"NUEE ARDENTE" DEPOSITS AT TATA SABAYA VOLCANO (BOLIVIAN-CHILEAN ANDES): PUMICES AND LAVA BLOCKS CRYSTALLIZATION FROM SINGLE MAGMA AT DIFFERENT DEPTHS

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RESUMEN

Los depósitos dejados por una reciente erupción tipo "nube ardiente" del volcán Tata Sabaya están formados por pómez y bloques de lava negra. La energía térmica de dicha erupción se estima en 1,2 x 10^{25} ergs. Lava y pómez tienen similares características geoquímicas y petrográficas (andesina, hornblenda edenítica, augita subcálcica y óxidos de Fe-Ti) y sus vidrios presentan líneas de cristalización feldespática (lavas) y cuárcica (pómez). La pómez y los bloques habrían cristalizado a partir de un magma único, a diferentes profundidades (6 y 13 km). Sin embargo, la cristalización de la pómez se produjo en condiciones de mayor temperatura, fugacidad de oxígeno y presión de agua, que las existentes durante la cristalización de las lavas.

ABSTRACT

Recent "nuée ardente" deposits from Tata Sabaya volcano consist of pumice and black lava blocks. The calculated thermal energy of the eruption is 1.2 x 10^{25} ergs. Both blocks and pumice have the same geochemistry and mineralogy: andesine plagioclase, edenitic hornblende, subcalcic augite and Fe-Ti oxides. Their glasses have, respectively, feldspar and quartz crystallization paths. The pumice and blocks may have crystallized from a single magma at 6 and 13 km depth, respectively. But higher temperature, oxygen fugacity and water pressure preside over the crystallization of pumice.

INTRODUCTION

In the recent years, numerous geologists have been infatuated with mafic silicic magma mixing. An impressive amount of papers have been published (see e.g. Eichelberger, 1975, 1978; Anderson, 1976; Sparks *et al.*, 1977; Sakuyama, 1978, 1981; Luhr and Carmichael, 1980; Anderson, 1982; Hawkesworth *et al.*, 1982). New explanations of petrological data, formerly interpreted in a purely differentiation way, have been put forward. Contrarily, the present paper explains the co-genesis of two types of andesitic lavas (lava blocks and pumices from a single "nuée ardente" deposit) by distinct differentiation conditions of the same magma.

GEOMORPHOLOGY

In the Central Andean Cordillera, near the Bolivian-Chilean frontier, at about 19° Lat. S (Fig. 1), recent "nuée ardente" deposits have been discovered at the base of the Tata Sabaya volcano.

The "nuée ardente" was emitted from the SE-flank of the Tata Sabaya volcano. Spreading of the

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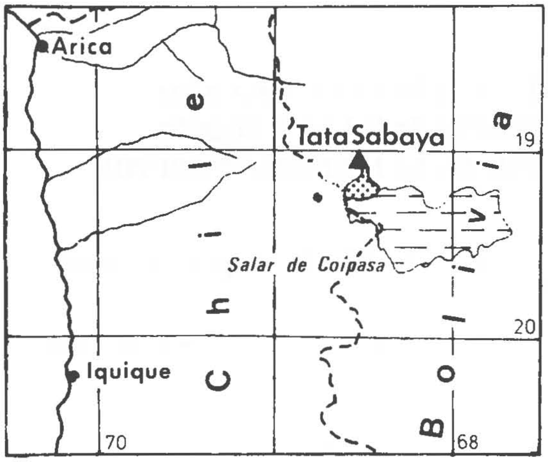

FIG. 1. Location of the "nuée ardente" deposits (stippled area) near the Bolivian-Chilean border.

basal pumice flow (basal avalanche deposits, according to Smith, 1960) was determined by topography and regional tectonics (Fig. 2). At first, the flow stretched out before spreading out in the graben of the Salar de Coipasa, where it was confined by N45°- 55°E faulting of Miocene to Pliocene age and N150°-160°E faulting of Pliocene to Quaternary age (Audebaud *et al.*, 1973). The same two directions (+ 10°N) correspond to Pliocene to Quaternary volcanic lineaments between 22 and 25° S (Déruelle *et al.*, 1978).

The pumice flow is almost 20 km long and 7 km wide, with a vertical drop of about 1,400 m. Downwards, the pumice has been carried away in the alluvia as far as the western part of the Salar de Coipasa (Fig. 3). Upwards, black and reddish altered lava blocks are scattered on the surface of the deposits, rather than buried within the smaller white pumice blocks (cm to dm; Fig. 4).

The black lava blocks show surface cracks (Fig. 5a) due to rapid cooling with a massive core and a thin columnar exterior (Fig. 5b). Similar prismatic blocks have been described by Lacroix (1904) from the 1902-1903 "nuées ardente" deposits of Mount Pelée (Martinique). These blocks, which have the same chemical composition as the pumice and matrix of the "nuée", may be considered as the products of the same eruption, ejected in a solidified state. On the contrary, the red blocks are massive and derive from altered lava flows on the flanks of the Tata Sabaya volcano (Fig. 6).

