TEPHROCHRONOLOGY: A DATING METHOD

By

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ABSTRACT

Quantitative evaluation of tephra deposit is a useful tool to indirectly date volcanic deposits and its associated sedimentary rocks. This method can bridge the gap of limitation of various radiometric methods. In the Philippines where volumetric deposits of tephra exists, "Tephrochronology" will certainly be a tool that can bring forth fruitful results.

INTRODUCTION

About 40 per cent of the Philippines is mantled or underlain by tephra deposits, most of it of late Pliocene or Pleistocene age. There are about 220 volcanoes of Quaternary age (Datuin 1982) both active and extinct in the country. Several of these volcanoes have numerous vents, over 200 (Wolfe, 1981) being counted within 100 km of Manila. Study of the tephra from these volcanoes offer an additional tool for dating the sediments found in the country and in the surrounding seas. Quantitative evaluation of these tephra deposits is essential to properly understand the volcanic hazards in the country, including Metro Manila.

While rudimentary studies of tephra go back to the days of Rome when Pompeii was buried by ash from Mt. Vesuvius in 79 A.D., scientific studies of tephra can be said to have originated in Iceland. Catastrophic volcanic eruptions have been recorded in that country for the last 1000 years. The term "tephra" was used by Thorarinsson (1944 as cited in 1981) to include all types of pyroclasts. That is, tephra is the airborne equivalent of lava. It includes ash, pumice, lithoclasts resulting from explosive eruptions, and pyroclastics flow or surge deposits with composition ranging from basalt to rhyolite. Thorarinsson selected the name tehpra, a Greek word for ash for these explosion products because it was euphonious, in harmony with magma and lava. He pointed out that Aristotle had applied the word to volcanic ash. "Tephrochronology", then, is the dating method based on tephra layers.

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Anyone living in Manila should be familiar with tephra, because about a kilometer of tephra and volcaniclastics under lie the city. The so-called "adobe" quarried in many places around the city and used as an attractive building stone is from welded ignimbrites which surged out of Laguna and Taal volcano-tectonic (caldera) eruption. Laguna Caldera appears to have a complex history (Wolfe 1981, Wolfe & Self; 1983) possibly with multiple eruption. The youngest dated explosive eruption, based on pumice in the welded ignimbrite north of the Jala Jala peninsula, is 1.0 m.y. Taal caldera is thought to be considerably younger, probably Holocene.

DATING METHODS

Tephrochronology is a system of indirect dating of volcanic deposits which utilizes all other methods. Charcoal within a pyroclastic surge can be dated by ^{14}C back to about 35,000 years (Wolfe, 1980). No radiometric method is applicable between the end of ^{14}C and the effective minimum time of $^{40}K/^{40}A$ which some use for rocks as young as 100,000 years but which becomes more reliable at about 200,000 years. K-A is not reliable for use on glass since argon leaks out of it readily and variable alteration (devitrification) also affects argon content. Dates have to be run on biotite or hornblende crystals but care must be taken to assure that the crystals are juvenile, not from reworked deposits.

Fission track dating may be applied to glass shards. However, great care must be taken because sometimes remobilized glass may be incorporated with juvenile glass in a new eruption. This is a painstaking and laborious technique, but it does not require a mass spectometer. It may help to bridge the gap between ^{14}C and $^{40}K/^{40}A$ methods of dating.

Magnetochronology can be applied to tephra studies in a gross sense. For example, the Guadalupe tuff at the Diliman campus of the University of the Philippines has reversed polarity (McCabe 1981, personal communication). This implies that it was deposited during the Matuyama reversed polarity stage, or more than 700,000 years ago. This correlates with the K-A date from Jala Jala. The later stage in the Pleistocene is the Brunhes, of normal polarity, which continues to today.

In applying paleomagnetic studies it is necessary to look out for magnetic excursions, short-term reversals that occur in each magnetic stage. For example the Jaramillo event was a short–term normal period within the Matuyama reversal. There has been no significant rotation or translation of Luzon in the Pliocene or Pleistocene (Fuller et. al., 1983), so that type of paleomagnetic study is not applicable. However, there have been secular variations that affect the entire region. Eventually a data base may be developed that will help to distinguish tephra layers by differences in magnetic declination.

