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An Investigation of Volcanic Depressions

Part I

AIRFALL AND INTRUSIVE PYROCLASTIC DEPOSITS

Part II

SUBAERIAL PYROCLASTIC FLOWS AND THEIR DEPOSITS

CASE FILE
COPY

by

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ILLUSTRATIONS FOR REPORT ON

PYROCLASTIC FALLS AND FLOWS AND THEIR DEPOSITS

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AIRFALL AND INTRUSIVE PYROCLASTIC DEPOSITS

The term 'tephra' was introduced by Thorarinsson in 1941 to include all ejecta blown through the air by explosive volcanic eruptions. Defined in this way, the term is synonymous with airborne pyroclastic ejecta and excludes fragmental debris produced and laid down under water or beneath the earth's surface, as in many volcanic pipes.

Pyroclastic ejecta and the deposits they form have been classified in many ways and many interpretations have been given to individual terms. A brief history has been presented elsewhere (Wentworth and Williams, 1932). Some classifications are based on the modes of origin and deposition of the ejecta; others emphasized the chemical and physical composition of the ejecta. It seems best, however, to use particle-size as the prime basis of subdivision, and to use the same size-limits as those employed in the classification of sediments and sedimentary rocks. Accordingly, Fisher's (1961) terminology and classification are reproduced as Tables 1 and 2.

Table 1.   Terminology and grain-size limits for epiclastic and pyroclastic fragments

Grade size mm	Epiclastic fragments	Pyroclastic fragments		Wentworth and Williams (1932)	
256	Boulders (and "blocks")	Coarse	Blocks and Bombs	Blocks and Bombs	256
64	Cobbles	Fine			64
32	Pebbles	Lapilli		Lapilli	32
4					4
2				Coarse ash	2
1/4	Sand	Coarse	Ash		1/4
1/16				Fine ash	1/16
	Silt	Fine			
1/256	Clay				1/256

Table 2.   Classification of epiclastic and pyroclastic rocks

Predominant grain size (mm)	Pyroclastic		Epiclastic*
256	Breccia and Agglomerate		Volcanic breccia
64	Lapillituff and Lapillistone		and
2			Volcanic conglomerate
1/16	Coarse	Tuff	Volcanic sandstone
1/256	Fine		Volcanic siltstone
			Volcanic claystone

*Add adjective "tuffaceous" to rocks containing pyroclastic material
    2 mm. in size (Modified from Fisher, 1961).

PYROCLASTIC EJECTA

Bombs

Bombs are clots of magma that measure more than 64 mm. in maximum dimension and are partly or entirely plastic when erupted. Some are of astounding size. For instance, bombs measuring 18 meters in circumference and weighing 200,000 kg. were blown 600 meters from the crater during an eruption of the Japanese volcano Asama in 1935.

The shapes of most bombs are determined chiefly by the character of the magma, particularly its degree of fluidity immediately before explosive discharge. Magma within a vent may already be flow-banded, marked by vesicular layers, or contain clusters of phenocrysts and xenoliths; if so, the shapes of the erupted clots will be affected by these internal structures, tending to break along surfaces of least resistance. Accessory factors that govern the shapes of bombs include the length and velocity of flight through the air, the amount of air-resistance, the rate of cooling, rate of expansion of contained vesicles, and deformation on impact. Contrary to a widespread belief, bombs seldom rotate fast enough to modify their forms in flight.

Magma is generally hurled from a vent as rounded blebs or as ribbons that vary in width along their length, though some ejecta, particularly those ripped from the incandescent linings of the conduits, have platy and leaflife forms. If small clots of very fluid magma are blown out at low velocities, surface tension may mold them into spheroidal bombs, but these are rare and virtually restricted to basaltic ejecta, most spheroidal fragments being smaller, of the size of lapilli (see page 9). Less fluid clots of magma usually produce almond- and spindle-shaped (bipolar) bombs such as typify eruptions of the volcano

Stromboli. A few bombs of this kind already have these shapes on eruption, but most of them result from the tearing apart of ribbons of irregular width, either during flight or upon impact. Surface tension tends to draw the thicker parts of the ribbons into spherical forms, and these, because of their liquid cores, tend to rotate more slowly than the thinner, more nearly solid parts; hence, many bombs have 'twisted ears'. Occasionally, one side of a bomb differs in surface-texture from the other, owing to the effects of air resistance during flight. For instance, the under side of a falling bomb may develop a smooth, glassy skin, while the upper side is marked by ribs and flutings and by smaller vesicles and fewer unburst blisters. Air-drag may also cause the ears of falling bombs to bend backward. Equatorial flanges may be produced during flight.

Ribbon bombs and thin parts of them that break to produce cylindrical bombs are usually fluted along their length, and most of their vesicles are elongated in the same direction. Bombs that are extremely viscous or almost completely solid when erupted, as were most of those blown from Paricutin volcano, Mexico, are angular or subangular, with irregularly cracked crusts, and some of them shatter when they land. On the other hand, extremely fluid bombs hurled only to moderate heights, so that they chill only slightly during flight, may flatten or even splash when they land, and adhere to adjacent fragments. Such ejecta are referred to as cow-dung or pancake bombs, and if their plastic skins anneal to each other they produce welded accumulations known as agglutinate or Schweisschlacken.

Cored bombs are those which have a nucleus of previously consolidated material. The nuclei may be connate, i.e. fragments of material laid down during earlier eruptions of the same volcano, but,

more commonly, they are <u>accidental</u>, ie. fragments torn from the sub-volcanic basement, whatever its nature. Many included fragments are metamorphosed; for instance, fragments of Paleozoic sandstone in cored basaltic bombs in the San Francisco volcanic field, Arizona, are partly vitrified, and some orthoclase crystals in the associated Pre-Cambrian plutonic fragments are converted to sanidine (Brady and Webb, 1943). Fragments of impure diatomite coated with basalt and blown from Pacaya volcano, Guatemala, in 1963, are largely changed to pumiceous glass, tridymite, and cordierite. Cores that are sufficiently reheated may develop banding parallel to that of the enclosing shell.

The distribution of cored bombs in a volcanic field is usually quite irregular; indeed only a few pyroclastic cones within a large cluster may contain them. Once the walls of an eruptive conduit become lined with plastic magma, the chance of discharging cored bombs with accidental nuclei is greatly diminished; hence, such bombs are usually most plentiful among the early ejecta of a given vent.

<u>Breadcrust bombs</u> (<u>Brotkrustenbomben; bombes en croûte de pain</u>). These are characterized by a quickly chilled crust of dense glass fissured by continued expansion of vesicles in the still molten core. The dense glassy crust generally increases in thickness with the size of the bombs. Phenocrysts are more or less equally distributed throughout, but micro-lites tend to increase in abundance inward. The more fluid the core and the greater the internal expansion, the more do the breadcrust-cracks gape; narrow, steep-sided cracks typify bombs that were extremely viscous or almost solid when erupted.

Breadcrust bombs are commonest among the ejecta of volcanoes that discharge relatively cool, viscous magmas of siliceous (rhyolitic and dacitic) composition; they are not uncommon among ejecta of intermediate

composition, but are quite exceptional among basaltic ejecta. And because rapid chilling of the crusts is essential to their formation, they are much more plentiful among the deposits of airborne ejecta than among those of pyroclastic flows in which all the ejecta remain eveloped by hot gases for long periods.

Among glass-rich bombs drastically chilled by falling into water or on to snow and ice, cracking may not be restricted to the crusts but may penetrate almost if not completely to the centers, so that the bombs become aggregates of crude cones loosely held together at their apices. Bombs of this type were to be seen among the 1915 ejecta of Lassen Peak, California, and among the initial ejecta of the 1947 eruptions of Hekla, Iceland, where they fell on to snow.

Vesicles in bombs tend to be spheroidal and to increase in size inward from the crust, and in bombs that are roughly ellipsoidal the vesicles are generally arranged concentrically, parallel to the crust. Phenocrysts and microliths may also be alined in this manner. In ribbon bombs, however, the vesicles are usually tubular, and elongated along the length. Tubular, sub-parallel vesicles may also be seen in spheroidal breadcrust bombs erupted by Vulcano. These were probably pre-formed by reheating, softening and rise of a glass-rich plug temporarily sealing the conduit (Bernauer, 1931).

Blocks

Blocks are erupted fragments of solid rock measuring more than 64 mm. in maximum dimension. Those consisting of rocks formed by previous eruptions of the same volcano are called 'accessory or cognate'; those derived from the coarse-grained margins of underlying

magma chambers are called 'plutonic cognate'; and those consisting of igneous, metamorphic, or sedimentary rocks torn from the sub-volcanic floor are called 'accidental'.

Blocks and smaller fragments of solid rocks make up all of the ejecta of steam-blast (phreatic) eruptions, and they generally constitute a large part of the ejecta of phreatomagmatic eruptions. In other types of eruption, however, their number is extremely variable, and more often than not they are absent.

Blocks weighing up to 14 tons (14,000 kg.) were blown out during the 1924 steam-blast eruptions of Kilauea, and one of them, weighing 8,000 kg., landed approximately 1,100 m. from the vent. Vesuvius is known to discharge blocks weighing between 2,000 and 3,000 kg. for distances of 100 to 200 meters. And during the 1968 eruptions of Arenal volcano, Costa Rica, inclined blasts blew bombs and blocks large enough to produce impact pits more than a meter in diameter at distances of approximately 5 km. from the vents.

Accidental blocks are usually most abundant during the initial stages of growth of a volcano, as they were at Paricutin volcano, Mexico, in 1943; however, they may be discharged in great quantities during late stages of growth, as exemplified by the Somma-Vesuvius volcano. Much depends on the depths of the explosion-foci, i.e. the levels at which explosions take place. Coarse vent-breccias outside the calderas of Mull, Scotland, contain abundant accidental blocks of gneiss torn from the sub-volcanic, Pre-Cambrian basement, whereas those within the calderas are devoid of them. The gneissic floor beneath the calderas was too deeply buried and the explosion-level was too shallow to bring up accidental fragments.

Accessory blocks tend to be most abundant when volcanic conduits are reopened after a long interval of quiet. An instructive example is to

be seen in the explosion-vent of Ben Hiant on Ardnamurchan, Scotland,
where the vent-filling consists of thin beds of very fine tuff that
alternate with massive beds of coarse, unsorted ejecta (Richey, 1938).
Each of the fifty or more pairs of beds, averaging approximately 8 m.
thick, represents the products of a single explosive cycle. The coarse
ejecta contain only a few accidental fragments, composed chiefly of
accessory trachyte blocks in a matrix of trachyte tuff; the finer ejecta,
on the other hand, carry abundant grains of quartz, mica, garnet, and
microcline derived from the Pre-Cambrian basement, mixed with accidental
chips of Tertiary basalt, accessory chips of vent-trachyte, and glassy
particles of fresh trachytic magma. Each outburst was initiated by
shattering of a plug of solid trachyte, followed by discharge of
frothing trachytic magma, hurled out as glass-dust along with comminuted
schist-debris abraded from the conduit walls.

Plutonic cognate blocks tend to be erupted most commonly during
late stages of catastrophic eruptions leading to the formation of
calderas, though they may be blown out at any stage of activity. They
are plentiful among the ejecta laid down during the eruptions of Vesuvius
in 79 A.D., and among those laid down immediately prior to the collapses
that formed the calderas of Crater Lake, Oregon, and Shikotsu, Japan.
At such times, the level of the magma in the feeding chambers is lowered
so far that some of the slowly solidified, coarse-grained roof-rocks
'backfire' into the partially evacuated chambers to be ejected along
with liquid magma.

Blocks are almost invariably angular, and most of them are
roughly equidimensional. Many blocks, however, are slabby or platy,
particularly if they are fragments of banded lava or of sedimentary
and schistose rocks. And in many volcanic pipes (diatremes), accidental

blocks derived from great depths may be so abraded during fluidization
and upward transport that they resemble rounded and polished, waterworn
pebbles and cobbles.

Blocks may be partly or thoroughly metamorphosed prior to
eruption. If they are only slightly reheated, they may have narrow,
steep-sided, surficial cracks ;   if they consist of reheated
glassy volcanic rocks, particularly obsidians, they may develop shells
of pumice, such as those to be seen among the 1883 ejecta of Krakatoa.
Brun (1911) was so impressed by this phenomenon that he was mislead
into thinking that reheating of glassy rocks (lebendige Gesteine) was
a principal cause of volcanic eruptions. Even holocrystalline blocks
may be partly converted to glass prior to eruption, as are many cognate
plutonic blocks blown from the Mount Mazama (Crater Lake) volcano in
Oregon.

Among examples of more intensely metamorphosed blocks, it
must suffice to mention a few. Blocks of hypersthene granulite were
hurled out by the steam-blast eruptions of Kilauea in 1924; these were
formed by thermal metamorphism of olivine basalts. Among accidental
blocks periodically blown from Vesuvius, those derived from shallow,
Tertiary sedimentary rocks are at most slightly fritted or weakly
indurated, whereas those derived from underlying Cretaceous limestones
are largely converted to marbles, and those derived from still deeper
Triassic dolomites forming the roof of the magma chamber are entirely
converted to calc-silicate metamorphic rocks of bewildering variety
(Rittmann, 1933).

Lapilli

The term lapilli or 'rapilli' was adopted from the Italian
name for gravel-like cindery fragments around Vesuvius. Wentworth and

Williams (1932) suggested that the size-limits of lapilli be placed at 4 to 32 mm., but it now seems better to extend the size-limits from 2 to 64 mm. (Fisher, 1961). Some lapilli are _juvenile_ (essential), consisting of fresh magmatic ejecta; others consist of already solidified rocks, whether accessory or accidental. Their shapes are subject to essentially the same controls as those of bombs and blocks.

Finely spun glass threads, known as 'Pele's hair' are normally a product of explosions from gas-rich, extremely fluid basaltic lava-lakes or of basaltic lava-fountains such as characterize the initial phases of most Hawaiian eruptions. Liquid droplets may be drawn into threads up to 2 meters or more in length that are carried aloft by up-drafts and are then drifted afar by winds, sometimes for distances of 10 to 15 kilometers. Other liquid droplets, measuring a few millimeters across, chill quickly to dense or vesicular glass-beads with pendant threads and smooth, greenish skins; these are known as 'Pele's tears'.

Crystal-lapilli. Aggregates of crystals and individual phenocrysts of lapilli-size are occasionally blown from volcanoes, either alone or, more commonly, encased in a jacket of quickly chilled glass. Examples of such lapilli are the showers of leucite and augite crystals discharged by Vesuvius, the anorthite-lapilli of Miyake-Sima, the anorthoclase-lapilli of Mount Erebus in Antarctica, and the olivine-clots erupted by many basaltic volcanoes. During the 1963 activity of Pacaya volcano, Guatemala, showers of euhedral calcic plagioclase crystals, mostly 1 to 2 cm. long, were erupted, each coated by a thin film of basaltic glass.

Lapilli in explosion-pipes. Spheroidal and ovoid lapilli are present in a few explosion-pipes (diatremes). Some pipes in Missouri contain such lapilli, from less than a millimeter to more than 3 cm. across, most of which have a phenocryst or a foreign lithic

fragment as a nucleus (Rust, 1937). No matter what the shapes of the nuclei, all the lapilli are oval in outline, and usually the igneous envelope surrounding each nucleus shows a concentric alinement of its lath-shaped crystals. Apparently, the nuclei were blown into spaces clouded with a spray of liquid magma and continued to rotate as they were being coated. Moreover, owing to rapid chilling, each pellet was essentially solid when it came to rest.

Similar lapilli are to be seen in some of the kimberlite pipes in the Missouri Breaks, south of the Bearpaw Mountains, Montana (Hearn, 1968). There, however, the lapilli are clustered in the upper parts of massive, unstratified, intrusive bodies of kimberlite injected into well-bedded airfall deposits of kimberlite tuff. The lapilli show a crudely concentric arrangement of phenocrysts around their nuclei, and some are characterized by an equatorial flange, which also suggests rotation during flight; nevertheless, they must have formed underground, pre-sumably by discharge of effervescing liquid into spaces opened by temporary withdrawal of rising magma.

Accretionary lapilli (volcanic pisolites, mud balls). These are spheroidal, concentrically layered pellets generally composed of vitric ash and dust of siliceous composition, though some consist of basaltic material and others are composed of fine lithic ash and dust, such as those that fell during the steam-blast eruptions of Kileau in 1790 and 1924. Most accretionary lapilli measure between 2 and 10 mm. in diameter, but some are described as being as large as a hen's egg, and a few that fell during the eruptions of Mt. Pelé in 1902 measured as much as 15 cm. across. They are formed chiefly through accretion of ash and dust by condensed moisture in eruption-clouds. First, structureless nuclei of relatively coarse particles form in the cloud;

then, as these fall, concentric shells of progressively finer ash are added, ranging in thickness from 0.5 to 0.02 mm., and in grain-size from 0.1 to 0.001 mm. (Moore and Peck, 1962). These successive shells reflect the increasing temperature and diminishing humidity of the eruption cloud at lower levels. Accretionary lapilli of this type usually fall within a few kilometers of the eruptive vent; they are rare at distances of more than 20 km.

Accretionary lapilli composed of basaltic ash are almost invariably products of phreatomagmatic eruptions accompanied by unusually voluminous vapor columns, i.e. of magmatic eruptions through watersoaked ground. They are common, for example, in basaltic ash cones built along and close to the shores of oceanic volcanoes, and in those built by eruptions through floodplains, e.g. the Quaternary cones of the Menon Buttes, near the margin of the Snake River plains in Idaho. At this locality, spheroidal lapilli form beds ranging up to 2 m. in thickness. Individual lapilli vary from a few millimeters to approximately 3 cm. in diameter, and each has a large crystal or small rock-chip as a nucleus. But none of them shows the delicate concentric banding seen in accretionary lapilli composed of siliceous vitric ash, and none shows a comparable diminution in the size of the constituent particles outward from the nucleus. They consist, on the contrary, of unsorted, irregular fragments of basaltic glass and broken crystals of olivine of coarse-ash size, with little or no debris of fine-ash size.

Accretionary lapilli may also form when light rains fall on fine ash hot enough to cause rapid evaporation. Gentle winds may roll the moist, nucleated pellets, enabling them to pick up more ash, as rolling snowballs increase in volume.

No matter how accretionary lapilli form nor what their composition, they only accumulate on land or in shallow water; those that

sink through deep water disaggregate and are lost from the geologic record.

Ash

Incoherent pyroclastic ejecta (tephra) that measure less than 4 mm. in maximum dimension are referred to as ash, particles between 0.25 mm. and 4 mm. being classed as '<u>coarse ash</u>' while smaller particles are classed as '<u>fine ash</u>'. Distinctions between ashes may also be based on their mode of origin, precisely as in the case of lapilli, '<u>juvenile or essential ash</u>' being derived from fresh magma (Magmaglasasche), '<u>accessory ash</u>' (Lava-asche) from previously consolidated volcanic material belonging to the same eruptive center, and '<u>accidental ash</u>' from sub-volcanic basement-rocks of any type. Further separation can be made into '<u>vitric', 'crystal', and 'lithic ashes</u>' according to the predominance of glass fragments, crystals, or rock fragments.

Vitric ash is generally typified by curved, crescentic, and crudely triangular shards of glass, many of which have concave outlines produced by the shattering of pumiceous fragments with roughly spherical vesicles. But in other vitric ashes the particles are almost flat plates formed by fragmentation of bubble-walls that originally enclosed large, lens-shaped vesicles, and in still other vitric ashes the particles are formed by comminution of fibrous pumice (Ross, 1928). Indeed, consistent differences in the shapes of shards in beds of vitric ash may be used as a basis for stratigraphic correlation (Swineford and Fry, 1946).

The texture of vitric ashes and of rocks derived from them is termed <u>vitroclastic</u> (Bogenstruktur), and in most deposits laid down by airfalls, the glassy particles are neither deformed nor welded

Exceptionally, however, hot vitric ashes that accumulate rapidly close to an eruptive vent, may remain sufficiently plastic to become welded, while the glassy particles are flattened by the overlying load. In vitric ash-flow deposits, on the other hand, welding and deformation of glass-shards is widespread (see page 75). Moreover, phenocrysts in most airfall vitric ashes are unbroken whereas most of those in deposits of vitric ash-flows are broken.

Glassy basaltic ash is commonly produced when voluminous, fast-moving lava flows enter the sea (Moore and Ault, 1965). Sudden contact of water with incandescent lava results in violent steam explosions that blow out molten ejecta as fine spray and clots in sufficient amount to build littoral cones ranging to more than 80 meters in height. Approximately fifty cones of this kind are to be seen along the shores of Mauna Loa and Kilauea. Almost all of them were built on aa flows, because these allow water to come in contact with abundant incandescent surfaces, but a few ash cones, including those built in five days during the 1868 eruption of Mauna Loa, developed on pahoehoe flows where steam was trapped beneath lava crusts at or below sea level (Fisher, 1968). Cones of glassy basaltic ash and scoria may also be formed where lava spreads over ponds and wet ground, as in Iceland.

Fine ash is occasionally produced by miniature explosions from the surfaces of moving flows. Perret witnessed myriads of minute bubbles bursting on the surface of a viscous flow from Etna, producing a spray of reddish ash that rose in clouds and vortex rings.

Scoria, cinders and pumice

In the foregoing pages, distinctions between various kinds of pyroclastic ejecta were drawn largely on the basis of the sizes of the fragments; consideration must now be given to long-established and still widely used terms applied to pyroclastic ejecta more on the basis of texture and composition than of size.

More than a century ago, Scrope (1862) wrote that the "vesicular ejecta of the heavier ferruginous lavas are called 'scoriae' from their resemblance to the cinders or slags of iron furnaces. The scoriae of the feldspathic lavas, which have an inferior specific gravity, are usually still more vesicular or filamentous, and have a vitreous fracture. They are called 'pumice'."

In English and American literature, the terms 'scoria' and 'cinders' have come to be synonymous, corresponding to the German 'Schlacken' and the French 'scories'. It should be noted, however, that the French term 'cendres' and the Italian term 'ceneri' are usually applied to ejecta finer than sand and sometimes to those as fine as dust.

Most scoria are within the size-range of lapilli, though some are larger. They are generally brownish or black, and are markedly vesicular, the specific gravity of typical Hawaiian specimens ranging from 0.47 to 2.1, and the porosity from 31 to 82 per cent (Wentworth and Macdonald, 1953). The content of crystals in their glassy matrices varies widely. Some scoria-fragments duplicate the surface features and shapes of bombs, but most have the irregular forms and textures that one associates with cinders and clinkers. Unlike spatter, scoria are already solid, at least superficially, when they land from flight. Most are of andesitic or basaltic composition.

Some writers apply the term 'scoria' to the frothy tops of lava flows, and a few restrict the term to such occurrences. It seems preferable, however, to call these frothy tops 'scoriaceous', an adjective that may also be applied to cinder-like ejecta smaller than lapilli (e.g. scoriaceous ash).

Thread-lace scoria (reticulite) is produced by such extreme vesiculation of fluid basalt that the walls of the vesicles burst at the thinnest points, leaving only retracted threads of glass connecting the solid angles of contiguous polyhedrons. The delicate network of threads is so open that the average porosity approximates 98 per cent, and the bulk specific gravity is only 0.043 (Wentworth, 1938). Nevertheless, thread-lace scoria is soon saturated when immersed in water and sinks because of free interconnection between the vesicles (Macdonald, 1967). The characteristic mode of occurrence is as thin crusts on gas-rich pahoehoe flows (laves en échaudés) close to the eruptive vent, but scoria of this type may also be of pyroclastic origin.

Distinction between pumice and scoria has always been rather arbitrary, though Scrope's suggestion that it be based mainly on composition has generally been followed. To most geologists, the term 'pumice' refers to vesicular, light-colored ejecta of intermediate and siliceous composition. Vesicle-walls are generally intact, and the vesicles themselves are so numerous that pumice floats on water for prolonged periods (page 31). The bulk specific gravity of scoria, as noted already, may be less than 1, though it is usually much more, whereas that of pumice is rarely more. Phenocrysts vary in amount from nil to approximately 50 per cent.

