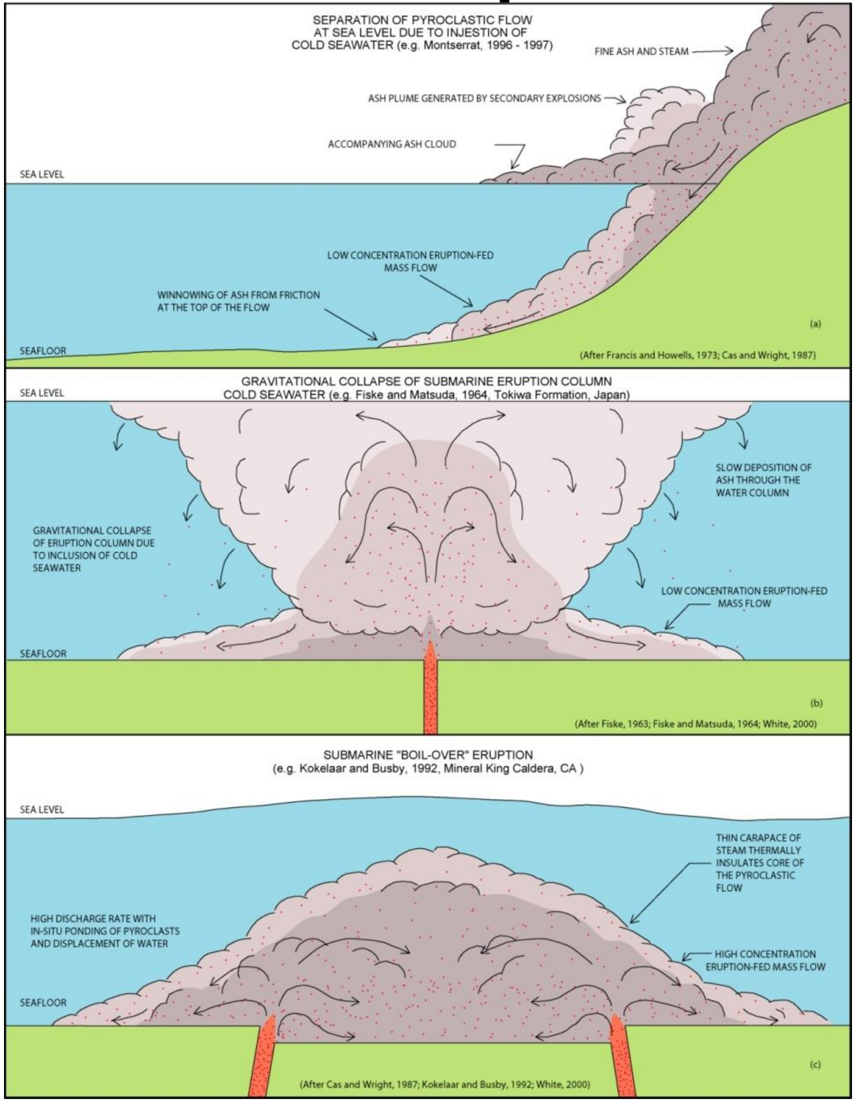
“Subaqueous Pyroclastic Flows”


SEPARATION OF PYROCLASTIC FLOW AT SEA LEVEL DUE TO INJESTION OF COLD SEAWATER (e.g. Montserrat, 1996 - 1997)

(After Francis and Howells, 1973; Cas and Wright, 1987)

GRAVITATIONAL COLLAPSE OF SUBMARINE ERUPTION COLUMN COLD SEAWATER (e.g. Fiske and Matsuda, 1964, Tokiwa Formation, Japan)

(After Fiske, 1963; Fiske and Matsuda, 1964; White, 2000)

SUBMARINE "BOIL-OVER" ERUPTION (e.g. Kokelaar and Busby, 1992, Mineral King Caldera, CA)

(After Cas and Wright, 1987; Kokelaar and Busby, 1992; White, 2000)

Syneruptive Products of Pyroclastic Volcanism

in Subaqueous Environments

“Subaqueous Pyroclastic Flows”

- Terminology, Definitions, Nomenclature
  - Contentious, confusing, frustrating
  - A better understanding of subaqueous volcanic processes from recent observations is helping to better define and describe these types of deposits
  - A classification scheme for submarine pyroclastic rocks
- General Differences in Environments between Subaerial / Subaqueous Eruptions
- Four Types of Subaqueous “Pyroclastic Flows”
  - Subaerial Eruptions into Water
  - Subaqueous High Concentration Mass Flows (subaqueous pyroclastic flows)
  - Subaqueous Low Concentration Mass Flows (eruption-fed turbidity currents)
  - Subaqueous lava-fed density currents (submarine “block-and-ash” flows)

General Thoughts on Explosive Submarine Volcanism

- The proportion of subaqueous explosive eruptions is larger than generally appreciated by still poorly constrained
  - Estimates range from 10% to 25% of subaerial explosive volcanism annually
- Processes associated with eruption, transportation and deposition are significantly different due to presence of water
  - Ability to vaporize when in contact with water
  - High density and resulting confining pressure
  - High viscosity relative to air
  - The differences in the heat capicities/thermal conductivities in air relative to water
- Interpretation of both modern and ancient products of submarine explosive volcanism are both academically and practically important
  - Gain understanding of how volcanoes work on ¾ of earth
  - Processes, environments, and products of explosive submarine explosive eruptions are associated with significant mineral deposits

Differences Between Studying Subaerial/Subaqueous Explosive Volcanism

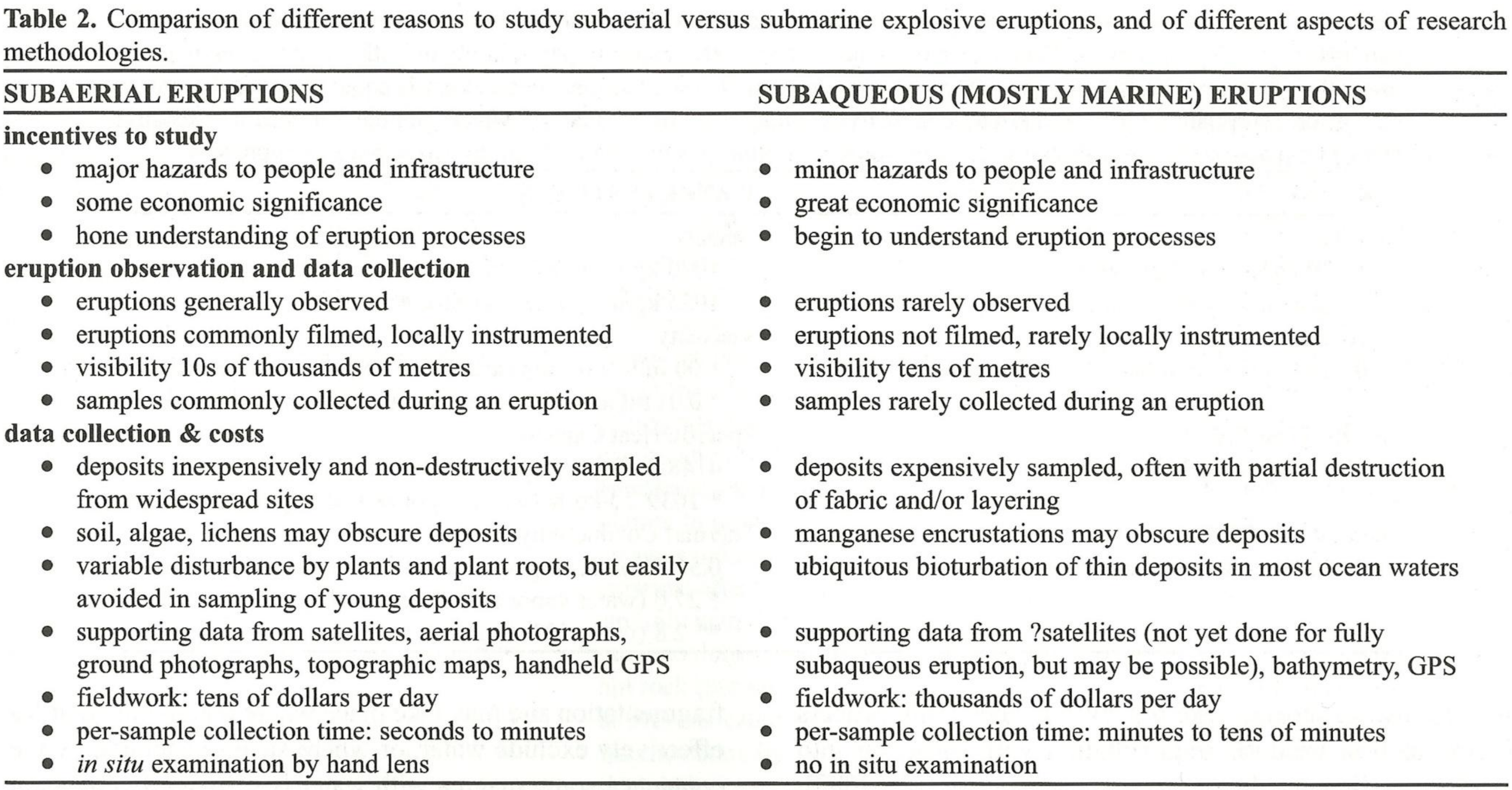


Table 2. Comparison of different reasons to study subaerial versus submarine explosive eruptions, and of different aspects of research methodologies.

SUBAERIAL ERUPTIONS	SUBAQUEOUS (MOSTLY MARINE) ERUPTIONS
incentives to study	
• major hazards to people and infrastructure	• minor hazards to people and infrastructure
• some economic significance	• great economic significance
• hone understanding of eruption processes	• begin to understand eruption processes
eruption observation and data collection	
• eruptions generally observed	• eruptions rarely observed
• eruptions commonly filmed, locally instrumented	• eruptions not filmed, rarely locally instrumented
• visibility 10s of thousands of metres	• visibility tens of metres
• samples commonly collected during an eruption	• samples rarely collected during an eruption
data collection & costs	
• deposits inexpensively and non-destructively sampled from widespread sites	• deposits expensively sampled, often with partial destruction of fabric and/or layering
• soil, algae, lichens may obscure deposits	• manganese encrustations may obscure deposits
• variable disturbance by plants and plant roots, but easily avoided in sampling of young deposits	• ubiquitous bioturbation of thin deposits in most ocean waters
• supporting data from satellites, aerial photographs, ground photographs, topographic maps, handheld GPS	• supporting data from ?satellites (not yet done for fully subaqueous eruption, but may be possible), bathymetry, GPS
• fieldwork: tens of dollars per day	• fieldwork: thousands of dollars per day
• per-sample collection time: seconds to minutes	• per-sample collection time: minutes to tens of minutes
• *in situ* examination by hand lens	• no in situ examination

(after White, 2003)

Terminology and definition

- Lot of confusion in literature and in the field about subaqueous pyroclastic flows
- This is evident in 1) the variety of terms used to describe such deposits:
  - Pyroturbidites
  - Pyroclastic debris flows
  - Sedimentary pyroclastic flows
  - Pumice breccias, volcanic sandstones
  - Mass flows of pyroclastic material
  - Bedded ash flow tuffs

Volcaniclastic Rock Terminology – We're in a Mess!

- *Volcaniclastic rock terminology has been used inconsistently for several years because there are a variety of classification schemes*
- *Four basic types of classification schemes have been used in the recent literature:*
  - *Particle formation or fragmentation mechanism (e.g. Fisher (1961, 1966)*
  - *Particle type within the deposit (e.g. Schmid, 1981)*
  - *Mode of fragmentation and deposition (e.g. Cas and Wright, 1987*
  - *Transport and deposition mechanisms (e.g. McPhie et al., 1993).*
- *As a result, the same rock could be classified numerous ways (e.g. "tuff" or "sandstone")*

Terminology and definition

The common misidentification of such deposits has risen largely due to the following:

1. The varied origin for deposits which have been described as “subaqueous pyroclastic flows”; how does one unambiguously interpret primary volcanic products that may have interacted with water during their genesis?
2. A lack of understanding of: 1) sub-aqueous explosive volcanism; 2) processes which form subaqueous pyroclastic flows; and 3) the inability to directly observe a subaqueous explosive eruption
3. Models and criteria that are used to define subaerial pyroclastic flows and eruptions have historically been applied to subaqueous explosive eruptions and their products – whale and elephants

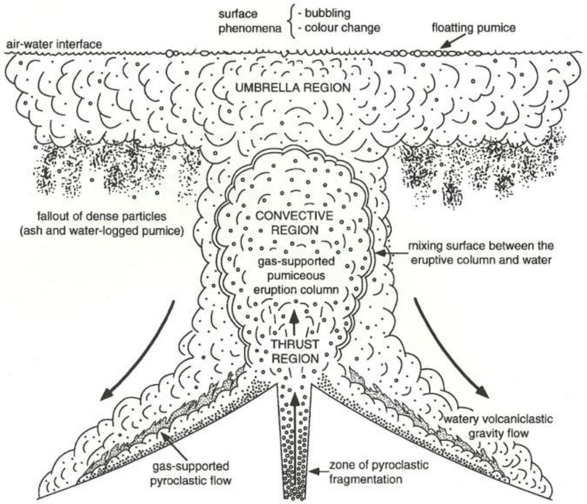


Fig. 9.2. Synthetic model for submarine explosive eruptions (from Kokelaar and Busby, 1992; Kano *et al.*, 1996). Collapse from the convective region of the eruption column leads to the generation of subaqueous pyroclastic flows, whereas pyroclastic fallout occurs from umbrella region. Shearing of the eruption column against sea water induces replacement of eruptive gases by water and the formation of watery volcaniclastic gravity flows. Submarine eruption columns from shallow explosions can cross the air-water interface, but the correlative effects are not represented on the sketch.

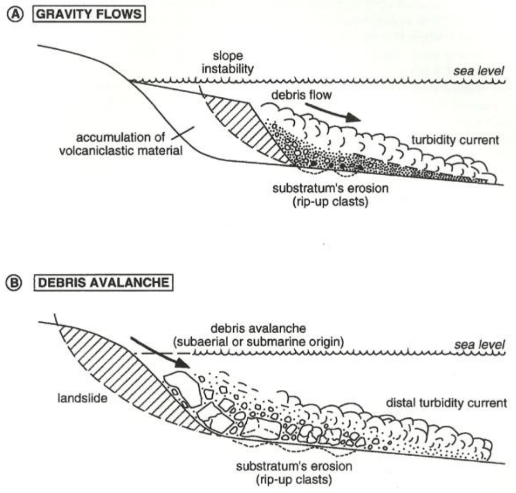


Fig. 9.6. Synthetic models for submarine resedimentation of volcaniclastic material during non-eruptive periods. A. Remobilisation by gravity flows related to slope instability. If the volume of reworked material is important, a dense debris flow can form, and it erodes the substratum if momentum is sufficient. The debris flow can distally transform into a more dilute turbidity current. B. Remobilization by debris avalanches originated by large-scale flank collapse of a volcano in subaerial or submarine domains. Submarine avalanches can generate distal turbidity currents by mixing with water and subsequent elutriation of fine particles.

