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The volcanic activity of Stromboli in the 1906–1998 AD period: mineralogical, geochemical and isotope data relevant to the understanding of the plumbing system

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Abstract

Volcanic activity of Stromboli in the last 100 years was characterised by regular Strombolian eruptions with some occurrences of major explosions and paroxysms at the summit crater and lava flows down into the Sciara del Fuoco. Two types of juvenile fragments, shoshonitic to high-K basalts in composition, are peculiarly outpoured during major explosions: black scoriae, similar to those erupted by the normal Strombolian activity, representing a highly porphyritic (45–60 vol%), volatile-poor magma (HP magma) and a small volume of light pumice, representing a low-porphyritic (< 10 vol%), volatile-rich magma (LP magma). Lava flows are constituted by the HP magma. The LP magma has a less evolved composition, lower incompatible trace element contents and Sr isotope ratios (0.70610) than the HP magma. Mineral phases in equilibrium with the LP and HP magmas have distinct compositions (Fo% in olivine: 80–85 and around 70, Mg# in clinopyroxene: 0.83–0.91 and around 0.75, An% in plagioclase: 80–90 and around 65, respectively), in spite of syn-eruptive mingling, and disequilibrium processes lead to large compositional ranges in minerals of both LP and HP magmas. Olivine and clinopyroxene of pumice were equilibrated at higher temperatures (and probably higher pressures) than the same crystals of scoriae. All these data provide evidence that the two magmas are characterised by sharply distinct physico-chemical conditions. It has also been pointed out that the plumbing system is under overall steady-state conditions. The HP magma resides at shallow level and evolves in a continuously erupting, crystallising (olivine+clinopyroxene+plagioclase) and replenished reservoir, which is fed by the LP magma. The LP magma derives from a deeper reservoir in which it undergoes limited crystallisation of feric phases. Plagioclase begins to crystallise only at lower depth. Significant geochemical, mineralogical and isotope variations with time in scoriae and lavas of the 20th century are observed. The MgO, V, Ni and Cr contents of magmas slightly increase from 1906 to 1930, then decrease from 1965 towards the present. Mineral chemistry data also vary accordingly. An increase of incompatible trace element contents after 1930 and a decrease of Sr isotope ratios after 1980–85 (from 0.70626 to 0.70616) have also been pointed out. These variations are thought to be due to changes in the crystallisation/replenishment equilibrium of the magma reservoir or to compositional modifications of the feeding magma. Some correlations between the main compositional variations and the type of eruptive activity also seem to be present. The occurrence of relatively frequent paroxysms during the first part of the 20th century, associated with the observed decrease of magma evolution, seems to indicate that more energetic explosions are associated with the rise of a higher volume of refreshing magma.

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1. Introduction

Stromboli volcano is characterised by a mild explosive ‘Strombolian’ activity since about 1800 years, which takes place from several vents at variable intervals, outpouring scoriaceous, black juvenile ejecta, with shoshonitic to high-K basaltic composition. This ‘normal’ activity is sometimes interrupted by more violent explosions and/or lava flow eruptions. A small amount of pumiceous, light juvenile material is also outpoured during the more violent eruptions.

In spite of many researchers that have recently focussed their studies on rocks and volatiles from this activity, in order to understand how it works, which parameters play an active role and when the more violent eruptions occur (e.g. Giberti et al., 1992; Allard et al., 1994, 2000; Bonaccorso et al., 1996; Harris and Stevenson, 1997; Francalanci et al., 1999; Rosi et al., 2000; Métrich et al., 2001), this Strombolian activity has still to be fully understood.

This paper reports a complete set of mineralogical, chemical and isotopic analyses (not available in the literature yet) on dated rocks erupted from Stromboli activity during the 20th century, with the aims to (1) reveal possible compositional variations with time useful to shed light on the behaviour of the volcanic system, (2) understand the relationships between the two magmas erupted and how these interferences act on the eruptive events, (3) make available a data base with which to compare the compositions of the new products erupted by the future Strombolian activity.

2. Volcanological and petrological background

Stromboli is a stratovolcano forming the northernmost island of the Aeolian volcanic arc in the Southern Tyrrhenian sea. It rises from a depth of about 2000 m below sea level (bsl) to an elevation of 924 m above sea level (asl) (Fig. 1), lying upon

a 20-km thick continental crust (Morelli et al., 1975). The subaerial part of the main cone was built up during the last 100 ka through mainly effusive activity and minor explosive eruptions. The Strombolicchio neck, located about 1.7 km NE of Stromboli and belonging to the same submarine edifice, is represented by the oldest subaerial rocks of the volcano, with an age of 204 ± 25 ka (Gillot and Keller, 1993). Several collapses alternated with periods of volcano building, leading to the formation of some peculiar features, such as the Sciara del Fuoco scar, a steep trough on the NW flank of Stromboli, and the crater terrace, where the present-day activity takes place (Fig. 1) (Rosi, 1980; Hornig-Kjarsgaard et al., 1993; Pasquare` et al., 1993; Kokelaar and Romagnoli, 1995). The rock composition shows a large variation, ranging from calc-alkaline (mainly basaltic andesites), to potassic-alkaline (potassic trachybasalts and shoshonites), through high-K calc-alkaline (high-K basalts to high-K andesites) and shoshonitic (shoshonitic basalts to few trachytes) (Francalanci et al., 1989; 1993a, 1993b; Hornig-Kjarsgaard et al., 1993). The rocks of the Recent period of activity, younger than 5.6 ± 3.3 ka (Gillot and Keller, 1993), are formed by the pyroclastic cone of Pizzo Sopra la Fossa, with shoshonitic basalt composition, by the high-K basalts of S. Bartolo lavas, and by the products of the present-day activity, which are younger than Pizzo pyroclastic rocks (Hornig-Kjarsgaard et al., 1993).

The potassium content is positively correlated with the incompatible trace element contents. A broad positive correlation is also observed between K_2O and Sr isotope ratios, with calc-alkaline magmas having lower $^{87}Sr/^{86}Sr$ than potassic-alkaline magmas (general range from 0.70519 to 0.70757, respectively; Francalanci et al., 1988; Luais, 1988). A detailed analysis of Sr isotope variations reveals, however, some exceptions to this rule. The old high-K calc-alkaline and shoshonitic series have similar $^{87}Sr/^{86}Sr$ values, between

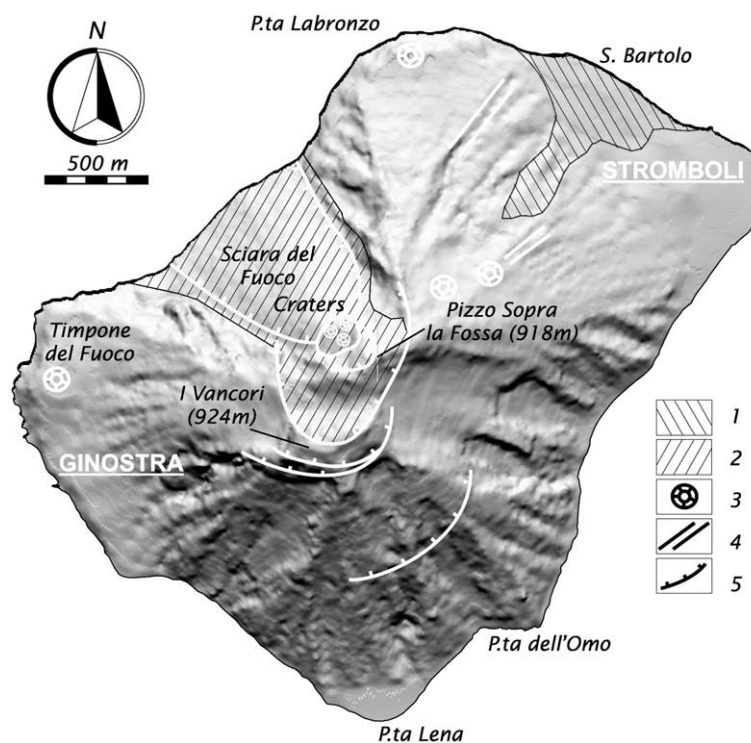


Fig. 1. Topographic map of the subaerial part of Stromboli volcano with reported deposits of the Recent period (from [Hornig-Kjarsgaard et al., 1993](#)) and the tectonic structures (from [Pasquare' et al., 1993](#)). Legend: 1, San Bartolo lavas; 2, Pizzo Sopra la Fossa pyroclastic deposits and products of the present-day activity; 3, eruptive vents; 4, eruptive fractures; 5, caldera and sector collapses.

0.70583 and 0.70599 ([Francalanci et al., 1988](#)), which are lower than younger rocks with a similar serial affinity. In the Recent period, for example, a basaltic shoshonitic scoriae of Pizzo Sopra la Fossa has given a $^{87}\text{Sr}/^{86}\text{Sr}$ value of 0.706638 ± 0.000010 and the high-K basaltic lavas of S. Bartolo have Sr isotope ratios around 0.70633 ([Francalanci et al., 1988](#)).

Stromboli magmas underwent variable and complex processes of evolution, such as simple fractional crystallisation, crustal assimilation, mixing and a combination of the previous processes (AEC, RTFA), probably occurring in magma reservoirs at various depths ([Francalanci et al., 1988; 1989; 1993a; Vaggelli et al., 2003](#)). Variable partial melting degrees of a heterogeneous mantle wedge have also been proposed in order to explain the genesis of the different parental magmas ([Francalanci et al., 1988; 1989; 1993a; Luais, 1988; Ellam et al., 1989](#)).

3. The present-day activity and its products

The present-day activity takes place from three main, NE–SW aligned, craters on a terrace at 750 m asl inside the Sciara del Fuoco depression and beneath the peak of Pizzo Sopra la Fossa (918 m). The routine activity consists of mild explosions lasting for a few seconds, at variable intervals (ca three to five events per hour), from vents where magma is usually visible in the open conduits. Each explosion ejects black scoriaceous bombs and lapilli, blocks and ash at variable heights (from a few tens to hundreds of metres), which fall around the craters and run off along the Sciara del Fuoco. A continuous stream of gas, with an estimated output of 6000–12 000 ton/day and mainly formed by H_2O , CO_2 and SO_2 ([Allard et al., 1994, 2000](#)), also commonly occurs.

The normal Strombolian activity is periodically broken by lava flow eruptions and by more vio-

lent explosions than those occurring during the ordinary activity. Lavas are constrained to flow down along the Sciara del Fuoco depression and are often associated with more violent explosions (Fig. 2). They are erupted with variable time intervals (ca 4 years on average, with a maximum time lag of 15 years; Fig. 2) and durations (< 3 days to 11 months) (Barberi et al., 1993). After the last noticeable event, which occurred in December 1985–April 1986 (De Fino et al., 1988), a lava flow was outpoured from the 28th of December 2002 to the end of July 2003.

The more violent explosions have been divided into ‘major explosions’ and ‘paroxysms’ by Barberi et al. (1993) (Fig. 2), on the basis of hazard implications and intensity of phenomena. ‘Major explosions’ do not generally have the potential of affecting the settled areas and consist of short-lived explosions, occurring as one discrete blast or as a cluster of blasts at intervals of a few seconds to tens of minutes. Metre-sized scoriaceous bombs and blocks fall within a distance of several hundreds of metres (including the Pizzo Sopra la Fossa rim and the path to the top), whereas lapilli and ash can reach the coastal zones (Barberi et al., 1993; Rosi et al., 2000). The frequency of these explosions is variable and some of them could not have been discovered in the past due to the lack of continuous observations. Three ‘major explosions’ per year have occurred over the period 1993–1998 (Bertagnini et al., 1999). ‘Paroxysms’ have generally produced some effects on inhabitants and/or villages of the island (e.g. the 1930 eruption) and are characterised by higher

volumes of erupted juvenile and lithic components. Coarse blocks and bombs up to 10 ton can reach the coast around the island and eruptions of lapilli and ash lead to the formation of widespread tephra layers (Barberi et al., 1993). The last paroxysm occurred on April 5, 2003, when the lava flow eruption was still going on.

Tsunami are sometimes associated with paroxysm crises, or with landslide phenomena as occurred on December 30, 2002 (Fig. 2).

During major explosions and paroxysms, two types of magmas are usually outpoured. The major component (ca 90%) consists of a highly porphyritic, volatile-poor magma, erupted as black scoriae and bombs, whereas the minor component (ca 10%) consists of a low-porphyritic, volatile-rich magma, erupted as highly vesiculated light pumice (Bonaccorso et al., 1996; Francalanci et al., 1999; Bertagnini et al., 1999; Métrich et al., 2001). The former magma has the same characteristics as that erupted from the normal mild explosive activity and lava flow effusion, whereas the magma forming light pumice is only erupted during the most energetic eruptions. Black scoriae and light pumice are often associated and sometimes strictly intertwined in the same ejecta, probably due to syn-eruptive mingling.

On the basis of stratigraphic and radiometric studies on recent tephra deposits, it has been found that this persistent Strombolian activity abruptly began between the 3rd and 7th century AD and seems to be linked to the presence of the two types of magma (Rosi et al., 2000).

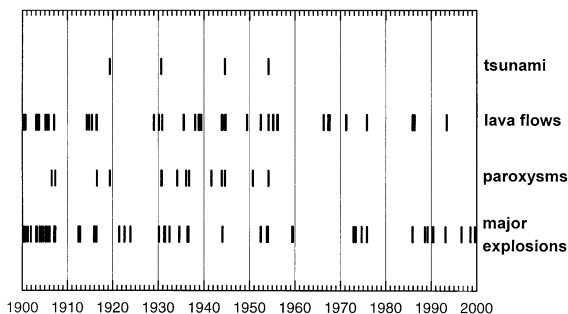


Fig. 2. More explosive events and effusive episodes occurred at Stromboli during the 20th century, according to the eruption classification and data base of Barberi et al. (1993).

4. Sampling and analytical techniques

In order to perform a time series analysis of the present-day activity of Stromboli during the 20th century, newly erupted samples have been analysed and their composition is compared with those available in the literature. New major and trace element data are reported on 22 samples erupted from 1994 to 1998, new isotope ratio analyses are performed, for $^{87}\text{Sr}/^{86}\text{Sr}$, on five samples from 1998 eruptions and, for $^{143}\text{Nd}/^{144}\text{Nd}$, on seven samples from 1996 and 1998 eruptive events.