The textures of pumice depend on many factors, including the extent to which vesicles nucleate in the magma prior to and during

eruption, the extent to which they expand or coalesce prior to solidification
of the magma, and the extent to which the magma flows before it solidifies
(Ewart, 1963). In some kinds of pumice, the vesicles are tubular and sub-
parallel, and these may be so numerous as to give the fragments a fibrous
texture; in other kinds, the vesicles are approximately spherical; in still
others they are extremely irregular. Moreover, the size of the vesicles and
the thickness of the vesicle-walls vary widely.

Changes may be noted in the size, number, and shape of pumice-
vesicles not only within ejecta of different eruptive cycles, but within
those of individual cycles. For instance, there is a progressive decrease
in vesiculation with time, reflecting a progressive loss of volatiles,
in each of the ten eruptive cycles that produced the Younger Taupo pumice-
deposits of New Zealand (Ewart, 1963). Most of the pumice that fell from
the air prior to the eruption of the glowing avalances of pumice from
Mount Mazama (Crater Lake) Oregon, is characterized by roughly spherical
vesicles, but at least one layer is rich in fibrous pumice. Murai (1963)
says that stretched, tubular vesicles are characteristic of the fine-
grained pumice in glowing-avalance deposits of Krakatoan type (see page 54),
because vesiculation begins within the eruptive conduit or even in the
underlying magma chamber; most of the gas-emission takes place before
discharge, and the vesicles are drawn out by flowage of the rising magma.
And Ewart points out that around Lake Taupo, the later pumice of a given
shower tends to have better developed flow-structure than the earlier
pumice. Normally, magma in the upper part of a conduit immediately
prior to an eruption is cooler and richer in gas than that at lower
levels; consequently, the initial blasts are usually more violent than
those which follow, and the pumice of the initial deposits therefore
tends to be strongly inflated and largely shattered into minute shards.

The crusts of many dark, glass-rich lava flows of intermediate and siliceous composition are pale-colored or whitish, and strongly vesiculated. Some volcanologists describe these crusts as 'pumice', but it seems preferable to call them 'pumiceous', reserving the term 'pumice' for pyroclastic ejecta of the type just discussed.

PYROCLASTIC ROCKS

Compaction and cementation convert loose fragmental ejecta into pyroclastic rocks, a preferred classification of which is given in Table 2, page 2 . In the notes that follow, rocks formed by subaerial eruptions are discussed first and in order of diminishing coarseness; intrusive pyroclastic rocks are discussed later. It must be emphasized at the outset that while it may be easy to classify a single hand-specimen on the basis of the size, shape, and composition of its constituents, a pyroclastic deposit may exhibit a bewildering admixture of rock-types, and in many instances, knowledge of field-relationships is an obvious pre-requisite to proper naming of a rock or of a deposit.

Agglomerates and agglutinates. Few terms in volcanological literature are interpreted in more ways than 'agglomerate'. Indeed, the tendency has been to apply the term to any heterogeneous accumulation of coarse volcanic debris, no matter how it was formed. It seems desirable

to restrict the term to pyroclastic deposits composed chiefly of bombs, i.e. coarse, subangular and rounded ejecta blown out while partly or entirely in a plastic condition. On this basis, almost all agglomerates are of intermediate or basaltic composition, and instead of being heterogeneous are usually monolithologic. The matrix between the bombs generally consists of scoriaceous fragments, but these may be mingled with accessory and accidental ejecta. And because agglomerates result from rapid accumulation close to the eruptive vents, they exhibit little, if any sorting or stratification. Those that occupy volcanic conduits may be referred to as 'vent-agglomerates'.

Eruption of extremely fluid basaltic bombs (cow-dung bombs) produces agglutinate (Schweissohlacken) if the fragments remain plastic enough on the outside after landing to anneal to one another. When discharge takes place from a small vent, an agglutinate-cone develops; when it takes place from elongate fissures, agglutinate-ramparts develop, and when simultaneous eruptions take place from a closely spaced, anastamosing network of fissures, extensive agglutinate-fields develop, as in North Jan Mayen (Hawkins and Roberts, 1963). If thick piles of agglutinate accumulate on steep slopes, they may slide downslope as 'rootless flows'.

Although the term agglutinate is normally restricted to welded basaltic spatter, hot and plastic ejecta of intermediate and siliceous composition may fall close enough to their vents to become firmly welded and even to flow downslope. The textures of such welded airfall ejecta closely resemble and may be indistinguishable from those that characterize the vastly more extensive welded ejecta laid down by glowing avalanches (see pages 75-78). Most airfall welded ejecta, however, exhibit a 'mantle bedding' that conforms to the underlying surface, whereas

the layering in welded ejecta of glowing avalanches is only exceptionally controlled by underlying surfaces. Even layers of mantle-bedded ejecta a few meters thick may be intensely welded, as may be seen in the Zavaritsky caldera in the Kurile Islands (Gorshkov in Cook, 1966).

No airfall welded ejecta are better known than those in the Phlegraean Fields, near Naples, and in other Italian volcanic fields, where they are referred to as 'piperno' (Rittman, 1962; Gottini, 1963). These are characterized by flattened, flamelike clots of dense, black obsidian and lighter colored clots of pumice in a welded matrix of ash. The obsidian clots are thought to be fragments blown from the de-gassed, but hot surficial parts of a lava lake, while the pumice clots represent fragments that were somewhat richer in gas, while the fine, ashy matrix represents the live, upwelling, foaming magma responsible for the ex-plosions.

Breccias and Tuff-breccias

Pyroclastic rocks resulting from subaerial eruptions and consisting chiefly of angular blocks blown out while solid are classed as 'volcanic breccias'; those occupying conduits are called 'vent breccias', and those with an abundant matrix of ash-size fragments are called 'tuff-breccias'. The composition of these coarse deposits is extremely variable, but those consisting of accessory ejecta of inter-mediate and siliceous composition are probably the most abundant. Some consist entirely or almost entirely of accidental, non-volcanic debris.

Breccias and tuff-breccias originate in a great many ways. Some result from explosive shattering of plugs that seal conduits during periods of quiescence; some represent the initial products of new vents; while others are deposits of glowing avalances discharged from the flanks

of steep-sided domes of Pelean type; and still others are products of
short-lived steam-blast eruptions in which only solid fragments are
ejected. None are more widespread than those laid down by blocky
mudflows (lahars).

Many breccias and tuff-breccias of pyroclastic origin are
difficult to distinguish from autoclastic flow breccias produced by
differential movements within lava flows that are almost, if not
completely solid. If auto-brecciation continues long enough, flows
may be converted to masses of angular blocks in a finely comminuted
matrix deceptively like ash. Usually, however, microscopic study of
the matrix and transitions from auto-brecciated into non-brecciated
material provide an answer.

No matter how breccias and tuff-breccias, whether by airfalls
close to eruptive vents, by glowing avalances, or by lahars, they
accumulate rapidly, and hence are poorly sorted and poorly stratified
or unstratified.

Lapillituffs and Lapillistones

Pyroclastic rocks in which lapilli are decidedly the main
constituents are called lapillistones (Fisher, 1966), while the more
abundant ones in which lapilli and finer constituents are present in
roughly equal amounts are called lapillituffs. Both may consist entirely
of essential, accessory, or accidental ejecta; on the other hand, they
may consist of mixtures in all proportions.

Tuffs

Tuffs are lithified ashes, and are commonly subdivided into
vitric, crystal, and lithic types according to the predominance of

glass particles, phenocrysts, and rock fragments. With rare exceptions, tuffs produced from the deposits of ashfalls are unwelded, because most ash is cool or cold when it lands from long flight through the air; however, airfall ashes that fall close to their eruptive vents may remain hot and plastic enough to anneal together, producing welded tuffs, as described already.

Tuffs of airfall-origin are generally much more widespread, better sorted and more distinctly stratified than are coarser pyroclastic rocks. How they differ from tuffs formed by pyroclastic flows (glowing avalanches) is discussed in the sequel.

STRUCTURES IN AIRFALL TEPHRA DEPOSITS

Bedding and Sorting. The deposits of airfalls, unlike those of pyroclastic flows, are generally well-bedded and well-sorted except close to the source, where they accumulate rapidly from turbulent clouds, and near the margins of extensive sheets, where the ejecta are extremely fine-grained.

Bedding generally becomes more pronounced as the degree of sorting improves. It depends on many factors, in addition to distance from the vent. Variations in the strength and duration of eruptions and in the length of quiet intervals, as well as changes in the directions of eruptions and in the direction and velocity of winds play a part. Even rain may be influential. For instance, during the 1963-1965 eruptions of Irazu, Costa Rica, much accessory, lithic ash was discharged, along with subordinate scoria and bombs of basaltic andesite. The fine ejecta accumulated on the upper slopes of the volcano in layers measuring a few millimeters to a few centimeters in

thickness. Ejecta that fell during the wet season could be distinguished easily from those that fell during the dry season, because downward percolating rainwater removed the finest particles and deposited them along less permeable horizons (Murata et al., 1966). It should also be noted that unusually fine bedding is to be seen in 'littoral cones' of basaltic ejecta that are sometimes built where lava flows enter the sea (page 14), and also in nearshore cones of basaltic ash built where rising magma comes in contact with copious groundwater to produce phreatomagmatic eruptions. In both cases, voluminous discharge of water vapor and resultant eruption-rains must influence the fall of ejecta and accentuate the layering of the deposits.

Within the products of a single eruption or of a brief eruptive cycle, bedding tends to show 'normal grading' from coarse material below to finer material above. But within a thick succession of deposits, representing several eruptions or a long eruptive cycle, the average size of the ejecta may increase upward, reflecting diminishing gas-pressure of the erupting magma. 'Reversed graded bedding', as noted earlier, may also be seen in waterlaid deposits of pumiceous ash owing to the fact that finer particles tend to sink faster than larger, more vesicular fragments.

Airfall deposits usually exhibit 'mantle bedding' except where they accumulate on rugged topography, the layers being draped over the pre-existing surface, as if 'ducoed' from above. But where ejecta accumulate on steep slopes or against cliffs, they are subject to repeated slides, particularly during and after heavy rains, and hence mantle bedding is usually lacking. 'Cuspate bedding' is developed where layers of ejecta are slightly domed above buried trunks, bushes, and other objects (Wentworth, 1938).

'Cross bedding' may result from changes in the strength and direction of winds during an eruption, from changes in the directions of discharge, and from the fall of ejecta from closely spaced vents erupting simultaneously or at approximately the same time.

Channeling. Loose pyroclastic ejecta may be rapidly channeled by erosion and be completely stripped within a short time. This is particularly the case among pumiceous ejecta that accumulate on steep slopes in regions marked by long and heavy rains. The mountainous region near Guatemala City provides a graphic illustration, for within a few kilometers the number of Recent airfall-pumice layers mantling the slopes may vary from zero to six, while the intervening valleys are deeply filled with flat-topped deposits of inwashed pumice (Williams, 1960). On the other hand, in regions of relatively low relief and moderate or little rainfall, such as the Taupo region, New Zealand, and the area northeast of Crater Lake, Oregon, ash- and pumice-blankets may persist for thousands of years with little modification.

Bomb-sags. When heavy bombs or blocks land on unconsolidated, bedded ash, particularly if it is dry, they dent the bedding to form pits or bomb-sags. During the 1968 eruption of Arenal volcano, Costa Rica, impact pits measuring a meter across were formed at a distance of 5 km. ~~If the bombs or blocks are~~. If the bombs or blocks are subsequently buried by ash, the bedding is either unaffected or is gently arched above them. Coarse ejecta do not produce sags if they fall in deep water, but, other things being equal, they produce sags of increasing size as the depth of shallow water diminishes. Thus, an upward increase in the size of bomb-sags among ejecta blown out by steam-blast eruptions through Laguna San Pedro, in southeastern Guatemala, testifies to progressive emptying of a crater lake (Williams, McBirney and Dengo, 1964).

Fused Tuffs. Airfall and fluviatile pumiceous beds, particularly
if they contain abundant groundwater, may be extensively fused by intrusions
or by being buried under a lava flow. For instance, a Tertiary rhyolite
flow in southern Nevada poured down a valley cut in well-bedded and
massive tuffs erupted from the same vent (Christiansen and Lipman, 1966).
The tuffs were fused and converted to dense glass, locally to a depth of
75 m. or more beneath the lava, and the fused zone is everywhere parallel
to the sides of the valley, cutting the bedding at high angles. Fusion
was brought about partly by conduction of heat from the lava but chiefly
by lowering of the melting temperatures of the tuff as groundwater was
converted to superheated steam. The fused tuffs and lava then cooled
as a unit so that locally the basal vitrophyre lies at the base of
the flow and elsewhere well within the zone of fused tuff.

DISPERSAL OF TEPHRA BY WINDS

The distribution of airborne ash depends largely on the direction
of winds at intermediate and high altitudes, between approximately 4,500
and 13,000 meters. And because upper-air winds generally trend more or less
east-west, the distribution of Recent ash is predominantly east or west of
the eruptive vents, particularly within the tropics (Eaton, 1964; At high
altitudes, the ash is carried by laminar flow, but at lower altitudes,
particularly in the vicinity of the vents, much of it is distributed by
turbulent flow and the directions of dispersal are considerably more
variable. The following example illustrates these points.

The culminating outburst of Mount Mazama prior to the collapse
which produced the Crater Lake caldera, Oregon, approximately 6,600 years
ago, began with showers of airborne ash and pumice, the average size of

the ejecta increasing as activity continued until the airfalls were finally followed by glowing avalanches of pumice and scoria. For the first 100 km. from Crater Lake the thickness of the airfall-deposits diminishes rapidly to 15 cm.; farther away, the thickness diminishes much more gradually. Around Mount Rainier, 450 km. from Crater Lake, the thickness is 5 cm., and in southern British Columbia, 1000 km. from the source, it is still 5 mm. Recent calculations (Williams and Goles, 1968) indicate whereas approximately 12 km^3. of ash fell within the 15 cm.-isopach, between 16 and 24 km^3. of finer ejecta fell beyond that line. Close to the source and close to the ground, the ash was transported by turbulent flow; farther away and at higher elevations, transport was mainly by large-scale, rapid laminar flow. Hence, the relatively abrupt diminution in the rate at which the deposits thin beyond the 15 cm.-isopach. The total area within which Mazama ash has been recognized exceeds 1 million km^2. The content of crystals and rock chips within the ejecta decreases rapidly away from the source, while that of pumiceous particles and glass shards shows a corresponding increase until only vitric dust is to be found near the limits of the fall.

Between 1900 and 1960, according to Eaton, 33 measured ash-columns rose to heights of more than 6 km., 17 rose more than 9 km., and several rose more than 20 km. In equatorial regions, clouds generally travel faster in the upper atmosphere than they do at higher latitudes. During the catastrophic eruptions of Krakatoa in 1883, fine ash rose to heights of more than 50 km.; one margin of the recognizable ash-fall lay 2,500 km. west of the volcano, and the total area within which recognizable ash fell was approximately 827,000 km^2. Much impalpable dust remained in the upper atmosphere for several years, causing brilliant sunsets all over

the world. The dust-clouds encircled the globe in 13½ days, and at altitudes of 30 to 50 km. their average velocity was 2 km. per minute.

Less than 12 hours after the 1875 eruption of Rudloff Crater in the Askja caldera, Iceland, rhyolitic ash began to fall in Norway, 1,300 km. away; 10 hours later it began to fall in Stockholm, 1,900 km. away. Ash from the 1912 eruption in the Valley of Ten Thousand Smokes, Alaska, covered more than 100,000 km^2. to a depth of more than 6 mm., and 2,400 km^2. to a depth of more than a meter. Maps showing the distributions of ashfall deposits from Quizapu volcano, Chile, from Icelandic volcanoes, Crater Lake, and some Japanese volcanoes are presented in figures 1 to 7.

Basaltic ash is generally much less widespread than siliceous ash. However, ash from Vesuvius has been recognized in Sicily and along the Dalmatian coast, approximately 350 km. away. No Hawaiian eruptions have produced beds of basaltic ash more than 0.3 m. thick at distances of 8 to 16 km. from the sources; indeed, no historic eruptions on the island have discharged ejecta with so much as a tenth of this volume (Wentworth, 1938).

Factors that control the erosion and redistribution of ash by running water and wind are too numerous to discuss in detail. They include the lithologic character and coarseness of the ejecta, amount and rate of rainfall, extent of mass-transfer by slides, amount and kind of vegetation as these influence the rate of runoff, nature of the underlying topography, strength and direction of winds, and the volume and velocity of streams. For a keen analysis of these subjects, the reader should consult Segerstrom's erosion-studies at the Paricutin volcano, Mexico (1950).
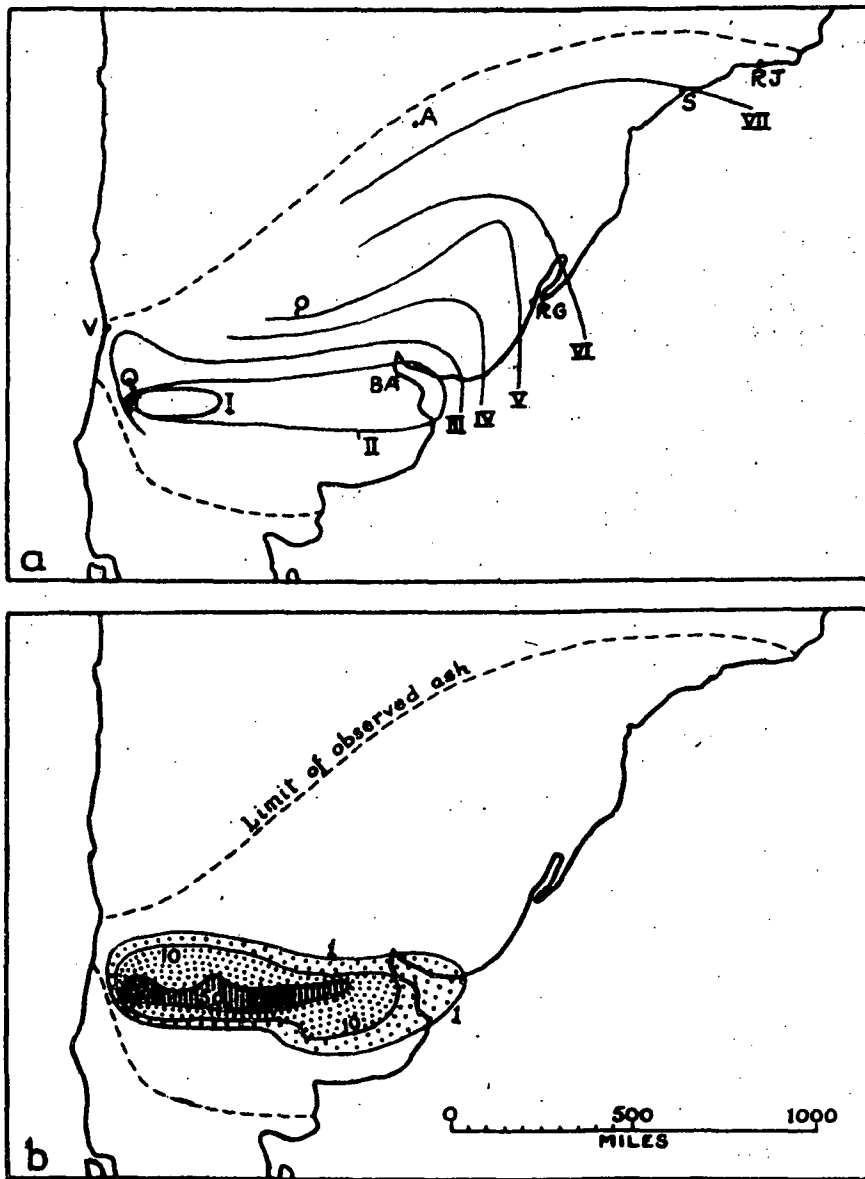
Figure 1. . The Pumice erupted by Quizapu, Chile in April 1932.
a - Position of the front of the pumice showers. I at 6 p.m., April 10;
II - at 6 a.m., April 11 ; III - at noon, April 11, IV - at noon, April 12 ; V -
at noon, April 13 ; VI - at noon, April 14; VII - at noon, April 15. Q = Quizapu;
V = Valparaiso; O = Olguita; BA = Buenos Aires; RG = Rio Grande ; R.J = Rio de
Janeiro; A = Asuncion. s=Santos. b = Thickness of deposits in millimeters. Areas
in black covered by more than 100 mm.
(After W. Larsson; Bull. Geol. Instit. Upsala, Vol. 26, 1936).
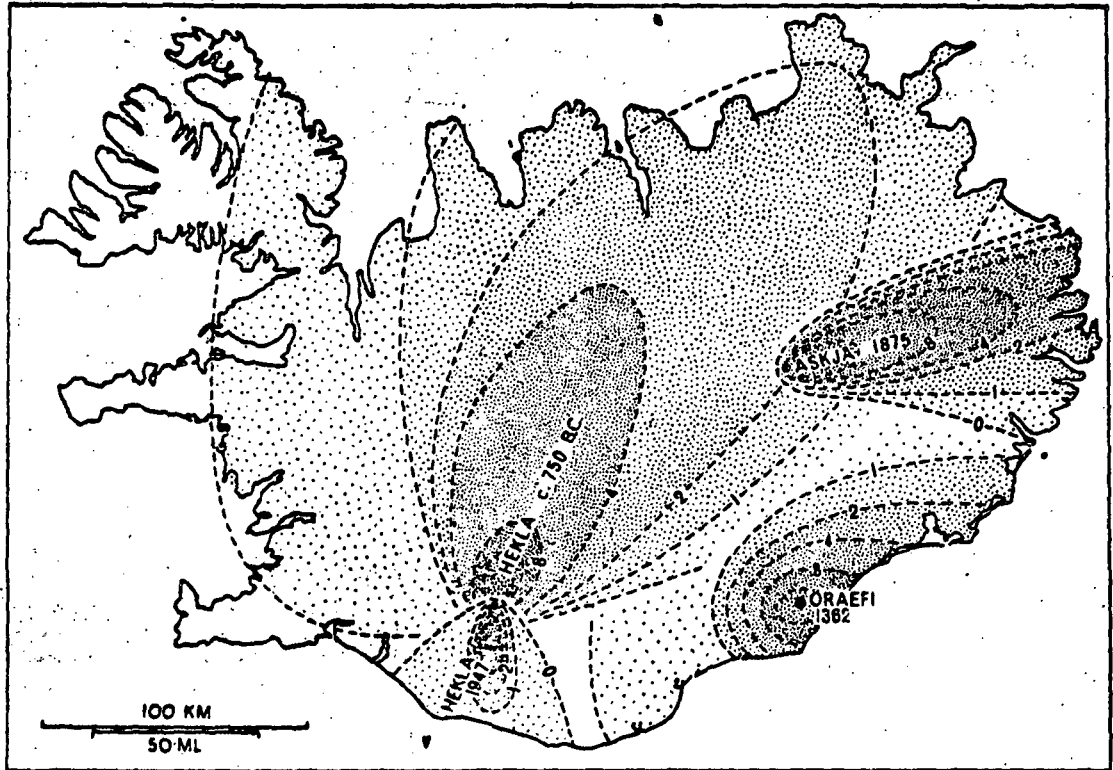
Fig. 6. Isopachyte map of ash layers from four Icelandic eruptions. In each the thickness is in
2   inches. (After Thorarinsson).

DISTRIBUTION
and **THICKNESS** *of*
CRATER LAKE PUMICE
South Central Oregon

Fig. 16. Map showing distribution and thickness of Crater Lake pumice. (Drawn by A. W. Severy.)

