Merapi Volcano (Java, Indonesia) and Merapi-Type Nuée Ardente

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ABSTRACT

A particular nuée ardente type (Merapi-type avalanche nuée) has been defined at the Merapi volcano because of its prominent role in the recent activity of the volcano: gravity plays a significant role during the eruption. However, some other eruption styles occur too producing surges and ashfalls. Three types of tephra, deposited in a very short time-span (15 years) are compared: chemistry and mineralogy are similar, but grain-size analyses are different. There is no vesicular glass, and it is concluded that there is an absence of new magma. This example shows clearly the variety of volcanic styles, with similar chemistry in a very short period.

Avalanche nuées from collapsed domes or flows are separated into two types:

(1) Merapi-type *sensu stricto*, without any fresh glass, derived from a wholly solidified dome.

(2) Arenal-type, containing pumiceous glass, derived from a dome, the interior of which is still liquid.

Merapi volcano (2911 m) is one of the most active volcanoes of Java (Indonesia). In 1006, a paroxysmic eruption occurred, which might have caused the collapse of the western part of the volcano (VAN BEMMELEN, 1949; NEUMANN VAN PADANG, 1951). Since that date, its activity has continued. Recently, the increasing dome often collapsed (1969, 1973, 1975 and on November 29th, 1981; S.E.A.N. Bulletin) in gas-enriched avalanche-nuées (« Merapi type » MACDONALD, 1972, p. 151). But other eruption-types occurred too, like the « vulcanian nuées ardentes » (HARTMANN, 1935; VAN BEMMELEN, 1949) and ash-falls (the last one in December 1981-January 1982; S.E.A.N. Bulletin). The aim of this paper is to focus on the chemistry, mineralogy and grain-size of the products of these different phenomena, the volcanological hazards of which are emphasized by the exceptionally high population density of the island (TAZIEFF, 1983).

OUTCROP AND TEPHRA DESCRIPTION

A good outcrop (at 1215 m altitude above the Jurangjero village, at a distance of 5 km from the dome, Fig. 1) allows one to identify some of the eruptive styles of the recent activity. This particular exposure is made up of five volcanic layers, from botton to top (BARDINTZEFF, 1983*a*):

(1) A non-welded breccia, resulted from typical Merapi type avalanche-nuée, several meters thick with blocks several meters in size.

(2) A homogeneous ash-layer.

(3) A « stratified » ash layer, including charred pieces of wood dating the deposit to 1955-1958 by the presence of C_{14} positive anomaly from atmospheric atomic explosions (G. DELIBRIAS, written communication, 1981). This layer may be related to the starting of explosive eruptions of 1956-1958, as noted by ZEN (1983).

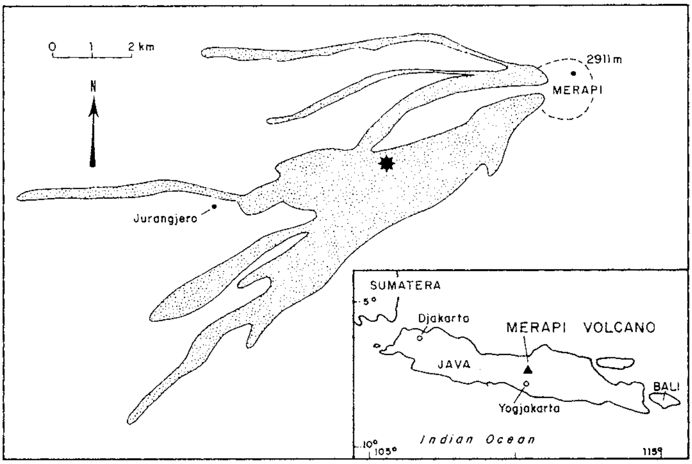

FIG. 1 – Merapi volcano in Java island. Dotted area: recent avalanche-nuées and lahars deposits (after Geological Survey of Indonesia, modified). Star: position of the studied exposure.

(4) A deposit of variable thickness which shows cross-bedding structures, typical of surges. It contains blocks several cm in size and large (10 cm) charred pieces of wood, which date back the layer to 1965-1967 (same methode as in (3); positive anomaly in C_{14} is about 70-80%). Is is not possible to correlate this layer with any eruptive activity because of lack of observations between 1965 and 1968.

(5) A non-welded breccia similar to (1) and distinctly separated from the underlying deposit (4).

A comparative study has been made of the chemistry, mineralogy and grain-size of these tephra originating from three different eruptive styles active in the very short time-span of 15 years.

TEPHRA CHEMICAL UNIFORMITY

Major element analyses of the different tephra are closely similar (Table 1): these tephra are high-K basaltic andesite, according to PECCERILLO and TAYLOR's

