A. G. MacGREGOR
(H. M. Geological Survey, Edinburgh).

Eruptive Mechanisms: Mt. Pelée, the Soufrière of St. Vincent and the Valley of Ten Thousand Smokes.

Abstract.

This paper (1) points out serious current misconceptions regarding eruptions at Mt. Pelée and the Soufrière of St. Vincent (1902) and in the Valley of Ten Thousand Smokes (1912); (2) provides systematic summaries of local evidence and hypothesis; (3) presents a synthesis of volcanic mechanism for each area; and (4) endeavours to eliminate ambiguity from current classifications of eruptions of *nuée ardente* type.

The main conclusions of LACROIX, as modified by PERRET, *in relation to Martinique*, and of TEMPEST ANDERSON and FLETT *in relation to St. Vincent*, are upheld. Certain modifications of FENNER'S most recent views on the Valley of Ten Thousand Smokes are suggested.

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Introduction

Volcanologists have commented frequently on the West Indian eruptions of 1902, at Mt. Pelée in Martinique and at the Soufrière volcano in St. Vincent, and on the Alaskan eruption of 1912, in the Valley of Ten Thousand Smokes 1). Some of the comments of the last twenty years ignore previously published facts, circumstantial evidence or inferences that appear to the writer to be of critical importance in volcanological theory. The objects of the present paper are: to point out certain fallacies that have crept into volcanological literature; to bring together systematically evidence derived from various sources; and to reassess the validity of current explanations and classifications of volcanic phenomena that give rise to gas-generating eruptive avalanches (*nuées ardentes; Glutwolken*) or incandescent tuff-flows (« sandflows »).

Mt. Pelée and the Soufrière of St. Vincent (1902-3)

Misconceptions.

According to A. LACROIX, *nuées ardentes* of 8 May, 20 May and 30 August 1902, at Mt. Pelée, were initiated by lateral propulsion due to powerful explosions 2) emanating from the side of a dome (tholoid) rising in the pre-existing summit crater. He regarded the minor *nuée ardente* eruptions of 26 May, 6 June and 9 July 1902 as representing stages of decreasing intensity of the same phenomenon. In the case of other *nuées*, at the lowest end of the scale, explosive propulsion fell to zero 3) (LACROIX, 1904, pp. 19, 312, 319-20, 354-56; 1930, pp. 458-60).

When TEMPEST ANDERSON and FLETT observed the *nuée*

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1) The writer while preparing the present paper was unable to obtain, in Great Britain, a recent publication, entitled « Steam Blast Volcanic Eruptions », that includes an analysis of the eruptions of Mt. Pelée and of the Soufrière of St. Vincent (JAGGAR, 1949).

2) See below (p. 59) for discussion of the mode of initiation of these explosions.

3) LACROIX recognised, however, a certain number of vertically generated explosions from the summit of Mt. Pelée (see below, and LACROIX, 1904, pp. 219, 221, 317-19, 331, 348, 372; 1930, p. 461).

ardente eruption at Mt. Pelée on 9 July 1902 1), they were under the impression that the summit topography of Mt. Pelée was then similar to that of the Soufrière of St. Vincent, where there was, and still is, an open (domeless) crater. Partly for this reason, they rejected LACROIX'S hypothesis connecting *nuées ardentes* at Mt. Pelée with laterally directed explosions (ANDERSON and FLETT, 1903, pp. 478-523). It does not seem to be generally known that TEMPEST ANDERSON subsequently admitted that he and FLETT had completely misinterpreted what they saw of the summit of Mt. Pelée on 9 July 1902; he stated that on that date they had, in fact, seen in the crater the dome (tholoid) that later rose to even greater heights (ANDERSON, 1908, pp. 296-97; see also p. 54 of the present paper).

It appears to the writer that this temporary misinterpretation of summit conditions at Mt. Pelée on 9 July 1902 has given rise to most of the controversy regarding the origin and kinetics of *nuées ardentes* in the West Indies (e. g. MERCALLI, 1907, p. 203).

C. A. COTTON would not appear to have seen TEMPEST ANDERSON'S recantation of 1908, for he quotes (as a fact) his original erroneous idea that there was an open crater at the summit of Mt. Pelée on 9 July 1902 (COTTON, 1944, p. 201). Moreover COTTON states that the *nuée ardente* from Mt. Pelée that overwhelmed St. Pierre on 8 May 1902 originated in an open crater, frothed over, and was sufficiently voluminous to spread widely (COTTON, 1944, pp. 4, 200); no mention is made of LACROIX's very different views on this eruption, or of the evidence on which they were based 2) (see MACGREGOR, 1946).

COTTON also states (1944, p. 200) « The formation and emission of an emulsion or intimate mixture of incandescent particles (still emitting gas as observers in Alaska and Martinique have clearly recognised) and the hot gases derived from them . . .

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1) LACROIX (1930, p. 460) states that the eruption witnessed by TEMPEST ANDERSON and FLETT took place on 20 July 1902. Here he made a slip, confined to this publication; no eruption of Mt. Pelée took place on 20 July 1902.

2) For later eruptions from Mt. Pelée COTTON, like many other volcanologists, accepts LACROIX'S views regarding the origin of *nuées ardentes* by directed lateral explosions.

has been likened by LACROIX to the boiling over of milk. Though such eruptions have proved very destructive to human life in Martinique . . . ». These statements rather obscure two facts: (1) LACROIX regarded no eruption at Mt. Pelée as in any way resembling the boiling over of milk, and (2) LACROIX'S « boiling milk» analogy was drawn with reference to C. N. FENNER'S conception of the mode of emission of the incandescent tuff-flow of the Valley of Ten Thousand Smokes in Alaska (see p. 62). LACROIX said, in this connection, that, if FENNER'S conception was correct, we have here a new method of generating *nuées ardentes;* but that judgement on this question must await the control of direct observation of another eruption (LACROIX, 1930, p. 466).

Summit Conditions.