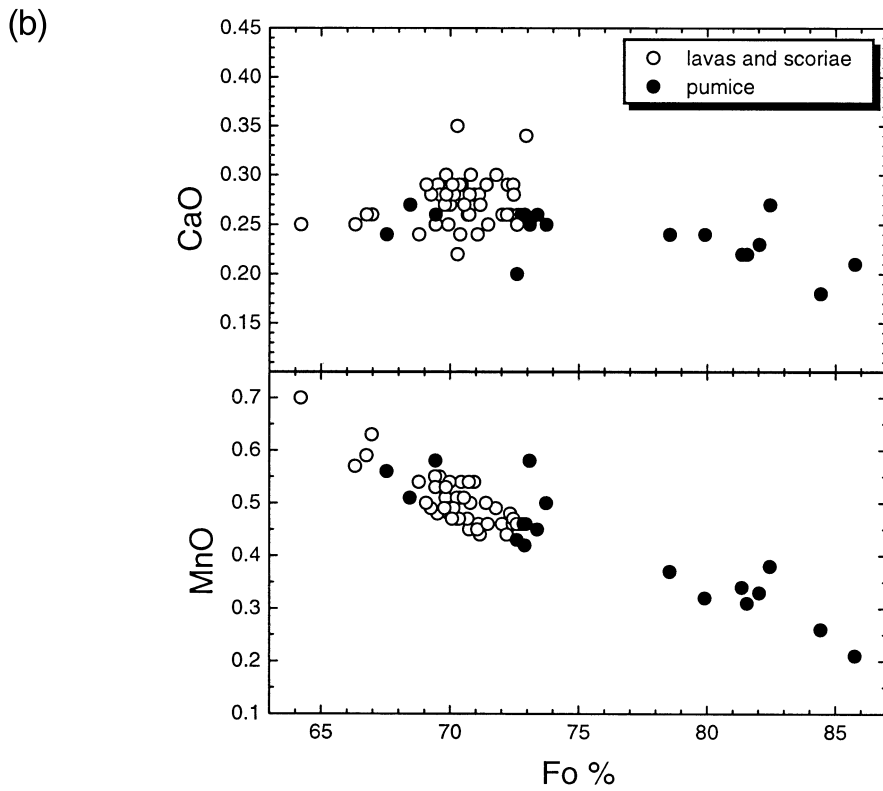
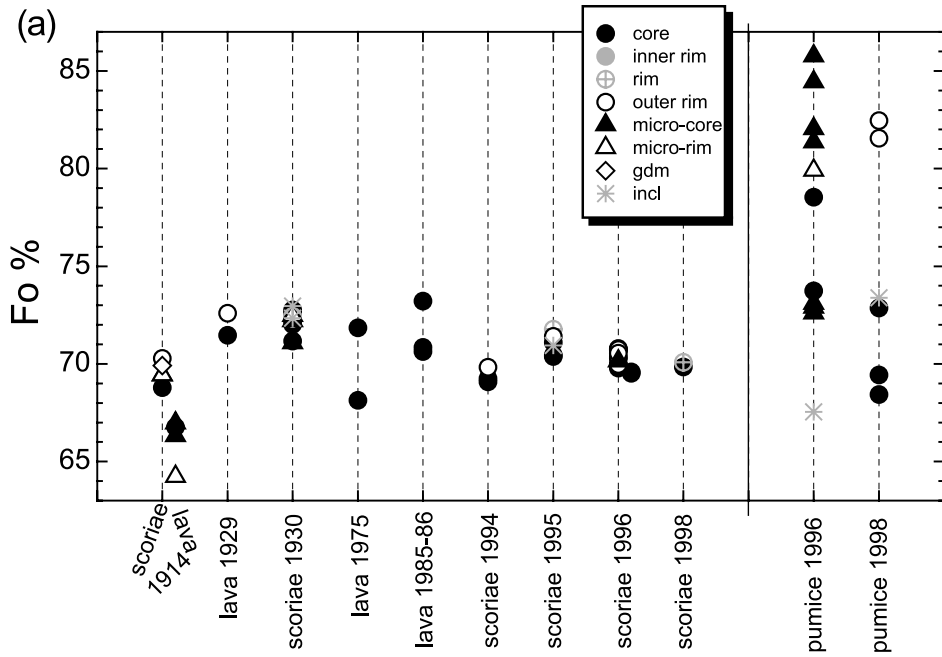
Table 1
Representative analyses of olivine from eruptions of the 20th century at Stromboli volcano

Year:	1914	1914	1914	1929	1929	1930	1930	1975	1985
Date:	March 29	March 29	March 29	?	?	Sept. 11	Sept. 11	Nov. 11	Dec. 12
Product:	scoria	lava	lava	lava	lava	scoria	scoria	lava	lava
Sample:	ES10	ES21	ES21	ES281	ES281	ES204	ES204	SR1	SR3
Analyses #:	8	1	2	6	7	13	14	–	–
Where:	gdm	micro core	micro rim	core	rim	core	rim	core	core
SiO ₂	37.4	37.3	37.1	38.2	38.1	38.4	37.9	37.8	37.2
TiO ₂	bdl	bdl	0.03	bdl	bdl	bdl	0.03	0.04	bdl
Al ₂ O ₃	0.05	bdl	0.05	bdl	bdl	0.04	0.04	bdl	bdl
Cr ₂ O ₃	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl
FeO	26.7	29.7	30.8	25.6	24.8	24.9	24.6	24.9	25.9
MnO	0.49	0.57	0.70	0.46	0.46	0.46	0.46	0.56	0.56
NiO	0.08	0.04	0.02	0.08	0.04	0.05	0.06	nd	nd
MgO	35.9	33.8	32.0	37.1	38.0	37.1	37.6	37.2	36.3
CaO	0.25	0.25	0.25	0.25	0.25	0.26	0.29	0.38	0.35
Sum	100.8	101.6	101.0	101.7	101.7	101.2	101.0	100.9	100.3
Fo	69.92	66.32	64.22	71.47	72.59	72.02	72.44	71.85	70.63
Fa	29.19	32.70	34.62	27.68	26.57	27.11	26.65	27.01	28.26
La	0.35	0.35	0.36	0.35	0.34	0.36	0.40	0.53	0.49
Tp	0.54	0.64	0.80	0.50	0.50	0.51	0.50	0.61	0.62
Year:	1994	1994	1995	1995	1996	1996	1996	1996	Olivine
Date:	Sept. 6	Sept. 6	Sept. 15	Sept. 15	Sept. 4	Sept. 4	Sept. 4	Sept. 4	San Carlos
Product:	scoria	scoria	scoria	scoria	pumice	pumice	scoria	scoria	USNM
Sample:	STR9/94a	STR9/94a	STR9/95b	STR9/95b	STR9/96d	STR9/96d	STR9/96e	STR9/96e	111312/444
Analyses #:	5	6	30	31	2	6	1	2	
Where:	core	rim	core	rim	micro core	micro rim	core	rim	
SiO ₂	37.6	38.0	37.7	37.6	40.0	39.1	37.9	37.7	40.9
TiO ₂	bdl	0.05	bdl	bdl	bdl	bdl	bdl	bdl	bdl
Al ₂ O ₃	bdl	bdl	bdl	0.03	0.03	bdl	0.10	bdl	bdl
Cr ₂ O ₃	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl
FeO	27.3	26.7	26.3	25.6	14.6	18.5	25.9	26.1	9.72
MnO	0.49	0.51	0.54	0.50	0.26	0.32	0.47	0.54	0.15
NiO	0.03	0.08	0.04	0.03	0.13	0.03	0.04	0.03	0.36
MgO	35.6	35.8	36.4	37.1	45.8	42.7	36.1	36.6	49.5
CaO	0.28	0.30	0.29	0.29	0.18	0.24	0.26	0.26	0.09
Sum	101.3	101.5	101.4	101.2	100.9	101.1	100.9	101.4	100.7
Fo	69.18	69.76	70.37	71.33	84.43	79.83	70.61	70.66	
Fa	29.78	29.16	28.53	27.62	15.05	19.41	28.40	28.29	
La	0.49	0.52	0.50	0.50	0.24	0.42	0.46	0.46	
Tp	0.54	0.56	0.59	0.55	0.27	0.34	0.52	0.59	

Fo, forsterite; Fa, fayalite; La, larnite; Tp, tephroite; gdm, groundmass. The data reported for the San Carlos Olivine reference sample are the average of about 70 analyses. bdl, below detection limit.

Newly erupted rocks were sampled using different methods: (1) sampling of scoriae that burned the electric wires of the permanent network of geophysical monitoring and interrupted the signal with the remote station, providing the precise date

and time of eruption; (2) collection, in the vicinity of the vents, of scoriae and pumice fallen down over sheets previously placed on the ground; (3) direct sampling of still hot samples, when it was possible to observe their falling trajectories.



Samples of the eruptions from 1906 to 1930 were from the ‘Stiftung Vulkaninstitut Immanuel Friedlander’ (Zürich, Switzerland) collection, and they have been kindly supplied by Jörg Keller (Freiburg, Germany).

Mineral chemistry data were obtained for the whole set of samples using a Jeol JXA 8600 superprobe with 15 kV accelerating voltage, 10 nA beam current and variable counting times for major and minor elements; matrix correction was performed according to the method of Bence and Albee (1968) and Albee and Ray (1970). A detailed description of the analytical procedure with precision and accuracy of measurements is provided by Vaggelli et al. (1999). CaO contents in olivine was determined using considerably higher counting times (120 s) to reach a precision of ± 0.01 wt% CaO. The San Carlos SC/KA olivine (Smithsonian Institution of Washington) was used as secondary reference sample. This reference sample was provided by courtesy of Gerhard Brey (Frankfurt am Main, Germany) who determined the Ca concentration by isotope dilution and ionic microprobe ($\text{Ca} = 524 \pm 4$ ppm) (Köhler and Brey, 1990).

Major and trace elements on whole rocks were determined by X-ray fluorescence (XRF), wet chemical methods and INAA. MgO, K_2O , Na_2O and random check on CaO contents were determined by AAS, FeO by titration (Shapiro and Brannock, 1962), and LOI using gravimetric method. The other major elements were determined by XRF, using the correction method proposed by Franzini et al. (1972). Trace elements were also determined by XRF using the matrix effect correction proposed by De Vries and Jenkins (1971), whereas Sc, Co, Ta, Hf, Th and RE elements were determined by INAA using the method proposed by Poli et al. (1977). Uncertainty for trace elements was estimated to be $< 15\%$ for Lu and Yb, $< 10\%$ for Tb, Y, Nd, Cr, and $< 5\%$ for all other elements.

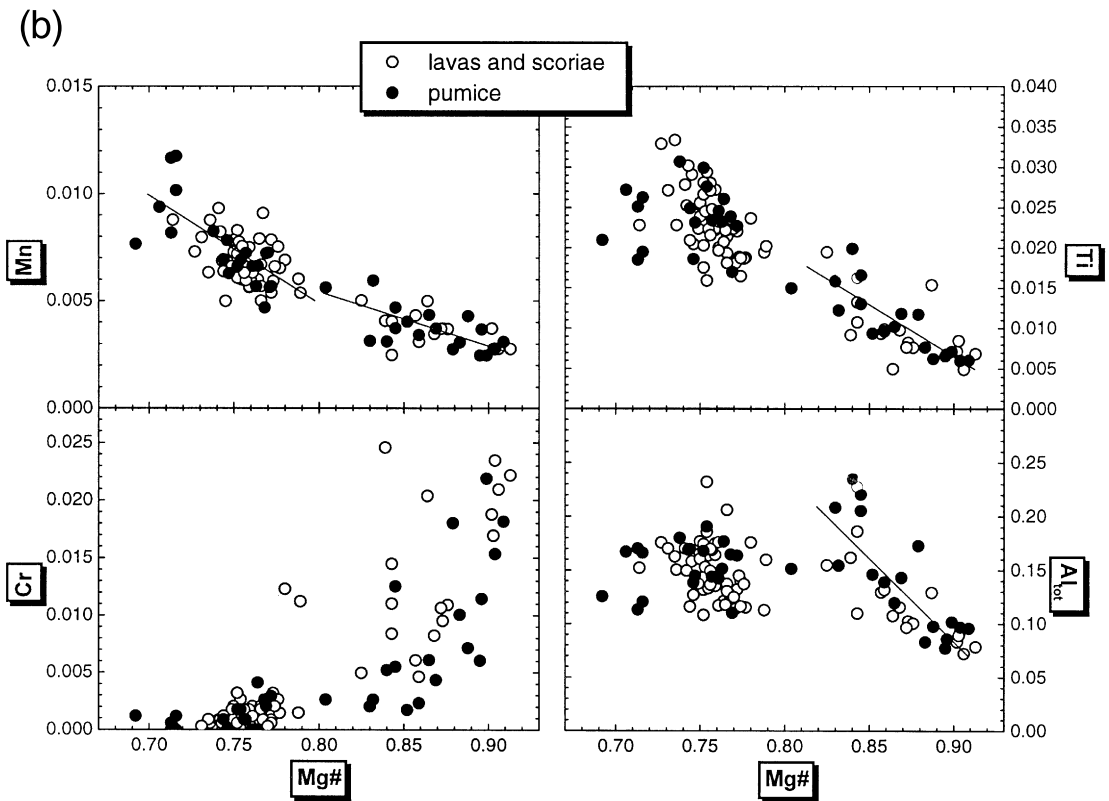
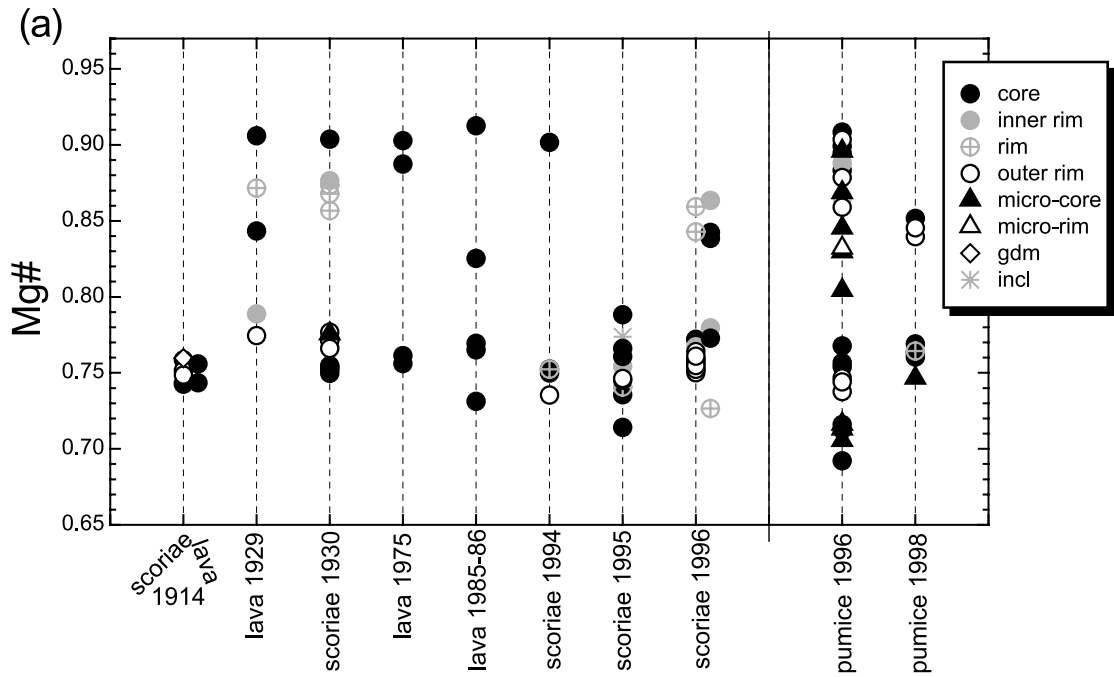
Sr and Nd isotope ratios have been performed at the Radiogenic Isotope Laboratory of the Dipartimento di Scienze della Terra of the Università degli Studi di Firenze using standard chemical separation techniques and a thermal ionisation mass spectrometer Finnigan Triton TI©, equipped with nine movable collectors. $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ values were measured in static mode, using the new ‘virtual amplifier’ technique. Sr and Nd isotope ratios are presented as exponential low corrected for mass fractionation to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$, respectively. Replicate measurement of NBS 987 and the La Jolla standard gave mean values of $^{87}\text{Sr}/^{86}\text{Sr} = 0.710257 \pm 10$ (2σ , $n = 25$) and of $^{143}\text{Nd}/^{144}\text{Nd} = 0.511844 \pm 11$ (2σ ; $n = 27$).

5. Petrography and mineral chemistry

Black scoriae and lavas show similar petrographic characteristics, which have not significantly changed since 1906. They have highly porphyritic seriate texture (ca 45–60 vol% of phenocrysts and microphenocrysts) with mainly hyaline groundmass in scoriae and mainly microcrystalline groundmass in lavas. Phenocrysts are composed of olivine (on average ≈ 5 vol%), clinopyroxene (on average ≈ 15 vol%) and plagioclase (on average ≈ 35 vol%). Clinopyroxenes are up to 2 cm long, showing the largest size, followed by olivine and some crystals of plagioclase (up to 0.5 cm). Microphenocrysts are mostly represented by plagioclase and rare olivine. Olivine and clinopyroxene often occur as glomeroporphyritic aggregates, sometimes associated with small interstitial plagioclase.

Light pumice shows poorly porphyritic seriate textures (< 10 vol%, usually ≈ 5 vol%) with glassy groundmass. Phenocrysts and microphenocrysts consist of olivine, clinopyroxene and plagioclase, with femic phases/plagioclase propor-

Fig. 3. Olivine composition of rocks erupted in the present-day activity of Stromboli during the 20th century. (a) Variation of forsterite (Fo mol%) content with time and within the same eruptive event and/or crystal. Circles, phenocrysts; triangles, microphenocrysts; diamonds, groundmass (gdm) crystal; asterisk, crystal included in other minerals. Data source for 1975 and 1985–86 eruptions from Capaldi et al. (1978) and De Fino et al. (1988). (b) Diagrams of forsterite (Fo mol%) versus MnO (wt%) and CaO (wt%) contents.



