Geochemical data on the 2005 lava flow of Barren Island volcano, Andaman Sea

The Barren Island volcano, belonging to the Andaman and Nicobar chain (Andaman Sea, Indian Ocean), is related to the subduction of the Indian Plate beneath the Burmese Plate. Its importance is relevant as the island represents the only active subaerial volcano in the Indian sub-continent and the northernmost active volcano of the Indonesian Volcanic Arc, one of the most tectonically active regions on Earth. The Barren Island volcanic activity possibly started during the Late Pleistocene[1], and continued during pre-historic, historic and present times (the Smithsonian Institution's Global Volcanism Program (SI-GVP) website (www.volcano.si.edu) reported that on 22 September 2015, an ash plume from Barren Island rose to an altitude of 1.8 km amsl and drifted 45 km E). Recently, Ray *et al.*[2] dated, crustal xenoliths and their host lava flows from the island using $^{40}Ar/^{39}Ar$ method; they found an age of 1.58 ± 0.04 Ma for the oldest subaerial Barren volcanics.

Barren is uninhabited by man and has restricted public access; the only means to reach the island are the Indian Coast Guard and the Indian Navy ships. The volcano eruptive style and its products have been the subject of several studies. Unfortunately, there has been no regular monitoring of the Barren activity and the volcanic products have been not adequately studied. Therefore, a dataset of trace elements and radiogenic isotopes for all Barren volcanics is lacking. We report some new data (major and trace elements, Sr and Nd isotopes) on volcanic products of the 2005 eruption, in order to partially fill the existing gap on this volcanics and to extend our knowledge on this important and unique volcano.

Barren Island is a mafic stratovolcano, which rises for more than 2 km from the sea floor. It consists of a ~2 km wide, roughly circular caldera, 355 m amsl high[3], breached to the sea on the WNW side. In the subaerial volcanic history of the Barren Island two main phases have been distinguished[4] – a pre-caldera (pre-historic) and a post-caldera (historic and recent) activity, characterized by effusive and explosive eruptions. Recently, Awasthi *et al.*[5], based on ^{14}C ages of inorganic carbon collected from sediment beds and Sr and Nd isotopic ratios measured in submarine ash layers (32 km southeast of the volcano) related to the caldera collapse, suggested an age younger than 10 ka for the caldera. During the

Table 1. Major (%), trace (ppm) element and isotopic (Sr, Nd) composition of 2005 Barren volcanics

	BAR 29	BAR 30	BAR 31	BAR 32
SiO_2	49,21	50,23	49,94	51,36
TiO_2	0,86	0,84	0,83	0,84
Al_2O_3	21,97	21,31	22,17	20,90
Fe_2O_3	2,84	2,73	2,24	2,05
FeO	5,18	5,45	5,37	5,50
MnO	0,16	0,16	0,16	0,14
MgO	3,63	3,82	3,69	4,20
CaO	12,40	11,41	11,84	10,93
Na_2O	2,85	3,11	3,02	3,14
K_2O	0,37	0,41	0,37	0,41
P_2O_5	0,06	0,07	0,07	0,10
LOI	0,47	0,47	0,31	0,42
Sum	100,00	100,00	100,01	99,99
Mg#	55,53	55,53	55,04	57,64
V	294	302	295	290
Cr	55*	56*	57*	70
Co	15*	13*	16*	20
Ni	37*	31*	37*	40
Rb	11	11	10	9
Sr	253	242	230	217
Y	22	23	21	20
Zr	59	66	57	58
Nb	0,75	0,76	0,61	nd
Ba	84	93	83	84
Cs	bdl	0,67	bdl	0,4
La	4,59	4,89	4,42	4,46
Ce	11,95	12,24	11,64	10,90
Pr	1,67	1,84	1,58	1,55
Nd	8,24	9,08	9,01	7,67
Sm	2,64	3,06	2,59	2,34
Eu	0,89	1,02	1,06	0,82
Gd	2,71	3,05	3,27	2,85
Tb	0,50	0,58	0,53	0,52
Dy	3,61	3,88	3,83	3,24
Ho	0,80	0,84	0,79	0,68
Er	2,28	2,29	2,15	2,09
Tm	0,36	0,38	0,33	0,32
Yb	2,10	2,47	2,28	2,15
Lu	0,29	0,38	0,33	0,37
Hf	1,53	1,63	1,45	1,5
Ta	0,08	0,06	bdl	0,02
Pb	< 5	< 5	< 5	< 5
Th	1,38	1,40	1,31	1,21
U	0,26	0,26	0,26	0,23
$^{87}Sr/^{86}Sr$	0,704062 ± 0,000010	0,703996 ± 0,000007	0,704014 ± 0,000007	nd
$^{143}Nd/^{144}Nd$	0,512899 ± 0,000016	0,512914 ± 0,000009	0,512919 ± 0,000010	nd