Before the eruptions of 1902 the summits of Mt. Pelée and the Soufrière of St. Vincent were in some respects very similar. Each volcano had an open crater containing a crater lake. Each crater rim was partly breached by a notch (*échancrure*), on the south-west (at the head of the Rivière Blanche valley) in the case of Mt. Pelée, and on the west (near the head of the Larikai River valley) in the case of the Soufrière. The bottom of the notch at Mt. Pelée was only 25 to 30 metres above the level of the crater lake (Étang Sec). At the Soufrière the lowest part of the notch was several hundred metres above the lake in the bottom of the crater. At both volcanoes the crater lake was ejected at an early stage of eruptive activity (LACROIX, 1904, pp. 19-21, 36, 44-45; ANDERSON and FLETT, 1903, pp. 376-77, 386, 489; ANDERSON, 1908, pp. 283-85 and Plates 15, 18).

During the eruptions the characters of the two volcano summits became radically different. An open crater persisted at the Soufrière of St. Vincent, and the rock barrier at the base of the western notch was not breached (ANDERSON, 1908, Plates 15, 18). At Mt. Pelée the weak barrier at the lowest part of the south-west notch was breached approximately to the level of the crater lake at an early stage (5 May; LACROIX, 1904,

p. 36) and behind it a dome (tholoid) rose in the crater. The date of the rise of this dome from the crater bottom is a matter of critical importance in relation to conflicting current hypotheses regarding the mechanism of the earlier outbursts from Mt. Pelée. The evidence will now be given.

LACROIX inferred from the statements of eye-witnesses that as early as 7 May 1902 there was in the crater a great mass of material, at high temperature and derived from depth (the embryo dome), that was already high enough to be seen through the notch which, it will be remembered, was deepened on 5 May (LACROIX, 1904, pp. 110-12). LACROIX'S inference seems fully justified, and its validity is strongly supported by subsequent events, for instance by the transport of large blocks by the first *nuée ardente*, that of 8 May (see pp. 56, 57, 60-61 below).

On 21 May a cone of debris within the crater was seen from the sea (through the notch) by E. O. HOVEY and others, and was estimated to be between 60 and 153 metres in height. LACROIX thought this « cone » was probably only the anterior part of the new dome, which was largely concealed by mist (HOVEY, 1903, pp. 270-71; LACROIX, 1904, p. 112). T. A. JAGGAR has described the cone on this date as a heap of scaly or crusty boulders « smouldering » in appearance and with brown dust clouds rising from the crevices between the fragments; its height was estimated as not more than 122 metres above its apparent base; its top appeared to be lower than the old crater rim. JAGGAR'S viewpoint is not mentioned (JAGGAR, 1904, p. 34).

On 31 May the « cone » was at least as high as the eastern crater rim and had possibly attained 440 metres above its base. It must therefore have grown with great rapidity (HOVEY, 1903, p. 271).

On 27 June the « cone » was seen (from Carbet) to have grown to a height somewhat above the rim of the crater. In about a month the « cone » had gained enormously both in height and breadth (JAGGAR, 1904, p. 34).

On 6 July JAGGAR saw the « cone » from St. Pierre, and a companion photographed it. On its summit was an extraordinary monolith, not less than 60 metres high and shaped like the dorsal fin of a shark (JAGGAR, 1904, p. 36 and Figs. 2 and 3). LACROIX has published a line-drawing of this « cone » (i. e. dome) as seen on the same date (LACROIX, 1904, Fig. 22, p. 114). The photographs and sketch all show the dome blocking the view into the crater through the notch or *échancrure*, and rising well above the top of the crater walls.

It is now clear how completely TEMPEST ANDERSON and FLETT misinterpreted the summit conditions when they saw the *nuée ardente* eruption of 9 July 1902, and formulated their much-quoted hypothesis regarding its mode of origin (ANDERSON and FLETT, 1903, pp. 506-14). Instead of their postulated open crater breached by a notch on the south-west side, there was a crater filled by a debris-mantled dome (tholoid) that rose well above the crater walls; immediately behind the great notch in the crater rim (*échancrure en V* of LACROIX) the south-west flank of the dome was exposed practically to its base, that is to say practically to the level of the old crater lake (cf. LACROIX, 1908, p. 101 : comments on MERCALLI'S criticisms). TEMPEST ANDERSON, in 1908, explained that he had subsequently realised that this was, without any doubt, what he saw on 9 July 1902; he had actually observed a large pointed rock projecting about 30 metres above the summit of the dome and this he identified quite definitely with the monolith seen by JAGGAR on 6 July. ANDERSON'S view had been periodically interrupted by trade-wind cloud on 9 July 1902, and he had then taken the monolith for a large crag on the further lip of the crater (ANDERSON, 1908, p. 297).

For the purposes of the present paper it is unnecessary to follow the history of the Pelée dome any further. Conditions at the *échancrure* remained essentially the same, although this notch was deepened during the eruption of 30 August 1902 (LACROIX, 1904, p. 331). The south-west flank of the dome remained freely exposed at the notch and formed a continuation upwards of the debris- smothered slopes at the head of the old Rivière Blanche valley (LACROIX, 1908, Fig. 246, p. 10).

General Distribution of Nuée ardente Deposits.

Lacroix has stressed the importance (in relation to volcanic theory) of the differences in the geographical distribution of the eruptive products at Mt. Pelée and at the Soufrière of St. Vincent (Lacroix, 1904, p. 56; see also Anderson and Flett, 1903, pp. 447-53, 488).

At Mt. Pelée the products of most of the eruptions covered well-defined sectors that had their apices at the point where the flank of the dome rose immediately behind the crater-rim notch (Lacroix, 1904, Fig. 1 p. 7 and p. 355; Fig. 87 p. 223; 1908, p. 80; Philémon, 1930, map facing p. 60). The first and most powerful *nuée ardente* (that of 8 May 1902, which destroyed St. Pierre) had an exceptionally wide angle of spread (between 60 and 100 degrees). This eruption also devastated the *upper* slopes of Mt. Pelée all around the summit, but this was an indirect effect (Lacroix, 1904, pp. 224, 355).