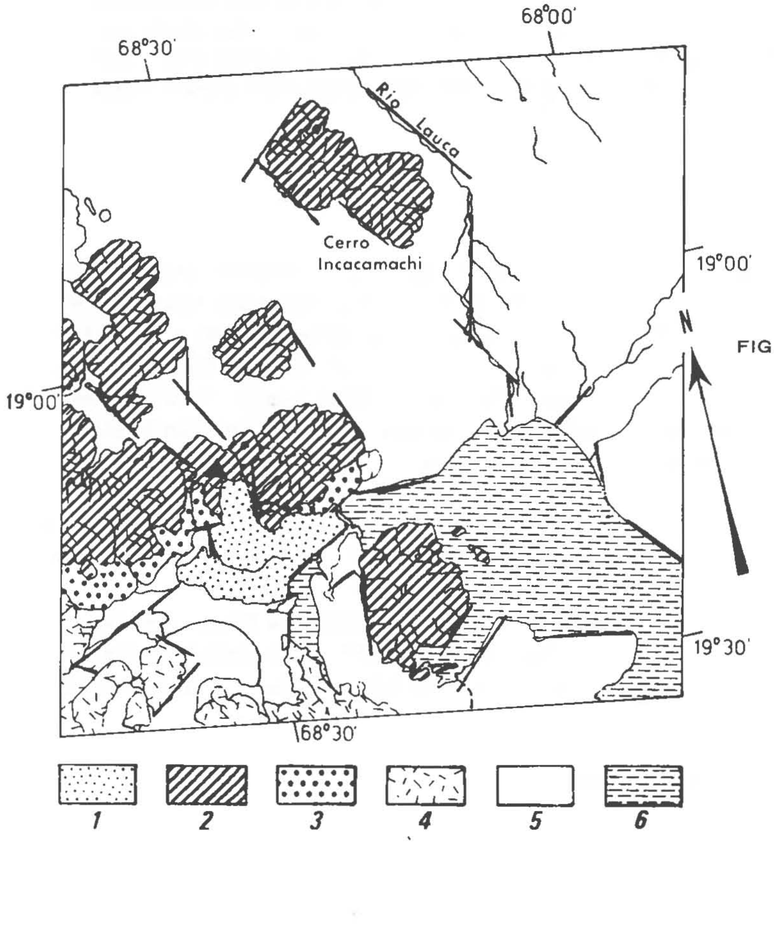

FIG. 2. Geological map of the Tata Sabaya volcanic zone. 1. "Nuée ardente" deposits; 2. Pliocene to Quaternary volcanic massifs; 3. Aprons of their clastic products; 4. Ignimbrites; 5. Pliocene to Quaternary sediments; 6. Salar de Coipasa (after ERTS photographic document E-1244-14051-7, 24 March 1973).