*XRF data; other trace elements by ICP: (BAR 29-31) University of Perugia, Italy and (BAR 32) Actlabs, Canada.

pre-caldera activity, the eruptions were both of Hawaiian and Strombolian type in succession[1] (photographs of pre-caldera sequences are given in Shanker *et al.*[1]) and emitted, almost exclusively, basaltic and basaltic andesitic products (Luhr and Haldar[3] also described the finding of rare andesitic rocks). After the caldera formation, the first historic eruption started in 1787 and continued until 1832 (ref. 1) with breaks of variable length[3,4,6]. During this long period, magmas of exclusively basaltic composition were emplaced. The volcanic activity resumed in 1991, after 159 years of quiescence, with predominant Strombolian eruptions, frequently coupled with the emission of lava flows, which reached the sea. Since 1991, the volcano has been active intermittently (1994–95, 2005–07, 2008–10, 2013–ongoing) with explosive and effusive events. During the 1994–1995 events, the volcano initially emitted ash and coarser clasts and, successively, basaltic lava[3,6]. In the 2005–07 activity, the eruption started from two vents (at the southern base and at the slope of the main volcanic cone)[3,7], aligned along a N–S trend[6]. The eruption was initially of Strombolian type and successively changed to sub-Plinian[3]: ash falls, coarse tephra (lapilli, cinders and blocks) and fragmented lavas of basaltic and basaltic andesitic composition were emitted; they completely covered the older (1991 and 1994–95) pyroclastic deposits and lava flows[3,5,7]. By September 2006, the activity become slow and sporadic[6]. According to the SI-GVP website, the successive eruptive activity at Barren Island volcano possibly started in May 2008. Interestingly, during this event, the lava flow moved westward to the sea[8]. During their fieldtrip (March 2009), Sheth *et al.*[6,8] reached the small lava delta formed by the still flowing lava and collected black basaltic specimens. Again, in December 2010, Sheth[9] observed continuous Strombolian eruptions. In January 2011, an expedition organized by the Geological Survey of India (GSI, http://www.portal.gsi.gov.in) observed that the eruption was still continuing even if with a lesser intensity compared to the violent eruptions observed from 2005 to 2009. Successively (February 2013 to September 2015), ash plume activity was reported (SI-GVP website).

The 2005 eruption began on 28 May with the ejection of gas, ash and coarser clasts[7,10,11]. At the beginning of

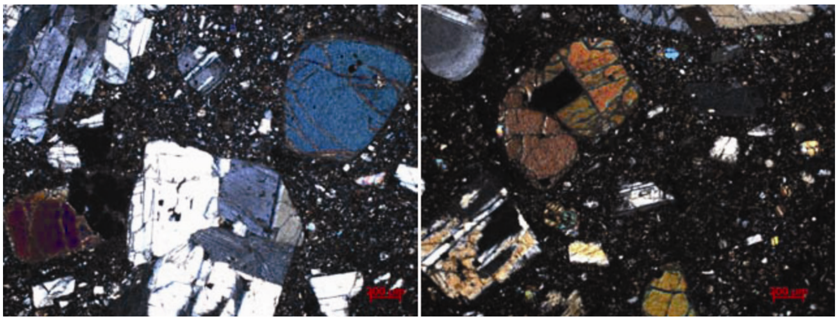

Figure 1. Cross polarized images (2.5X) of 2005 Barren lavas.