During the eruption of 30 August 1902, the overwhelming of Morne Rouge (to the south-east of the summit of Mt. Pelée) and of Ajoupa Bouillon (to the north-east) was due to the radial dispersal of the products of explosions from the dome. Lacroix attributed the radial distribution to vertical explosions, possibly combined with lateral explosions low down on the east or south-east flank of the dome (for more complete explanation see below, p. 57). During the same eruption, debris restricted to a south-westerly sector emanated from the apex of that sector, where the flank of the dome was exposed at the crater-rim notch (Lacroix, 1904, pp. 222-24, 325, 348, 359-60).

In the case of the Soufrière, eruptive debris, although rather more abundant in an area south of the crater, was deposited radially by *nuées ardentes* that flowed down the hill slopes in all azimuths. *The crater-rim notch did not have an appreciable effect on the distribution of debris,* for ash deposits were not found in the Larikai valley (into which the notch led) in very great quantity. The preferential accumulation of thick *nuée ardente* ash deposits south of the crater was attributed to two facts: (1) the crater rim, as a whole, was lower on the south than it was on the north, and (2) to the north of the crater rim, beyond a valley, was a great « Somma-ridge » rampart - the remains of a larger and older crater wall. Leaving local thicknesses of deposits out of account, the effects of the « hot blast » of the great eruption were very marked everywhere around the volcano, except in the extreme north, behind the fosse and rampart of the old « Somma-ridge » (ANDERSON and FLETT, 1903, pp. 448-53, 507, 511).

Sizes of Constituents of Nuée ardente Deposits.

Other points stressed by LACROIX in relation to volcanic theory are connected with the differences in size of rock fragments in the *nuée ardente* deposits of Mt. Pelée and the Soufrière of St. Vincent. In St. Vincent the maximum dimensions of volcanic fragments, especially of those composed of new lava, were infinitely smaller than at Mt. Pelée; this fact has genetic significance (LACROIX, 1904, pp. 369-70; 1908, p. 82; 1930, p. 464).

In the case of the *nuées ardentes* of the Soufrière, originating by initial vertical explosion from an open crater, any relatively large fragments fell back into the crater or in its immediate vicinity and only relatively fine material was deposited far from the crater. In the case of the *nuées ardentes* at Mt. Pelée, their origin by directed lateral explosive propulsion is consistent with the fact that there was no « grading » of any kind; large blocks, smaller fragments and fine dust travelled *en masse* for long distances and gave rise to deposits of volcanic debris with an extraordinary range of size of individual constituents. The contrast between the deposits at the two volcanoes can best be appreciated by studying contemporary photographs (see LACROIX, 1904, pp. 372-80; and compare LACROIX, 1904, Figs. 160, 162, 163 and LACROIX, 1908, Fig. 255 with ANDERSON and FLETT, 1903, Plates 30-33 and ANDERSON, 1908, Plate 10).

There were, in point of fact, no very large blocks in the St. Vincent deposits. It may be inferred that this was because there was no crusted crateral dome of new lava to provide them. This inference may have been made by LACROIX, but if so the writer has not found it clearly expressed. LACROIX (and later PERRET) found that the large blocks at Mt. Pelée were almost entirely, if not exclusively, of domal origin and were newly consolidated or semiconsolidated (LACROIX, 1904, p. 370; PERRET, 1935, pp. 45-50). Within the last 25 years evidence has been brought forward to show that the large domal blocks were porous and emitted compressed gas during transit and that this gas-emission was the secret of their travel for long distances (PERRET, 1935, pp. 84-89, 93, 101, 103; MACGREGOR, 1938, pp. 31-33; see also below, p. 61).

At Mt. Pelée the *nuées ardentes* that covered restricted sectors south-west of the summit carried volcanic fragments of all sizes from the finest dust up to great blocks as large as small cottages (LACROIX, 1904, p. 370 and Figs. 161, 166 and Plate V). On the other hand the *nuées ardentes* with radial dispersal (those that overwhelmed Morne Rouge and Ajoupa Bouillon on 30 August 1902) carried no large blocks. For this fact LACROIX gave two possible explanations; (1) after a vertical discharge the larger components fell back within the crater 1); (2) large blocks and fragments discharged by flank explosions on the east or south-east of the dome were trapped in the fosse (*rainure*) between the dome and the crater rim, while the finer material was carried over the barrier (LACROIX, 1904, pp. 331, 359-60; 1908, p. 79).

The line of transport of large blocks during the eruption of Mt. Pelée on 8 May 1902 was carefully considered by LACROIX. He found that some of the largest carried by the *nuée ardente* had travelled along a line joining the crater and St. Pierre. On leaving the crater they had not rolled down the line of steepest slope; at the outset they had passed over the Rivière Blanche, which was then a deep ravine. LACROIX could not understand this trajectory without postulating initial explosive projection in a direction determined by an opening produced in the flank of the rising dome opposite the notch or *échancrure*. He argued that

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1) The writer suggests that really large blocks from the fractured domal carapace would be impelled vertically upwards, or obliquely upwards with a trajectory that would not carry them over the crater rim, or would simply be blown sideways into the fosse between the dome and the crater wall.

this directed explosion must have had sufficient force and spread to prevent the *nuée* following exclusively the line of steepest slope (to the south-west), and to direct it south to St. Pierre across rivers and streams, several of which had broad deep valleys (LACROIX, 1904, pp. 354-56; 1908, p. 102; 1930, p. 459; see also ROMER, 1936, pp. 104-08).

Eruptive Mechanisms.

The essentials of the evidence set out in the preceding paragraphs may be tabulated as follows:

MT. PELÉE	THE SOUFRIÈRE OF ST. VINCENT
Dome formation.	No dome formation.
Deposits normally restricted to a sector within the SW. quadrant of a circle centred on the summit; notch in crater-rim at apex of sector; flank of dome clearly seen behind notch during most of eruptive period.	Deposits radially distributed. Notch in crater-rim bears on relation to distribution of deposits.
Sector deposits characterised by large blocks. No large blocks in deposits of *nuées ardentes* that issued from dome-filled crater and were *radially* distributed.	No large blocks. Average size of constituents of deposits very much less than at Mt. Pelée.

