

Drift pumice in the Central Indian Ocean Basin: geochemical evidence

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Abstract

Abundant white to light grey coloured pumice without ferromanganese oxide coating occurs within the Quaternary sediments of the Central Indian Ocean Basin. Two distinct groups of pumice are identified from their geochemical composition, which allow one to define two different origins linked to two separate eruptions. One group of pumice is a dacitic type characterized by high Fe, Ti, Mg, Al and Ca with comparatively low contents of Si, rare earth elements (Σ REE-69 ppm), Rb, Sr, U, Th, Ba, V, Nb, Sc, Mo and Co which strongly suggest an origin from the 1883 Krakatau eruption. The other group is rhyolitic and is characterized by low contents of Fe, Ti, Mg and Ca and high Si, Σ REE content (121 ppm), Rb, Sr, U, Th, Ba, V, Nb, Mo, Co, and Sc and correlates well with the composition of the Youngest Toba Tuff (YTT) eruption of ~ 74 ka from Northern Sumatra and is being reported for the first time. Therefore, correlation of the pumice to the 1883 Krakatau and YTT eruptions indicates that the pumice drifted to the Central Indian Ocean Basin and eventually sank when it became waterlogged. However, physical properties such as density, specific gravity, porosity and degree of saturation required for sinking of pumice for both 1883 Krakatau and YTT are almost similar.

Keywords: Pumice; Central Indian Ocean Basin; Chemical composition; 1883 Krakatau; Youngest Toba Tuff ~ 74 ka; Drift Origin

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1. Introduction

Pumice is a common product of explosive volcanic eruption, porous in nature and low in density (1.2 to 1.4 g/ cm³) (Fisher and Schmincke, 1984). It is the only rock that can float for many months and be transported thousands of kilometers depending on the connectedness of its vesicles. It eventually sinks from water saturation through the vesicles and breaks up on the water surface by attrition (Whitham and Sparks, 1986). A large pumice field covering an area of 600, 000 km² in the Central Indian Ocean Basin (CIOB) has been reported by Iyer and Sudhakar (1993). Nearly 84 % of the pumice is free from ferromanganese oxide coatings (Iyer, 2005), whereas some of it may act as nuclei for ferromanganese nodules (Martin-Barajas and Lallier-Vergès, 1993). Pumice in the CIOB that acts as nuclei for ferromanganese oxide growth could be considered to be of significant age because of the extremely slow accretion of Fe-Mn oxide (Banakar, 1990). Conversely, pumice that is free from any oxide coatings is likely to be younger. Therefore, pumice ages could range from a few million years for coated pieces to a few thousand years for uncoated ones. Several origins for the pumice in the CIOB have been proposed, including *in-situ* submarine volcanic activity (Hedervari, 1982; Iyer and Sudhakar, 1993), deposition from the 1883 Krakatau eruption (Mudholkar and Fujii, 1995) and from Indonesian Arc Volcanism (Iyer and Karisiddaiah, 1988; Martin-Barajas and Lallier-Vergès, 1993), indicating uncertainty about its source. In this paper, we present major, trace and rare earth element (REE) data of younger pumice from the CIOB in order to assess its possible source.

2. Materials and Methods

During a recent cruise of the *R.V. Akadamik Boris Petrov – II* (Jan-Feb. 2005) in the CIOB, samples of ferromanganese nodules and associated sediments were collected with a Van Veen grab at 56 locations (Fig.1). The grab generally penetrates ~ 40 cm into the sediment. Sediments in the CIOB have an accumulation rate of ~ 2 mm/ka (Banakar

et al., 1991), and thus sediment collected by grab is of Quaternary age (~200 ka). Small pumice fragments were recovered at all 56 locations. Five large pumice pieces (up to 12 cm in diameter) collected by dredging during an earlier cruise are also used in the present study. The average water depth in the study area is ~ 5300 m, and the seafloor appears to be smooth with a few small seamounts up to 800 m height present only in the southern part. The coarse fraction (>63 μm) of the sediment contains abundant pumice fragments without oxide coatings, volcanic glass shards, manganese micronodules and radiolarians. Pumice fragments were ultrasonically cleaned, powdered and treated with 6N HCl to remove carbonate and ferromanganese oxide traces. The whole-rock analysis for major elements was carried out using an x-ray fluorescence spectrometer (XRF) (PANalytical - Axios) at National Institute of Oceanography, Goa. Trace and REE were analysed at Wadia Institute of Himalayan Geology, Dehra Dun by inductively coupled plasma – mass spectrometer (ICP-MS) (Perkin Elmer, ELAN DRCe) following the procedure of Balaram and Rao (2003). The accuracy for the standard reference material (JR-1) with XRF is $\pm 4\%$, and for trace and REE with ICP-MS is $\pm 10\%$. A few pumice samples were also observed under scanning electron microscope (JEOL, JSM-5800 LV) to study the nature of the vesicles. Physical properties such as density, specific gravity and porosity of pumice were determined following the ASTM procedures. Degree of saturation of pumice required for sinking was carried out by boiling in water for two hours at 100°C .

3. Results and Discussion

The colour of the pumice ranges from white to light grey. Pumice size varies from 0.25 cm to 12 cm in diameter (Fig.2 a-d). Pumice samples are mainly well rounded to sub-rounded suggesting abrasion during transport. Vesicles in the pumice are both circular and elongated with diameters varying between 5 and 15 μm (Fig.2 e, f, h). A few well-developed crystals are present within the vesicles (Fig.2 g).