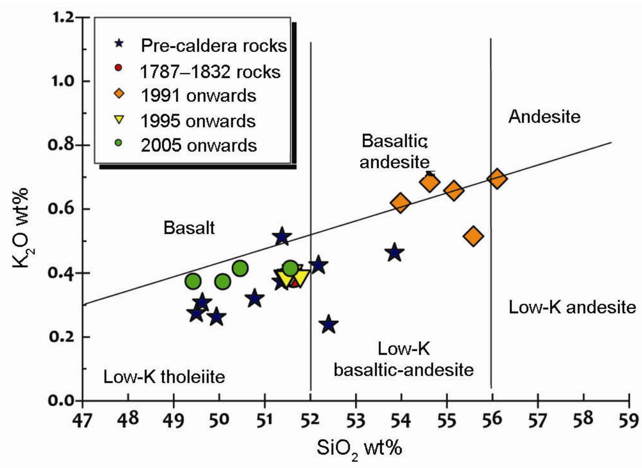

Figure 2. K_2O versus SiO_2 (wt%) classification diagram[12]. Chemical data are plotted on water-free basis. Data for the 2005 lava eruption are from the present study. Other data are from Chandrasekharam *et al.*[4].

Appendix 1. Analytical techniques.

Major element compositions were obtained by combined wet chemical techniques [Na_2O, MgO, FeO and loss on ignition] and X-ray fluorescence at the Department of Earth Sciences, University of Florence, Italy.

Abundance of trace elements like Y, Zr, Nb, Ba, Cs, REE, Hf, Ta, Pb, Th and U was measured by ICP-MS microanalysis at Activation Laboratories, Ancaster, Canada and at the Department of Earth Sciences, University of Perugia, Italy. Spot size used in the analyses was 40 μm with spacing between consecutive data points of 40 μm. The use of this spot size permitted to study in detail the compositional variability in the experiments. Analytical precision is better than 10% for all the analysed elements[17]. Cr, Co and Ni concentrations were measured by X-Ray fluorescence (Department of Earth Sciences, University of Florence) using several international rock standards for curve calibration. Precision is better than 10%. Sr and Nd isotope ratios were determined using TIMS technique at the Pisa,Istituto di Geoscienze e Georisorse of C.N.R. (Italian National Research Council) with a Finnigan MAT 262 multicollector mass spectrometer running in dynamic mode. The measured $^{87}Sr/^{86}Sr$ ratios have been normalized to $^{86}Sr/^{88}Sr = 0.1194$, and $^{143}Nd/^{144}Nd$ ratios to $^{146}Nd/^{144}Nd = 0.7219$. During the measurement period, the mean measured value of $^{87}Sr/^{86}Sr$ for the NIST–SRM 987 standard was 0.710242 ± 0.000013 (2SD, $N = 25$), while the mean $^{143}Nd/^{144}Nd$ for the La Jolla standard was 0.511847 ± 0.000008 (2SD, $N = 25$). The JNdi-1 standard[18] was also analysed and yielded a $^{143}Nd/^{144}Nd$ value of 0.512100 ± 0.000010 (2SD, $N = 25$). The total procedure blanks, 0.5 and 0.1 ng of Sr and Nd respectively, were negligible for the analysed samples.