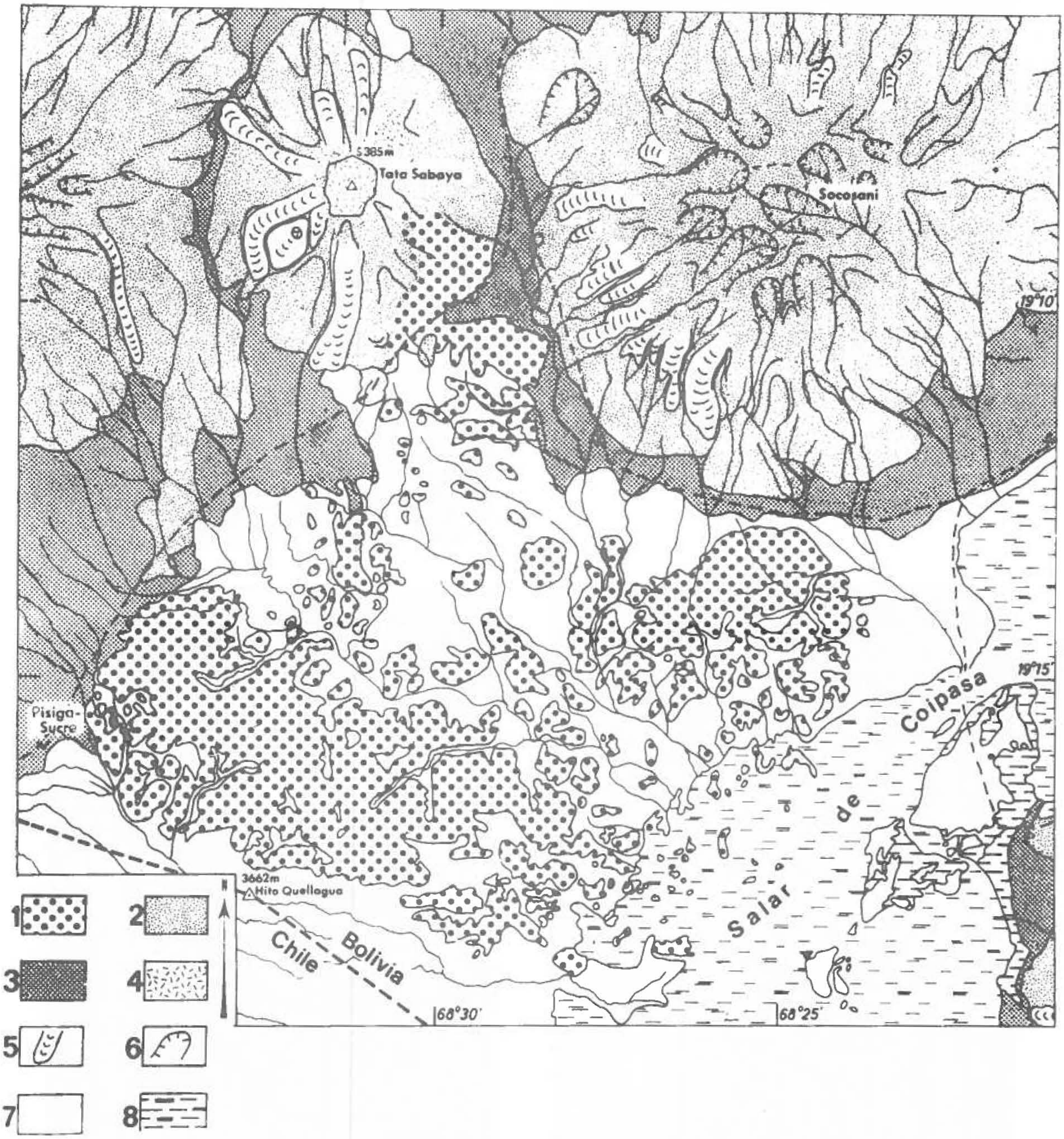

FIG. 3. Geological map of the Tata Sabaya "nuée ardente" deposits. 1. "Nuée ardente" deposits; 2. Pliocene to Quaternary volcanic cones; 3. Clastic aprons; 4. Volcanic breccia; 5. Lava-flows; 6. Valley glaciers; 7. Recent sediments; 8. Salar de Coipasa. (Based upon the geological maps No. 5836 and 5936, scale 1:100,000, of Ponce *et al.*, 1967a, b).

FIG. 4. Black lava blocks scattered on the surface of the deposits.

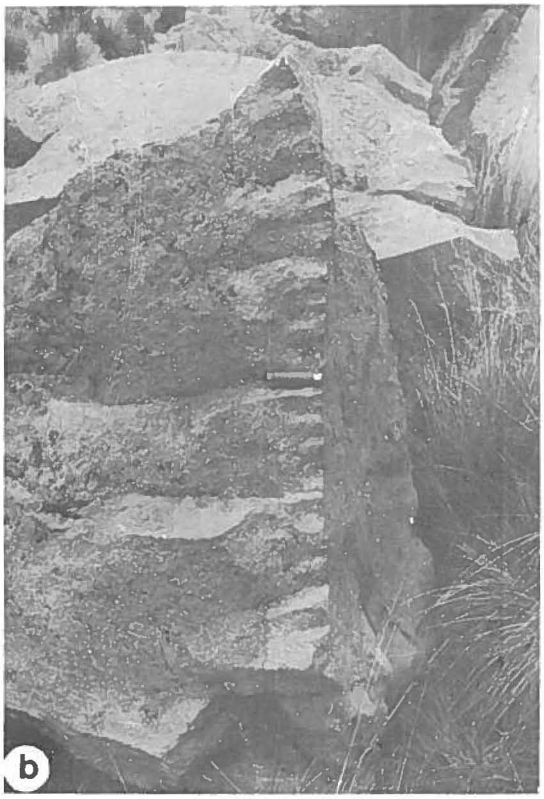

FIG. 5. Surface cracks (a), massive core and thin columnar exterior (b) of black lava block. The lighter is 8 cm long.

FIG. 6. Reddish lava block; the surface cracks result from re-heating and re-cooling of the lava.

ENERGY

Similar deposits with pumices, black lava blocks and old altered lava blocks, have been observed in the South Central Andes at the bases of the San Pedro-San Pablo volcanoes (Francis *et al.*, 1974) and Socompa volcano (Déruelle, 1978). The horizontal distance (L) travelled by the front of the pumice flow is more than 20 km, and the vertical drop (H) is about 1,400 m (average gradient: 4°; H/L = 0.07). This fact denotes a release of substantial amounts of kinetic energy during the eruption. In a H/L diagram (Fig. 7), the Tata Sabaya deposits lie just within the data of Nairn and Self (1978). It is probable that the greater the volume of the flow, the farther it is likely to travel, but it does not seem (as suggested by Francis *et al.*, 1974) that the pumiceous "nuées ardentes" deposits give larger H values than the largest cold avalanches.