Terminology and Definition

- Some geologists would restrict the term subaqueous pyroclastic flow deposits to volcaniclastic units deposited underwater which show characteristics of emplacement in a hot state – *this can't always be done due to subsequent alteration/diagenesis (e.g. active hot springs and associated hydrothermal alteration)*
- Deposits from pyroclastic flows which interact with water and are transformed into water-supported mass flows are called subaqueous pyroclastic debris flow deposits by some.
- Distinction between bullets 1 and 2 in terms of depositional and eruptive environment, and process of fragmentation are trivial –
  - Case 1: insulated from water-remained water-poor and hot
  - Case 2: interacted with water and transformed "in situ" into cool water abundant flows of pyroclastic debris.
- *Both represent primary erupted and primary deposited pyroclastic material*

Terminology and Definition

- *Sensu-stricto*: “Pyroclastic flow” refers to *a highly concentrated pyroclastic density current composed entirely of freshly-erupted pyroclastic debris (e.g. glass shards, crystals, pumice, and rock fragments*
- For submarine pyroclastic flows, we use a *sensu-lato* definition: *“Submarine pyroclastic flow” refers to a highly concentrated pyroclastic density current composed entirely of freshly-erupted pyroclastic debris regardless of the emplacement temperature.*
  - Gravity controlled
  - Can be emplaced in either hot or cold state
  - Can still be applied to ancient deposits where depositional temperature cannot be unambiguously determined
  - Enables eruption-fed deposits to be distinguished from much later processes associated with resedimentation by means of detailed mapping and facies analysis

Terminology and Definition

- Need to be able to make distinction between subaqueous pyroclastic flow deposits and subaqueous debris flow deposits.
  - Debris flows may be post-eruptive, secondary mass flows of redeposited or reworked volcaniclastic debris. These can form between eruptions, during eruptions and long after volcanic activity has ceased.
- Debris flow deposits tell nothing about eruptive environment and nothing about processes in magma chamber – they give information regarding source and post-eruptive erosional/depositional processes.
- Unfortunately, many debris flows have been mapped as pyroclastic flow deposits – this has permeated literature
- At times not easy to differentiate
  - Debris flows are commonly polymict, whereas most pyroclastic flow deposits are essentially pumiceous ± minor percentages of accessory/accidental fragments

Volcaniclastic Particle Types

- *Volcaniclastic particles may be classified based on whether they are juvenile (primary), lithic (may be primary or epiclastic), or composite (combines both primary and epiclastic components – White and Houghton, 2006)*

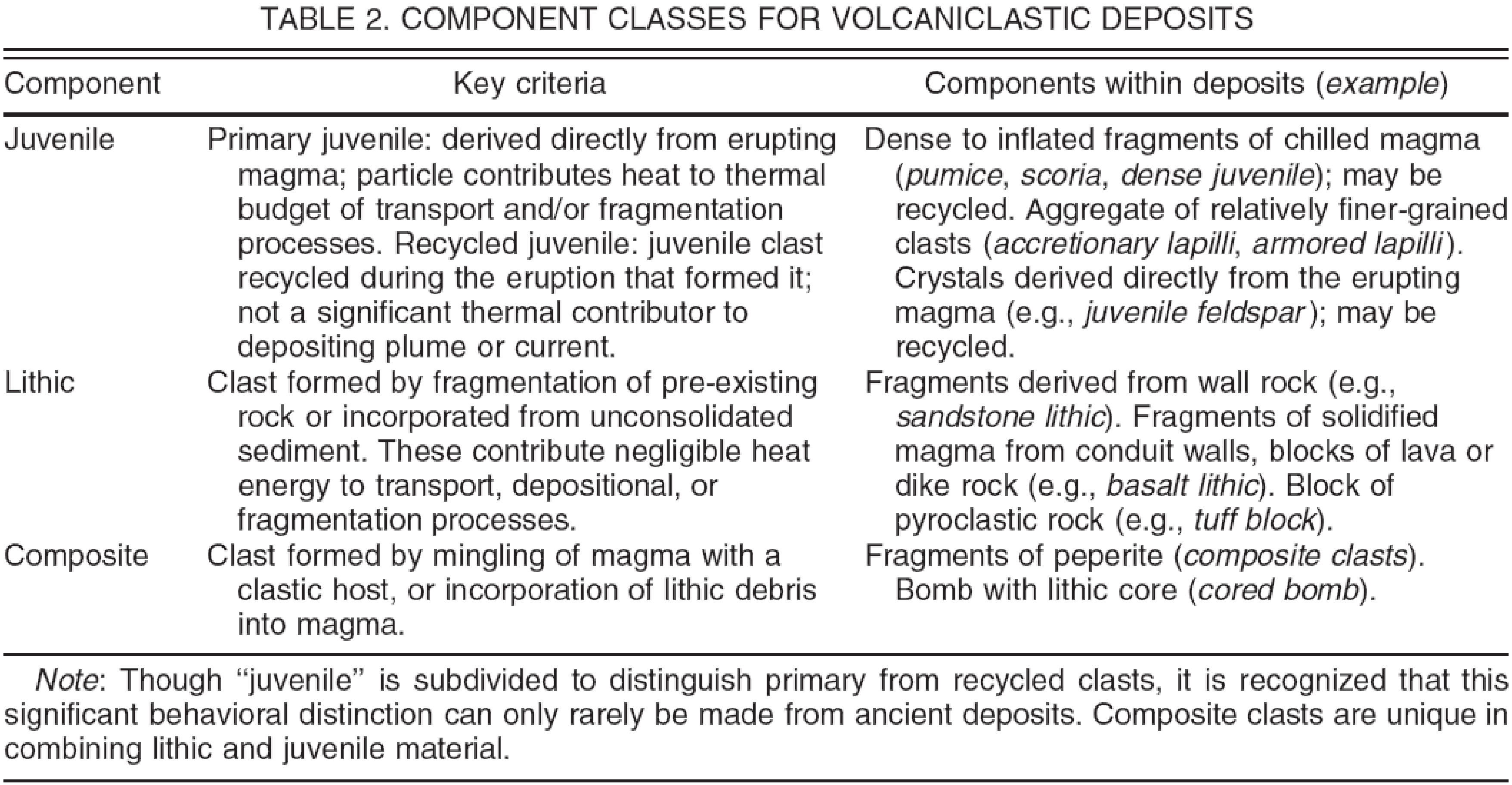


TABLE 2. COMPONENT CLASSES FOR VOLCANICLASTIC DEPOSITS

Component	Key criteria	Components within deposits (*example*)
Juvenile	Primary juvenile: derived directly from erupting magma; particle contributes heat to thermal budget of transport and/or fragmentation processes. Recycled juvenile: juvenile clast recycled during the eruption that formed it; not a significant thermal contributor to depositing plume or current.	Dense to inflated fragments of chilled magma (*pumice*, *scoria*, *dense juvenile*); may be recycled. Aggregate of relatively finer-grained clasts (*accretionary lapilli*, *armored lapilli*). Crystals derived directly from the erupting magma (e.g., *juvenile feldspar*); may be recycled.
Lithic	Clast formed by fragmentation of pre-existing rock or incorporated from unconsolidated sediment. These contribute negligible heat energy to transport, depositional, or fragmentation processes.	Fragments derived from wall rock (e.g., *sandstone lithic*). Fragments of solidified magma from conduit walls, blocks of lava or dike rock (e.g., *basalt lithic*). Block of pyroclastic rock (e.g., *tuff block*).
Composite	Clast formed by mingling of magma with a clastic host, or incorporation of lithic debris into magma.	Fragments of peperite (*composite clasts*). Bomb with lithic core (*cored bomb*).

Note: Though “juvenile” is subdivided to distinguish primary from recycled clasts, it is recognized that this significant behavioral distinction can only rarely be made from ancient deposits. Composite clasts are unique in combining lithic and juvenile material.

Volcaniclastic Particle Types

- *Volcaniclastic particles can result from fragmentation of volcanic material both during and after volcanic activity*
- *Primary (juvenile) volcaniclastic particles include:*
  - *Pyroclasts – form by explosive fragmentation of the magma into particles (including ash, highly vesiculated glass (pumice/scoria), crystals and crystal fragments, and lithic fragments)*
  - *Hydroclasts – form by explosive interaction with external water (via phreatic and phreatomagmatic explosions) or by non-explosive quenching and granulation of lava (lava flows and shallow subsurface intrusions)*
  - *Autoclasts – form by frictional breakage of moving viscous lava flows*
- *Secondary volcaniclastic particles are "epiclasts":*
  - *Epiclasts are lithic clasts and/or crystals derived from physical weathering and erosion of pre-existing rocks; they are volcaniclasts when the pre-existing rocks are volcanic*

Why Classification is Difficult

“Volcaniclastic rocks are essentially igneous on the way up and sedimentary on the way down”

R. V. Fisher

“…the ugliest and most undistinguished rocks I’ve seen in my 30 years of petrology!”

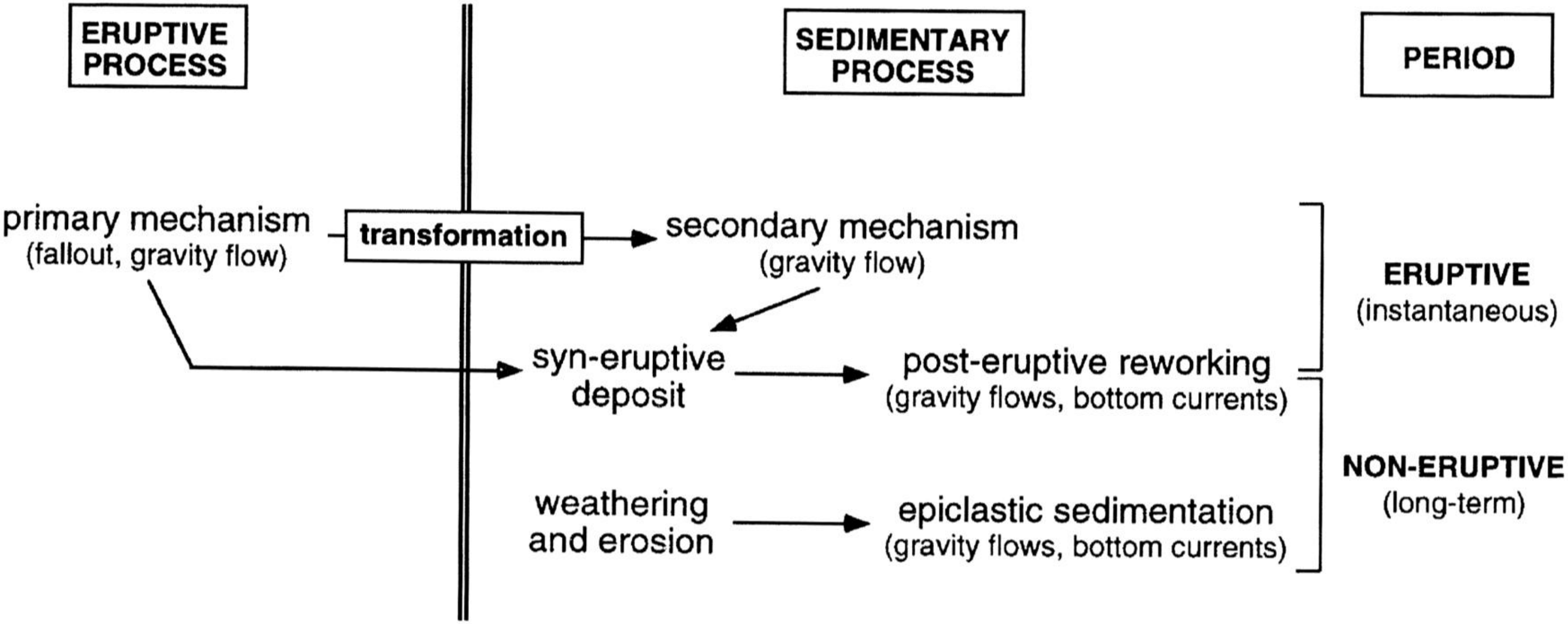
R. V. Fisher’s thesis advisor on his samples of volcaniclastic rocks

“Lapilli Tuff” or “Pumice Breccia”?

“Tuff Breccia” or “Conglomerate”?

Diversity of Processes Responsible for Forming Volcaniclastic Rocks

(after Schneider, 2000)



ERUPTIVE PROCESS

SEDIMENTARY PROCESS

PERIOD

primary mechanism
(fallout, gravity flow)

transformation

secondary mechanism
(gravity flow)

syn-eruptive deposit

post-eruptive reworking
(gravity flows, bottom currents)

ERUPTIVE
(instantaneous)

weathering and erosion

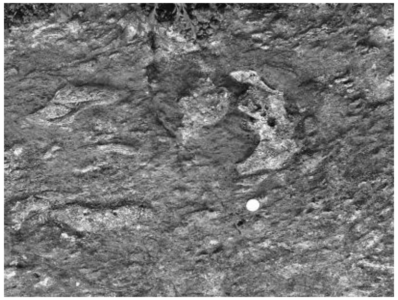
epiclastic sedimentation
(gravity flows, bottom currents)

NON-ERUPTIVE
(long-term)

Fig. 9.1. Diversity and mutual genetic relationships of volcaniclastic transport mechanisms. Primary processes occur during eruptive periods. Sedimentary processes can be genetically related to transformation of primary mechanisms into gravity flows. During non-eruptive periods primary deposits are remobilized, and older formations are eroded.

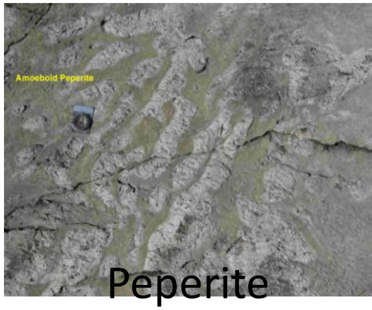
Primary Volcaniclastic Deposits(White and Houghton, 2006)

- *Primary Volcaniclastic Deposits include:*
  - *Pyroclastic Deposits: Generated from volcanic plumes and jets or pyroclastic density currents as particles first come to rest; deposition by suspension settling, traction, and/or en masse freezing*
  - *Autoclastic Deposits: Generated during effusive volcanism when lava cools and fragments; deposition is under the influence of continued lava flowage*
  - *Hyaloclastite Deposits: Generated during effusive volcanism when magma or flowing lava is chilled and fragmented from contact with water; deposition is under the influence of the continued emplacement of the lava*
  - *Peperite Deposits: Generated during effusion and shallow intrusion of magma through unconsolidated clastic material as magma/lava mingles with (generally wet) debris; deposition is effectively in-situ*


Pyroclastic


Autoclastic


Hyaloclastite



Peperite

Non-Genetic and Genetic Classifications of Volcaniclastic Rocks (Cas and Wright, 1987)

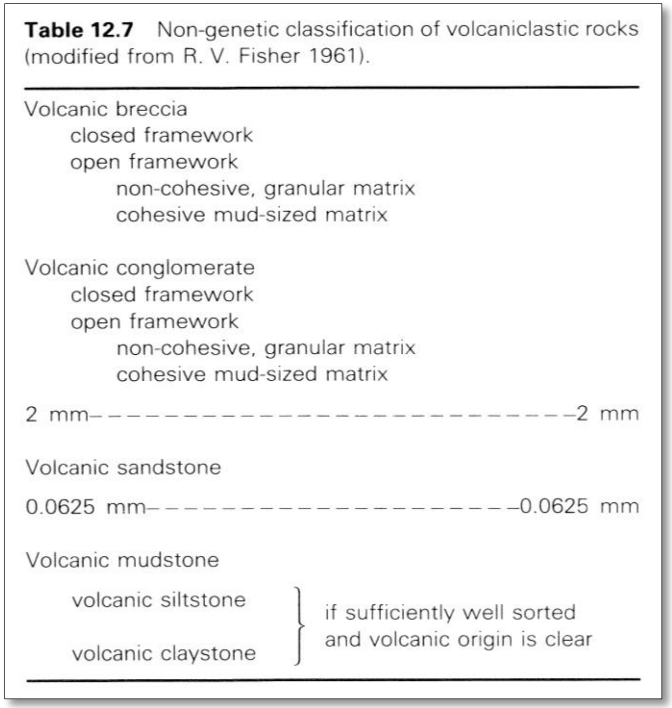


Table 12.7 Non-genetic classification of volcaniclastic rocks (modified from R. V. Fisher 1961).