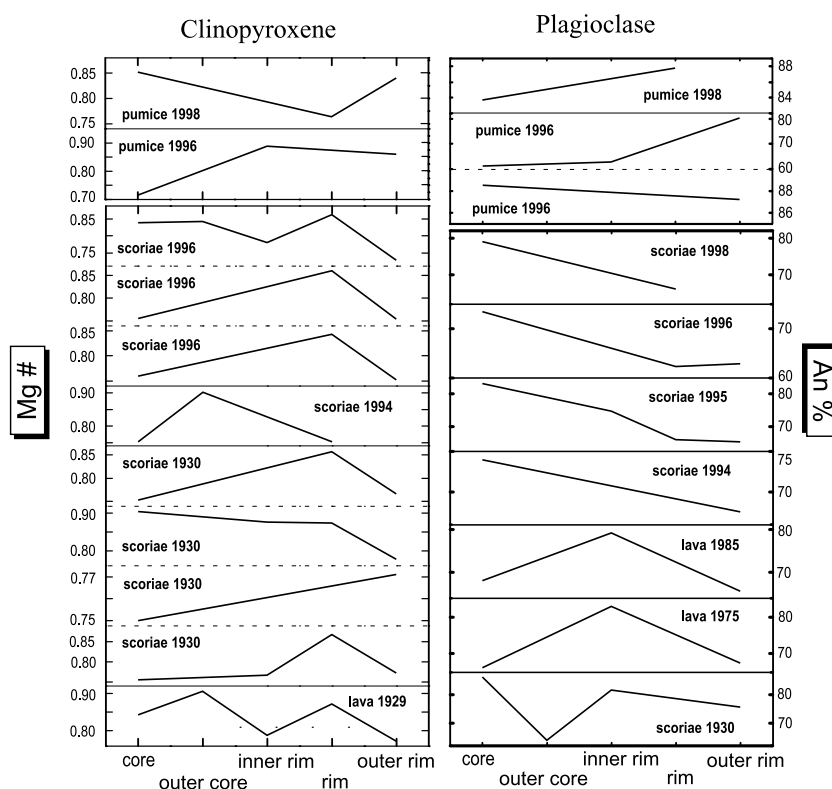


Fig. 5. Compositional zoning in clinopyroxene and plagioclase of rocks erupted from Stromboli during the 20th century. Mg#, mol $Mg^{2+}/(Mg^{2+}+Fe^{2+})$ in clinopyroxene; An % = anorthite percentage in plagioclase.

tions generally higher than unity, although also variable among the samples of the same eruption. Crystals have usually smaller size than those of black scoria and lavas, with a large prevalence of microphenocrysts.

5.1. Olivine composition

Olivine cores are often rich in melt inclusions. Olivine from black scoriae and lavas has not shown significant variations since the beginning of the 20th century, ranging from 64% to 74% of forsterite (Fo) content (Table 1 and Fig. 3a). Only small differences are observable in detail.

Olivine from 1914 lava has lower Fo content (Fo < 68%) than all of the other olivine, including those of 1914 scoriae. Olivine from 1914 lava and scoriae also shows lower Fo content than those of the successive 1929 and 1930 eruptions. If present, zoning is usually small (e.g. 68.8–70.2% of Fo content) and it can be normal (e.g. 1914 lava) or reverse (e.g. 1914 scoriae, 1929 lava).

Olivine crystals from light pumices cover a larger range of composition than those from scoriae and lavas, varying from Fo 68% to 86% (Fig. 3a and Table 1). Cores of phenocrysts have compositions generally similar to the olivine from scoriae and lavas (Fo 68–74%), whereas rims and

Fig. 4. Clinopyroxene composition of rocks erupted in the present-day activity of Stromboli during the 20th century. (a) Variation of Mg# (mol $[Mg^{2+}/(Mg^{2+}+Fe^{2+})]$) with time and within the same eruptive event and/or crystal. Circles, phenocrysts; triangles, microphenocrysts; diamonds, groundmass (gdm) crystal; asterisk, crystal included in other minerals. Data source for 1975 and 1985–86 eruptions from Capaldi et al. (1978) and De Fino et al. (1988). (b) Diagrams of Mg# versus Cr, Mn, Ti and Al_{tot} .

Table 2

Representative analyses of clinopyroxene from eruptions of the 20th century at Stromboli volcano

Year:	1914	1914	1929	1929	1930	1930	1975	1975	1985	1985
Date:	Mar. 29	Mar. 29	?	?	Sept. 11	Sept. 11	Nov. 11	Nov. 11	Dec. 12	Dec. 12
Product:	scoria	scoria	lava	lava	scoria	scoria	lava	lava	lava	lava
Sample:	ES10	ES10	ES281	ES281	ES204	ES204	SR1	SR1	SR3	SR3
Analyses #:	2	1	1	5	12	15	DF'88	DF'88	DF'88	DF'88
Where:	core	rim	out rim	core	core	out rim	core	rim	core	rim
SiO ₂	49.9	51.1	51.3	52.2	50.3	51.8	53.2	50.0	50.6	50.6
TiO ₂	0.90	0.73	0.67	0.39	0.92	0.68	0.31	0.97	0.70	0.80
Al ₂ O ₃	3.40	2.49	2.66	2.54	3.68	2.67	2.08	3.88	3.55	2.85
Cr ₂ O ₃	0.03	bdl	0.07	0.38	0.07	0.05	0.59	0.06	0.17	bdl
FeO	8.83	8.90	7.72	5.23	8.60	7.74	3.20	8.04	5.80	7.86
MnO	0.26	0.20	0.21	0.13	0.25	0.21	0.09	0.20	0.16	0.23
MgO	14.7	15.5	15.3	16.2	14.9	15.5	17.2	14.3	15.8	15.2
CaO	20.9	20.9	21.3	22.6	20.9	21.6	23.4	22.0	22.2	21.5
Na ₂ O	0.35	0.36	0.27	0.25	0.35	0.31	0.15	0.27	0.21	0.27
Sum	99.2	100.1	99.5	99.9	100.0	100.6	100.2	99.7	99.2	99.3
Fe ₂ O ₃	3.59	3.62	1.96	1.74	3.06	2.44	0.65	2.79	2.63	3.00
FeO	5.60	5.64	5.96	3.67	5.85	5.55	2.61	5.53	3.44	5.16
En	42.26	43.48	43.60	45.73	42.65	43.74	47.94	41.28	45.04	43.11
Fe	14.66	14.37	12.70	8.49	14.25	12.56	5.16	13.31	9.53	12.91
Wo	43.08	42.16	43.70	45.77	43.10	43.70	46.90	45.41	45.43	43.98
Mg#	0.742	0.752	0.774	0.843	0.750	0.777	0.903	0.756	0.825	0.770

Year:	1994	1994	1995	1996	1996	1996	1996	1996	1996	Augite
Date:	Sept. 6	Sept. 6	Sept. 15	Sept. 4	Sept. 4	Sept. 4	Sept. 4	Sept. 4	Sept. 4	Kakanui
Product:	scoria	scoria	scoria	pumice	pumice	pumice	scoria	scoria	scoria	USNM
Sample:	STR9/94a	STR9/94a	STR9/95b	STR9/96d	STR9/96d	STR9/96d	STR9/96e	STR9/96e	STR9/96e	122142
Analyses #:	11	12	6	14	10	8	3	2	5	
Where:	core	out rim	core	core	out rim	mic core	core	rim	out rim 3	
SiO ₂	49.7	49.6	50.1	52.8	51.4	51.4	51.0	50.5	49.6	50.3
TiO ₂	0.85	1.19	0.82	0.22	0.43	0.43	0.79	0.59	0.90	0.85
Al ₂ O ₃	3.76	3.70	3.45	2.23	4.05	3.32	3.02	5.27	4.01	8.36
Cr ₂ O ₃	0.03	0.03	bdl	0.63	0.63	0.15	0.03	0.29	0.05	0.13
FeO	8.35	8.95	9.47	3.01	4.06	4.43	7.77	5.05	8.29	6.41
MnO	0.23	0.20	0.28	0.10	0.09	0.12	0.25	0.08	0.20	0.15
MgO	14.4	14.3	15.2	17.3	16.9	16.9	15.3	15.4	14.3	16.4
CaO	21.4	21.3	20.4	23.2	22.9	22.7	21.3	22.6	21.2	16.0
Na ₂ O	0.35	0.31	0.35	0.13	0.22	0.19	0.24	0.20	0.33	1.30
Sum	99.1	99.6	100.1	99.6	100.6	99.5	99.6	99.9	98.9	99.8
Fe ₂ O ₃	3.57	3.18	4.37	1.18	3.00	3.03	2.09	1.84	2.81	
FeO	5.14	6.09	5.54	1.95	1.36	1.70	5.89	3.39	5.76	
En	41.67	41.13	43.10	48.52	47.34	47.27	43.52	44.71	41.68	
Fe	13.90	14.80	15.49	4.89	6.54	7.15	12.85	8.34	13.89	
Wo	44.43	44.07	41.41	46.60	46.12	45.58	43.63	46.95	44.43	
Mg#	0.750	0.735	0.736	0.909	0.879	0.869	0.772	0.843	0.750	

Fe₂O₃ calculated from stoichiometry after recalculating mineral formulae on the basis of four cations. En, enstatite; Fe, ferrosilite; Wo, wollastonite; gdm, mineral from groundmass. bdl, below detection limit. Mg#, Mg/(Mg+Fe²⁺). The composition here reported of the Augite Kakanui reference sample is the average of 254 analyses. DF'88 are data from De Fino et al. (1988).

Table 3
Representative analyses of plagioclase from eruptions of the 20th century at Stromboli volcano

Year:	1930	1930	1930	1930	1975	1975	1986	1986	1986	1994	1994
Date:	Sept. 11	Sept. 11	Sept. 11	Sept. 11	Nov. 11	Nov. 11	Jan. 1	Jan. 1	Jan. 1	Sept. 6	Sept. 6
Product:	scoria	scoria	scoria	scoria	lava	lava	lava	lava	lava	scoria	scoria
Sample:	ES204	ES204	ES204	ES204	SR1	SR1	SR4	SR4	SR4	STR9/94a	STR9/94a
Analyses #:	32	33	34	35	DF'88	DF'88	DF'88	DF'88	DF'88	9	10
Where:	core	outer core	inner rim	outer rim	core	rim	core	inner rim	outer rim	micro core	micro rim
SiO ₂	46.6	52.1	47.4	49.1	51.6	46.3	48.6	48.0	51.2	51.6	51.5
TiO ₂	bdl	0.03	0.06	0.07	nd	nd	nd	nd	nd	0.07	0.07
Al ₂ O ₃	33.7	30.0	32.8	31.3	30.2	32.9	31.0	32.1	30.1	29.7	30.1
Fe ₂ O ₃	0.88	0.87	0.81	1.34	0.83	0.97	0.88	0.89	0.81	0.87	0.80
MgO	0.08	0.11	0.12	0.28	nd	nd	nd	nd	nd	0.10	0.12
CaO	17.3	12.8	16.1	15.0	13.3	16.7	15.5	16.0	13.3	12.6	13.0
Na ₂ O	1.40	3.54	1.81	2.28	3.15	1.70	2.36	2.11	3.24	3.51	3.43
K ₂ O	0.20	0.68	0.27	0.56	0.69	0.29	0.79	0.45	0.67	0.66	0.60
SrO	0.16	0.31	0.26	0.13	nd	nd	nd	nd	nd	0.18	0.22
BaO	bdl	0.13	0.06	0.09	nd	nd	nd	nd	nd	0.08	0.05
Sum	100.3	100.6	99.7	100.2	99.8	98.8	99.1	99.6	99.3	99.4	99.9
Ab	12.62	31.88	16.61	20.81	28.80	15.31	20.64	18.72	29.42	32.13	31.18
An	86.19	63.85	81.65	75.66	67.05	82.97	74.81	78.65	66.58	63.74	65.14
Or	1.19	4.03	1.63	3.36	4.15	1.72	4.55	2.63	4.00	3.98	3.59
Cn	0.00	0.24	0.11	0.17	0.00	0.00	0.00	0.00	0.00	0.15	0.09

Year:	1995	1995	1995	1996	1996	1996	1996	1996	1996	1996	Anorthite
Date:	Sept. 15	Sept. 15	Sept. 15	Sept. 4	Sept. 4	Sept. 4	Sept. 4	Sept. 4	Sept. 4	Sept. 4	G. Sitkin
Product:	scoria	scoria	scoria	pumice	pumice	pumice	pumice	pumice	scoria	scoria	USNM
Sample:	STR9/95b	STR9/95b	STR9/95b	STR9/96d	STR9/96d	STR9/96d	STR9/96d	STR9/96d	STR9/96e	STR9/96e	137041
Analyses #:	11	17	18	1	2	4	9	10	7	8	
Where:	enclosed in cpx	micro core	micro outer rim	micro core	micro outer rim	gdm	micro core	rim sieved	core sieved	outer rim	
SiO ₂	51.7	51.0	51.1	46.0	45.5	45.7	50.8	47.3	50.0	50.2	44.1
TiO ₂	bdl	0.08	0.11	0.06	0.04	bdl	0.05	0.06	0.04	0.07	0.01
Al ₂ O ₃	29.5	30.1	29.5	33.9	34.7	34.6	29.9	33.3	31.4	31.1	35.4
Fe ₂ O ₃	0.81	0.89	0.93	0.68	0.51	0.58	0.91	0.94	0.87	0.90	0.52
MgO	0.18	0.12	0.15	0.21	0.15	0.10	0.27	0.43	0.16	0.16	0.04
CaO	12.7	13.4	13.0	18.0	18.3	18.2	13.7	16.3	14.5	14.1	19.0
Na ₂ O	3.79	3.20	3.66	1.20	1.07	1.16	3.29	1.84	3.01	3.01	0.52
K ₂ O	0.69	0.58	0.62	0.14	0.08	0.09	0.45	0.30	0.50	0.50	0.01
SrO	0.25	0.13	0.11	0.15	0.19	0.16	0.30	0.13	0.28	0.22	0.09
BaO	0.08	0.05	0.26	0.04	0.06	bdl	0.03	0.06	0.09	0.06	0.00
Sum	99.7	99.5	99.4	100.4	100.6	100.5	99.7	100.7	100.8	100.3	99.7
Ab	33.57	29.14	32.42	10.69	9.51	10.29	29.46	16.63	26.54	27.08	
An	62.26	67.29	63.50	88.42	89.91	89.19	67.84	81.47	70.40	69.85	
Or	4.02	3.48	3.61	0.82	0.47	0.52	2.65	1.78	2.90	2.96	
Cn	0.14	0.09	0.47	0.07	0.11	0.00	0.05	0.11	0.16	0.11	

Ab, albite; An, anorthite; Or, orthoclase; Cn, celsian; gdm, mineral from groundmass. DF'88 are data from the paper of De Fino et al. (1988). bdl, below detection limit; nd, not determined. The data reported for the Anorthite Great Sitkin reference sample are the average of 54 analyses.

microphenocrysts have higher Fo contents (80–86%). Thus, phenocryst zoning is reverse and larger than that of olivine from scoriae.

The Fo vs MnO and CaO diagrams clearly point out two distinct olivine groups (Fig. 3b).

One group is only constituted by pumice olivine and has higher Fo and lower MnO and CaO content than the other group, which is mainly formed by scoriae and lava olivine. A gap between 74% and 78% in Fo content is also evident.