To the writer the items of evidence, *when considered as a whole,* seem to justify LACROIX'S explosive lateral propulsion hypothesis for many of the eruptions at Mt. Pelée; but the propulsion was not entirely horizontal or downwards, and was due to a type of explosion not admitted by LACROIX (see below, p. 59).

F. A. PERRET observed many *nuée ardente* eruptions (including some that involved vertical explosions) from the new dome formed during the period 1929/32. It is significant that, after this prolonged study, he gave strong support to the idea of *more or less* horizontal explosive propulsion of some *nuées ardentes* (including the *nuée* of 8 May 1902) from the 1902 Mt. Pelée dome (PERRET, 1935, pp. 84-89).

PERRET differed from LACROIX in postulating the self-explosive (gas-generating) properties of the fragments of new lava *during transit*. The essentials of this feature of *nuées ardentes* (now widely accepted as fundamental) were first expressed by TEMPEST ANDERSON and FLETT; this was their great contribution to the explanation of the West Indian eruptions of 1902. The conception was not accepted by LACROIX, partly because of the scarcity of true pumice in *nuée ardente* deposits (ANDERSON and FLETT, 1903, pp. 507-08, 512; LACROIX, 1904, Chapter VIII, p. 350; 1930, p. 460; PERRET, 1935, pp. 84, 93, 95; MACGREGOR, 1938, p. 31-33).

Another major contribution of ANDERSON and FLETT was their insistence on the rôle played by gravity in giving to *nuées ardentes* their direction, speed and momentum. At the Soufrière of St. Vincent the force of gravity was (apart from topography) the only factor involved. At Mt. Pelée LACROIX admitted that gravity was a very important factor but, as we have seen, maintained that gravity and topography could not explain the direction taken by some block-carrying *nuées ardentes* of Martinique (ANDERSON and FLETT, 1903, p. 509; LACROIX, 1904, p. 356; 1930, p. 459).

Since 1935 it has been clear that the type of Mt. Pelée domal explosion envisaged by PERRET — but *not* by LACROIX (1930, p. 460) — is a sudden vesicular expansion of hot viscous semi-crystallised lava within the jagged domal carapace with its mantle of loose (detached) debris. PERRET points out that the energy of such an explosion does not come directly from a relatively deep-seated source, as it does in what he calls a « normal vertical explosion from a volcanic vent »; the explosion is initiated behind, or occasionally below, a domal rupture at a weak spot in the carapace, and is thus of superficial origin (PERRET, 1935, p. 86).

The writer has found no evidence in LACROIX'S writings to show that explosions directed *entirely below the horizontal* occurred at Mt. Pelée (as was alleged: LACROIX, 1908, p. 80); he infers that LACROIX, like PERRET, simply observed many explosions initiated on the exposed flank of the dome, and that these often had a horizontal component, but also produced blast directed obliquely upwards, downwards and to left and right. The direction and spread of the blast would be affected by the nature, shape and depth of the domal rupture, and by its position on the flank (low or high). The unusually powerful initial explosive eruption of 8 May 1902 presumably originated near the top of the south-west flank of the dome at a time when this tholoid had not risen very high; blocks were projected obliquely upwards, and to left and right.

The writer pictures the general sequence of events as follows. Viscous magma in the upper part of the volcanic conduit was being forced up continuously by the expansion of gas largely generated by crystallisation in more fluid magma below (cf. MOREY, quoted in FENNER, 1950, p. 602). Gas pressure within the pasty and porous plug was built up while the gas slowly penetrated it. The almost consolidated outer carapace of the dome acted as a leaky membrane through which some of the gas escaped. The inner, hotter magma was also potentially self-explosive because of gases still dissolved in its uncrystallised residuum. Hot, relatively mobile, magma was nearer the surface of the partially fissured carapace at some places than it was at others. On the south-west flank of the dome, behind shifting weak spots in the carapace, potentially self-explosive magma was « touched off » by local release of pressure. These flank (lateral) explosions of rapidly expanding gas burst through the carapace just as compressed air expands through a puncture in a football bladder; their general direction of propagation was thus perpendicular to the flank of the dome. It was relatively seldom that temporarily weakened spots on the top of the dome provided the expanding gas with means of exit easier than those afforded by weak spots on the south-west flank. It is uncertain to what extent sudden local vesicular expansion in the dome may have been induced by the reheating of semi-glassy gas-rich lava to a critical temperature.

Regarding the blocks in *nuées ardentes,* the writer would make the following additional comments:

(1) Blocks derived by explosion from the inner, hotter part of the carapace were only semi-crystallised; they became markedly porous when their primary content of dissolved gas was released during transit.

(2) Blocks broken off the outer, cooler part of the carapace at the time of the initial explosion, although consolidated, were somewhat porous; they contained gas trapped in their pores, and this gas expanded and was released during transit. Such blocks were self-explosive only in a secondary sense: their contained gas had been generated *in the dome.*

(3) A relatively small proportion of the blocks carried by domal *nuées ardentes* (both during the 1902 and 1929 eruptive periods) were derived from the superficial detached domal debris: these blocks were fully consolidated, relatively cool, gas-free and inert.

Synthesis.

The writer would summarise the characteristics of the erupiions of Mt. Pelée and the Soufrière of St. Vincent as follows. *Nuée ardente* eruptions at Mt. Pelée differed from those at the Soufrière because, at Mt. Pelée, a dome was rising behind a deep crater-rim notch during the whole period of activity. During most of the eruptions the notch gave rise to, or coincided with, an area of relative weakness on the flank of the dome; behind the weak area originated explosions necessarily of a somewhat directional character. The explosions originated in dome magma that was not fully consolidated, and produced self-explosive (gas-generating) avalanches (*nueés ardentes*) of varying degrees of magnitude and initial energy; they carried lava fragments with a great range of size, including large blocks derived from the carapace of the dome. Gravity, as a rule, was by far the dominating factor in giving speed and momentum to the avalanches. The *nuées ardentes* at the Soufrière of St. Vincent were initiated by vertical explosion in a domeless crater, were distributed radially on the slopes of the volcano, and owed their speed and momentum entirely to gravity; the lava fragments in these *nuées* were finely comminuted. As at Mt. Pelée, the mobility of the *nuées* was due to the self-explosive (gas-generating) properties of fragments of new lava. At the Soufrière these were produced by the minute explosive fragmentation of new, semi-crystallised, magma in the conduit immediately below the open crater.