Volcanic breccia
- closed framework
- open framework
  - non-cohesive, granular matrix
  - cohesive mud-sized matrix

Volcanic conglomerate
- closed framework
- open framework
  - non-cohesive, granular matrix
  - cohesive mud-sized matrix

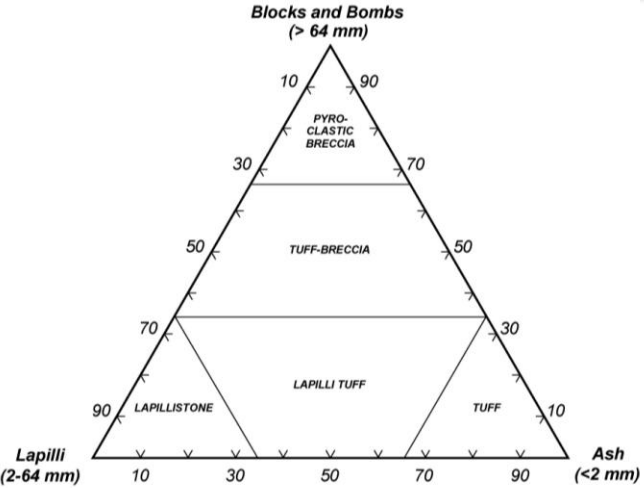
2 mm– –2 mm

Volcanic sandstone

0.0625 mm– –0.0625 mm

Volcanic mudstone
- volcanic siltstone
- volcanic claystone

} if sufficiently well sorted and volcanic origin is clear



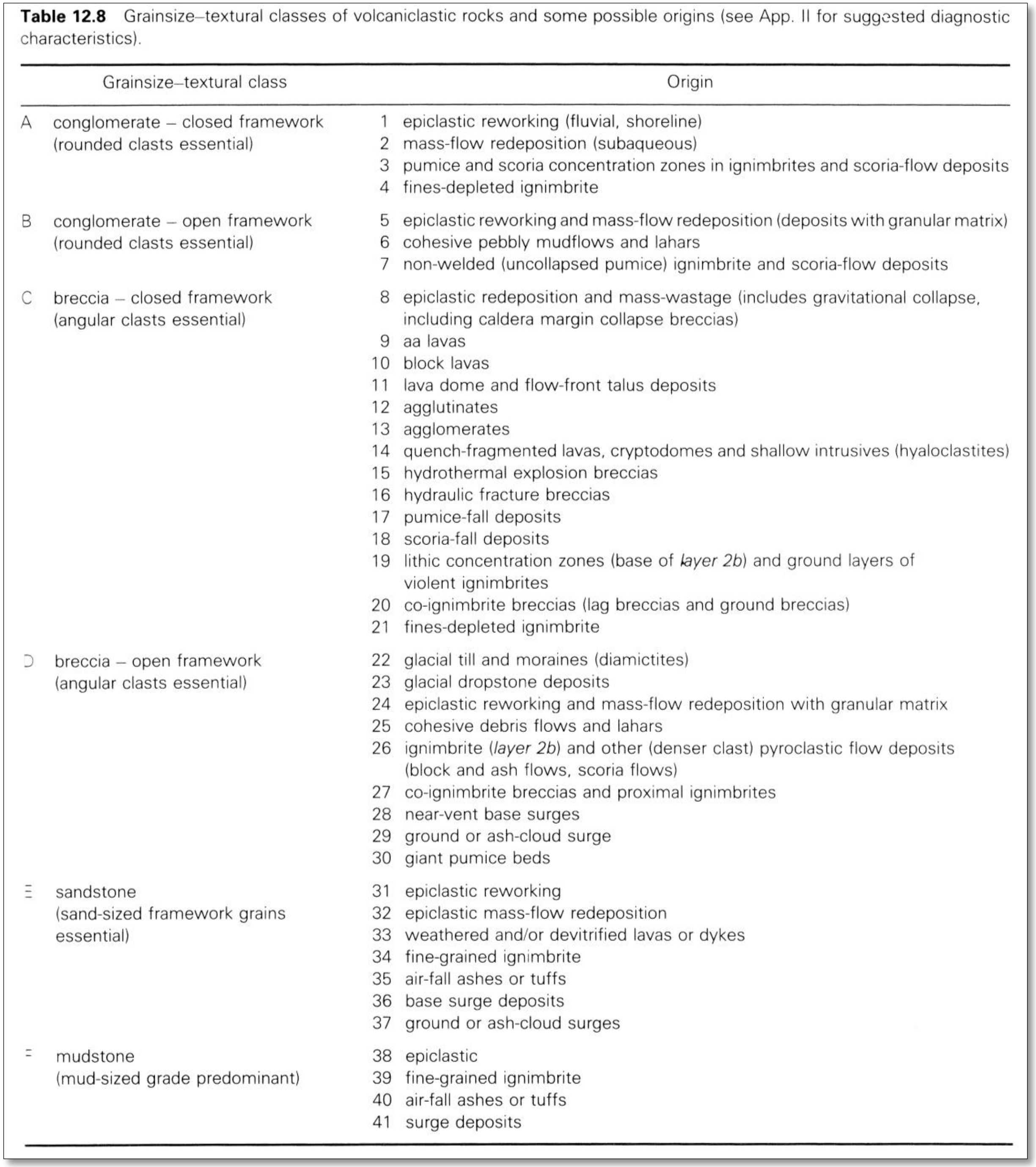
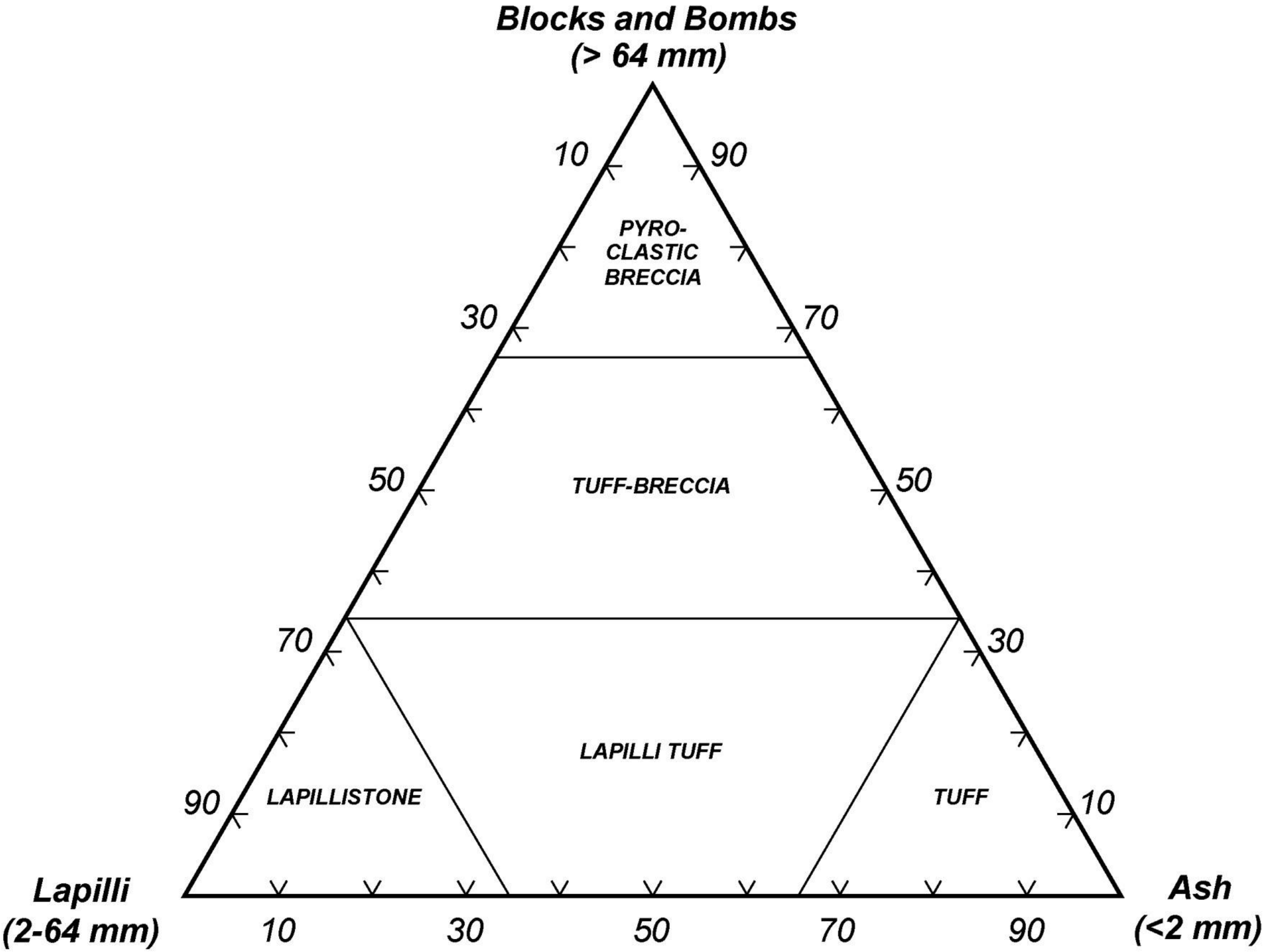


Table 12.8 Grainsize–textural classes of volcaniclastic rocks and some possible origins (see App. II for suggested diagnostic characteristics).

	Grainsize–textural class		Origin
A	conglomerate – closed framework (rounded clasts essential)	1	epiclastic reworking (fluvial, shoreline)
		2	mass-flow redeposition (subaqueous)
		3	pumice and scoria concentration zones in ignimbrites and scoria-flow deposits
		4	fines-depleted ignimbrite
B	conglomerate – open framework (rounded clasts essential)	5	epiclastic reworking and mass-flow redeposition (deposits with granular matrix)
		6	cohesive pebbly mudflows and lahars
		7	non-welded (uncollapsed pumice) ignimbrite and scoria-flow deposits
C	breccia – closed framework (angular clasts essential)	8	epiclastic redeposition and mass-wastage (includes gravitational collapse, including caldera margin collapse breccias)
		9	aa lavas
		10	block lavas
		11	lava dome and flow-front talus deposits
		12	agglutinates
		13	agglomerates
		14	quench-fragmented lavas, cryptodomes and shallow intrusives (hyaloclastites)
		15	hydrothermal explosion breccias
		16	hydraulic fracture breccias
		17	pumice-fall deposits
		18	scoria-fall deposits
		19	lithic concentration zones (base of *layer 2b*) and ground layers of violent ignimbrites
		20	co-ignimbrite breccias (lag breccias and ground breccias)
		21	fines-depleted ignimbrite
D	breccia – open framework (angular clasts essential)	22	glacial till and moraines (diamictites)
		23	glacial dropstone deposits
		24	epiclastic reworking and mass-flow redeposition with granular matrix
		25	cohesive debris flows and lahars
		26	ignimbrite (*layer 2b*) and other (denser clast) pyroclastic flow deposits (block and ash flows, scoria flows)
		27	co-ignimbrite breccias and proximal ignimbrites
		28	near-vent base surges
		29	ground or ash-cloud surge
		30	giant pumice beds
E	sandstone (sand-sized framework grains essential)	31	epiclastic reworking
		32	epiclastic mass-flow redeposition
		33	weathered and/or devitrified lavas or dykes
		34	fine-grained ignimbrite
		35	air-fall ashes or tuffs
		36	base surge deposits
		37	ground or ash-cloud surges
F	mudstone (mud-sized grade predominant)	38	epiclastic
		39	fine-grained ignimbrite
		40	air-fall ashes or tuffs
		41	surge deposits

Fisher, 1966
Rocks Composed of Volcanic Fragments and Their Classification



Some Recent Modifications to Fisher’s Classification Scheme

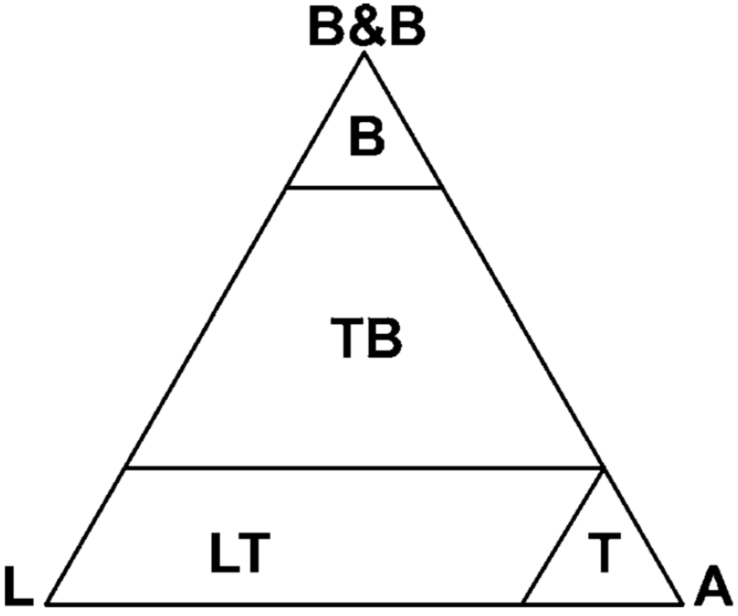


Figure 1. Grain-size ternary diagram for naming primary volcaniclastic rocks after Fisher (1961). Triangle apices: B&B—blocks and bombs; L—lapilli; A—ash. Fields: B—breccia; TB—tuff breccia; LT—lapilli tuff (follows Schmid [1981] in abandoning “lapillistone”); T—tuff. Blocks are angular large pyroclasts, and bombs are their fluidal equivalent. Divisions are at 75% blocks and bombs, 25% blocks and bombs, and 25% ash versus lapilli. Unconsolidated deposits—minor-major constituent, e.g., lapilli-ash deposit.