November, the lava flow reached the sea forming a thick black patch from the eruption vent to the sea (SI-GVP website). The presently studied rock samples were collected from the front of the lava flow near to the seashore and consist of vesiculated greyish-black or brownish-black rocks (Figure 1). Table 1 lists the whole-rock compositions (major, trace element and Sr and Nd isotopic ratios). The petrography of the 2005 lava flow closely resembles that of the previously (1995) erupted magmas. Rocks are porphyritic (25–30 vol%) and display hypocrystalline seriate texture. The phenocryst mineralogy mainly consists of plagioclase (variously twinned and zoned) and subordinately by clinopyroxene, occurring as subhedral and fractured crystals and olivine (showing an iddingsitic rim); Ti-magnetite and ilmenite are present in accessory amounts. The groundmass contains the same mineral phases as the phenocrysts and microphenocrysts. Overall, the mineral phase composition is in the same range of the older Barren volcanics[3,5]. Plagioclase phenocrysts display a core composition in the range An 93–85%; the forsterite content of olivine core phenocrysts varies between 82% and 78%; clinopyroxene composition is diopsidic in the microphenocrysts and pigeonitic in the groundmass. In the classification diagram (Figure 2)[12] the composition of representative 2005 rocks is reported together withthat of volcanics emplaced during Barren previous eruptions. All Barren rocks vary in a short compositional range; in particular, many pre-caldera rocks, and the 1787–1832, 1995 and 2005 rocks plot in the low-K tholeiite field, whereas a few pre-caldera rocks and the 1991 rocks display higher SiO_2 content falling in the basaltic andesite field. The lack of highly silicic magmas on Barren Island was considered an indication of the relatively short life of the volcano[6]. Sheth[9] suggested a different hypothesis, according to which the lack of evolved magmas is due to the frequent recharge of the Barren magmatic system. Figure 3 shows the variation of silica and Mg# with time: despite the small compositional variations, it is possible to observe that the Barren magma compositions vary discontinuously with time. Unfortunately, the emplacement ages of the pre-caldera lavas are unknown. However, some considerations can be done on the post-caldera rocks: among these, the higher enrichment in silica (and the corresponding lowest Mg#) is observed between the 1787–1832 and 1992 eruptions, i.e. at the longer interval between two successive eruptions in the post-caldera history of the Barren volcano. This fact could be explained with time-dependent processes of refilling-fractionation in the magma reservoir, where magmas stationing for a longer period may differentiate.

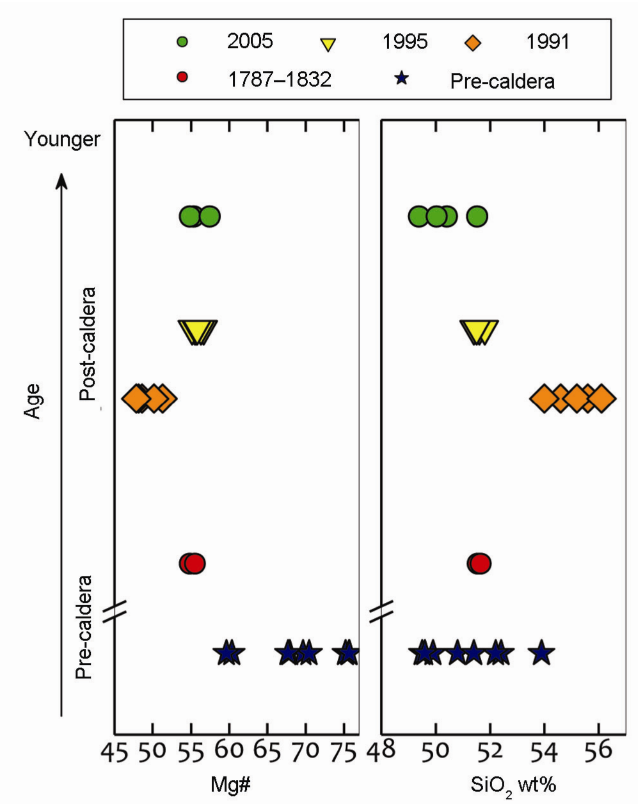

Figure 3. SiO_2 (wt%) and Mg# variation with time for the Barren volcanics. Chemical data are plotted on water-free basis. Data for the 2005 eruption are from the present study. Other data are from Chandrasekharam *et al.*[4].