The kinetic energy of the eruption can be calculated from the formula $E_k = 1/2mv_o^2$ (Minamaki, 1950), where m is the ejecta mass (2.3 x 10^{15} g, estimating an ejecta volume of 1.3 x 10^{15} cm^3 and an ejecta density of 1.8) and v_o the initial speed. If ejection speeds of 300, 400, 500 or 600 m s^{-1} are assumed, kinetic energies of 1.05 x 10^{24}, 1.8 x 10^{24}, 2.9 x 10^{24} or 4.2 x 10^{25} ergs are obtained, respectively. As a comparison, the initial speeds of the "nuée" of the Valley of Ten Thousand Smokes and of the eruption of Bezymianny (30 March 1956; Gorshkov, 1959) have been respectively estimated at 480 m s^{-1} and 600 m s^{-1}. From the energy required to displace buildings, Lacroix (1904) calculated the average speed of the 8 May 1902 "nuée ardente" in Saint-Pierre (Martinique) 8 km away from Mount Pelée, at 130-150 m s^{-1}.

The thermal energy E_{th} released during the eruption of the "nuée ardente" is calculated from the empirical formula of Hédervari (1967): log E_{th} = 11.8 + 1.5 M_e; where M_e = (log V + 4.95)/1.59 is the magnitude of the eruption, and V the volume of the ejecta: E_{th} = 1.2 x 10^{25} ergs. The kinetic energy/thermal energy ratio can be stimated at about 9, 16, 24 or 36%, depending upon the assumed initial speed.

These estimated energies are greater than the energy of the 1960 earthquake that produced a tsunami in Valdivia, Southern Chile (1.6 x 10^{23} ergs), but lower than those liberated at the time of the 1912 eruptions of the Valley of Ten Thousand Smokes (2 x 10^{26} ergs), Bezymianny, 1966 (2.1 x 10^{25} ergs) (data after Hédervari, 1967) or of Socompa volcano (Negros de Aras) "nuée ardente" (Déruelle, 1978).

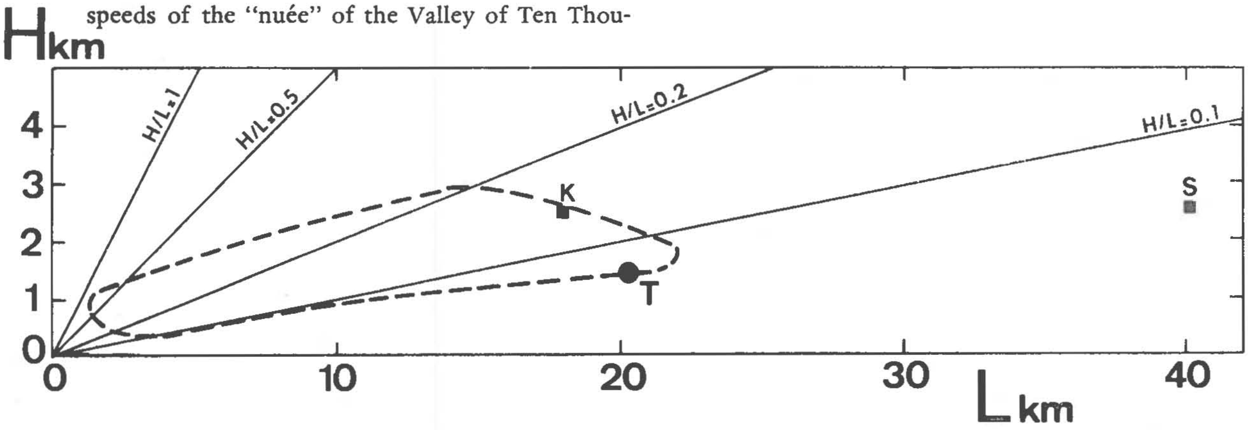

FIG. 7. H (vertical distance) – L (horizontal distance travelled) diagram for avalance and "nuée ardente" deposits. T: Tata Sabaya deposits. The dashed line limits deposits recorded by Francis *et al.* (1974) and Nairn and Self (1978); S: Negros de Aras deposits of Socompa volcano (Déruelle, 1978), K: Ten Thousand Smokes Valley deposits.

PETROGRAPHY

Microscopically, the pumice (N14D) shows rather abundant large (4 mm), often fractured, zoned phenocrysts of plagioclase (An_{35-45}), magnetite, brown sometimes twinned hornblende with apatite inclusions, biotite with zircon inclusions, and rare alkali feldspars. All these phenocrysts are scattered within a groundmass composed mainly of glass (as shards or stretched into fiammes) and microlites of alkali feldspar, plagioclase (An_{40}), brown hornblende and opaque minerals. The black

TABLE 1. MODAL COMPOSITION (VOLUME PERCENT) OF PHENOCRYSTS

Sample	Plagioclase	Amphibole	Biotite	Oxide	Pyroxene	Glass
Block (N14E)	27.1	7.9	0.9	2.0	tr.	62.1
Pumice (N14D)	30.8	6.0	tr.	1.7	tr.	61.5

tr.: trace amount.

lava (N14E) has the same mineralogy; the magnetite phenocrysts are blunt, and the plagioclase can be found as rare phenocrysts (An_{35}) or abundant small rods (An_{40}). The groundmass consists of light-brown glass, commonly rendered opaque by microcrystalline to cryptocrystalline oxides, and acicular microlites of feldspar and amphibole. In this lava, magnetite crystallized first, followed by plagioclase, hornblende, clinopyroxene and biotite.