The Valley of Ten Thousand Smokes (1912)

Misconceptions.

There were no eye-witnesses of the Alaskan eruption of 1912 that deposited a great sheet of tuff in a valley near Mount Katmai. The area was visited, however, in 1916-17 and thoroughly investigated by C. N. FENNER in 1919, when innumerable fumaroles were still active all over the floor of the valley. This activity gave rise to the name « the Valley of Ten Thousand Smokes », which will here, where convenient, be abbreviated to « the Valley ».

FENNER wrote a number of papers in which he set out the local volcanological evidence and inferred from it the nature and mechanism of the eruption. LACROIX has pointed out that FENNER'S conception is entirely a matter of inference; FENNER was fully aware of this (LACROIX, 1930, p. 466; FENNER, 1923, p. 71).

At first FENNER (1920, pp. 580, 589, 605) regarded the site of the new volcano Novarupta *merely as a probable source* of some of the tuff that filled the Valley (at a lower level) 1). He regarded Novarupta as having developed at a spot where chance conditions had favoured the enlargement of a volcanic orifice that was originally simply a fissure. Most of the tuff, he thought, might well have issued from many fissures now concealed below the Valley-floor tuff deposit (FENNER, 1920, pp. 580, 589).

In a later paper (published in 1923) which gives his main analysis of the Valley phenomena, FENNER said, however, that *Novarupta was believed to have played an important part as a*

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1) Novarupta has a comparatively small circular crater in which there is a dome (tholoid) 800ft. in diameter and 200ft. high (FENNER, 1923, p. 53 and photos on pp. 14, 44, 52); the volcano is situated a little way up a gentle slope on the east side of the head of the south branch of the Valley.

vent from which Valley tuff came; he further expressed the opinion that Valley tuff also issued from fissures now concealed by the tuff *and from visible fissures in Baked Mountain, Broken Mountain and Falling Mountain, which form relatively high ground* between the two upper arms of the Y-shaped depression formed by the Valley (FENNER, 1923, pp. 41-43, 51, 59).

A number of volcanologists appear to have overlooked the paper of 1923, or to have misread it, for they have said that, according to FENNER, the tuff of the Valley of Ten Thousand Smokes issued from fissures in the Valley; in these brief comments they have not mentioned Novarupta volcano as a source (LACROIX, 1930, p. 466; MARSHALL, 1935, p. 19; WILLIAMS, 1941, p. 379; COTTON, 1944, p. 202).

LACROIX stated that FENNER did not regard Novarupta as a source of the Valley tuff. MARSHALL said the tuff did not issue from any of the local volcanic cones. WILLIAMS mentioned only fissures in the valley floor as a source of the tuff. COTTON stated that the tuff apparently issued *simultaneously* from many fissures in the Valley (FENNER said in 1923 that it appears as if all the Valley extrusions were nearly simultaneous; he has since stated that such an inference cannot be made: FENNER, 1923 p. 73; 1950, p. 709).

FENNER himself is probably responsible for some of the misrepresentation. In two papers, published in 1925 and 1937, he made brief references to the Valley phenomena; these, *if not read in conjunction with his detailed analysis of 1923,* appear to minimise the rôle of Novarupta and to emphasise the importance of innumerable fissures on the Valley floor (FENNER, 1925, pp. 194, 222; 1937, p. 236; see also 1948, p. 882).

It is thus clear that between 1930 and 1945 a number of leading volcanologists published incomplete, and in some cases misleading, summaries of FENNER'S inferences regarding the Valley eruption of 1912. These half-truths that have appeared in volcanological literature take on a serious aspect when we read FENNERS'S latest contribution to the problem, published postumously in 1950. His final conclusions are as follows (FENNER, 1950, pp. 707-08: see also p. 718):

« The breaking out of Novarupta and the innumerable lesser vents of the Valley . . . seems to have been caused by the following succession of events. When the new magma first rose in the (Mount) Katmai conduit . . . a portion escaped as a sill injected under the floor of the Valley . . . The floor of the Valley was upheaved, the defile of Katmai Pass was broken open, the lower slopes of Mount Trident that face the Valley were badly shattered, a great slice of Falling Mountain collapsed and Broken Mountain was cut to pieces. From the vents thus produced the great incandescent tuff-flows were poured out. Novarupta was the chief of these vents and its orifice later became enlarged and it passed into violent eruption . . . Vents broke out in both branches of the Valley . . . Probably all were orifices of extrusion of incandescent tuff-flow and they were sites of intense fumarolic activity for years afterward . . . ».

Here we see the antithesis of what appear to be the ideas widely held regarding FENNER'S conclusions. The chief sources of the Valley tuffs were, in order of importance, (1) Novarupta volcano and (2) fissures *above* the Valley floor-level, on Mount Trident, Falling Mountain and Broken Mountain. Concealed Valley-floor fissures, on which some commentators have fixed their attention, are regarded by FENNER merely as *probable* sites of tuff-extrusion. The writer is not at the moment attempting to assess the validity of FENNER'S synthesis (see pp. 65-68), but he would point out that a different explanation of the Valley phenomena of 1912, alleged to be that of FENNER, has been used in the interpretation of deposits believed to have originated as incandescent tuff-flows in other parts of the world (e. g. COTTON, 1944, pp. 209, 211; van BEMMELEN, 1949, p. 212).

Nature of the Tuffs.

FENNER has described the general nature of the tuff deposits of the Valley in a number of papers. His scattered descriptions may be summarised as follows:

(1) The tuff deposit has an almost plane surface, is almost wholly unstratified, and consists mainly of fine material in which are mingled, rather promiscuously, lumps of pumice and nu-

merous bits of sedimentary and volcanic rock (FENNER, 1923, pp. 13, 25, 35; 1937, p. 236).