The bulk analyses of seven pumice samples by XRF are recalculated to 100 % for comparison and presented in Table 1. Data for trace and rare earth elements of 15 pumice samples are given in Table 2. The SiO_2 content (69 % to 79 %), TiO_2 (0.1 % to 0.69 %) and total Fe (1.61 % to 4.04 %) contents show strong variations (Table 1). On the other

hand, Al, Mn, Ca and P contents are less variable (Table1). Total rare earth element concentrations (Σ REE - 49 ppm to 150 ppm) and incompatible elements (Rb, Sr, U, Th, Ba, V, Nb, Mo, Co, Sc and Y) also exhibit strong variations between them (Table 2).

Major element analysis of the pumice allows the distinction between two groups, Group I consisting of two samples (SS-13/ #683 and AAS-21/DR-09) and Group II consisting of five samples (AAS-21/DR-01, AAS-21/DR-12, ABP-II #113, AAS-21/D-1 and AAS-21/D-10). Group I pumice has an average SiO_2 content of 69.67 % and total alkalis of 7 %, suggesting a dacitic composition, and is characterized by relatively high Ti (0.58%) and total Fe (3.70 %) (Table 3). In contrast, Group II has higher SiO_2 (75.42 %), and total alkalis (6.3%), indicating a rhyolitic composition with low contents of Ti (0.27 %) and total Fe (1.93 %) (Table.1). Some major element scatter plots are made for all the pumice along with published results where two distinct groups are observed (Fig.3). REE concentrations vary considerably, from 49 ppm to 150 ppm (Table 2), and are low in Group I (69 ppm) compared to Group II (121 ppm) pumice. Although there are considerable differences in REE concentration between the two groups, their chondrite – normalized patterns are very similar (Fig. 4). The chondrite-normalized REE pattern shows enrichment of light REE compared to heavy REE with a negative Eu-anomaly (Fig.4). Heavy REE in both groups are flat, without any variation. There is a distinct difference in the concentrations of incompatible elements (Rb, Ba, U, Th, Nb, V, Mo and Y) between the two groups; their concentrations are higher by 0.5 to 3 times in Group II pumice compared to Group I (Table 4).

Major element data of Group I pumice match well with those of the 1883 Krakatau eruption reported by Mandeville et al (1996). Furthermore, the analyses of 1883 Krakatau pumice by different techniques are also close to the present study (Oba et al., 1983; Frick and Kent 1984). These similarities suggest that the Group I pumice samples are from the 1883 eruption of Krakatau and are similar to those studied earlier for the same eruptive event (Mudholkar and Fujii, 1995). Krakatau pumice is generally rich in TiO_2 as indicated by the fact that lavas from Java Trench are generally enriched in TiO_2 (Van Padang, 1951). On the other hand, chemical data of Group II pumice are close to those of pumice ejected during the eruption of the Youngest Toba Tuff (YTT) about 74

ka from Northern Sumatra (Chesner, 1998). The slight variation in the chemical data could be due to different instruments and or different effects of contact with seawater during sinking and transport. This is the first report of its occurrence in the CIOB. Martin-Barajas and Lallier-Vergès (1993) analysed pumice by electron microprobe and proposed that their origin could be Indonesian Arc volcanism, but their data did not allow them to exactly specify the source of volcanic event. Their REE content and chondrite-normalized pattern of 1883 Krakatau pumice normally show depletion in light REE as compared to YTT pumice, but heavy REE contents of both Krakatau and YTT pumice are similar. The REE patterns of pumice of the YTT eruption and glass shards of YTT origin are closely comparable to that reported from the CIOB, Northern Sumatra, the South China Sea, the western continental margin of India and the Indian subcontinent (Shane et al., 1995; Pattan et al., 2001; 2002; Westgate et al., 1998; Song et al., 2000), further supporting YTT as source for Group-II pumice (Fig.5). Further, Group I and II pumices are distinguished by Nb/Y and La/Rb ratios. The mean Nb/Y and La/Rb ratios of Group I and II pumice are 0.15 and 0.28; 0.04 and 0.33, respectively. The mean Nb/Y ratio of Group I pumice from the CIOB correlates very well with that of the 1883 Krakatau eruption (0.15), as reported by Mandeville et al. (1996) and Pearce (1982), whereas the mean La/Rb ratio of Group II pumice from the CIOB matches with that of YTT caldera (0.33) as reported by Chesner (1998). The plot of Nb/Y versus La/Rb shows two distinct fields such as the 1883 Krakatau and YTT eruptions, further confirming their different sources (Fig. 6). The 1883 eruption of Krakatau produced about 18-21 km³ of products (Self and Rampino, 1981), and the occurrence of pumice all along the east African coast, the Indian Ocean islands (Frick and Kent, 1984) and the CIOB (Mudholkar and Fujii, 1995) has been well documented. On the other hand, Youngest Toba Tuff was the largest volcanic event in the earth's history during the late Quaternary period and is believed to have emitted 2800 km³ of magmatic products (Chesner, 1998). This suggests that the YTT eruption released nearly 150 times more magmatic products than the 1883 Krakatau eruption. Although these two events are of significantly different sizes, their products have been spread over a similar large area of the Central Indian Ocean Basin.

The dispersal of floating pumice by ocean surface currents is an effective mechanism for transport over a great distance. Pumice from both Krakatau and YTT, after reaching the sea, might have started moving in the South Java Current which gets stronger with the Indonesian Throughflow water coming from the Pacific. The Indonesian Throughflow joins the South Equatorial Current (SEC) and increases its moment westward (Gordon et al., 1997) and brings it to the CIOB (Fig.7). Frick and Kent (1984) reported the 1883 Krakatau pumice along Madagascar, South Africa and other Indian Ocean coasts. Similarly, we suspect YTT pumice also reached Indian Ocean coasts but because of its age and the high sedimentation rates along the coast it may not be possible to trace it.