The modal analysis of both black lava and pumice (Table 1), calculated without taking into account the bubbles (more than 40% of the volume of the pumice) and counting the fiammes as glass, are quite similar, although the pumice is slightly enriched in plagioclase.

GEOCHEMISTRY

The two rocks are andesites (K-rich andesites according to the classification of Peccerillo and Taylor (1976)). The distribution of the major elements is the same in both of them, although they are quite different in their magmatic expression. They are undoubtedly co-magmatic, analogous with the "nuées ardentes" of the San Pedro-San Pablo volcanic massif (Francis *et al.*, 1974), the Mount Pelée (Lacroix, 1904, p. 527) and Negros de Aras (Déruelle, 1978). The pumice was produced from a gas-rich magma, whereas the blocks originated from the same degassed magma. The groundmass residual glasses are, however, different in both lavas. They are strongly enriched in silica and alkalies, but depleted in iron and magnesium. The glasses of the blocks are richer in normative quartz and poorer in normative albite than the glasses of the pumice, which are near the theoretic minimum at 0.5 kb P_{H_2O} (Tuttle and Bowen, 1958). The glasses of the blocks plot inside the quartz field, whilst those of the pumice plot in the fledspar field (Fig. 8). Normative orthoclase contents are almost equal. The glasses of the blocks are relatively homogeneous; those of the pumices show an evolutionary trend which suggests that significant mixing of the glasses is not a feasible mechanism.

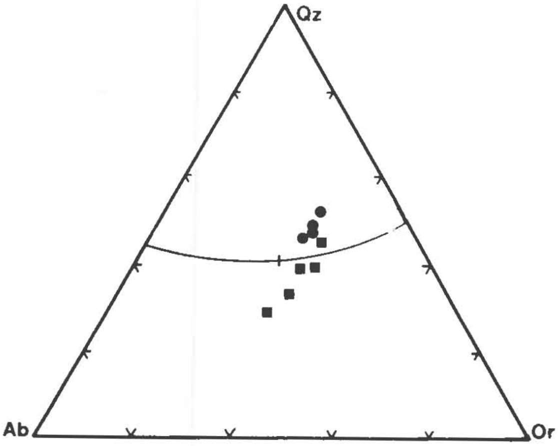

FIG. 8. Plots of normative quartz, sanidine and albite of blocks (circles) and pumice (squares). The boundary curve at 500 bars water pressure and the minimum on this curve are taken from Tuttle and Bowen (1958).

TABLE 2. CHEMICAL ANALYSES AND C. I. P. W. NORMS OF THE ROCKS.
PARTIAL ANALYSES OF GLASS PHASE (ELECTRON MICROPROBE)
WERE SELECTED ACCORDING TO THEIR SILICA CONTENTS

	Block N14E	Pumice N14D	Glass in			
			Block		Pumice	
SiO_2	60.86	59.19	76.45	76.62	71.48	74.32
TiO_2	0.87	0.88	0.18	0.21	0.05	–
Al_2O_3	16.41	16.68	12.81	12.65	13.44	13.46
Fe_2O_3	2.10	2.33	–	–	–	–
FeO	2.23	2.89	1.00	0.90	1.36	1.41
MnO	0.07	0.11	–	–	–	–
MgO	2.30	2.18	0.15	0.18	0.29	0.21
CaO	4.32	4.27	0.65	0.55	1.06	0.90
Na_2O	4.03	4.48	2.40	2.12	3.88	3.41
K_2O	3.01	2.84	4.89	4.79	5.10	5.44
P_2O_5	0.22	0.24	–	–	–	–
H_2O^+	1.43	2.51	–	–	–	–
H_2O^-	0.21	0.54	–	–	–	–
Total	98.26	99.14	98.53	98.02	96.66	99.15
Q	13.02	10.15	41.47	43.91	25.86	30.27
Or	17.80	16.80	28.92	28.33	30.17	32.18
Ab	34.06	37.86	20.28	17.92	32.79	28.82
An	17.75	16.97	3.23	2.73	4.15	4.47
Co	–	–	2.37	2.96	–	0.31
Di	1.94	2.26	–	–	0.95	–
Hy	7.65	6.45	1.91	1.79	2.64	3.11
Mt	3.05	3.38	–	–	–	–
Ilm	1.65	1.67	0.34	0.40	0.10	–
Ap	0.52	0.57	–	–	–	–

MINERALOGY

Minerals have been analysed in the blocks and pumice with an automated microprobe analyser CAMECA MS46 (Table 3).