In areas of continental glaciation (Greenland and Antarctica) cores in ice and, elsewhere, sometimes varved lake deposits make it possible to count annual layers back at least to the end of the Wisconsin (glacial stage 2). Since the Laguna caldera probably had a fairly deep basin after eruption, the lacustrain sediments may be varved and ash layers of younger eruptions in the region may be studied in cores taken from the lake.

Other clues as to age of tephra layers may be obtained from rates of hydration of glass, rates of soil formation and amino acid racemization of bones if fossils are found. Distinctive soil horizons may also be tools for correlation of tephra deposits. On travelling south from Manila on the Superhighway, several tephra horizons can be seen in road cuts. The layers are separated by red fossil soils of varying thickness, reflecting the time between ashfalls.

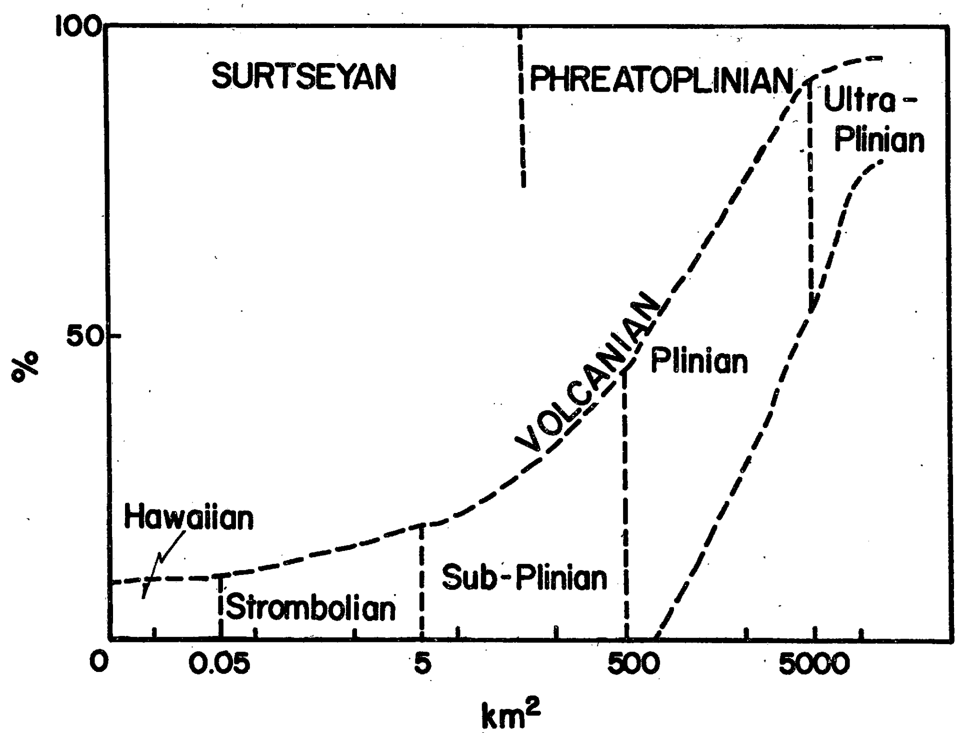

FIG. 1. Classification of pyroclastic fall deposits as related to types of eruptions. Energy intensity increases to the right. (After Wright et al, 1981 A)

CLASSIFICATION OF TEPHRA DEPOSITS

When knowledge in any field is expanding very rapidly, terminology also changes. Tephra has been intensely studied in the past few years and many new terms have been defined while some previously in use have essentially lost their meaning. The book Tephra Studies was compiled from papers presented at the NATO Advanced Study Institute held in Iceland in June 1980. It is the only book devoted entirely to the subject and it is relatively up to date.

One of the papers at the NATO meeting, recognizing the need for a concise definition of terms, presented classification charts which are reproduced as Tables I and II, (Wright et. al., 1981). This makes the distinction that there are two major classes of tephra deposits, pyroclastic surge deposits and pyroclastic ash flow deposits.

Nomenclature of volcanic eruptions is sometimes confusing. Figure 1, reproduced from Wright et. al. (1981) shows the relationships between different kinds of volcanic eruptions. The ordinate of this chart shows weight per cent of the tephra deposit smaller than particle size of 1 mm, as measured on the axis of the deposit, at the point where the isopach representing 0.1 (10%) of the maximum thickness of the deposit crosses it. This of course is predicated on full study of the eruption. On the abscissa is plotted the area in km^2 of the deposit within the isopach representing one one hundreth (1%) of the maximum thickness of the deposit. (Note this is a logrithmic scale). The eruption of Taal in 1965 was initially phreatoplianian and in 1968-69 became strombolian, with outpouring of lava.

