Ignimbrite Bibliography and Review

by

E. F. COOK

State of Idaho
ROBERT E. SMYLIE, Governor
Idaho Bureau of Mines and Geology
E. F. COOK, Director
IGNIMBRITE BIBLIOGRAPHY AND REVIEW

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LEFT: Thin, highly welded, vitric ignimbrites in southern Twin Falls County, Idaho. RIGHT: A feature that distinguishes such ignimbrites from lava flows is the abrupt downward gradation from highly welded, dark, glassy tuff to nonwelded, pulverulent, light-colored ash.

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INTRODUCTION

In recent years, many rhyolitic and dacitic volcanic sheets, including some in Idaho, have been recognized as ignimbrites instead of the lava flows they were formerly thought to be. As their true nature is revealed, the great usefulness of ignimbrites in structural and stratigraphic studies becomes apparent. Ignimbrites are the object of an increasing amount of research.

To help the geologist seeking references on ignimbrites, an Ignimbrite Bibliography was prepared and published in August 1959 as Information Circular No. 4 of the Idaho Bureau of Mines and Geology. R. L. Smith (1960, p. 799) called it "nearly complete"; but more than 75 papers that should have been included did not appear in Information Circular No. 4. The incompleteness of the 1959 bibliography and the publication in 1959-61 of some 140 papers qualifying for inclusion prompted the present revision, which again, in all probability is only "nearly complete."

The text has been expanded into a brief review of the literature. In writing this review, I assume that you, the reader, will have read the comprehensive papers by Smith (1960) and by Ross and Smith (1961), or will have them available. Because Ross and Smith competently and thoroughly explain the development of present-day concepts of the origin of ash-flow tuffs (ignimbrites), I cover the same ground quickly, but with side excursions to consider the development of ideas about volcanic rocks in areas of the world of exceptional historic interest to students of ignimbrites. Because Ross and Smith clearly and completely describe the criteria for recognition of ignimbrites, I ignore that subject. Since these two excellent papers appeared, there have been two conferences on ignimbrites, one in Moscow (USSR) in April 1961 and one in Italy in September and October 1961. Some of the new information and new ideas presented at those conferences are included in this present review.

Some students of these interesting rocks--especially some American students--do not accept ignimbrite as a useful term. In light of the nomenclature controversy that exists, objectivity would require that this circular be titled, "Bibliography and Review of Literature on Nonsorted Sheet-like Volcanic Rock Units, Some of Which Grade from Tuff into Lava-like Rock, and of the Eruptive Mechanisms by Which They May Have Formed."

To save the patience of other bibliographers, to avoid whichmires / in title and text,

and because of personal preference, I have used ignimbrite in the title to represent all rocks that have been identified as welded tuffs, ash-flow tuffs, glowing avalanche deposits, or ignimbrites.

HISTORICAL OUTLINE

Development of the nuée ardente-ignimbrite concept

Dr. Zirkel thought the pumice fragments in the Nevada rhyolite he was studying under his microscope were welded together. He said so, 2/ thus becoming the first geologist to use the word welded in the description of a rock type whose origin has become a subject of increasing interest and controversy in the ensuing 85 years. Strangely enough, the welded pumice fragments, the microlenticular structure, and the shivered crystal fragments that Zirkel so clearly described in the Nevada rhyolites collected during the Fortieth Parallel Survey seem to have aroused no suspicion in his mind that he might not be dealing with flow rocks, despite the fact that several years before he had noted both tuffaceous and flow features in some New Zealand rhyolites. 3/

It remained for J. P. Iddings, 4/ again using the word welded, in his descriptions of Yellowstone rhyolites, to formulate the first clear hypothesis 5/ designed to explain the presence of both pyroclastic and liquid-flow features in a single rock unit. This he did by supposing that a gas-charged lava flow under certain conditions might vesiculate so violently at and near its surface that it would form glass and pumice fragments which thereafter might be compressed while yet hot enough to fuse or weld together. In

2/ Zirkel, P., 1876, United States Geological Exploration of the 40th Parallel, v. 6, Microscopical Petrography, p. 267.


5/ Abich in 1882 had already put forward a froth-flow hypothesis for the Armenian tufflavas. Even earlier, von Frisch and Reiss (1868, Geologische Beschreibung der Insel Tenerife, p. 420-422) had attempted to explain the eutaxitic structure and foreign fragments in some Canary Island rocks as the result of partial remelting of a tuff or agglomerate.
what appears at first glance to be a restatement of this hypothesis, ten years later, 6/ Iddings omitted the vesiculating flow idea, proposing merely that hot glass fragments may fall together and become welded into a mass that may then flow and harden into a firm rock. The change is perhaps significant in view of the great volume of literature which had appeared in the intervening decade on the nuee ardente eruptions of Mont Pelée in Martinique.

The Pelée outbursts provided geologists with a possible explanation of the puzzling features of those volcanic rock units which seemed to grade from lava rock into tuff and which, locally or overall, shared the characteristics of both rock types. 7/

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7/ For interesting descriptions of rocks which were later interpreted as ignimbrites, see:


Within a few years following the Martinique eruptions, 9/ rocks in Wales (Dakyns and Greenly, 1905), France (Boule, 1905; Glangeaud, 1918), Germany (Völling, 1910), Japan (Yamasaki, 1911), and Italy (Zambonini, 1919) were interpreted as deposits of Peléan origin.

Many geologists remained unwilling to extrapolate the Peléan phenomena to cover the origin of large rhyolite and dacite sheets. After the interpretation in Peléan terms of the Katmai "sand flow" by Fenner (1920, 1923), however, realization began to spread that puzzling features of the large acidic sheets might be explained by a nuée origin. In New Zealand the sheet rhyolites of North Island were named ignimbrites (fiery rain cloud rocks) by Marshall (1932, 1935) who assigned a Katmai eruptive origin to them. 9/ Interestingly, Marshall was preceded in such an interpretation by Ferrar (1931), who cited the Katmai parallel, and to some extent, by Henderson 10/ who, in 1913, had described a rock unit with flattened glass lenses in which the smaller fragments were fritted together, as well as by Morgan 11/ who had suggested that the peculiar features of this same rock type "are best explained by supposing that the individual fragments were all extremely hot, and semi-viscous, or in part quite viscous, when they fell."

9/ Although descriptions of the nuées ardentes of Mt. Pelée obviously stimulated geologists throughout the world into a re-examination of ancient pyroclastic deposits, it is interesting to note, as Fenner (1923, p. 65) did, that an excellent description of such an eruption had long been in print. Theodor Wolf in 1878 described lava boil-over the crater of Cotopaxi in Ecuador, "like the foam from a boiling-over rice pot" (Der Cotopaxi und seine letzte Eruption an 26 Juni 1877: Neues Jahrb. Mineralogie, Geologie u. Paläontologie, p. 113-167).