PYROXENES

Clinopyroxene is the only kind of pyroxene found. This consists of subcalcic augite (Ca 26.3 to Ca 27.3 atom percent) similar to the metastable product which crystallized near the miscibility gap, between augite and pigeonite in near-desiquilibrium conditions (Evans and Moore, 1968). Under these conditions, the liquid does not stay in contact with the solid. Subcalcic augite may also crystallize when liquids are locally strongly depleted in some of the pyroxene components (Smith and

TABLE 3. REPRESENTATIVE MICROPROBE ANALYSES AND STRUCTURAL FORMULAE FOR PYROXENE (CATIONS FOR 6 OXYGENS), PLAGIOCLASE (CATIONS FOR 8 OXYGENS), AMPHIBOLE (CATIONS FOR 23 OXYGENS) AND BIOTITE (CATIONS FOR 22 OXYGENS); FOR EACH MINERAL, MEAN OF 5 ANALYSES AT LEAST

Mineral	Pyroxene		Plagioclase			Amphibole			Biotite
	Block	Pumice	Block	Pumice		Block		Pumice	Block
Sample	Phen	Phen	Phen	Phen	Grm	Phen	Grm	Phen	Phen
SiO_2	46.84	45.56	55.74	59.68	58.04	44.15	46.32	43.72	36.44
TiO_2	2.41	1.88	0.07	–	0.16	2.65	1.89	2.20	4.96
Al_2O_3	7.55	8.45	26.77	24.76	25.06	9.25	8.14	9.59	14.25
FeO	12.30	13.83	0.30	0.44	0.21	13.19	11.92	14.47	14.62
MnO	0.46	0.49	–	–	0.07	0.36	0.20	0.41	0.10
MgO	14.92	14.31	–	0.05	0.09	13.22	14.44	13.35	14.96
CaO	10.92	10.97	9.53	6.75	8.20	11.29	11.20	10.88	–
BaO	–	0.09	0.24	0.14	0.10	–	–	–	1.13
Na_2O	1.95	1.92	6.22	7.02	6.44	2.24	2.09	2.10	0.66
K_2O	0.68	0.76	0.34	0.91	0.71	0.77	0.80	0.90	9.29
Total	98.03	98.26	99.21	99.75	99.08	97.12	97.00	97.62	96.41
Si	1.78	1.75	2.54	2.68	2.63	6.58	6.83	6.51	5.46
Al^{IV}	0.22	0.25	1.44	1.31	1.34	1.42	1.17	1.48	2.52
Al^{IV}	0.12	0.13	–	–	–	0.20	0.24	0.20	–
Ti	0.07	0.05	0.00	–	0.01	0.30	0.21	0.27	0.56
Fe^{2+}	0.39	0.44	0.01	0.02	0.01	1.64	1.47	1.50	1.83
Mn	0.02	0.02	–	–	–	0.05	0.03	0.05	0.01
Mg	0.85	0.82	–	–	0.01	2.93	3.17	3.13	3.34
Ca	0.45	0.45	0.46	0.33	0.40	1.80	1.77	1.78	0.13*
Na	0.14	0.14	0.55	0.61	0.57	0.65	0.60	0.62	0.19
K	0.03	0.04	0.02	0.05	0.04	0.15	0.15	0.20	1.78

(*) Ba.

Lindsley, 1971). These near subcalcic augites, which lie within the two-pyroxene solvus, are relatively silica-poor (Si 1.68-1.79) and alumina-rich (7.0 to 8.6 Al_2O_3 %). Al occupies both Z (Al^{IV}: 0.21 to 0.32) and Y(Al^{VI}: 0.07 to 0.12) sites. The Al^{VI}/Al^{IV} ratio is high (0.33 to 0.38), characteristic of high-pressure conditions during crystallization (Aoki and Shiba, 1973). The entry of Al_2O_3 depends not only of pressure variations on the possible equilibrium

$$\begin{array}{lclcl} CaAl_2Si_2O_8 & = & CaAl_2SiO_6 & + & SiO_2 \\ \text{Plagioclase} & & \text{Ca-Tschermak's} & & \text{Liquid} \end{array}$$

but also on silica activity, which in turn, depends on P-T variations and diffusion reactions around the growing crystals (Heming, 1977).

PLAGIOCLASE

In the absence of alkali feldspars, the andesine (An_{33-45}) is relatively K-rich (Or_{04-05}). It shows normal zoning and is more basic ($An_{\leqslant 45}$) in the blocks than in the pumice ($An_{\leqslant 37}$). Since the chemistry of the two lavas is quite similar, the increase on the An content in the plagioclase of the blocks may be due to a higher pressure condition during the crystallization. Plagioclase has been analysed only in the pumice groundmass; it is less sodic (An_{40}) than the coexisting phenocrysts, as observed also in Rabaul lavas (Heming, 1977).