(White and Houghton, 2006)

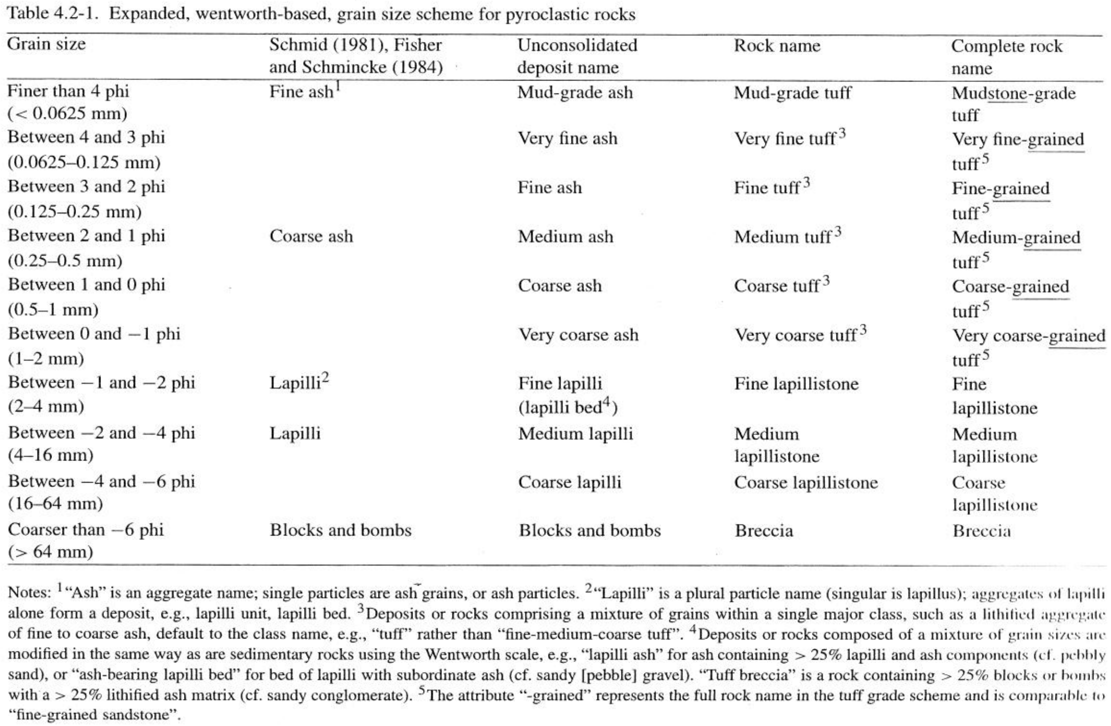


Table 4.2-1. Expanded, wentworth-based, grain size scheme for pyroclastic rocks

Grain size	Schmid (1981), Fisher and Schmincke (1984)	Unconsolidated deposit name	Rock name	Complete rock name
Finer than 4 phi (< 0.0625 mm)	Fine ash[1]	Mud-grade ash	Mud-grade tuff	Mudstone-grade tuff
Between 4 and 3 phi (0.0625–0.125 mm)		Very fine ash	Very fine tuff[3]	Very fine-grained tuff[5]
Between 3 and 2 phi (0.125–0.25 mm)		Fine ash	Fine tuff[3]	Fine-grained tuff[5]
Between 2 and 1 phi (0.25–0.5 mm)	Coarse ash	Medium ash	Medium tuff[3]	Medium-grained tuff[5]
Between 1 and 0 phi (0.5–1 mm)		Coarse ash	Coarse tuff[3]	Coarse-grained tuff[5]
Between 0 and −1 phi (1–2 mm)		Very coarse ash	Very coarse tuff[3]	Very coarse-grained tuff[5]
Between −1 and −2 phi (2–4 mm)	Lapilli[2]	Fine lapilli (lapilli bed[4])	Fine lapillistone	Fine lapillistone
Between −2 and −4 phi (4–16 mm)	Lapilli	Medium lapilli	Medium lapillistone	Medium lapillistone
Between −4 and −6 phi (16–64 mm)		Coarse lapilli	Coarse lapillistone	Coarse lapillistone
Coarser than −6 phi (> 64 mm)	Blocks and bombs	Blocks and bombs	Breccia	Breccia

Notes: [1] “Ash” is an aggregate name; single particles are ash grains, or ash particles. [2] “Lapilli” is a plural particle name (singular is lapillus); aggregates of lapilli alone form a deposit, e.g., lapilli unit, lapilli bed. [3] Deposits or rocks comprising a mixture of grains within a single major class, such as a lithified aggregate of fine to coarse ash, default to the class name, e.g., “tuff” rather than “fine-medium-coarse tuff”. [4] Deposits or rocks composed of a mixture of grain sizes are modified in the same way as are sedimentary rocks using the Wentworth scale, e.g., “lapilli ash” for ash containing > 25% lapilli and ash components (cf. pebbly sand), or “ash-bearing lapilli bed” for bed of lapilli with subordinate ash (cf. sandy [pebble] gravel). “Tuff breccia” is a rock containing > 25% blocks or bombs with a > 25% lithified ash matrix (cf. sandy conglomerate). [5] The attribute “-grained” represents the full rock name in the tuff grade scheme and is comparable to “fine-grained sandstone”.

(Mueller and White, 2004)

Grain Size-based Genetic Nomenclature for Volcaniclastic Deposits (after McPhie et al., 1993)

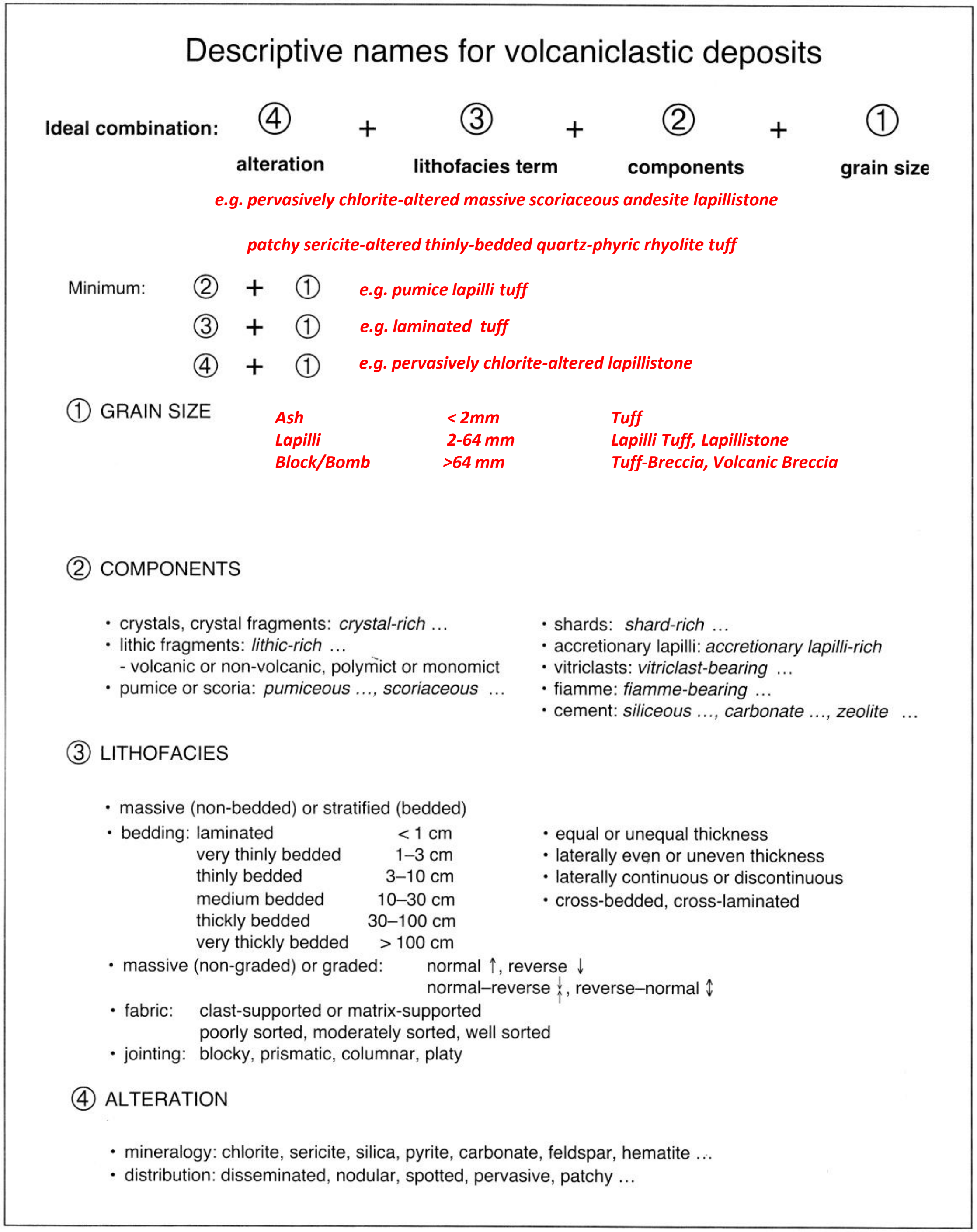
GRAIN SIZE (mm)	*VOLCANICLASTIC DEPOSITS IN GENERAL & VOLCANOGENIC SEDIMENTARY ROCKS*	*AUTOCLASTIC DEPOSITS*			*RESEDIMENTED AUTOCLASTIC DEPOSITS*
		HYALOCLASTITE	*AUTOBRECCIA*	*MIXTURE OR UNCERTAIN ORIGIN*	
<1/16	Volcanic Mudstone	Fine Hyaloclastite	?	Autoclastic Mudstone	Resedimented Fine Hyaloclastite Resedimented Autoclastic Mudstone
1/16 - 2	Volcanic Sandstone	Hyaloclastite Sandstone		Autoclastic Sandstone	Resedimented Hyaloclastite Sandstone Resedimented Autoclastic Sandstone
2 - 4	Volcanic Conglomerate or Volcanic Breccia	Granular Hyaloclastite	Granular Autobreccia	Granular Autoclastic Breccia	Resedimented Granular Hyaloclastite Resedimented Granular Autobreccia Resedimented Granular Autoclastic Breccia
4 - 64		Hyaloclastite Breccia	Autobreccia	Autoclastic Breccia	Resedimented Hyaloclastite Breccia Resedimented Autobreccia Resedimented Autoclastic Breccia
>64		Coarse Hyaloclastite Breccia	Coarse Autobreccia	Coarse Autoclastic Breccia	Resedimented Coarse Hyaloclastite Breccia Resedimented Coarse Autobreccia Resedimented Coarse Autoclastic Breccia

Grain Size-based Genetic Nomenclature for Volcaniclastic Deposits
(after McPhie et al., 1993)
Used to Distinguish Primary vs Resedimented Deposits

GRAIN SIZE (mm)	*PYROCLASTIC DEPOSITS*		*PYROCLAST – RICH DEPOSITS*	
	UNCONSOLIDATED TEPHRA	*CONSOLIDATED PYROCLASTIC ROCK*	*RESEDIMENTED SYN-ERUPTIVE*	*POST-ERUPTIVE RESEDIMENTED OR UNCERTAIN ORIGIN*
<1/16 mm	*Fine Ash*	*Fine Tuff*	*Resedimented Ash-rich Mudstone*	*Tuffaceous Mudstone*
1/16 – 2 mm	*Coarse Ash*	*Coarse Tuff*	*Resedimented Ash-rich Sandstone*	*Tuffaceous Sandstone*
2-64 mm	*Lapilli Tephra*	*Lapillistone* *Lapilli Tuff* *Tuff-Breccia*	*Resedimented Pyroclast-rich Lapillistone* *Resedimented Pumice Lapillistone*	*Tuffaceous Conglomerate* *Tuffaceous Breccia*
> 64 mm	*Bomb (fluidal shape)* *Tephra Block (angular) Tephra*	*Agglomerate (fluidal bombs)* *Pyroclastic Breccia*	*Resedimented Pyroclast-rich Breccia* *Resedimented Pumice Breccia* *Resedimented Pumice & Lithic Breccia*	*?*

A Methodology for Naming Precambrian Volcaniclastic Rocks

- *Based on Fisher's (1961, 1966) non-genetic classification scheme and McPhie et al.'s (1993) descriptive classification scheme*
- *Name = Alteration + Lithofacies + Component + Grain Size*
  - *Alteration term encompasses mineralogy and distribution*
  - *Lithofacies term encompasses stratification, bedding type, welding, sorting/grading, supporting mechanism (e.g. matrix, clast), and jointing*
  - *Component term encompasses crystals, lithic fragments (monomict/polymict and type or types of fragments), juvenile fragments (pumiceous, scoriaceous), as well as other fragment types (e.g. shards, accretionary lapilli, vitriclasts, fiamme, cement*
  - *Grain size term is based on Fisher's classification (e.g. tuff, lapilli tuff, lapillistone, tuff-breccia, or volcanic-breccia)*



Descriptive names for volcaniclastic deposits

Ideal combination: ④ alteration + ③ lithofacies term + ② components + ① grain size

e.g. pervasively chlorite-altered massive scoriaceous andesite lapillistone

patchy sericite-altered thinly-bedded quartz-phyric rhyolite tuff

Minimum:
② + ① *e.g. pumice lapilli tuff*
③ + ① *e.g. laminated tuff*
④ + ① *e.g. pervasively chlorite-altered lapillistone*

① GRAIN SIZE

Ash	*< 2mm*	*Tuff*
Lapilli	*2-64 mm*	*Lapilli Tuff, Lapillistone*
Block/Bomb	*>64 mm*	*Tuff-Breccia, Volcanic Breccia*

② COMPONENTS

- crystals, crystal fragments: *crystal-rich* …
- lithic fragments: *lithic-rich* …
  - volcanic or non-volcanic, polymict or monomict
- pumice or scoria: *pumiceous* …, *scoriaceous* …
- shards: *shard-rich* …
- accretionary lapilli: *accretionary lapilli-rich*
- vitriclasts: *vitriclast-bearing* …
- fiamme: *fiamme-bearing* …
- cement: *siliceous* …, *carbonate* …, *zeolite* …

③ LITHOFACIES

- massive (non-bedded) or stratified (bedded)
- bedding:

laminated	< 1 cm
very thinly bedded	1–3 cm
thinly bedded	3–10 cm
medium bedded	10–30 cm
thickly bedded	30–100 cm
very thickly bedded	> 100 cm

- equal or unequal thickness
- laterally even or uneven thickness
- laterally continuous or discontinuous
- cross-bedded, cross-laminated
- massive (non-graded) or graded: normal ↑, reverse ↓
  normal–reverse ↕, reverse–normal ↕
- fabric: clast-supported or matrix-supported
  poorly sorted, moderately sorted, well sorted
- jointing: blocky, prismatic, columnar, platy

④ ALTERATION

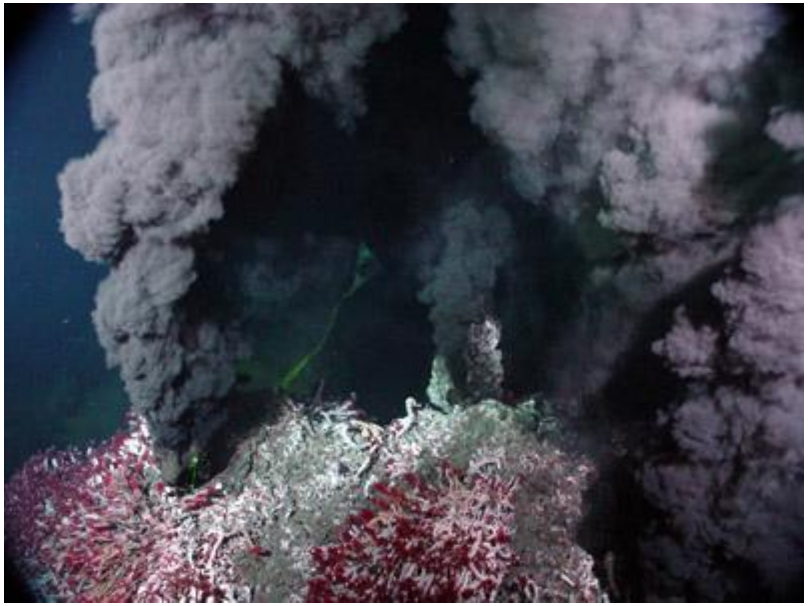
- mineralogy: chlorite, sericite, silica, pyrite, carbonate, feldspar, hematite …
- distribution: disseminated, nodular, spotted, pervasive, patchy …

A Methodology for Naming Ancient Volcaniclastic Rocks

- *Modified from McPhie et al., 1993*
- *Main change is utilizing Fisher's size classification terms rather than "sedimentary - genetic" size classification terms*
- *Allows later modification of rock names once more detailed genetic information is available*
- *Care must be taken not to confuse alteration with lithology!*

Terminology and Definition

- Submarine Geothermal Systems
  - Common in active subaqueous volcanic environments
  - Close spatial and temporal relationship between subaqueous pyf’s, shallow magma chambers and submarine hot springs
  - Warm water cools deposit and causes syndepositional alteration and recrystallization



Differences Between Subaerial/Subaqueous Explosive Eruptions

- Processes associated with eruption, transportation and deposition are significantly different due to presence of water
  - Ability to vaporize when in contact with water
  - High density and resulting confining pressure
  - High viscosity relative to air
  - The differences in the heat capicities/thermal conductivities in air relative to water