636 Y. KATSUI
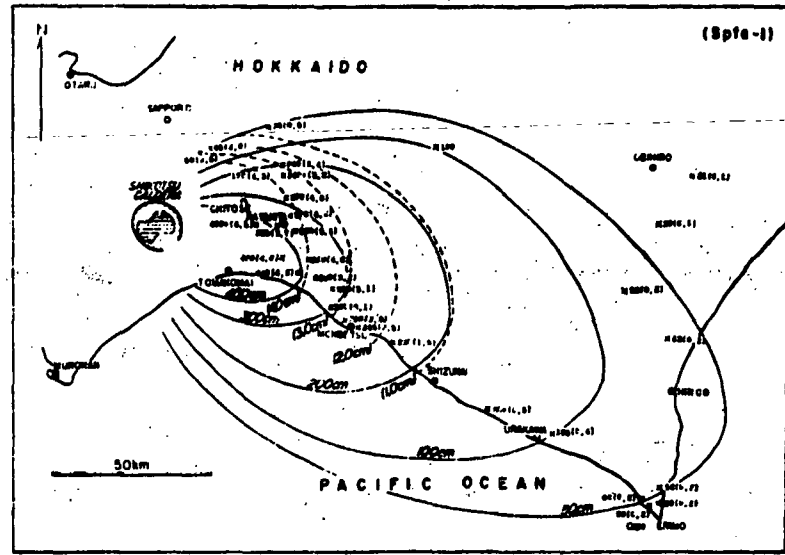
full line : thickness contour of the deposit.
broken line: contour of arerage of maximum grain size of pumice.
  x   : observed point showing thickness and grain size in cm.
Fig. ●. Distribution of the Shikotsu pumice-fall deposit (Spfa-1).
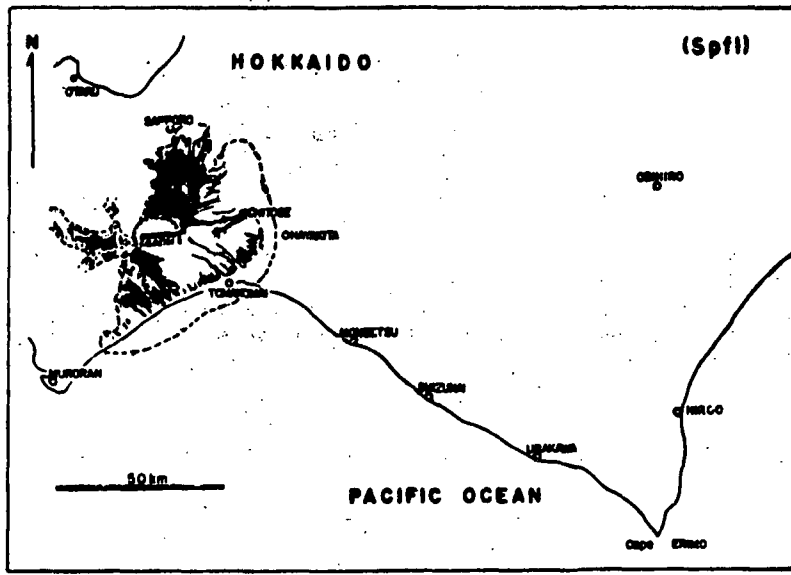
Fig. 4. Distribution of the Shikotsu pumice-flow deposit (Spfi-1 and 2). after
DOI and OSANAI (1956)

Figure 26. Pumice-fall and pumice-flow deposits
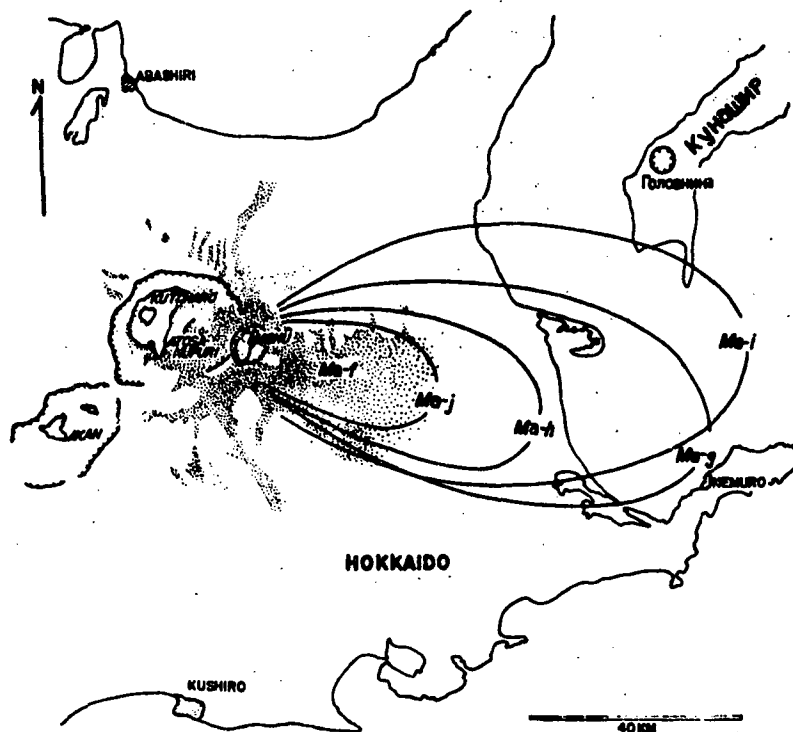 4 around the Shikotsu caldera, Hokkaido.
      (After Y. Katsui, 1963).

HOKKAIDO

KUSHIRO

40 KM

Fig. 9. Map showing the distribution of the Mashû pyroclastic deposits erupted
5 during the culminating phase.
Ash-fall and pumice-fall deposits, Ma-j, i, h and g, are represented by
10cm thickness contour lines; and pumice-flow deposit, Ma-f, is shown
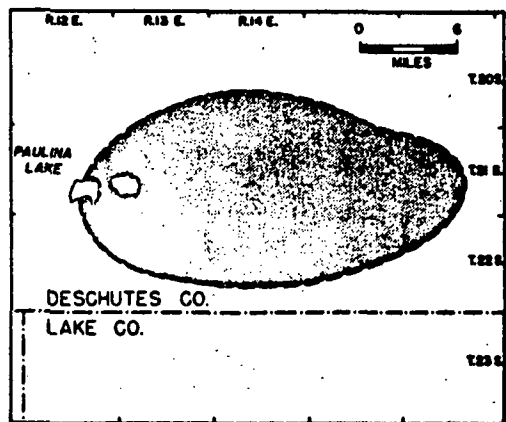by dotted area.

Figure 26. Pyroclastic deposits around the Mashu
   5   caldera, Hokkaido. (After Y. Katsui,
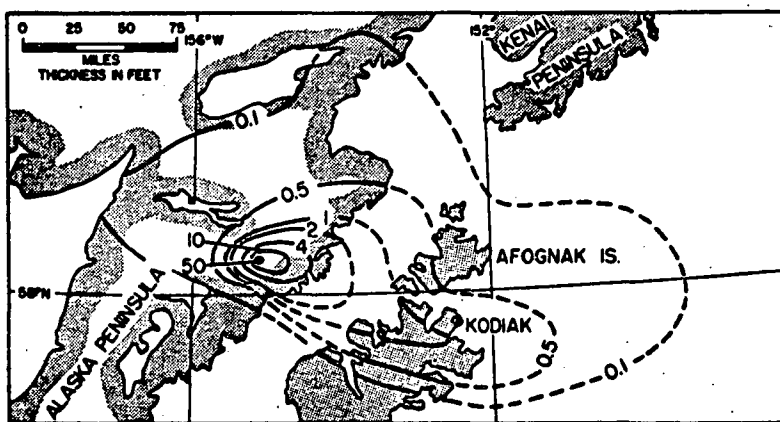   1963).
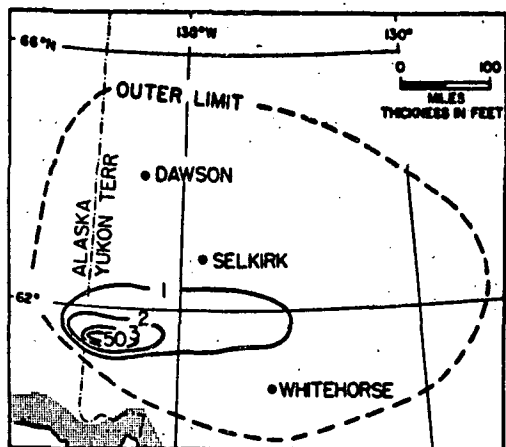
MOUNT NATAZHAT (?) ALASKA-CANADA
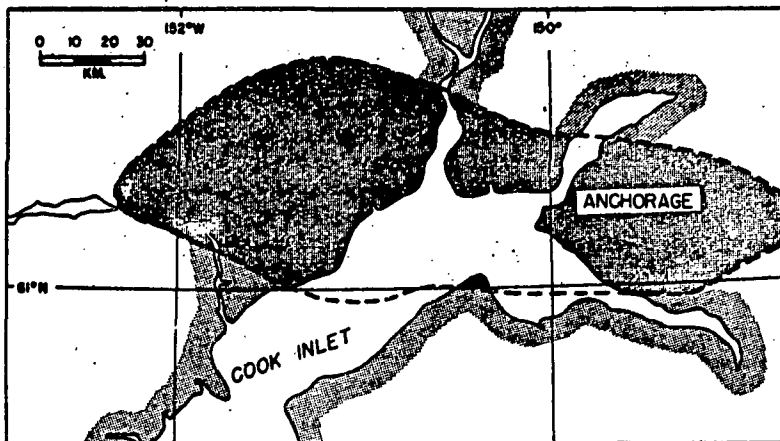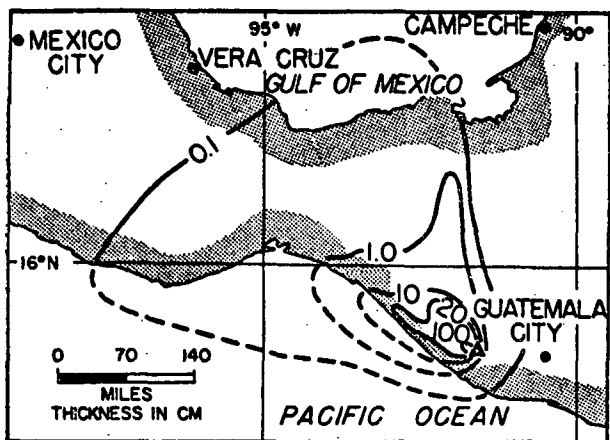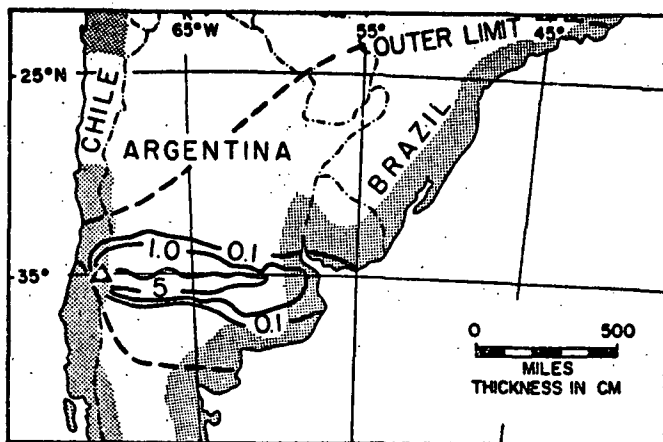
MT. SPURR, ALASKA

NEWBERRY, OREGON

MOUNT KATMAI, ALASKA

FIG. 6.—Isopach and distribution maps of ash falls in Alaska, Yukon Territory, and Oregon. Note variations in scale (data from Capps, 1915; Griggs, 1922; Moore, 1937; and Wilcox, 1959).
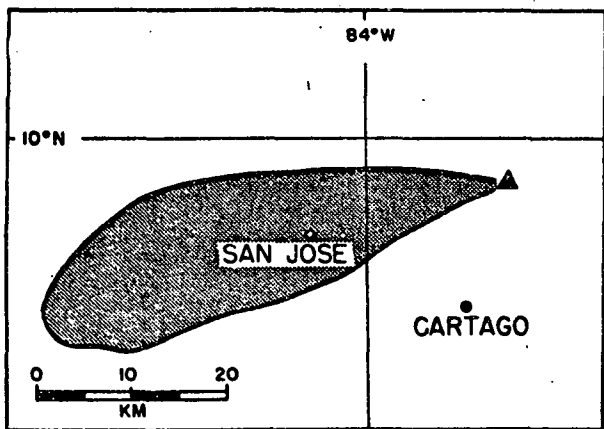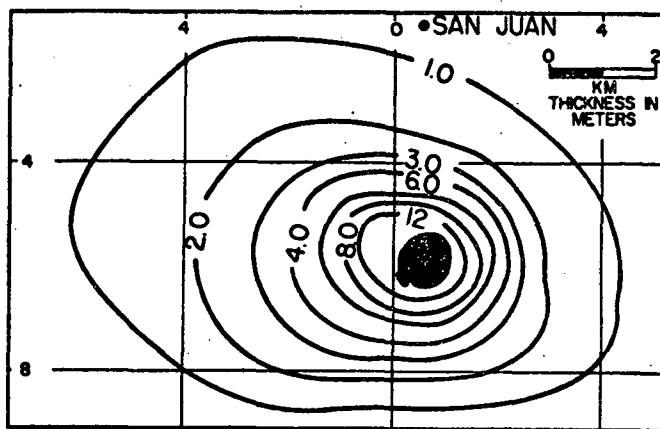
From Eaton (1963).

SANTA MARIA, GUATEMALA

QUIZAPU, CHILE

IRAZU, COSTA RICA

PARICUTIN, MEXICO

Fɪɢ. 7.—Isopach and distribution maps of ash falls in Central and South America. Note variations in scale (data from Sapper, 1905; Tristan, 1923; Larsson, 1935; and Segerstrom, 1950).

From Eaton (1963).

EOLIAN DIFFERENTIATION OF TEPHRA

Deposits of airborne pyroclastic ejecta generally exhibit lateral, and, not uncommonly, vertical variations in the nature and size of their constituent fragments. Vertical variations may be caused in many ways, e.g. they may reflect an increasingly basic composition of the ejecta during a single eruptive cycle, as at Vesuvius in 79 A.D.; they may reflect diminishing gas pressure as activity proceeds, the fragments of ash and pumice tending to increase in size upward; or an upward diminution in the number and size of lithic fragments in a given layer may reflect the opening of a new eruptive conduit.

Lateral variations, on the other hand, reflect variations in the settling velocities of fragments, for normally the largest and heaviest fragments fall nearest the vent while progressively smaller and lighter fragments fall at increasing distances. Not only do fresh magmatic ejecta tend to diminish in size away from the source, but the proportion of admixed crystals and of lithic fragments also tends to diminish, until at the outermost limits of an ashfall-deposit most of the ejecta consist of glass dust. These, however, are only generalities. How soon ejecta land from flight depends to some extent on their shapes; moreover, extremely vesicular fragments of large size may fall at the same time as much smaller fragments of dense glass devoid of vesicles.

The degree of sorting of ejecta is largely a function of wind velocities, i.e. time, as well as distance of transport, and it is also influenced by the nature of wind-motion, whether turbulent or laminar. Wentworth (1938) says that sorting is most effective among ejecta of sand- and fine gravel-size, and least effective among bombs and lapilli, on the one hand, and extremely fine ash, on the other.

Sorting by size is very much more pronounced among deposits of airfall ejecta than it is among those of glowing avalanches (ash- and pumice-flows), as illustrated in figures 12 & 13. The subject has been discussed by Fisher (1964, 1966), Murai (1961), Kuno (1941) and by Kuno et al. (1964).

Early settling of crystals and lithic fragments near an eruptive vent and of glassy, vesicular fragments at greater distances has been observed during many eruptions. For instance, Koto (1916-1917) noted that whereas more than three-quarters of the andesitic ash erupted from Sakurajima volcano, Kyusyu, in 1914, was made up of sand- and silt-sized particles of hypersthene, plagioclase, and glass, the ejecta that fell to a thickness of 0.007 to 0.008 mm. on Tokyo, 1,000 km. away, contained only a single chip of hypersthene and only 8% plagioclase, the remainder consisting of glass dust.

Ash that fell close to the source during the 1902 eruption of the Soufriere of St. Vincent was unusually rich in crystals. Crystals of pyroxene, plagioclase, and magnetite made up 45% of the bombs and 73% of the juvenile ash finer than 2 mm. (Hay, 1959). Yet the ash that fell on Jamaica, 1,600 km. away, consisted entirely of particles of glass-dust averaging 0.02 mm. in diameter. Ash-fall layers deposited during the 1941 eruptions of Gunung Smeru, Java, show a decrease from 15% to 8% in heavy minerals and an increase from 40% to 50% in glassy particles as they are traced from 11 to 39 km. away from the volcano (Baak, 1949). However, the proportions of the various kinds of mafic minerals remained essentially the same within this interval. Some of the older layers of ash related to the Mount Lamington volcano, Papua, show a marked decrease in their content of heavy minerals away from their source, but other layers exhibit no significant variations.

Study of the ash blown from Quizapu volcano in the Chilean Andes in 1932 shows that eolian differentiation of ejecta may lead to variations in composition comparable with those that result from magmatic differentiation by crystal-settling in volcanic reservoirs. The eruption began on April 10 at 6 a.m., and reached its maximum intensity a few hours later. The ash-front traveled eastward across Argentina at an average rate of 69 km. an hour, moving at hurricane speed at first and then less rapidly. Successive positions of the ash-front are depicted in figure 1 a. After 34 hours, fine ash fell on Rio de Janeiro, 1,350 km. from the source. The Sierra de Cordoba, east of the Andes, acted as a wind shadow, and turbulent air on its lee side caused a local thickening of the layer of ash (figure 1 b).

The ejecta generally became finer away from the volcano, but exceptions were common, chiefly because of variations in wind velocity and in the vesicularity of the pumiceous particles. For example, ash that fell in Olguita, 780 km. away, was better sorted and its average grade-size was less than that which fell approximately two days earlier on Buenos Aires, 1,120 km. away. Moreover, fine pumice that fell on Buenos Aires was heavier (Sp. Gr. - 0.633) than that which fell only 250 km. from the volcano. Extremely vesicular, coarse pumice fell side by side with much smaller fragments of comminuted pumice poor in vesicles.

Crystals mixed with the pumiceous particles tended to diminish as the time of transport increased, and mafic crystals tended to fall before plagioclase crystals of the same size. Accordingly, the bulk chemical composition of the ejecta varied laterally. Coarse ejecta that fell near the volcano had the composition of quartz diorite, with a silica percentage of approximately 64, whereas glass-rich dust that stayed in suspension a day or more had a granitic composition, with a

silica percentage of approximately 70. The content of other oxides in the ejecta also varied with distance from the source, in much the same way as they do in magmas differentiated by crystal settling. Similarly, andesitic ash blown for long distances during the eruption of Krakatoa in 1883 had silica-percentages of 68.5 to 69.4, whereas that which fell close to the source had silica-percentages of 60.1 to 66.3 (von Wolff, 1914). On the other hand, crystal-rich ashes blown for long distances may be less siliceous than relatively crystal-poor bombs and lapilli that fall close to the vent, as was the case during some of the eruptions of Mont Pelé in 1902. Clearly, a single sample of ash may be far from representing the composition of the magma from which it was derived.

OCEANIC DISPERSAL OF PUMICE AND ASH

Fine glass dust may float for long periods on fresh water, but tends to coagulate and settle rapidly in brackish water or in the sea. Coarse glass-ash also settles rapidly, particularly if the particles contain few or no vesicles. But fragments of pumice, especially if they are large, can float for tremendous distances and for very long periods. This is why pumice and ash deposits laid down in lakes usually exhibit reverse graded bedding.

A graphic illustration of the efficacy of ocean currents to disperse pumice was provided by the eruption of Barcena volcano in the Mexican Revillagigedo Islands in 1952 (Richards, 1958). Abundant lumps of trachyte pumice reached Hawaii after 264 days, with a mean drift-rate of 800 m. an hour. Some lumps reached Johnston Island, 6,100 km. from Barcena, in 225 days, including a few hundred kilograms of rounded pieces measuring up to 7.5 cm. in diameter. Other lumps reached Wake Island and

the Marshall Islands in 560 days, having traveled almost 9,000 km. Most of the fragments that landed on Wake Island were of walnut- to potato-size, but at least one fragment measured 19 cm. in length. Dense rafts of Barcena pumice were seen close to the Western Caroline Islands, all of them encrusted with barnacles, and many that landed on the Marshall Islands had corals attached to them.

Rhyolitic or rhyodacitic pumice erupted in the South Sandwich Islands, Antarctica, in March 1962 was also dispersed widely by ocean currents (Gass et al., 1963; Sutherland, 1965). Soon after the eruption, a 'raft' of floating pumice covered more than 5,000 km^2., approximately a fortieth of this area being covered to a depth of more than 5 meters. The total volume of the raft was 0.6 km^3. Strandings were first reported on the coast of Tasmania, 13,000 km. from the source in late December, 1963, or early January, 1964. During January, 1965, pumice-gravel was washed on to the south coast of Western Australia. One pumice-raft traveled 13,000 km. at an average rate of 30 km. a day. Larger lumps, being more responsive to the winds, traveled much faster than smaller ones, but the average drift-rate of even fine pumice forming the tail of the raft was between 10 and 12 km. a day.

During the great eruption of Cosequina volcano, Nicaragua, in 1835, airborne ash and pumice fell on Jamaica and Bogota, covering an area 2,500 km. across, and floating pumice covered the Pacific Ocean for a distance of 250 km., interfering greatly with the navigation of ships (Williams, 1952a).

Well over a century ago, the great naturalists, Bates and Darwin, one working in the Amazon Basin and the other on oceanic islands, independently reached the conclusion that floating pumice may be a potent means

of dispersal of many animals and plants, and our own studies in the

Galápagos archipelago (McBirney and Williams, press) lend support to

their opinions. Lumps of pumice that lie on river banks and beaches

before being washed into the sea may carry with them, embedded in soil,

sediment, and organic debris not only the eggs of insects and seeds of

plants but the young of both, and some of these undoubtedly survive

transport to distant islands. Copious volumes of pumice erupted during

Late Tertiary and Quaternary times by volcanoes in Central America and

the Andes must have been carried during the space of a few months to the

Galápagos archipelago by the westward-flowing Humboldt and El Niño

currents, and it seems certain that the islands were populated in part

by this means.

Within the tropics, winds and ocean currents generally trend

in approximately east-west directions (fig. 8). Thus, Neeb's study (1943) of

Quaternary ash deposits on the sea-floor in the East Indies shows that

the distribution-pattern reflects local wind directions at high altitudes

as clearly as does the distribution of ash on land (fig. 9). Submarine ash-

patterns do not seem to have been modified much by ocean currents.

Outside the tropics, however, the directions of winds and ocean currents

are much more variable, and hence the distribution of both subaerial

and submarine deposits of ash and pumice generally varies much more,

as figure 10 exemplifies.

At least 27 beds of altered rhyolitic ash (bentonite) of

Ordovician age covered the sea-floor over an area of between 750,000

and 100,000 km^2. in what is now the Upper Mississippi Valley (Eaton, 1964; fig. 11).

The ejecta seem to have been blown from volcanoes in the southern part of

the Appalachians, and their aggregate volume probably exceeds 300 km^3.