TABLE 4. ANALYSES OF ILMENITE AND TITANOMAGNETITE IN BLOCK (b) AND PUMICE (p)

		Ilmenite				Titanomagnetite	
Sample	6(b)	9(b)	32(p)		6(b)	9(b)	32(p)
SiO_2	0.19	–	0.07		0.10	0.23	0.15
TiO_2	33.83	35.10	31.96		6.09	6.03	7.00
Al_2O_3	0.18	0.22	0.37		1.67	1.62	2.18
Cr_2O_3	–	–	–		0.10	–	–
FeO	56.22	56.34	59.81		83.03	81.17	81.39
MnO	0.58	0.43	0.23		0.63	0.55	0.52
MgO	2.21	2.47	2.16		1.52	1.53	2.19
CaO	0.03	0.03	–		0.04	0.05	0.10
BaO	0.40	0.30	0.09		–	0.09	0.19
Total	93.64	94.89	94.61		93.18	91.27	93.72
Recalculated analyses							
Fe_2O_3	33.56	32.73	38.78		54.97	53.56	53.12
FeO	26.02	26.88	24.92		33.56	32.98	33.60
Total	97.00	98.16	98.50		98.68	96.64	99.05
He_C	36.83	35.55	41.44	Usp_C	13.33	13.84	14.58
He_A	33.17	31.83	37.77	Usp_A	18.13	16.62	20.85
T° C(C)	890	888	942				
$-\log fO_2$ (C)	9.4	9.6	8.5				
T° C(A)	925	896	995				
$-\log fO_2$ (A)	9.2	9.7	8.0				

He_C and Usp_C by the method of Carmichael (1967); He_A and Usp_A by the method of Anderson (1968). T and $-\log fO_2$ are taken from the curves of Buddington and Lindsley (1964).

HORNBLENDE, BIOTITE

In analogy with dacites and silica-rich andesites ($SiO_2 > 60\%$) from Pliocene to Quaternary lavas of the South Central Andes (Déruelle, 1979), brown amphibole occurs in both rocks. The amphibole is edenitic hornblende with a significant amount of TiO_2 (1.89 – 2.65%; Table 3). Neither the oxidation state of the iron nor the amount of water or fluorine in these hornblendes was determined. The hornblende phenocrysts from the two rocks are slightly different in composition; for instance, the hornblende of the pumice is higher in Al^{IV} than the hornblende in the blocks, indicating a higher P_{H_2O} during the crystallization. But the volatile pressure must have been also high when the blocks crystallized, since they contain Ti-rich biotite (TiO_2 : 4.60 – 4.96%).

OPAQUE MINERALS

Titanomagnetite and ilmenite phenocrysts are ubiquitous and coexist within the blocks and pumice (Table 4). Their ülvospinel content, recalculated according to the methods described by Carmichael (1967) and Anderson (1968) is low (Usp_C 13.3 – 14.6). The ilmenites of the blocks have a slightly lower hematite content (He_C 35.5 – 36.8) than the ilmenites of the pumice (He_C 41.4).

THERMODYNAMIC EQUILIBRIUM

Pumice and blocks would be the result of two different processes within a single magma. Mineral parageneses are identical and mineral distributions are the same. However, the blocks would have been formed before the "nuée ardente" eruption, whereas the pumices would be contemporaneous with the explosion. Thermodynamic conditions which determine the solidification of the two rocks appear to be distinct.

The magnetite-ilmenite equilibrium permits calculation of a higher equilibrium temperature (950° C) for the pumices than for the blocks (900° C). Since many of these rocks contain a small number of iron-titanium phenocrysts, the oxide equilibrium-temperatures may be close to their liquidus temperatures. The 900-950° C temperatures are in fair agreement with those obtained from a suite of Californian rhyolitic obsidians (Carmichael, 1967) and pumice flows from New Guinea (Heming and Carmichael, 1973).

Parallel with temperature differences, crystallization oxygen fugacities are higher ($10^{-8.5}$) in the pumice than in the blocks ($10^{-9.5}$). Such fugacities are higher than others that have been measured either within pumices or calc-alkaline lavas (Fig. 9). They have been buffered by the hornblende biotite equilibrium as in Lassen Peak dacites (Carmichael, 1967). The temperatures derived from the plagioclase geothermometer (Kudo and Weill, 1970) have been compared with the Fe-Ti oxides temperatures, and an estimation of the P_{H_2O} was made by extrapolating the P_{H_2O} – (plagioclase) T curve of Fe-Ti oxides temperatures. The P_{H_2O} are about 1.5 kb and 1.75 kb for the blocks and pumice, respectively. The difference is small but may correspond to higher water-pressure during the crystallization of the pumice.