TABLE 1 – Chemical analyses (R. DURET, Orsay) and C.I.P.W. norm (with Fe_2O_3 recalculated to 1.5%; COOMBS, 1963) of products of Merapi volcano. (1) to (5) are layers studied in this work; (6) and (7) other avalanche-nuées and (8) dome 1978. All samples are representative of each type of layers or dome.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
SiO2	53.68	56.96	54.99	54.84	54.70	53.21	54.47	55.22
TiO2	0.78	0.61	0.74	0.78	0.72	0.90	0.78	0.74
Al2O3	19.53	19.11	19.12	19.38	19.33	18.36	19.83	18.98
Fe2O3	4.68	3.06	4.38	5.04	4.35	4.57	4.44	3.90
FeO	3.24	3.22	3.27	2.82	3.23	4.77	3.32	3.68
MnO	0.18	0.15	0.17	0.17	0.17	0.22	0.18	0.21
MgO	1.85	0.63	1.73	1.94	1.69	2.62	1.72	2.20
CaO	8.75	6.89	8.00	8.80	8.58	9.75	8.18	8.57
Na2O	3.85	4.16	3.99	3.90	3.84	3.42	3.90	3.82
K2O	2.08	2.70	2.30	1.97	1.98	1.93	2.19	2.15
P2O5	0.28	0.40	0.29	0.28	0.28	0.37	0.28	0.35
H2O+	0.73	1.81	0.99	0.56	0.54	0.31	0.42	0.17
H2O-	0.10	0.21	0.12	0.09	0.10	0.06	0.04	0.05
Total	99.73	99.91	100.09	100.57	99.51	100.49	99.73	100.04
Qz	1.07	6.36	2.43	2.32	3.25	0.61	2.01	2.79
Or	12.47	16.32	13.77	11.69	11.87	11.42	13.07	12.76
Ab	33.03	36.00	34.19	33.13	32.94	28.98	33.32	32.44
An	30.30	26.09	27.84	29.69	30.09	29.10	30.45	28.42
Wo	4.96	2.59	4.36	5.14	4.69	7.07	3.63	5.00
En	1.72	0.54	1.49	1.86	1.59	2.61	1.23	1.96
Fs	3.37	2.23	2.99	3.39	3.23	4.60	2.51	3.10
En	2.95	1.07	2.87	2.99	2.68	3.93	3.10	3.54
Fs	5.77	4.44	5.74	5.46	5.42	6.94	6.34	5.59
Mt	2.21	2.23	2.20	2.18	2.21	2.18	2.20	2.18
Il	1.50	1.19	1.42	1.49	1.39	1.71	1.50	1.41
Ap	0.67	0.97	0.70	0.67	0.67	0.88	0.67	0.83

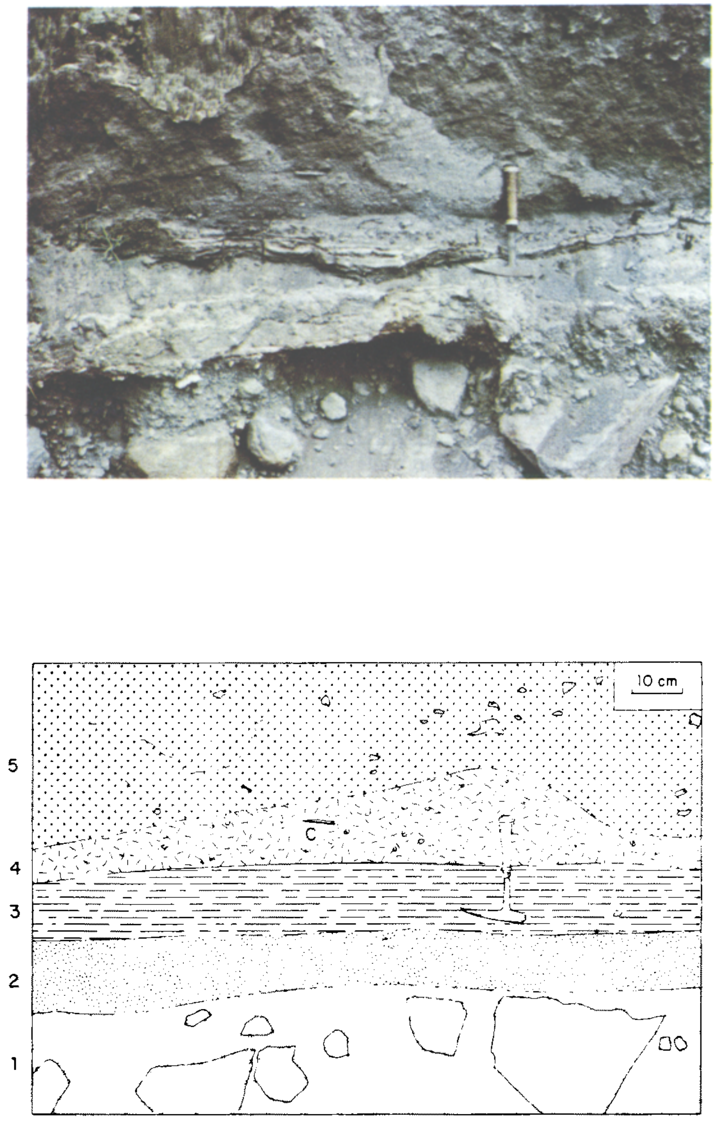

FIG. 2 - The studied exposure on the SW flank of Merapi volcano (altitude: 1,215 m): 5 layers can be distinguished (see text). C = charred piece of wood.

TABLE 2 – Rare earth element contents (p.p.m.). Same numbers as for Fig. 1 (analyst. F. KERINEC, C.E.N. Saclay, Laboratory P. Sue, 1982).

	(2)	(3)	(4)	(5)	(8)
U	1.81	1.57	1.46	1.38	1.52
Th	8.14	6.88	6.19	6.29	6.77
Zr	135	140	119	106	118.
Hf	3.2	2.7	2.37	2.43	2.8
Ta	0.38	0.33	0.3	0.3	0.34
Ba	570	510	460	469	494
Sr	499	530	516	534	541
Cs	4.67	4.13	3.6	3.7	4.03
Rb	57.8	49.8	42.8	43.7	48.6
Sb	0.33	0.25	0.23	0.23	0.24
Cr	28.	36	34	34	34
Co	12.6	15.8	15.5	15.7	15.3
Ni	2.0	4.0	2.4	2.6	4.0
Zn	115	130	77	77	136
Sc	9.6	12.4	12.6	13	12.8
La	20.2	18.8	17	17.6	19.2
Ce	39.4	36.4	35.4	35.3	37.7
Eu	1.36	1.45	1.38	1.51	1.43
Tb	0.62	0.61	0.58	0.59	0.65
Th/Ta	21.42	20.85	20.63	20.97	19.91

classification (1976) as all the other products of Merapi volcano (see analyses in NEUMANN VAN PADANG, 1951; KERINEC, 1982). Rare earth element contents (Table 2) are also closely similar. The Th/Ta ratio is always between 20.6 and 21.4, a value typical of a subduction zone (JORON and TREUIL, 1977). Thus, the Merapi volcano products are characterized by a *chemical uniformity* which has existed for several thousands of years. Such a uniformity is worth noting for a volcano of this size.