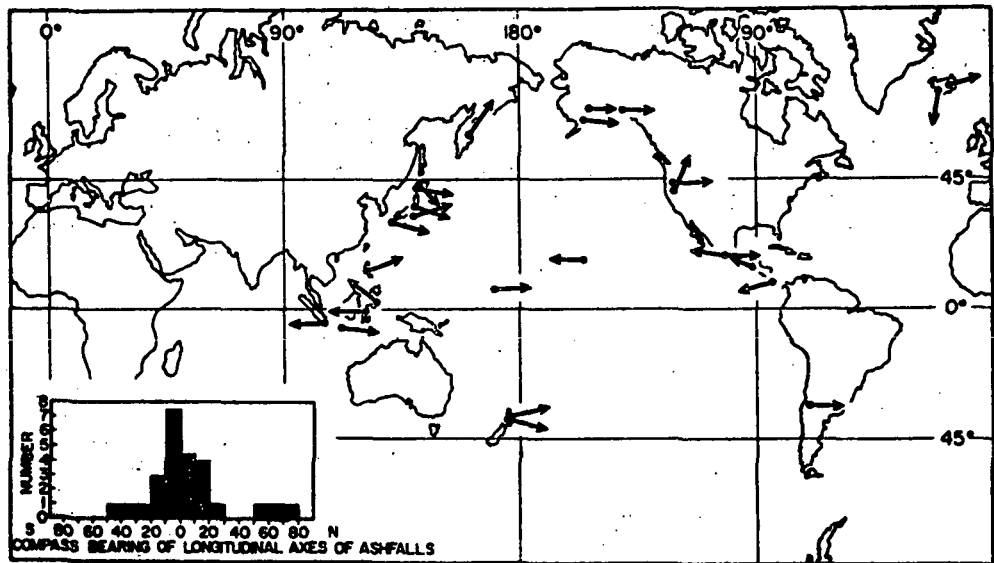FIG. 8.—World-wide distribution of longitudinal axes of Recent ash falls. Inset shows histogram of compass bearings of these deposits; the predominance of an east-west component is obvious. Notable exceptions are evident in Iceland, the northwestern United States, the Soviet Union, Japan, and the East Indies. The east-trending arrow in mid-Pacific Ocean represents radioactive fallout from a nuclear-bomb test.
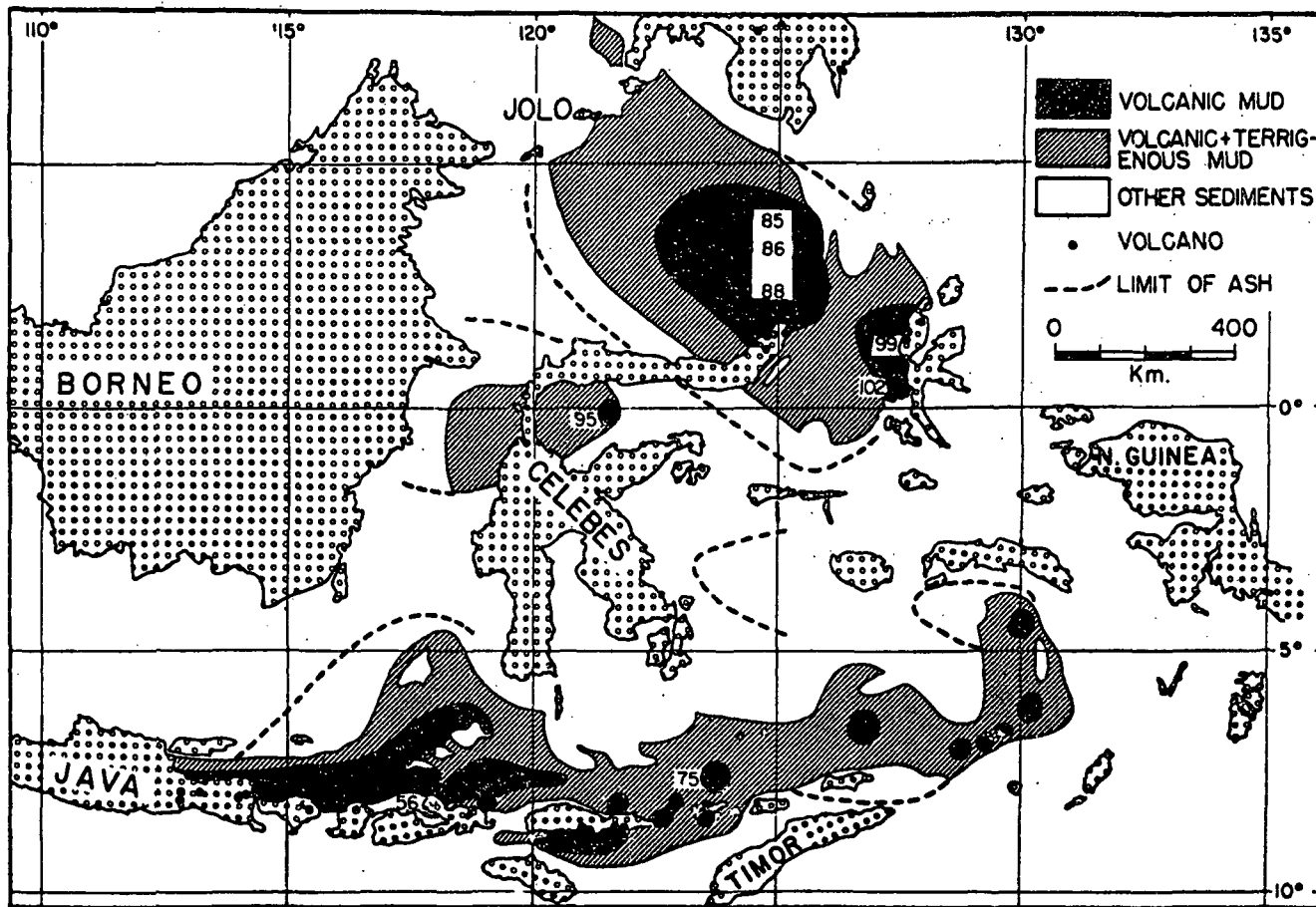
FIG. 8.—Distribution of late Quaternary volcanic ash on the sea floor in the East Indies. Patterns of the major deposits are largely the result of eolian transport. The preservation of these deposits and their reflection of the winds responsible for their transport suggest that tuffs and bentonites in ancient marine rocks could be used to determine the direction of high altitude winds in the geologic past. Numbers refer to volcanoes mentioned in the text (after Neeb, 1943).

From Eaton (1963).
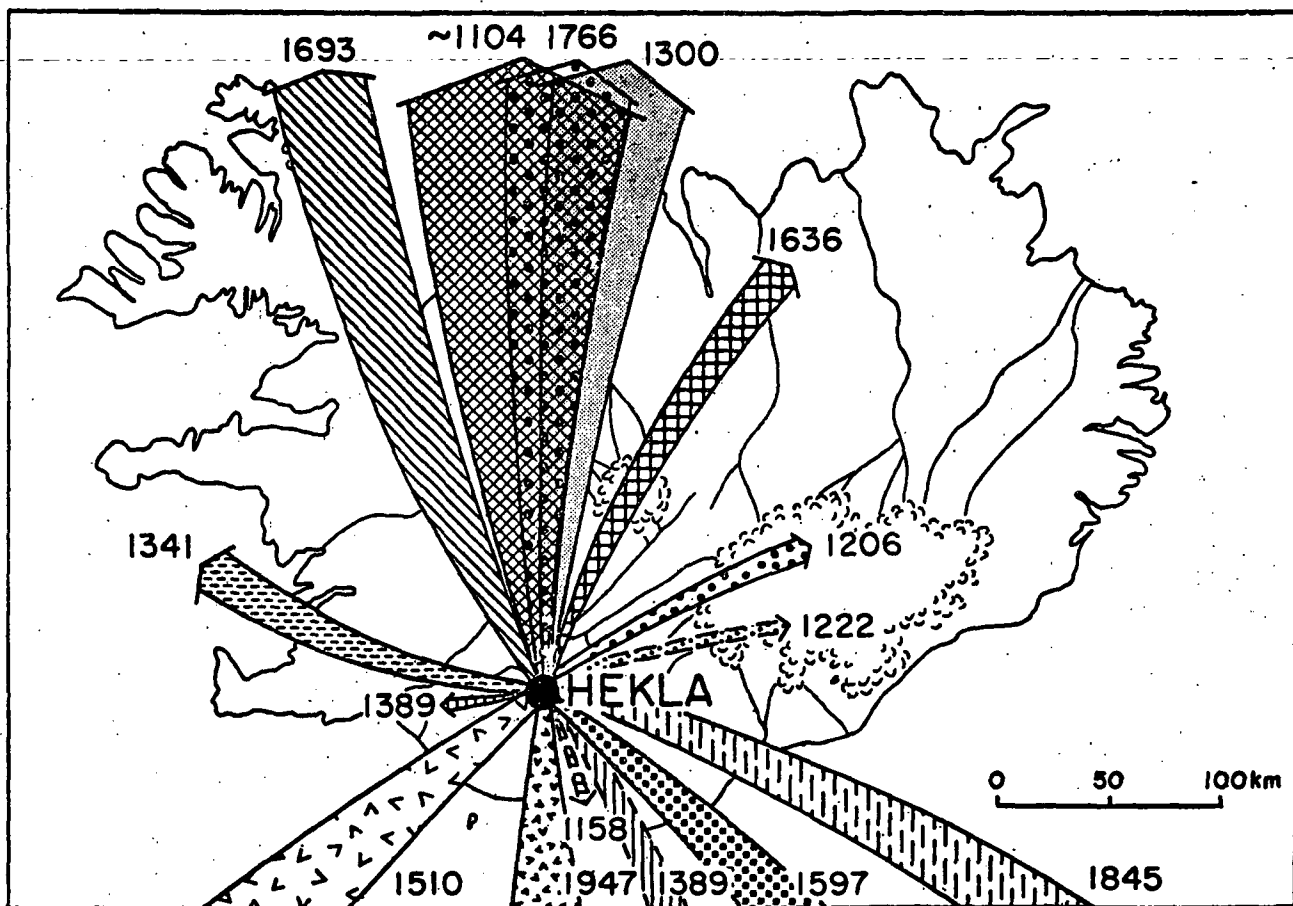
Fig. 10. Directions of tephra-spread during initial phases of Hekla's historic eruptions. (From Thorarinssen, 1967).

CRETACEOUS BENTONITE
PERMIAN BENTONITE
DEVONIAN BENTONITE
ORDOVICIAN BENTONITE
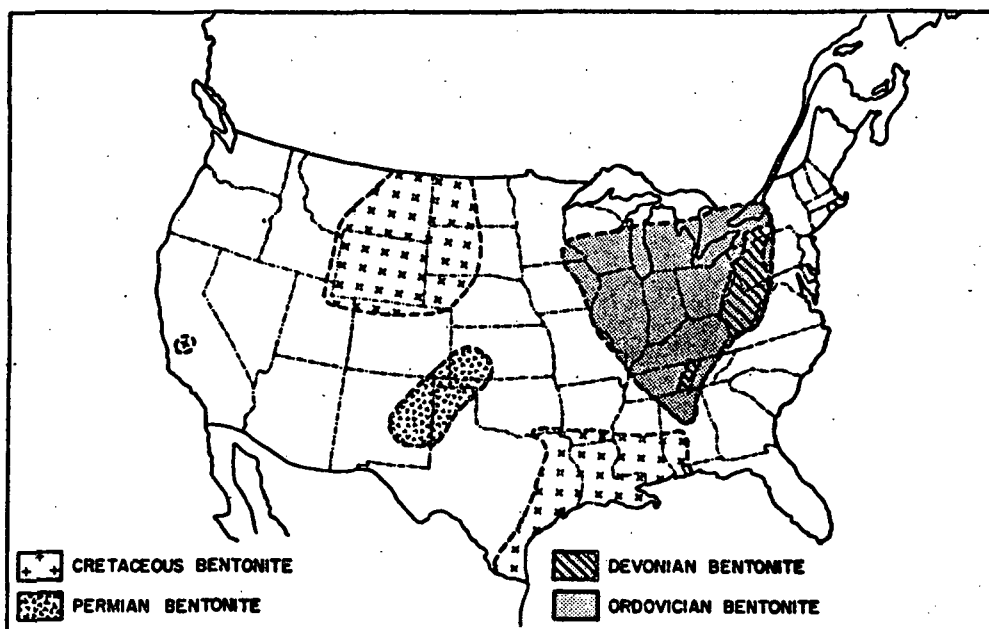
FIG. �及.—Geographic distribution of pre-Tertiary volcanic ash and bentonite in the continental United States. The areas outlined could serve as starting points for studies of high-altitude winds in the geologic past (data from Hass, 1948; Flowers, 1952; Ross, 1955; Marsh, 1960; and Reeside and Cobban, 1960).

From Eaton (1963).

One sheet has a volume of 96 km^3.; this is, perhaps, the most voluminous airfall deposit on record (Bowen, 1967). Colossal deposits of Late Cretaceous and Early Tertiary siliceous ash accumulated in shallow seas on the present site of the High Plains of the United States and Canada during eruptions in the Rocky Mountains to the east, but how much of this ash fell from the air and how much was washed into the seas and further redistributed cannot be told. In view of the foregoing, it seem surprising that so little tuffaceous material has been recognized among the Paleozoic quartzite-carbonate marine deposits of the Cordilleran region despite prolonged volcanic activity in the adjacacent Pacific coastal belt.

VOLUMES OF AIRFALL TEPHRA

The volume of pyroclastic material erupted during historic times greatly exceeds that of lava flows. Sapper (1927) estimated that between 1500 and 1914, 64 km^3. of lava and 328 km^3. of tephra were discharged on to the earth's surface. Continental and island-arc volcanoes, particularly those in orogenic belts -- e.g. the Circum-Pacific belt -- are normally much more explosive than oceanic volcanoes, and have contributed 95 per cent or more of all the pyroclastic deposits laid down during historic times. Rittmann (1962) employed an 'explosion index' (E) to denote the percentage of tephra among the total erupted material in various volcanic fields. Using Sapper's figures for the period 1500 to 1914, he found, for example, that E in volcanic island arcs is generally between 90 and 95 and may reach 99, as in the East Indies; in the Andes, Central America and the Alaskan-Aleutian Chain, E again exceeds 90. But E for volcanoes in the Atlantic and Indian

Oceans, though extremely variable, averages only 16, and for mid-Pacific volcanoes, characterized by relatively quiet effusions of lava, E drops to 3 or less. E for continental volcanoes in anorogenic belts has intermediate values, approximating 40.

It is important to note, however, that the explosivity of individual volcanoes and of volcanic groups may vary with time. For instance, basaltic shield volcanoes of Hawaiian type are rarely explosive during the mature stage of growth, when copious eruptions of fluid lava take place at short intervals, as at Mauna Loa and Kilauea. During late stages of growth, however, they become much more explosive, building clusters of cinder cones around the summit, as on Mauna Kea. And many of the most explosive eruptions of continental and island-arc volcanoes take place during the closing stages of growth, immediately prior to caldera-formation on large composite cones built chiefly of lava flows. On the other hand, during single eruptive episodes in the history of many volcanoes, activity almost invariably begins with explosive eruptions, building cinder- and pumice-cones, and generally diminishes in intensity and virtually ends while relatively gas-poor lavas continue to be discharged.

Tephra of basaltic composition are generally much less voluminous than are those of intermediate and siliceous composition. There are 132 basaltic cinder cones on Mauna Kea, but their total volume is only 2 km^3., and the largest has a volume of no more than 0.1 km^3. Ejecta blown from these cones cover approximately 8,000 km^2., but their total volume may not exceed 12 km^3. (Wentworth, 1938). During the first four years of its activity, Paricutin volcano, Mexico, erupted 0.66 km^3. of tephra and 0.33 km. of lava, almost all of the cinder cone

with a volume of approximately 0.25 km^3., being built within the first year.
On the other hand, the catastrophic eruption of Tamboro, in the East Indies,
in 1815, is said to have discharged 150 km^3. or more of basaltic ejecta.
This estimate is certainly excessive, and probably most of the ejecta
did not fall from the air but were laid down by glowing avalanches.

One of the most voluminous explosive eruptions of andesitic
magma during historic times was that of Coseguina, Nicaragua, in 1835.
It is often quoted that 50 km^3. of ejecta were discharged during these
short-lived eruptions, but recent studies suggest that the volume did
not exceed 10 km^3., and much of this was deposited by glowing avalanches
(Williams, 1952). A Recent deposit of andesitic pumice in the Upper
Yukon basin, apparently the product of a single eruption, covers more
than 350,000 km^2. and has a volume of at least 40 km^3. (Capps, 1915:
figure 5).

But most of the major tephra deposits of the world are of
dacitic to rhyolitic composition, and the most voluminous of these
are related to calderas. The caldera of Coatepeque, in El Salvador,
is surrounded by the deposits of 18 successive pumice-falls, one of
which has a volume of 32 km^3., and all together have a volume of
73 km^3. (Meyer, 1964). The Quaternary sheets of rhyolitic pumice
bordering Lake Taupo, New Zealand, have an aggregate volume of 16 to
20 km^3. And airfall-pumice blown from the Mount Mazama (Crater Lake)
volcano, Oregon, prior to the glowing avalanches of pumice and scoria,
has a volume of between 16 and 24 km^3., even though it was probably
laid down within a few months or years. Caldera-forming eruptions are,
however, relatively rare. Far more commonly, the volumes of siliceous
ash discharged during a single eruptive episode in the history of a

large composite volcano measure only a small fraction of a cubic kilometer.
The greatest eruption of this kind in Iceland, for example, was that of
Oraefajokull in 1362, which blew out 2 km^3. of pumiceous ash. The eruption
of Rudloff crater, in Askja, Iceland, in 1875, laid down 0.5 km^3. of
rhyolitic ash. Approximately the same volume of rhyolitic ash was laid
down during the 1104 eruption of Hekla, but the total volume of siliceous
tephra discharged by this and many other historic eruptions of Hekla is
only a little more than 1 km^3. (Thorarinsson, 1967).

INTRUSIVE TUFFS AND BRECCIAS

Explosive eruptions may take place at shallow depths when
rising magma comes in contact with unconsolidated, wet sediments or
watersoaked ground; they may also take place both near the surface and
at much greater depths when rising gases fluidize the overlying rocks
and drill volcanic pipes (diatremes) either to the surface or to levels
not far below. Some of the fragmented material is expelled from the
pipes, and some remains underground where it shows intrusive contacts
with the wall-rocks.

a. Peperites

Scrope introduced the term peperite in 1827 for certain basaltic
tuff and breccias in the Limagne district of central France, noting their
resemblance to some of the pyroclastic deposits near Naples which are
called 'piperno' on account of the pepper-like admixture of dark and
light constituents. He noted, moreover, that some Limague peperites
are interstratified with limey lakebeds of Tertiary age, whereas others,

consisting of basaltic fragments in a calcareous matrix, are completely
devoid of stratification and grade into bodies of compact basalt. And
he correctly concluded that both the stratified and unstratified peperites
were formed by eruptions through soft, wet, limey muds on the bottoms
of lakes. Subsequent studies have amply confirmed Scropes' views, showing
that the 'massive peperites' were produced by injection of basaltic
magma into unconsolidated, watersoaked muds. Steam explosions coupled
with strains set up by drastic chilling of the magma and by the onward
urge of more magma from below shattered the basalt into fragments. The
comminuted debris was then injected as a slurry into the soft lakebeds,
and, occasionally forced its way to the surface to pour for short distances
across the lake floors.

Comparable intrusive peperites are associated with basaltic
sills that were injected into unconsolidated, limey marine sediments
in the Coast Ranges of California (Macdonald, 1939), and others
formed among diatomaceous lakebeds in Annam. (Blondel and Lacroix,
1927). In New South Wales, irregular stringers of tuff, consisting of
a mixture of chert, limestone, spilitic diabase and keratophyre fragments,
cut across well-bedded submarine cherts and tuffs, and some broke through
to the sea-floor to deposit their load. Disturbances accompanying the
intrusions caused periodic slumping and sliding of the unconsolidated
deposits (Benson, 1915).

The magma involved in formation of peperites is, with rare
exceptions, fluid basalt; however, even viscous rhyolitic magma intruded
into wet sediments at shallow depth may cause peripheral explosions that
forcefully inject fragmented rhyolitic debris into the surrounding beds,
as may be seen in the Sutter (Marysville) Buttes, California (Williams,
1929).

Most peperites fall into the category of 'hyaloclastites' (Rittmann, 1960) because they involve the comminution of glassy volcanic rocks; many also fall into the category of 'aquagene tuffs' because they originate by decrepitation and explosive shattering of magma in contact with water. Most hyaloclastites and aquagene tuffs, however, are not intrusive but form on the floors of seas or lakes or beneath a cover of melting ice. These more widespread fragmental deposits are discussed on later pages.

b. Intrusive tuffs and breccias in volcanic pipes and related structures.

Subterranean explosions may produce pyroclastic deposits ranging in coarseness from tuffs to breccias and in composition from entirely juvenile, accessory, or accidental to mixtures in any proportion. The fillings of diamond pipes, for example, are composed of ultramafic debris of magmatic origin mingled with accidental fragments of many kinds; other volcanic pipes are filled almost entirely by triturated fragments of wall-rocks, and still others contain just as much fresh magmatic ejecta.

Already solidified rocks within a volcano, particularly within a conduit, may be shattered by the repeated rise and fall of underlying magma to produce 'intrusion-breccias', and these may be extruded at the surface by subterranean explosions or by renewed upthrust of magma (Parsons, 1967). Such remobilized intrusion-breccias become 'intrusive breccias' (Wright and Bowes, 1963). Rising magma and gases heat and dilate the roof-rocks, and withdrawal of magma causes rock-bursts from the roof. The comminuted debris may then be fluidized by rising gases and be mixed with magmatic clots and spray, forming intrusive tuffs (tuffisites of Cloos, 1941). In many volcanic pipes, the content of

accidental fragments derived from wall-rocks diminishes inward as that of magmatic debris increases, and, commonly, accidental fragments close to the walls have subsided whereas those near the center have risen. Accidental fragments carried upward from great depths are usually rounded and polished by abrasion, whereas those that have only been transported short distances are usually angular or subangular and tend to be larger.

Tuffs and breccias within volcanic pipes are typically unstratified and poorly sorted. Occasionally, however, well-bedded deposits may originate by backfall of ejecta into the uppermost parts of pipes that broke through to the surface. Well-bedded ejecta formed in this way may subsequently subside within the pipes, as they did to depths of more than 1,500 m. in the Kimberlite pipes of north-central Montana (Hearn, 1968).

SUBAERIAL PYROCLASTIC FLOWS AND THEIR DEPOSITS

1. Types of flows

2. Flow related to domes
   A. Merapi type
   B. Pelean type

3. Flows from open craters
   A. Asama type
   B. St. Vincent type
   C. Krakatoan type pumice flows
      a. Eruption of Komagatake, Hokkaido, in 1929
      b. Eruption of Krakatoa in 1883
      c. Flows of Mount Mazama (Crater Lake), Oregon

4. Flows from fissures
   A. Valley of Ten Thousand Smokes type
   B. Valles type
      a. Nomenclature
      b. Extent, thickness and volume
      c. Composition
      d. Sorting
      e. Phenocrysts
      f. Welding
      g. Compaction during welding
      h. Other zonal features
      i. Recognition of individual flow-units
      j. Modes of eruption, flow and deposition
      k. Origin of ignimbrite - magmas of Valles type

SUBAERIAL PYROCLASTIC FLOWS AND THEIR DEPOSITS

1. Types of Flows

Three eruptions focussed the attention of geologists on the impor-
tance of pyroclastic flows, namely the eruptions of Mont Pelé and the
Soufrière of St. Vincent in the West Indies in 1902, and the eruption
in the Valley of Ten Thousand Smokes, Alaska, in 1912. The first of these
was related to the rise of a steep-sided dome of viscous lava; the second
issued from the open summit-crater of a large composite volcano; the third
issued from swarms of fissures not directly related to a particular volcano.

The deposits laid down during these three eruptions differed
greatly in texture and composition, but all were laid down by glowing
avalanches of fragmental ejecta that swept rapidly over the ground. Their
distribution, unlike that of airfall pyroclastic deposits, was controlled
chiefly by the dictates of topography.