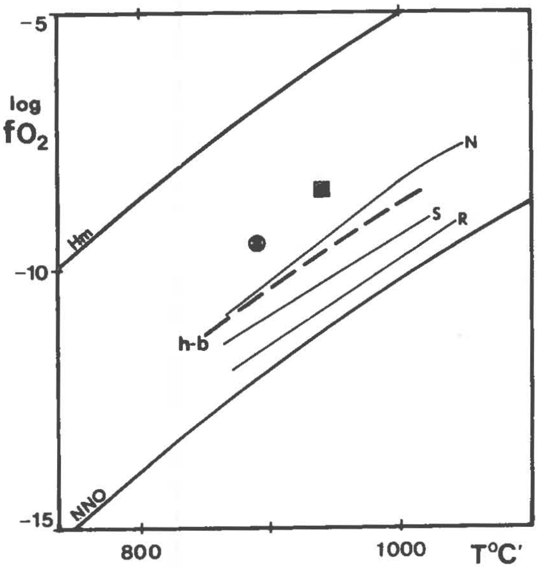

FIG. 9. Temperature-oxygen fugacity diagram for Tata Sabaya blocks (circle) and pumice (square). Various calc-alkaline lava series have been plotted for comparison: N: Namosi, S: Shasta (data from Gill, 1978, Fig. 2); R: Rabaul (Heming and Carmichael, 1973); h-b (hornblende biotite) curve from data of Lassen Peak (Carmichael, 1967); Hm and NNO curves: Hematite and Ni-NiO buffers, respectively (after Buddington and Lindsley, 1964).

PETROGENESIS OF THE "NUEE ARDENTE"

The presence of near subcalcic augite suggests strong desequilibrium during the magma ascent. Apparently, the liquid was not in equilibrium with the pyroxene phenocrysts. It is then obvious that the chemical analyses of the pumice and blocks are different from their calculated composition using the modes and chemical analyses of their components (Tables 1 to 4).

We consider that the blocks originate from a deeper part of the conduit, where the total pressure is higher than in the shallower part, where the pumices originate. It is even possible to estimate the depth at which pumice and blocks crystallized. The theoretic activity of $Mg_2Si_2O_6$ in the orthopyroxene component of the subcalcic augite ($a^{Opx}_{-Mg_2Si_2O_6}$) may be estimated if the activity of $Mg_2Si_2O_6$ in the clinopyroxene component ($a^{Cpx}_{-Mg_2Si_2O_6}$) is known. After the method of Wood and Banno (1973) with the estimated Fe^{2+}/Fe^{3+} ratios (Neumann, 1976) and the approximation $X^{Opx}_{-Fe} = a^{Opx}_{-Fe}$ (Nicholls *et al.*, 1971), the theoretical values for $X^{Opx}_{-Mg_2Si_2O_6}$ at temperatures T (theoretic equilibration of pyroxenes) are 0.18 for the pumice and 0.27 for the blocks. The corresponding silica activities $a^{liq}_{-SiO_2}$ (according to the reaction

$$\underset{\text{magnetite}}{1/3\ Fe_3O_4} + \underset{\text{glass}}{SiO_2} = \underset{\text{ferrosilite}}{FeSiO_2} + 1/6\ O_2)$$

that leads to the equality

$$\log a^{liq}_{-SiO_2} = G°/2.303\ RT + \log a^{pyr}_{-FeSiO_3} + $$
$$+ 1/6 \log \underline{f}O_2 - 1/3 \log a^{mt}_{-Fe_3O_4}$$

give a total pressure equilibria of 1.9 kb for the pumice and 4.5 kb for the blocks. So the water pressure would be close to the total pressure for the pumice but lower, by a factor of 3($P_{H_2O} = 1/3\ P_T$), for the blocks.

The order of crystallization, as outlined above, puts further constraints on the P-T regime, because the plagioclase crystallized before the hornblende. Experimental phase relations studies in rocks of andesitic to dacitic (or tonalite) composition (Piwinskii and Wyllie, 1968; Piwinskii, 1973; Lambert and Wyllie, 1974) show that hornblende is a liquidus phase at water pressures greater than 2-3 kb.

Hydrous melting data at low pressures, where $\underline{f}_{H_2O} < P_{total}$, are given by Holloway and Burnham (1972) for an olivine tholeiite ($\underline{f}_{H_2O} \cong 0.6\ \underline{f}^{\circ}_{H_2O}$). These runs, buffered with Ni-NiO, suggest that the first effects of reducing P_{H_2O} are to extend the field of amphibole, and to widen the pressure range in which plagioclase crystallizes before amphibole to 1.5 – 2.5 kb.

The crystallization of the pumices took place in the upper part of the conduit. An increase in $\underline{f}_{H_2O}$ at high temperatures, gives as a consequence, a rise in $\underline{f}_{O_2}$ due to the dissociation reaction $2H_2O \rightleftharpoons 2H_2 + O_2$ (Hamilton and Anderson, 1967).

CONCLUSION

Great differences in pressure are to be noticed in the magmatic column which is chemically constant. For that reason, the "nuées ardentes" differ from those lava columns that are poorer in gas and which are characterized by chemical variation accompanied by progressive changes in pressure and temperature. Of course, the pressure at which the crystallization began tells us nothing about the source and previous evolution of the "nuée ardente" melts.

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