Physical properties of pumice are important which helps to understand the process of floating and sinking in the water. The 1883 Krakatau and YTT pumice have similar dry density (0.326; 0.385), specific gravity (2.341; 2.390), porosity (87.7 %; 86.1%) and degree of saturation required for sinking (80 %; 78.6 %). It has been proposed that large pieces of pumice absorb proportionally less water than small (Whitham and Sparks, 1986), and that the time required for pumice to saturate is proportional to the square of its radius (Manville et al., 1998). The floating behavior of pumice was studied following the methodology of Whitham and Sparks (1986) to find the water content of pumice as a function of time. Pumice pieces of 2 x 2 x 2 cm (Krakatau) and 1.5 x 1.5 x 1.5 cm (YTT) were dropped in water, allowed to float and at regular time intervals were removed from the water and weighed. The results show that the two samples followed very similar trends and exhibited increasing density as a function of time (Fig.8). These results are consistent with those reported by Whitham and Sparks (1986) and Esposito and Guadagno (1998). Within 1 hour in water, density of pumice increases from 0.3 to 0.7 g/cm³. Then from 1 to 145 hours density gradually increases (Fig.8). Risso et al. (2002) suggested that sinking of pumice is controlled by the length of the c-axis rather than the volume of clast. Some pumice remained afloat for one and half years (Whitham and Sparks, 1986). However, sinking of pumice depends upon a number of factors such as pumice vesicle size, connectedness of the vesicles, association of organisms during

settling, trapping of suspended sediment within the vesicles, depth of the occurrence of pumice within the water column (pressure) and temperature.

The magma volume erupted during the YTT event is enormous compared to the 1883 Krakatau eruption; therefore, we suggest that most of the pumice in the CIOB could have been supplied from the YTT eruption. The occurrence of pumice and ash beds of YTT origin suggests that the CIOB is one of the sink for volcanic products from the Toba eruption. YTT ash covers entire Indian subcontinent, Indian Ocean and South China Sea. There is every possibility of occurrence of pumice of YTT origin in Pacific Ocean which needs to be looked into detail. The present study therefore resolves the controversy regarding source of pumice in CIOB.

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Table 1. Whole rock analysis of pumice from Central Indian Ocean Basin by XRF.

GROUP I			GROUP II				
Oxide	AAS-21/ DR-09	SS-13/ # 683	AAS-21/ DR-01	AAS-21/ DR-12	ABP-II/ # 113	AAS-22/ D-01	AAS-22/ D-10
SiO₂ (%)	69.58	69.76	74.94	73.36	75.58	79.65	73.61
TiO₂	0.48	0.69	0.19	0.29	0.33	0.31	0.24
Al₂O₃	15.55	15.56	14.61	14.19	13.54	15.55	15.01
Fe₂O₃	4.04	3.36	1.61	3.06	1.54	1.86	1.60
MnO	0.13	0.15	0.07	0.09	0.10	0.12	0.09
MgO	0.58	1.05	0.33	0.39	0.34	0.69	0.04
CaO	1.81	2.99	1.61	1.85	1.24	2.67	1.67
Na₂O	4.17	4.81	3.61	3.61	4.70	4.85	1.72
K₂O	3.26	1.75	2.98	3.10	2.59	1.04	3.22
P₂O₅	0.08	0.07	0.05	0.04	0.02	0.03	0.05

Table 2. Rare earth and trace element concentration (ppm) of pumice from Central Indian Ocean Basin.