Ash layer n. 2 is a little more acid and more potassic, and is enriched in hygromagmaphile elements: Ta, La, Ce, Hf, Zr, U, Rb, Cs and Th.

MINERALOGICAL UNIFORMITY

A systematic study was performed with microprobe analyses (15 kv, 12 nA, 6s counting-rate) on free broken crystals (less than 0.5 mm in size) from the different tephra.

Pyroxenes (Fig. 3, Table 3).

Two types of clinopyroxenes coexist: Al-poor augites (Wo 40-44.5) with 50.6-53.8 wt% SiO_2 testifying a high SiO_2 activity (GUPTA *et al.*, 1973) and some Al-rich salites (Wo 44.6-48.4). Some salites (in layer 1) containing up to 7.19 wt.% Al_2O_3 (*i.e.* 35% Al^{VI}), are similar to early clinopyroxene of St. Vincent Soufriere volcano (BARDINTZEFF, 1984*a*), and indicate high pressure crystallization conditions (8 kbar, THOMPSON, 1974). The early stage of these salites is confirmed by the occurrence of zoned crystals with salitic core and augitic rim. Moreover, KERINEC (1982) described very early diopside (Table 3) trapped in pargasite in the recent dome.

Orthopyroxenes occur in all layers and contain 65-74 Enstatite. They are MnO rich. Some times, in layer (4), traces of iron oxide (0.3 μ wide) have migrated along (110) planes under the action of magmatic fluids. Some small (50 μ) pigeonite (Wo 8.2, En 52.6; 1.65 wt% MnO)

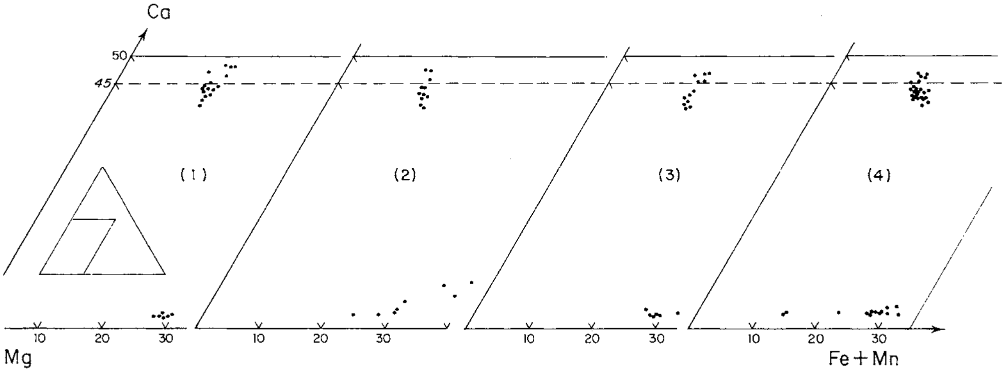

FIG. 3 – Pyroxene compositions of layers (1) (2) (3) (4).

TABLE 3 – Pyroxene analyses and numbers of ions on the basis of 6 oxygen, olivine analysis (4 oxygen) and amphibole analysis (23 oxygen). Layer number or dome is indicated. SAL = salite; AUG = augite; PIG = pigeonite; OPX = orthopyroxene; DIO = diopside; OL = olivine; AMP = amphibole (pargasite). 1 is high Al core of salite. The minerals of dome (16, 17, 18) were analysed by F. KERINEC.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
	SAL	SAL	SAL	SAL	SAL	AUG	AUG	AUG	AUG	PIG	OPX	OPX	OPX	OPX	OPX	DIO	OL	AMP
layer	(1)	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)	(2)	(1)	(2)	(3)	(4)	(4)	dome	dome	dome
SiO_2	47.21	51.44	51.81	49.50	49.66	51.17	51.58	52.22	53.31	54.62	54.21	53.83	53.48	54.65	56.67	50.56	36.66	41.42
TiO_2	1.19	0.53	0.52	0.63	0.78	0.58	0.40	0.35	0.27	0.14	0.05	0.20	0.14	0.09	0.10	0.55	0	1.65
Al_2O_3	7.19	3.63	3.26	5.08	4.31	2.84	2.48	1.81	1.35	0.16	1.11	1.38	1.03	0.60	0.43	4.38		14.46
Fe_2O_3																		
Cr_2O_3	0	0.10	0.02	0	0.01	0	0	0.01	0	0	0	0.09	0.09	0	0	0.04		0.09
FeO	9.33	7.99	7.65	8.76	8.43	8.76	8.26	9.15	8.28	22.31	16.52	16.36	17.26	16.34	7.81	5.62	35.20	9.53
MnO	0.32	0.18	0.21	0.35	0.37	0.54	0.32	0.53	0.65	1.50	1.22	1.20	1.28	1.29	1.69	0.06	1.52	0.15
MgO	11.57	13.67	13.97	13.30	13.28	15.06	15.47	16.12	15.31	17.91	25.85	25.08	25.29	25.23	31.78	14.85	26.95	15.24
CaO	21.90	22.37	23.04	22.05	21.75	19.64	21.25	20.36	20.31	3.88	1.38	1.30	1.24	1.41	1.41	23.36	0.19	12.04
Na_2O	0.36	0.20	0.26	0.46	0.32	0.37	0.28	0.28	0.33	0.96	0	0.02	0	0.03	0.04	0.22	0.03	2.02
K_2O	0	0	0			0	0		0	0	0	0	0	0	0.03	0	0.04	1.39
Total	99.07	100.10	100.74	100.14	98.91	98.96	100.05	100.84	99.81	101.47	100.34	99.48	99.51	99.64	99.96	99.63	100.59	97.97
Si	1.792	1.910	1.913	1.851	1.875	1.920	1.917	1.929	1.977	2.030	1.967	1.969	1.961	1.994	1.987	1.874	1.015	6.047
Ti	0.034	0.015	0.015	0.018	0.022	0.016	0.011	0.010	0.008	0.004	0.002	0.006	0.004	0.003	0.003	0.015	0	0.181
Al	0.322	0.159	0.142	0.224	0.192	0.126	0.108	0.079	0.059	0.007	0.047	0.060	0.044	0.026	0.018	1.191		2.488
Fe^{3+}																		
Cr	0	0.003	0.001	0	0	0	0	0	0	0	0	0.003	0.003	0	0	0.001		0.010
Fe^{2+}	0.296	0.248	0.236	0.274	0.266	0.275	0.257	0.283	0.257	0.693	0.501	0.501	0.529	0.499	0.229	0.174	0.815	1.164
Mn	0.010	0.006	0.007	0.011	0.012	0.017	0.010	0.017	0.020	0.047	0.038	0.037	0.040	0.040	0.050	0.002	0.036	0.019
Mg	0.654	0.757	0.769	0.741	0.747	0.842	0.857	0.887	0.846	0.992	1.398	1.368	1.362	1.373	1.661	0.820	1.112	3.316
Ca	0.891	0.890	0.911	0.883	0.880	0.790	0.846	0.806	0.807	0.155	0.054	0.051	0.049	0.055	0.053	0.928	0.006	1.883
Na	0.027	0.015	0.019	0.033	0.023	0.027	0.020	0.020	0.024	0.069	0	0.002	0	0.002	0.003	0.016	0.002	0.571
K	0	0	0			0			0	0	0	0	0	0	0.002	0	0.001	0.259
Ca	48.11	46.83	47.39	46.26	46.18	41.04	42.96	40.44	41.80	8.19	2.70	2.60	2.44	2.80	2.66	48.21		
Mg	35.34	39.83	39.98	38.81	39.22	43.77	43.50	44.54	43.83	52.56	70.23	69.91	69.10	69.81	83.33	42.63		
Fe+Mn	16.55	13.35	12.63	14.93	14.59	15.18	13.55	15.02	14.37	39.24	27.07	27.49	28.46	27.39	14.02	9.15		