Chondrite normalized REE patterns of 2005 lavas display very moderate fractionation (La/Yb = 1.31–1.48) and a certain scatter of values[13]. Also, when compared to the older Barren volcanics, they fall with the exception of a few cases, in the wide range of pre-caldera rocks or are similar to the 1787–1832 and 1995 products. Incompatible trace element patterns (Figure 4), normalized to primitive mantle values[14], are those typical of island-arc basic rocks[15]. They are similar to some pre-caldera and to the 1787–1832 and 1995 rocks (Figure 3). They are characterized by moderate fractionation, negative anomalies of Ta, Nb, P and Ti, and slight enrichment of Th, K and Sr. Sr and Nd isotopic ratios, obtained on representative samples of the 2005 eruption (Table 1), are poorly variable ($^{87}Sr/^{86}Sr$ = 0.703996–0.704062; $^{143}Nd/^{144}Nd$ = 0.512899–0.512919) and fall within the range of all Barren products[3–5,16]. Among the latter (Figure 5), the higher variability of Sr isotopic ratios is observed in the pre-caldera rocks (0.703805–0.704010) which, however, are of unknown age. During the post-caldera activity ($^{87}Sr/^{86}Sr$ range = 0.703950–0.704150), when several data are available, it is possible to observe small but significant variations of $^{87}Sr/^{86}Sr$ among rocks of the same eruptive phase. The 2007 and 2009 rocks[4] show the highest post-caldera $^{87}Sr/^{86}Sr$ values; these are similar to Sr isotopic ratios obtained by Awasthi *et al.*[4] in very old (10.1–70 ka) submarine ash layers related to the Barren caldera collapse and outcropping 32 km southeast of the volcano, and falling in the range 0.703950–0.704140. This characteristic seems to confirm a certain periodicity of the evolutionary processes of Barren magmas for which a complex petrogenetic history has been hypothesized[3,5,7]. The 2005 magmatic products display geochemical and isotopic

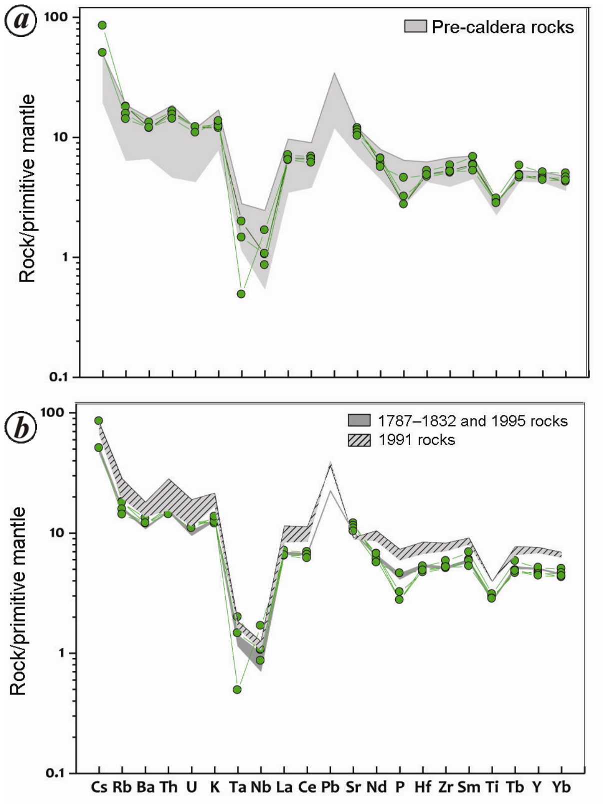

Figure 4. Mantle-normalized[14] incompatible trace element patterns for the 2005 eruption rocks compared to the range of pre-caldera rocks (***a***) and post-caldera rocks (***b***). Data for the 2005 eruption are from the present study. Other data are from Chandrasekharam *et al.*[4].

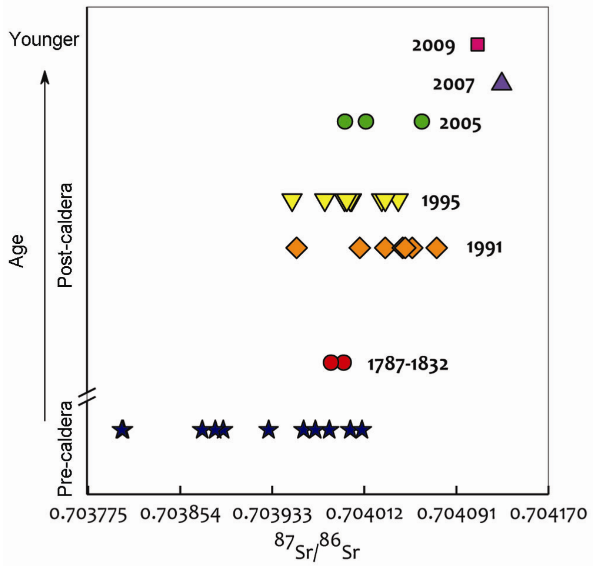

Figure 5. $^{87}Sr/^{86}Sr$ variation with time for the Barren volcanics. Data for the 2005 lava eruption are from the present study. Other data are from the literature[3–5,16].