9/ Earlier, Marshall (1929, Building stones of New Zealand: New Zealand Dept. Sci. Indus. Research Bull. 11, 1. 31) had described a vitric tuff of the Waikato district as "mainly formed by minute fragments of glassy rhyolite which were ejected by the explosion of steam in melted volcanic rock and fell back to the ground while still hot and united together sufficiently to form a moderately compact rock."


The early (1905–1919) publications on rocks interpreted as Peléan or nuée ardente deposits were all in foreign publications, most of them not readily available to American geologists. Related stimulus for recognizing such deposits in the United States, as in New Zealand, was given mainly by Fenner’s series of papers (published in the U. S., beginning in 1920) on the Katmaián “tuff flow,” but also by the arrival of Howel Williams at the University of California; Williams, fresh from work on the Snowdon volcanics of Wales, brought a new approach to the explanation of American pyroclastic deposits. From the University of California, in subsequent years, came one of the most comprehensive and informative papers on a nuée ardente deposit yet written (Gilbert, 1938), as well as the first stratigraphic use of a known ignimbrite to correlate widely separated rock series (Anderson and Russell, 1939).

Throughout the Western United States, the 1930’s were the pioneer decade of ignimbrite study. C. S. Ross (1931) reported briefly on the ash-flow deposits of the Valles Mountains in New Mexico; Moore (1934) recognized pumice-flow deposits near Crater Lake and published size-analysis histograms that illustrate the striking contrast in sorting between deposits of pumice flow and those of pumice fall (in the same year, Kozi distinguished between pumice-flow and pumice-fall deposits at Komagatake in Japan, and Richards and Bryan recognized the Brisbane tuff of Australia as an ignimbrite); Fuller (1935) described welded pumice in Oregon; Mansfield and Ross (1935) found highly welded tuff extending over a considerable part of southeast Idaho and Fenner (1936, 1937, 1938) recognized welded tuff in the Yellowstone Park rhyolites. In 1940 Lonsdale made the first published mention of welded tuff in west Texas.

Since 1940 ignimbrites have been recognized in every continent except Antarctica. They are believed to be abundant on the Moon. They are known to range in age from Precambrian to Recent.

Most students of ignimbrites believe them to have been formed by deposition from a hot, rapidly expanding, turbulent, highly mobile, magmatic gas “cloud” which carries with it intratelluric crystals, liquid droplets of the exploding magma (and the resultant glass shards), as well as rock fragments torn from the walls of the vent or picked up from the ground surface. At least the lower part of such a gas “cloud” consists of a density or turbidity current, which carries by far the greater part of the solid and liquid matter, and from which rises a continuously dissociating cloud of gas and fine particles. The competence of this density current to carry material in suspension depends on turbulence and density. In the lower-order nuées such as the block-and-ash flows of Perret, turbulence decreases, but density greatly increases; thus suspension competence is maintained.

The turbulence of a density current depends on its velocity and the amount of dilution by additional fluid. Both laboratory experiment with aqueous density currents and observation of dust storms have shown that “mixing across the interface is rarely
Although dilution in a nuée may take place by emission of gas from suspended particles, it is probably true that turbulence, and therefore suspending power, “is influenced chiefly by velocity” (Bell, 1942, p. 5). As a nuée spreads to fill depressions, its velocity decreases and material can no longer be kept in suspension. Rude sorting in some ignimbrites indicates a relatively slow velocity decrease; but in other ignimbrites lack of sorting suggests that the solid, plastic, and liquid components of the nuée were suddenly left unsupported and they collapsed together without much opportunity to segregate according to size and density.

Suspension competence, defined as the quantity of material that can be carried in a nuée, depends mainly on turbulence which in turn is a function of velocity; but defined as the maximum size of particle that can be carried in a nuée, it will probably depend to a great extent on density—blocks and lapilli are carried, in other words, only if there is a large amount of ash in suspension.

Alternative, liquid-flow hypotheses

The principal opposing hypotheses of origin for ignimbrites invoke either (a) highly gaseous and/or pumice-charged lava flows, or (b) nonhomogenized lava flows. These ideas are briefly reviewed by Smith (1960, p. 809) who concludes that “the evidence from published studies of welded tuffs overwhelmingly favors emplacement by avalanche or flowage of fragmented material and hot gas. None of the other proposed mechanisms has been convincingly demonstrated even for a minor deposit."

Neither Smith (1960) nor Ross and Smith (1961) cite the recent Russian publications on "tufflavas" or Steiner’s (1960) paper on his concept of the origin of the New Zealand ignimbrites.

Vladavets (1953) proposed that "tufflava" from the River Semyachkinsk in Kamchatka was formed as a result of subterranean explosion in the magma chamber producing an incomplete mixing of two slightly differentiated magmas, a mixture subsequently extruded as a lava flow in which one magma was discontinuously distributed as drawn-out clots, lenses, and fibers in the other. Favorovskaya (1956a, 1957b) favors a lava-flow origin for similar rocks in the Sikhote-Alin region of eastern Siberia; she holds that parallel lenticular inclusions represent flattening of plastic fragments in a viscous flowing mass. Vladavets (1957) contends that acid lavas are not necessarily viscous, and that a small increase in water content of a magma markedly decreases its viscosity and increases its fluidity. He suggests that "tufflavas" are special lavas that may form:

Dark, glassy, parallel discoids mark the ignimbrite rock type called "wilsonite" by Marshall. Note the absence of lineation in the plan view (top). The discoids represent material flattened during compaction, not stretched during flowage. Photos of "wilsonite" from the Bishop Tuff, California.
(a) by magmatic differentiation and simultaneous eruption of a mixed, nonhomogenized lava; (b) from banded lava; (c) from lava inflated into foam (frost flows). The consensus of the Russian group who met in Moscow in the spring of 1961, as reported by Vladovets at the Catania symposium of the International Association of Volcanology in September 1961, was that ignimbrite and tuff lava should not be considered synonyms, but as representing rocks of two different origins that may be distinguished by field and microscopic criteria. Dissatisfaction with tuff lava as a term was expressed; the term clastolava was proposed to replace it. From the papers presented at the Moscow meeting, however, it appears there was considerable disagreement on what the term tuff lava encompasses. For example, Shirinian (1961) in Armenia, recognizes as tuff lavas only those rocks that contain large pumice inclusions in a lava-like, finely vesicular groundmass (a specimen of this rock sent to me by M. Favorusky has lineation and a porous, fluidal structure; it resembles the froth-flow dacite of the Pine Valley Mountains in southwest Utah—see Cook, 1957, p. 58). Shirinian regards the "flame" tuffs, those that contain compact black inclusions of glass, as true ignimbrites. Since these "flame" tuffs are similar to the rocks described by Vladovets (1953) and Favorusky (1956a, 1957b) as tufflavas, there appears to be yet room for accommodation among individual concepts in the USSR.