occurs in layer (2). According to WOOD and BANNO's geothermometer (1973), an equilibration temperature of 1214°C of clinopyroxene 9 (Table 3) and orthopyroxene 14 is obtained, and that of NIELSEN and DRAKE (1979), with orthopyroxene 14 and the whole rock analysis of the tephra (4) considered as the liquid, gives 1140°C. An average of these two temperatures (1177°C) is used.

Fe-Ti oxides (Table 4)

Most of Fe-Ti oxides are titanomagnetites, typical (EWART, 1976) of andesitic rocks. Those of ash-layer (2) contain up to 17 wt% TiO_2 (*i.e.* 53.5% usp).

TiO_2-poor iron spinels, rich in Al, Mg and Mn (analyses 1 and 2, table 4) are included (30 μ) in titanomagnetites or are free (120 μ) in the tephra. They were formed in an early crystallization stage (OSBORN and WATSON, 1977) like the Al_2O_3-rich salites. They are unlike Cr-bearing spinels described in some andesitic suites (ARCULUS, 1974; MARCELOT *et al.*, 1981; D'ARCO, 1982; BARDINTZEFF, 1984*a*). Some minerals have an intermediate composition between the titanomagnetite and iron spinel end-members.

Titanomagnetites sometimes contain ilmenite a few microns wide exsolved in (111) planes. These exsolutions, resulting from oxidation (BUDDINGTON and LINDSLEY, 1964) are described in a dacite from Peru (LEFEVRE, 1979) and can be compared with those observed in orthopyroxenes: they are interpreted as due to subsolidus reequilibration. In spite of their minute sizes close to the limit of the detection with a microprobe, an analysis of ilmenite was performed (16.6%, hematite). An estimation of thermodynamical conditions of the subsolidus phase with the POWELL and POWELL (1977) geothermometer has given 791°C and log fO_2 = −12.8.

TABLE 4 - Fe-Ti oxide analyses, number of ions on the basis of 32 oxygen, and ulvospinel percentage (according to CARMICHAEL, 1967). Layer number is indicated. SPI = spinel; MT = magnetite. Magnetite 4 contains exsolution of ilmenite.

	1	2	3	4	5	6
	SPI	SPI	MT	MT	MT	MT
layer	(1)	(3)	(1)	(1)	(3)	(4)
TiO_2	1.12	1.94	9.85	3.80	8.91	9.53
Al_2O_3	6.99	8.43	2.70	3.48	3.23	2.59
Fe_2O_3	60.54	55.84	47.33	57.32	48.86	47.78
Cr_2O_3	0.09	0.11	0	0	0	
FeO	26.24	25.60	36.71	32.30	35.52	36.19
MnO	1.44	0.90	0.80	0.65	0.70	1.19
MgO	3.66	4.53	1.90	1.19	2.27	1.72
Total	100.09	97.36	99.30	98.74	99.49	99.00
Ti	0.243	0.424	2.209	0.863	1.983	2.150
Al	2.369	2.889	0.950	1.238	1.127	0.916
Fe^{3+}	13.102	12.218	10.624	13.012	10.882	10.785
Cr	0.021	0.025	0	0	0	
Fe^{2+}	6.311	6.227	9.159	8.151	8.793	9.079
Mn	0.350	0.223	0.203	0.166	0.175	0.302
Mg	1.571	1.963	0.843	0.534	1.002	0.769
Usp c	3.57	6.49	29.37	11.70	26.71	28.50

Feldspars (Fig. 4, Table 5)

Feldspars are very abundant, and up to 5 mm in size. They are commonly strongly zoned (An 91.3 to An 49.1 in the same crystal) with a very basic core. Some others are more sodic and may be rimmed by alkali feldspars (core An 52 and rim Or 34 in the same crystal). Some microliths of alkali feldspars (Or 32-46.5) occur too. The cores of the most basic plagioclase would be equilibrated (KUDO and WEIL, 1970) at 3.4 kbar water pressure with the whole rock (4) considered as the liquid, at 1177°C.

Others Minerals

Rare pargasites and olivines (Fo 67-57) complete the mineralogy of Merapi volcano (CLOCCHIATTI *et al.*, 1982).