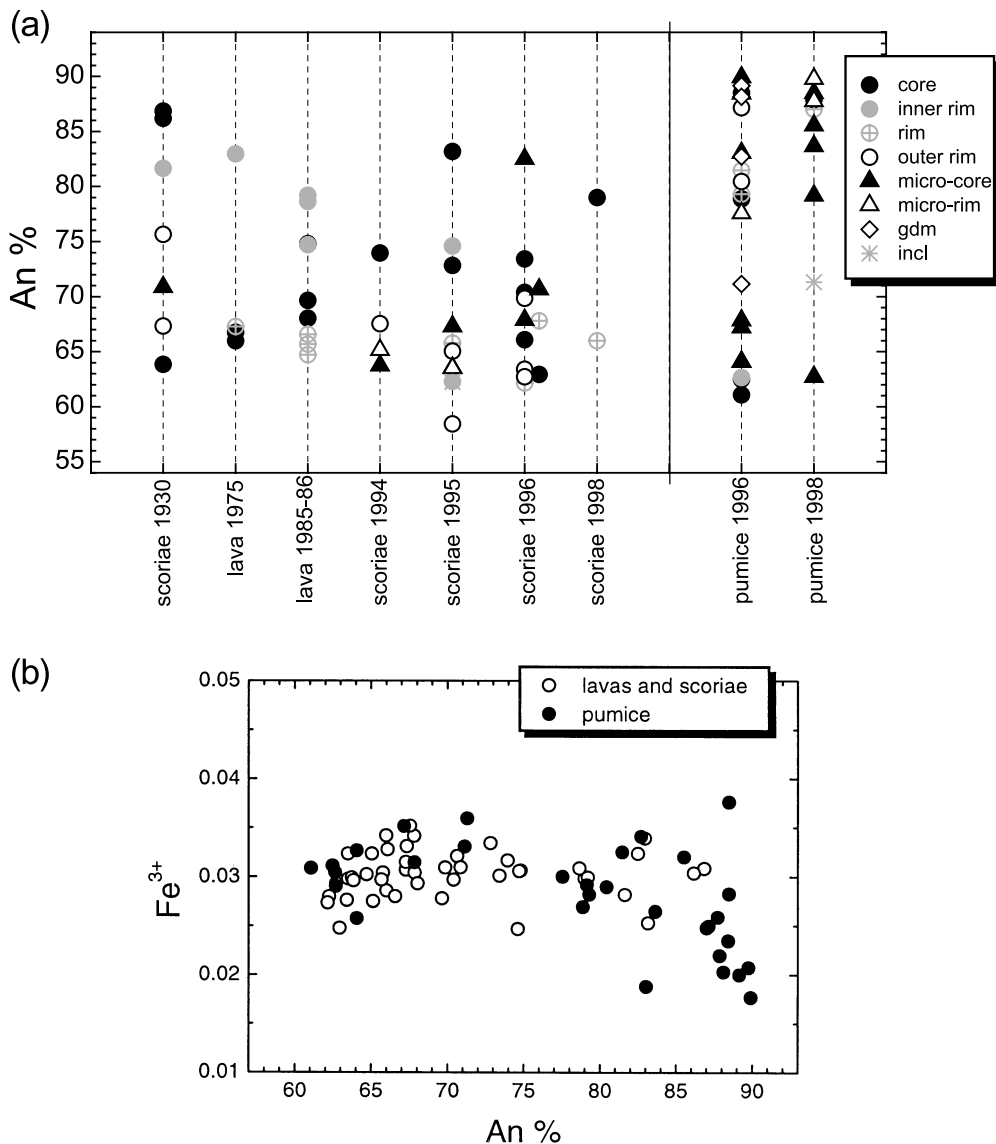


Fig. 6. Plagioclase composition of rocks erupted from Stromboli during the 20th century. (a) Variation of anorthite (An mol%) content with time and within the same eruptive event and/or crystal. Circles, phenocrysts; triangles, microphenocrysts; diamonds, groundmass (gdm) crystal; asterisk, crystal included in other minerals. Data source for 1975 and 1985–86 eruptions from Capaldi et al. (1978) and De Fino et al. (1988). (b) Diagram of anorthite (An mol%) versus Fe³⁺ contents.

5.2. Clinopyroxene composition

Under the optical microscope, clinopyroxene reveals mainly augitic composition but complex zoning, usually found in crystals of larger size. Indeed, layers (about 100–400 μm thick) of light diopsidic clinopyroxene can be found once or

twice passing from core to rim of crystals. Outer rims of clinopyroxene from scoriae and lavas have always an augitic composition and variable size (about 100–500 μm), whereas outer rims (about 50 μm thick) of clinopyroxene from pumice are sometimes diopsidic. Resorbed clinopyroxene cores, sometimes with patchy zoning, are often

Table 4
Representative analyses of glass from eruptions of the 20th century at Stromboli volcano

Year:	1930	1975	1985	1986	1986	1994	1995	1996	1996	1996	1996
Date:	Sept. 11	Nov. 11	Dec. 12	Jan. 1	Jan. 1	Sept. 6	Sept. 15	Sept. 4	Sept. 4	Sept. 4	Sept. 4
Product:	scoria	lava	lava	lava	lava	scoria	scoria	pumice	pumice	scoria	scoria
Sample:	ES204	SR1	SR3	SR4	SR4	STR9/94a	STR9/95b	STR9/96d	STR9/96d	STR9/96e	STR9/96e
Analyses #:	28	DF'88	DF'88	DF'88	DF'88	4	12	3	3	4	6
Where:	gdm	gdm	gdm	gdm	inclusion	gdm	inclusion in plg #11	gdm	gdm	gdm	gdm
SiO ₂	52.4	55.1	52.4	52.1	51.1	51.5	55.4	49.3	48.6	51.9	52.3
TiO ₂	1.44	1.54	1.62	1.62	1.56	1.73	1.25	1.02	1.05	1.69	1.53
Al ₂ O ₃	15.6	16.4	15.7	15.6	15.3	15.5	17.5	18.2	17.5	15.4	15.7
Cr ₂ O ₃	bdl	nd	nd	nd	nd	0.02	0.02	0.04	0.03	bdl	bdl
FeO	9.24	8.22	9.47	9.75	9.81	10.12	6.33	8.10	7.96	9.32	9.71
MnO	0.19	0.20	0.22	0.23	0.20	0.22	0.13	0.20	0.15	0.18	0.18
MgO	3.70	2.72	3.39	3.59	3.55	3.42	2.34	6.30	6.31	3.48	3.50
CaO	7.45	6.93	7.10	7.16	7.06	7.14	3.45	11.3	11.1	7.01	6.93
SrO	0.16	nd	nd	nd	nd	0.12	bdl	0.12	0.24	0.07	0.10
BaO	0.20	nd	nd	nd	nd	0.20	0.16	0.14	0.12	0.22	0.20
Na ₂ O	3.43	3.55	2.99	2.92	3.16	3.15	3.83	2.28	2.73	3.56	3.57
K ₂ O	4.12	4.97	4.78	4.81	5.02	4.64	6.47	1.98	2.09	4.31	4.79
P ₂ O ₅	0.95	nd	nd	nd	nd	1.20	nd	0.68	0.71	1.14	1.33
F	0.00	nd	nd	nd	nd	0.16	0.17	0.05	0.06	0.14	0.00
S	bdl	nd	nd	nd	nd	bdl	0.02	0.03	0.03	bdl	bdl
Cl	0.09	nd	nd	nd	nd	0.14	0.23	0.11	0.10	0.12	0.12
Sum	99.04	99.58	97.68	97.76	96.76	99.27	97.29	99.81	98.80	98.55	100.03
(F,Cl,S)=O	0.02	0.00	0.00	0.00	0.00	0.10	0.14	0.07	0.07	0.08	0.03
Sum	99.02	99.58	97.68	97.76	96.76	99.17	97.15	99.74	98.73	98.46	100.00
Mg#	0.417	0.371	0.390	0.396	0.392	0.376	0.397	0.581	0.586	0.400	0.391
Results of C.I.P.W. norm calculations											
or	24.66	29.46	28.88	29.04	30.62	27.76	39.50	11.77	12.56	25.95	28.37
ab	28.62	26.69	22.35	20.89	17.04	25.79	29.14	19.40	19.18	28.84	26.08
an	15.31	14.04	15.59	15.53	13.06	14.63	11.80	33.63	29.84	13.59	12.78
ne	0.43	1.87	1.90	2.36	5.72	0.65	2.35	0.00	2.33	1.01	2.27
wo	6.62	8.54	8.53	8.67	9.64	5.55	2.46	7.57	8.99	5.96	5.42
di	13.23	17.15	17.10	17.37	19.33	11.16	4.91	14.83	17.59	11.92	10.87
hy	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.86	0.00	0.00	0.00
ol	10.96	6.28	9.17	9.77	9.23	11.92	8.58	11.42	13.24	10.91	11.76
mt	1.79	1.58	1.86	1.91	1.94	1.97	1.26	1.56	1.56	1.82	1.87
il	2.77	2.93	3.15	3.14	3.06	3.33	2.45	1.95	2.03	3.27	2.91
ap	2.23	0.00	0.00	0.00	0.00	2.81	0.00	1.58	1.67	2.69	3.09
sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

gdm, glass making the groundmass. DF'88 are data from the paper of De Fino et al. (1988). bdl, below detection limit; nd, not determined.

present, especially in scoriae and lavas. Mineral chemistry data confirm the complex zoning found by the petrographic study, with oscillatory zoning also showing large Mg# [mol Mg²⁺/(Mg²⁺+Fe²⁺)] variations (e.g. 0.77–0.91) (Figs. 4a and 5a).

Clinopyroxene of lavas, scoriae and pumice

shows a similar compositional range, with Mg# from 0.69 to 0.91 (Table 2). The wide Mg# variation is also found within clinopyroxene from the same eruption and sometimes within single-large crystals (Fig. 4a).

The compositional variation of clinopyroxene during the 20th century is time-independent

Table 5a
Compositions of main eruptive events between 1906 and 1930 AD at Stromboli volcano

Year:	1906	1914	1914	1914	1929	1930	1930
Day:	–	March 29	March 30	March 15	–	Sept. 11	Sept. 11
Product:	scoria	scoria	scoria	lava	lava	scoria	scoria
Sample:	ST06	ES10	ES15	ES21	ES281	ES204	ES203
Reference:	1	1	1	1	1	1	1
SiO ₂	51.3	51.2	51.1	51.4	50.8	50.9	50.7
TiO ₂	0.91	0.88	0.87	0.92	0.82	0.84	0.84
Al ₂ O ₃	17.7	18.1	17.4	18.0	16.7	17.0	17.2
Fe ₂ O ₃	2.64	2.35	3.15	2.86	3.61	2.34	3.93
FeO	5.45	5.67	4.94	5.32	4.39	5.69	4.31
MnO	0.16	0.15	0.15	0.15	0.15	0.15	0.15
MgO	5.16	5.42	6.04	5.04	6.49	6.44	6.35
CaO	10.3	10.7	11.0	10.1	11.3	11.3	11.1
Na ₂ O	2.74	2.72	2.64	2.93	2.57	2.52	2.61
K ₂ O	2.28	2.10	2.01	2.32	2.05	2.09	2.03
P ₂ O ₅	0.53	0.47	0.45	0.52	0.47	0.48	0.50
LOI	0.40	0.27	0.32	0.35	0.62	0.25	0.30
Mg#	0.540	0.554	0.581	0.532	0.602	0.596	0.591
V	281	295	302	296	295	303	299
Cr	17	22	68	29	23	104	81
Co	36	38	39	33	40	33	37
Ni	30	31	43	27	52	47	48
Sc	21	24	22	19	22	26	24
Rb	69	65	61	71	61	61	59
Sr	662	614	587	633	632	628	637
Y	27	25	25	25	24	27	26
Zr	190	154	151	167	150	153	157
Nb	19	16	15	17	17	17	18
Ba	880	856	801	896	818	861	867
La	46	43	41	48	49	60	39
Ce	94	87	102	134	101	95	113
Nd	39	40	49	44	42	35	47
⁸⁷ Sr/ ⁸⁶ Sr _m	0.706266	0.706236	na	0.706251	0.706266	0.706259	na
2σ	0.000012	0.000011	–	0.000010	0.000010	0.000010	–
⁸⁷ Sr/ ⁸⁶ Sr _N	0.706271	0.706241	–	0.706256	0.706271	0.706264	–

Major and trace elements are from Hornig-Kjarsgaard et al. (1993). ⁸⁷Sr/⁸⁶Sr_m are values measured at Vrije Universiteit, Amsterdam, The Netherlands. ⁸⁷Sr/⁸⁶Sr_N are values normalised (Francalanci et al., 1999) to the standard values of NIST reference sample SRM 987 (0.710248; Thirlwall, 1991). na, not analysed.

(Fig. 4a), although clinopyroxene from the 1914 eruptions, like the associated olivine, has a homogeneous composition and quite low Mg# values (= 0.74–0.76). Clinopyroxene crystals of 1995 scoriae also have a narrow compositional variation, with Mg# from 0.72 to 0.79.

Two distinct groups of clinopyroxene are distinguished on the basis of minor element contents and Mg#, with a gap in Mg# from 0.79 to 0.83 where very few clinopyroxene data are found (Fig. 4b). Both groups are constituted by minerals

from scoriae and pumice. One group is characterised by higher Mg# and Cr content, lower Mn and Ti and well-defined correlations with Mg# which are negative for Al_{tot}, Mn and Ti and positive for Cr. The group at lower Mg#, on the contrary, shows a good correlation only between Mg# and Mn, even if the slope is higher than that of the correlation within the other group. Cr is present in very low amounts, Ti content is scattered at higher values, whereas Al_{tot} abundance is similar to those of the other group.

Table 5b

Compositions of main eruptive events between 1965 and 1985 AD at Stromboli volcano

Year:	1965	1975	1975	1975	1983	1984	1985
Day:	–	Nov. 11	Nov. 12	–	–	April 28	Dec. 6
Product:	scoria	scoria	lava	lava	scoria	scoria	lava
Sample:	ST65.2	Sr2	Sr1	STR153	ST346	STR45	Sr5
Reference:	1	2	2	3	1	3	2
SiO ₂	50.2	49.4	49.5	50.8	50.0	51.0	49.3
TiO ₂	0.89	1.00	0.96	0.95	0.89	0.94	1.01
Al ₂ O ₃	16.6	16.6	18.5	18.1	17.3	17.7	18.4
Fe ₂ O ₃	2.59	2.97	3.13	3.73	2.64	2.65	2.44
FeO	5.43	5.64	5.22	4.27	5.55	5.39	6.20
MnO	0.16	0.18	0.17	0.15	0.15	0.15	0.17
MgO	6.65	6.66	5.50	5.80	6.30	5.80	5.66
CaO	11.7	11.5	11.2	10.2	11.2	10.6	11.1
Na ₂ O	2.52	2.43	2.68	2.64	2.66	2.50	2.56
K ₂ O	2.21	2.11	2.14	2.43	2.25	2.22	2.16
P ₂ O ₅	0.58	0.41	0.41	0.55	0.56	0.48	0.41
LOI	0.54	1.13	0.68	0.32	0.48	0.50	0.58
Mg#	0.605	0.588	0.550	0.576	0.586	0.571	0.546
V	283	260	274	245	281	270	269
Cr	110	82	85	84	74	78	75
Co	42	34.9	34.1	33	35	33	33.9
Ni	53	46	39	37	41	42	36
Sc	25	30.8	32.2	30	26	na	30.8
Cu	na	na	96	89	na	99	88
Zn	na	na	70	67	na	71	73
Rb	63	70	81	78	62	74	83
Sr	717	722	789	746	660	736	757
Y	27	29	27	27	26	28	27
Zr	194	176	163	155	165	162	160
Nb	19	22	23	21	18	22	21
Ba	1003	1055	1088	990	911	1023	989
La	59	49.7	49.4	57	63	50	48.5
Ce	109	106	100	102	113	97	97
Nd	44	46	49	42	42	45	51
Sm	na	8.9	8.5	9.9	na	na	8.5
Eu	na	2.30	2.30	2.20	na	na	2.20
Tb	na	0.87	0.83	0.94	na	na	0.94
Yb	na	2.6	2.9	2.3	na	na	2.6
Lu	na	0.39	0.36	0.47	na	na	0.28
Ta	na	1.6	1.4	1.4	na	na	1.3
Hf	na	3.7	3.5	3.9	na	na	3.7
Pb	na	na	47	16	na	16	22
Th	na	17.3	16.2	15.9	na	16	15.7
⁸⁷ Sr/ ⁸⁶ Sr _m	0.706255	na	0.706224	na	0.706203	0.706250	0.706218
2σ	0.000011	–	0.000010	–	0.000011	0.000020	0.000012
⁸⁷ Sr/ ⁸⁶ Sr _N	0.706260	–	0.710212	–	0.706208	0.706258	0.706206

Major and trace elements are from: (1) Hornig-Kjarsgaard et al. (1993); (2) De Fino et al. (1988); (3) Francalanci et al. (1989). ⁸⁷Sr/⁸⁶Sr_m are values measured at (1) Vrije Universiteit, Amsterdam, The Netherlands; (2) Università di Napoli, Naples, Italy (Civetta, 1986); (3) Università la Sapienza, Rome, Italy (Francalanci et al., 1988). ⁸⁷Sr/⁸⁶Sr_N are values normalised (Francalanci et al., 1999) to the standard values of NIST reference sample SRM 987 (0.710248, Thirlwall, 1991). na, not analysed.