Steiner (1960) holds that ignimbrite magma has the inherent property to split into two immiscible liquids when extruded on the surface and that the glass shards in an ignimbrite represent one of these immiscible liquids, and that the mesostasis or glassy groundmass in which the shards are embedded represents the other liquid. His evidence is that the shards and the mesostasis differ in their refractive index.

**Piperno**

A rock exposed in the Phlegrean Fields near Naples, characterized by conspicuous lenses or discoids (fiamme) of black glass is locally known as piperno. It appears to be an extreme form of the lenticulite (welded tuff with black glass discoids) that Marshall called owharoite or wilsonite. Because of its singular appearance the piperno has been much discussed. Early workers considered it of lava-flow origin. But Dell’Erba, in a classic paper, concluded that the rock was a tuff instead of a lava. Zambonini (1919) was the first to invoke a "Pelean cloud" origin for piperno. Although Zavaritsky (1946a) suggested that the fiamme are collapsed and strongly welded pieces of pumice, that interpretation is disputed to this day, as it is for the similar glass discoids of the Armenian flame tuffs. Rittmann (1944, p. 92-93; 1950, p. 139-142; 1960, p. 94-97) holds that the fiamme are chilled clots of trachytic magma thrown out by a volcano in lava fountains. Thus, although the piperno, which has a welded-ash matrix, may be called welded tuff or welded tuffbreccia, it is, in his mind, not of ash-flow or nuée-ardente origin, and therefore a sheet of piperno might not properly be called an ignimbrite. On the Island of Ischia

there are also banks of piperno which, according to Rittmann, are made essentially of flattened and welded pieces of lava thrown out of a lava lake in lava fountains while the pieces were still liquid. Ross and Smith (1961) appear to agree with Zavaritsky that the piperno is a type of welded tuff. So the problem of the origin of piperno is not settled.

The Armenian tuflavas

The volcanic rocks of Armenia, especially those in the vicinity of Mt. Aragatz (or Alagez), have long been of interest to geologists. Abich, in 1882, described these as "a class of very similar rocks which lie between tuff and lava." He visualized rhyolitic magma changing gradually, upon extrusion, into "a porous, almost frothy condition with long, rifled pores and fibrous structure and without anywhere a visible break in the continuity of the more and more elongated stream. The end result of the process is a tuff-like rock which appears in frothy masses."

Zavaritsky (1946a) described the Armenian tuflavas (or tufolavas) as ordinarily horizontal, without bedding, and commonly with pronounced jointing. "They enclose lenticular or flattened patches of dark material, usually glass embedded in a lighter matrix. The dark inclusions do not show any elongation viewed in plan. Fragments of pumice are collapsed in streaks." Zavaritsky (1947) explained these tuflavas by assuming they were deposited by glowing clouds of Katmai type in a state of incandescent, glassy, volcanic ash mixed with lava patches. He described the most intensely welded varieties as a streaky kind of rock, its primary pyroclastic texture being entirely destroyed because of complete welding and some crystallization.

The puzzling feature of these two accounts is not that the authors came to different conclusions, but that they seem to have described two different groups of rocks.

The first light I had on this problem came when I received two "ignimbrite" specimens from Armenia. One was a compact "flame" tuff, the other a porous pumice-like rock with linear vesicles. The first specimen fits Zavaritsky’s description and concept of origin; features of the second accord with Abich’s picture. Now, with the publication of Shirinian’s recent papers (1958a, 1958b, 1961) it becomes clear that there exist in Armenia ignimbrites of several different types, as well as porous or frothy "tuflavas."

Shirinian recognizes three varieties of ignimbrites in Armenia:

(1) the Erevan-Leninakan type, consisting of ash tuff,

(2) the flame type, containing compact black glass inclusions embedded in a lighter-colored groundmass of vitric texture; the inclusions represent "the remains of glowing liquid lavas,"

(3) pumice ignimbrites.
He distinguishes tufflavas from any of these ignimbrites by the "lava-like, finely porous glassy structure" of the tufflava and its lack of vitroclastic texture; he describes tufflava as "this extremely porous lava mass" in which there are inclusions of pumice-cinder lapilli and small quantities of fragments of other rocks (Shirinian, 1958, p. 127). The Armenian tufflava, as defined by Shirinian, has been previously called the "artiksk-type" tuff or tufflava. Shirinian finds gradual transition from ignimbrites to tufflavas, and from tufflavas to typical lavas. Such transitions are of great significance, for the question of whether a flowing lava can give rise to a nüe is still highly debatable, because of the absence of evidence in observed eruptions, as well as in most ancient deposits.

**The Bolzano porphyries**

The narrow valleys of the Alto Adige in northern Italy are cut deep into a massive porphyry platform, above which rise the jagged, snow-capped Dolomite Alps. The platform consists of Permian volcanic rocks; in places it is well over 3,000 feet thick; it underlies at least 1,600 square miles. Generally, the whole volcanic sequence has been described as an alternation of lavas and pyroclastic materials. The sequence is somewhat difficult to separate into rock units; in a descent across the porphyry platform a short distance west of Bolzano I found only one exposed contact, although lithologic changes suggested four units. Several units are clearly exposed along the twisting road that climbs from Ponte Gardena to Castelrotto (Mittemperger, 1958).

The literature on these Permian volcanic rocks around Bolzano is voluminous. Many efforts have been made to arrange the information into a stratigraphic sequence or system. Division into a lower, dark, trachyandesitic tuff-and-flow series and an upper quartz-porphyry series is clear. Stratification or flow structure within units of the porphyry series has rarely been reported. From a distance a faint stratification may be reflected in topographic breaks and vague color changes on hillsides; if these do represent breaks between depositional units, those units are layers over 300 feet thick.

Mittemperger (1958) concluded that the upper layers of the porphyry platform consist of ignimbrites. The older ignimbrites are quartz latites, the younger ones are rhyolites. In addition to petrographic criteria, Mittemperger cited the considerable thickness and extent of individual porphyry sheets, their low dips, and acid composition as evidence in support of his conclusion.

In rebuttal Andreatta (1959) maintained that the porphyries are lavas which locally are rich in inclusions incorporated by "engulfment" and which have produced gradational contacts with true tuff lenses by a process of "reheating, refusion, and slow homogenization." He also contended that lateral variations in composition are far greater and more abrupt than Mittemperger implied.
Pichler (1959) likewise was unconvinced. He noted that the tuffs are certainly compact, but show, in contrast to ignimbrites, no required "flow" texture, nor are they of fine structure, nor do they show a strong prismatic jointing. Among the quartz porphyries, he saw no rocks that met the conditions Marshall set up for ignimbrites.

Maucher (1960), however, reporting on the 1959 excursion of the German Geologische Vereinigung to the South Tyrol, recognizes the existence of ignimbrites in the upper or younger "cycle" of the Permian platform, but contends that just how many ignimbrites or how much ignimbritic material exists in the upper part of the platform must await the clarification of the definition of ignimbrite and the establishment of criteria for the recognition of ignimbrites.