Pyroclastic flows discharged from domes are relatively small in
volume, few exceeding a cubic kilometer; those discharged from open craters
may be much larger, though few exceed 10 km^3. in volume; but many of those
discharged from fissures produce by far the most voluminous of all pyro-
clastic deposits, commonly exceeding 10 km^3., and, not uncommonly, exceeding
100 km^3.

The pyroclastic flows erupted in the West Indies in 1902 were
called nuées ardentes, Glutwolken, and glowing avalanches. Subsequently,
Japanese volcanologists and members of the U. S. Geological Survey began
to use the terms 'pumice flows' and 'ash flows'. But no particular name
was given to the deposits of glowing avalanches until 1935, when Marshall,
in describing Plio-Pleistocene rhyolite tuffs that cover $25,000 \text{ km}^2$. of the

North Island of New Zealand, introduced the name 'ignimbrite' supposing that

the ejecta which produced them were laid down from "immense clouds or showers

of intensely heated but generally minute fragments of volcanic magma". The

fragments were hot and viscous enough to weld together after they reached

the ground, and, in his opinion, the deposits were formed in the same way

as the "indurated sand-flow rocks" of the Valley of Ten Thousand Smokes.

Unfortunately, Marshall's definition of the term 'ignimbrite' was not

exact and it was misleading, because it suggested that the deposits in

question were laid down by "fiery showers" rather than by glowing avalanches.

Moreover, it was not clear whether the term was to be applied to a rock-type

or to a deposit formed in a particular way. And because Marshall implied

that welding of the constituent particles was characteristic of ignimbrites,

many geologists erroneously used the terms 'welded tuff' and 'ignimbrite'

interchangably. It now seems best, in our opinion, to extend usage of the

term ignimbrite to include not only deposits formed in the way that Marshall

envisaged but all other deposits laid down by glowing avalanches, no matter

what their composition and texture, and no matter whether welded or not.

The context in which the term is used should suffice to indicate if it

refers to a rock-type or a mode of deposition. It may not be possible

to say whether a single specimen or a single outcrop is an ignimbrite or

some other kind of pyroclastic rock; but, similarly, a single specimen or

a single outcrop may not suffice to distinguish a dike from a lava; usually,

however, study of field-relations resolves the doubts.

Classifications of pyroclastic flows have been proposed by

Lacroix (1930), Escher (1933), MacGregor (1955), Aramaki (1957), and

Murai (1961). Some of these classifications are based partly on criteria

of secondary importance, e.g. the location of eruptive domes and fissures,

and the character of the explosions, whether vertical or lateral, 'directed'

or not. No rigid classification is possible; nonetheless, the following
simplified scheme is recommended, even though more than one type of flow
may be discharged during a single eruptive cycle.

A. **Flows related to domes or the crumbling fronts of lava flows.**

1. **Merapi type.** This type, first named by Escher, forms by non-explosive disintegration and collapse of the flanks of steep-sided domes and summit-spines (e.g. at Merapi, Java, in 1930-1931, and at Santiaguito, Guatemala, periodically since 1922), or by break-up of the snouts and marginal levees of viscous lava flows on steep slopes (e.g. at Ngauruhoe, New Zealand, and Fuego, Guatemala). Glowing avalanches of this kind have been called 'Absturzglutwolken'.

2. **Pelé type.** Form by explosive eruptions immediately before or during the rise of volcanic domes ('Explosionsglutwolken') (e.g. at Mont Pelé in 1902-1905 and again in 1929-1932; also at Hibok Hibok in the Philippines in 1952-1953).

B. **Flows from open craters.**

1. **Asama type.** Intermediate between those of Peléan type and those described below.

2. **St. Vincent type.** Crystal-rich, sand-like pyroclastic flows produced by backfall of ejecta from the margins of vertical eruption-columns (e.g. at the Soufrière of St. Vincent in 1902).

3. **Krakatoa type.** Glass-rich, pumiceous flows discharged from the summit-craters of large composite cones following pumice- and ash-falls (e.g. at Krakatoa in 1883, at Komagatake in 1929, and at Mount Mazama (Crater Lake, Oregon) about 6,600 years ago).

C. **Flows discharged from fissures.**

1. **Valley of Ten Thousand Smokes type.** Eruptions issue from swarms of narrow, sub-parallel or irregularly oriented, linear fissures (e.g. in Alaska in 1912).

2. **Valles type.** Eruptions of siliceous, pumiceous ejecta issue from arcuate fissures formed by regional arching of the roofs of large bodies of rising magma. The pyroclastic flows are almost always preceded by pumice-falls, and the volumes of ejecta are usually so great that the roofs of the magma-chambers collapse along the arcuate fissures to produce calderas. Pyroclastic flows may issue later from arcuate fissures on the floors of the calderas (e.g. in the Valles caldera, New Mexico, the Creede caldera, Colorado, and the Timber Mountain caldera, southern Nevada).

The foregoing pyroclastic flows have been listed roughly in the order of increasing volume, increasing gas-content, and diminishing viscosity of the magmas involved.

A. Flows related to Domes

Merapi-type. Pyroclastic flows of this type issued from time to time from the flanks of the dome of Mont Pelé, particularly during periods of relative calm, and flows of Peléan type issued from time to time from the flanks of the Merapi dome, particularly during periods of rapid growth. When the name of a volcano is applied to a particular kind of eruption, all that is implied is that this kind of eruption is characteristic of that volcano.

Pyroclastic flows of Merapi-type (Absturzglutwolken or Glutlawinen) result from gravity-collapse of the fractured, oversteepened flanks of domes and unstable summit-spines. They may be triggered by quakes or by internal expansion of domes, when rising magma shatters the solid carapace. Even heavy rains falling on the cracked, hot crust of a dome may be a trigger. Avalanches of this kind are often seen when the solid or nearly solid fronts and margins of viscous lava flows descending the steep sides of a volcano are shattered by the onward urge of liquid lava from above.

Stehn (1936) observed many pyroclastic flows (glowing avalanches) that were not accompanied by explosions but caused by collapse of part of the dome of Merapi during its 1933-1935 activity. Their average velocity was 60 km. an hour, and on the steep, upper parts of the volcano they traveled twice as fast. They consisted of solid fragments from the outermost parts of the dome mixed with glowing effervescing blocks from

within. Many blocks burst, releasing abundant gas, and many were pulverized to powder and dust by mutual attrition. Smaller and slower avalanches of sand-like fragments occasionally intervened between the major flows.

The larger avalanches swept down valleys with a pendulum motion, striking one wall and rebounding to the other, leaving unscorched areas on the bends, and compression of air in front of the avalanches blew trees down in parallel rows.

Similar pyroclastic flows were observed during relatively quiet spells during the growth of the dome of Mont Pelé in 1929-1932. Perret called them 'block and ash flows', to distinguish them from the more typical, more gas-rich flows of explosive origin. Not being buoyed up by gas as much as the typical flows, they slid rather than rolled, and they grooved, scratched, and polished the surfaces over which they swept.

The chaotic, unsorted and unstratified deposits left by pyroclastic flows of Merapi-type are generally less extensive than those left by Peléan flows; they differ also in containing less juvenile material in the form of ash, and correspondingly more angular blocks. Obviously, however, there are all gradations between them.

B. Peléan Type

Pyroclastic flows of Peléan type are produced by explosions immediately before, but more commonly during the rise of volcanic domes. They range from gas-rich to gas-poor, and the ejecta they carry vary from almost wholly lithic to almost wholly juvenile, depending on the volume and gas-content of the exploding magma.

The history of Mont Pelé between 1902 and 1905, and again between 1929 and 1932, shows that the largest, most gas-rich, and most destructive avalanches usually took place during initial phases of these two eruptive

episodes. The activity of 1902 began late in April with explosions from the summit-basin, when a small dome began to grow near the edge of the crater lake. Eruptions increased in violence until May 4 when a major explosion took place, accompanied by tremendous mudflows that rushed down the valley of the Rivière Blanche on the southern flank of the volcano

For a few days thereafter, clouds obscured the mountaintop. On the morning of May 8, glowing avalanches raced down the mountainside at speeds of approximately 160 km. an hour, utterly destroying the town of St. Pierre and killing all but two of its 30,000 inhabitants. To some extent, these avalanches were caused by 'directed explosions' through a notch in the crater-rim at the head of the valley of the Rivière Blanche. The notch was the surface expression of a radial fissure that continued down the valley, and the 'directed blast' of May 8, like many of the later avalanches, was controlled in part by this underlying structure (Jaggar, 1949). It must be emphasized, however, that gravity was always the principal control. Most of the ejecta laid down during this first and most violent pyroclastic flow consisted chiefly of fresh magma in the form of dust, fine cinders, and small lapilli; lithic debris seems to have been quite subordinate. Subsequently, however, when the avalanches issued from the flanks of the growing dome, the deposits became much coarser and included abundant lithic blocks of great size.

Twenty-four years of quiet followed the growth of the 1902-1905 dome of Mont Pelé. During August, 1929, tremors were felt on top of the dome, and fumarole gases became more abundant and more acid (Perret, 1935). On September 16, steam-blast eruptions issued from the top of the dome. Then, there was quiet for a month. On October 14, stronger explosions began, most of themddirected vertically, the ejecta consisting mainly of fragments

of the old dome. About mid-November, strong luminous effects were observed
near the summit, and shortly thereafter a series of glowing avalanches
began, attaining their maximum size in mid-December, when some of them
rivaled in size the great flows of 1902. The average speed of the smaller
avalanches ranged from 40 to 70 km. an hour, but many of the larger ones
traveled more than 120 km. an hour. Explosive activity then declined,
and it was not until early January, 1930, that incandescent lava rose
to the surface near the top of the old dome to initiate growth of the
second dome. For the next two years, growth of the new dome alternated
with destructive avalanches from the flanks, all of them pouring through
the V-shaped notch in the crater-rim to empty into the valley of the
Rivière Blanche.

That some pyroclastic flows of Peléan type are caused by directed,
low-angle blasts was clearly demonstrated during the rise of the Hibok Hibok
dome in the Philippines in 1948-1953 (Macdonald and Alcaraz, 1956). Indeed,
the largest glowing avalanches from Hibok Hibok were related to such blasts
from the lower slopes of the dome. Clouds were often seen rushing down the
mountainsides before uprushing clouds began; moreover, the distribution and
impact-patterns of ejected blocks indicated a considerable horizontal com-
ponent of momentum. Some pyroclastic flows contained abundant pumice,
in addition to solid blocks, showing that much fresh magma was involved;
other flows consisted chiefly of blocks. It seems likely that the hot,
plastic interior of the dome was riddled with branching tongues of more
fluid magma, spreading like distributaries, and that some tongues were
richer in gas than others. Variations in the deposits of the pyroclastic
flows may therefore have been controlled chiefly by the depths of the
explosion-foci within the dome, and the volumes of exploding magma.
Rapid vesiculation inside the dome was the trigger.

Discussion of the manner in which Peléan pyroclastic flows move and the reasons for their mobility is deferred until other kinds of pyroclastic flows have been described.

Deposits of Peléan-type flows. Deposits of Peléan flows vary greatly in texture depending on the proportion of solid debris to fresh magma, and on the rate of vesiculation of the magma both before discharge and while the flows are in transit. As might be expected, the deposits are almost wholly confined to topographic depressions, though fine ash from clouds above the avalanches is draped over hill and valley alike. An individual flow leaves a heterogeneous, unstratified and, for the most part, unsorted deposit made up of angular blocks, torn from the solid carapace of the parent dome, subangular, still effervescing bombs torn from the plastic interior of the dome, and sand- to dust-sized debris, some of it derived from fresh, effervescing magma and bursting bombs, and some being produced by attrition of larger fragments in their turbulent descent. But when, as usually happens, flows follow each other in rapid succession, the deposits as a whole display an ill-defined but regular bedding determined by an alternation of beds in which the average size of the blocks or the proportion of fine matrix varies (MacGregor, 1938). Some blocks are of enormous size; one discharged from Hibok Hibok measured 10 by 8 by 5 meters across. Blocks may explode after coming to rest, revealing their incandescent cores, but rounded, Strombolian bombs are never present, and breadcrust bombs are relatively rare because few ejecta are chilled sufficiently by flight through the air. Impact-pits are also uncommon, except in deposits of pyroclastic flows produced by inclined explosions.

A notable feature of almost all Peléan deposits, particularly those in which the proportion of unconsolidated magma was large at the

time of eruption, is the high degree of porosity of both the larger fragments
and the sand- and dust-sized matrix. This porosity, as MacGregor noted on
Montserrat, typifies almost completely crystalline as well as vitrophyric
fragments. It may be obvious to the naked eye but often a hand-lens or
even a microscope is needed to detect it. And, generally, the greater
the porosity the more abundant is the interstitial glass. Porosity is
rarely due to the presence of ovoid and spherical vesicles; normally,
it results from the presence of abundant, minute, closely spaced,
polyonal cavities between crystal-laths and prisms of random orientation
that give the rocks a diktytaxitic texture. For this reason, most of the
glass particles in the fine matrix are not pumiceous or cuspate, but
irregular splinters attached to shattered crystals; in other words, the
matrix rarely shows a typical vitroclastic texture (Bogenstruktur).

Layers and lenses of fine sand- and dust-sized ash are commonly
interbedded with the coarser debris of Pelean flow-deposits. They consist
chiefly of broken crystals and chips of glass-rich, diktytaxitic lava,
and, occasionally, they contain accretionary lapilli. Some layers are
produced by settling of fine ejecta from the air after the avalanches
come to rest, and though most of these layers measure less than a meter
in thickness, they may be more than 3 m. thick. Layers of this kind
usually become thicker toward and beyond the distal ends of the flows.
Other fine-grained layers result from the combined action of wind-
transport and rainwash working on avalanche deposits during intervals
of quiescence.

Pelean flow-deposits are characteristically monolithologic,
consisting of accessory and juvenile debris of uniform composition.
Accidental lithic fragments are rare, and most of them are swept up and

incorporated by the flows in transit. Block-rich Peléan flows that enter rivers or are reworked by torrents, therefore give rise to essentially monolithologic mudflows (lahars), a heterogeneous assemblage of blocks in a lahar denoting some other mode of origin.

Peléan pyroclastic flows are almost all of intermediate or siliceous composition, andesites and dacites predominating, and invariably the rocks are rich in glass. If, as is commonly the case, the rocks contain hornblende, the mineral retains its green color in ejecta that were highly gas-charged and quickly chilled (ie. in the live, exploding magma), whereas in fragments that were solid or semi-solid when erupted, the mineral is brownish or reddish oxyhornblende or is largely replaced by 'opacite' (MacGregor, 1938).

The deposits of Peléan flows are never welded. They may, however, be firmly and quickly indurated by compaction and by the tight interlocking of irregular particles in the fine matrix. Within a few weeks after one of the pyroclastic flows from Merapi was laid down, the deposits were so compact that they could not be penetrated with a crowbar or hand-borer for more than 30 to 40 cms. (Neumann van Padang, 1931). Charred vegetation is not uncommon in Peléan deposits, and signs of fumarolic and solfataric activity may be present, though they are usually much less conspicuous and widespread than they are in most of the pyroclastic flow-deposits that remain to be considered.

3. Flows from Open Craters

A. Asama types.

The eruption of Asama in 1783 was one of the greatest volcanic calamities in recorded Japanese history. An initial discharge of gas-rich

magma produced a pumice fall that was followed by two pyroclastic flows
of diminishing gas-content and increasing viscosity, and these were
followed by a gas-poor flow of blocky lava (Aramaki, 1957). Both pyro-
clastic flows issued from the summit-crater, and both display features
transitional between those of Peléan and Krakatoan flows. The chemical
composition of the erupted magma remained essentially the same throughout.

The first pyroclastic flow -- the Agatsuma avalanche -- resembled
Krakatoan flows in its high content of gas. Magma foamed over the crater-
rim and swept downslope, leaving a thin sheet over 20 km^2. in extent. The
ejecta were less vesicular than those of the preceding pumice-falls, but
more veiscular than those of the second pyroclastic flow -- the Kambara
avalanche. Most of the ejecta were hot and plastic enough to anneal;
even at the snout and along the margins of the flow, where the deposits
are less than 30 cm. thick, they are compact and crudely jointed. None,
however, show any flattening of the constituents under load. Pumiceous
bombs are scattered throughout, including many breadcrust bombs.

The destructive Kambara pyroclastic flow issued a day after
the Agatsuma flow. It seems to have been caused by a powerful explosion,
directed almost vertically. All the juvenile ejecta were much more viscous
than those in the first flow, and many fragments were solid. The ejecta
did not spread widely as did those of the Agatsuma flow, but were confined
to relatively narrow channels, and because they were not buoyed up as much
by abundant gas they had strong erosive power, particularly near their
source, where they "dug a ditch" between 1 and 2 km. wide, bordered in
places by scarps up to 40 m. high. The deposit, most of which is only
about a meter thick, consists of angular to rounded, compact or slightly
vesicular blocks and bombs and a little juvenile ash. Some breadcrust
bombs measure more than 30 m. across, and one may have measured 160 m.

across before it broke. Like the deposits of Peléan flows, but unlike
those of the Agatsuma flow, the Kambara deposits are neither welded nor
indurated. In their mode of formation, they resembled the flows on St.
Vincent, but their deposits resembled much more closely those of Mont Pelé.

Ultimately, gas-poor magma rose from lower levels in the
eruptive conduit, producing a viscous flow of blocky andesite that
descended slowly from the summit-crater. In brief, the Asama activity
of 1783 changed within a few days from high-pressure Vulcanian eruptions
of pumice through pyroclastic flows of diminishing gas-content, intermediate
in character between Peléan and Krakatoan flows, to end with the discharge
of dense, blocky lava.

B. St. Vincent Type

The northern end of the West Indian island of St. Vincent is
occupied by the Soufrière volcano. An almost semicircular cliff, the
somma-rim of an old caldera, partly encloses the active cone, as Vesuvius
is partly enclosed by Monte Somma. The inner cone had been quiescent for
90 years prior to the great eruptions of 1902, and its steep-walled crater,
which measured 1.7 km. across at the rim, surrounded a lake 160 m. deep,
so that the overall depth of the crater was more than 550 meters.

Small quakes and subterranean rumblings began early in March,
1901, and they grew in frequency and intensity during the latter part of
April, 1902, precisely when explosive activity began at Mont Pelé, 170 km.
away.

The first eruption of the Soufrière took place about noon on
May 6, and the first discharge of the crater lake followed during the
night. Next day, raging, hot mudflows swept down the flanks of the volcano,

and before noon the crater lake was virtually emptied. An eruption-column
rose, at first intermittently and then continuously, to heights of approxi-
mately 9 km.

The climax came just before 2 p.m. of May 7, less than a day
before St. Pierre was wiped out by the first of many glowing avalanches
from Mont Pelé. An eruption-column rose to great heights above the crater,
while a huge "black cloud" swept down the mountainsides in "globular,
surging masses", mostly following the valleys of the Rakata and Wallibu
rivers. Within a few minutes, much of the northern part of the island
lay beneath a pall of ash, and more than 1,500 people perished. There-
after much weaker, intermittent explosions took place until activity came
to an end in March, 1903 (Anderson and Flett, 1903; Robson and Tomblin, 1966).

The ejecta of the great eruption of May 7, 1902 were derived from
crystal-rich andesitic magma, and were deposited chiefly by pyroclastic
flows. Shortly before the flows, eyewitnesses noted that the vertical
eruption-column became darker and grew in height, and that showers of
coarse fragments began to fall. Indeed, according to Hay (1959), the
flows originated by 'backfall' of the outer, more slowly rising parts of
the heavily loaded eruption-column. Certainly, the lowermost 365 meters
of the column were dense enough to produce glowing avalanches, for one
swept across the somma-rim high above the crater. Once heavy falls began,
they obstructed later upblasts. The paucity of lithic blocks among the
avalanche-deposits, the sorting of the ejecta, and the fact that the
diameter of the crater was not appreciably enlarged during the eruptions
indicate that there were no "base surges" such as accompany vertical
eruption-columns at some other volcanoes (Moore, 1967).

Deposits. The deposits left by the pyroclastic flows of
St. Vincent differ radically from those left on the flanks of Mont Pelé.

All are typically unstratified or poorly stratified, and poorly sorted, but those of St. Vincent are characterized by their fine texture and richness in crystals. Large bombs and blocks make up only 3% to 5% of the total volume, and few of them measure more than a meter across. Even lapilli constitute only a small proportion of the whole. More than 90% of the deposits in the Wallibu valley was of sand-size. The median diameter of a representative sample is 0.6 mm., and the sorting coefficient is 2.9. Crystals make up 45% of the bombs, which probably represent the original magma, but they make up 58% of all the juvenile ejecta and 73% of the juvenile ash (Hay, 1959). Concentration of crystals relative to vitric ash in deposits only a few hundred meters from the crater-rim denotes that gravity-separation took place either in the eruption-column prior to the pyroclastic flows or early in its descent, or both. Most of the coarse ejecta and crystals were concentrated in the flows while the fine vitric ash was concentrated in the overlying clouds responsible for the accompanying "hot blasts". The total volume of the deposits approximates 1.4 km^3.; none show signs of welding.

C. Krakatoa-type Pumice Flows

Pumiceous pyroclastic flows that issue from the summit-craters of long-established composite volcanoes during late stages in their history are almost invariably preceded by pumice falls, because upper, gas-rich levels of the magma-chambers are expelled at higher pressures than the underlying, relatively gas-poor levels. Magmas involved in Krakatoan eruptions are usually more fluid than those involved in Peléan, St. Vincent and Asama types of eruption, just discussed; consequently there is a much higher proportion of pumiceous material among the deposits and correspondingly

less lithic debris. If enough pumiceous magma is erupted, the roof of the magma-chamber may collapse to form a caldera, as at Krakatoa in 1883; commonly, however, as in the first of the three cases now to be discussed, the ejecta are not voluminous enough to bring about engulfment.

a. Eruption of Komagatake, Hokkaido, in 1929. A particularly instructive eruption, involving the discharge of pumice falls and flows, took place at Komagatake in 1929. It lasted no more than a day, but the character of the activity and the nature and sequence of ejecta closely resembled those of the much longer-lived and more voluminous eruptions that produce calderas. Many people witnessed the eruption, and several Japanese geologists studied it carefully (Tsuya, 1930; Kôzu, 1934; Kuno, 1941; Murai, 1960).

The eruption followed 5 years of quiet. No changes were noted among the adjacent hot springs prior to the outbreak, and the first recorded shock took place only a few hours before the first ash began to fall at 3 a.m. of June 17. By 10 a.m., an imposing eruption-column rose from the summit-crater. The winds were blowing southeastward, and grains of pumice, up to 2 mm. in diameter, began to fall at Shikabe, 11 km. away. An hour later, many falling fragments measured 1 cm. across, and some measured 5 cm. across. It was not until midday that the first pumice flow swept down from the summit; the second followed between 2 and 3 p.m., but most of them descended later, the last at 10 p.m. The longest flow traveled 6.5 km. down the mountainside, and the fastest moved at a speed of 15 km. per hour. While the pumice flows poured downslope, the eruption-column continued to rise over the crater, and showers of pumice continued to fall to the southeast. By the time of

the last pumice flow, the deposits of the pumice falls at Shikabe were more than

a meter thick. Lumps of falling pumice more than 10 cm. across were still fairly

hot when they landed, and glassy, lithic fragments less than half as big were

too hot to handle. Lumps of pumice more than 40 cm. across were red-hot inside,

and some set fire to houses 6.5 km. from the crater. By 11:30 p.m., the

intensity of the eruptions had diminished greatly, and by 1:30 a.m. of June 18

they had virtually come to an end. The eruption had been brief, yet the total

volume of the pumice falls was 0.4 km^3., and that of the pumice flows was

0.15 km^3.

The pumice deposits. The pumice falls laid down well-sorted and

well-stratified deposits that diminish in thickness away from the source.

The average size of the fragments also diminishes in that direction: 2 km.

from the crater it is 30 cm.; 6 km. away it is 10 cm.