Mineralogical Conclusion

The mineralogy of the studied layers is nearly identical. The ash-layer (2) shows however some mineralogical differences (a relative abundance of pigeonite and occurrence of high Ti-magnetite) which will be interpreted later.

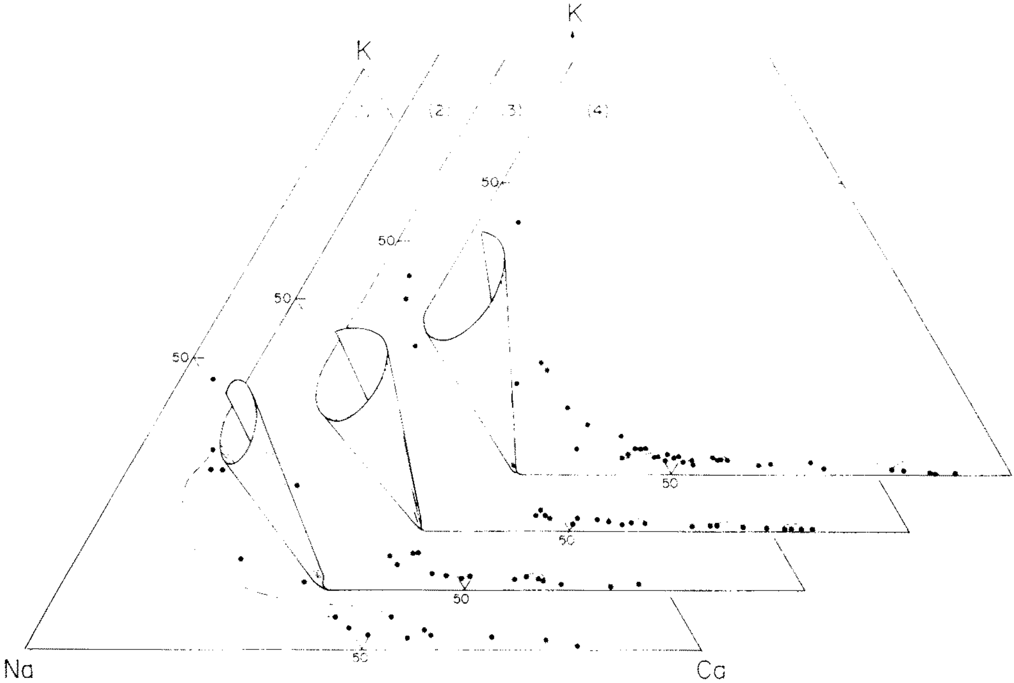

FIG. 4 – Feldspar compositions of layers (1) (2) (3) (4).

All the products have a similar chemistry and mineralogy like that of dome (KERINEC, 1982; KERINEC *et al.*, 1982). Thus, the differences between eruptive styles, which produced the five described layers, are not due to differences between magmas.

NON VESICULAR RHYO-DACITIC GLASSES (Fig. 5, Table 6)

Numerous glasses were analysed with microprobe (scanning: 5μ): as free grain 60 to 300 μ in size in tephra or as inclusions 30 to 100 μ in size in pyroxenes. All are very acid and have the chemical composition of dacite and rhyolite. They contain high alkalis, especially potassium. The sums of oxides is mostly between 96 and 97 wt.% and the difference with 100 (3 to 4 wt.% in this case) is considered (ANDERSON, 1979) essentially as water. The glasses always contain microliths of pyroxene, andesine and tridymite. Plagioclase-liquid geothermometer applied between plagioclase An 25 and glass, gives thermodynamic conditions of the end of crystallization: 1064°C and 500 bars water pressure.

Glass grains observed with the scanning electron microscope (in collaboration with C. JEHANNO) are angular (Fig. 6a). Highly vesicular or pumiceous magmatic glasses, as described by HEIKEN (1972) and SHERIDAN and MARSHALL (1983), have not been observed. Thus, these glass fragments can be interpreted as pulverized material, most probably from the mesostasis of the dome lava. Tephra, emitted by the recent activity of Merapi volcano, do not contain any fresh glass: NEUMANN

TABLE 5 – Feldspar analyses and numbers of ions on the basis of 8 oxygen. Layer number is indicated. c = core; r = rim; m = microlith.

	1	2	3	4	5	6	7	8	9	10	11
layer	(1)	(1) c	(1) r	(1) m	(2) c	(2) r	(2)	(3) c	(3) r	(3)	(4) c
SiO_2	48.98	55.77	65.16	65.67	51.60	53.34	63.28	47.43	53.87	64.29	45.54
TiO_2	0	0.07	0.05	0.07	0	0	0	0	0	0.03	0
Al_2O_3	32.28	27.96	19.93	19.16	31.02	28.52	21.09	32.99	29.29	30.39	34.18
FeO	0.43	0.50	0.52	0.20	0.57	0.51	0.44	0.66	0.53	0.45	0.32
CaO	14.92	10.68	2.23	0.93	14.42	11.81	3.32	17.07	12.27	2.32	17.67
Na_2O	2.49	4.90	6.19	5.24	3.19	4.57	7.40	1.74	4.54	6.19	0.91
K_2O	0.21	0.99	5.74	7.55	0.12	0.39	3.07	0.06	0.33	5.30	0.04
Total	99.32	100.88	99.83	98.81	100.92	99.15	98.59	99.95	100.82	98.98	98.66
Si	2.251	2.502	2.926	2.976	2.330	2.439	2.861	2.184	2.424	2.905	2.123
Ti	0	0.002	0.002	0.002	0	0	0	0	0	0.001	0
Al	1.749	1.479	1.055	1.024	1.651	1.537	1.124	1.790	1.553	1.086	1.877
Fe	0.017	0.019	0.020	0.008	0.021	0.020	0.017	0.025	0.020	0.018	0.013
Ca	0.735	0.513	0.107	0.045	0.698	0.579	0.161	0.842	0.592	0.112	0.883
Na	0.222	0.426	0.539	0.460	0.279	0.405	0.649	0.155	0.396	0.542	0.082
K	0.013	0.057	0.329	0.437	0.007	0.023	0.177	0.004	0.019	0.306	0.002
Or	1.29	5.69	33.72	46.35	0.69	2.25	17.96	0.35	1.85	31.82	0.22
Ab	22.89	42.78	55.27	48.86	28.40	40.25	65.76	15.51	39.37	56.46	8.49
An	75.82	51.53	11.00	4.80	70.91	57.50	16.28	84.14	58.77	11.71	91.29

VAN PADANG (1932) has already observed « the very small amount of new material ».