Dietzel (1960), van Hilten (1960), Agterberg (1961), and van Bemmelen (1961) hold that the quartz porphyries are ignimbrites. Vardabasso, who did much mapping in the Bolzano region, now recognizes that he mapped some ignimbrites in the Bolzano porphyry platform (written communication).

D. A. White (written communication) observes that the Bolzano porphyries are almost identical to North Queensland ignimbrites. He suggests that the whole succession west of Bolzano (about 3,000 feet thick) may be a single cooling unit consisting of three or four ash flows. I can only agree with him. The one contact I found in that section has welded tuff both above and below it. Near the base of the sequence there is a layer of highly welded tuff with parallel dark lenses and wisps (flattened pumice?). Nowhere in the sequence is there any zone that looks like a devitrified glass zone, nor is there any loose ash. The appearance is that of a few thick nües or ash flows erupted in quick succession, the deposited layers cooling together in one great mass.

Accordi believes the Bolzano eruptions were limited to a roughly circular volcano-tectonic depression or cauldron. The volcanism is considered as the volcanic aftermath of the hercynian era of mountain building (Bemmelen, 1961).

NOMENCLATURE PROBLEMS

Eruptive mechanism

The hot gas-ash emulsions that have produced ignimbrites have been called nuées ardentes, sand flows, tuff flows, glowing avalanches, pyroclastic flows, and ash flows. Of these the term most used in the literature is nuée ardente—and its equivalents: glowing cloud, nube ardente, Glutwolke.

It is generally recognized, however, that the geologically important feature of such an eruption is not a cloud. As Ross and Smith (1961, p. 6) point out:

Usage has not always differentiated between the clouds themselves and the dense ash- or block-and-ash-transporting basal part. If so used, this basal part would constitute the noncloud portion of a glowing cloud, which may not even be glowing. In general it glows only by reflecting the incandescent underlying ash flow.

Ross and Smith contend that the term nuée ardente has led some geologists into the error of visualizing the ash in such eruption as strictly airborne; this misconception, they say, has "beclouded the whole approach." Following Smith (1960), many geologists in the United States now use ash flow in place of nuée ardente, when they speak of the emplacing mechanism.

Logical as the reasons for abandoning nuée ardente are, they lose some force if we allow that the concept of the eruption and transporting mechanism is now so clearly defined that it seems improbable that any geologist will be led into error by the term—in other words, the approach is no longer "beclouded." As for the term ash flow, it seems subject to question on these grounds: that the flow itself is a gas flow; that the material borne by the gas may include a large amount of lapilli and even blocks in addition to ash; and that there is a different kind of ash movement to which ash flow might be more appropriately applied.

Ash flows that were composed essentially of solid material cushioned and lubricated by a minor amount of gas, have been described and probably account for some deposits of modest dimensions in the immediate vicinity of volcanic vents. Such ash flows at Vesuvius were clearly described and analyzed by Lacroix (1908) who called them avalanches sèches, and who pointed out the distinction between such avalanches and nuées. The avalanches sèches or ash flows originate as backfall of solid material from vulcanian clouds onto slopes down which the ash rushes, impelled only by gravity. The resulting deposits, according to Lacroix, show a rude bedding, even cross-bedding. Similar ash flows may be initiated on unstable slopes of volcanic ash by shock.

Both Aramaki (1957) and van Bemmelen (1961) would restrict the term nuée ardente—Aramaki to eruptions of high magma viscosity, van Bemmelen to eruptions of
strictly Pélégan character-central vent eruptions in which the nüees are relatively small and cool. Both use pyroclastic flow, Aramaki for eruptions intermediate between his nüees and pumice flows, van Bemmelen for the eruptive mechanism that results in an ignimbrite (in the sense of an extensive, at least partially welded, sheet. There is certainly no accord on (a) whether nüée ardente should be used, or (b) if used, what it means.

Rock units

Rock-unit terms in the literature. --Sheet-like pyroclastic deposits of probable nüée ardente origin have been called sand flows (Fenner 1920); tuff flows (Fenner 1948; Erickson 1953); ash-flow tuffs (Ross and Smith 1961); welded tuffs (Mansfield and Ross 1935; Gilbert 1938; Mackin and Nelson 1950; Barksdale 1951; Enlows 1955; tufflavas (Zavaritsky 1946, 1947); glowing avalanche deposits (Williams 1957); and ignimbrites (Marshall 1932, 1935, 1953; Westerveld 1943; MacGregor 1946; Zavaritsky 1947; Osborne 1950; Solovev 1950; Mackin 1952, 1960; Bouladon and Jouravsky 1954b; Cook 1955, 1960a, 1960b; Hjelmqvist 1956; Jenks and Goldich 1956; Roberts 1956; Francis 1959; Mau 1959; Aprelkov 1961; Shirinian 1961; Vlodavets 1961; Weyl 1961a).

Only three of these terms are now in common use for nüée deposits: ash-flow tuff (or ash-flow sheet); welded tuff; and ignimbrite.

Ash-flow tuff or ash-flow sheet -- As defined by Ross and Smith (1961, p. 3), "ash-flow tuff is an inclusive general term for consolidated ash-flow beds that may or may not be either completely or partly welded." It is primarily a rock-type term; Smith (1960a, p. 800) proposes ash-flow sheet for "any unspecified sheetlike unit or group of units considered to be of ash-flow origin." Use of these terms commits one to accept ash flow for the eruptive mechanism, and may lead to designation as an ash-flow sheet of a rock unit that is composed of tuffbreccia.

Welded tuff -- Welded tuff, widely used as a rock-unit term, is primarily a rock type term. Because many if not most nüée deposits are partially nonwelded, it seems illogical to speak of such rock units as welded tuffs. Oliver in 1954 pointed out that some recognized welded tuffs are part only of a deposit which is essentially nonwelded and cited the Bishop Tuff (Gilbert, 1938) as an example. Fenner in 1948 had already suggested that welded tuff be restricted to those nüée deposits which are welded and proposed sillar for those which are not. Jenks and Goldich (1956) in a paper on the phyllitic tuff flows in southern Peru support Fenner by proposing that "sillar may be used to describe all ignimbrites which show no obvious welding or refusing of glass shards," and they point out that none of the Peruvian ignimbrites they studied are welded. As rock-unit terms welded tuff and sillar represent extremes; most nüée deposits fall between.
Ignimbrite redefined -- In his first description of the New Zealand ignimbrites Marshall (1932, p. 200) wrote:

The actual method of eruption was probably similar in its general nature to that described by Fenner as associated with the sand flow at Katmai.... Fenner describes the eruptive material there as similar to ignited fine carbonate of magnesia which flows like a liquid. Lacroix compares its condition with that of milk when boiling over, and considers the eruptive matter to have been a type of nuée ardente. The type of rocks formed in this way varies greatly, but it is suggested that they should all be included in a separate group, for which the name "Ignimbrite" seems satisfactory.

