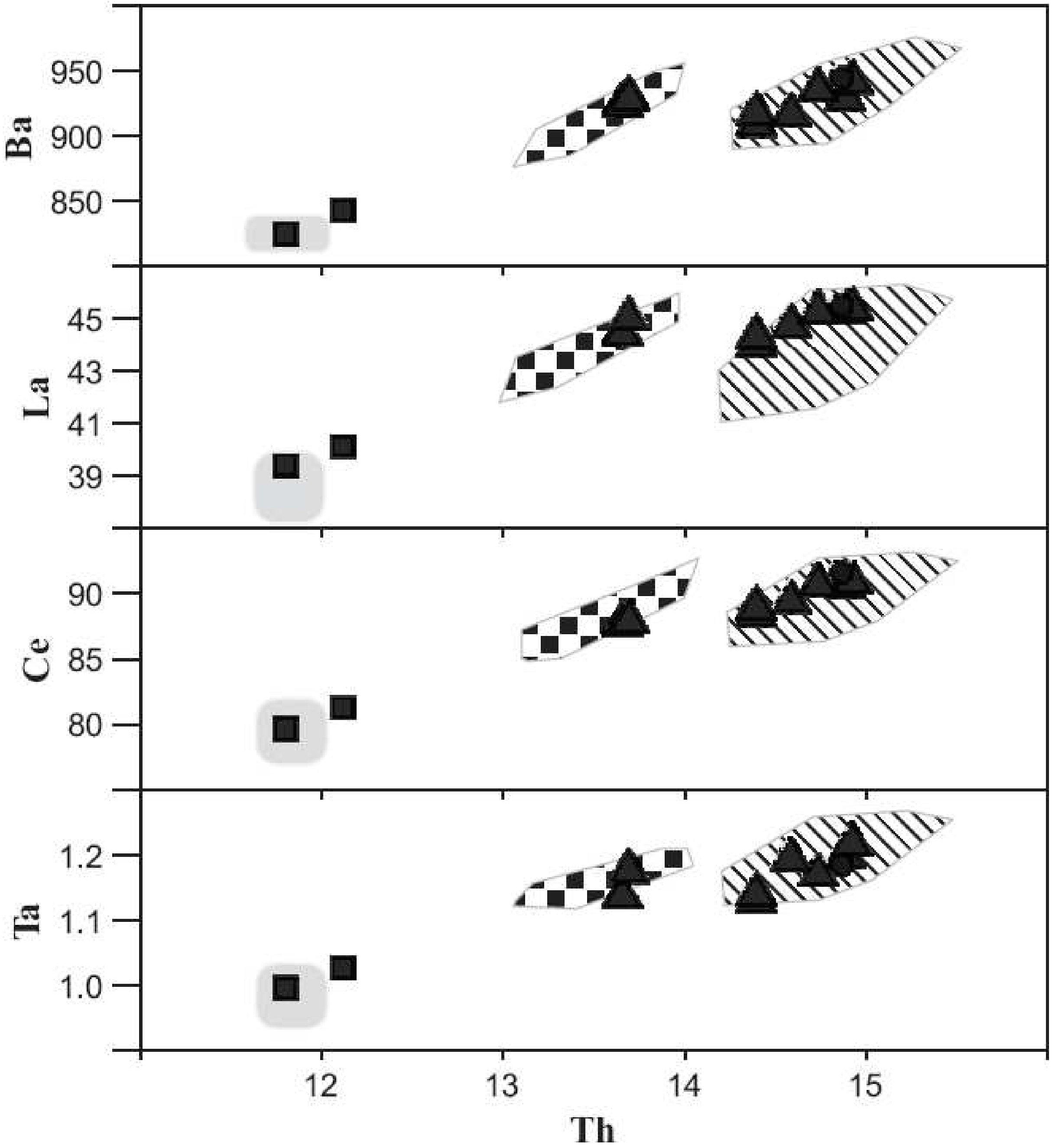

Fig 10

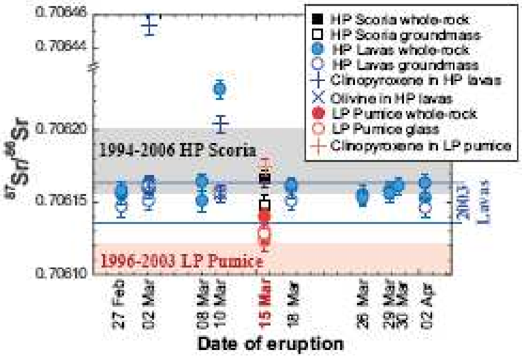
$^{87}Sr/^{86}Sr$
0.70646
0.70644
0.70620
0.70615
0.70610
1994-2006 HP Scoria
1996-2003 LP Pumice
2003 Lavas
■ HP Scoria whole-rock
□ HP Scoria groundmass
● HP Lavas whole-rock
○ HP Lavas groundmass
+ Clinopyroxene in HP lavas
× Olivine in HP lavas
● LP Pumice whole-rock
○ LP Pumice glass
+ Clinopyroxene in LP pumice
27 Feb
02 Mar
08 Mar
10 Mar
15 Mar
18 Mar
26 Mar
29 Mar
30 Mar
02 Apr
Date of eruption

Fig 11

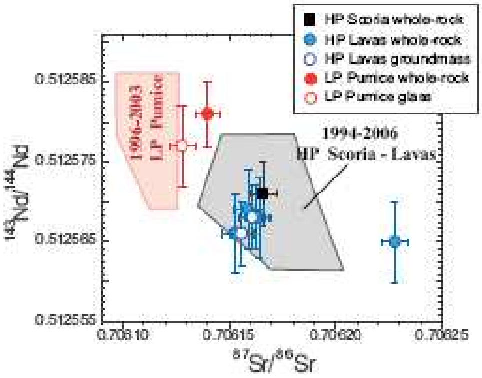
HP Scoria whole-rock
HP Lavas whole-rock
HP Lavas groundmass
LP Pumice whole-rock
LP Pumice glass
1996-2003
LP Pumice
1994-2006
HP Scoria - Lavas
0.512585
0.512575
0.512565
0.512555
0.70610
0.70615
0.70620
0.70625
$^{143}Nd/^{144}Nd$
$^{87}Sr/^{86}Sr$

Table 1: Modal analyses of selected lava samples of the 2007 effusive eruption

Sample	**vol% pl**	**vol% px**	**vol% ol**	**vol% crystals**
STR270207	33	13	5	51
STR020307	31	12	4	47
STR080307	32	12	5	48
STR100307	31	14	5	50
STR180307	31	11	5	47
STR260307	29	11	4	45
STR290307	31	11	5	47
STR020407	32	12	4	49

TABLE 2 - Average (±σ) glass matrix compositions of selected samples from the 2007 eruption.