In connection with Figure 1, the volcano with low energy of eruption is at the left end, the high energy at the right. A high volcanic peak with a perfect cone like Mt. Mayon is a low energy volcano. A topographically low volcano like Laguna is one of extremely high energy, ultraplinian. (The name "plinian" comes from the Roman author Pliny who described the explosive eruption of Mt. Vesuvius in 79 A.D. which buried Pompeii and Hurculaneum.)

TEPHRA FACIES

Tremendous strides have been made in tephra studies in the past 15 years. Moore et. al. (1966) studied the eruption of Taal Volcano of 1965 and introduced a new term "base surge" for the type of explosion which occurred at that time, comparing the blast to a hurricane. The the term base surge is becoming obsolete, replaced by "pyroclastic surge" divided into facies by Sparks et. al. (1978).

In order to understand tephra deposits, it is necessary to visualize the events that result in their formation. They are violent volcanic eruptions, although the scale of the explosion can vary widely, from the small phreatomagmatic eruptions of Taal in 1976 and 1977 to the moderate-sized eruptions of 1965 and 1911 (Volcano Explosivity Index, V.E.I., of 3-4) to the catastrophic eruptions which formed the giant calderas of Laguna, Taal and other large lakes and scalloped bays of the country. One of the best descriptions of a large caldera eruption, of Toba on Sumatra, 75,000 b.p., is by Ninkovich et. al. (1978). This eruption blasted out about 2000 km^3 of tephra in an estimated two weeks time. That amounts to 6 km^3 per hour, or 100 M m^3 per minute, exceeding all of the material handled by all of the mines in the Philippines per year, every minute.

A giant caldera eruption must be one of the most awesome sights of nature. The firey eruption must shoot up to 10 to 25 km high. As the tephra begins to fall back it pours off of new material rising to meet it, so it is shed off of the column. With as much as 15 km of head, this giant fountain splashes to earth and shoots off to the side at possibly 200 km per hour. Riding on a cushion of trapped air and exsolved gases it flows like water and may run out for 100 km, may rise over obstructions as high as a kilometer and eventually "runs out of gas" and collapses. If hot enough this flow unit becomes a welded ignimbrite, instant rock. This would then be classed as an ignimbrite sheet, taking less than 30 minutes to form. However, back at the source, fountaining is continuing, and a second and third sheet may be following closely behind, and others are shooting off in other directions.

To bring this close to home, this description is probably appropriate for the caldera eruptions of Laguna and Taal, the latter possibly one of the youngest on earth. The massive pile of Tagaytay ridge is composed of the lag-fall facies of the ignimbrite sheets. The gently-sloping tephra from the ridge down into Manila Bay is the ignimbrite delta formed. The mountains of western Cavite, formerly a separate island, acted as a guide-way to the flow units pouring north, welding Cavite to Luzon. Flow units spread south to Batangas Bay and west to Balayan Bay. To the east, at Lipa City, the ignimbrite sheets piled up to 300 m, but the waves piled up, dammed by Mt. Malepunno east of the city, to 400 m. In contrast, on the east side of the mountain the foothills are about 100 m in elevation. To the southeast there was no obstruction and flow units inundated the sites of Padre Garcia, Rosario, Taysan and reached San Juan, thinning as they spread east to Tayabas Bay. Eventually the eruption ceased, and all of South Luzon was a scene of desolation, without a sprig of green.

The eruption of Taal caldera was apparently not just one sequence, since in the upper section of the cliff below Tagaytay Ridge there are several thin soil horizons between layers (Wolfe and Self, 1983). However, a major portion of the deposits, possibly 500 km^3, may have been formed in the principal eruption. Following the eruption of the top of the magma pool, the volcano tectonic depression collapsed on normal faults, at least one of which, on the south side, was pre-existing.

Tall volcano is resurgent, has erupted many times since the massive explosion. Sometimes there have been major outpourings of ash, forming layers a few meters thick on top of old soil horizons.