Differences Between Subaerial/Subaqueous Explosive Volcanism

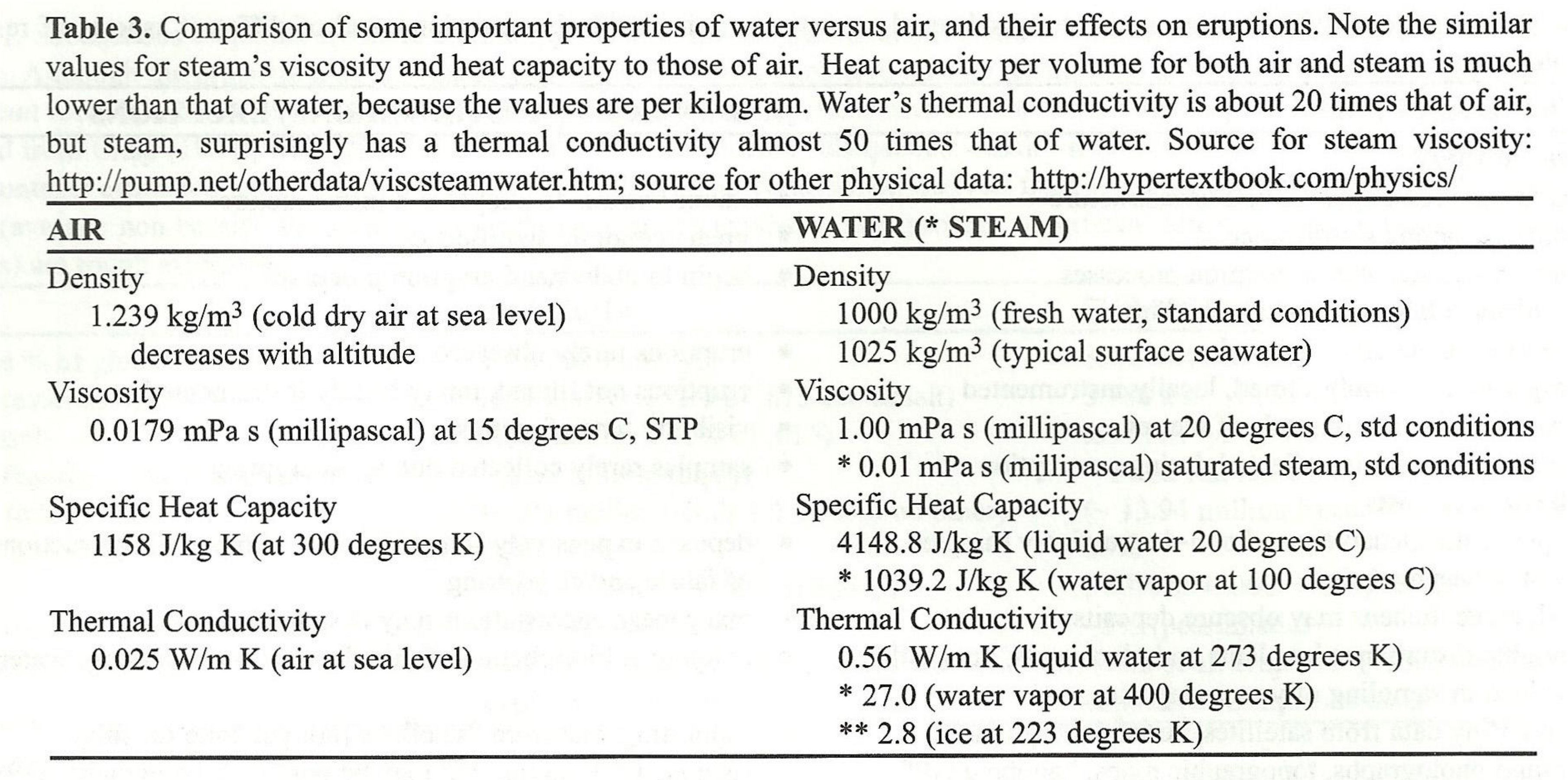


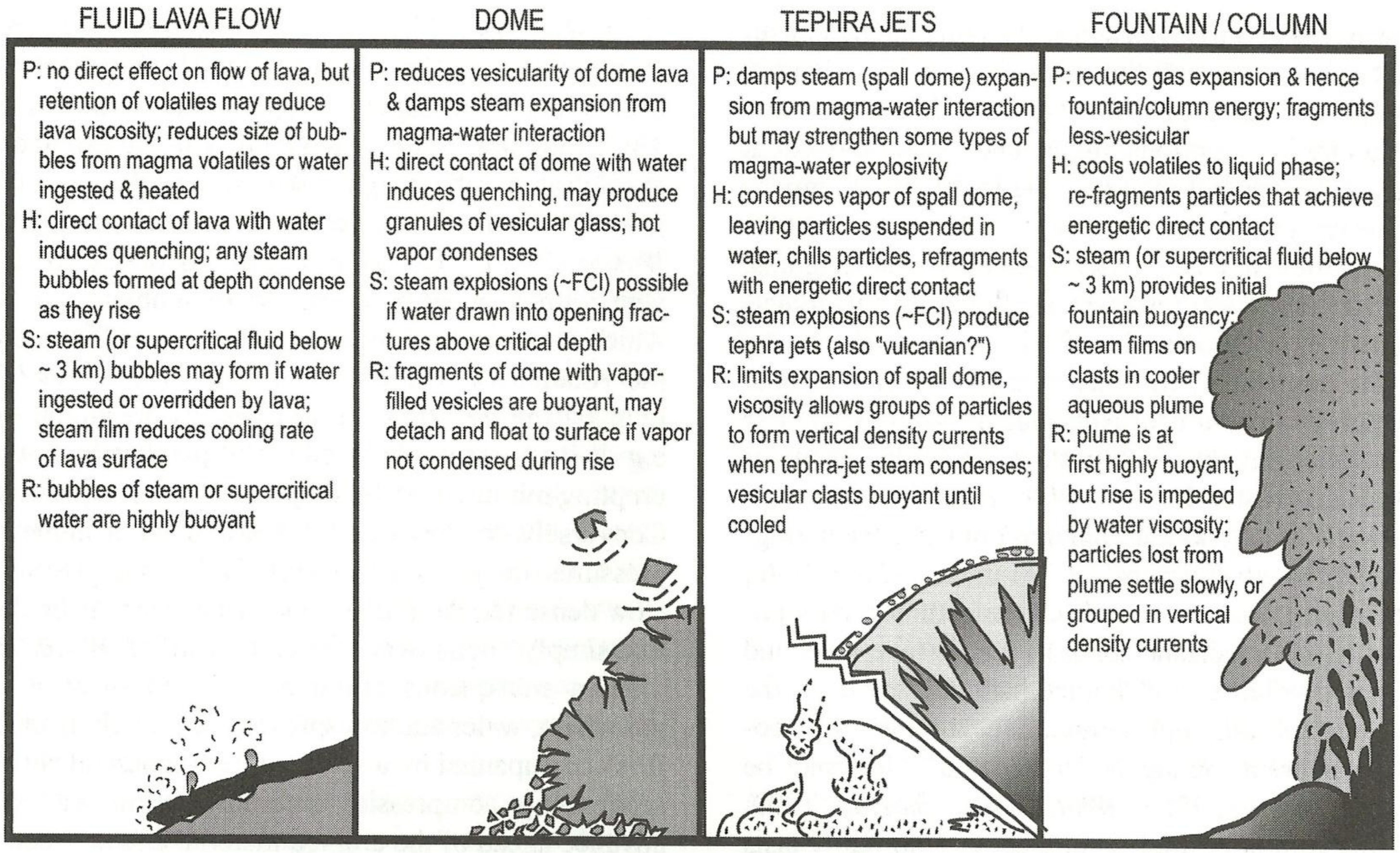
Table 3. Comparison of some important properties of water versus air, and their effects on eruptions. Note the similar values for steam's viscosity and heat capacity to those of air. Heat capacity per volume for both air and steam is much lower than that of water, because the values are per kilogram. Water's thermal conductivity is about 20 times that of air, but steam, surprisingly has a thermal conductivity almost 50 times that of water. Source for steam viscosity: http://pump.net/otherdata/viscsteamwater.htm; source for other physical data: http://hypertextbook.com/physics/

AIR	WATER (* STEAM)
Density	Density
1.239 kg/m^3 (cold dry air at sea level)	1000 kg/m^3 (fresh water, standard conditions)
decreases with altitude	1025 kg/m^3 (typical surface seawater)
Viscosity	Viscosity
0.0179 mPa s (millipascal) at 15 degrees C, STP	1.00 mPa s (millipascal) at 20 degrees C, std conditions
	* 0.01 mPa s (millipascal) saturated steam, std conditions
Specific Heat Capacity	Specific Heat Capacity
1158 J/kg K (at 300 degrees K)	4148.8 J/kg K (liquid water 20 degrees C)
	* 1039.2 J/kg K (water vapor at 100 degrees C)
Thermal Conductivity	Thermal Conductivity
0.025 W/m K (air at sea level)	0.56 W/m K (liquid water at 273 degrees K)
	* 27.0 (water vapor at 400 degrees K)
	** 2.8 (ice at 223 degrees K)

(after White, 2003)

Differences Between Subaerial/Subaqueous Explosive Volcanism

- <u>Major differences due to effects of pressure, heat capacity/conductivity of water, presence of steam, and water rheology</u>



FLUID LAVA FLOW	DOME	TEPHRA JETS	FOUNTAIN / COLUMN
P: no direct effect on flow of lava, but retention of volatiles may reduce lava viscosity; reduces size of bubbles from magma volatiles or water ingested & heated H: direct contact of lava with water induces quenching; any steam bubbles formed at depth condense as they rise S: steam (or supercritical fluid below ~ 3 km) bubbles may form if water ingested or overridden by lava; steam film reduces cooling rate of lava surface R: bubbles of steam or supercritical water are highly buoyant	P: reduces vesicularity of dome lava & damps steam expansion from magma-water interaction H: direct contact of dome with water induces quenching, may produce granules of vesicular glass; hot vapor condenses S: steam explosions (~FCI) possible if water drawn into opening fractures above critical depth R: fragments of dome with vapor-filled vesicles are buoyant, may detach and float to surface if vapor not condensed during rise	P: damps steam (spall dome) expansion from magma-water interaction but may strengthen some types of magma-water explosivity H: condenses vapor of spall dome, leaving particles suspended in water, chills particles, refragment with energetic direct contact S: steam explosions (~FCI) produce tephra jets (also "vulcanian?") R: limits expansion of spall dome, viscosity allows groups of particles to form vertical density currents when tephra-jet steam condenses; vesicular clasts buoyant until cooled	P: reduces gas expansion & hence fountain/column energy; fragments less-vesicular H: cools volatiles to liquid phase; re-fragments particles that achieve energetic direct contact S: steam (or supercritical fluid below ~ 3 km) provides initial fountain buoyancy; steam films on clasts in cooler aqueous plume R: plume is at first highly buoyant, but rise is impeded by water viscosity; particles lost from plume settle slowly, or grouped in vertical density currents

Figure 3. Summary of some major influences of pressure (P), high heat capacity and conductivity of water (H), steam (S) and water rheology (R) on different eruptions. See text for further discussion.

Differences Between Subaerial/ Explosive Subaqueous Volcanism

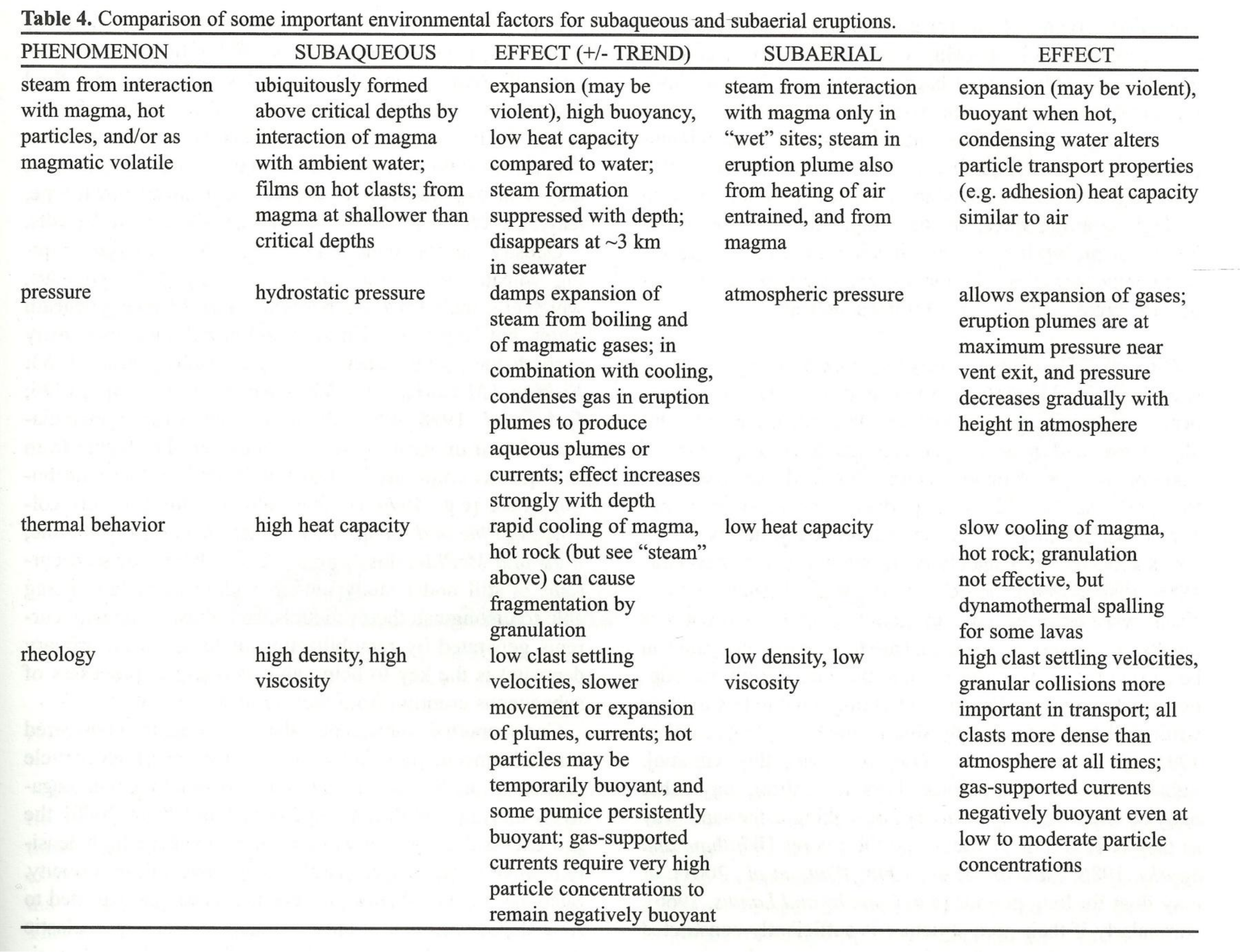


Table 4. Comparison of some important environmental factors for subaqueous and subaerial eruptions.