sample	STR270207	STR020307ASH	STR080307B	STR150307A	STR150307B	STR150307F	STR180307 ASH	STR260307 COA ASH
eruption date	27 February	2 March	8 March	15 March	15 March	15 March	18 March	26 March
product	HP lava flow	HP ash	HP lava flow	LP lapilli	HP lapilli	HP scoria bomb	HP ash	HP ash
#	13	10	22	10	10	20	11	21
SiO_2	52.39 (0.14)	52.61 (0.27)	52.30 (0.18)	49.12 (0.22)	52.90 (0.75)	52.40 (0.13)	52.36 (0.39)	51.75 (0.27)
TiO_2	1.87 (0.06)	1.70 (0.05)	1.85 (0.05)	1.03 (0.05)	1.67 (0.04)	1.75 (0.06)	1.56 (0.07)	1.69 (0.05)
Al_2O_3	15.11 (0.07)	15.46 (0.10)	15.29 (0.20)	17.79 (0.11)	15.89 (0.07)	15.33 (0.13)	15.73 (0.14)	16.05 (0.18)
FeO	11.45 (0.11)	10.57 (0.04)	11.06 (0.22)	8.60 (0.10)	9.65 (0.62)	10.59 (0.14)	10.56 (0.24)	10.34 (0.12)
MnO	0.22 (0.05)	0.21 (0.03)	0.23 (0.03)	0.13 (0.03)	0.22 (0.03)	0.22 (0.05)	0.20 (0.04)	0.17 (0.06)
MgO	3.06 (0.08)	3.45 (0.18)	2.91 (0.08)	6.02 (0.08)	3.80 (0.10)	3.33 (0.08)	3.56 (0.16)	3.52 (0.09)
CaO	7.38 (0.12)	7.74 (0.26)	6.92 (0.13)	12.44 (0.16)	8.43 (0.13)	7.83 (0.11)	8.32 (0.34)	8.14 (0.19)
Na_2O	2.76 (0.11)	2.87 (0.19)	3.21 (0.12)	2.47 (0.07)	2.74 (0.03)	3.01 (0.10)	2.80 (0.09)	2.76 (0.42)
K_2O	4.77 (0.06)	4.38 (0.18)	5.14 (0.11)	1.84 (0.05)	3.75 (0.04)	4.50 (0.08)	4.05 (0.24)	4.58 (0.20)
P_2O_5	0.86 (0.05)	0.88 (0.05)	0.93 (0.05)	0.42 (0.03)	0.81 (0.06)	0.90 (0.06)	0.72 (0.07)	0.87 (0.06)
Cl	0.13 (0.02)	0.12 (0.02)	0.15 (0.03)	0.15 (0.02)	0.14 (0.03)	0.13 (0.02)	0.13 (0.04)	0.13 (0.03)
CaO/Al_2O_3	0.49 (0.01)	0.50 (0.02)	0.45 (0.01)	0.70 (0.01)	0.53 (0.01)	0.51 (0.01)	0.53 (0.03)	0.51 (0.01)
$FeOt/MgO$	3.74 (0.11)	3.07 (0.16)	3.80 (0.12)	1.43 (0.03)	2.54 (0.12)	3.18 (0.08)	2.97 (0.11)	2.94 (0.10)

# indicates the analyses number. Data are recalculated to 100% total.

TABLE 3 - Major (wt%) and trace (ppm) element bulk rocks of selected samples from the 2007 eruption.