As Marwick (1946) pointed out, this original definition refers not to the size of ejecta nor to the degree of welding nor to composition; consequently, ignimbrite may be applied to tuffbreccia (of nuée origin) as readily as to tuff and to partially welded or nonwelded deposits as well as to completely welded ones.

Perhaps unfortunately, Marshall's redefinitions (1935, p. 1, p. 38) appear to require ignimbrites to be acid, tuffaceous, and welded. These restatements led logically to the conclusion that ignimbrite equals welded tuff. 15/

Marshall made no distinction between rock unit and rock type; he used ignimbrite for both, as have many later authors. As a rock-type term ignimbrite is unnecessary. But redefined as a rock unit (Cook, 1955, p. 1544; 1957b, p. 197-198; 1960a, p. 134; Mackin, 1960, p. 84-86), freed of the welding, size-range and composition restrictions that Marshall appended in 1935, it can be very useful. Ignimbrite would then be defined as "a mappable, sheet-like deposit of relatively nonsorted and nonstratified pyroclastic material, of probable nuée ardente origin." Steiner (1960, p. 10) has even proposed that the genetic connotation might profitably be removed and ignimbrite used as a descriptive term.

Ignimbrite, thus redefined, is not equivalent to welded tuff, but is equivalent to the "ash-flow sheet" or "cooling unit" of Smith (1960a, p. 800-801). As end members, ignimbrite includes sills and welded tuff (both are rock-type terms which may be used as rock-unit terms when the sheet or ignimbrite is dominantly composed of one or the other). Beavon, Fitz, and Rast (1961) use essentially this same nomenclature.

Sillar or nonwelded tuff, nonwelded tuffbreccia (Ross and Smith, 1961, p. 5) for the nonwelded material and welded tuff, welded tuffbreccia, and welded breccia cover the range of rock types found within ignimbrites. Adjectives to indicate the composition and degree of welding may be added to these basic rock names.

Even in the seemingly simple matter of the nomenclature of pyroclastic rocks according to size and physical composition we find problems. The several classification schemes for pyroclastic fragments and rock names are reviewed by Fisher who (1) proposes that the limits of lapilli be reset at 2 mm and 64 mm to equate pyroclast terminology to sediment terminology; (2) points out that there is no word for a rock composed mainly of lapilli and proposes lapilli-limestone; (3) limits volcanic or pyroclastic breccia to a rock with fragments mainly over 64 mm (the AGI Glossary, following Wentworth and Williams, uses 32 mm; at least one current textbook uses 4 mm; and Fisher cites a 1959 proposal to make the lower limit 2 mm); and (4) defines lapilli tuff as a rock formed of nearly equal amounts of lapilli and ash, "analagous in use to tuff breccia."

Because many pyroclastic rocks are made up of lapilli or lapilli and blocks in an ash matrix, a name (or names) is needed. Lapilli tuff, restrictively limited by Fisher and loosely defined (as an indurated pyroclastic rock essentially made up of lapilli in a fine tuff matrix) by Wentworth and Williams, may be useful but it depends on two size limits that vary from author to author, and does not take into account the tuff that contains abundant blocks; in addition, it is isocogenic, analogous to "pebbles-sandstone." At least until pyroclastic nomenclature settles into a recognized classification, tuffbreccia (or tuff breccia), defined as a rock composed of abundant lapilli or blocks or both, in an ash matrix, can be a useful term.

Although the Wentworth and Williams classification of tuffs as vitroic, crystal, or lithic, according as most of the particles are glassy, crystalline, or stony may be applied to ignimbrite rocks, a modification of their classification has been found useful. All three elements are important in the constitution of ignimbrites and it might seem that a classification should give equal weight to each, as the Wentworth and Williams definitions do. In field recognition of ignimbrites, however, lithic fragments commonly have greater importance.

16/ To designate the rock formed by a froth-flow, Gabor Pantó, at the Catania symposium in September 1961, proposed the term "foam lava." This would be equivalent to tufflava (or tuflava) as described by Shirinian (1961) but not to tuflava as described by other geologists. Later, Pantó (written communication) suggested "ignispumite," certainly more appropriate for a rock type.

The southern portion of the Potosi Range in central Nevada is built exclusively of flat-lying iphidolerite, the eroded appearance of which may have given the Range its name. These layered iphidolerites lend themselves readily to geologic mapping and stratigraphic measurement.

Photomicrographs. LEFT: Vitreous texture in a moderately welded, crystal tuff (Harney Hills Tuff, southwest Utah); note angular glass shards, and the elongated, flattened quartz crystals. RIGHT: Fluidal structure in a fresh flow (Bunker Formation, southwest Utah); solid glass containing small crystals lies between the many drawn-out swirled vesicles.
than their actual percentage would indicate; for example, there are ignimbrites containing 10-15 percent of lithic fragments in which those fragments are a striking and characteristic element. Consequently it has been suggested (Cook, 1960b) that the lithic component be given greater importance than the other two and that lithic enter the name whenever rock fragments make up more than 10 percent of the rock. In ignimbrite rock types, it is only possible to apply the lithic adjective accurately if the pumice fragments, which may undergo a great change in volume vertically within an ignimbrite are regarded as vitric rather than lithic.

In addition, because the crystalline content of ignimbrites rarely exceeds 50 percent, it has been proposed that crystal enter the name at 10 percent and that a rock containing more than 50 percent crystals be called crystal. A triangle illustrating these limits has been published (Cook, 1960b, p. 33).

Wargo also solved this problem by means of a triangle, but with different limits.

**Rheoignimbrites**

Ignimbrites that develop secondary flowage because of their high temperature and because they come to rest on a slope, have been called **rheoignimbrites** by Rittmann (1958). According to Smith (oral communication), laboratory experiments make it seem probable that such post-depositional flowage is restricted to vitric tuffs. Some thin, highly welded vitric ignimbrites in southern Twin Falls County in Idaho (see title page for illustrations) show lineation and contorted banding; they might be called rheoignimbrites, although it is questionable whether this new term should be applied to units that show only local contortions of compaction structures and restricted development of flow banding. Perhaps rheoignimbrites should be those ignimbrites whose basal portions became rather thoroughly homogenized and mobile, as inferred by Rutten and van Everdingen (1961) for certain Norwegian rock units.

**STRATIGRAPHIC AND STRUCTURAL USE OF IGNIMBRITES**

Ignimbrites can have regional extent. In the Basin Range province individual ignimbrites have been recognized over distances greater than 100 miles (Cook, 1958) and some of these ignimbrites have an extent of as much as 10,000 square miles (Mackin, 1960).