The deposits of the pumice flows, unlike those of the falls, remained

hot for a long time, and they were mantled in places by varicolored sublimates

of sulphur and iron- and ammonium-chlorides from secondary fumaroles. Between

8 and 11 days after the eruptions, temperatures ranging from 450° to 510°C.

were measured at a depth of 40 cm. where fumes still rose from the deposits;

and even where no fumes rose, temperatures at 40 cm. depth ranged from 310°

to 387°C. A year or so after the eruptions, a temperature of 105°C. was

measured where fumes rose; elsewhere temperatures ranged up to 57°C. Some

secondary fumaroles persisted for 10 years.

The deposits of the pumice flows, unlike those laid down by the

pumice falls, are poorly sorted, and their stratification is irregular and

indistinct. Except near the top, where most of the fragments are coarse,

the deposits consist chiefly of sand-sized pumice. Crystals tend to be

concentrated in the lower parts. The surfaces of the flows, particularly

near their snouts, are characterized by long, sub-parallel ridges, half
a meter to a meter high, composed almost entirely of large pumice-lumps,
many of them between 0.5 m. and 3 m. in diameter. These surficial ridges
and stringers of coarse pumice within the deposits were segregated from
the finer pumice by differential rates of flow, the larger lumps tending
to move faster than the smaller ones. And whereas the deposits of the
pumice falls thicken toward the source, those of the flows thicken
toward their snouts. Near and beyond the snouts of some flows, there
are thin deposits of fine vitric ash laid down from the upper, lighter
parts of the clouds that accompanied the flows in their descent. On the
steep, upper slopes of the volcano, the flows scarred and gullied the
surfaces over which they moved and in so doing incorporated much lithic
debris. Petrographically and chemically, the compositions of the pumice-
fall and pumice-flow deposits are essentially identical: all consist of
pyroxene andesite. None of the ejecta are welded.

     Origin of the pumice flows. The pumice flows of Komagatake
did not follow the pumice falls, as flows followed falls during the
voluminous eruptions that preceded formation of such calderas as those
of Krakatoa and the Valles; on the contrary, the Komagatake flows swept
down at intervals during late stages of the pumice falls. They did not
begin until the gas-pressure of the magma had diminished enough to
produce abundant large bombs in addition to the lapilli and finer ejecta
typical of the early falls. Ultimately, the coarse pumice and crystals
were concentrated in the more slowly rising outer parts of the eruption-
column and began to fall back en masse on to the upper slopes of the
volcano, producing a succession of pyroclastic flows while the finer
ejecta, richer in vitric ash, were carried to great heights in the faster-

rising, inner parts of the eruption-column, to be drifted southeastward by the prevailing winds and fall in showers. In brief, the Komagatake pumice flows originated in essentially the same manner as the crystal-rich ash flows of St. Vincent.

b. Eruption of Krakatoa in 1883. Prior to 1883, the main island of Krakatoa consisted of three coalescing cones, namely Rakata at the southern end, Danan in the middle, and Perboewatan at the northern end. The initial eruptions issued from Perboewatan on May 20, and were resumed on June 19. Five days later, a new vent opened at the foot of Danan. There are no records of activity during July, but on August 11, when the island was last seen before the final paroxysm, four vents were mildly active.

All of the deposits laid down before the paroxysm were products of high-pressure Vulcanian eruptions that hurled ash and pumice far above the vents to fall in showers. Consequently, most of the early deposits are well-stratified, and generally each individual layer shows a pronounced gravity sorting from coarse material at the base to fine dust at the top. There are, however, a few unstratified layers, up to 8 m. thick, containing pumice-bombs up to 60 cm. across. In addition, there are two distinctive layers, one pink and the other smoke-gray in color, that seem to have been laid down by submarine eruptions from the flanks of Perboewatan. More than 95 per cent of all the ejecta discharged before the paroxysm consist of fresh magma in the form of pumice and vitric ash and included crystals; the remainder consist of small lithic chips torn from the old cones.

The climax came on August 26 and 27, when a series of voluminous pyroclastic flows was discharged and repeated collapses took place, each propelling a tidal wave. The largest wave, which was more than 30 m. high, drowned more than 36,000 people on the adjacent coasts of Java and Sumatra.

So loud were the explosions that they were heard in parts of Australia, 3,000 km. away, and barographs and tide-gage records show that they caused world-circling air-sea waves. Atmospheric-pressure pulses of the same magnitude would require explosions of 100 to 150 megatons (Press and Harkrider, 1966). When the paroxysm ended, the Perboewatan and Danan cones and half of Rakata had disappeared, and a caldera approximately 5 km. across had taken their place.

The ejecta discharged during the paroxysm were so voluminous and were expelled so rapidly that most of them fell en masse, some on to the islands of the Krakatoa group, but probably more on to the ocean floor. At the same time, fine ejecta rose to heights of 70 to 80 km. to be drifted by winds for vast distances.

The visible pyroclastic flow deposits are confined mainly to the remnant part of the Rakata cone and the southern end of Verlaten Island, where they are locally more than 80 m. thick. They consist of a chaotic, unstratified and unsorted mixture of fresh magmatic ejecta in the form of andesitic pumice lightly charged with phenocrysts, and lithic fragments. Few pumice bombs measure more than a meter across; most measure less than 0.25 m. Pumice lapilli are much more numerous, but the bulk of the pumice is of ash-size. Predominant among the lithic debris mingled with the pumice are angular fragments of obsidian, pitchstone, and porphyritic andesite ripped from the old volcanoes; accompanying these are a few fragments of sandstone and mudstone torn from the sub-volcanic basement. On Rakata Island, lithic fragments constitute about 10 per cent of the total ejecta, few measuring more than 0.25 m. across. On Verlaten Island, the proportion of lithic fragments increases southward from about 10 to 30 per cent; several blocks measure 3 m. across, one measuring 5 by 7 m. across on its exposed face.

The total volume of ejecta is said to have been 18 km^3., but this is no more than a rough estimate, because the volume of the pyroclastic-flow deposits on the ocean floor remains unknown. It seems certain, however, that more than 90 per cent of all the ejecta was discharged during the paroxysm of August 26-27. Additional comments on the Krakatoa caldera are presented elsewhere.

      c.   Flows of Mount Mazama (Crater Lake), Oregon. The dacite-pumice falls that initiated the climactic eruptions of Mount Mazama have already been discussed (page 25). They were followed immediately by voluminous pyroclastic flows, noteworthy because they provide a graphic illustration of a drastic change in composition during activity. Most of the flows are composed of dacite pumice, but toward the close of activity, they changed abruptly to hornblende-rich basaltic scoria (McBirney, 1968). Many flows swept down glacial canyons on the flanks of Mount Mazama, one pouring down the Rogue River canyon for 60 km. Another flow swept north-ward across the surface of Diamond Lake to empty into the canyon of the North Umpqua River. Other flows spread widely over the less dissected east and northeast slopes of the volcano. Their descent down the steep, upper slopes was so swift that they swept up and incorporated much coarse glacial debris. The final flows of basaltic scoria were less voluminous and did not travel as far as the pumice flows. They were much richer in crystals and were hotter, some of the scoria being hot and plastic enough to weld into coherent masses with large-scale columnar jointing.

All of the pyroclastic-flow deposits are poorly sorted, as typical ~~histograms~~ cumulative curves show (figure 10). Lumps of pumice and scoria, many measuring more than 0.25 m. across, are scattered at random throughout the deposits. They show no systematic variation in size with distance from

the source; in fact the largest bombs, which exceed 3 m. in diameter, are to be found 33 km. from the source.

Dust-sized particles are far more abundant than in most of the pumice-fall deposits (figure 13). They seem to have been produced by internal explosions within the moving flows rather than by mutual attrition of larger fragments, because these show little variation in roundness from the source to the distal ends of the flows (Murai, 1961). Stratification is exceptional and at best is crude, though there are thin lenses and stringers of fine ash that formed by settling of dust-swirls during brief lulls between successive flows.

Lithic debris is more abundant than it is in the deposits of the preceding pumice falls, (15 to 20% as against 3 to 4%), and it is more abundant in the scoria flows than in the pumice flows. Surprisingly, all but a few of the lithic fragments measure less than about 5 cm. across, and most are of sand- and gravel-size. No systematic variation was detected in the abundance or size of the lithic debris away from the source, nor were any fragments of pre-Mazama rocks observed. However, as first noted by Edward Taylor, the final scoria flows contain many plutonic fragments, some measuring a meter or so in diameter, that range in composition from gabbros to granodiorites. Most of them are partly vitrified and hence exhibit crude breadcrust surfaces. They were not derived from a plutonic basement, but from coarse-grained, solidified parts of the magma chamber that 'backfired' into the magma when its level sank far enough to cause rock-bursts from the roof.

Charred logs and branches and a few upright stumps are present within the pumice-flow deposits, and signs of fumarolic activity are widespread, especially among the scoria flows. Narrow, irregular, vertical cracks mark the passageways of the fumarolic gases, and alteration of

their walls, followed by differential erosion, has etched some of the deposits into conspicuous pillars ("fossil fumaroles").

The total volume of the pumice- and scoria-flow deposits around Crater Lake is between 24 and 32 km^3., and all were laid down rapidly, probably within a few days.

4. Flows from Fissures

All the pyroclastic flows discussed thus far issued from the summit-craters of long-lived composite cones or from the flanks of summit-domes. We turn now to discuss pyroclastic flows erupted from fissures. Those erupted from swarms of sub-parallel fissures of tectonic origin are here termed flows of the 'Valley of Ten Thousand Smokes type', while those erupted from arcuate fissures produced by uparching of broad regions, whether volcanic or not, by rising bodies of siliceous magma are assigned to the 'Valles type'. The latter include by far the most extensive of all pyroclastic flows, and their eruption is generally accompanied or followed by large-scale collapses that form calderas. No pyroclastic flows of fissure-origin have yet been witnessed.

A. Valley of Ten Thousand Smokes Type

Perhaps no eruption surpasses in importance in the history of volcanology the one which took place in 1912 in the Valley of Ten Thousand Smokes, Alaska. It was the first eruption in which it could be demonstrated that pyroclastic flows of pumice and ash were discharged from fissures, and it led to the recognition that vast sheets of siliceous volcanic rocks of all ages, in many parts of the world, formerly regarded as lava flows, are

in reality of pyroclastic origin. Unfortunately, however, early accounts of this Alaskan eruption must be drastically revised.

A long chain of andesitic volcanoes runs along the length of the Alaska Peninsula, passing through Mounts Katmai, Trident, Mageik, and Martin. At the head of the Valley of Ten Thousand Smokes, this andesitic chain is bordered by a subsidiary, approximately parallel chain of rhyolite domes, including Mount Cerberus, Falling Mountain, and the recently formed dome of Novarupta. During the great eruptions of 1912, andesitic magma from the main fissure-system migrated underground to mingle with rhyolitic and rhyodacitic magma in the subsidiary system. Hybrid magma then foamed to the surface through fissures at the head of the valley, producing a quick succession of ash- and pumice-flows.

Fenner (1923) maintained that activity began with intrusion of an extensive sill of rhyolitic magma at shallow depths beneath the floor of the valley, where it was slowly assimilated andesitic debris in ground moraines. The hybrid magma then issued through fissures on the floor and sides of the valley as "incandescent sand flows", and it was thought that gases rising through the hot deposits from the underlying sill then produced the "Ten Thousand Smokes".

Immediately before the eruptions, the large cone of Katmai contained only a small summit-crater, and this was occupied, in Fenner's opinion, by a lake of rhyolitic lava that was rapidly assimilating its andesitic walls. Soon after the pyroclastic flows inundated the adjacent Valley of Ten Thousand Smokes, so he thought, explosions from the Katmai crater discharged showers of hybrid pumice having a volume of almost 20 cubic kilometers. When activity ended, the top of Katmai had vanished, leaving in its place a caldera about 3 km. across and 1,200 m. deep. Supposedly, this resulted partly from the explosions, partly

from internal assimilation of the andesitic cone, and partly from collapse of the crater floor.

Recent studies (Curtis, 1968) have led to a radically different interpretation of the events of 1912. It is now apparent that no sill of rhyolite was injected under the floor of the valley, and that all but a few of the 'Ten Thousand Smokes' were fed from the pyroclastic deposits themselves. Hence, by 1950, only a few fumaroles remained and these were concentrated along or near eruptive fissures at the head of the valley. Moreover, examination of the thickness of the bedded ash deposits laid down after the pyroclastic flows shows that Katmai contributed little if anything to their volume. The airfall deposits were laid down almost, if not entirely by explosions from vents at the head of the valley. Gas-poor rhyolitic magma subsequently rose into the principal vent to build the dome of Novarupta. Andesitic magma had drained from the central conduit of Katmai to mingle with rhyolitic magma in the fissure system to the north, and the mixture was expelled on to the valley floor as pyroclastic flows. It was this drainage of the conduit that caused the top of Mount Katmai to founder and form the present caldera. Shortly thereafter, andesitic magma returned to the conduit, producing a small scoria cone on the caldera floor.

The activity just reviewed began on the morning of June 6, 1912, and was essentially over by midnight of June 8. Earthquakes had been felt at Katmai village, approximately 30 km. away, for at least five days before the eruptions started (Fenner, 1925). And during the eruptions, severe shocks were felt at Cold Bay, 60 km. away, while at Iliamna Bay, 170 km. away, "the earth never ceased to move for 12 hours". Few volcanic eruptions have been attended by as much strong seismic

activity, felt over as wide an area. The shocks were presumably related,
at least in part, to the opening of fissures at the head of the Valley of
Ten Thousand Smokes. Part of the dome of Falling Mountain collapsed at
an early stage of the eruptive episode; grabens and fault-scarps were
formed, especially on and near Broken Mountain, and fissures and
explosion-craters, alined N. 60° E., were produced near Novarupta,
precisely where most of the hottest and longest-lived fumaroles were
concentrated after the eruptions came to an end. Available evidence
thus combines to indicate that the pyroclastic flows which swept down
the Valley of Ten Thousand Smokes issued from a swarm of sub-parallel
fissures trending roughly northeastward across the valleyhead. They
buried the valley to a maximum depth of more than 200 m., and their
total volume was approximately 7 km^3.

Papers by Curtis (1968) and by Bordet et al. (1963) present a
detailed account of the ejecta. It must suffice to say that the deposits
of some flows consist partly or wholly of whitish, rhyolitic ash and pumice,
whereas those of other flows consist partly or wholly of brownish, andesitic
debris; most of the deposits, however, consist of strongly banded, black-
and-white, hybrid pumice, the silica-percentage of the dark bands approxi-
mating 60 while that of the light bands approximates 75. Mingled with the
effervescing magmatic ejecta were many small chips of solid andesite and
sedimentary rocks.

The deposits are almost completely unsorted, and, except near
the lower end of the valley, where they are distinctly bedded, they are
almost completely unstratified. They consist predominantly of pumiceous
particles of the size of sand and dust mingled with lapilli. Pumice-
bombs and lithic blocks are rare, and few measure more than 0.5 m. across.

Lenses of cross-bedded, fluviatile pumice separate the flow-deposits in places; these were laid down rapidly by floods when rivers burst temporary dams.

The degree of compaction of the deposits varies considerably, even over short distances. Most of them are only weakly indurated, but some were hot enough to be slightly welded and developed columnar jointing as they cooled. None exhibit distortion of glass shards or flattening of pumice-lumps by superincumbent load. Fumarolic incrustations were once conspicuous on the surface of the deposits but they were soon removed by erosion. Signs of former fumaroles may still be seen, however, particularly in the upper parts of canyon walls, where irregular, vertical cracks are bordered by altered and discolored ash. Lower down the canyon walls, the signs of fumarolic action disappear, indicating clearly that the fumaroles were not fed by an underlying sill but by the pyroclastic deposits themselves, deriving most of the materials they sublimated at the surface by breakdown of mafic minerals within the ash.

Trees at the lower end of the valley were felled by winds, proof that the pyroclastic flows traveled at hurricane speeds, even though the gradient down which they swept for approximately 20 km. averaged only $1^{\circ}08'$. Their mobility came partly from gases liberated by the effervescing, incandescent ejecta, and partly from violent expansion of air entrapped during their turbulent advance.

Pyroclastic flows of Krakatoan type are almost invariably preceded, as noted already, by voluminous pumice- and ash-falls produced by high-pressure outbursts of Vulcanian type. But the flows that swept down the Valley of Ten Thousand Smokes were preceded only by minor pumice falls; on the other hand, they were followed by exceptionally violent

eruptions of gas-rich, hybrid magma from vents at and near Novarupta. These were the eruptions wrongly attributed to Mount Katmai. Why they followed the lower-pressure eruptions that caused the pyroclastic flows is problematical. It seems likely, however, that a new batch of gas-rich magma found its way into the eruptive fissures after the flows had ceased, and, once it was violently expelled, gas-poor magma rose sluggishly to build the dome of Novarupta.

B. Valles Type

We come finally to the most widespread of all pyroclastic flows, those discharged from arcuate fissures. Eruptive fissures may develop in regions where there has been little or no volcanism for long periods, as in parts of the North Island of New Zealand; they may also develop in regions where long-continued eruptions from scattered vents have already laid down thick volcanic deposits, as in southern Nevada, Colorado, and New Mexico, during Tertiary time; or, again, they may develop on the sites of groups of overlapping cones. All originate where large bodies of siliceous magma rise in the crust and dome their roofs. Once the fissures open, foaming magma escapes explosively, first producing ash- and pumice-falls and then ash- and pumice-flows. And, usually so much magma is expelled that the roofs of the magma chambers collapse along the predisposing arcuate fissures to produce calderas, such as that of the Valles Mountains of New Mexico, an account of which has been presented elsewhere.

a. Nomenclature. The term 'ignimbrite' was introduced by Marshall to describe certain pyroclastic flow deposits in New Zealand which are now known to be of the Valles type. Some geologists still

restrict the term to such deposits, though we advocate that it be applied to all pyroclastic flow deposits of subaerial origin.

A single pyroclastic flow is commonly termed an 'ash flow', and its deposits are commonly called 'ash-flow tuffs', though many of them are much too coarse-grained to warrant that term. To most European geologists, these two terms are synonymous with ignimbrite.

An ash-flow deposit or sequence of deposits that cooled uninterruptedly, because it was laid down at once or in rapid succession, is referred to as a 'simple cooling unit'. If, on the other hand, an ash flow was partly cooled before being buried by others, the combined deposits comprise a 'compound cooling unit'. And a cooling-unit complex that grades from a single unit near the source into two or more units away from the source is termed a 'composite sheet' (Smith, 1960a).

When Marshall introduced the term ignimbrite, he had in mind deposits composed of fine particles that were hot enough to weld together after coming to rest. Hence, many writers have erroneously considered that all ignimbrites are 'welded tuffs', and vice versa. Such, however, is far from being the case; indeed, very few ignimbrites are welded throughout, except close to the eruptive vents, and many are completely unwelded.

Ignimbrites may be moderately compact, not because the constituent particles are strongly welded, but mainly because of devitrification and deposition of 'vapor-phase minerals', chiefly tridymite and cristobalite, in pore-spaces. Rocks of this kind are called 'sillars', a name used in Peru by quarrymen who work them for building purposes (Fenner, 1948).

b. Extent, thickness, and volume. Pyroclastic flows of Valles type are vastly more extensive than all other types. At intervals

over a span of about 30 million years, from Early Oligocene to Late Pliocene time, the northern part of the Great Basin, including most of Nevada and much of western Utah, was inundated by pyroclastic flows. They covered more than 200,000 km^2., and their aggregate volume was more than 50,000 km^3. Many composite sheets once covered more than 5,000 km^2. For instance, the five sheets that make up the 'Needles Range ignimbrites' combined to cover more than 20,000 km^2., with a total volume of more than 4,000 km^3. The 'Hiko Sheet' covered 12,800 km^2. to an average depth of 170 m., its total volume approximating 2,000 km^3. (Cook, 1965). The 'Rainier Mesa ignimbrite' extends 60 to 80 km. away from the Timber Mountain caldera which was produced by the eruption; its original extent was 8,000 km^2. and its volume was 1,140 km^3. Even where the pre-volcanic surface was almost flat, with a maximum relief of 100 m., some individual sheets spread for tens of kilometers.

Other ignimbrite fields of vast extent are those of Plio-Pleistocene age in New Zealand (25,000 km^2.), of Pleistocene age in the Yellowstone Plateau (5,000+ km^2.) and in the Lake Toba region of Sumatra (c. 25,000 km^2.), of Mio-Pliocene age in the Sierra Madre Occidental of Mexico and in the Andes of northern Chile and southern Peru, and those of Late Cretaceous age in southern Arizona and southern New Mexico (e.g. the Mogollon Highlands, 25,000 km^2.).

The thickness of individual sheets varies greatly, even if the topography of the pre-eruption surface was almost flat. Single cooling units commonly exceed 100 m. in thickness, and a few exceed 200 meters. The Superior dacite ignimbrite of southern Arizona, which covers 1,000 km^2., is locally almost 500 m. thick, and prior to compaction it was probably 700 m. thick (Peterson, 1961). Some single cooling units

in the San Juan Mountains, Colorado, range from 1,300 to 1,800 m. in thickness; before compaction, parts of some of them must have been approximately 2,500 m. thick. Within the Great Basin, according to Peterson and Roberts (1961 and 1963), 'welded ash tuffs', in which phenocrysts make up between 5 and 25 per cent of the volume, are usually less than 30 m. thick, but may be twice or three times that thick, whereas 'welded lapillituffs', in which the crystal-content is between 25 and 50 per cent, range in thickness from 30 m. to 600 m. Cook (1965), working in the same area, also concluded that crystal-poor sheets tend to be thinner than crystal-rich ones, no sheets composed principally of vitric ash exceeding 150 m. in thickness, and most measuring less than 80 m. thick. It should be borne in mind, however, that most sheets do not represent individual flows but are simple or compound cooling units. In Yellowstone Park, for example, individual ash-flows are generally a meter to about 10 m. thick, whereas cooling units may be more than 300 m. thick (H. R. Blank, oral communication).

c. Composition. Most ignimbrites of Valles type are rhyolitic; in diminishing order, follow quartz latite, rhyodacite, and dacite ignimbrites. Comendite and other soda rhyolites, trachytes and phonolites are not uncommon, but andesitic ignimbrites are relatively rare. No basaltic ignimbrites have been identified among the products of fissure eruptions. A few, however, result from Krakatoan eruptions, as at Crater Lake, Oregon, and others of intermediate and basic composition result from airfalls, e.g. some of the pipernos of the Alban Hills and Phlegraean Fields, Italy. A few ignimbrites laid down by fissure eruptions are of hybrid origin, magmas of different compositions having mingled prior to eruption. Mingling of rhyolitic and andesitic magmas preceded eruption of the pyroclastic flows in the Valley of Ten

Thousand Smokes, as discussed already, and mingling of quartz latite and
basaltic andesite preceded discharge of the flows that inundated the Meseta
Central Occidental of Costa Rica during Quaternary times (Williams, 1952 b).

Except in unusually thick cooling units, vertical and lateral
variations in the proportion and kinds of phenocrysts are not sufficient
to interfere with stratigraphic correlations over wide areas; in many
thick sheets, however, vertical variations are pronounced. The basal
part of one ignimbrite sheet in southern Nevada, for example, is of
rhyolitic composition (77% SiO_2), containing only 1% of phenocrysts,
whereas the upper part is quartz latite (69% SiO_2) containing 21% of
phenocrysts (Lipman et al., 1966). Similar vertical variations have
been observed among ignimbrites related to the Creede caldera, Colorado
(Ratté and Steven, 1967) and those of Aso, Japan (Lipman, 1967). Lateral
variations within cooling units may be equally pronounced, the content and
size of phenocrysts increasing toward the source, as they do in some of
the Yellowstone sheets.