(2) There is white pumice with a little quartz and acid plagioclase; dark pumice with basic plagioclase, augite, hypersthene and magnetite; banded pumice; and homogeneous « intermediate » pumice (FENNER, 1923, pp. 35, 38).

(3) The finer material consists (? entirely) of angular to cusplike shards of volcanic glass that originated by the disruption of bubbles (FENNER, 1925, p. 194; 1937, p. 236).

(4) There are no large blocks anywhere, but the materials 1) are coarser towards the head of the Valley (FENNER, 1923, p. 21.)

(5) In the upper part of the Valley, where the temperature of the tuff was relatively high, the deposits are firmly consolidated by innumerable tiny growths of secondary minerals, mainly tridymite and orthoclase. This consolidation, which accompanied the recrystallisation in the tuff, was accomplished shortly after the flow came to rest, by gases evolved from the tuff itself (FENNER, 1937, p. 236; 1950, p. 709).

(6) In the upper part of the Valley the pumices are grey or dark brown in colour and contain large quantities of mafic phenocrysts (FENNER, 1950, p. 708).

(7) In the lower part of the Valley, where the temperature of the tuff was relatively low, the deposits have little cohesion (FENNER, 1937, p. 236).

(8) In the lower part of the Valley the pumices are almost all pure white or very pale buff in colour and contain only a few small phenocrysts of quartz and albite-oligoclase; only occasional specimens show dark streaks (FENNER, 1950, pp. 708-09).

(9) Some of the fumaroles in the tuff were believed to be due to gases evolved from the tuff itself; but most were distributed along lines of fissures that intersected the surface and were believed to be of deep-seated origin (FENNER, 1923, pp. 41-47).

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1) It is not clear if this statement refers in part to relatively late Novarupta products that were not extruded as incandescent tuff.

Eruptive Mechanism.

FENNER'S explanation of the Valley phenomena is as follows:

(1) The general succession of events outlined in FENNER'S own words on p. 64 is supposed to have been brought about by the intrusion (at a depth of possibly several thousand feet) of a sill of rhyolitic magma emanating from the Mount Katmai conduit before the magma there reached the explosive stage 1). The intrusion of this sill resulted in fracturing and fissure formation in various places and caused the development of the main Valley-tuff orifice at the site of Novarupta volcano.

(2) There were three merging phases in the activity of Novarupta; (I) in the first it contributed to the incandescent tuff-flow; (II) then it became explosively active and ejected much pumice to distances of several miles 2); (III) finally a dome of viscous magma, nearly free of gases, was pushed up from the vent (FENNER, 1923, p. 53; 1950, pp. 621, 707-08, 715-18).

(3) While phase (I) of Novarupta was in operation, incandescent tuff issued from fissures in lower mountain slopes near the head of the Valley; Valley-floor fissures *probably* served also as orifices for the emission of incandescent tuff (FENNER, 1950, p. 708). There was continuous evolution of gas during the remarkably mobile flow of the tuff (FENNER, 1923, pp. 60, 62).

FENNER regarded the history of Novarupta as intimately related to the features of the Valley tuff. From a study of the banded rock of the dome he inferred that a rhyolitic magma had there reacted with basic andesitic rock fragments and assimilated them in varying degree. The source of the basic rock was said to be a thin surface deposit of moraine. FENNER inferred that the banded pumice of the earlier tuff-flow repre-

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1) There was a great explosive « ashfall » eruption from Mount Katmai after the tuff-flow in the Valley took place (FENNER, 1923, pp. 9, 47; 1925, p. 215; 1950, pp. 613, 621, 707). Apparently there was also a later (independent) incandescent tuff-flow from Mount Katmai crater (FENNER, 1923, p. 31; 1950, pp. 621, 700): the writer has not been able to find a clear statement of the evidence for this tuff-flow and its distribution.

2) This contradicts a previous statement that during this phase ejecta were not thrown out to a great distance (FENNER, 1923, p. 51).

sented rhyolitic magma contaminated in a similar manner. In order to get a volume of basic rock sufficient to produce the large amount of hybridised material in the tuff, he assumed, in his 1923 paper, that all over the Valley floor the necessary basic morainic lava was present; all over the Valley floor, as at Novarupta, rhyolitic magma rose quietly to the surface in fissures, spent some time in assimilating basic lava-moraine fragments, and then frothed up and gave rise to the incandescent tuff-flow (FENNER, 1923, pp. 51-61). The assimilation and frothing up were accounted for as follows. Relief of pressure (according to FENNER) produced a shift of equilibrium in the magma and favoured escape of gases; thus (hypothetical) internal exothermic reactions proceeded in this direction, the heat generated enabled the ryolitic magma to assimilate the basic rock, and eventually gas was explosively released without further relief of pressure (FENNER, 1923, pp. 59-61, 72; 1934, pp. 64-66; 1950, pp. 601-04, 617-18, 699).

The differences in the pumice in the upper and lower parts of the Valley (items 6 and 8 on p. 65) were not mentioned by FENNER until 1950. These differences upset part of the 1923 hypothesis. FENNER therefore modified it by saying that in the lower part of the Valley (where the pumice is non-hybrised rhyolite) there was apparently very little reaction with foreign material because there the rhyolitic magma, having travelled (underground) further from the Mount Katmai conduit, had lost most of its heat reserve (FENNER, 1950, p. 709). FENNER had previously attributed the lack of consolidation of the tuff in the lower part of the Valley (items 5 and 7 on p. 65) to a relatively lower extrusion temperature (FENNER, 1937, p. 236).

There is little doubt in the writer's mind that FENNER did not find these explanations really satisfactory 1), and that for this reason he relegated the Valley-floor fissures to the status

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1) In relation to heat supply used up in assimilating basic lava, it is not convincing to maintain *at the same time*: (1) that heat newly generated, as the result of exothermic reactions due to relief of pressure on extrusion, is of critical importance, and (2) that original pre-extrusion heat is of critical importance.

of *probable* sources of tuff, while retaining them as *definite* sources of fumaroles (FENNER, 1950, p. 708).