GROUP I					GROUP II										
Element	AAS-21/ D-11	AAS- 21/D-13	ABP- II/ #112	SS- 13 /683	ABP- II/ # 80	ABP- II/# 71	ABP- II/ # 107	ABP- II/ # 119	ABP- II/# 114	ABP- II/# 111	ABP- II/ # 120	ABP- II/# 113	ABP- II/ # 93	ABP- II/# 100	SS- XI /664F
La	13.5	10.11	10.01	11.42	26.10	21.10	16.46	21.50	27.65	22.54	29.21	23.05	17.98	22.96	24.50
Ce	26.9	22.45	18.04	21.8	48.45	33.04	36.40	38.70	57.50	43.13	47.81	48.20	41.70	44.6	50.33
Pr	3.15	2.57	2.20	3.38	4.86	4.21	4.02	4.20	6.97	4.67	5.164	5.8	4.05	4.37	6.38
Nd	13.64	11.79	8.80	16.64	20.20	16.13	17.96	16.72	31.35	19.3	20.73	25.63	18.31	17.9	29.54
Sm	3.30	2.92	1.81	4.43	4.85	3.44	4.44	3.59	7.57	4.20	5.46	6.44	4.23	3.76	7.22
Eu	0.60	0.66	0.33	0.91	0.87	0.59	0.77	0.70	1.12	0.76	1.03	0.99	0.89	0.76	1.29
Gd	3.34	2.89	1.49	4.20	4.52	2.86	4.35	3.28	7.33	3.93	4.53	6.28	4.18	3.23	6.87
Tb	0.62	0.56	0.27	0.86	0.81	0.52	0.84	0.57	1.35	0.71	0.79	1.21	0.77	0.57	1.33
Dy	4.27	3.80	1.73	5.96	5.39	3.27	5.51	3.66	9.02	4.59	5.15	8.20	5.16	3.63	8.82
Ho	1.06	0.97	0.41	1.41	1.31	0.77	1.36	0.86	2.16	1.11	1.27	2.02	1.21	0.82	2.1
Er	2.92	2.52	1.19	3.79	3.45	2.13	3.59	2.33	5.72	2.92	3.29	5.32	3.25	2.27	5.6
Tm	0.44	0.40	0.18	0.55	0.47	0.32	0.55	0.34	0.80	0.45	0.48	0.76	0.46	0.35	0.81
Yb	3.16	2.74	1.30	3.63	3.30	2.18	3.63	2.44	5.53	3.05	3.25	5.24	3.15	2.4	5.38
Lu	0.53	0.45	0.21	0.56	0.52	0.37	0.56	0.40	0.88	0.49	0.52	0.83	0.48	0.38	0.82
Sc	3.78	5.42	B.d	18.17	18.50	6.13	11.4	6.2	12.62	9.44	11.04	8.47	27.6	2.29	14.97
Y	27.34	24.25	38.66	29.64	31.80	19.92	31.22	22.3	33.5	28.3	31.11	29.90	30.30	21.51	22.5
Nb	2.62	2.62	5.56	5.08	10.05	6.89	8.35	6.34	7.45	10.66	9.10	5.95	9.97	6.34	5.19
Th	4.68	3.36	5.96	4.86	16.53	11.5	8.8	12.03	10.54	11.77	22.89	8.93	7.61	12.33	8.05
Sr	116	170	142	136	179	94	113	194	180	158	96	93	179	211	190
Rb	24.3	20.62	36.7	16.2	102	69.29	49.65	87.21	62.92	76.5	119	60	56.30	91	53.25
Ba	224	272	307	217	773	421	290	383	359	412	538	358	320	559	341
V	12.77	10.57	1.41	9.28	57.13	30	10.17	11.97	15.3	30.97	14.15	5.95	59.90	9.42	25.34
U	0.92	0.52	1.32	0.69	3.31	1.44	1.76	2.16	2.00	2.13	3.52	1.77	1.33	2.26	1.68
Co	1.03	1.94	1.02	3.66	10.68	3.51	3.46	2.70	2.65	3.97	6.69	0.87	11.60	1.91	2.32
Mo	1.05	1.02	1.74	1.08	6.42	1.82	2.91	0.81	1.68	2.18	19.13	1.93	9.49	1.93	1.44

B.d - below detection limit

Table 3. Comparison of chemical composition of pumice by XRF from Central Indian Ocean Basin with that of 1883 Krakatau and Youngest Toba Tuff caldera.

Oxide	Group I Pumice-CIOB n=2, (1)	1883 Krakatau Pumice n=8, (2)	Group II Pumice-CIOB n=5, (3)	YTT caldera Pumice n=12, (4)
SiO ₂ (%)	69.67	68.40	75.42	72.78
TiO ₂	0.58	0.76	0.27	0.33
Al ₂ O ₃	15.55	14.98	14.58	13.91
Fe ₂ O ₃	3.70	3.51	1.93	2.86
MnO	0.14	0.14	0.09	0.13
MgO	0.81	0.94	0.36	1.11
CaO	2.40	2.93	1.81	3.49
Na ₂ O	4.49	4.87	3.70	3.32
K ₂ O	2.51	2.23	2.59	4.97
P ₂ O ₅	0.07	Nd	0.04	0.04

(1) Present study, (2) Mandeville et al., 1996, (3) Present study and (4) Chesner, 1998.

nd - not determined, n - number of samples analysed.

Table 4. Comparison of trace and REE concentration (ppm) of pumice from Group I and Group II from CIOB.

Element	Group I (n=4)	Group II (n=11)
Σ REE	69	121
Ba	255	423
Co	1.91	4.58
Mo	1.22	4.52
Nb	3.97	7.84
Rb	24.46	75.19
Sc	9.12	11.70
Sr	141	153
Th	4.72	11.91
U	0.86	2.12
V	8.51	24.57