An ignimbrite sheet has several facies with size gradiations decreasing away from the source. (Sparks et. al. 1978). The proximal facies consists of the lag-fall fragments. The large, heavy fragments drop out of the stream first, at the head of the sheet. Boulders, cobbles and pebbles of lithic material are common, most of them rounded in the explosive column, possibly from falling back into the source and being repeatedly blown out. Some of the clasts are angular to subangular. (Fig. 2)

Second is the ground-surge facies. It is composed largely of coarse to fine sand-sized grains, largely of lithics, building up dunes and antidunes resembling fluviatile deposits in part. Cross bedding is common, channels can be eroded in finer deposits and refilled with coarser material. This facies is formed by the hurricane-force winds accompanying the flow, and the gases upon which it is riding.

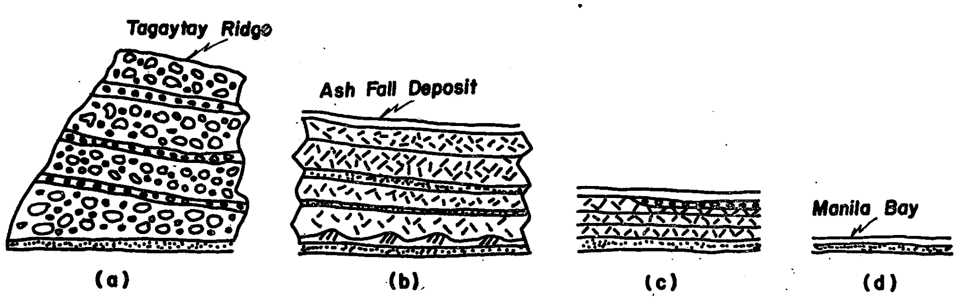

FIG. 2. Facies of Taal Ignimbrites (After Wright et al 1981 B). (a) Extensive co-ignimbrite lag-fall deposits make up Tagaytay Ridge. Landslide scars into caldera mark collapse of volcano-tectonic deprssion (b) Main body of the ignimbrite flow units, many welded. Ground surge deposits may be found near base with dunes. This may be repeated between ignimbrite sheets. At 25 km from source ash fall deposits are found on top of cooling units. (c) Ignimbrite sheets thin toward Manila Bay and lahars are eroded into top of some sheets. Possibly 35 km from source. (d) Distal co-ignimbrite ash fall deposits near and within Manila Bay. Underlying all of the ignimbrite units may be a Plinian fall deposit.

Third is the fluidized ash flow, composed largely of fine-grained, juvenile, glassy particles plus older, reworked volcanic material in the same size range. This is a dense, hot cloud and if it passes through a forest it can consume it, leaving only the stumps which were below the cloud. Within this cloud there may be extensive amounts of juvenile pumice, which tend to float to the top of the sheet. Many of these fragments are of cobble size (3-10 cm in diameter) or even boulder size (to 30 cm or more). This is the material which becomes welded upon exhaustion of the contained gas. The upper portions of the sheet containing the pumice pebbles and cobbles constitute the popular "adobe" building stone in Manila. This suggests that the density of the ash cloud may build up to possibly 0.2.

The top of the ash cloud is unstable with gas escaping upward, elutriating the finest material with it. This fine ash may travel far beyond the density flow and forms the ash fall, the fourth facies, the distal end of the ignimbrite. At the same time fine ash is spreading from the central explosion column and intermingling with the ash facies of the pyroclastic surge. It was ash clouds formed by the eruption of Galungung in Java in 1982 that engulfed two commercial jets, nearly wrecking the planes. (This was not a caldera eruption, however).

These then are the four facies of a pyroclastic surge: lag-fall, ground surge, ash flow and ash fall. When they come to rest they constitute an ignimbrite sheet, which may, if hot enough, become welded. The sheet may extend for 100 km or it may be limited to less than 10 km. One tephra layer includes all facies which grade into each other, but they represent the same instant (few minutes) of formation. One layer may be broad, the next overlying layer may be narrow, so sorting out individual layers may be difficult. All of the ignimbrite sheets of one eruption are called, collectively, a cooling unit.

Following formation of ignimbrites, or during brief cessation of eruption, there may be torrential rains. There may be substantial topographic difference between the upper and lower ends of the ignimbrites (600 meters between Tagaytay Ridge and Manila Bay) and nothing to obstruct run-off. Coarse fragments from the lag-fall facies plus large amounts of ash may be incorporated in mud flows or lahars which can be carried for tens of kilometers down slope. These fluids can build up to quite heavy density, possibly close to 2.0. They can move large boulders by traction and coarse gravel by turbulent flow, eroding channels into the top of the ignimbrite sheet and depositing mixed sand, gravel and ash. These deposits frequently become strongly indurated but they are not welded. Materials of this nature outcrop along the highway west of Alabang. The best exposures of the ignimbrite sheets from Taal are found in the deeply incised stream valleys west of Carmona on the highway to Puerto Azul.