The writer would offer the following comments on certain assumptions or inferences made by FENNER at different times:

(1) An apparently fatal objection to the Valley-floor fissure idea is that, if the extruded material issued from such widely distributed sources with the exceptional mobility postulated by FENNER, it should have been found down the Valley *far below the lowest fumaroles*; but this was not the case (cf. FENNER, 1923, pp. 4, 42).

(2) FENNER gave no evidence to support what appears to have been one of his original assumptions - that the Novarupta orifice was linear (simply a fissure) at the time of the tuff-flow. If this had been the case, some linear structure along a line bisecting the site of the volcano (line of fumaroles; major zone of surface fissuring) would surely have been visible in 1919; this clearly was not the case (FENNER, 1923, photos pp. 14, 44, 52).

(3) FENNER postulated that relief of pressure, by initiating exothermic reactions in magma exposed at the surface, generates heat sufficient to make possible the (pre-frothing) assimilation of large quantities of basic lava. Why, then, do rhyolitic and dacitic surface lava-flows (in which heat is *not* used up in assimilating foreign matter) show no evidence of having frothed up and emitted incandescent vitric tuffs?

(4) FENNER did not explain how, at Novarupta, the magma represented by the dome managed to assimilate *surface moraine* after explosive eruptions of phases (I) and (II) had drawn heavily on its reserves of heat (cf. FENNER, 1950, p. 709) and of dissolved gases. The writer finds this conception unacceptable, and regards the surface assimilation of moraine, at earlier stages, as highly improbable.

Synthesis.

In the light of all FENNER'S evidence, the writer would suggest that the following modification of his hypothesis is worth consideration.

The tuff was extruded explosively from Novarupta (a cylindrical volcanic conduit) and possibly from fissured ground at the head of the Valley. Most of the fumaroles that gave the Valley of Ten Thousand Smokes its name emanated from contemporaneously formed Valley-floor fissures that did not become sufficiently deep and wide to allow underlying rhyolitic magma to rise to the critical explosion level; other fumaroles originated in the tuff itself.

At the source (or sources) of extrusion, hybridisation of slowly rising rhyolitic magma by old basic lava (*in situ*: not morainic debris) took place at a moderate depth, *before* it broke through to the surface. Breaking through occurred at Novarupta, and possibly in fissures (through which it was forcing its way upwards) at Mount Trident and Falling Mountain, and perhaps at Broken Mountain 1).

At the stage when reaction with old basic lava was taking place, the rhyolitic magma was very hot and still contained its volatiles in solution. Eventually the contaminated magma, in its progress upwards, reached a critical level where relief of pressure, taking effect under suitable temperature conditions, touched it off to explode upwards, perhaps to a considerable height. Under the influence of gravity its comminuted gas-generating fragments, mixed with some finely divided sedimentary and old igneous debris, then descended, and flowed down the Valley as highly mobile incandescent tuff. The blowing out of the upper hybridised magma reduced the pressure on underlying pure rhyolitic magma in the volcanic conduit, or conduits, and the pure rhyolite exploded in its turn. As is sometimes the case even in relatively viscous composite lava flows (KENNEDY, 1931, p. 176), the last extruded magmatic portion flowed furthest; during the first part of its journey down the Valley this rhyolitic material overrode the earlier hybridised tuff (and while doing so kept the latter warm);

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1) Mount Trident and Falling Mountain are said to be igneous, and presumably could thus provide basic lava for the rhyolite to assimilate. The upper country rocks at Novarupta are not known to be sedimentary (FENNER, 1923, pp. 41, 42, 59). Although we are told that Broken Mountain is made up of sedimentary rocks (FENNER, 1923, p. 59), it is also stated that bedrock is not there exposed (FENNER, 1923, p. 43).

its flow, owing to gas-emission and lack of basal chilling, was so mobile and so nearly frictionless that it passed onwards *en masse*, and was eventually deposited as almost pure rhyolitic tuff in the lower part of the Valley. This rhyolitic tuff, with heat radiating continuously from its surface, had travelled farther than the hybridised tuff; moreover, during the period of its passage over the hybridised tuff, it had « blanketed » the radiation of heat from the upper part of that tuff; the rhyolitic tuff was therefore relatively cooler when the flowage of tuff in the Valley ended.

After the eruption of the tuff-material, explosive ejection of volcanic debris took place at Novarupta and produced cold « ash-fall » types of deposit. During this period the diameter of the orifice was somewhat enlarged, and more old basic lava from the walls of the volcanic pipe was incorporated (in depth) in the still rising rhyolitic magma. As compared with the tuff-flow outburst, the explosive release of gas took place, during later phases, in relatively small instalments, temperature fell progressively and latterly gas was released with decreasing energy. Finally the banded dome (tholoid) was extruded in the crater.

There are not enough definite local geological and volcanological data to render any Valley hypothesis of very high probability. It may perhaps be thought, however, that the above new synthesis encounters rather fewer difficulties among the facts that FENNER brought together with such skill and pertinacity, and makes rather less improbable basic assumptions.

Classification of Volcanism that involves the production of incandescent gas-generating Eruptive Avalanches or Tuff-flows.

Various classifications of *nuées ardentes* and incandescent tuff-flows, and of the types of eruption that produce them, are extant (e. g. LACROIX, 1930, pp. 457-66; ESCHER, 1933, pp. 47, 53 and Plate 6; NEUMANN VAN PADANG: see van BEMMELEN, 1949, p. 193; COTTON, 1944, pp. 4, 199-204). Those referred to are set out in tabular form in Table I. An amended classification, proposed by the writer, is shown in Table II.

The new classification corresponds very closely to LACROIX'S

1930 subdivision of *nuées ardentes*, but has been designed to give more precision. A special feature is the statement of the approximate kind of magma connected with each type of eruption. Types of eruption similar to those tabulated, but connected with other magmas (e. g. trachytic) should not be described with reference to Merapi, Pelée, Katmai etc. as prototypes.

Table II has been set out in such a way that (1) the classification can readly be extended, and (2) volcano names need not *necessarily* be used in defining types of eruption.