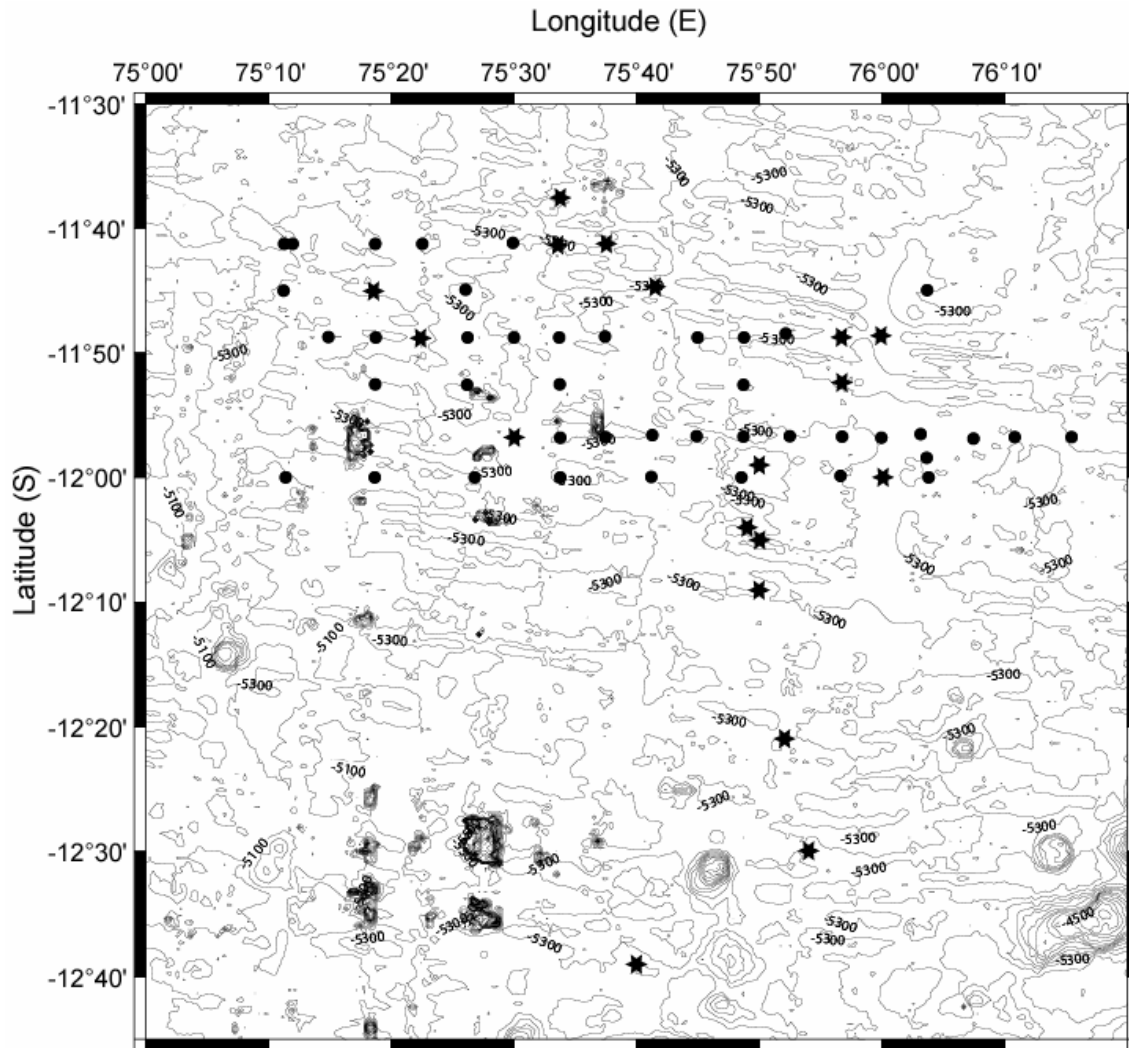


Fig. 1. Map showing detailed bathymetry along with location of pumice recovered from the sediment (Filled star indicates pumice analysed for chemical composition and filled circles indicate the location of Van Veen grab samples).