Table 5c

Compositions of main eruptive events between 1985 and 1993 AD at Stromboli volcano

Year:	1985	1985	1986	1986	1989	1993	1993
Day:	Dec. 12	Dec. 13	Jan. 1	April 17	–	Feb. 10	Feb. 10
Product:	Lava	lava	lava	lava	scoria	scoria	pumice
Sample:	Sr3	STR202	Sr4	Sr7	STR89.0	STR93-1	STR93-2
Reference:	1	3	2	2	1	4	4
SiO ₂	49.4	49.6	49.5	49.3	50.6	49.9	49.1
TiO ₂	1.00	1.00	1.02	1.01	0.87	0.99	1.02
Al ₂ O ₃	18.5	18.1	17.8	17.8	17.3	17.8	17.1
Fe ₂ O ₃	2.44	3.52	2.60	2.57	2.89	1.82	4.18
FeO	6.10	5.31	6.02	6.24	5.17	6.63	5.09
MnO	0.17	0.16	0.17	0.18	0.16	0.16	0.17
MgO	5.45	6.01	5.89	6.08	6.22	6.30	6.25
CaO	11.2	11.0	11.2	11.2	11.1	10.9	12.2
Na ₂ O	2.60	2.42	2.54	2.51	2.54	2.51	2.30
K ₂ O	2.16	1.98	2.18	2.13	2.16	2.07	1.65
P ₂ O ₅	0.40	0.57	0.42	0.41	0.47	0.45	0.45
LOI	0.57	0.27	0.67	0.70	0.31	0.52	0.48
Mg#	0.540	0.558	0.557	0.559	0.588	0.576	0.557
V	259	273	278	274	258	na	na
Cr	73	86	71	67	90	49	38
Co	33.3	34.0	33.2	34.6	na	na	na
Ni	36	38	39	42	44	35	37
Sc	30.7	30.9	31.2	30.0	na	na	na
Cu	90	103	92	92	na	na	na
Zn	70	73	74	74	na	na	na
Rb	82	80	82	82	63	67	48
Sr	759	762	757	740	682	707	720
Y	28	28	27	28	na	na	na
Zr	161	166	162	161	17	na	na
Nb	21	23	22	22	na	25	18
Ba	983	1004	1014	988	938	na	na
La	47.8	52	47.7	47	na	na	na
Ce	100	99	98	98	na	na	na
Nd	47	40	47	42	na	na	na
Sm	8.9	9.4	8.3	8.8	na	na	na
Eu	2.10	2.10	2.10	2.10	na	na	na
Tb	0.77	1.00	0.83	1.10	na	na	na
Yb	2.6	2.6	2.5	2.7	na	na	na
Lu	0.37	0.45	0.4	0.36	na	na	na
Ta	1.3	1.3	1.3	1.5	na	na	na
Hf	3.6	3.9	3.5	3.7	na	na	na
Pb	21	21	19	20	na	na	na
Th	16.3	15.9	15.0	16.6	na	9	7
⁸⁷ Sr/ ⁸⁶ Sr _m	na	0.706220	0.706230	0.706211	0.706243	na	na
2σ	–	0.000020	0.000010	0.000009	0.000008	–	–
⁸⁷ Sr/ ⁸⁶ Sr _N	–	0.706228	0.706218	0.706199	0.706249	–	–

Major and trace elements are from: (1) Hornig-Kjarsgaard et al. (1993); (2) De Fino et al. (1988); (3) Francalanci et al. (1989); (4) Bonaccorso et al. (1996). ⁸⁷Sr/⁸⁶Sr_m are values measured at (1) Vrije Universiteit, Amsterdam, The Netherlands; (2) Università di Napoli, Naples, Italy (Civetta, 1986); (3) Università la Sapienza, Rome, Italy (Francalanci et al., 1987). ⁸⁷Sr/⁸⁶Sr_N are values normalised (Francalanci et al., 1999) to the standard values of NIST reference sample SRM 987 (0.710248, Thirlwall, 1991). na, not analysed.

Table 5d

Compositions of main eruptive events between 1994 and 1995 AD at Stromboli volcano

Year:	1994	1994	1995	1995	1995	1995	1995
Day:	July 26	Sept. 6	March 3	March 7	March 15	July 8	Sept.7
Product:	scoria	scoria	scoria	scoria	scoria	scoria	scoria
Sample:	STR7/94	STR9/94a	STR3/95a	STR3/95b	STR3/95c	STR7/95	STR9/95a
SiO ₂	48.8	49.0	48.6	49.1	49.2	49.0	49.2
TiO ₂	0.98	0.96	1.05	1.02	1.02	0.96	0.97
Al ₂ O ₃	17.9	18.0	18.1	18.6	18.0	18.3	18.0
Fe ₂ O ₃	2.39	2.33	3.71	2.90	3.00	2.50	2.61
FeO	6.56	6.53	5.64	6.00	6.32	6.24	6.12
MnO	0.17	0.17	0.18	0.17	0.18	0.17	0.17
MgO	6.58	6.56	5.84	5.87	5.72	6.53	6.57
CaO	11.2	11.2	11.4	11.4	11.2	11.0	11.1
Na ₂ O	2.54	2.55	2.43	2.41	2.40	2.50	2.50
K ₂ O	2.03	2.03	2.13	2.02	2.09	2.02	2.04
P ₂ O ₅	0.37	0.37	0.39	0.38	0.39	0.37	0.38
LOI	0.41	0.35	0.44	0.16	0.49	0.50	0.42
Mg#	0.574	0.576	0.537	0.549	0.531	0.578	0.581
V	264	267	260	262	265	264	266
Cr	68	67	60	67	63	70	64
Co	33.7	34.0	30	29	30	28	30
Ni	39	34	33	30	35	32	35
Sc	30.7	31.5	na	na	na	na	na
Cu	112	92	103	88	96	96	106
Zn	76	74	73	71	74	72	73
Rb	78	80	85	80	83	80	79
Sr	765	756	797	777	768	760	751
Y	21	21	28	27	27	23	23
Zr	171	164	164	153	162	177	177
Nb	17	15	22	20	22	21	20
Ba	963	967	966	957	986	959	970
La	52	51	53	50	49	46	42
Ce	94	96	98	96	83	93	101
Nd	39	36	45	43	40	42	45
Sm	9.1	9.1	na	na	na	na	na
Eu	2.12	2.18	na	na	na	na	na
Tb	1.00	1.00	na	na	na	na	na
Yb	2.3	2.5	na	na	na	na	na
Lu	0.39	0.55	na	na	na	na	na
Ta	1.5	1.4	na	na	na	na	na
Hf	3.5	3.6	na	na	na	na	na
Pb	20	23	25	21	21	31	27
Th	15.8	15.8	22	22	18	20	15
⁸⁷ Sr/ ⁸⁶ Sr _m	0.706167	na	na	na	na	na	na
2σ	0.000007	–	–	–	–	–	–
⁸⁷ Sr/ ⁸⁶ Sr _N	0.706172	–	–	–	–	–	–

⁸⁷Sr/⁸⁶Sr_m, value measured at Vrije Universiteit, Amsterdam, The Netherlands. ⁸⁷Sr/⁸⁶Sr_N, value normalised (Francalanci et al., 1999) to the standard values of NIST reference sample SRM987 (0.710248, Thirlwall, 1991). na, not analysed.

5.3. Plagioclase composition

Plagioclase displays a large range in anorthite

(An) content, passing from 60% to 90% (Table 3). The highest values are, however, only found in plagioclase crystals of pumice, whereas most of

Table 5e

Compositions of main eruptive events between 1995 and 1996 AD at Stromboli volcano

Year:	1995	1996	1996	1996	1996	1996	1996	1996
Day:	Sept. 27	April 16	April 19	June 1	August 5	Sept. 4	Sept. 4	Sept. 4
Product:	scoria	scoria	scoria	scoria	scoria	bomb	pumice	scoria
Sample:	STR9/95c	STR4/96a	STR4/96b	STR6/96	STR8/96	STR9/96a	STR9/96d	STR9/96e
SiO ₂	49.3	49.4	49.3	49.3	49.4	49.5	48.6	49.5
TiO ₂	0.97	0.97	0.99	0.98	0.98	1.00	0.99	0.96
Al ₂ O ₃	17.9	18.0	18.1	18.3	18.0	18.2	16.3	18.1
Fe ₂ O ₃	2.58	3.23	2.97	2.87	2.93	4.60	3.60	2.87
FeO	6.08	5.70	5.92	5.92	5.96	4.20	5.75	6.00
MnO	0.16	0.17	0.17	0.17	0.17	0.17	0.18	0.17
MgO	6.57	6.08	6.08	6.25	6.05	6.10	7.84	6.08
CaO	11.2	11.3	11.2	11.2	11.3	10.9	12.2	11.2
Na ₂ O	2.47	2.45	2.42	2.43	2.40	2.37	2.05	2.49
K ₂ O	2.04	2.08	2.07	2.06	2.06	2.17	1.68	2.08
P ₂ O ₅	0.38	0.38	0.38	0.37	0.38	0.43	0.37	0.38
LOI	0.34	0.25	0.33	0.18	0.27	0.30	0.43	0.17
Mg#	0.582	0.558	0.558	0.567	0.557	0.566	0.609	0.558
V	269	273	271	269	275	271	287	280
Cr	76	64	65	62	61	60	54	62
Co	35.0	29	31	32	33.0	32.8	36.6	32
Ni	35	37	38	36	38	33	46	36
Sc	33.2	na	na	na	31.8	31.4	35.9	32.2
Cu	110	103	99	92	100	94	106	97
Zn	73	74	75	73	74	70	75	73
Rb	78	80	82	81	80	78	66	82
Sr	753	762	758	756	760	752	748	757
Y	24	28	28	27	28	27	27	28
Zr	174	162	162	156	162	156	142	161
Nb	20	22	22	20	22	20	19	21
Ba	971	992	988	990	987	1027	818	998
La	50	52	45	50	50	51	42	50
Ce	98	90	100	97	96	96	87	97
Nd	38	42	47	42	39	37	34	39
Sm	9.4	na	na	na	8.7	9.0	8.2	9.0
Eu	2.26	na	na	na	2.19	2.17	2.10	2.22
Tb	1.10	na	na	na	0.98	0.95	0.93	0.95
Yb	2.8	na	na	na	2.3	2.4	2.4	2.4
Lu	0.46	na	na	na	0.55	0.43	0.48	0.5
Ta	1.7	na	na	na	1.2	1.4	1.14	1.5
Hf	3.7	na	na	na	3.5	3.8	3.2	3.7
Pb	27	20	19	24	20	19	20	23
Th	17	20	19	18	18	16	13	17
⁸⁷ Sr/ ⁸⁶ Sr _m	0.706157	0.706157	na	0.706159	na	na	0.706100	0.706160
2σ	0.000007	0.000009	–	0.000009	–	–	0.000008	0.000008
⁸⁷ Sr/ ⁸⁶ Sr _N	0.706162	0.706162	–	0.706164	–	–	0.706105	0.706165
¹⁴³ Nd/ ¹⁴⁴ Nd	na	na	na	na	na	na	0.512570	0.512556
2σ	–	–	–	–	–	–	0.000008	0.000006

⁸⁷Sr/⁸⁶Sr_m are values measured at Vrije Universiteit, Amsterdam, The Netherlands. ⁸⁷Sr/⁸⁶Sr_N are values normalised (Francalanci et al., 1999) to the standard values of NIST reference sample SRM987 (0.710248, Thirlwall, 1991). ¹⁴³Nd/¹⁴⁴Nd are values determined at the Università degli Studi di Firenze, Florence, Italy. na, not analysed.

Table 5f
Compositions of main eruptive events during 1998 AD at Stromboli volcano

Year:	1998	1998	1998	1998	1998	1998	1998	1998
Day:	July 19	Aug. 23	Aug. 23	Aug. 23	Aug. 23	Aug. 23	Aug. 23	Sept. 8
Product:	scoria	bomb	scoria	pumice	pumice	glass gdm	scoria	scoria
Sample:	STR7/98a	STR8/98a	STR8/98b	STR8/98e	STR8/98i	STR8/98i	STR8/98m	STR9/98a
SiO ₂	49.0	49.2	48.9	48.1	48.6	na	49.4	49.1
TiO ₂	1.00	0.99	0.98	1.10	1.05	na	1.03	0.99
Al ₂ O ₃	18.6	18.3	18.2	16.6	17.0	na	18.2	18.3
Fe ₂ O ₃	2.77	3.73	2.93	4.55	3.53	na	2.77	2.44
FeO	5.98	5.04	6.02	5.65	6.21	na	6.16	6.38
MnO	0.17	0.16	0.17	0.19	0.19	na	0.17	0.17
MgO	6.37	6.40	6.43	6.54	6.58	na	6.09	6.08
CaO	11.0	11.1	11.1	12.1	11.8	na	11.0	11.2
Na ₂ O	2.62	2.49	2.59	2.36	2.46	na	2.58	2.63
K ₂ O	2.09	2.05	2.05	1.78	1.91	na	2.14	2.07
P ₂ O ₅	0.38	0.37	0.37	0.38	0.38	na	0.38	0.36
LOI	0.14	0.18	0.31	0.61	0.31	na	0.14	0.27
Mg#	0.573	0.576	0.570	0.545	0.556	-	0.557	0.558
V	261	267	268	277	277	na	267	267
Cr	48	55	54	46	50	na	51	51
Co	26	32	31	36	35	na	33	34
Ni	34	39	39	45	44	na	36	38
Cu	107	108	101	110	111	na	105	105
Zn	74	75	76	77	77	na	75	74
Rb	67	65	67	55	60	na	69	67
Sr	776	761	765	779	777	na	774	774
Y	27	27	27	27	27	na	27	27
Zr	157	156	158	144	150	na	161	159
Nb	20	21	20	18	19	na	21	21
Ba	971	969	954	820	886	na	976	953
La	46	49	51	42	50	na	47	47
Ce	100	93	98	87	89	na	96	103
Nd	45	43	45	41	41	na	47	46
Pb	22	22	21	20	18	na	22	22
Th	24	18	17	15	16	na	15	19
⁸⁷ Sr/ ⁸⁶ Sr _m	-	-	0.706169	0.706116	0.706137	0.706116	0.706173	-
2σ	-	-	0.000007	0.000006	0.000004	0.000007	0.000005	-
⁸⁷ Sr/ ⁸⁶ Sr _N	-	-	0.706160	0.706107	0.706128	0.706107	0.706164	-
¹⁴³ Nd/ ¹⁴⁴ Nd	-	-	0.512551	0.512564	0.512562	0.512558	0.512564	-
2σ	-	-	0.000006	0.000007	0.000005	0.000011	0.000006	-

⁸⁷Sr/⁸⁶Sr_m and ¹⁴³Nd/¹⁴⁴Nd are values measured at the Università degli Studi di Firenze, Florence, Italy. ⁸⁷Sr/⁸⁶Sr_N are values normalised to the standard values of NIST reference sample SRM987 (0.710248, Thirlwall, 1991). na, not analysed. Sample STR8/98i is a glass separated from the groundmass (gdm) of the same pumice sample.

plagioclase crystals of scoriae and lavas have An content between 60% and 70% (Fig. 6a,b). Plagioclase, like olivine and clinopyroxene, does not show systematic variations with time since 1930.