Chemical variations in some ignimbrites result mainly from
differences in groundmass (glass) composition rather than from differ-
ences in the amount and kind of phenocrysts (Lipman et al., 1966;
Lipman, 1967); on the other hand, the compositions of the glasses in
the dacite pumice and basaltic scoria ignimbrites around Crater Lake
differ much less than do the bulk compositions (McBirney, 1968), and
the glassy groundmasses of some rhyolites and quartz latites in the
Great Basin are notably similar, suggesting that the main reason for
differences in the bulk compositions of these particular tuffs is the
amount and kind of phenocrysts (Peterson and Roberts, 1963). Crystal-
and lapilli-rich ignimbrites in the Great Basin tend to be dacites or
quartz latites, whereas crystal- and lapilli-poor ones tend to be

rhyolites. In Honduras, however, most crystal-rich ignimbrites are
rhyolites, because almost all the phenocrysts consist of quartz and
alkali feldspar; besides, andesitic ignimbrites in Honduras are notably
poor in phenocrysts of any kind.

The bulk composition of an ignimbrite may differ considerably
from that of the parent magma, as the youngest sheet around the Aso
caldera indicates (Lipman, 1967). This sheet exhibits the usual increase
in phenocryst content from the bottom upward, changing from rhyodacite to
trachyandesite. However, this normal variation was obscured by mixing of
upwelling batches of magma of different composition, particularly during
waning stages of the eruption, as indicated by layering and other hetero-
geneities within single pumice-lumps. It was obscured further by mixing
of fragments of varied compositions and by sorting of phenocrysts from
vitric ash during flowage and deposition of the ejecta at the surface.
To these primary variations must be added secondary ones brought about
by volatile transfer of constituents during cooling of the ignimbrite,
and groundwater leaching, especially removal of soda from glassy
particles after consolidation.

d. Sorting. Ignimbrites of Valles type, in common with those
of other types, are poorly stratified and poorly sorted by comparison with
airfall deposits, as may be seen in figures 12 and 13. Characteris-
tically, they are chaotic mixtures of pumice-bombs and lapilli in an ashy
matrix much of which is dust-sized, and generally there is no systematic
variation in the size of pumice-bombs and lapilli, except near the distal
ends of long flows where diminishing turbulence permits many of them to
settle according to size. Glass-shards may become finer toward the top
of an ignimbrite sheet (Rast, 1962), but this is unusual, and is probably

A: thickness of deposit (m) (represented by observed thickness ×2).
B: average of maximum grain size of pumice (cm).
C: average of maximum grain size of lithic fragment (cm).
D: number of lithic fragment (>1 cm in diameter) per m². (represented by observed number ×10⁻²).
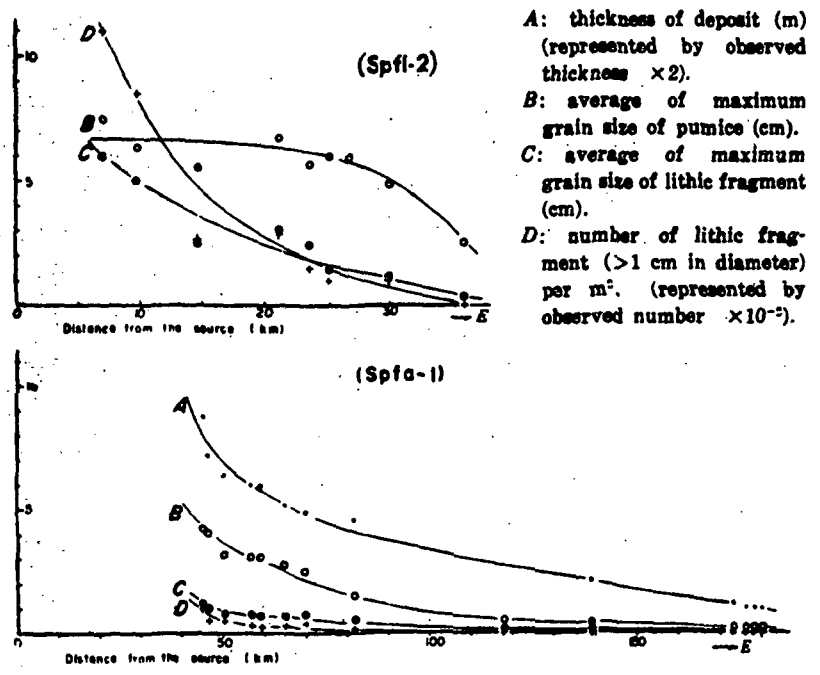
Fig. 5. Variation of grain size of the Shikotsu pumice-fall deposit (Spfa-1) and the Shikotsu pumice-flow deposit (Spfl-2).

Figure 27. Characters of the pumice-fall deposits
12 around the Shikotsu caldera, Hokkaido.
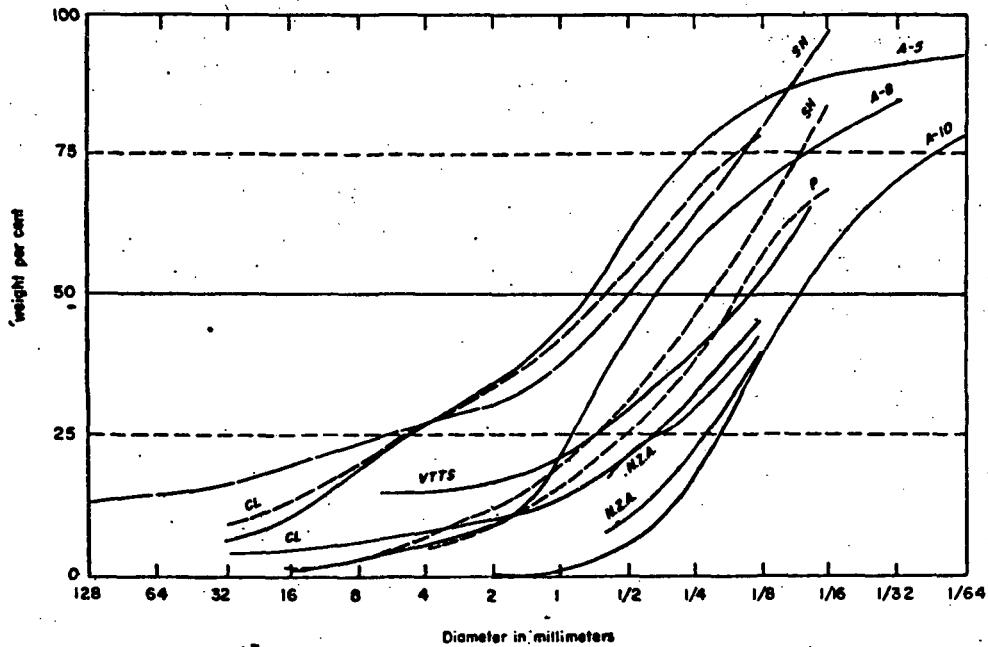(After Y. Katsui, 1963).

FIGURE 4.—CUMULATIVE CURVES SHOWING SORTING IN ASH FLOWS

SH curves: "Shirasu" deposits, South Kyushu, Japan (Taneda, 1954; 1957; Taneda, Miyachi, and Nishihara, 1957)

A curves: Asama volcano, Komoro deposits, Japan (Tsuya, Murai, and Hosoya, 1958)

CL curves: "Older pumice," Crater Lake, Oregon (Moore, 1934)

VTTS curve: "Sand flow," Valley of Ten Thousand Smokes, Alaska (Fenner, 1923)

P curve: "Sillar" near Arequipa, Peru (Jenks and Goldich, 1956)

N.Z.A. curve: Nonwelded portion of "ignimbrite," Arapuni, New Zealand (Marshall, 1935)

From Smith (1960a).

caused by settling of vitric dust from clouds after a flow has come to rest. Sorting is most clearly revealed by variations in the amount and size of crystals and lithic fragments. Some of this sorting reflects downward increase in the content of crystals in the magma prior to eruption, and some reflects the fact that initial flows tend to incorporate more accidental fragments from the walls of the eruptive fissures and sweep up more fragments from the surfaces over which they rush. Part of the sorting, however, takes place during transit and deposition.

Studies of pumice-flow deposits of Krakatoan type around Towada caldera, Japan, show that lithic fragments generally diminish in size and number away from the source. Close to the caldera-rim, such fragments may constitute half the total volume. Five kilometers from the rim, their maximum size is 150 mm.; 25 km. away it is 50 mm.; and 50 km. away it is 10 mm. (Ishikawa et al., 1957). Similar variations have been noted in a Tertiary ignimbrite of Valles type that covers 3,000 km^2. in Central Oregon. Lithic blocks in this ignimbrite measure between 7.5 cm. and 1.25 m. near the source, but less than 2.5 cm. near the Snout. Pumice-bombs diminish in size in the same direction; so does the content of feldspar, pyroxene, and magnetite crystals (Fisher, 1966). Even glass particles in an extensive sheet of ignimbrite may diminish in size toward the margins and distal end.

Lithic blocks of enormous size may be incorporated in ignimbrites close to their source when these areas have been uparched enough by rising magma before the eruptions to cause gravity slides on the flanks. An example is to be seen in the Bull Valley area of southwestern Utah (H. R. Blank, oral communication).

e. <u>Phenocrysts</u>. The content of phenocrysts in ignimbrites ranges from less than 1 to approximately 50 per cent, and, as noted

already, it may vary greatly, both vertically and laterally, within a single

cooling unit. The composition of the phenocrysts may also vary within the

same ignimbrite, as it does in one of the Picture Gorge ignimbrites of

Central Oregon, in which plagioclase becomes more calcic and clinopyroxene

becomes less ferriferous upward, while magnetite increases in amount in

the same direction (Fisher, 1966).

Phenocrysts in ignimbrites, unlike those in most lava flows,

are generally broken, owing to explosive impacts within the eruptive vent

and subsequently, during turbulent flow at the surface. The more the

phenocrysts, the more they are shattered, until all may be reduced to

splinters. This is particularly true of quartz phenocrysts because they

split readily along conchoidal fractures. Moreover, shattering of quartz

phenocrysts usually continues after the ignimbrites have come to rest,

owing to strains set up by compaction of the deposits and cooling of the

glassy matrix. The phenocrysts become slightly dismembered along con-

choidal fractures, permitting narrow lanes of glass to penetrate between

the separate parts. It should be noted, however, that in ignimbrites

that contain pumice bombs and lenticular or flamelike clots of obsidian,

the phenocrysts in the matrix are invariably more shattered than those in

the bombs and clots, where many retain euhedral forms. If biotite flakes

are present, they are commonly bent or even crumpled, particularly where

they lie between other phenocrysts. Such deformation of biotite, which

is extremely rare in lava flows, results chiefly from differential compac-

tion of ignimbrites as they cool and lose gas.

Phenocrysts in the densely welded parts of ignimbrites tend to

be fresh, whereas those in the more porous, overlying parts, which have

been subjected to the influence of fumarolic gases, are generally altered or

mantled by overgrowths. For example, sanidine or anorthoclase phenocrysts may exhibit their mantles of soda-sanidine, sanidine phenocrysts may unmix to produce crypto-perthites ("moonstones"), brown biotite may become reddish, and green hornblende becomes russet oxyhornblende in the 'vapor-phase zone'. If alteration proceeds far enough, the mafic minerals may be completely replaced by iron ore. And while magnetite may be plentiful in the densely welded part of an ignimbrite, making it strongly magnetic, it is largely replaced by hematite in the porous, overlying part, making that part much less magnetic.

f. Welding. The term 'welded tuff' was introduced in 1935 by Mansfield and Ross. The degree of welding ranges from incipient annealing of glass shards to thorough welding in which the shards are intensely deformed and porosity is reduced almost to zero. Indeed, in some welded tuffs all traces of original vitroclastic textures are obliterated, so that in hand-specimens and under the microscope, the rocks resemble delicately banded obsidians. Even thin sheets of airfall tuff, like part of the Wineglass tuff on the walls of Crater Lake, may simulate obsidian flows. But it is especially in the basal parts of ignimbrite-sheets laid down on wet ground, that welding is most thorough, owing to the development of abundant superheated steam. Not only may the pyroclastic texture disappear entirely, but the glass-particles, and, locally, even xenolithic inclusions, are thoroughly homogenized, changing to massive, perlitic glass (McBirney, 1968 b).

Color changes accompany welding. As glass shards become more tightly appressed, and light-colored pumice-lumps become increasingly flattened by load-pressure, the ignimbrite becomes darker, the larger fragments darkening more rapidly than the finer matrix, some of them becoming flamelike clots of black obsidian.

Some of the Ordovician ignimbrites of Snowdonia, Wales, show a
systematic relationship between the size of the glass shards and the degree
of welding, the most strongly welded tuffs being those composed of the
smallest shards (Rast, 1962). This, however, is far from being a general
rule, because much depends on the degree to which the fine particles have
been cooled in flight before being incorporated into a pyroclastic flow.

Ignimbrites tend to be more welded toward their source, and in
a sequence of flows erupted in quick succession, the later and hotter ones
tend to be more welded than the earlier ones, even though they contain
less gas. Indeed, as noted already, airfall tuffs with flattened,
flamelike clots, may be hot enough to become firmly welded and even to
move downslope for short distances, producing what Rittmann has called
'rheoignimbrites'.

The degree of welding depends on many factors, most of which
also control the degree of artificial sintering (Guest and Rogers, 1967).
It depends primarily on the viscosity of the glassy particles, which is
controlled in turn by their bulk composition, the nature and amount of
their contained gases, and particularly by their temperature at the
time the ignimbrite comes to rest, for viscosity varies exponentially
with temperature. The degree of welding is also influenced by the rate
of cooling and crystallization, by the thickness of the deposit (i.e. the
pressure applied), and by particle-size. Under low pressures, the smaller
particles tend to weld more readily than do the larger ones, but at high
pressures the welding rate is independent of particle-size.

The minimum temperature for incipient welding of the rhyolite
tuff of the Valles caldera was estimated by Smith (1960) to be below 535°C.
He found that the degree of welding was controlled principally by temperature,
water-vapor pressure, and load. Deformational welding to form black glass

takes places in 50 hours below 635°C. at a load of 40 kg./cm^2., 20 atm. of water-vapor pressure. For ignimbrites 30 m. or less in thickness, Smith thought that temperatures of more than 735°C. must have obtained to produce densely welded facies.

g. <u>Compaction during welding</u>. The initial bulk porosity of most ignimbrites is thought to be between 50 and 60 per cent, but by compaction the porosity is reduced by any amount down almost to zero. Assuming an initial porosity of 50%, one can make a rough estimate of the original thickness of a given sheet by adding the thickness of its unwelded part to 1½ times the thickness of zones of partial welding and twice the thickness of the zone of dense welding (Smith, 1960). Some effects of compaction on porosity are illustrated in figure 14 . Under load, eutaxitic textures develop by flattening of glass shards and pumice-clots, and many shards are bent and buckled between adjacent phenocrysts.

High 'strand lines' and marginal fault-scarps testify to compaction of the ignimbrites laid down in the Valley of Ten Thousand Smokes, and the fairly regular downward increase in the flattening of included pumice-lumps in most ignimbrites provides another graphic illustration of compaction. Peterson (1961) studied the flattening ratios of pumice-lumps in an ignimbrite near Superior, Arizona, the maximum thickness of which is now 600 m., the average being 150 m. Fragments in the upper parts are approximately equidimensional and show little preferred orientation. Lower down, they become ovoid; then they become thin streaks and stretched lenses; lower still, they may be represented by mere coatings on horizontal parting planes; finally, they disappear. Local reversals in the flattening trend denote that the
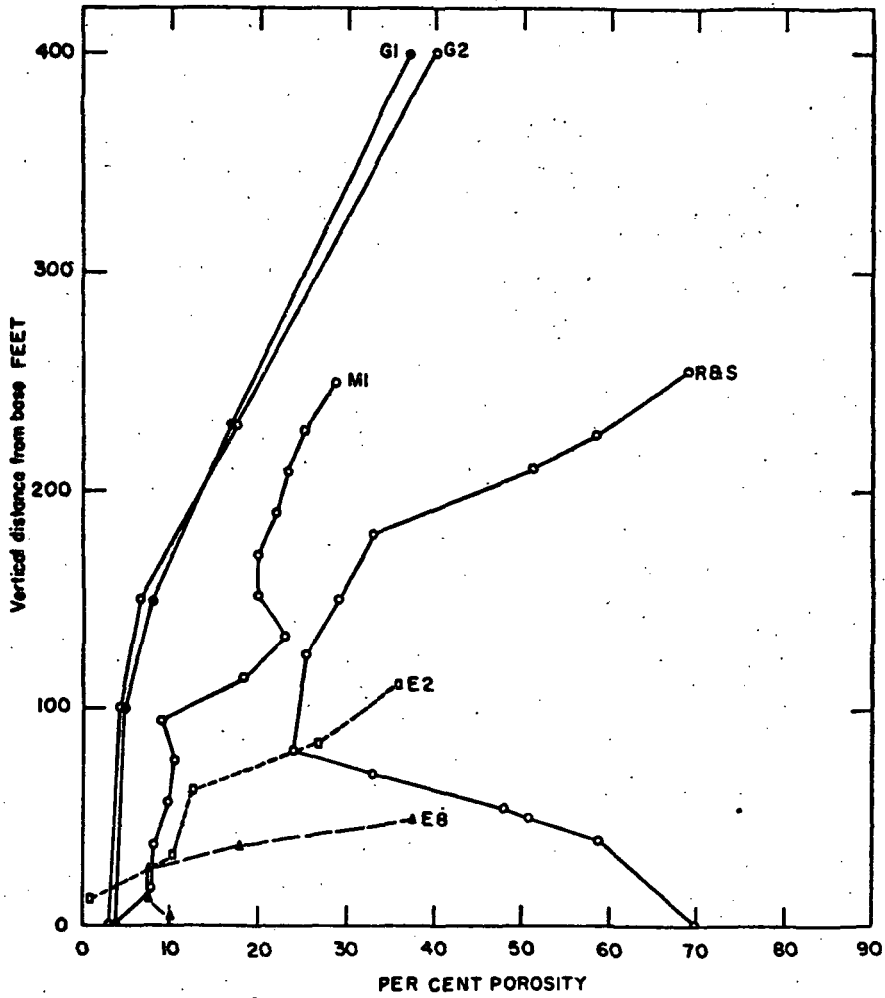
FIGURE 14.—POROSITY CURVES FOR WELDED-TUFF SHEETS

G curves: Bishop tuff, California (Gilbert, 1938)
M1 curve: Motutere "ignimbrite," New Zealand (Marshall, 1935)
E curves: Chiricahua "welded tuff," Arizona (Enlows, 1955)
R and S curve: Battleship Rock "ash flow," New Mexico (Ross and Smith, in press)
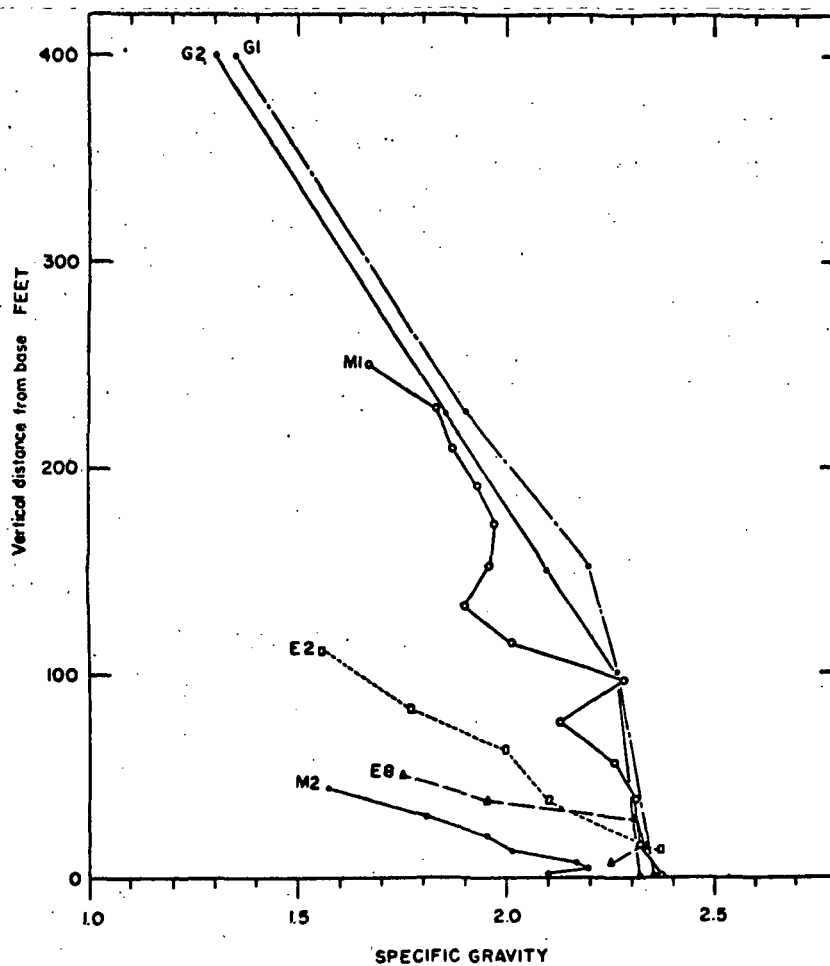From Smith (1960 a).

FIGURE 15.—SPECIFIC-GRAVITY CURVES FOR WELDED-TUFF SHEETS

G curves: Bishop tuff, California (Gilbert, 1938)
M1 curve: Motutere "ignimbrite," New Zealand (Marshall, 1935)
M2 curve: Arapuni "ignimbrite," New Zealand (Marshall, 1935)
E curves: Chiricahua "welded tuff," Arizona (Enlows, 1955)

From Smith (1960a).

material was laid down in several pulses, but the fairly regular downward
increase in flattening shows that intervals between pulses were brief.
Indeed, the flattening ratios are so nearly consistent that they can be
used to determine where isolated outcrops belong in the sequence, and
abrupt changes in the ratios can be used to detect faults and calculate
their throws.

h. Other zonal features. In addition to the variations just
described, several others may be observed in vertical sections of ignim-
brites of the Valles type, chief among which are variations in the degree
of welding. In a typical sheet, the basal and topmost parts are non-
welded and pass inward through zones of partial welding into a densely
welded core which, if sufficiently welded and thick enough, may contain
an innermost zone characterized by lithophysae. Transitions from non-
welded to partly welded tuff are marked by the first recognizable
deformation of glass shards and by flattening of pumice-lumps, and commonly
it coincides with a change from grayish to brownish colors (Lipman and
Christiansen, 1964).

Zoning due to variations in the degree of welding is least
pronounced and may be lacking in ignimbrites laid down at low temperatures.
No simple rules can be applied; some thick sheets are non-welded throughout
while others only a few meters thick may be strongly welded except for a
thin layer at the top. It is generally true, however, that in a given
sheet the thickness of the strongly welded zone increases in proportion
to the total thickness.

Superposed on the vertical zonation produced by differences in
the amount of welding are zones of devitrification, vapor-phase crystalli-
zation, and fumarolic alteration (Smith, 1960). Boundaries between glassy
and devitrified zones are commonly sharp. The principal textures formed

by devitrification are pectinate, axiolitic and spherulitic. Each glass shard and pumice fragment usually behaves as a separate unit during devitrification, fibers of cristobalite and alkali feldspar growing inward perpendicular to the margins; not uncommonly, however, particularly in densely welded tuffs, fibrous intergrowths may cross shard-boundaries at random. In ancient ignimbrites, these intergrowths are generally replaced by microgranular and micrographic intergrowths of quartz and alkali feldspar (micro- and crypto-felsite). Spherulitic and axiolitic intergrowths tend to spread outward from shard-boundaries from the sides of phenocrysts across the matrix of vitric dust, and they are commonly localized in bands along parting planes. Lithophysae develop only by devitrification of the most densely welded tuffs while they are still hot, and these are also localized by parting planes. Gases released during devitrification, if confined in small openings, force the walls apart to produce spheroidal and ovoid cavities or they crack the walls, pushing them aside to produce star-shaped cavities that may be filled later with chalcedony deposited from percolating groundwater, as in so-called "thunder eggs" (Staples, 1965).