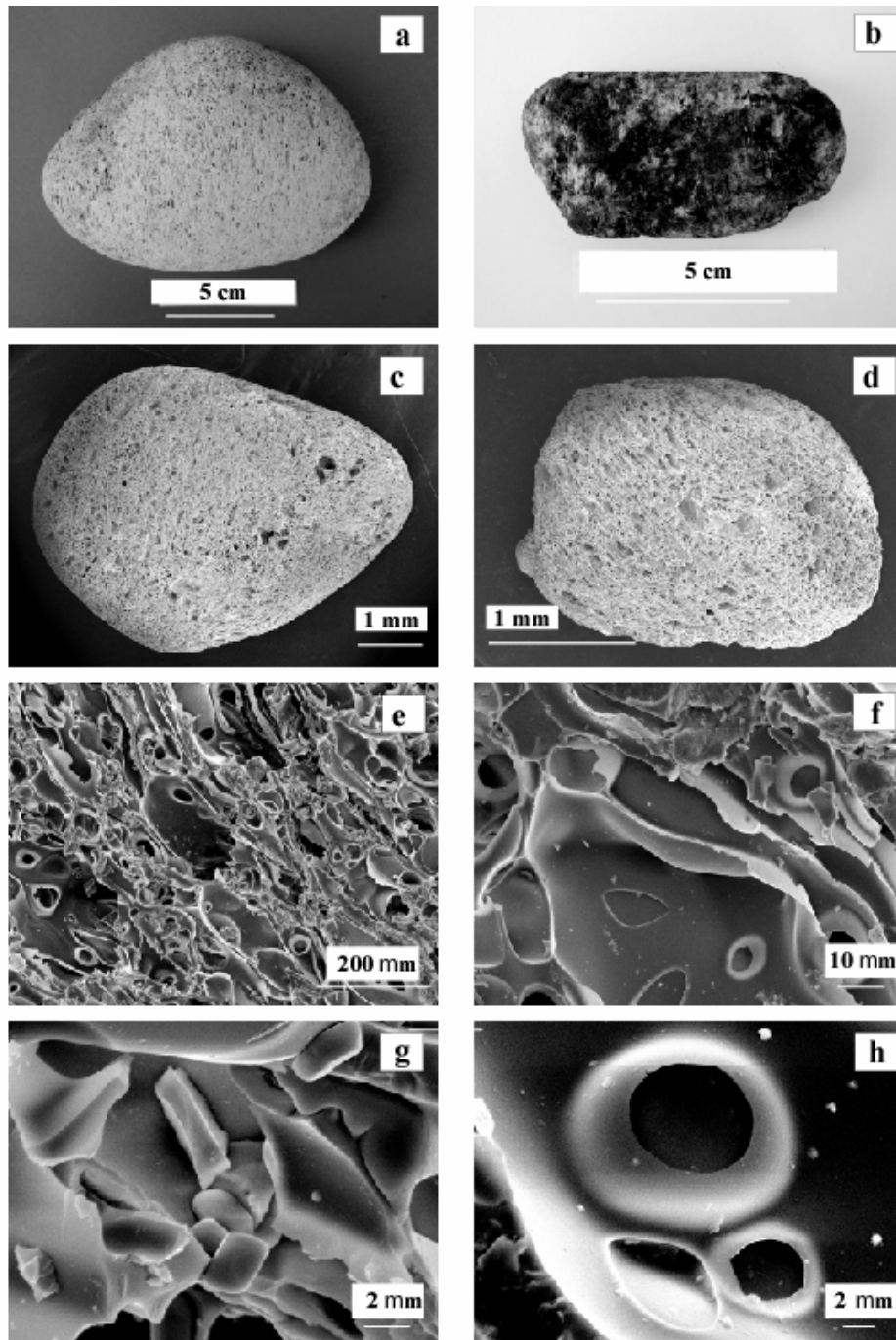


Fig. 2. Photograph of pumice (a,b), scanning electron microphotograph of pumice (c,d), nature of vesicles (e,f), well-developed crystals (g) and circular gas escapes (h).