GRAIN-SIZE ANALYSES

In order to compare the different tephra layers we studied (BARDINTZEFF and MISKOVSKY, 1984) the grain-size of the ash fraction (finer than 2 mm, or greater than −1 Ø unit) only, as in some other studies of this type (SPARKS *et al.*, 1973; FISHER and HEIKEN, 1982; FISHER *et al.*, 1983). The 3 types of tephra can clearly be distinguished (Table 7) by the parameters Md Ø and σ Ø of INMAN (1952): avalanche nuée are, of course, the coarser (Md = 0.75-0.8 Ø), while the median of the surge is 1.15 Ø and those of ash-falls are 2.8 to 4.25 Ø. In the σ versus Md diagram (similar to WALKER's diagram (1971) but used in the present work for the ash fraction only) (Fig. 7a), the representative data points of avalanches are situated in a particular field. Grainsize analyses of some other avalanche nuées from Arenal (Costa Rica) 1968 (MELSON and SAENZ, 1973) and prehistoric eruptions, and from Mont Pelée, Martinique (Trou Congo quarry, 2480 y B.P.; TRAINEAU, 1982; WESTERCAMP and TRAINEAU, 1983) were also performed in this work and results are plotted in Fig. 7a: avalanche nuées are characterized by a median coarser than 0.5 mm (less than 1 Ø) and a sorting greater than 1.3 Ø. This field is distinct from those determined for nuées ardentes s.s. (Pelée and St. Vincent

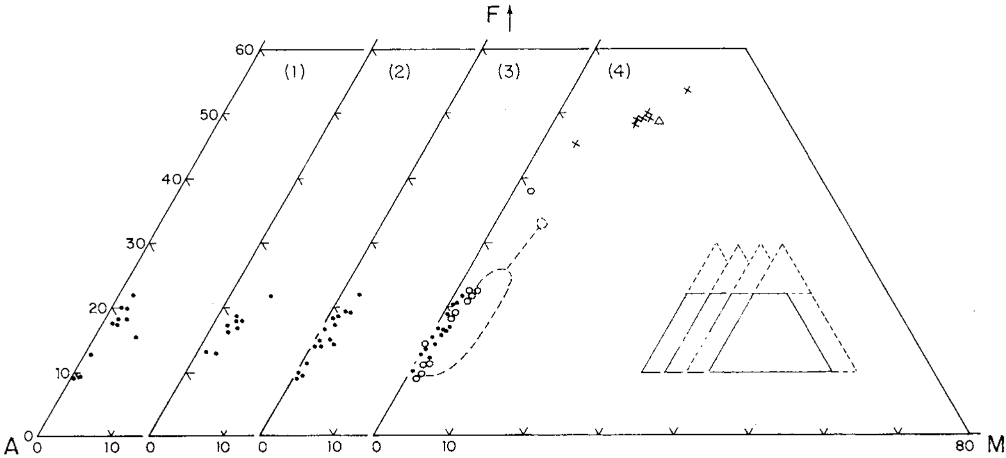

FIG. 5 – A ($Na_2O + K_2O$) – F ($FeO + MnO$) – M (MgO) diagram. Glasses of layers (1) (2) (3) (4): Free glass (solid circles), melt inclusion in pyroxenes (open circles). Whole rocks: tephra (crosses) and dome (triangles).

type, MACDONALD, 1972, p. 149), surges and pumice falls (BARDINTZEFF and MISKOVSKY, 1984). The equivalent diagram (Fig. 7b), which interests the sand-size fraction (between 2 and 1/16 mm, *i.e.* −1 Ø and 4 Ø), confirms that the avalanche nuées are distinctive. The representative point of the surge is close to those described by FISHER and HEIKEN (1982) at Mont Pelée, Martinique. Ashes are very poorly sorted. The percentage of products finer than 1/16 mm (Table 7), is

TABLE 6 – Glass analyses and C.I.P.W. norm. Layer number is indicated. Those are free glasses except for 9, 10, 11 trapped in pyroxenes.

	1	2	3	4	5	6	7	8	9	10	11
Layer	(1)	(1)	(2)	(2)	(3)	(3)	(4)	(4)	(4)	(4)	(4)
SiO2	67.79	68.91	68.44	69.35	68.32	72.73	69.84	72.80	63.80	68.84	69.05
TiO2	0.35	0.39	0.34	0.43	0.31	0.51	0.41	0.47	1.37	0.43	0.69
Al2O3	15.94	15.10	14.21	14.40	15.14	11.52	15.08	12.55	13.33	14.67	15.32
FeO	2.08	2.67	2.05	2.14	1.68	1.66	1.77	1.73	5.69	2.43	1.43
MnO	0.04	0.12	0.16	0.04	0.10	0.03	0.06	0.08	0.32	0.05	0.03
MgO	0.15	0.22	0.26	0.40	0.22	0.03	0.16	0.20	0.42	0.28	0.03
CaO	1.51	1.06	1.23	1.03	1.12	0.21	0.90	0.41	0.81	0.85	1.34
Na2O	4.42	4.35	4.63	4.21	4.74	2.69	4.03	2.86	3.82	3.15	5.20
K2O	5.22	5.09	5.86	5.81	5.35	5.73	5.32	5.95	5.91	5.64	4.00
Total	97.50	97.91	97.18	97.81	96.98	95.11	97.57	97.05	95.47	96.34	97.09
Qz	17.60	19.93	16.11	19.17	17.11	35.38	23.24	32.02	13.73	25.91	20.50
Or	31.63	30.71	35.63	35.10	32.59	35.59	32.21	36.22	36.57	34.59	24.34
Ab	38.34	37.58	40.30	36.40	41.34	23.92	34.93	24.92	33.84	27.65	45.30
An	7.68	5.37	0.71	3.32	4.38	1.10	4.57	2.10	1.86	4.38	6.85
Co	0.28	0.52	0	0	0	0.54	1.09	0.68	0	1.91	0
Wo	0	0	2.32	0.80	0.56	0	0	0	0.98	0	0
En	0	0	0.39	0.20	0.10	0	0	0	0.11	0	0
Fs	0	0	2.12	0.65	0.51	0	0	0	0.96	0	0
En	0.38	0.56	0.27	0.82	0.46	0.08	0.41	0.51	0.98	0.72	0.08
Fs	3.40	4.58	1.48	2.72	2.34	2.38	2.75	2.63	8.24	3.99	1.59
Il	0.68	0.76	0.66	0.83	0.61	1.02	0.80	0.92	2.73	0.85	1.35