PHENOMENON	SUBAQUEOUS	EFFECT (+/- TREND)	SUBAERIAL	EFFECT
steam from interaction with magma, hot particles, and/or as magmatic volatile	ubiquitously formed above critical depths by interaction of magma with ambient water; films on hot clasts; from magma at shallower than critical depths	expansion (may be violent), high buoyancy, low heat capacity compared to water; steam formation suppressed with depth; disappears at ~3 km in seawater	steam from interaction with magma only in "wet" sites; steam in eruption plume also from heating of air entrained, and from magma	expansion (may be violent), buoyant when hot, condensing water alters particle transport properties (e.g. adhesion) heat capacity similar to air
pressure	hydrostatic pressure	damps expansion of steam from boiling and of magmatic gases; in combination with cooling, condenses gas in eruption plumes to produce aqueous plumes or currents; effect increases strongly with depth	atmospheric pressure	allows expansion of gases; eruption plumes are at maximum pressure near vent exit, and pressure decreases gradually with height in atmosphere
thermal behavior	high heat capacity	rapid cooling of magma, hot rock (but see "steam" above) can cause fragmentation by granulation	low heat capacity	slow cooling of magma, hot rock; granulation not effective, but dynamothermal spalling for some lavas
rheology	high density, high viscosity	low clast settling velocities, slower movement or expansion of plumes, currents; hot particles may be temporarily buoyant, and some pumice persistently buoyant; gas-supported currents require very high particle concentrations to remain negatively buoyant	low density, low viscosity	high clast settling velocities, granular collisions more important in transport; all clasts more dense than atmosphere at all times; gas-supported currents negatively buoyant even at low to moderate particle concentrations

(after White, 2003)

Differences Between Subaerial/Subaqueous Explosive Volcanism

- Behavior of pumice differs in subaerial and submarine environments

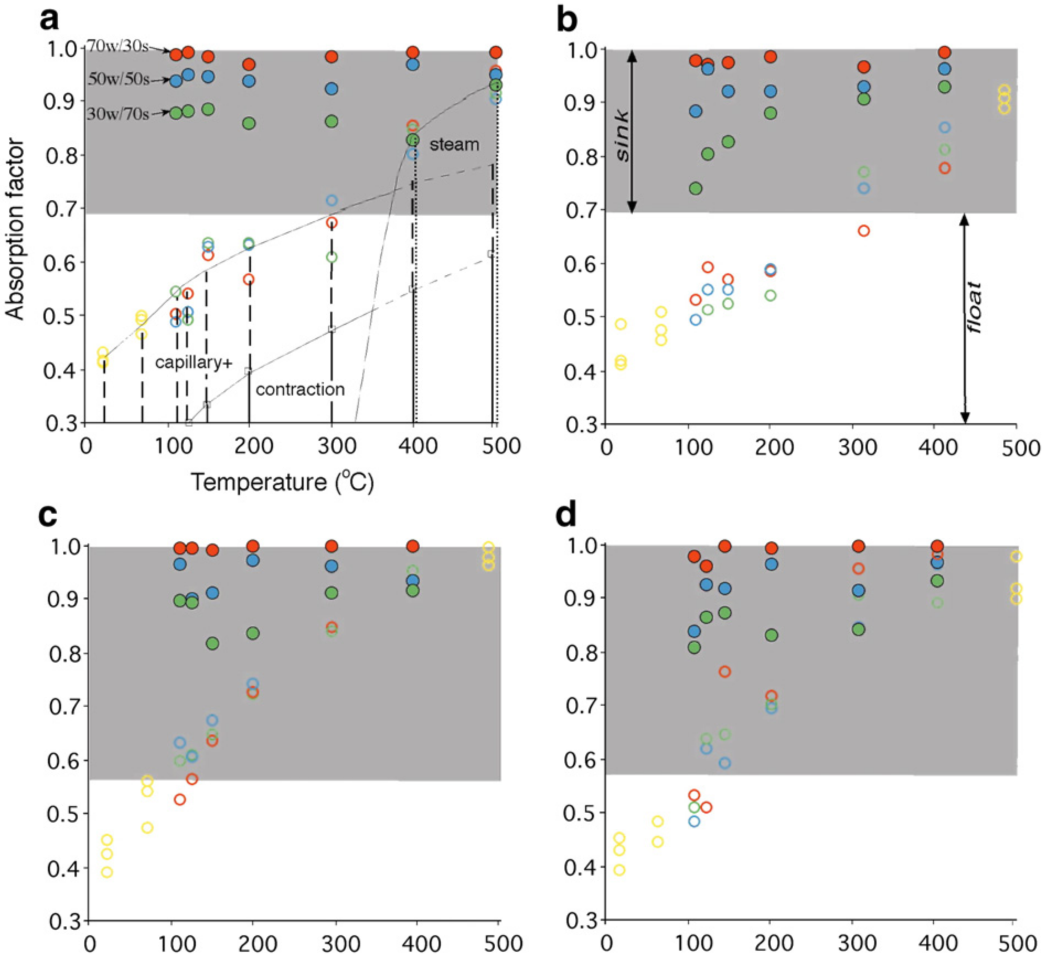
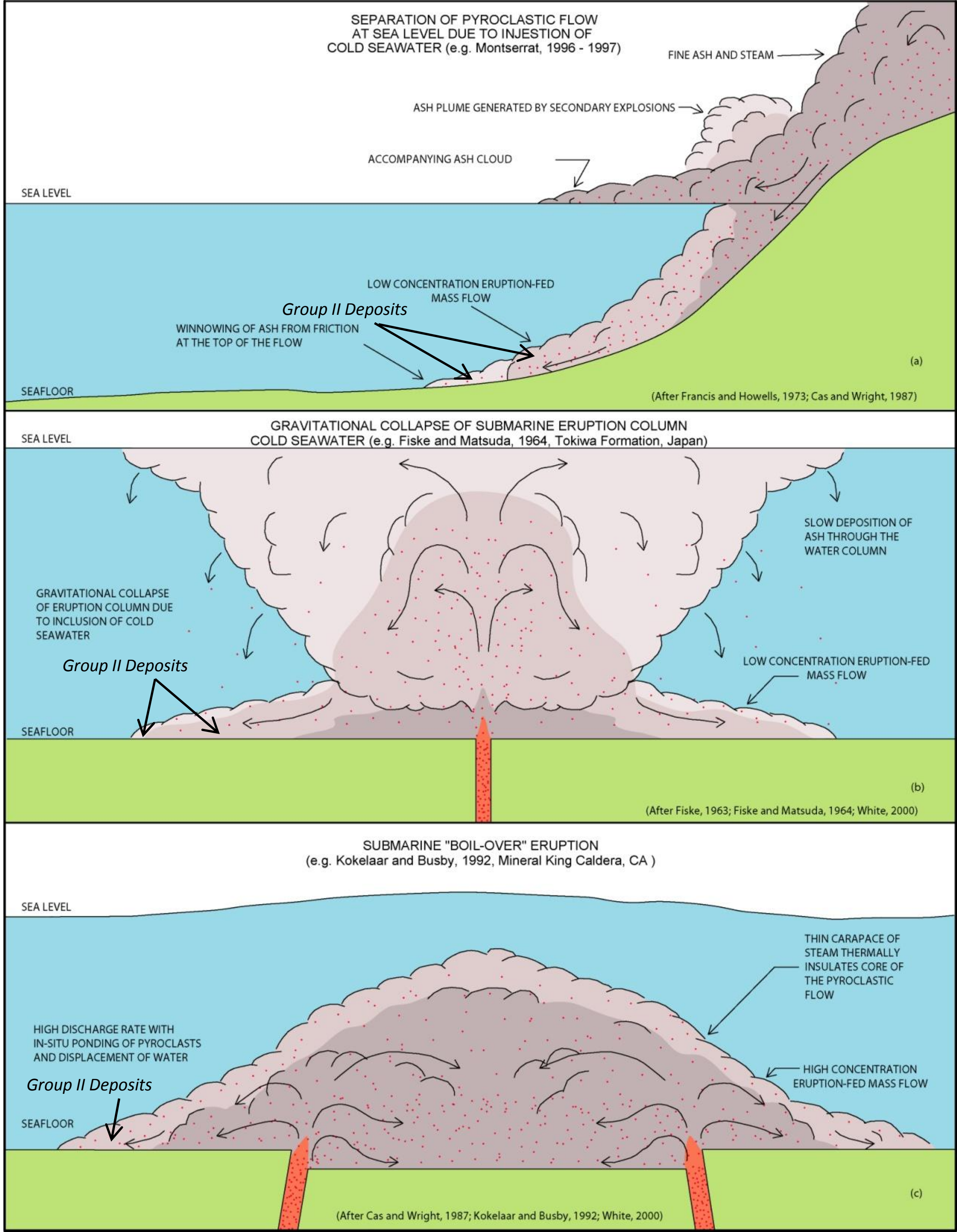


Fig. 3. Absorption factors after quenching of heated steam-charged pumice cubes (filled circles) and repeated experiments with dry air-filled cubes (open circles; colour identifies the same steam-charged cube). Each dot is the result of a single experiment. (a) D7, 80 vol.% vesicles, (b) 337-5, 80 vol.% vesicles, (c) 337-1, 73 vol.% vesicles, and, (d) 339-8, 73 vol.% vesicles. Yellow circles represent dry air-filled experimental runs at both higher and lower temperatures than the steam-filled runs. 70w/30s; represents 70% water, 30% steam. Labeled fields show the degree of absorption anticipated for initially air-filled cubes for contraction of air alone, contraction + capillary forces, and additional saturation due to the condensation of steam generated from the interaction of the hot glass with water.

(after Allen et al., 2008)

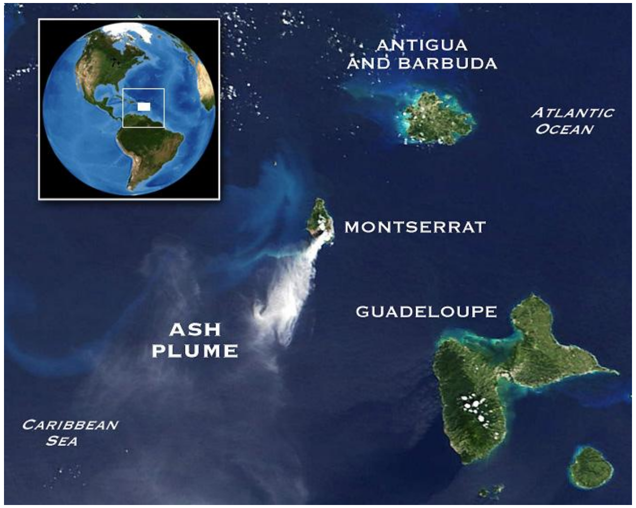
Types of Submarine Pyroclastic Flows

- *Group II deposits result from explosive fragmentation with deposition from a water-supported current*

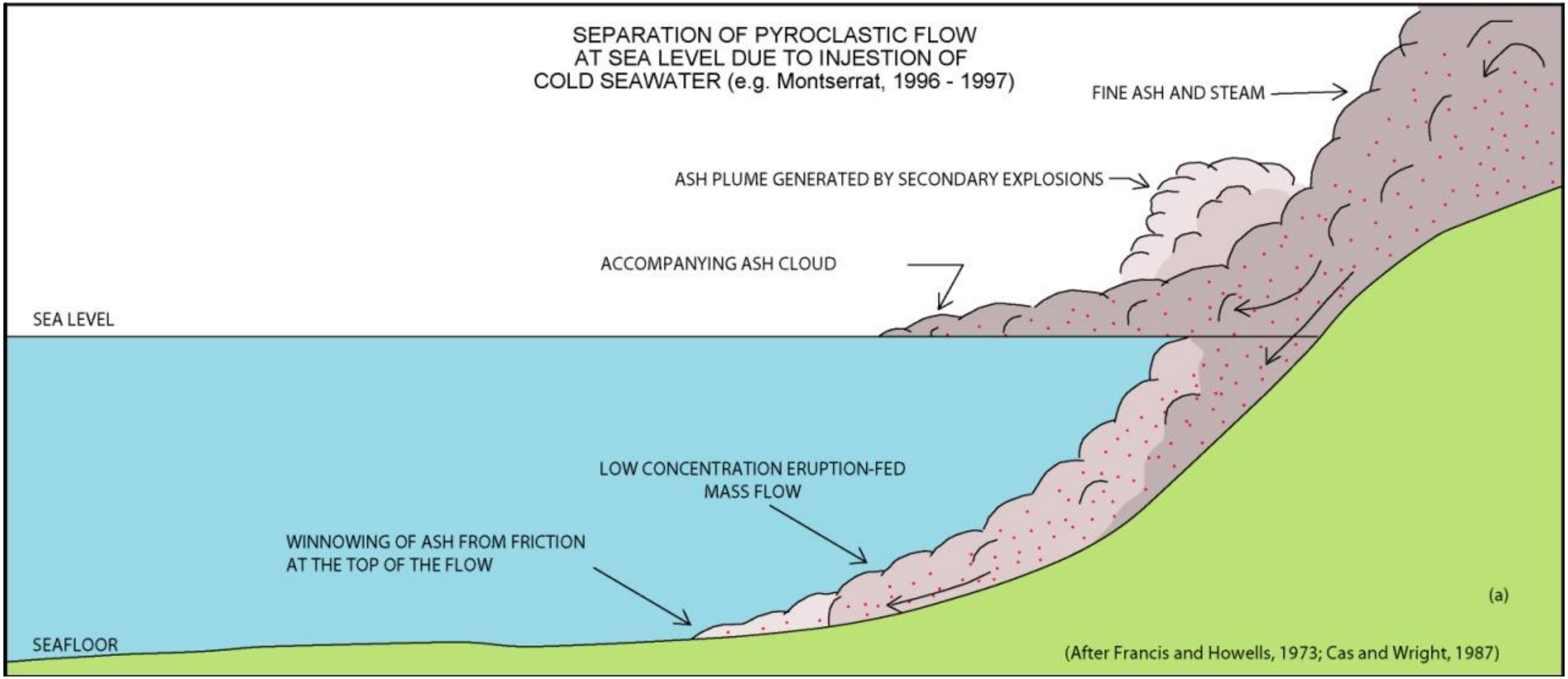


Pyroclastic Flows Entering Water

- Numerous historical and modern examples of these types of eruptions
  - Krakatau (1883)
  - Montserrat (1996 to present)
- Three possible ways of interacting
  - Mix with water – explosions at coast line and then transfer into d/f or turbidity current (Montserrat)
  - Travel across water (Krakatau)
  - Remain intact and either push aside shallow water near shore or flow under water until stop or change into d/f (also Krakatau?)
- Deposits range from massive tuffs and lapilli tuffs that locally retain heat-retention features (Krakatau) to fines-depleted tuffs that grade laterally into finely bedded tuff (Montserrat)



Pyroclastic Flows Entering Water



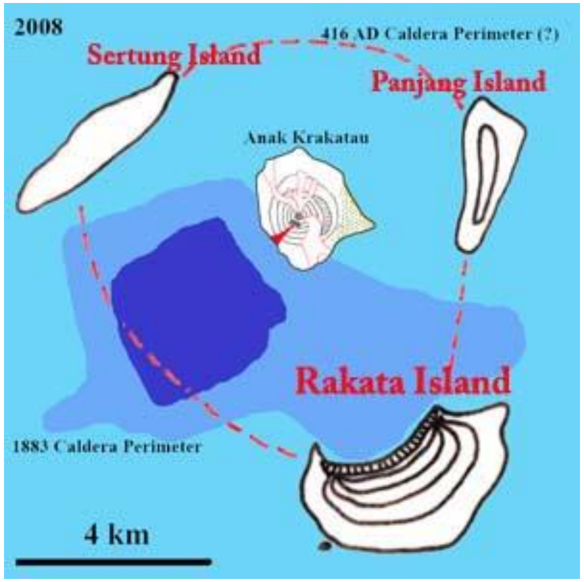
(After Francis and Howells, 1973; Cas and Wright, 1987)

Figure 5. Behavior of subaerial pyroclastic flows entering the sea. Pyroclastic flow may a) continue to move laterally over the sea: b) the pyroclastic flow may enter the sea and continue to flow underwater; and c) the pyroclastic flow may react explosively with seawater and produce widespread steam-generated ash eruptions.

Krakatau, 1883

- Krakatau has had numerous plinean eruptive events that have led to formation of numerous calderas and stratovolcanoes
- Most famous is the series of eruptions that culminating in the August 26-27 1883 catastrophic event
- The 1883 eruption ejected anywhere from 6-10 cubic kilometers (dry rock equivalent) of tephra
- May have produced the loudest sound historically reported – seismic and atmospheric waves circled the earth for several days following the eruption
- 165 local villages completely destroyed, 132 seriously damaged with loss of life (officially) at 36,417
- Large loss of live due to combination of pyroclastic flows traveling at large speeds across water, as well as subsequent tsunamis associated with submarine caldera collapse

Krakatau 1883



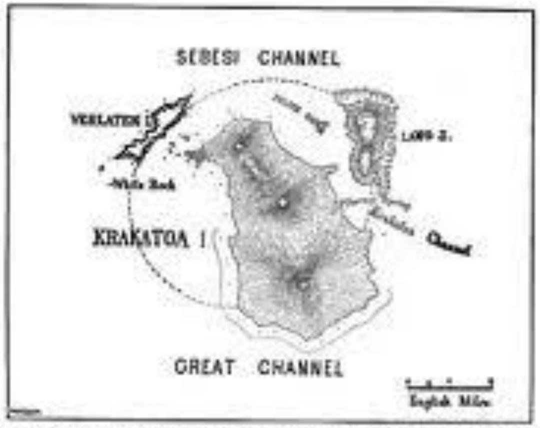


FIG. 3.—Map of the islands of the Krakatoa Group before the eruption (from the Admiralty Chart). The nearly circular line ------- indicates approximately the submerged edge of the great crater.