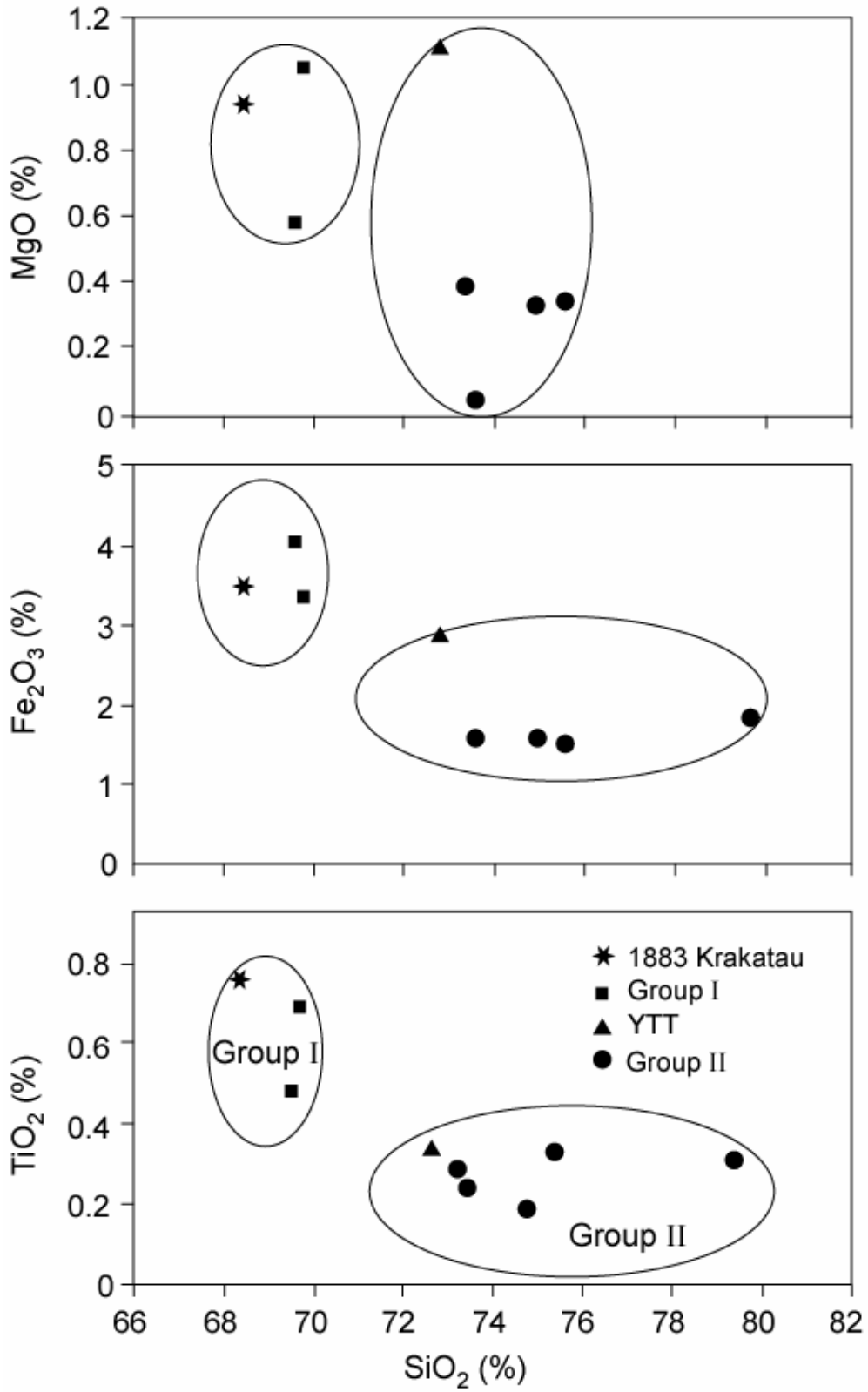


Fig. 3. Some important scatter plots of major elements from pumice

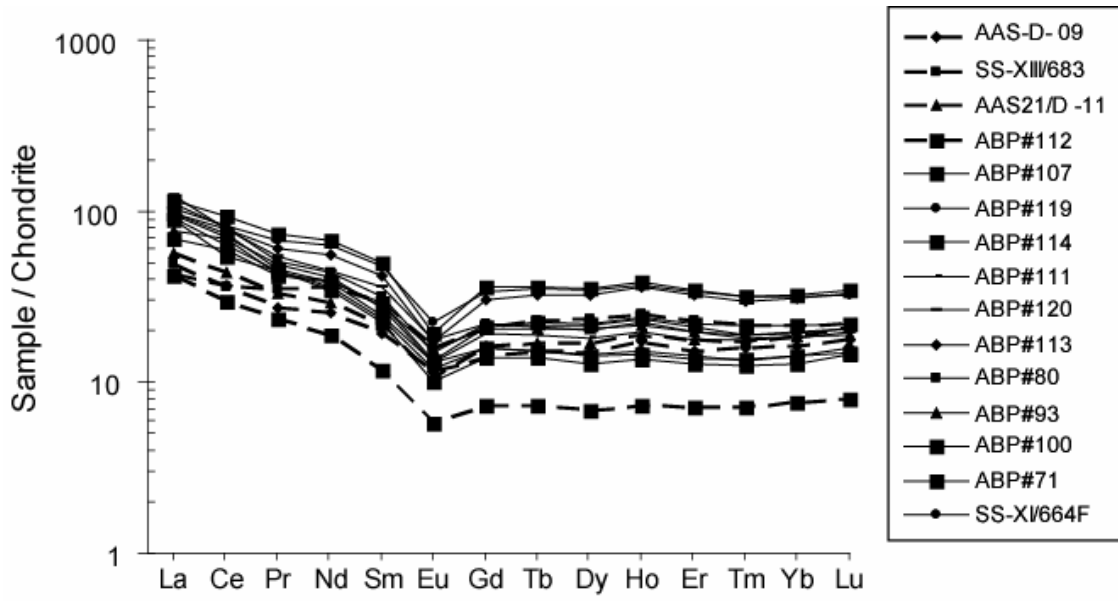


Fig. 4. Chondrite-normalized REE pattern of pumice from CIOB (sample code numbers with thick dotted line belongs to Group I and thin continuous line belongs to Group II)

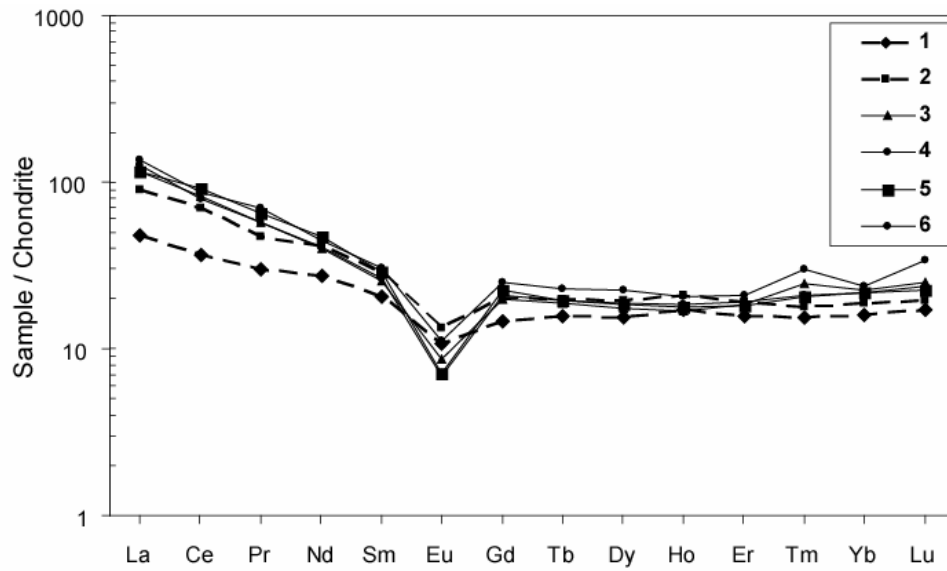


Fig. 5. Comparison of chondrite-normalized REE pattern of pumice and ash layers (1. Group I pumice from CIOB, 2. Group II pumice from CIOB, 3. YTT ash from CIOB (Pattan et.al., 2002), 4. YTT ash from Northern Sumatra (Westgate et.al., 1998), 5. YTT ash from South China Sea (Song et.al., 2000), 6. YTT ash from western continental margin of India (Pattan et.al., 2001),

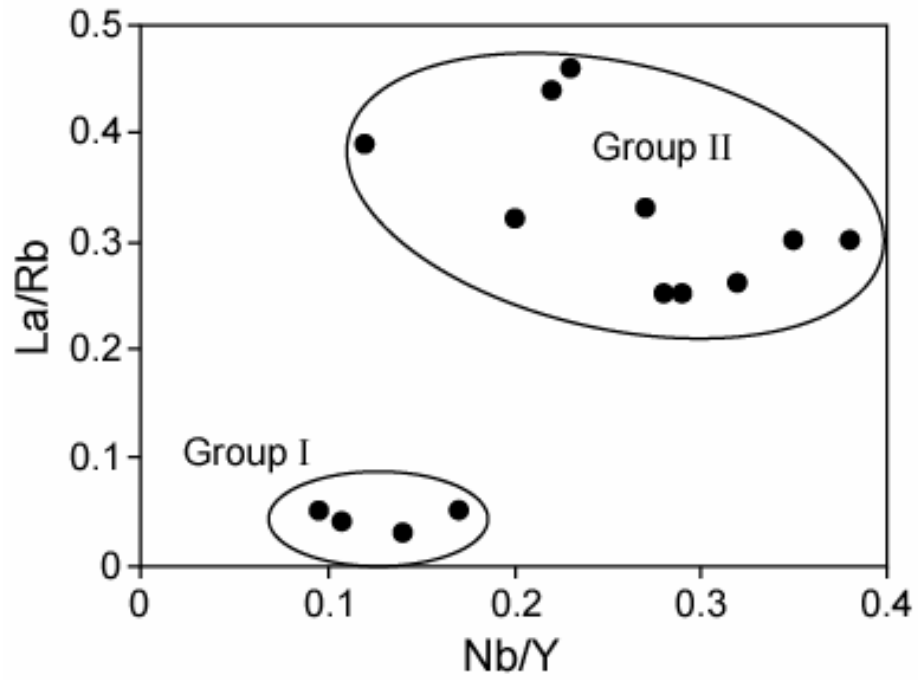


Fig. 6. Scatter plot of La/Rb versus Nb/Y showing two distinct groups of pumice.