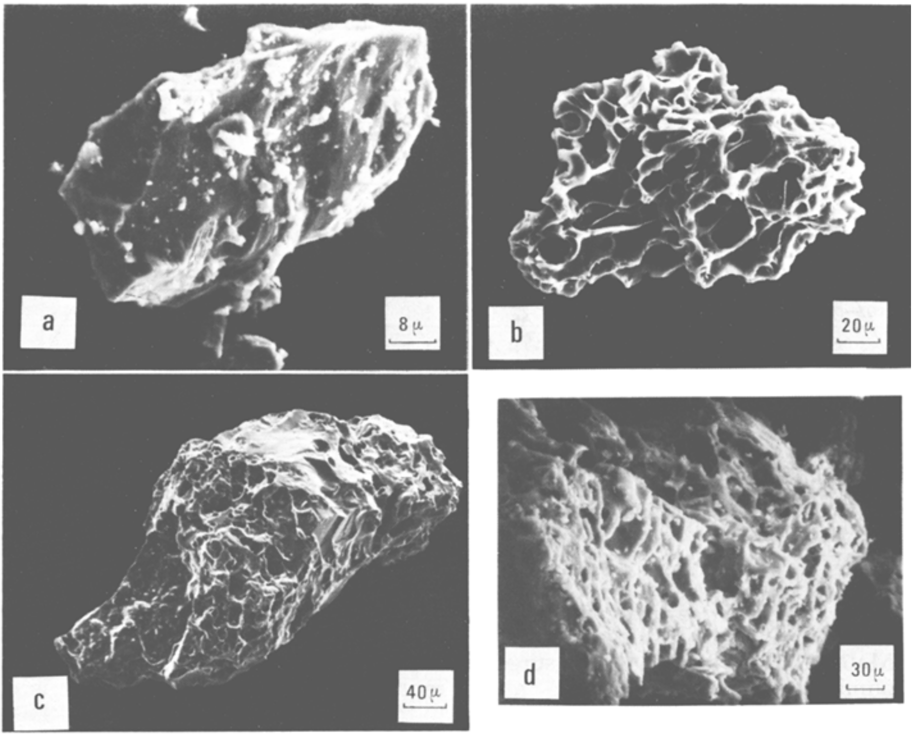

FIG. 6 – SEM images of glasses (C. JEHANNO, C.F.R., Gif-sur-Yvette). a: angular glass of the layer (2) of Merapi volcano; b: vesicular glass of the 1980 Mount St. Helens ash; c: vesicular glass of the 1979 St. Vincent Soufriere volcano nuée ardente; d: micropumice of the 1968 Arenal volcano eruption.

the same in avalanche-nuée and surge (2.1 to 3.5 wt.%) but is greater in ash-falls (27.5 to 54.2 wt.%).

DISCUSSION

The different volcanological products (dome, lava flow, tephra) of Merapi volcano, show a high chemical and mineralogical uniformity of the magma. This uniformity is due to the steady and voluminous production of magma (20,000 m^3/day; ALLARD and TAZIEFF, 1979) preventing crustal fractionation or differentiation.

Whatever the grain size, tephra are essentially made up of crystals (clino-and orthopyroxenes, feldspars, Fe-Ti oxides) and lithic fragments. Glass fragments not very abundant, are always very acid. It has not been observed, for this recent period, any vesicular glass, indicative of new magma and the angular glasses which do occur, contain microliths and come from preexisting materials.

This work shows that the same magmas can produce very different eruption styles. This variety depends on the amount of gas (water and CO_2 essentially, ALLARD, 1980; LE GUERN *et al.*, 1982). It is worth

TABLE 7 – Grain-size analyses of the ash fraction of tephra of Merapi volcano. Md Ø = median and σ Ø = sorting, in Ø unit (INMAN, 1952).

Ø	mm	avalanches (1)	avalanches (5)	surge (4)	ashes (2)	ashes (3)
- 1	2	100	100	100	100	100
0	1	71.8	74.6	82.7	92.4	93.4
1	1/2	42.7	45.1	56.2	83.3	82.6
2	1/4	22.2	20.8	29.6	74.6	65.8
3	1/8	9.7	7.6	10.8	66.1	46.8
4	1/16	3.5	2.3	2.1	54.2	27.5
Md Ø		0.75	0.8	1.15	4.25	2.8
σ Ø		1.45	1.33	1.38	?	2.05
Md Ø (-1,4)		0.65	0.75	1.15	1.75	2.1
σ Ø (-1,4)		1.33	1.24	1.3	1.7	1.41

noting that in Merapi volcano, there are not only Merapi-type nuées (*i.e.* avalanche-nuées), but also ash-falls and surges.

Ash-fall deposits are made up of crystals and angular glass fragments (Fig. 6a). Layers (2) and (3) are produced by ash-falls of phreatic eruptions: These are extremely violent eruptions which pulverized the materials to very small fragments (size finer than 100 μ).