Caldera eruptions are just one type of explosive eruption in andesitic volcanoes in the island arcs; fortunately they are rare. The type of eruption of Mt. St. Helens in Washington state (Anonymous, 1980 Crandell and Mullneaux, 1980, Fruchter et. al., 1980) has probably been common in South Luzon in the Quaternary. A dome formed on the north flank of St. Helens as magma rose in the central column. An earthquake ruptured the stressed dome, 'uncorking' the magma with explosive violence. The blast destruction extended to over 20 km on a 180^{o} arc, knocking down the forest radially, sending ash flows down valleys and dust into the stratosphere, where it was carried around the world in about two weeks. A thin ash layer extended into eastern Washington and into Montana. This explosive eruption is typical of the build-up of composite or starto-volcanoes in the island arcs.

The large summit or avalanche calderas (Siebert, 1982) on the Bataan lineament (Wolfe and Self, 1983), for example Mt. Natib, attest to major explsovie eruptions in South Luzon. There is a convex bulge on the northwest face of Mt. Makiling which appears to be a dome, one that solidified instead of exploding. Between Mt. Makiling and Mt. Banahaw are numerous maar craters which erupted explosively sending ash into the atmosphere. All of these explosive eruptions contribute tephra which may or may not be preserved in the sedimentary record. Most of the tephra layers would be lost, but never-the-less the preserved tephra in South Luzon is a very impressive record of volcanic activity.

METHOD OF STUDY

In addition to the dating methods described in a previous section it is important to be able to recognize a tephra unit or sequence so that the same unit at a different location can be correlated with it. Frequently units have distinct characteristics that assist in discriminating between layers. Eruptions from different volcanoes may be fairly easy to recognize, possibly even in the field. However, much of the work depends upon careful sampling of outcrops or drill core and meticulous laboratory evaluation. To build up an adequate data base that will be useful in long-range correlation, for example in distant marine sediments, as much information as possible should be obtained. Some of the field criteria (Westgate and Garton, 1981) are color, degree of weathering, extent of soil formation, lithic and mineralogic content, granulometric parameters, sedimentary structures, distribution, thickness and stratigraphic context. However, to identify distal tephras, far from the source, detailed petrographic and petrochemical studies are usually necessary. The properties of glass shards do not change over distance. Bulk analyses are subject to distortion because of fractionation, but do give useful information about the source.

Shard morphology can be distinctive. Features can be imparted by the character of the magma and the erutpive mechanism. For example, one unit may contain shards from thin-walled bubbles that have shattered. Another may have chunky shards or flat and elongated, or may contain distinctive vesicles, or may contain microcrystalline inclusions which are diagnostic. Petrographic characteristics can be one of the most sensitive clues to a tephra unit.

Refractive index of the glass has been used extensively in the past, but this is not as reliable as other methods. Refractive indices of glasses of similar composition may vary less than the degree of hydration, which alters the index of refraction. If many meticulous measurements are made and a statistical analysis made of the results, it can be useful. One of the distinct advantages of the method is that it only requires a petrographic microscope and a set of index oils, not extremely expensive equipment and a complete laboratory.

Major element chemistry determined by microprobe on individual shards can be a good criterion, whereas bulk chemical methods can be badly distorted. Iron, calcium and potash are frequently diagnostic. Sodium is rapidly volatilized from glass in microprobe studies and great care must be exercised in using this element. Low current, large beam diameter and short counting time help to overcome this difficulty (Keller 1981). Ilmenites and titano magnetites are among the most commonly studied minerals. Their chemical composition is very sensitive to environmental conditions. They are ubiquitous, do not weather readily and are easy to extract by magnetic methods. The magnesia (MgO) content may be distinctive (above 5% in ilmenite from kimberlites that originate in the depth zone where diamond can form).

Minor and trace elements in glasses are reputed to be among the best means of discriminating between tephra layers. Bulk techniques are required because the content is usually below the detection limit of the microprobe. X-ray fluoresence is not sensitive enough for these elements. Atomic absorption is highly sensitive and most useful for first transition and heavy elements (Ag, Cd, Hg, Pb, etc.) but concentrations may be too low and in the lower range interference from other elements may be difficult to eliminate. Neutron activation is most useful for the rare earth elements, but the equipment is expensive and results frequently cannot be reproduced between operators or between laboratories.