The largest plagioclase crystals usually have re-sorbed cores with complex zoning in the rims (10–100 μm), or sieved textures occurring in the cores or inner rims of crystals. Mineral chemistry data

indicate that zoning is usually large (e.g. from 65% to 85% of An content) and can be normal, with An-rich (75–87%) cores, or oscillatory, with cores at variable An content (e.g. 65% or 85%) (Figs. 5b and 6a). The outer rims of plagioclase crystals in scoriae and lavas from different types of eruptions, however, always have lower An content than the rims, whereas the opposite is ob-

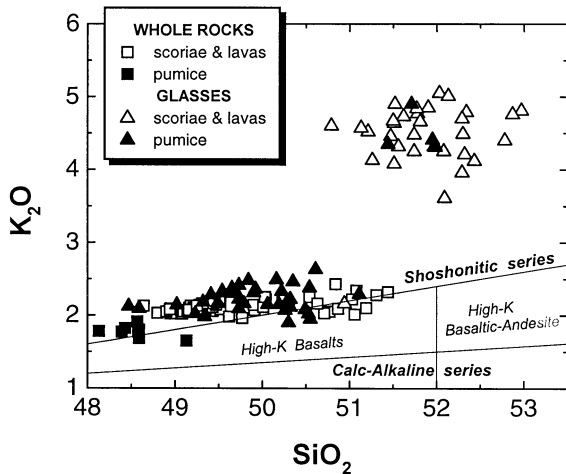


Fig. 7. K_2O (wt%)– SiO_2 (wt%) classification diagram (Pecce-rillo and Taylor, 1976) for whole rocks and glasses of products erupted in the present-day activity of Stromboli. Scoriae and lavas are for the period from 1906 to 1998, whereas pumice are from 1993 to 1998. Data are plotted on water-free bases. Data source as in Table 5a–f.

served in plagioclase from pumice, where the outer rims are usually very thin ($< 50 \mu m$) (Fig. 5b). Microphenocrysts are also zoned, but the An variation is smaller (e.g. 63–67%).

Plotting An versus Fe^{3+} contents for all plagioclase, two groups seem to be present (Fig. 6b). Plagioclase with $An > 77\%$ is mostly from pumice and forms a rough negative correlation in the diagram of Fig. 6b. Instead, the group with $An < 75\%$ is mainly constituted by plagioclase crystals of scoriae and lavas and shows a general positive correlation between An and Fe^{3+} .

6. Geochemistry of whole rocks and glasses

Products erupted during the present-day activity at Stromboli have mafic compositions, ranging from high-K to shoshonitic basalts, with a prevalence of the latter (Tables 4 and 5a–f). The composition has remained constant, not only during the entire 20th century (Fig. 7 and Table 5a–f), but also since the beginning of ‘Strombolian activity’ between the 3rd and 7th century AD (Rosi et al., 2000).

The compositions of pumice samples are slightly less evolved than those of scoriae and

lava samples, with silica contents in the range 48.2–49.2 wt% for pumice, and 48.6–51.5 wt% for scoriae and lavas. Pumice samples are also characterised by slightly lower K_2O content (1.5–2 wt%) than scoriae and lavas (2–2.5 wt%) (Fig. 7).

Compositional differences between glasses of pumice and glasses of scoriae and lavas are larger than those observed between whole-rock samples. Pumice glasses are still shoshonitic basalts, very similar to the whole-rock composition of the scoriae and lavas, whereas scoriae and lava glasses are shoshonites, with SiO_2 between 51 and 53 wt% and K_2O between 3.5 and 5.2 wt% (Fig. 7).

Pumice glasses are sharply distinct from scoriae and lava glasses, not only for silica and potassium content, but also for all of the other major element and BaO abundances (Fig. 8 and Table 4). In particular, the two types of glass display concentration gaps in MgO (between 3.8 and 5.5 wt%), CaO (7.8–10 wt%), Al_2O_3 (16–17 wt%), FeO (8.6–9.2 wt%) and TiO_2 (1.1–1.4 wt%). Scoriae and lava glasses show lower MgO, CaO, Al_2O_3 , SrO, SO_3 and higher P_2O_5 , TiO_2 , FeO, Na_2O and BaO content than pumice glasses. Each group of glass is characterised by a quite homogeneous composition (Fig. 8 and Table 5a–f). It is worth noting that some pumice glass is compositionally similar to the more evolved scoriae and lava glass, pointing to syn-eruptive mingling processes.

Although the whole-rock composition of scoriae and lavas has not shown large changes since 1906 AD (Fig. 7), possible small significant variations of major and trace element contents can be discovered in variation diagrams versus time (Fig. 9). In this case, however, it is difficult to evaluate them in detail, because we compare rocks analysed by different laboratories (see Table 5a–f for data source). Nevertheless, small but significant compositional changes seem to be pointed out from the diagrams of Fig. 9. From 1906 to 1930 eruptions, MgO (from 5 to 6.5 wt%) and compatible trace element (hereafter the elements that for the mantle mineralogy have $K_{solid/liquid}^d > 1$) contents (e.g. Ni: from 30 to 50 ppm, V: from 280 to 300 ppm) of scoriae and lavas slightly increase, whereas Al_2O_3 , SiO_2 and

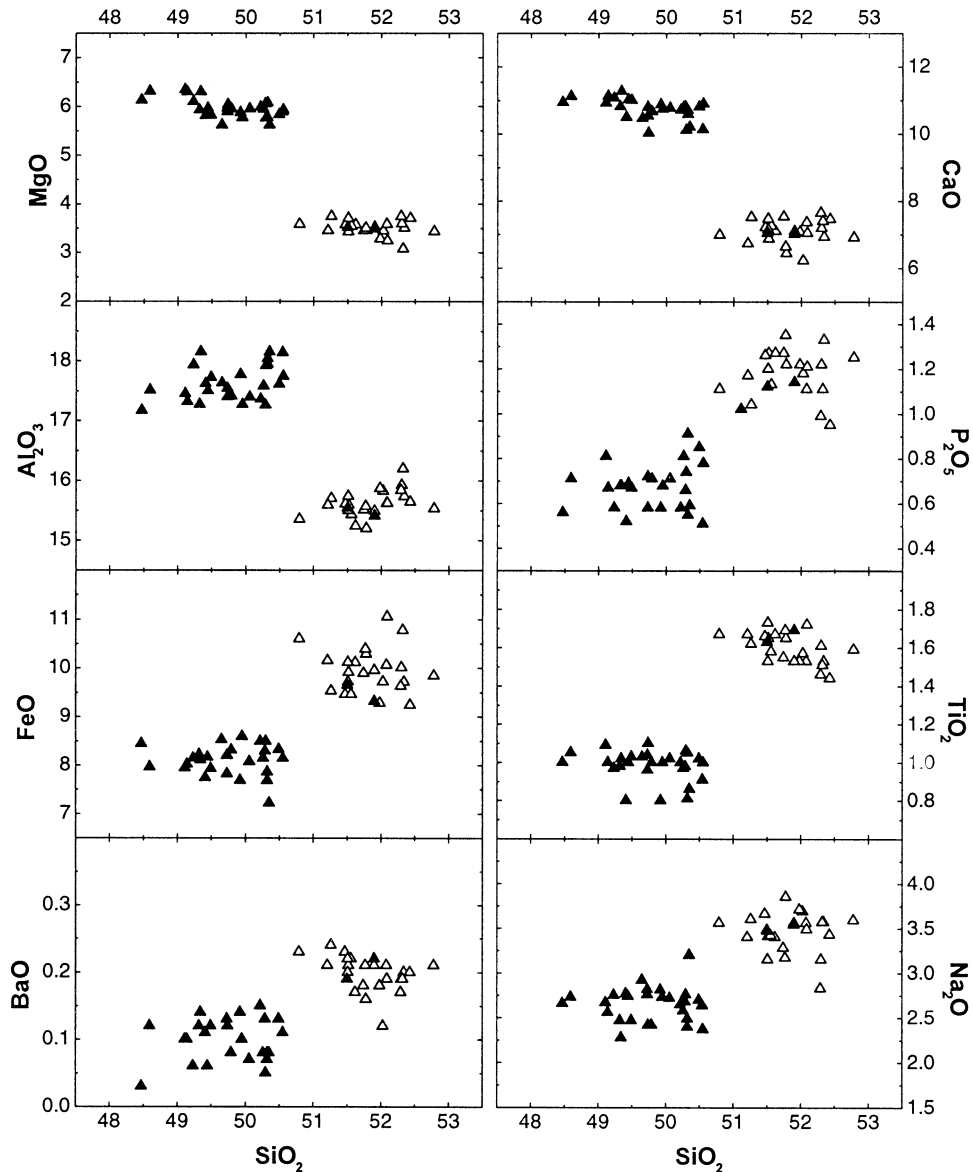


Fig. 8. Variation diagrams versus silica (wt%) of major elements (wt%) and BaO (wt%) for glasses of scoriae, lavas and pumice erupted from 1930 to 1998 in the present-day activity of Stromboli. Open triangles, scoriae and lava glasses; full triangles, pumice glasses.

incompatible element abundances slightly decrease (Fig. 9 and Table 5a–f). After 1930, a quite large sampling gap of 35 years does exist. The compatible element and MgO contents of the 1965 sample, however, remains nearly similar to those of the 1930 eruption (e.g. Ni: 53 ppm, Cr: 110 ppm, MgO: 6.65 wt%), slightly decreasing

towards present-day rocks (Fig. 9). A different behaviour is observed for the incompatible trace element contents, especially for Ba, Sr, Rb, Nb and LREE, that are more enriched after the 1930 eruption (e.g. Ba > 900 ppm, Sr > 650 ppm, Nb mainly > 18 ppm).

The pumice samples display slightly lower in-

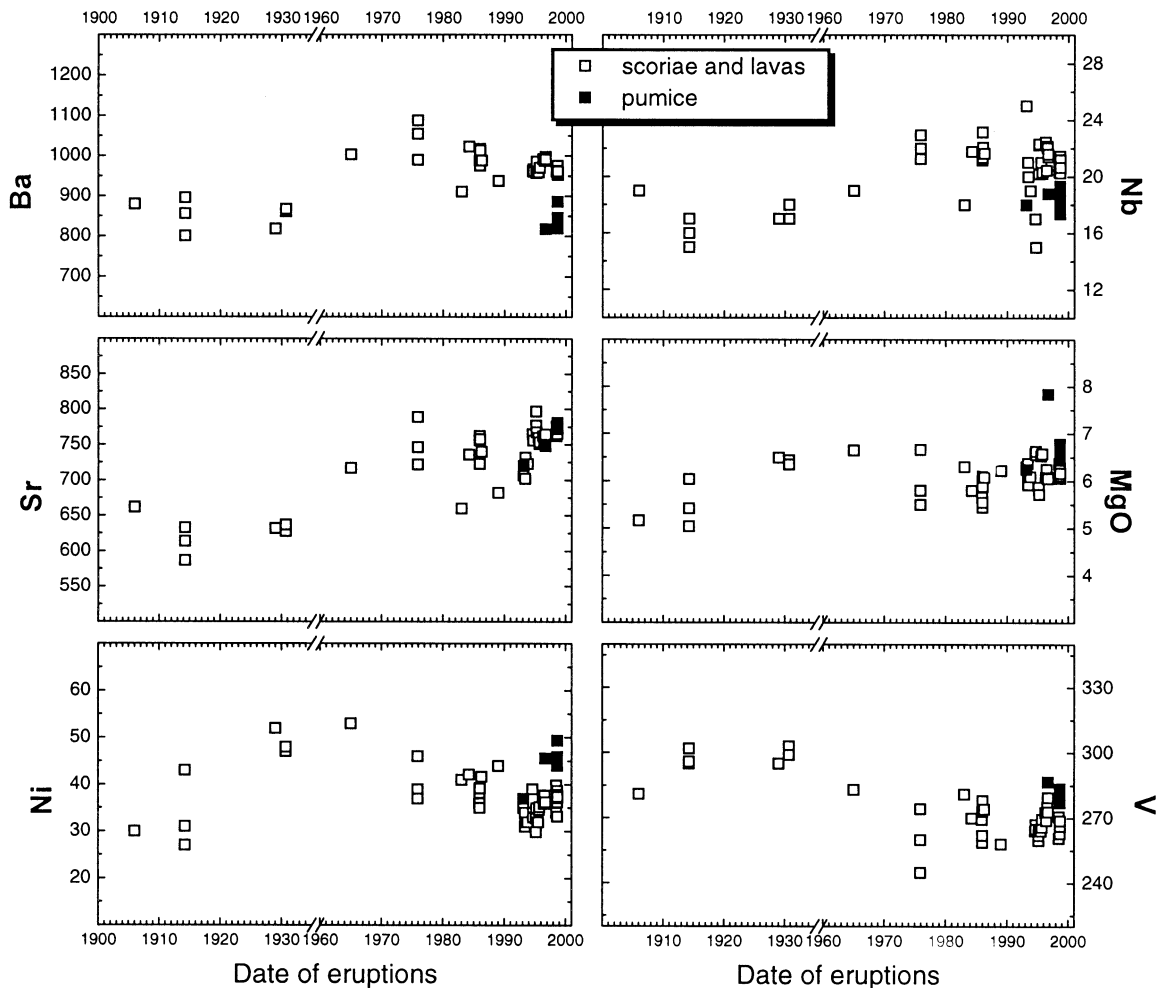


Fig. 9. Variations of some major (wt%) and trace (ppm) elements with time from 1906 to 1998 rocks erupted in the present-day activity of Stromboli. Data source as in Table 5a–f.

compatible and higher compatible element contents than scoriae and lavas erupted in the same period. On the other hand, Sr abundances are similar.

Sr isotope data from 1906 to 1996 were already reported in Francalanci et al. (1999), and were used to demonstrate a short residence time (≈ 19 years) of the magma feeding the volcanic activity at Stromboli. It is noteworthy that the new Sr isotope ratios reported for the samples of the August 23, 1998 major eruption remain similar to the respective values of scoriae and pumice of the 1996 eruption. Only one whole-

rock sample of 1998 pumice has a higher Sr isotope ratio (0.706128 ± 4), but the glassy groundmass has a lower value, identical to that of another whole-rock sample of 1998 pumice (Fig. 10 and Table 5a–f). This makes the lowest $^{87}\text{Sr}/^{86}\text{Sr}$ value more probable for the magma erupted as pumice in 1998 and the highest Sr isotope ratio is probably due to the syn-eruptive mingling process with the magma erupted as scoriae and lavas. Sr isotope ratios in scoriae and lavas from the beginning of the century to around 1980–85 are constant, with an average of $0.70626 (\pm 2, 2\sigma)$, then start to smoothly decrease up to a value of

0.70616 in 1998 scoriae (Fig. 10 and Table 5a–f). Pumice samples erupted from the major explosions of 1996 and 1998 have significantly lower Sr isotope ratios than scoriae, with $^{87}\text{Sr}/^{86}\text{Sr} \approx 0.70610$.

Nd isotope ratios of 1996 and 1998 samples, both pumice and scoriae, are quite similar, ranging from 0.51255 to 0.51257 (Table 5a–f). Even if pumice and scoriae are not well distinct on the basis of $^{143}\text{Nd}/^{144}\text{Nd}$ values, as occurs for $^{87}\text{Sr}/^{86}\text{Sr}$ values, the 1996 pumice has a Nd isotope ratio slightly higher than the 1996 scoriae (Fig. 11 and Table 5a–f). On the other hand, no differences exist between Nd isotope ratios of 1998 scoriae and pumice. The glassy groundmass of a pumice sample from the 1998 eruption has given a lower value than the whole-rock one; considering its high error range, however, the two Nd isotope ratios are almost coincident.

7. Discussion

Collected data show there are only small differences with time in the mineral chemistry and in the major and trace element composition of sco-

riae and lavas erupted in the present-day activity of Stromboli during the last century. Sr isotope ratios, on the other hand, have a marked decrease starting around 1980–85 (Fig. 10). Major element and petrographic characteristics of pumice seem also to have remained constant with time, according to the composition of pumice samples collected in stratigraphic trenches dug in the recent tephra deposits (Rosi et al., 2000).