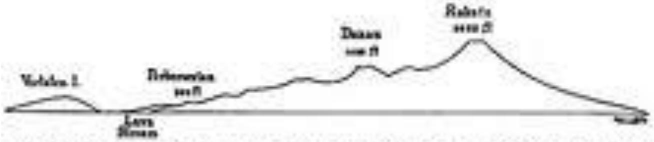
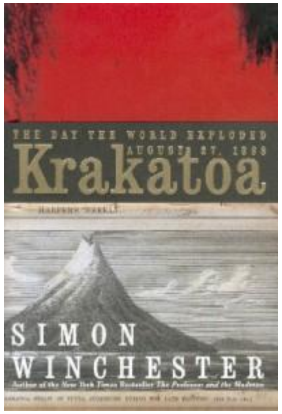


FIG. 4.—Outline-section viewed from south-west showing the position of the volcanic cones upon the Island of Krakatoa previous to the eruption.

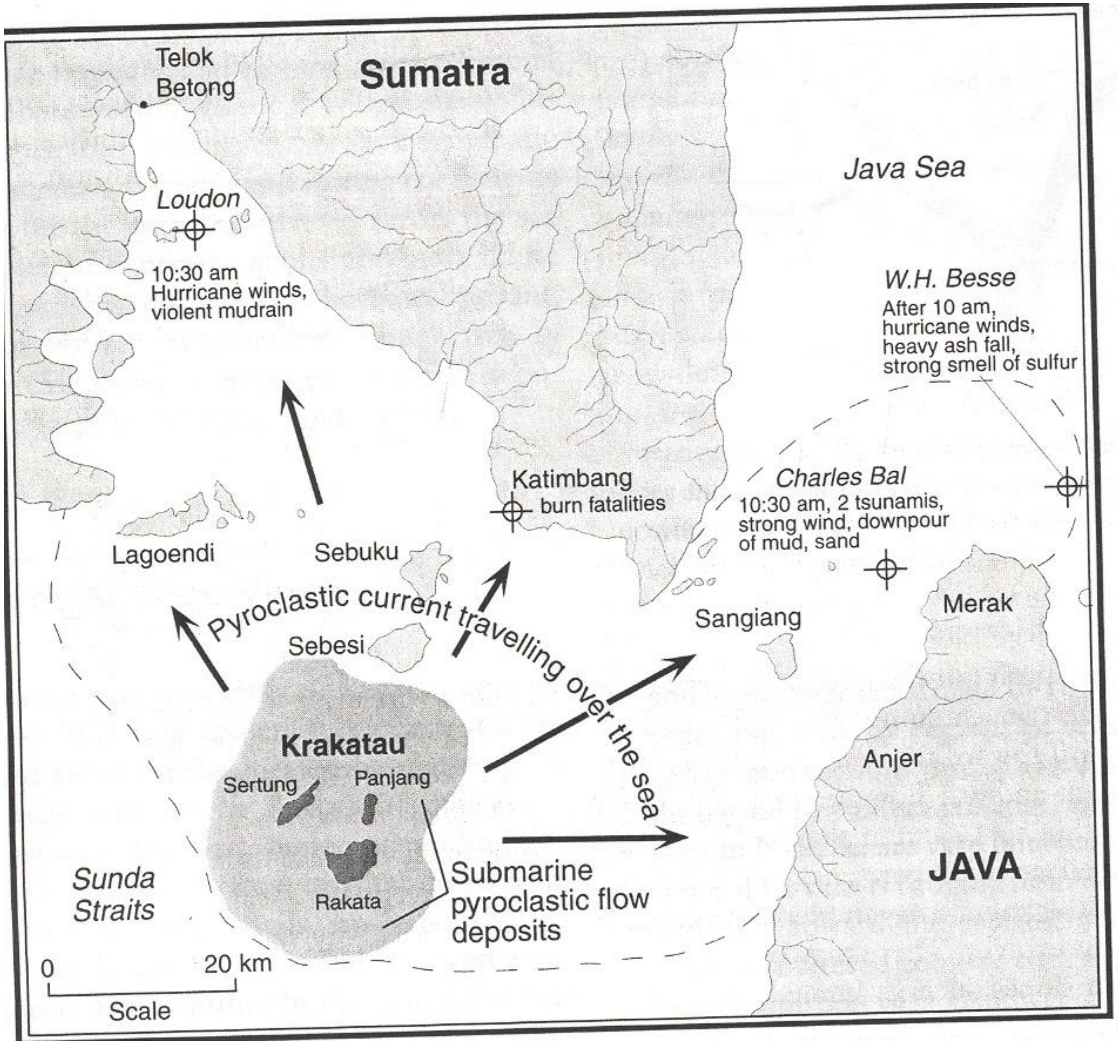


Krakatau 1883

- **Plinean Phase of August 26-27, 1883**
  - **Huge explosions began and the eruption column soared to 16 miles**
  - **Tsunamis were generated**
  - **Pyf’s and surges reached Sumatra**
  - **Ash and pumice fell up to 20m thick within a 20km radius**

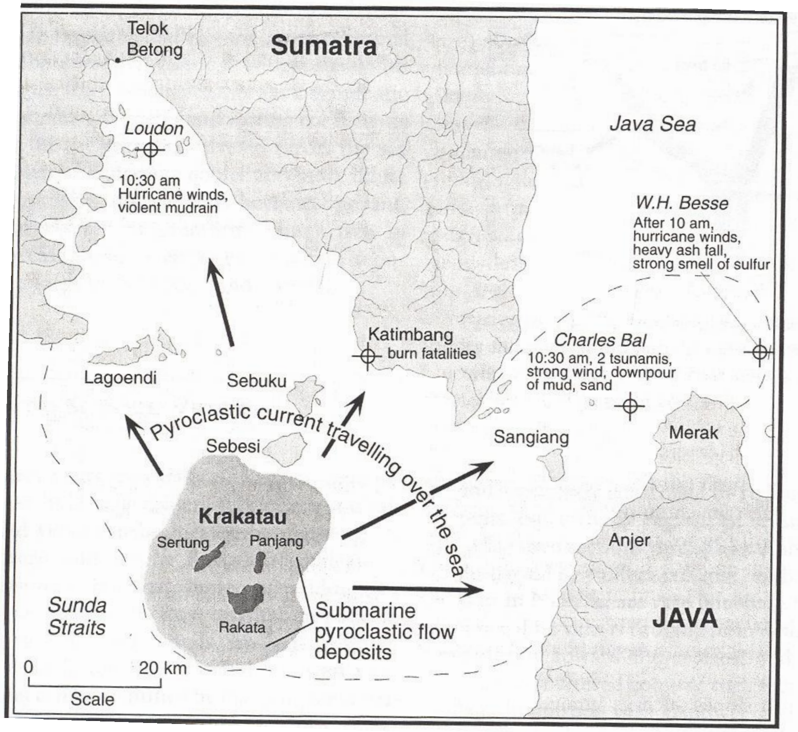
Krakatau 1883

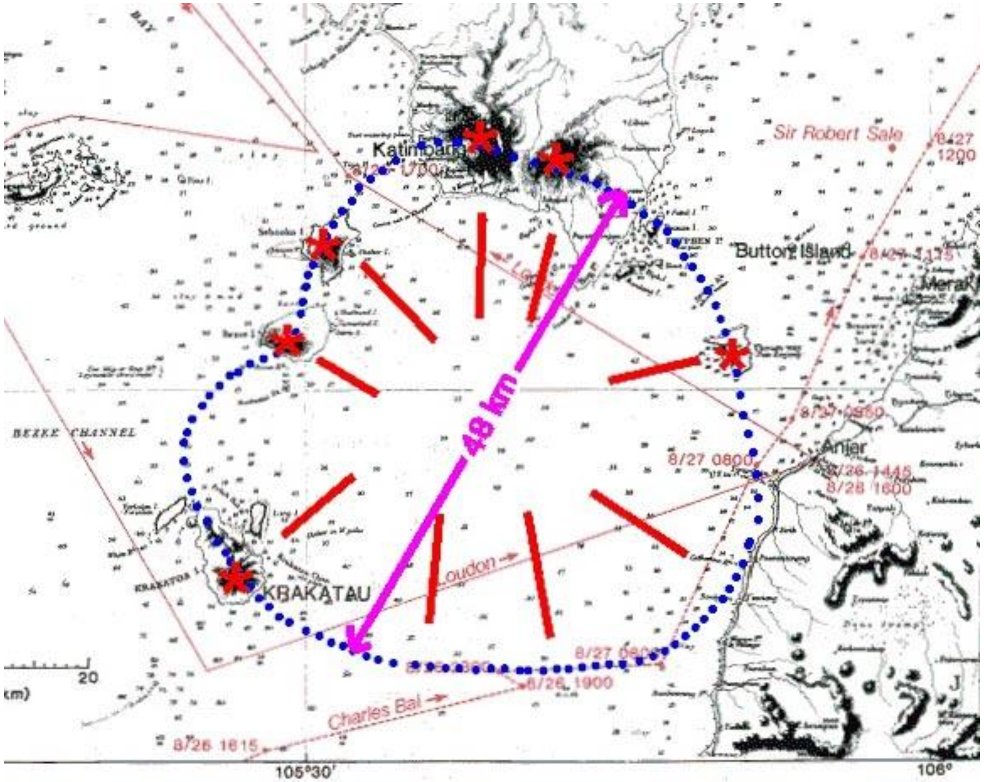
- Submarine units:
- Massive, poorly sorted,
- Mix of pumice, shards in a gray ash matrix with some crystals and lithics
- And laminated, better sorted, finer grained
- Hot flows under water (Mandeville et al., 1996)



Krakatau 1883

- Also traveled over water:
- Burn fatalities 40 km away
- Ships 65-80 km away engulfed by ash clouds
- Island vegetation burned
- Deposits-poorly sorted, massive beds of pumice, charcoal, lithics in an ash matrix





Montserrat (1995 – present)

http://www.youtube.com/watch?v=7h5XOS7uaWA

Montserrat (1995 – present)

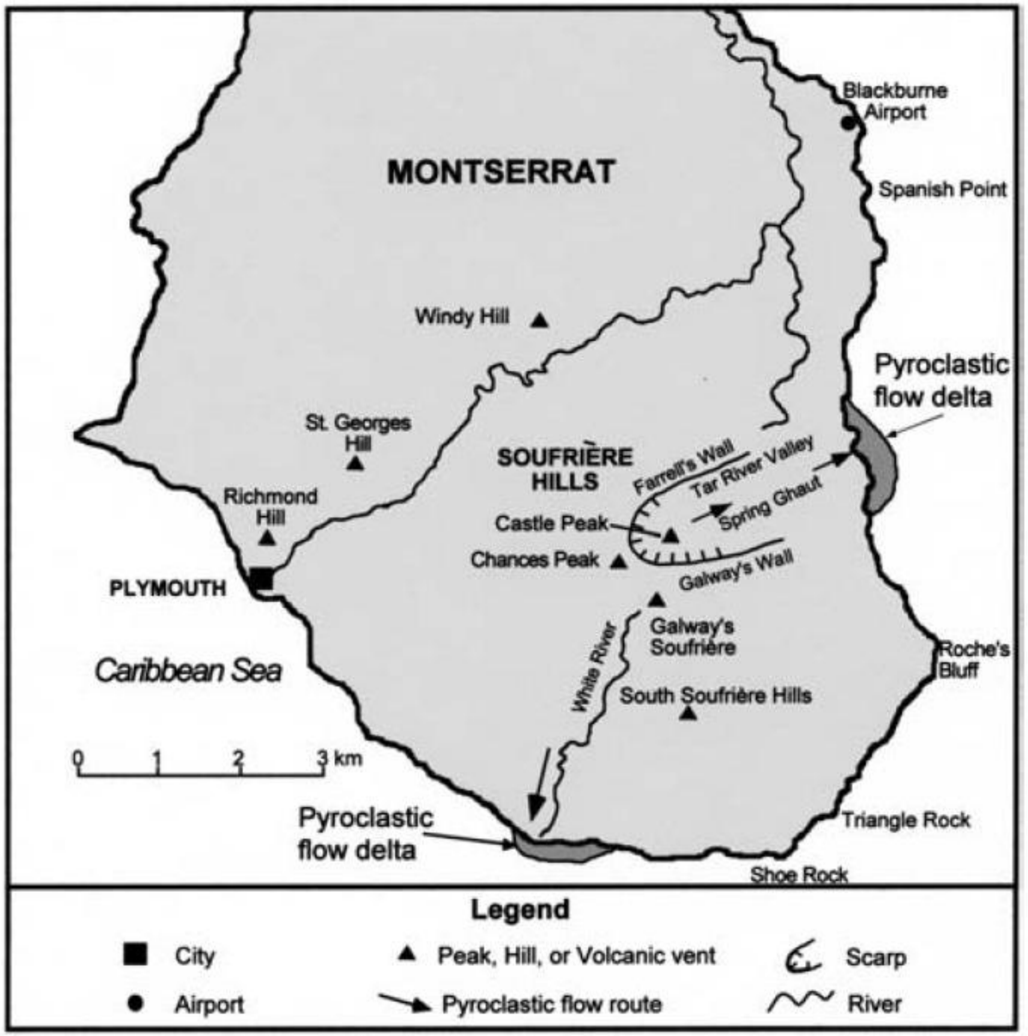


Fig. 1 Map showing the location of the Soufrière Hills volcano and the routes that major pyroclastic flows have taken to the sea. Two new deltas have been formed in the area of the Tar and White River valleys

(Hart et al., 2002)

Montserrat (1995-1998)

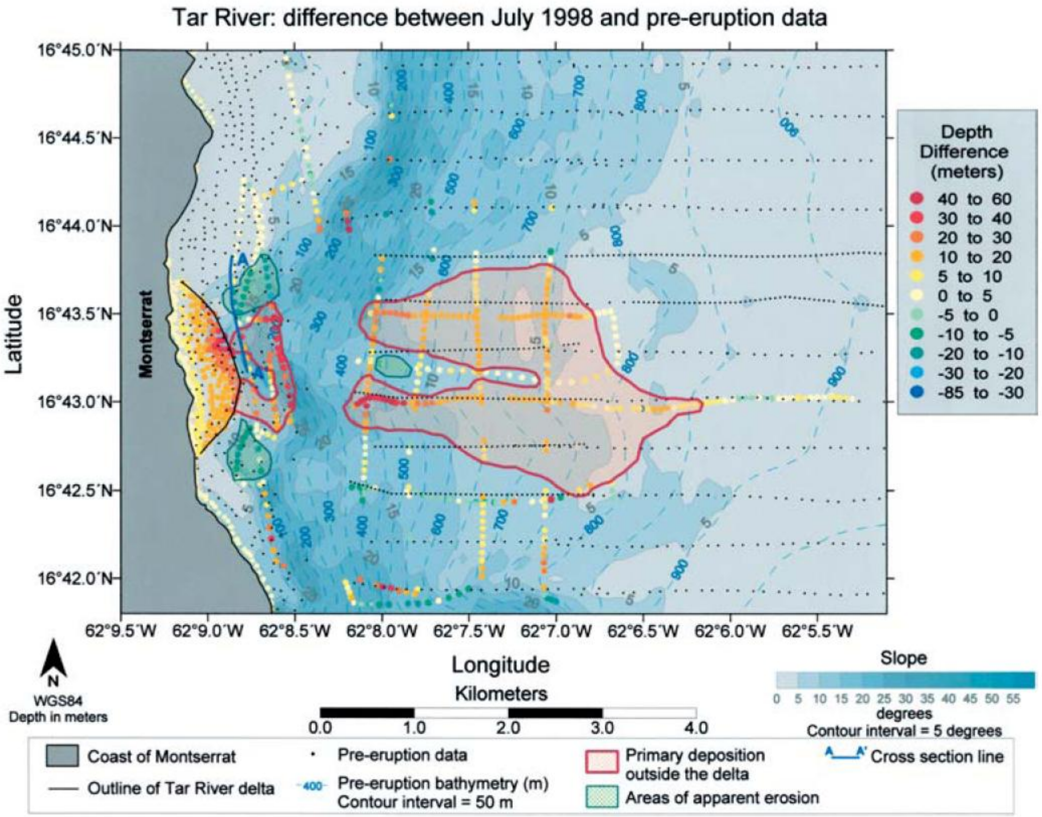


Fig. 7 Map of the Tar River region showing primary areas of deposition outlining the distribution of difference points and slope contours. A line showing the location of Tar River transect A–A' is drawn on the map. Pre-eruption bathymetric contours are posted on the map and areas of apparent erosion are indicated. July 1998 points were shifted 30 m to the east relative to the 1985 HMS *Fawn* pre-eruption survey data to display the best comparison