Extensive ignimbrites are valuable stratigraphic markers because each depositional unit was probably formed almost simultaneously (at least in the geologic time perspective) over its entire extent, by dissociation and compaction of solid, plastic, and liquid material from a nüe (or a series of closely spaced nüées) which moved with great speed from the eruptive vent or vents. Since, in addition, ignimbrites contain radioactive pyrogenic minerals such as K-feldspar and biotite, whose age can be determined, they may be used to calibrate historical events.

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Judged by the character of extensive ignimbrites of inferred nuée origin as well as from observations of small "glowing clouds", a nuée has great mobility, following and filling depressions like a flood of water. It follows that the solid, plastic, and liquid burden of each cloud, consisting of crystal and rock fragments and magma droplets, when collapsed together will have depositional horizontality, modified only by differential compaction over topographic highs. Planar structure developed during compaction allows interpretation and measurement of the attitude of each unit just as does bedding in a sedimentary rock.

Because of their rapid formation, their original horizontality, their measurable attitudes, and the possibility of determining their absolute ages, extensive ignimbrites are more useful in structural-stratigraphic studies than are most sedimentary units. But even extensive ignimbrites would be of limited use could they not be correlated from mountain range to mountain range. Stratigraphic work in the eastern Great Basin has proved (for that region, at least) that the limits of variability in physical and chemical properties of ignimbrites as a group sufficiently exceed the limits for any one ignimbrite that individual units may be distinguished one from another and may be correlated in isolated sections throughout thousands of square miles by characteristics that tend to remain laterally constant or predictably variable within a unit (Cook, 1958).

Because they formed with approximately horizontal upper surface, ignimbrites are useful in mapping structure in volcanic terrain or in inferring structure in subjacent sedimentary rocks where the angularity of the unconformity is known.

Graphically restoring faulted and deformed ignimbrites to their original horizontality will, with knowledge of their stratigraphic relations, give a true picture of the prevolcanism topography and geology (Harris 1958), and will serve to distinguish the effects of prevolcanism, intravolcanism and postvolcanism deformation (Cook, 1957b).

SOURCE OF IGNIMBRITE MAGMA

Most ignimbrites represent the eruptions of granitic and granodioritic magmas. But whether these magmas are generated within the granitic layer of the crust by melting, or whether they are differentiated from a deeper-seated, more basic parent magma is a question of great interest.

Many ignimbrites are associated with volcano-tectonic depressions (Bemmelen, 1961; Westerveld, 1947, 1953; Williams and Meyer-Abich, 1953, 1955; Ross and Smith, 1961, p. 17-18) where collapse apparently compensated for extrusion. Collapse of the roof of the magma chamber after evacuation of the magma indicates a shallow magma chamber. Blank 19/ has demonstrated the rupture of the roof of a shallow laccolithic body resulting in lava flows and perhaps nuées ardentes.

Branch (1961), discussing the source of ignimbrites in North Queensland writes:

...granitic magma was probably generated five miles below the surface of the crust by partial melting of the sediments at the base of the Tasman geosyncline.... Magma for the second epoch was derived from melting of the lower part of the granite of the first epoch. Renewed fracturing...formed cauldron subsidence areas and rifts, which were quickly filled with rhyolite and ignimbrite.

Branch points to the absence of contemporaneous basic igneous rocks in the region; he believes sudden release of pressure by faulting caused rapid melting (in the second epoch) of base of the batholith, with the resultant eruption of 700 cubic miles of ignimbrite sheets "in one or several days."

Clark (1960b, p. 128) similarly points to the volcanic rock-type distribution of the North Island of New Zealand as evidence of the shallow origin of the ignimbrite magmas:

In the volcanic belt of the North Island acid eruptives furnish the great bulk of the rocks. Ignimbrite, together with relatively minor rhyolite, probably exceeds 2,000 cubic miles. Less than 10 percent as much andesitic rock is present, and basalts occur in only incidental amount.

It appears unlikely that the large volume of acid eruptives could have resulted from fractional crystallization of basaltic magma. Production by fractionation alone of 2,000 cubic miles of acid lavas would have required some 20,000 cubic miles of parental basalt, and an extremely large ultrabasic complementary differentiate would have been produced--of this there is no evidence.

An hypothesis compatible with the available evidence involves the former existence of two parental magmas underlying the volcanic belt formed by crustal fusion. At depth, a body of basaltic magma; above it, temperature gradient sufficiently steep to fuse, at least partly, overlying sialic rocks...producing an extensive mass of acidic magma.

It is likely that most of the acidic material was emitted as ignimbrite, consequent upon tectonically induced relief of pressure on the magma...

This hypothesis seems as valid for the Great Basin of the western United States as it does for New Zealand.
IGNIMBRITES IN IDAHO

Ignimbrites are widespread in the Tertiary volcanic sequences of the southeast half of Idaho. Most are relatively thin sheets of strongly welded, vitric, rhyolitic tuff.

Mansfield and Ross (1935) found welded tuff in patches in the Ammon and Paradise Valley quadrangles, and in a broad apron at the northern tip of the Blackfoot Mountains. The tuff appeared to have been laid down as a blanket with "surprisingly uniform thickness (20-50 feet)" over hill and valley alike, giving the appearance of material "sprayed or ducoed...over the surface." The Caribou, Snake River, and Bighole ranges all have ignimbrite aprons, as does the west slope of the Teton Range and the south slope of the Centennial Range. Mansfield and Ross (1935) suggested Yellowstone Park as the probable source, for they noted a tendency for the tuffs to be coarser and less well sorted in that direction. These rocks are similar to Pliocene ignimbrites in Jackson Hole, Wyoming.

Pliocene silicic ignimbrites are also found near American Falls, (Stearns, Crandall, and Steward 1938; Stearns and Isotoff 1956), and in the Bellevue quadrangle (Schmidt, 1960). The thin, crystal-poor, highly welded, rhyolitic ignimbrites of the Bellevue area are similar to units in southern Twin Falls County, where Youngquist and Haegele (1956, p. 15) noted "a very thick section of welded tuffs...in the vicinity of Salmon Falls Creek."

Silicic ignimbrites occur in the Oligocene Challis Volcanics. Anderson (1956, p. 22) notes that "Much of the rhyolite and quartz latite of the Challis Volcanics is composed of ignimbrites (welded tuffs)." They generally contain abundant quartz and feldspar and considerable biotite. A specimen from the Yankee Fork member of the Challis Volcanics has been identified as welded rhyolite tuff (Davidson and Powers, 1959).