Vapor-phase crystallization results from deposition of tridymite, alkali feldspar (usually sanidine), hematite and other less common minerals in pore-spaces by fumarolic gases. It is, consequently, most pronounced in poorly welded or unwelded zones that overlie the most densely welded zone. Fumarolic alteration is also most pronounced in these zones, and many ignimbrites have reddish or brownish tops that reflect near-surface sublimation of magnetite, hematite, etc. by fumarolic gases.
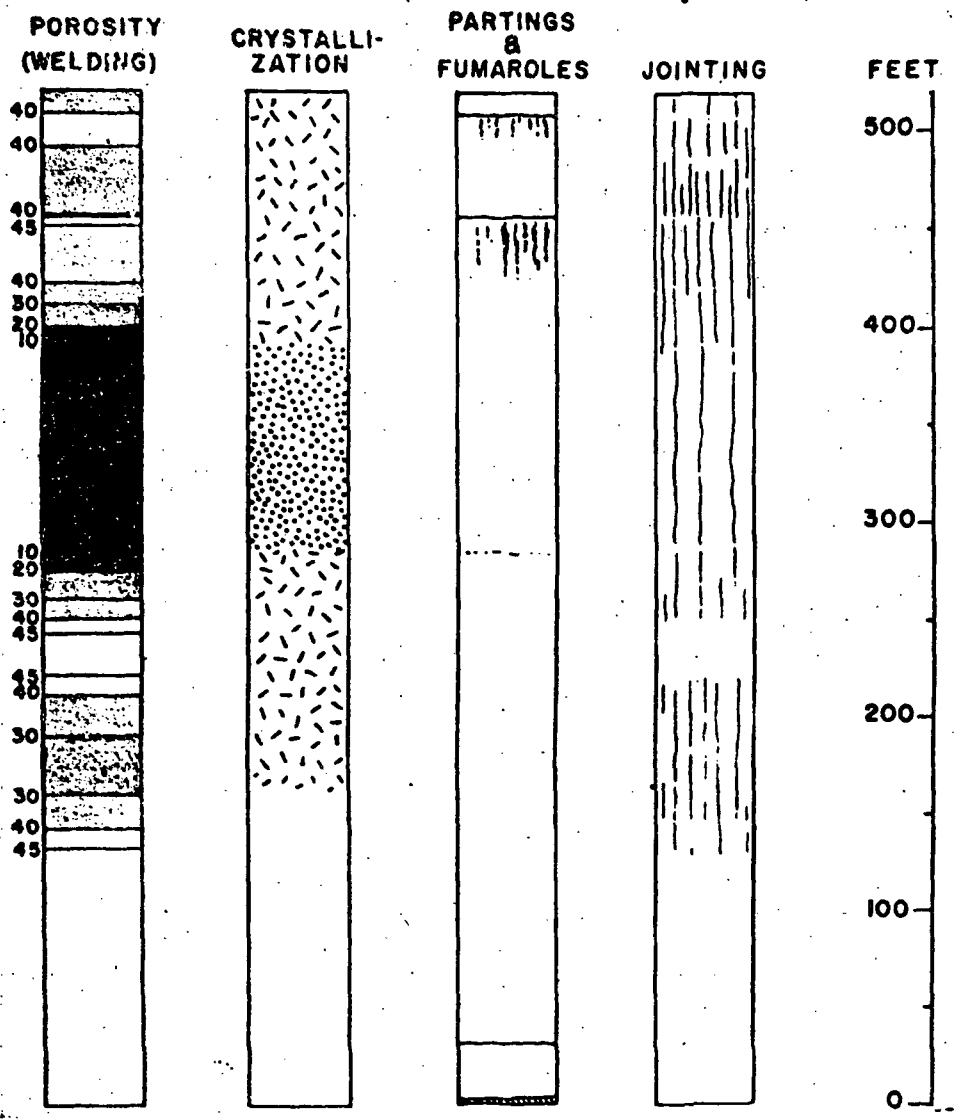
Fig.16 - A sample stratigraphic section of the upper member of the Bandelier Tuff, showing recorded changes in degree of welding (percent porosity, shaded), crystallization, (vapor phase, dashed; devitrification, dotted) position of partings and fumaroles, and spacing of joints.

From Smith and Bailey (1966).

1. <u>Recognition of individual flow-units</u>. Whether the boundaries between successive flows are distinct or obscure depends largely on the time-intervals between them; if the flows form part of a single cooling unit, particularly if all are strongly welded, it may prove difficult or impossible to detect the boundaries. Helpful criteria include the following:

1. The most obvious breaks between flow-units are those produced by weathering or erosion. However, erosional breaks do not necessarily signify long time-intervals; thick layers of fluviatile ash and pumice may accumulate rapidly on erosion-surfaces, even within a few hours, as they did between successive flows in the Valley of Ten Thousand Smokes.

2. Crystals and lithic fragments may be concentrated at the base of a unit, along with debris swept up from the consolidated top of an underlying unit.

3. Layers of airfall tuff may separate flow-units. These may be formed by settling of fine dust on the surface of a flow or they may be formed by showers of ash preceding discharge of a flow; in either case, they may contain accretionary lapilli.

4. Reversals in porosity- and welding trends, and in the flattening ratios of pumice-lumps may indicate breaks.

5. Changes in the composition or grade-sizes of the ejecta may also denote breaks.

6. The abrupt upward termination of 'fumarolic pipes' and the presence of reddish and brownish 'fumarolic tops'.

7. Changes in joint-patterns. A cooling unit that contains many flow-units may behave, however, in much the same way as a single

flow of basaltic lava, developing an upper and a lower colonnade of columns of different sizes separated by a median zone (entablature) in which jointing is irregular or obscure. It should also be noted that an earlier, already solidified ignimbrite-sheet may be reheated by later ones, so that all cool together and jointing extends uninterruptedly from one sheet to another.

8. In exceptional instances, flow-units may be distinguished by a magnetic reversal, provided, of course, that the lower sheet was not reheated above its Curie point by the overlying sheet.

j. Modes of eruption, flow and deposition. Eruption. Backfall of ejecta from the sides of vertical eruption-columns undoubtedly initiates some pyroclastic flows of Valles type, as they initiate flows of St. Vincent type. The scarcity of airfall-interbeds in many ignimbrite fields suggests, however, that most of the ejecta are not blown high above the eruptive vents and sorted in flight; instead, foaming magma bursts into an expanding cloud of incandescent clots and spray that begins at once to rush downslope like a 'base surge'.

Several estimates have been made of the water-vapor pressures that develop during differentiation and crystallization of the source-magmas of ignimbrites. Lipman (1966), for example, calculated that the source-magmas of some rhyolitic ignimbrites in Nevada may have developed pressures of 500 to 1,200 bars; others have calculated pressures of as much as 5,000 bars. But if exception be made of the great eruption of Bezymianny volcano, Kamchatka, for which Gorshkov calculated a pressure of 1,000 atmospheres, even the most violent explosive eruptions that have been studied involve pressures of no more than about 450 atmospheres, and, of course, most eruptions involve much lower pressures. By analogy

with the dispersal of ejecta in explosive eruptions that have been witnessed, it seems probable that the magma which issues from fissures to form ignimbrites does so at gas-pressures of less than 100 atmospheres.

Not much is known about the depths at which vesiculation begins in various kinds of magma. Perlaki (1966) says that rhyolitic and dacitic magmas retain their water content to depths corresponding to pressures of less than 15 atmospheres.(= 50 m.), and he quotes Nasedkin to the effect that release of water takes place gradually in the temperature-range of softening of basaltic melts but abruptly in granitic melts. Volarovich and Chepurin (1944), from heating experiments on obsidian, concluded that pumice may form at the surface at temperatures below 870°C., but at depths of 16 to 20 m. (= 5 atm.), it forms only at about 950°C., and at depths of 40 to 50 m. (= 12 to 15 atm.), the pumice-making temperature rises to 1000°C. Strict application of these experimental results to natural magmas is, however, unwarranted. Cook (1963) noted the presence of vitroclastic textures and shattered phenocrysts in the dike-feeder of a Tertiary ignimbrite near Tonopah, Nevada, at a depth of approximately 500 m. below the eruption-surface.

2. Flow. Pyroclastic flows travel almost wholly by turbulent rather than by laminar movement. They behave as fluidized systems, the solid and liquid fragments being enveloped in hot, expanding gases. As the gas-content diminishes and slopes become steeper, gravity plays an increasing role in propulsion until it becomes the dominant factor in many flows of Pelean type and in all of Merapi type. On the contrary, as the gas-content increases, flows travel vast distances over extremely gentle gradients.

The amazing mobility of pyroclastic flows is due to their fluidized state. This results partly from what Perret called the

"self-explosive, gas-generating properties of fragments in transit", and
partly from the violent expansion of air engulfed by the flows. Gas is
added to the flows continually as vesicles burst and bombs shatter by
internal explosion or by impact, and some is added by diffusion from
incandescent, glassy particles. Even a small amount released at high
pressure and high temperature may be adequate to cause extensive fluidi-
zation, but whether or not gas-emission can be maintained sufficiently
to permit flows to travel for great distances over gentle slopes remains
a debatable problem. In McTaggart's opinion (1960), mobility must be
maintained by envelopment and expansion of air. "The hot, ever-
diminishing avalanche engulfs, rolls over, draws in, and momentarily
entraps cool air. In this way, the front part of the mass is constantly
fluidized by fresh supplies of air that on heating, expand progressively
and explosively as they rise through the avalanche". It is enough to
pour hot ashes and cinders from a shovel to be reminded of the mechanism!
Indraft of air toward a glowing avalanche is indicated by the nearly
vertical sides of overlying clouds. Moreover, eyewitnesses speak of
Peléan avalanches as "rolling down in globular, surging masses".
Perret (193 5) described the more active ones as rolling rather than
sliding over the ground, and Lacroix (1904) noted that in the low,
frontal parts of avalanches, volutions rolled over one another in the
direction of advance. Finch (1935), examining the effects of a "down-
ward blast" from Lassen Peak, California, in 1915, also concluded that
there was a vortex-like circulation within the frontal part, many
short cylinders, whose axes were not parallel, rotating on horizontal
axes, with intervening areas of less turbulence. This complex internal
motion, it seemed to him, explained why some trees within the 'Devastated

Area' retained their limbs while adjacent ones were snapped off near the

base. Damage done in St. Pierre during the destructive avalanche of 1902

also denoted great variations of internal velocity. Boiler plate was

punctured by flying fragments, and heavy monuments were overthrown,

indicating local velocities of 150 m./sec. (Perret, 1935). Forward-

springing jets have been observed at the fronts of avalanches where

they make an abrupt descent. These, in McTaggart's opinion, result

from sudden compression and then expansion of air trapped and heated

by the overriding debris. In part, they resemble the "air explosions"

at Niagara Falls where plunging water encloses and compresses air until

it bursts out in jets of spray. Sudden release of large volumes of gas

at high pressure by the smashing of big bombs of pumice might also produce

forward-springing jets.

McTaggart's conclusion that gas exsolved from the liquid and

solid particles could not maintain the mobility of glowing avalanches

was questioned by Brown (1962), who pointed out that although an indi-

vidual particle cannot support its own weight by exsolving gas for more

than a fraction of a second, the effect of gas emission in a bed of

fine particles is cumulative. If data for industrial applications of

fluidization are applied, the time for deflation of the exsolved gases

is found to be much longer. When McTaggart (1962) reconsidered the

problem in terms of empirical data on industrial fluidization processes

he concluded that the time necessary to deflate a turbulent nuée is

greatly extended if particle-sizes are small and, even if no gas were

exsolved from the particles after they left the vent, times of the

order of 15 minutes would be required for a bed 100 feet thick to

become de-gassed. He suggested that the initial gas-solid mixture

would lose gas upward and at the same time deposit particles at the

base as it moves forward. Entrapped air would add to the time necessary for deflation, increasing the distance the nuee would travel.

O'Keefe and Cameron (1962) pointed out that in addition to the inertial force of upward streaming gas, viscous resistance of gas becomes an important factor when particles are small and closely spaced. Since the space between particles is narrow and gas immediately adjoining the particles is at rest with respect to the solid, there are steep velocity gradients in the adjacent gas layer. Viscosity of the gas then becomes a significant factor in supporting small particles.

According to Leva's (1959) form of the Poiseuille equation for flow through capillary tubes,

$$\Delta p = \frac{32 \; \mu \; u_0 \; L}{D_t^2} \qquad (1)$$

where p is pressure, μ viscosity, u_0 the average velocity, L the length of the passage and D_t the diameter of the tube. It can also be shown that the weight of the column of material that must be supported is

$$L(\rho s - \rho f)(1-e) \; g = \Delta p \qquad (2)$$

where g is the acceleration of gravity ($\rho s - \rho f$) the density of the solid less the buoyant effect of the gas, and e the fraction of the volume occupied by voids. $\rho s(1-e)$ is then the average density of the aggregate fluid-solid mixture.

Equating these two equations for Δp and substituting for $\rho f \; u_0$ the rate of flow G in grams per second per cm^2 gives

$$G = \frac{1-e}{32} \cdot \frac{D_t^2 \; \rho f(\rho s - f) \; g}{\mu} \qquad (3)$$

This equation does not take into account irregularities of the passages between particles and the difference between the actual path-length and L in equation (1). Moreover, the diameter of particles is more useful than the highly irregular diameter of the passage D_t. A directly applicable form of the equation (3) has been given by Leva (1959), who shows that for a wide range of densities, flow rates, particles sizes, and fluid viscosities for both gases and liquids, the minimum flow G_{mf} required to maintain a fluidized bed is

$$G_{mf} = C \frac{D_p^2 \, \rho f (\rho s - \rho f) \, g}{\mu} \qquad (4)$$

where C is a constant that varies with the Reynolds number R:

$$C \propto R^{-0.63} \qquad (5)$$

where

$$R = \frac{G D_p}{\mu} \qquad (6)$$

The empirical equation in cgs units, if buoyant effects are neglected, becomes

$$G_{mf} = 1.09 \times 10^{-3} \frac{D_p^{1.82} (\rho f \, \rho s \, g)^{0.94}}{\mu \, 0.88} \qquad (7)$$

The effective particle diameter D_p is close to the lower limit of the size-range because small particles between larger ones govern the space through which gases can move.

Application of this equation to nuées depends on the source of gases which are assumed to fluidize the solid particles. O'Keefe and Cameron assumed that water vapor to the amount of (0.1 percent by weight) is exsolved from the glass fragments and calculated that the duration of fluidization of a bed 100 m. thick by this water vapor would be almost an hour. Their estimate assumes that the only gas available is that

exsolved during transport. It is likely, however, that the magma already contains a large proportion of gas at the time of eruption and entraps air at the front of the turbulent cloud.

Fluidization can be greatly prolonged by slow diffusion of this gas through a mass of particles small enough to have an important particle-particle interaction. Eden et al. (1967) estimate that for particles in the range of 40 microns with a spacing of less than 10 microns, permeability will be so low that settling would be greatly retarded even without emission of gases. This is essentially the concept suggested by McTaggart (1962), when he questioned the importance of exsolved gases in certain historic nuees ardentes.

In large ignimbrites, mobility is probably produced by a combination of all of these factors -- entrapped atmospheric gases, water vapor exsolved during transport, and retarded deflation of the initially gas-rich eruptive cloud. Their relative importance is impossible to evaluate without observational data on large ignimbrite eruptions.

Thermal Relations

The most complete study of the thermodynamics of nuees is Boyd's (1961) work on the rhyolites of Yellowstone Park. He has shown that fluidized ignimbrites must have a high thermal efficiency. Combined heat losses through conduction to the ground and radiation from the surface could not amount to much more than 5°C. per hour. By far the greatest cooling effect is that which results from exsolution of water vapor and adiabatic expansion of the gas-liquid system. Boyd concluded that the Yellowstone tuff would be cooled by an amount that is a direct function of the initial water content, and if water contents of less than 4 percent are assumed, enough heat would be retained to

produce strongly welded rocks even 10 hours after the magma issued from its vent.

      Laminar flow may take place near the fronts of ignimbrite sheets during penultimate stages of advance (Walker and Swanson, 1968); it may also take place on steep slopes during or after welding of the deposits. During the turbulent stage of advance, there is no alinement of the pumice-lumps, lithic fragments, and phenocrysts; subsequently, however, when laminar flow begins, a lineation may develop parallel to the main direction of movement, and just before flow ceases this may be rotated at right angles. An example is to be seen in one of the Yellowstone ignimbrites, where slender bombs, ten times as long as wide, are alined perpendicular to the main direction of flow (H. R. Blank, Jr., oral communication). Laminar flow is also indicated by overturned isoclinal and asymmetric folds and 'ramp structures' with axes parallel to the strike of the banding. Secondary laminar flowage following welding is well-developed in soda-rich, trachytic ignimbrites on Grand Canary Island
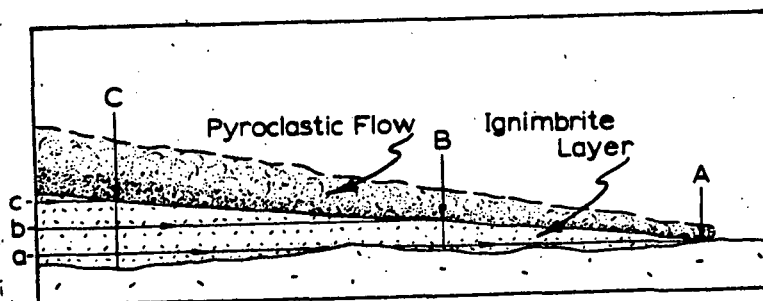

Fig. 7. Diagrammatic illustration of a moving pyroclastic flow and its gradually thickening ignimbrite deposit. Particles along line "a" were deposited from the portion of the flow that has reached station A. Particles along line "b" were deposited from the portion of the flow that has reached station B and so on through innumerable theoretical lines parallel to the base of the deposit deposited by innumerable theoretical turbulent "fronts" that follow the leading edge of the pyroclastic flow.

From R.V.Fisher (1966a).

(Schmincke and Swanson, 1967), where the lower parts of some cooling units are intricately folded and apparently were mobile enough to flow an unknown distance carrying their upper parts passively with them. In addition, imbricated discs of flattened pumice lapilli that dip $25°$ to $35°$ upslope are to be found in the basal few meters of some ignimbrites. These discs were probably rotated from a horizontal position during secondary downslope movement following compaction and welding.

3. Deposition. Pyroclastic flows lay down debris all along their paths, as basal parts lose gas by upward escape and lose velocity by frictional drag along the ground. And as gases rise within the flows, the upper parts become increasingly fluidized, turbulent, and mobile, so that they tend to travel farther and faster than the lower parts. Each part of a flow therefore tends to override the part below, and each in turn becomes the basal part of minimum velocity, where it ceases to be fluidized and so drops its load, fragments of all sizes dropping together. Other things being equal, a thick flow tends to travel farther and faster than a thin one, and a flow composed mainly of fine particles tends to travel farther and faster than one made up mainly of coarser fragments.

Reference to Fisher's diagram, reproduced here as figure 17 , shows that the thickness of the deposits laid down by a pyroclastic flow at a particular point increases continually as the flow moves past. Particles along line 'a' were laid down by the part of the flow that has reached point A; particles along line 'b' were laid down by the part that has reached point B, and so forth. The flow itself is thicker at B than at A because it has not traveled as far; and the deposits at B are thicker than at A because more of the flow has moved beyond B. Time-planes thus cross depositional planes. Particles along line 'a' were laid down first

at point C, then B, then A; hence the deposits along this line are not synchronous. The time-planes parallel the interface between the flow itself and its deposits.

Diminution in the content of lithic fragments and crystals and in the size of glass shards and pumice-lumps toward the fronts and sides of some ignimbrite sheets reflects a gradual loss of energy and turbulence in those directions, doubtless because of loss of gas. However, the fact that such sorting is never pronounced and commonly too obscure to detect suggests constant re-vitalizing of the fronts and sides of flows by entrapment, heating, and expansion of cool air, in the manner advocated by McTaggart.

k. Origin of ignimbrite-magmas of Valles Type. There seems to be general agreement concerning the origin of magmas involved in the formation of pyroclastic flows related to volcanic domes and those related to eruptions from the open craters of long-established volcanic cones. These magmas appear to have evolved chiefly by crystal-differentiation, gas-transfer, and reaction with wall-rocks in near-surface reservoirs. There is much less agreement concerning the origin of the vastly more voluminous magmas involved in the formation of pyroclastic flows of Valles type. Such flows are relatively rare within eugeosynclinal belts, and their eruption rarely coincides in time with orogenic deformation of those. Their maximum distribution is outside eugeosynclinal belts (Westerveld, 1963); the same holds true for most of the world's ring-dike complexes, of which more than 300 are known (Elston et al., 1968).

The immense volumes of ignimbrites of rhyolitic to dacitic composition, and the scarcity of associated andesites and basalts cast doubt on the view that the parent magmas were derived by crystal-

differentiation of more basic melts. The compositional-range of most ignimbrites of Valles type corresponds with that of the granite-quartz monzonite-granodiorite-tonalite calc-alkaline suite, these being the dominant plutonic rocks of orogenic belts.

Plutonic rocks of this type do not occur on truly oceanic islands, and ignimbrites are extremely rare there, being restricted to alkaline types. Taken together these facts suggest that voluminous ignimbrites of Valles type are derived from magmas produced by anatexis of sialic rocks within the crust. The compositions of the ignimbrites are restricted to a relatively small range with respect to Q, Or, and Ab, the principal constituents, and this range corresponds closely with that of the eutectic points in granitic systems and in experimentally formed anatectic melts at water-vapor pressures of 2,000 bars (Winkler, 1965).

If ignimbrite-magmas originate by fractional melting of crustal rocks, such as shales, graywackes, schists and gneisses, the initial liquids would be those most nearly rhyolitic in composition, and, as melting continued the liquids would tend to change to quartz latitic, and dacitic compositions. A fractionated liquid column might thus develop, increasingly silicic and alkalic upward. Neither xenocrysts nor xenoliths would be likely to survive in such a column. However, no ignimbrite-field shows a regular upward succession from rhyolites to dacites; hence, it seems probable that if the parent magmas originate by anatexis, they rise to various levels in the crust to occupy large reservoirs within which they then undergo differentiation by crystal-settling, gas-transfer, and wall-rock contamination. The fact that many ignimbrite fields contain large collapse-calderas suggests that these proximal feeding chambers lie at depths of only a few kilometers.

Many calculations have been made of the depths at which ignimbrite-magmas crystallize, but all are open to serious doubt. As Lipman says (1966), if water pressures in ignimbrite-magmas are generally less than load pressures, precise values for the temperature, depth, and water content of the magmas cannot be estimated from data currently available. It is probable, moreover, that the depths at which anatexis and crystallization take place are markedly different.

The composition of glasses and their coexisting crystals in certain ignimbrites in Nevada led Scott (1965) to conclude that eutectic crystallization of the parent magma took place under water-vapor pressures of approximately 3,000 to 5,000 bars (equivalent to depths of 11 to 17.5 km.). If the magma was saturated with water during crystallization, he estimated that its temperature would have been 650°C. to 680°C. Lipman et al. (1966), in their work on ignimbrites in southern Nevada, assumed that an equilibrium water-vapor pressure of 600 bars was effective during the formation of phenocrysts as well as during anatectic differentiation, and concluded that the top of the magma-chamber lay at a depth of approximately 2 km.

Ignimbrites are common in many ring complexes, and generally they were erupted from ring-fractures tapping the upper, silicic parts of plutonic cupolas. Field studies suggest that the tops of such cupolas lie at depths of approximately 4 to 6 kms.

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