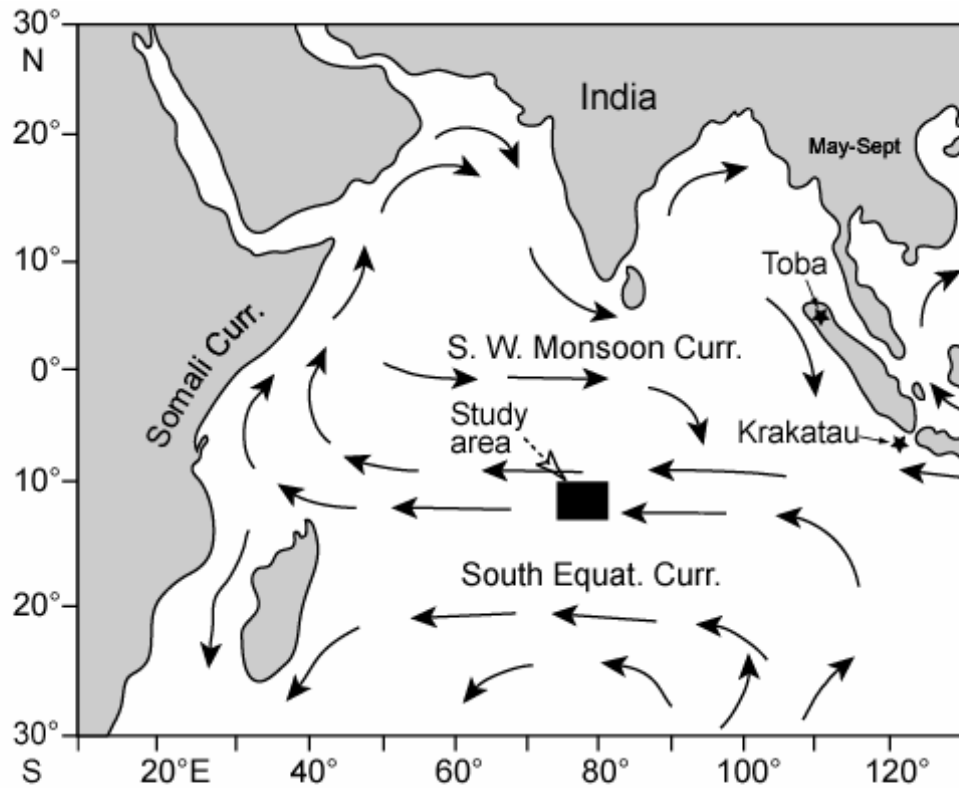


Fig. 7. Map showing surface currents responsible for drifting of pumice to CIOB (Source : Introductory Oceanography, J. Weisberg and H. Parish, 1974, p-146)

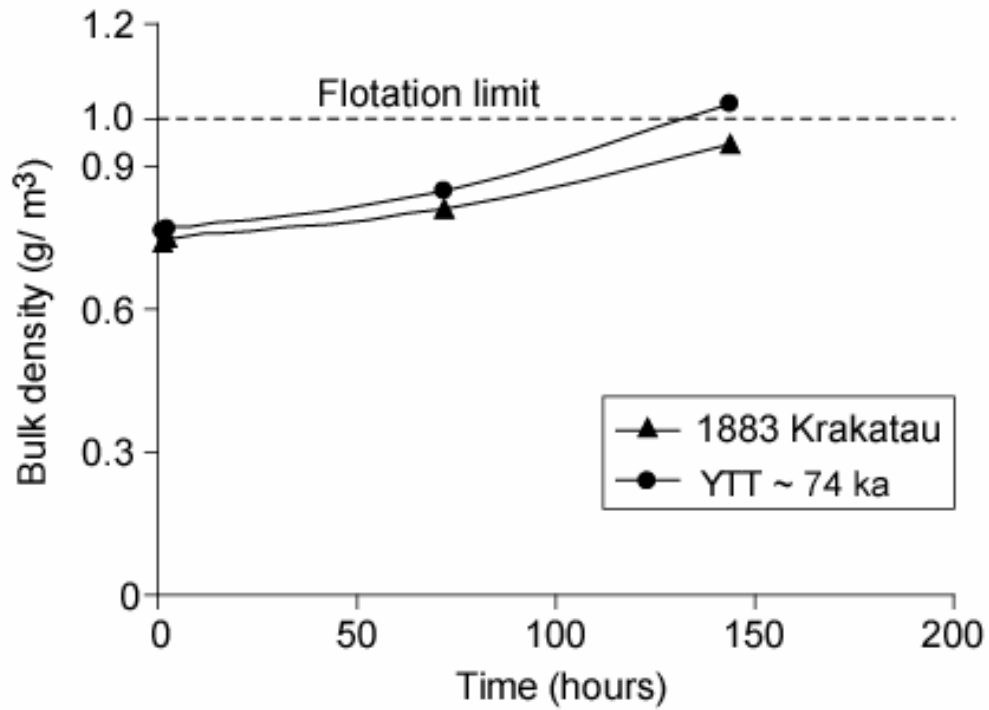


Fig. 8. Graph showing the results of measurement of the density of floating pumice as a function of time