sample	STR270207	STR020307	STR080307A	STR100307A	STR150307A	STR150307D	STR150307F	STR180307	STR260307	STR290307	STR020407
eruption date	27 February	2 March	8 March	10 March	15 March	15 March	15 March	18 March	26 March	29 March	2 April
product	HP lava flow	HP lava flow	HP lava flow	HP lava flow	LP lapilli	LP scoria bomb	HP scoria bomb	HP lava flow	HP lava flow	HP lava flow	HP lava flow
SiO_2	49.46	49.76	50.01	49.68	49.15	49.19	49.91	49.60	49.25	49.52	49.59
TiO_2	0.94	0.92	0.93	0.93	0.92	0.91	0.93	0.92	0.92	0.92	0.93
Al_2O_3	17.10	17.20	17.44	16.78	17.53	17.44	16.97	17.11	17.17	17.25	17.04
Fe_2O_3	1.32	1.35	1.34	1.37	1.34	1.33	1.36	1.35	1.33	1.35	1.35
FeO	6.59	6.74	6.69	6.84	6.72	6.63	6.82	6.76	6.63	6.73	6.72
MnO	0.16	0.16	0.16	0.16	0.16	0.15	0.16	0.16	0.16	0.16	0.16
MgO	6.06	6.30	6.13	6.56	6.39	6.31	6.52	6.40	6.10	6.16	6.31
CaO	11.21	11.19	11.23	11.26	11.61	11.75	11.33	11.24	11.12	11.12	11.22
Na_2O	2.53	2.71	2.66	2.58	2.53	2.46	2.54	2.66	2.65	2.55	2.53
K_2O	2.18	2.19	2.20	2.14	1.88	1.89	2.15	2.15	2.13	2.16	2.16
P_2O_5	0.55	0.56	0.57	0.56	0.56	0.54	0.56	0.56	0.56	0.56	0.56
LOI	0.51	0.80	0.54	0.69	0.99	1.10	0.48	0.73	0.93	0.48	0.39
TOTAL	98.59	99.89	99.89	99.56	99.76	99.69	99.72	99.65	98.94	98.95	98.96
CaO/Al_2O_3	0.66	0.65	0.64	0.67	0.66	0.67	0.67	0.66	0.65	0.64	0.66
Rb	67.35	67.39	68.25	65.95	54.81	55.09	65.94	67.74	65.89	67.26	66.43
Cs	4.26	4.30	4.34	4.24	3.49	3.41	4.30	4.24	3.88	3.99	4.36
Sr	689.30	706.30	706.80	681.30	678.50	685.30	699.30	715.80	697.80	697.80	693.00
Ba	910.20	929.80	943.30	917.90	843.20	824.90	944.10	937.40	924.90	930.45	919.10
Ta	1.13	1.20	1.22	1.20	1.03	1.00	1.19	1.17	1.14	1.18	1.14
Th	14.39	14.88	14.92	14.58	12.12	11.80	14.86	14.73	13.66	13.69	14.39
U	3.75	3.88	3.90	3.85	3.11	3.05	3.87	3.87	3.55	3.56	3.78
Zr	153.10	160.20	158.70	157.20	137.50	138.40	155.40	159.40	155.30	157.20	156.70
Hf	3.59	3.77	3.70	3.71	3.31	3.13	3.76	3.68	3.54	3.60	3.54
Nb	17.31	17.82	17.74	17.15	14.88	14.88	17.55	18.16	17.74	17.91	17.75
La	44.06	45.34	45.49	44.83	40.11	39.39	45.49	45.36	44.54	45.10	44.43
Ce	88.60	90.77	91.04	89.52	81.29	79.67	91.60	90.87	87.82	88.09	89.09
Nd	40.34	41.32	41.79	41.39	38.15	37.34	42.23	41.75	40.74	41.22	40.69
Sm	8.06	8.22	8.30	8.19	7.74	7.49	8.36	8.29	7.99	8.14	8.01
Eu	2.14	2.19	2.19	2.18	2.08	2.05	2.20	2.20	2.11	2.14	2.17
Tb	0.90	0.93	0.92	0.94	0.88	0.85	0.95	0.92	0.90	0.91	0.90
Yb	2.22	2.25	2.30	2.33	2.16	2.13	2.33	2.32	2.23	2.27	2.22
Lu	0.34	0.36	0.35	0.36	0.33	0.33	0.36	0.35	0.34	0.35	0.35
Y	25.29	26.01	25.50	25.73	24.06	23.74	25.92	25.68	25.13	25.49	25.24
Ni	40.92	42.59	41.69	44.72	44.97	45.89	46.15	44.86	41.22	41.42	45.77
Cr	54.94	58.33	51.90	57.16	49.76	51.08	67.39	53.88	50.63	53.80	53.94
V	259.40	269.80	265.00	274.40	255.30	260.90	268.90	262.50	257.10	263.05	265.20
Co	30.95	31.64	30.67	33.86	31.48	32.36	33.46	33.20	30.46	30.94	32.78
Cu	86.79	102.30	88.88	86.64	106.60	105.80	86.07	80.37	98.08	98.26	90.34