The general homogeneous composition of the products erupted in the Strombolian activity, associated with the presence of an open conduit system with continuous activity and with evidence from thermal and gas budget balances, allows us to consider the present plumbing system of the volcano in steady-state conditions (Giberti et al., 1992; Allard et al., 1994, 2000; Harris and Stevenson, 1997; Francalanci et al., 1999). The dynamics of the shallow magmatic system capable of maintaining these conditions in an open conduit volcano with permanent activity like Stromboli, could be described as a continuously erupting, crystallising and replenished magma chamber (Francalanci et al., 1999). The behaviour of the volcano, however, will be better understood by analysing in detail the compositional variations

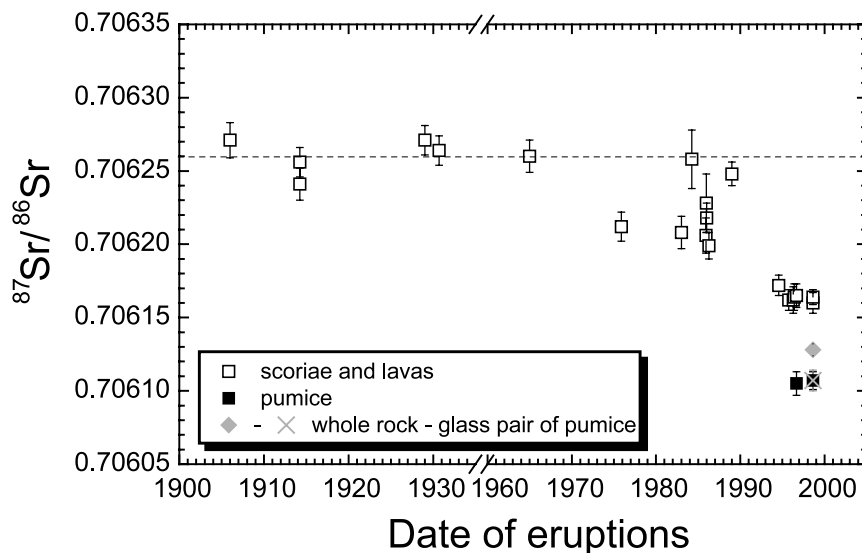


Fig. 10. Variation of Sr isotope ratios with time from 1906 to 1998 rocks of the present-day activity of Stromboli. Dashed line indicates the average value of rocks erupted before ca 1980–85. Data of the 1998 eruption are from this paper, the other data are from Francalanci et al. (1999) and references therein.

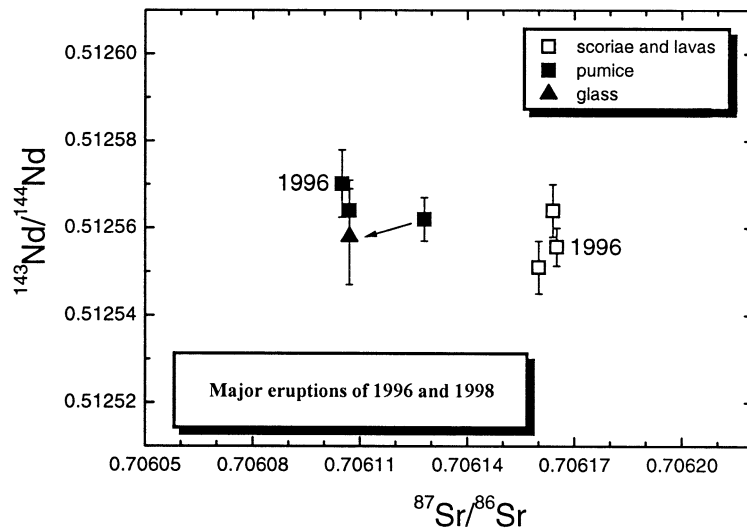


Fig. 11. Diagram of Sr versus Nd isotope ratios. $^{87}\text{Sr}/^{86}\text{Sr}$ of 1996 rocks are from Francalanci et al. (1999).

of scoriae and lavas with time and their relationships with the composition of magma erupted as pumice.

7.1. Relationships between pumice and scoriae

Pumice is only outpoured during major explosions and paroxysms and usually represents nearly 10% in volume of the total amount of magma erupted. This obviously demonstrates that the low-porphyrific magma erupted as pumice (hereafter called ‘LP magma’) is far from representing the main component in the shallowest reservoir feeding the normal Strombolian activity.

From a petrographic point of view, pumice is clearly distinct from scoriae and lavas, although mineral phases are identical (e.g. olivine, clinopyroxene and plagioclase). Pumice has a very low porphyritic index, with mainly microphenocrysts, whereas scoriae and lavas contain about 50 vol% of phenocrysts and microphenocrysts, with clinopyroxene up to 2 cm long and olivine and some plagioclase up to 0.5 cm large. These characteristics clearly suggest that the two types of magmas are characterised by, at least, different physical conditions of crystallisation.

On the basis of whole-rock composition, it is reasonable to suppose that the LP magma and the

highly porphyritic magma (hereafter ‘HP magma’), erupted as scoriae and lavas, are also characterised by slightly different chemical conditions. Indeed, pumice is less evolved than scoriae and lavas, with higher CaO and compatible trace element contents and lower Al_2O_3 , SiO_2 , K_2O and incompatible trace element abundances (Figs. 7 and 9). These chemical differences suggest a fractionation of femic phases from the LP magma to generate the composition of the HP magma. Nevertheless, the slightly, but significantly, lower Sr isotope ratios of pumice (Fig. 10) clearly indicate that the linkage between the two magmas is more complex than a simple fractional crystallisation process.

Nd isotope ratios are usually less selective for discriminating magmatic processes than Sr isotope ratios. Nevertheless, even if Nd isotope data of scoriae and pumice are similar among the 1998 samples, they agree with the variation of $^{87}\text{Sr}/^{86}\text{Sr}$ in the 1996 samples (Fig. 11).

As a consequence of the highly different degree of crystallisation, pumice is well distinguished by scoriae and lavas also on the basis of glass composition. The pumice glass is less evolved than the scoriae and lava glass, and a compositional gap divides the two glass groups (Fig. 8).

The last fundamental and significant difference

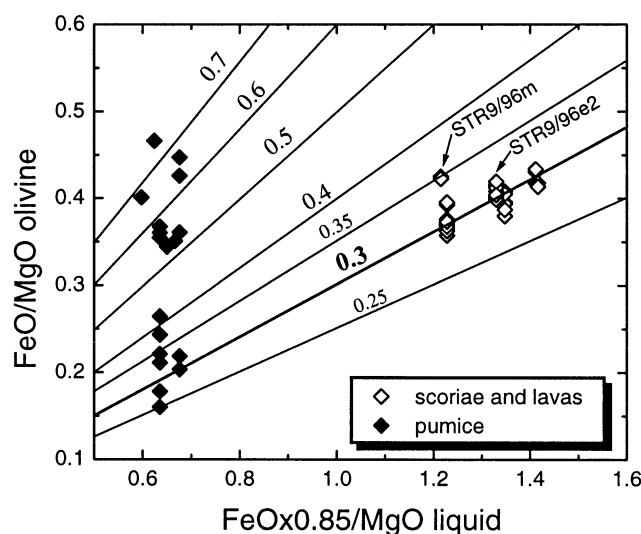


Fig. 12. Diagram of FeO/MgO (mol) in olivine versus FeOx0.85/MgO (mol) in glassy groundmasses of host rocks. Each line reports a value of $K_{\text{olivine/liquid}}^{\text{d}}$ for FeO/MgO. An average composition of glass has been used for each sample analysed. STR9/96e2, scoriae erupted in the major eruption of September 4, 1996; STR9/96m, scoriae erupted in the 'normal' activity of September 22, 1996.

between LP and HP magmas is based on the volatile element content. As also suggested by the particular type of ejecta formed during the major eruptions, a light pumice with a basic composition, the LP magma is rich in volatile elements, whereas magmas erupted as scoriae and lavas are highly degassed. On the basis of melt inclusion analyses in olivine, Métrich et al. (2001) determined the volatile element composition (H_2O , CO_2 , Cl, F, S) of the LP and HP magmas. They found, for example, H_2O contents of 2.3–2.8 wt% and 0.12–0.18 wt% and CO_2 abundances of 894–1689 ppm and <40–50 ppm (below detection limit) in the LP magma and HP magma, respectively. The different volatile element contents of the two magmas, associated with the distinction in crystal abundance, also led to the generation of magmas with different density and viscosity values. Métrich et al. (2001) calculate densities of 2500 and 2700 kg/m^3 and viscosities of 15–20 and 1.4×10^4 Pa/s for LP and HP magmas, respectively.

7.1.1. Evidence from mineral chemistry data

A careful examination of mineral chemistry data constrains the behaviour of the plumbing system.

Olivine, clinopyroxene and plagioclase are all characterised by the presence of two distinct groups of compositions (Figs. 3, 4 and 6). In particular, these groups are well distinct in olivine, where a compositional gap between Fo 74% and 78% is present and minerals with Fo > 78% are exclusively found in pumice, because of the more mafic character of the LP magma. Olivine from scoriae and lavas has a constant $K_{\text{olivine/liquid}}^{\text{d}}$ for FeO/MgO (hereafter $K_{\text{Fe/Mg}}^{\text{d}}$) of 0.3, indicating equilibrium conditions with the host liquid (Roeder, 1974; Roeder and Emslie, 1970; Gerlach and Grove, 1982; Jurewicz and Watson, 1988) (Fig. 12). Only the olivine of sample STR9/96m shows a slightly higher $K_{\text{Fe/Mg}}^{\text{d}}$ (=0.35). In contrast, olivine of pumice displays a wide $K_{\text{Fe/Mg}}^{\text{d}}$ range. The group with $K_{\text{Fe/Mg}}^{\text{d}}$ between 0.25 and 0.4 (with Fo > 78%) can be considered nearly in equilibrium with their host liquid, although they show a larger $K_{\text{Fe/Mg}}^{\text{d}}$ range with respect to olivine of scoriae and lavas. On the contrary, the group of olivine with $K_{\text{Fe/Mg}}^{\text{d}}$ between 0.5 and 0.7 (with Fo < 74%) is not in equilibrium with the host liquid, and these high $K_{\text{Fe/Mg}}^{\text{d}}$ values point to a crystallisation from a more evolved liquid. In particular, because the latter olivine crystals are

compositionally similar to the olivine of scoriae and lavas (Figs. 3 and 12), they obviously appear to be in equilibrium (with $K_{\text{Fe/Mg}}^{\text{d}}$ around 0.3) with the scoriae and lava liquid (Fig. 12). In addition, olivine with $\text{Fo} > 78\%$ is mainly constituted by microphenocrysts and outer rims of phenocrysts, whereas those with $\text{Fo} < 74\%$ are mostly cores of phenocrysts and show inverse zoning. All these arguments suggest that the LP magma also contains olivine that is crystallised in the HP magma; it can be transported into the LP magma by a syn-eruptive mingling process.

The only olivine from scoriae with higher $K_{\text{Fe/Mg}}^{\text{d}}$ ($=0.35$) is that of a scoriae sample (STR9/96m) erupted a few days after the major explosion of September 4, 1996 (Tables 4 and 5). Since olivine composition has not changed, the higher $K_{\text{Fe/Mg}}^{\text{d}}$ is due to a slightly higher MgO of STR9/96m glass than the glass of scoriae erupted in the previous major eruption of September 4, 1996 (e.g. sample STR9/96e2). STR9/96m glass also has fairly higher CaO and lower K_2O contents than STR9/96e2 glass. This slightly less evolved composition of STR9/96m glass, associated with the presence of olivine with unchanged composition, is evidence of the arrival of fresh magma in the reservoir of the scoria magma during the occurrence of the major eruption of September 4, 1996. Indeed, olivine of STR9/96m had no time to re-equilibrate with the new and slightly less evolved composition of the host hybrid liquid.

Fig. 4b shows that the two groups of clinopyroxene occur both in pumice and scoriae. Like the olivine, however, the clinopyroxene crystals of pumice with $\text{Mg}\# < 0.80$ are mainly represented by phenocrysts and cores of phenocrysts, whereas those with $\text{Mg}\# > 0.82$ are mostly outer rims of phenocrysts or microphenocrysts. This indicates a reverse zoning in phenocrysts of pumice, at least from rim to outer rim (Figs. 4a and 5). This characteristic demonstrates that clinopyroxene crystals with $\text{Mg}\# > 0.82$ are in equilibrium with the LP magma composition, whereas those with lower $\text{Mg}\#$ are xenocrysts that were crystallised from the HP magma and were embraced in the LP magma during or slightly before eruption.

On the contrary, among clinopyroxene crystals of scoriae and lavas there are no outer rims, mi-

crophenocrysts and groundmass crystals with $\text{Mg}\# > 0.82$; these compositions are, instead, found in one or two repeated layers of the inner part of phenocrysts (Fig. 4a). This indicates the presence of phenocrysts with complex zoning, but always with normally zoned rims (Fig. 5), suggesting that the outer rims (together with microphenocrysts and groundmass crystals) are in equilibrium with the composition of the scoriae glass. The presence of repeated layers with $\text{Mg}\# > 82$ in most of the scoriae phenocrysts is another clear evidence of multiple refreshing of the HP magma composition, and is due to the lack of clinopyroxene/liquid re-equilibration.

Apart from the presence of a small $\text{Mg}\#$ range where few clinopyroxene analyses are found, the two groups of clinopyroxene compositions are also pointed out by different slopes in the correlation trends between $\text{Mg}\#$ and minor element contents. This fact suggests two distinct magmatic systems in which different mineral/liquid equilibria occur. Due to stoichiometric substitutions in the clinopyroxene lattice, Cr, Mn, Al and Ti contents increase when Mg abundances (or $\text{Mg}\#$) decrease, forming a single correlation trend if the physical and chemical conditions of crystallisation remain constant. For example, following the negative correlation formed by the minerals with high $\text{Mg}\#$ in the diagram of Al_{tot} versus $\text{Mg}\#$ (Fig. 4b), the clinopyroxene crystals with low $\text{Mg}\#$ should have higher Al_{tot} contents. The involvement of an Al-bearing phase (plagioclase, in this case) only in the crystallisation assemblage of the latter group of host magmas is the most probable hypothesis capable of explaining this discrepancy in the Al_{tot} contents. Thus, different crystallisation conditions for the two groups of host magmas are suggested.

The compositional characteristics of plagioclase are similar to those of clinopyroxene. Zoning is complex and the two groups of Fig. 6b are again not distinct between pumice and scoriae, although plagioclase with $\text{An} < 75\%$ are mainly found in scoriae, whereas those with $\text{An} > 77\%$ are mostly found in pumice (Figs. 5 and 6a). Due to the similarity of clinopyroxene and plagioclase compositional variations, analogous processes can be invoked in order to explain their compositions.

It is noteworthy that the compositional characteristics of olivine are different with respect to those of clinopyroxene and plagioclase. Indeed, the scoriae and lavas lack highly zoned and forsteritic (with $Fo > 78\%$) olivine (Fig. 3), thus making the olivine of pumice well distinct from the olivine of scoriae and lavas. This characteristic is linked to the different types of crystal structure. Indeed, depending on the degree of mineral polymerisation, the lack of crystal/liquid re-equilibration is a common characteristic of pyroxene and plagioclase, but it can be absent in olivine, where zoning is usually lacking. The olivine structure, in fact, consisting of isolated silica tetrahedra, requires the least disruption to homogenise iron and magnesium in the octahedral sites (Philpotts, 1990). All of the mineral chemistry arguments demonstrate that the groups of olivine, clinopyroxene and plagioclase with higher $Fo\%$, $Mg\#$ and $An\%$, respectively, are representative of minerals that crystallised from the LP magma, whereas the composition of the other groups of minerals indicates a crystallisation from the HP magma system. The presence of small compositional gaps between the two groups and the fact that mineral composition of the different groups often forms trends with variable slopes in the diagrams of Figs. 3b, 4b and 6b (e.g. $Mg\#$ versus Al_{tot}) corroborate the hypothesis that LP and HP magmas are characterised by sharply distinct physico-chemical conditions. Accordingly, plagioclase crystallisation does not seem to have an important role in the LP magma, while becoming particularly consistent in the HP magma.