PHILIPPINE TEPHROCHRONOLOGY

The problem of establishing a tephrochronology in the Philippines is that to date the fundamental work is just beginning. The new Petrolab of the Bureau of Mines and Geosciences will not be fully operational for some time. Interest by international groups has not yet been aroused. In contrast, much work has been done in the marine environment in the eastern Mediterranean to correlate with volcanoes on land. This was stimulated by historical events and references in mythology to prehistoric volcanic eruptions of massive proportions, such as that of Vesuvius in 79 AD which buried Pompeii and Hurculaneum. The eruption of Santorini (Thera) about 3400 b.p. apparently wiped out the Minoan civilization and this is thought by some to be the time of destruction of mythical Atlantis. American universities have done extensive work in oceanography and in Central and South America. Iceland has had a great deal of attention because of the major eruptions near communities. Likewise Japanese and New Zealand volcanologists have initiated studies in their homelands. However, in southeast Asia, the Philippines and Indonesia, where the density of Quaternary volcanoes is greatest, only limited studies have been conducted.

There is adequate justification for an intensive study of tephra in southern Luzon. It is essential to the evaluation of the volcanic hazard of the region. The first known classification of Laguna de Bay as a caldera-volcanotectonic depression in the international literature was that of Wolfe and Self (1983). This appears to be one of the world giant caldera complexes, with limits yet undefined. Seismic evidence suggests that it extends westerly to the Marikina fault. This would give an east-west width of at least 45 km. Northern limits are clear but southern are not. Are Banahaw and Makiling resurgent volcanoes within the complex? Is it interconnected with Taal caldera, that feature just the most youthful recurrence of massive eruption? Yellowstone caldera in Wyoming and Idaho is known to have had three eruptions in the Pleistocene at about 600,000 year intervals and there has been speculation that the magma chamber is still very much alive and capable of a fourth event. It is possible that 2500-3000 km^2 of South Luzon directly overly the magma chamber which has been active periodically throughout the Quaternary.

Contributions to the marine sediments of the South China Sea and the Philippine Sea by Philippine volcanoes must be significant. Since a monsoon climate prevails, the direction of the prevailing wind at time of eruption would determine which sea received the bulk of the ash. In addition to the Laguna-Taal caldera complex, the several composite volcanoes on the volcanic arc of west Luzon (the Bataan Lineament, Wolfe and Self, 1983) most of which have had late stage summit caldera eruptions should also have produced ash layers in the marine sediments. Thus there is fruitful field for building up a tephrochronology in the Philippines.

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TABLE I GENETIC CLASSIFICATION OF PYROCLASTIC FLOWS (After Wright et al, 1981)