LIMITS OF THE BIBLIOGRAPHY

Only works published before 1962 in which ignimbrites or nubes ardentes (by these or other names) are specifically mentioned are included in this bibliography. By this criterion many papers of profound interest on deposits later interpreted as ignimbrites are excluded (some have been cited in footnotes), whereas several of considerably less interest, but which contain mention of such deposits, are included. Not included are maps that mention welded tuff or ignimbrites only in their legends. Nor is unpublished material, such as theses, included.
Papers on volcanic mudflows (lahars); 20/ volcanic breccias of vulcanian or of flow origin; airfall or waterlaid tuffs and tuffbreccias are not listed. I have also eliminated popular or semi-popular accounts of the eruptions of Mt. Pele and of the Valley of Ten Thousand Smokes and I have not included theoretical papers on the solubility of water in magmas, on the mechanics of ash formation, and the like, unless they contain specific references to nüees or similar eruptive phenomena.

In summary, this bibliography includes all papers (1961 or older) which have come to my attention on the rocks called ignimbrites, welded tuffs, tufflavas, or ash-flow tuffs, and on the mechanisms by which they are supposed to have been produced.

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20/ For information on volcanic mudflows, refer to the following good papers:


Schmidt, K. G., 1934, Die Schutttströme am Merapi auf Java nach dem Ausbruch von 1930: De Ingenieur in Nederlandsch-Indie, IV. Mijnbouw en Geologie (De Mijningenieur), v. 1, p. 91-120, 123-133, 194-172.


Bell, H. S., 1942, Density currents as agents for transporting sediments: Jour. Geol., v. 50, p. 512-547.


Garder, D. S., 1959, Eruption of March 5-6, 1958, of Manam Volcano off the north coast of New Guinea (abs.): Geol. Soc. America Bull. v. 70, p. 1711-1712.


1957a, Geology of the Pine Valley Mountains, Utah: Utah Geol. and Mineralog. Survey Bull. 58, 111 p.


_1933a_, On a classification of central eruptions according to gas pressure of the magma and viscosity of the lavas: Leid. Geol. Meded., Decl. VI, Afl. 1, p. 45-49.


———1940, Geología de los alrededores de Arequipa: Rev. de la Univ. de San Augustín de Arequipa, Año 14, p. 170-206.


González Bonorino, F., 1944, Nota sobre la presencia de ignimbritas en la Argentina: Inst. del Museo de la Universidad Nacional de la Plata, Notas del museo de la Plata, t. 9, geol., n. 35, p. 577-590.


Kemmerling, G. L. L., 1921, De hernieuwde werking van den vulkaan G. Merapi (midden Java) van begin Augustus 1920 tot en met Februari 1921: Vulcanologische Mededeelingen no. 3, Dienst van het Mijnwezen in Nederlandsch-Oost-Indie.

1932, De controverse uitgeschoten gloedwolken (nuées ardentes d'explosion dirigée) of lawinen gloedwolken (nuées ardentes d'avalanche): De Ingenieur, v. 47, no. 13, p. 129-137.


Marel, H. W. van der, 1941, Onderzoek omtrent het voorkomen van de mineralen orthiet en zirkoon in de liparietgronden van Sumatra's Oostkust: De Ingenieur in Nederlandsch-Indie, IV, Mijnbouw en Geologie (De Mijningenieur), VIII, no. 4, p. 33-38.


Morris, H. T., and Lovering, T. S., 1961, Stratigraphy of the East Tintic Moun-

Murai, I., 1960a, On the mud flow of the 1926 eruption of Volcano Tokachidake, cen-

1960b, Pyroclastic deposits distributed on the east foot of Volcano Myoko:

1960c, Pumice-flow deposits of Komagatake volcano, southern Hokkaido:

1961, A study of the textural characteristics of pyroclastic flow deposits

Murai, I., and Tsuya, H., 1959, Size characteristics of the "Shirasu" deposit dis-
tributed in the southern part of Kyushu Island (in Japanese with English abs.):


Neumann van Padang, M., 1933, De uitbarsting van den Merapi (midden Java) in

1951, Catalogue of the active volcanoes of the world including solfatara

Nikolayev, S. V., 1961, Physico-mechanical properties of some types of ignim-
brites of the Chatalsky-Kuraminsky zone (in Russian): in Tufflavas and Ig-

Oftedahl, C., 1957, On ignimbrite and related rocks: No. 16 of studies of the
igneous rock complex of the Oslo region, Skrifter Utgitt av Det Norske Viden-

Oliver, R. L., 1954, Welded tuffs in the Borrowdale volcanic series, English Lake district, with a note on similar rocks in Wales: Geol. Mag. (Great Britain), v. 91, p. 473-483.


Rittman, A., 1944, Vulcani, attività e genesi: Napoli.

1950a, Sintesi geologica dei Campi Flegrei: Soc. geol. italiana Boll. v. 69, p. 117-128.

1950b, Rilevamento geologico della Collina dei Camaldoli nei Campi Flegrei: Soc. geol. italiana Boll., v. 69, p. 129-177.


Romer, M., 1936, La dernière éruption de la Montagne Pelée: Bull. volcanologique, 8th yr., nos. 27 to 30, p. 89-116.


Ross, C. S., 1958, Welded tuff from deep-well cores from Clinch County, Georgia: Am. Mineralogist, v. 43, p. 537-545.


Rutten, M. G., 1959b, Ignimbrites or fluidised tuff flows on some mid-Italian volcanoes: Geologie en Mijnbouw (N.W.) 21e jr, p. 396-399.


_________1960b, Cuadrangulo Llampos, Provincia de Atacama: Carta Geol. Chile: v. 2, n. 2.


1958b, Main features of latest volcanicity in Armenia: Bull. volcanologique, s. 2, t. 19, p. 116-133.


Stehn, Ch. E., 1935, Volcanic phenomena during the months of October, November, and December 1934: Netherlands Indies Volcanological Survey Bull. n. 70, p. 119-133.


Wargo, J. G., 1958, Structure and volcanic stratigraphy in the Schoolhouse Mountain area, Grant County, New Mexico (abs.): Geol. Soc. America Bull., v. 69, p. 1748.

1959, Sequence of volcanic rocks in southwestern New Mexico (abs.): Geol. Soc. America Bull. v. 70, p. 1754.


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SUBJECT INDEX
GEOGRAPHIC INDEX OF PAPERS ON NUEES AND NUEE DEPOSITS*

*New localities, reported in September 1961 at the Catania Symposium of the IAV are: Israel (S. K. Bentor); Katanga (I. de Magnée); Pantelleria (Marinelli and others).

AFRICA---

Cameroon: Weecksteen 1957.

Chad: Gâze, Hudeley, Vincent, Wacrenier 1957; Vincent 1961; Wacrenier 1958.


ASIA---

China: Kuno 1952.

Hong Kong: Ruxton 1959.

Indonesia: Akkersdijk 1941; Bemmelen 1949, 1961; Escher 1931, 1933b; Grandjean 1931; Hartmann 1933; Kemmerling 1921; Marel 1941; Neumann van Padang 1933; Stehn 1935, 1936; Westerveld 1943, 1947, 1952, 1953.


Korea: Ross, Smith 1961.