Table 4 - Sr and Nd isotope ratios on the products erupted in the 2007 crisis

Sample	Lithotype	Date	$^{87}Sr/^{86}Sr$	2σ	$^{143}Nd/^{144}Nd$	2σ
STR 270207	**Lava**	**2/27/2007**	**0.706158**	**0.000006**	**-**	**-**
STR 270207	Lava	2/27/2007	0.706155	0.000006	-	-
STR 270207 pdf	Lava groundmass	2/27/2007	0.706147	0.000007	-	-
STR 020307	**Lava**	**3/2/2007**	**0.706159**	**0.000007**	**0.512550**	**0.000005**
STR 020307	Lava	3/2/2007	0.706160	0.000007	-	-
STR 020307 gm	**Lava groundmass**	**3/2/2007**	**0.706161**	**0.000006**	**0.512549**	**0.000004**
STR 020307 pdf	Lava groundmass	3/2/2007	0.706151	0.000006	-	-
STR 020307 px	**Lava Clinopyroxene**	**3/2/2007**	**0.706454**	**0.000006**	**-**	**-**
STR 020307 ol	**Lava Olivine**	**3/2/2007**	**0.706162**	**0.000006**	**-**	**-**
STR 080307 A	**Lava**	**3/8/2007**	**0.706164**	**0.000006**	**0.512549**	**0.000005**
STR 080307	Lava	3/8/2007	0.706151	0.000007	-	-
STR 100307 A	**Lava**	**3/10/2007**	**0.706228**	**0.000006**	**0.512546**	**0.000005**
STR 100307 A gm	**Lava groundmass**	**3/10/2007**	**0.706156**	**0.000006**	**0.512547**	**0.000004**
STR 100307 A px	**Lava Clinopyroxene**	**3/10/2007**	**0.706204**	**0.000006**	**-**	**-**
STR 100307 A ol	**Lava Olivine**	**3/10/2007**	**0.706156**	**0.000006**	**-**	**-**
STR 150307 A	**Pomice lapilli**	**3/15/2007**	**0.706140**	**0.000006**	**0.512562**	**0.000004**
STR 150307 A v. ch.	**Pumice light glass**	**3/15/2007**	**0.706127**	**0.000006**	**-**	**-**
STR 150307a Pdf1	Pumice light glass	3/15/2007	0.706123	0.000007	-	-
STR 150307b Pdf	Pumice light glass	3/15/2007	0.706127	0.000007	-	-
STR 150307 A v. sc.	**Pumice reddish glass**	**3/15/2007**	**0.706128**	**0.000006**	**0.512558**	**0.000005**
STR 150307a Pdf2	Pumice reddish glass	3/15/2007	0.706130	0.000007	-	-
STR 150307 A px	**Pumice Clinopyroxene**	**3/15/2007**	**0.706174**	**0.000006**	**-**	**-**
STR 150307 F	**Scoria bomb**	**3/15/2007**	**0.706166**	**0.000006**	**0.512552**	**0.000004**
STR 150307d Pdf	Scoria bomb glass	3/15/2007	0.706148	0.000007	-	-
STR 180307	**Lava**	**3/18/2007**	**0.706162**	**0.000005**	**-**	**-**
STR 180307	Lava	3/18/2007	0.706160	0.000007	-	-
STR 180307	Lava groundmass	3/18/2007	0.706151	0.000006	-	-
STR 260307	**Lava**	**3/26/2007**	**0.706153**	**0.000006**	**0.512547**	**0.000005**
STR 260307	Lava	3/26/2007	0.706155	0.000007	-	-
STR 290307	**Lava**	**3/29/2007**	**0.706156**	**0.000006**	**-**	**-**
STR 290307	Lava	3/29/2007	0.706158	0.000006	-	-
STR 300307	Lava	3/30/2007	0.706161	0.000006	-	-
STR 020407	**Lava**	**4/2/2007**	**0.706163**	**0.000006**	**0.512549**	**0.000004**
STR 020407	Lava	4/2/2007	0.706153	0.000007	-	-
STR 020407 pdf	Lava groundmass	4/2/2007	0.706146	0.000007	-	-

Data from the Florence lab: in larger character and not in bold, data from the Naples lab: in smaller character and in bold; 2σ =internal error.