ESSENTIAL FRAGMENT	ERUPTIVE MECHANISM	PYROCLASTIC FLOW	DEPOSIT	COMMENTS	DESCRIPTION
VESICULATED	ERUPTION COLUMN COLLAPSE	PUMICE FLOW	IGNIMBRITE; PUMICE AND ASH DEPOSIT	Large volume deposits envisaged to form by continuous collapse of a plinian eruption column Salic in composition Small volume deposits probably formed by interrupted column collapse as in the case of scoria flows described below. Intermediate to salic in composition.	Unsorted ash deposits containing variable amounts of rounded salic pumice lapilli and blocks up to 1 m in diameter. In flow units pumice fragments can be reversely graded while the lithic clasts can show normal grading; upgraded flow units are as common. A fine grained basal layer is found at the bottom of flow units. They sometimes contain fossil fumarole pipes and carbonized wood. The coarser smaller volume deposits usually form valley infills while the larger volume deposits may form large ignimbrite sheets. Sometimes they may show one or more zones of welding.
	ERUPTION COLUMN COLLAPSE	SCORIA FLOW	SCORIA AND ASH DEPOSIT	Small volume deposits probably formed by interrupted eruption column collapse produced by short explosions Basalt to andesite in composition.	Topographically controlled, unsorted ash deposits containing basalt to andesite vesicular lapilli and scoriaceous ropey surfaced clasts up to 1 m in diameter. They may in some circumstances contain large non-vesicular cognate lithic clasts. Fine grained basal layers are found at the bottom of flow units. Fossil fumarole pipes and carbonized wood may also be present. The presence of leveés, channels and steep flow fronts indicate a high yield strength during transport of the moving pyroclastic flow.
	ERUPTION COLUMN COLLAPSE	VESICULAR ANDESITE FLOW	VESICULAR ANDESITE AND ASH DEPOSIT	Small volume deposits composed of vesiculated angular andesite clasts.	Topographically controlled unsorted ash deposits containing intermediate vesicular (between pumice and non-vesicular juvenile clasts) andesite lapilli, blocks and bombs. Fine grained basal layers, fossil fumarole pipes and carbonized wood all may be present.
NON-VESICULATED	LAVA DOME COLLAPSE — EXPLOSIVE	BLOCK AND ASH FLOW; NUEE ARDENTE	BLOCK AND ASH DEPOSIT	Small volume deposits, usually andesitic or dacitic in composition. Produced both by explosive collapse of an actively growing dome or lava flow and by the collapse of vertical eruption column as recognized in the early eruptions (eg. May 8 and 20) of Mt. Pelee 1902	Topographically controlled, unsorted ash deposits containing large, generally non-vesicular, jointed cognate lithic blocks which can exceed 5 m in diameter. The deposits are generally reversely graded. Fine grained basal layers are again present. Again they may contain fossil fumarole pipes and carbonized wood. Surface manifestation include the presence of leveés, steep flow fronts and the presence of large surface blocks, all of which again indicate a high yield strength during transport of the flow.
	LAVA DOME COLLAPSE — GRAVITATIONAL	BLOCK AND ASH FLOW; NUEE ARDENTE	BLOCK AND ASH DEPOSIT	Small volume deposits usually andesitic or dacitic in composition. These have been termed hot avalance deposits	

TABLE 2 GENETIC CLASSIFICATION OF PYROCLASTIC SURGES (After Wright et al, 1981)

ESSENTIAL FRAGMENT	ERUPTIVE MECHANISM	TYPE OF SURGE	COMMENTS	DESCRIPTION
VESICULATED NON-VESICULATED	COLLAPSE OF A PHREATOMAGMATIC ERUPTION COLUMN	BASE SURGE	Base surges from the explosive interaction of magmatic material and water and are consequently cool.	Stratified and laminated deposits containing juvenile vesiculated fragments ranging from pumice to non-vesiculated cognate lithic clasts, ash and crystals with occassional accessory lithics (larger ballistic ones may show bomb sags near-vent) and deposits produced in some phreatic eruptions which are composed totally of accessory lithics. Juvenile fragments are usually less than 10 cm in diameter due to the high fragmentation caused by the water/magma interaction. Deposits show undirectional bedforms. Generally they are associated with maar volcanoes and tuff rings. When basaltic in composition they are usually altered to palagonite.
VESICULATED NON-VESICULATED	ACCOMPANYING PYROCLASTIC FLOWS ERUPTED BY MECHANISMS GIVEN IN TABLE I	GROUND SURGE	Ground surge, although originally introduced to encompass all pyroclastic surges, is here used to describe those surges found at the base of pyroclastic flow deposits, as well as those produced without any accompanying pyroclastic flow.	Generally less than 1 m thick, composed of ash juvenile vesiculated fragments, crystals and lithics in varying proportions depending on constituents in the eruption column. Typically enriched in denser components (less well vesiculated juvenile fragments, crystals and lithics) compared to accompanying pyroclastic flow. Again they show unidirectional bedforms; carbonized wood and small fumarole pipes may be present.
VESICULATED (non-vesiculated)	ALSO ASSOCIATED WITH AIR-FALL DEPOSITS BY COLLAPSE OF AN ERUPTION COLUMN BUT WITHOUT GENERATION OF PYROCLASTIC FLOW	GROUND SURGE		
VESICULATED NON-VESICULATED		ASH CLOUD SURGE	Ash cloud surges are the turbulent, low density flows derived from the overriding gas-ash cloud of pyroclastic flows. These may in some cases become detached from the parent pyroclastic flow and move independently.	Stratified deposits found at the top of and as lateral equivalents flow units of pyroclastic flows. They show unidirectional bedforms, pinch and swell structures and may occur as discrete separated lenses. Grain size and proportions of components depend on the parent pyroclastic flow. Can contain small fumarole pipes.