ASIA (Continued)---

Turkey:

Westerveld 1957.

USSR:


AUSTRALIA---

Branch 1961; Bryan, Jones 1954; Jones, Jones 1956; Opik 1958; Osborne 1950; Richards, Bryan 1934; White 1961.

CENTRAL AMERICA---

Costa Rica:

Crosby 1940; Weyl 1961a; Williams 1952b.

El Salvador:


Guatemala:

Sapper, Termer 1930; Weyl 1961a; Williams 1960.

Nicaragua:

Weyl 1957a, 1961; Williams 1952a.

Panama:

Weyl 1961a; Woodring 1957.

EUROPE---

Corsica:

Bodenhausen 1955.

England:


France:

Boule 1905; Glangeaud 1918; Guitard 1956; Lacroix 1906a; Rittmann 1944; Rutten 1959a; Saucler, Millot, Jost 1959.

Germany:

Ahrens 1930; Volzinger 1910; Weyl 1961.

Hungary:

EUROPE (Continued)---


Italy: Agterberg 1961; Bemmelen 1961; Dietzel 1960; Hjelmovist 1956; Maucher 1960; Mittempergher 1958; Pichler 1959; Rittman 1951, 1958; Rutten 1959b; Zambonini 1919.


Switzerland: Amstutz 1954.


Wales: Beavon, Fitch, Rast 1961; Dakyns, Greenly 1905; Oliver 1954; Williams 1928.


THE MOON--- Green 1960; Green, Poldervaart 1960.


NORTH AMERICA--- Ross, C. S., 1953.
NORTH AMERICA (Continued)---

Alaska: Allen, Zies 1923; Curtis 1955; Fenner 1920, 1923, 1925, 1934, 1937; Griggs 1922; Loring 1957; Sayre, Hagelbarger 1919; Shipley 1920; Williams 1954b; Williams, Curtis, Juhle 1956; Zies 1924, 1929.


Canada: Thomson 1957; Thomson, Williams 1956; Williams 1957.

Colorado: Burbank 1941; Kelley 1946; Larsen, Cross 1956; Luedke, Burbank 1961; Ratte, Steven 1959; Steven, Ratte 1959, 1960.


Mexico: Anderson 1950; Fries 1960; Smith, Segerstrom, Guiza 1950; Wilson, Rocha 1948; Wilson, Veytia 1949.

NORTH AMERICA (Continued)---


Texas: Amsbury 1958; DeFord 1958; Eifler 1951; Erickson 1953; Lonsdale 1940; McAnulty 1955; Moon 1953.


SOUTH AMERICA---

Argentina:
González Bonorino 1944; Piccoli 1960.

Brazil:
Mau 1959; Melcher, Mau 1960.

Chile:

Peru:
Amstutz 1956; Fenner 1939, 1940, 1948; Francis 1959; Jenks 1945, 1946, 1948; Jenks, Goldich 1956.

WEST INDIES---

Anderson, T. 1908; Anderson, Flett 1902, 1903; Barrabé 1955; Berryhill 1961; Hay 1959; Hovey 1902a, 1902b, 1903, 1904; Jaggar 1949; Lacroix 1902a, 1902b, 1902c, 1903, 1904, 1906, 1908, 1930; Lacroix, Rollet de l'Isle, Giraud 1902; MacGregor 1939; Maxwell 1938; Perret 1935; Philemon 1930; Romer 1936; Sapper 1905; Shepard, Merwin 1927.
HISTORIC NUÉE ARDENTE ERUPTIONS---

Japan: Aramaki 1956, 1957b; Ata 1940; Koto 1916; Kozu 1932, 1934; Kozu et al 1929; Tsuya, Minakami 1940; Tsuya et al 1930; Yamasaki 1957.

Kamchatka: Gorshkov 1959a, 1959b.

Katmai: Curtis 1955; Fenner 1920, 1923.

Lassen: Day, Allen 1925; Williams 1932.

Merapi: Escher 1933b; Grandjean 1931; Hartmann 1933; Kemmerling 1921; Neumann van Padang 1933, 1951; Stehn 1935, 1935.

Pele: Anderson, T., 1908; Anderson, Flett 1902, 1903; Hovey 1902a, 1902b, 1904; Jaggar 1949; Lacroix 1902, 1903a, 1903b, 1903c, 1904, 1908, 1930; Perret 1935; Philemon 1930; Romer 1936; Sapper 1905.


Santa Maria, Guatemala: Sapper, Termer 1930.

IGNIMBRITES (Special subjects)---


IGNIMBRITES (Special subjects) (Continued)---

Internal structure:
Bailey 1957; Gilbert 1938; Martin 1959; Nasedkin 1961; Roberts 1956; Roberts, Peterson 1961; Rutten 1959b; Shirinian, Aslanian 1956; Smith 1960a, 1960b.

Liquid-flow hypothesis of origin:

Nomenclature of deposits:

Recognition of non-welded ignimbrites:
(Aillis)
Aramaki, Akimoto 1957; Cook 1955; Kuno 1941; Lacroix 1908, 1930; Moore 1934; Williams 1926.

Rheoignimbrites:

Stratigraphic use of ignimbrites:

NUEES ARDENES---

Classification:
Aramaki 1957a, 1957b; Escher 1933a, 1933b; Lacroix 1904, 1930; MacGregor 1952, 1955; Rittman 1944.
**Mechanism:**

- Anderson, T., 1908; Anderson, Flett 1903; Bell 1942; Boyd 1961; Boyd, Kennedy 1951; Clark 1960b; Cole 1918; Escher 1931; Fenner 1920, 1923, 1948; Ferrar 1931; Finch 1935; Gilves 1957; Hartmann 1933; Hentschel 1955; Hovey 1902a, 1902b, 1904; Jaggar 1949; Kemerling 1932; Lacroix 1902, 1903a, 1903b, 1903c, 1904, 1906b, 1908, 1930; MacGregor 1946, 1952; Marshall 1932, 1935; Matschinski 1952; Perret 1924, 1935, 1940, 1950; Reynolds 1954; Rutten 1959a; Shepard, Merwin 1927; Smith 1960a, 1960b; Williams 1941b, 1953, 1954.

**PRE-CENOZOIC IGNIMBRITES---**

**Cretaceous:**

**Triassic:**
- Bryan, Jones 1954; Richards, Bryan 1934; Ross, Smith 1961.

**Permian:**

**Carboniferous:**
- Bodenhausen 1955; Osborne 1950.

**Late Paleozoic(?):**
- Jones, Jones 1956.

**Devonian:**

**Early Paleozoic(?):**

**Ordovician:**
- Beavon, Fitch, Rast 1961; Dakyns, Greenly 1905; Fitman 1957; Mitchell 1956; Oliver 1954; Williams 1928.

**Cambrian(?):**
- Guitard 1956.

**Precambrian:**