Different geothermometers using mineral chemistry data have been taken into account to calculate the temperature of HP and LP magmas. With the algorithm of Roeder (1974), based on olivine/liquid equilibrium, lower temperatures (1050–1150°C) have been calculated with respect to the temperatures obtained by the algorithms of Nielsen and Drake (1979) and Putirka et al. (1996) (1125–1275°C and 1160–1220°C, respectively), which are based on clinopyroxene/liquid equilibrium (Fig. 13). Apart from absolute value, however, it is noteworthy that generally higher temperatures have been found for LP magma with respect to those of HP magma of the same erup-

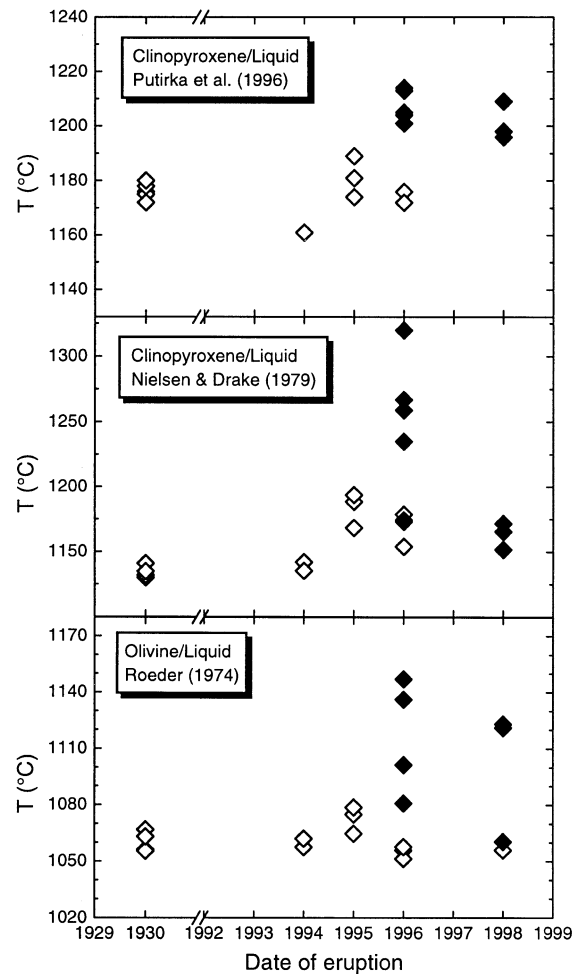


Fig. 13. Temperature (T) calculated by different geothermometers for some scoriae and LP magmas erupted during the 20th century in the present-day activity of Stromboli. Open diamond, scoriae; full diamond, pumice.

tion. A similar temperature range has been found by Clocchiatti (1981) applying the algorithm of Nielsen and Drake (1979) to augitic and diopsidic layers of clinopyroxene separately ejected by the present-day activity of Stromboli. Lower temperature differences between scoriae and pumice are, instead, found by Métrich et al. (2001) using melt inclusion homogenisation in olivine. Furthermore, small but systematic temperature variations, which are consistent with the different geothermometers, seem to be present among magmas

erupted in different years. Slightly higher temperatures, for example, have been calculated for the HP magma of 1995 than the HP magmas of 1994 and 1996, and for the LP magma of 1996 than the LP magma of 1998 (Fig. 13).

Reliable geobarometers for the close surface conditions do not exist. The proposed geobarometers of Nimis (1995) based on the site distribution in single clinopyroxene crystal was also calibrated for high-pressure equilibria, but it was proposed by the author for being extrapolated to low pressures. The application of this method to our samples fails to give meaningful data for some scoriae samples. In the case that data were obtained, a difference between clinopyroxene from scoriae and pumice is observed. Clinopyroxene crystals from pumice are equilibrated at a pressure of 100–200 MPa higher than those of scoria. On the other hand, Métrich et al. (2001) also evaluate distinct pressures for LP and HP magmas. Indeed, on the basis of $\text{CO}_2+\text{H}_2\text{O}$ contents of LP magma, they estimate a total pressure of 350–400 MPa for this magma, whereas they propose that the HP magma results from the crystallisation of the LP magma within the cone itself, driven by decompression and H_2O exsolution.

7.2. The plumbing system setting

All of the previous data and discussion provide evidence that: (1) the present plumbing system of Stromboli is in general steady-state conditions, which are maintained by a continuously erupting, crystallising and replenished reservoir; (2) this is a shallow reservoir in which the HP magma is formed by processes of evolution; (3) the LP magma is deep-seated and represents the refreshing magma of this reservoir.

This indicates that the pre-eruptive processes of evolution affecting the magma feeding the present-day activity of Stromboli is the crystallisation of olivine+clinopyroxene+plagioclase associated with mixing with refreshing magma. As already suggested by Francalanci et al. (1999), the decrease of Sr isotope ratios in scoriae and lavas starting from 1980–85 AD, associated with the lowest Sr isotope ratios of pumice, represents one of the most robust tools that demonstrates

the occurrence of the mixing process. The complex zoning shown by phenocrysts is another important constraint for this process.

The differences in whole-rock compositions from pumice to scoriae and lavas (e.g. increase of Al_2O_3 contents) and the distinct correlation trends among the two groups of clinopyroxene crystals suggest that the plagioclase crystallisation starts to play an important role only in the HP magma. The higher volatile content associated with the higher depth of the LP magma suppresses the crystallisation of plagioclase, which begins to crystallise as microphenocrysts only at lower depth.

Regarding the plumbing system configuration, Pompilio and Coltelli (1997) suggested the LP magma resides at the base of the degassed highly porphyritic magma in a continuous vertical dyke, coinciding with the conduits in the upper part. Being an abstract, it is difficult to evaluate in detail the proposed model. It is our opinion, however, that this kind of configuration cannot work for several reasons.

First of all, the higher volatile content and the lower density and viscosity of the LP magma compared to the HP magma rule out the possibility that the LP magma resides as a stable layer at the base of the HP magma in the same magma column. The large density and viscosity differences calculated by Métrich et al. (2001) probably are not the real values when LP and HP magmas interface, because the calculation has been done applying the maximum differences in volatile contents. It is reasonable to suppose that the two magmas come in contact when the HP magma is not highly degassed. These magmas would not mix if they have highly different viscosity and density, but probably the LP magma would arrive more frequently to the surface, passing undisturbed through the HP magma, and this would especially occur in the case of the existence of a single magma column. Even though the real volatile contents of the two magmas at their interaction is unknown, it can be hypothesised that the LP magma is still less degassed than the HP magma and, in any case, they still have a different porphyritic index, which makes the HP magma heavier than the LP magma and difficult to be

maintained at the top of a magma column with the LP magma at the base.

In addition, if the two magmas were permanently in contact, we should find a larger number of xenocrysts in the pumice samples, and transitional petrographic, chemical, isotopic, and physical characteristics in the erupted magma. These features are not observed among the studied samples. Furthermore, if the HP magma resides in a small magmatic reservoir, isotopic homogenisation is more feasible to be attained (Francalanci et al., 1999) than in a 1000-m-long magma column.

Keeping in mind these considerations, we propose the presence of two distinct and geologically separated reservoirs. The LP magma occupies the deeper one (probably with a total pressure of 350–400 MPa, following the calculations of Métrich et al., 2001), in which limited crystal fractionation of olivine and clinopyroxene occurs. It is noteworthy that persistent polybaric rests of Stromboli magmas, at around 300 and 100 MPa, have been found from 200 to 60 ka, on the basis of fluid inclusion studies in quartzite nodules of calc-alkaline magmas (Vaggelli et al., 2003). Similar rest pressures for the magmas of the present-day activity have also been hypothesised. Thus, probably the highest residing pressure is nearly coincident with that found by Métrich et al. (2001) for LP magmas.

The HP magma is sited in a shallow reservoir, small in size (Francalanci et al., 1999), in which it undergoes processes of olivine+clinopyroxene+plagioclase crystallisation associated with mixing with LP magma. Following the extrapolation of Vaggelli et al. (2003), a pressure around 100 MPa for this HP magma reservoir may be hypothesised. This should be the place in which LP and HP magma mix and crystallise, becoming the isotopically homogeneous magma erupted as scoriae and lavas. Crystallisation is probably already driven by degassing, but decompression and H₂O exsolution mainly occur along the conduit in which magma continues to crystallise, forming most of the plagioclase microphenocrysts. Thus, in the shallow reservoir the rheologic characteristics of the two magmas are probably not so different and they can mix more easily.

Major eruptions and paroxysms probably occur when a higher volume of LP magma arrives at shallow level. Its rapid decompression and immediate volatile release cause it to be erupted as pumice and to be variably mingled with the HP magma.

7.3. Compositional variations with time

In spite of the general steady-state conditions, these data have also pointed out some small but significant differences with time among the scoriae and lavas that allow us to better understand the behaviour of the magmatic system.

From 1906 to 1930, and probably up to 1965 eruptions, the degree of magma evolution slightly decreases, as shown by the increase of compatible element and MgO contents (Fig. 8 and Table 5a–f) and by the lower Fo content of olivine and Mg# of clinopyroxene in 1914 than in 1929–1930 rocks (Figs. 3a and 4a; Tables 1 and 2). Small variation trends in the degree of magma evolution with time also seem to be present afterward (Fig. 8 and Table 5a–f). Keeping in mind the high crystal contents of scoriae and lavas, variable amounts of mineral accumulation could be invoked as processes capable of causing these compositional modifications. Nevertheless, it is reasonable to suppose that these kinds of processes do not generate systematic variations with time and they could be responsible for the chemical variations occurring among samples from a single eruption. Moreover, the increase of MgO content in femic phenocrysts from 1914 to 1930 rocks suggests an increase of the mafic character of the host magma, instead of a process of mineral accumulation. These systematic variations are more probably reconciled with small changes in the steady-state conditions, which can be determined by, at least, two different processes: (A) Changes in the supply rate with respect to mineral phase crystallisation rate. This can occur by several mechanisms, such as by the arrival of higher volumes of fresh magma batches, or by more frequent inputs of fresh magma batches with similar volumes, or by variations in the crystallisation rate; (B) Changes in the evolution degree of the replenishing magma. It is not easy to recognise if

these compositional variations are linked to changes in the dynamics of the magmatic system (process A), or in the chemical composition of the input magma (process B). In order to check process B, analyses of more pumice samples with known eruption date of the 20th century are necessary. On the other hand, in the case of process A, modifications of the eruption rate should also be expected. Records of historical data available in the literature (Barberi et al., 1993 and reference therein) do not allow us to recognise any systematic change of the eruption rate corresponding to compositional variations of scoriae and lavas. The first part of the 20th century with respect to the period after 1954, however, is characterised by the occurrence of relatively frequent paroxysms (15 paroxysms; Barberi et al., 1993) (Fig. 2). This could indicate that more energetic explosions are associated with the rise of a higher volume of refreshing magma.

Incompatible trace element contents seem to point out another significant variation (Fig. 9). Indeed, they increase from 1930 to 1965 rocks and, in spite of a general decrease toward younger products, they remain higher than those of pre-1965 rocks. This characteristic is not associated with a compatible element decrease from 1930 to 1965 samples, a fact leading us to rule out an increase of the evolution degree of HP magma as a possible explanation for this compositional change. Thus, an increase of the incompatible trace element contents of the replenishing magma seems to be a more probable hypothesis for this type of variation.

In 1930 AD the volcanic activity was particularly violent and this year is remembered as one of the worst periods in the history of the volcano, with six casualties and several people injured. The activity was characterised by lava flows, major explosions and two paroxysms, which were dominated by ejection of old material or by lava fountains, respectively. Hot avalanches and large block (up to 150 kg), bomb and scoriae fallout affected the villages of Stromboli and Ginostra; a tsunami was also generated with a 2.5-m high wave (Imbò, 1928; Abruzzese, 1935; Barberi et al., 1993). As for magma composition, it is to be noted that the year 1930 signified both the

end of a period with decreasing degree of evolution and a clear increase in the incompatible trace element contents. This suggests some sort of correlation between compositional variations of magma and the occurrence of more violent eruptions, pointing out the importance of chemical surveillance on the erupted rocks in open conduit volcanoes like Stromboli.

The Sr isotope ratio is the chemical factor that changes more significantly with time, starting to decrease from a period around 1980–85 AD (Fig. 10). Indeed, major and trace element contents remain nearly constant for the same period of time. The homogeneous $^{87}\text{Sr}/^{86}\text{Sr}$ value of rocks erupted before 1980–85 and the lower Sr isotope ratios of pumice provide evidence for a change in the isotopic composition of the input magma around 1980–85 (Francalanci et al., 1999), with the other geochemical characteristics remaining constant. This variation in Sr isotope ratios seems to be concomitant with one of the most voluminous lava flows of the 20th century (December 6, 1985–April 25, 1986, volume of $5.6 \times 10^6 \text{ m}^3$; Capaldi et al., 1978; De Fino et al., 1988), again pointing out a correlation between compositional changes of magmas and the type of eruptive activity.

It is noteworthy that a decoupling between Sr isotope ratio and trace element behaviour is present among the shoshonitic rocks erupted by the present-day Strombolian activity. The inferred compositional variation of replenishing magma occurring around 1930 AD has involved only trace and major elements, whereas the variation occurring around 1980–85 mainly affected Sr isotope ratios. This decoupling at Stromboli seems only to be a characteristic of the products erupted in the Recent period. Indeed, the present-day shoshonitic basalts have higher incompatible trace elements and lower Sr isotope ratios than the high-K basalts of San Bartolo. Contrarily, during most of the subaerial history of the volcano (from Strombolicchio, about 200 ka, to about 5 ka, with the eruption of potassic products), incompatible trace element contents were positively correlated with $^{87}\text{Sr}/^{86}\text{Sr}$ values (Francalanci et al., 1988, 1993a).

Several processes can be responsible for the de-

coupling between trace element and isotope ratio behaviour, depending on the variable mechanisms affecting the different chemical factors. Processes like fractional crystallisation and partial melting can only determine variations in the trace element concentrations, but crustal assimilation and mantle source heterogeneity can also affect isotope ratios. It can, therefore, be suggested that different processes caused the inferred compositional changes of replenishing magma at different times. For example, regarding the decrease of Sr isotope ratios around 1980–85, it can be hypothesised that the parental LP magma starts to be generated by partial melting of a less radiogenic mantle source. Note that a possible depletion in incompatible element contents of parental LP magma generated by the same process would not be evident in the HP magma composition, due to the large amount of crystallisation, which tends to re-enrich the contents of the same elements, but does not affect the Sr isotope ratios.

8. Conclusions

Detailed mineralogical, chemical and isotope data on rocks erupted in the present-day activity of Stromboli during the 20th century provide evidence that the two magmas erupted as pumice or lavas and scoriae are characterised by sharply distinct physico-chemical conditions. Geothermobarometers based on mineral chemistry data have allowed the calculation of higher T (and higher P) for the LP magma than for the HP magma.

It has also been pointed out that the plumbing system is under overall steady-state conditions, which are maintained by a continuously erupting, crystallising and replenished reservoir, where the scoria magma resides and evolves. The LP magma represents the feeding magma of this reservoir, deriving from a deeper reservoir in which reduced fractional crystallisation of femic phases occurs. Plagioclase crystallisation plays an important role only in the shallow reservoir and along the magma conduit to the surface. During major eruptions and paroxysms a higher volume of LP magmas probably arrives in the shallower reservoir.

A detailed examination of the possible compositional variations with time in scoriae and lavas has provided evidence for small variations in the steady-state conditions during the 20th century. Indeed, the mafic character of magmas slightly increases from 1906 to 1930, while decreasing from 1965 towards the present. These variations can be due to changes in the crystallisation/replenishment equilibrium of the magma reservoir or to compositional modifications of the feeding magma. The occurrence of relatively frequent paroxysms during the first part of the 20th century, however, seem to be evidence that more energetic explosions are associated with the rise of a higher volume of refreshing magma.

An increase of incompatible trace element contents after 1930 and a decrease of Sr isotope ratios after 1980–85 have also been pointed out, and they seem to be determined by respective variations in the composition of the input magma. Different causes probably lead to these variations at different times, as suggested by the decoupling between the behaviour of Sr isotope ratios and trace element contents.

Finally, it is noteworthy that the main compositional variations seem to have occurred in concomitance with more violent eruptions (e.g. 1930) or more voluminous lava flows (e.g. 1985–86), thus suggesting some correlation with the type of eruptive activity.

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