Small particles may be sorted during transport along a distance of 5 km from the volcano. 15 cm-thick homogeneous ash-fall layer 2, a little higher in SiO_2 and enriched in microliths (pigeonites and Ti-magnetites) may be interpreted as resulting from acid glass accumulation (about 10%) emphasized by whole rock X-ray study. This kind of sorting does not occur in ash-fall layer 3, with several rhythmic thin strata of 1 cm.

Some rare explosions, the violence of which was due to gas-enrichment, produced surges (MOORE, 1967; SPARKS and WALKER, 1973; SHERIDAN, 1979). The «vulcanian nuées» described by HARTMAN (1935) may be close to this type. This surge (layer 4) does not contain any vesicular glass according to MOORE's definition (1967) and to SHERIDAN and MARSHALL's observations (1983) on Taal volcano.

The layer (4), without associated pyroclastic flow, would be produced by a mechanism close to «base surge» (WRIGHT *et al.*, 1980), resulting from a phreatomagmatic column collapse: a tangential component due to the initial explosion is superimposed on the gravity-collapsed component. Temperatures of emplacement of this surge, mesured by means of infra-red spectrometry on charred pieces of wood (method of MAURY, 1971) are between 325-350°C, a little more than those of ash-fall (300-325°C).

Avalanche nuée deposits make at least up 90% of Merapi volcano. Gravity plays a preponderant role with a weak horizontal component. From the lack of any new magma, they have to be distinguished from the Pelée- and St. Vincent-type nuée ardentes (MACDONALD, 1972) produced by magmatic eruption with a mean to strong horizontal component. Fresh pumiceous glasses are described at St. Vincent Soufrière Volcano (SIGURDSSON, 1982; BARDINTZEFF 1983b-Fig. 6c) as at Mont Pelée (TRAINEAU, 1982; WESTERCAMP and TRAINEAU, 1983).

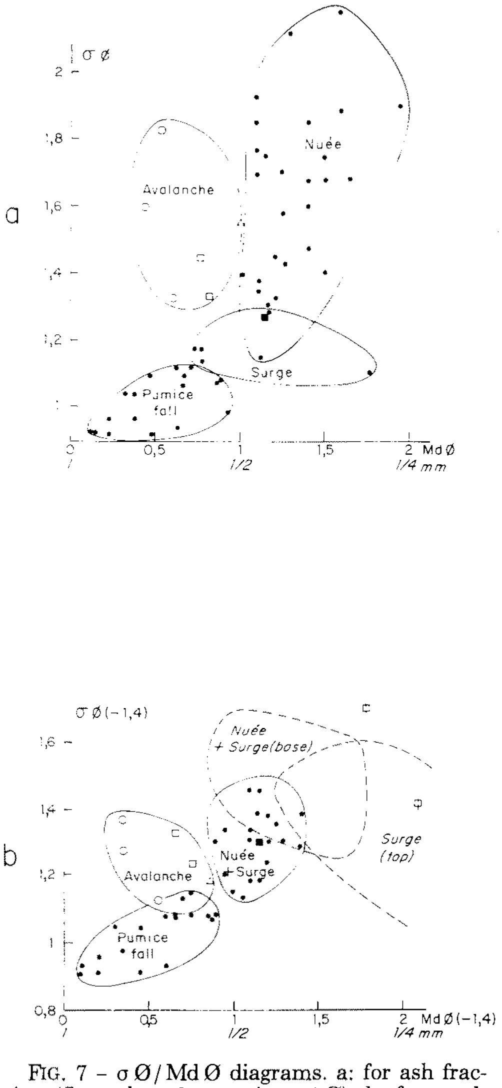

FIG. 7 – σ Ø / Md Ø diagrams. a: for ash fraction (finer than 2 mm, *i.e.* −1 Ø); b: for sand-size fraction (between 2 and 1/16 mm, *i.e.* −1 to 4 Ø). *Merapi volcano:* open square: avalanche nuée; full square: surge; striped square: ash fall. *Other avalanche nuées:* open circle: Arenal; open triangle: Mont Pelée.

Full lines encircle representative fields of the different eruption styles (dots: compiled data from Fuego, Santiaguito, Arenal, Mont. Pelée, St. Vincent-Soufrière and Central Italian volcanoes) (BARDINTZEFF and MISKOVSKY, 1984); dotted lines: fields after FISHER and HEIKEN (1982).

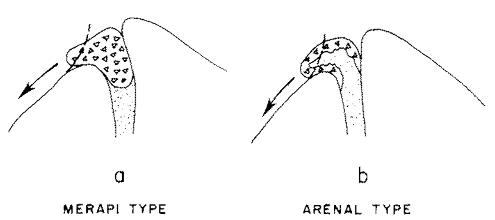

FIG. 8 – Two types of avalanche nuees: Merapi-type (a) after MACDONALD, 1972 modified and Arenal-type (b). Triangles: block lava dome; stipples: fresh magma.

These avalanche nuées as at Fuego (Guatemala) and at Izalco (Salvador) (WILLIAMS, 1960) issue from a collapse of front-lava flow. In avalanche nuées of Arenal, fresh magma participates and forms micropumice up to 1 mm size (Fig. 6d). Thus avalanche nuées, from a dome or lava flow collapsing, which are characterized by a median of ash-fraction coarser than 0.5 mm must be divided into two types:

i) Merapi type sensu stricto in which the collapsing part of the dome is completely solid (Fig. 8a).

ii) Arenal type: (BARDINTZEFF, 1984*b*) the dome flow of which is liquid in its interior (Fig. 8b) so that the magma can pour out through cracks of the dome during strong avalanches.

The difference between the two types might be due to a difference in viscosities of the lavas, or of convection in the lava.

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NOTE ADDED IN PROOF

The Arenal type proposed here, is typical of the 1975 avalanche nuée in Rio Tobaccon. The 1968 eruption presents evidence of avalanche nuée characteristics (coarse deposits) as well as of Pelean-nuée characteristics (BARDINTZEFF, 1985).

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