characteristics similar to those of the previously erupted magma, leading to the hypothesis that similar genetic and evolutionary processes were also active for these magmas. These processes have possibly played an important role since the pre-historic times, resulting in similar eruption-types at more or less regular intervals. As a consequence, this periodicity may represent an important effort to understand the future Barren eruptive activity and volcanic hazards.

1. Shanker, R., Haldar, D., Absar, A. and Chakraborty, S. C., *Geol. Surv. India Spec. Publ.*, 2001, **67**, 88.
2. Ray, J. S., Pande, K. and Bhutani, R., *Bull. Volcanol.*, 2015, **77**(6), 1–10.
3. Luhr, J. F. and Haldar, D., *J. Volcanol. Geother. Res.*, 2006, **149**, 177–212.
4. Chandrasekharam, D., Santo, A. P., Capaccioni, B., Vaselli, O., Alam, M. A., Manetti, P. and Tassi, F., *J. Asian Earth Sci.*, 2009, **35**, 469–487.
5. Awasthi, N. *et al.*, *Bull. Volcanol.*, 2010, **72**, 1131–1136.
6. Sheth, H. C., Ray, J. S., Bhutani, R., Kumar, A. and Smitha, R. S., *Bull. Volcanol.*, 2009, **71**, 1021–1039.
7. Pal, T. *et al.*, *J. Asian Earth Sci.*, 2010, **39**, 12–23.
8. Sheth, H. C., Ray, J. S., Bhutani, R., Kumar, A. and Awasthi, N., *Curr. Sci.*, 2010, **98**(5), 620–626.
9. Sheth, H. C., *J. Volcanol. Geotherm. Res.*, 2014, **289**, 64–80.
10. Pal, T., Bandopadhyay, P. C., Mitra, S. K. and Raghav, S. R., *J. Geol. Soc. India*, 2007, **69**, 1195–1202.
11. Bandyopadhyay, P. C., Mitra, S. K., Pal, T. and Raghav, S., *Curr. Sci.*, 2006, **90**, 620–622.
12. Peccerillo, A. and Taylor, S. R., *Contrib. Miner. Petrol.*, 1976, **58**, 63–81.
13. McDonough, W. F. and Sun, S. S., *Chem. Geol.*, 1995, **120**, 223–253.
14. Sun, S. S. and McDonough, W. F., *Geol. Soc. London, Spec. Publ.*, 1989, **42**, 313–334.
15. Gill, J. B., *Orogenic Andesites and Plate Tectonics*, Springer, 942 Berlin, 1981, p. 390.
16. Streck, M. J., Ramos, F., Gillam, A., Haldar, D. and Duncan, R. A., In *Topics in Igneous Petrology* (Ray, J., Sen, G. and Ghosh, B.), Springer, 2011, pp. 241–273.
17. Petrelli, M., Perugini, D., Poli, G. and Peccerillo, A., *Microchim. Acta*, 2007, **158**, 275–282.
18. Tanaka, T. *et al.*, *Chem. Geol.*, 2000, **168**(3–4), 279–281.

ACKNOWLEDGEMENTS. I thank Prof. Dornadula Chandrasekharam (IIT Bombay, India) for providing the rock samples and Dr Samuele Agostini (CNR, Pisa, Italy) and Prof. Giampiero Poli (University of Perugia, Italy) for help with isotope and ICP analyses respectively.

Received 2 December 2015; revised accepted 4 March 2016

ALBA PATRIZIA SANTO

Department of Earth Sciences,
Via G. La Pira, 4,
50121 Florence, Italy
e-mail: alba.santo@unifi.it