ESCHER'S Merapi type has been made more precise because Merapi volcano has a number of different ways of erupting, none of which appears to be characteristic (VAN BEMMELEN, 1949, pp. 199-200).

The St. Vincent type has been adopted from ESCHER, but has been restricted to the only type of *nuée ardente* eruption that has been recorded in the island. It is confusing to refer to the eruption of glowing clouds of St. Vincent type at a volcano such as Merapi, which has not got an open crater (e. g. VAN BEMMELEN, 1949, p. 200).

The term « Katmaian eruption » was proposed by FENNER, in 1937, to describe the type of eruption that produced the tuff deposit of the Valley of Ten Thousand Smokes (FENNER, 1937, p. 236; 1948, pp. 882-83). Unfortunately the 1937 paper is one of those from which readers would get the impression that the Valley tuff came exclusively from numerous fissures (of unstated location). For this reason alone the term should now be dropped. The adjective « Katmaian » used in connection with the Valley of Ten Thousand Smokes is in any case most confusing. FENNER, as we have seen (p. 66 footnote) has recorded an incandescent tuff-flow that came *from the summit crater of Mount Katmai*, and a still greater eruption of that volcano that produced a cold ashfall.

The Mount Katmai tuff-flow type has been introduced to cover eruptions that have produced incandescent *rhyolitic* tuff-flows from the summit of a high volcano with an open (domeless) crater.

In view of FENNER'S final conclusions, Novarupta has been introduced as the obvious name to use in connection with the type of eruption supposed to have occurred in the Valley of Ten Thousand Smokes.

No locality name is proposed in connection with incandescent rhyolitic tuff-flows believed to have come from concealed fissures.

The classification of *nuées ardentes* and tuff-flows should not be used as a kind of substitute for a lithological classification of volcanic debris. Deposits that are lithologically similar (e. g. certain vitric tuffs) may be formed by different eruptive mechanisms, or by mechanisms which it may be impossible to specify (cf. BARKSDALE, 1951, pp. 441-42).

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It is hoped that the method of presentation of the writer's proposed classification (Table II) incorporates satisfactorily certain helpful suggestions made at the Brussels Assembly of the International Union of Geodesy and Geophysics, notably by NEUMANN VAN PADANG.

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TABLE I

Current classifications of volcanism that involves the production of incandescent gas-generating eruptive avalanches or tuff-flows

LACROIX 1930	ESCHER 1933	NEUMANN VAN PADANG 1933	COTTON 1944 (Includes andesitic, dacitic and rhyolitic eruptions)	
Nuées ardentes	*Eruptions & nuées ardentes*	*Glowing clouds*	*Eruptions*	*Nuées ardentes*
Nuée ardente peléenne d'explosion dirigée	Pelée type (Discharged glowing cloud)	—	Pelean variant. Horizontal or oblique explosive discharge from flank of dome (tholoid) in volcano crater.	[Only second-order (non-voluminous) nuée ardente admitted].
Nuée ardente peléenne d'avalanche	—	—	Pelean variant. Horizontal or oblique mild explosive discharge from flank of dome (tholoid) in volcano crater.	Second-order (non-voluminous) nuée ardente.
	—	—	As above, with still milder explosive discharge.	Block and ash flow (PERRET)
	Merapi type (Glowing avalanche with glowing cloud)	Glowing cloud formed by lava avalanche	—	—
Nuée ardente vulcanienne	St. Vincent type (Vertical eruption with glowing cloud)	Glowing cloud formed by volcanic explosion	Pelean variant. Vertical explosive discharge from open volcano crater.	First-order (voluminous) nuée ardente
Nuée ardente du Massif du Katmai	—	—	Pelean variant. (Katmaian type: FENNER, 1937). Vertical explosive discharge from fissures.	First-order (voluminous) nuée ardente

TABLE II

Proposed classification of volcanism that involves the production of incandescent gas-generating eruptive avalanches or tuff-flows

ERUPTIVE MECHANISM	ANDESITIC OR DACITIC MAGMA		RHYOLITIC MAGMA	
	Type of nuée ardente eruption	Caracteristics of nuée ardente	Type of incandescent tuff-flow eruption	Caracteristics of incandescent tuff-flow
Lateral disintegration of exposed flank of dome (tholoid) in volcano crater.	Avalanche of domal disintegration. *(Merapi lateral disintegration type).*	Gas evolved from pores in blocks.	—	—
Lateral discharge, by mild explosion, from exposed flank of dome (tholoid) in volcano crater.	Discharged domal avalanche. *(Pelée discharged lateral type).*	Carries some large blocks: debris generates gas. Becomes a “ block and ash flow „ (Perret), with small blocks preponderant, when initial explosion approaches zero.	—	—
Lateral discharge, by violent explosion, from exposed flank of dome (tholoid) in volcano crater.	Directed domal avalanche. *(Pelée directed lateral type).*	Carries some large blocks: debris generates gas.	—	—
Vertical explosive discharge from domal area of volcano crater containing a tholoid.	Vertically initiated domal nuée ardente *(Pelée vertical type).*	May carry no large blocks: debris generates gas.	—	—
Vertical explosive discharge from open (domeless) crater of a volcano.	Vertically initiated crateral nuée ardente. *(St. Vincent vertical type)*	Carries no large blocks: debris generates gas.	Tuff-flow vertically initiated from volcano crater. *(Mount Katmai tuff-flow type).*	Essentially fine-grained gas-generating pumice-tuff.
Vertical explosive discharge from low-level volcanic vent at head of a valley, and possibly from adjacent fissures.	—	—	Tuff-flow vertically initiated from small volcanic vent, and possibly from adjacent fissures. *(Novarupta tuff-flow type).*	Essentially fine-grained gas-generating pumice-tuff; deposit confined to a valley.
Vertical explosive discharge from innumerable fissures.	—	—	Tuff-flow vertically initiated from widely distributed fissures. *(Concealed fissure-orifice type).*	Essentially fine-grained gas-generating pumice-tuff; deposit covers up the hypothetical fissures.