Table 3 Calculated volumes from 1998 geophysical data for the Tar and White River areas

Location	Area (km^2)	Volume ($x10^6$ m^3) Calculated (non-DRE)	Volume ($x10^6$ m^3) Calculated (DRE) ρ=1,800 kg m^{-3}	Description
Tar River	0.64	10.5	7.3	Deposition in the delta below sea level
	4.4	69.3	48	Deposition outside the delta
	5.04	89.8	55.3	Total in the Tar River
White River	0.46	4.0	2.8	Deposition in the delta below sea level
	1.85	21.7	15	Deposition outside the delta
	2.31	25.7	17.8	Total in the White River
Totals	7.35	115.5	73.1	Combined deposition in the Tar and White River areas

Montserrat (1995-present)

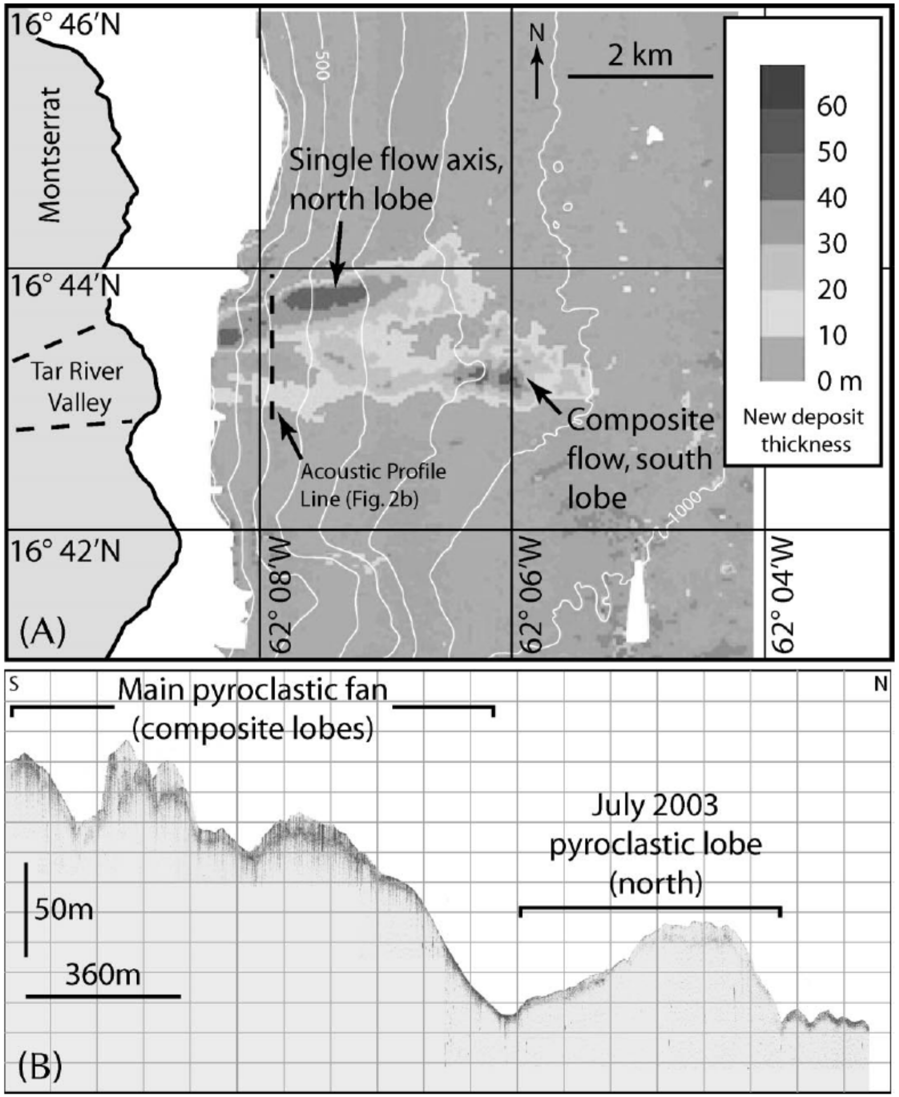


Figure 2. (A) Topographic difference map showing the thickness of the material deposited between the JR123 cruise (May 2005) and the Caraval cruise (March 2002). Two steep-sided lobes were identified, corresponding to material deposited during the July 2003 dome collapse event. The section shown in B is marked. (B) Acoustic (TOPAS) profile across the two new Tar River fan pyroclastic lobes. The stacked, intercalated pyroclastic lobes of the main fan are imaged together with the single July 2003 peak collapse lobe, which was deflected around the previously emplaced deposits.

Montserrat (1995-present)

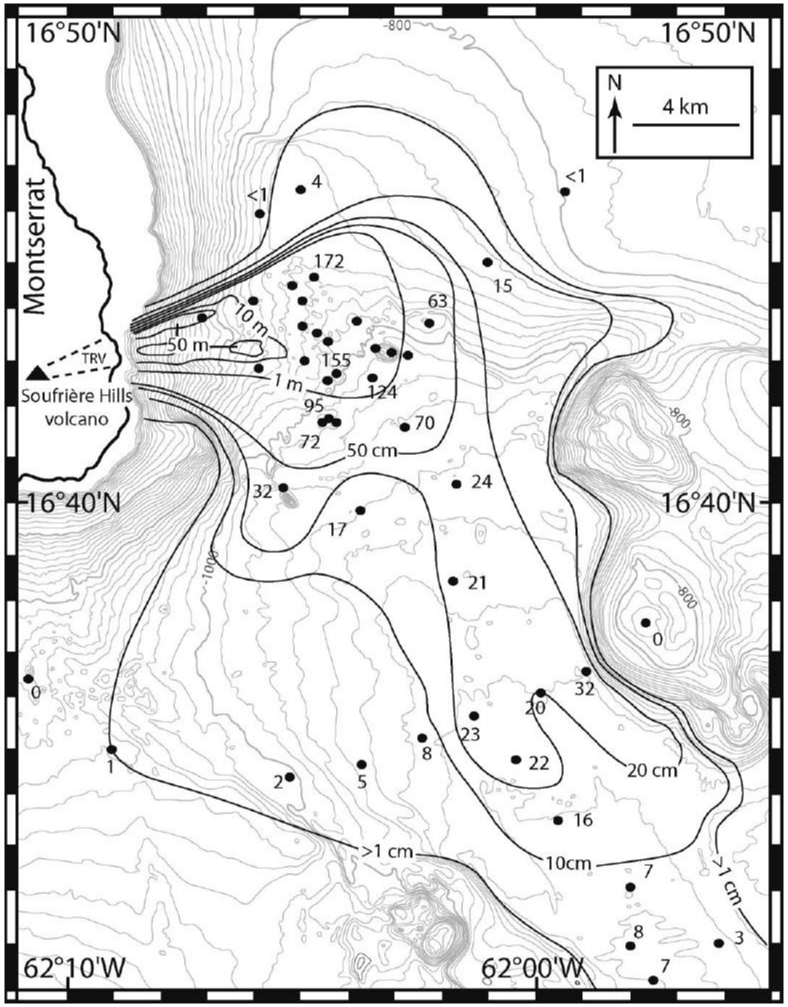


Figure 3. Isopach map showing the cumulative thickness within the 1995–2003 Soufrière Hills deposits within the Tar River valley (TRV) submarine pyroclastic fan. Contours are as marked in meters and centimeters. The core thickness measurements are given in centimeters.

(Trofimovs et al., 2006)

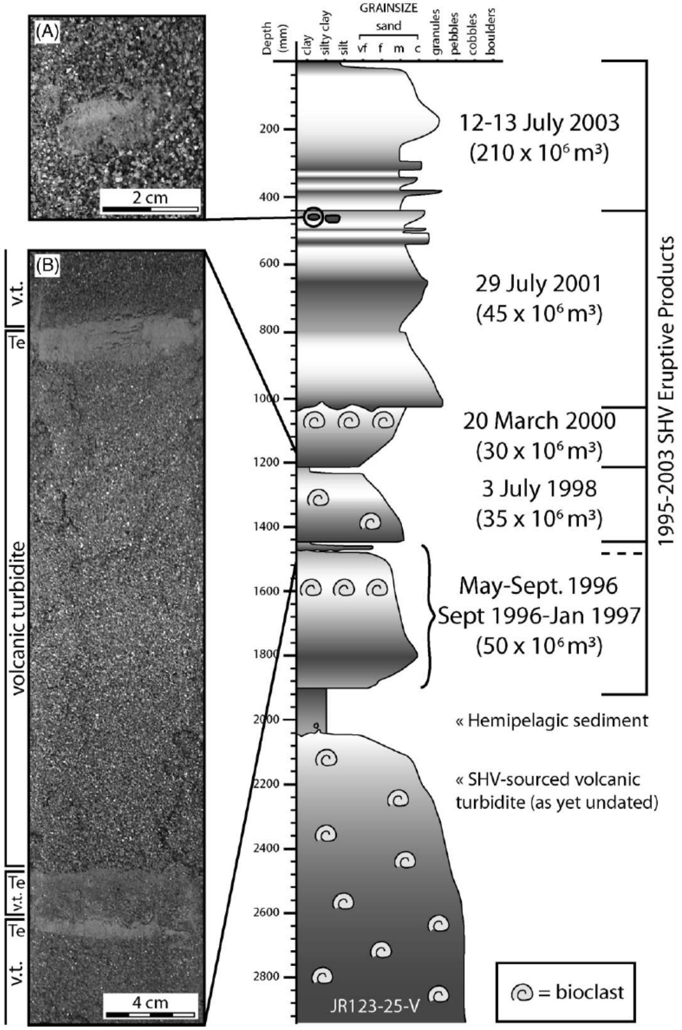


Figure 4. Stratigraphic log and photographs from the marine sediments taken from Vibrocore sample JR123–25-V (16°44′47″N, 62°05′12″W). Six volcanic turbidite units were identified as originating from the 1995–2003 Soufrière Hills volcano (SHV) eruption. (A) Centimeter-scale mud intraclast at the top of a volcanic turbidite unit (450 mm depth). (B) Series of stacked volcanic turbidite units separated by fine-ash Te layers (1190–1450 mm depth); v.t.—volcanic turbidite; vf—very fine; f—fine; m—medium; c—coarse.

Montserrat (Trofimovs et al., 2006)

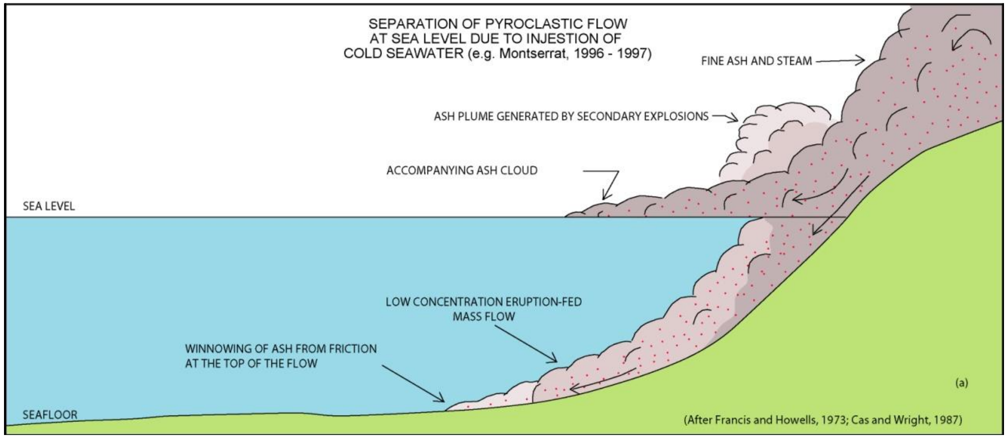
ABSTRACT

The Soufrière Hills volcano, Montserrat, West Indies, has undergone a series of dome growth and collapse events since the eruption began in 1995. Over 90% of the pyroclastic material produced has been deposited into the ocean. Sampling of these submarine deposits reveals that the pyroclastic flows mix rapidly and violently with the water as they enter the sea. The coarse components (pebbles to boulders) are deposited proximally from dense basal slurries to form steep-sided, near-linear ridges that intercalate to form a submarine fan. The finer ash-grade components are mixed into the overlying water column to form turbidity currents that flow over distances >30 km from the source. The total volume of pyroclastic material off the east coast of Montserrat exceeds $280 \times 10^6\ \mathrm{m}^3$, with 65% deposited in proximal lobes and 35% deposited as distal turbidites.

The Soufrière Hills volcano pyroclastic flows that entered the sea are poorly sorted mixtures, from large blocks to fine ash; typically the subaerial deposits are composed of over 50% ash (<2 mm), including 10% fine ash (<1/16 mm). There is little sorting in the main basal avalanche of these flows during subaerial transport, although some ash (typically 15%) is elutriated into the overlying surge and ash clouds (Cole et al., 2002). The submarine deposits form proximal lobes with abrupt lateral margins and tapering frontal regions, similar to the morphology of large-volume pyroclastic flows on land (e.g., Cole et al., 2002). However, coring of the submarine lobes shows that the proximal deposits are comprised mostly of blocks and a coarse sand matrix; the ash-grade material (<2 mm fractions) is largely missing.

The proximal lobes merge via sharply tapering margins into turbidite deposits, which extend up to 30 km. The turbidite deposits are dominantly sand grade and become finer grained with distance. The turbidite facies makes up at least 35% of the deposit volumes and thus largely accounts for the ash component of the pyroclastic flows that entered the ocean. However, the turbidite facies itself contains only minor amounts of fine ash (<1/16 mm) except in the Te division, which is very widely distributed well beyond the area inundated by the sandy turbidite facies. Thus, the original mixture of particles in the source pyroclastic flows has been efficiently sorted and physically differentiated in the submarine flows. These observations suggest that the pyroclastic flows mix thoroughly with seawater and generate sediment gravity currents, which are stratified in grain size and concentration (cf. McLeod et al., 1999). Coarse particles are retained in the basal parts of the flow, while ash particles are mixed into the upper levels. The abrupt lateral margins of the proximal lobes and absence of finer deposits beyond these margins indicate that these fines-depleted basal regions behaved as concentrated mass flows. However, downslope, the flows developed into more mobile turbidity currents as coarse material was lost.

The mixing with seawater appears to have been rapid and violent. Flows entering the ocean at the Soufrière Hills volcano have been observed to generate small-scale explosions (Cole et al., 2002) and a large explosion at the culmination of the July 2003 collapse (Edmonds and Herd, 2005). We envisage mixing taking place between the shore and 500 m depth where the deposition of basal coarse-grained components of the flow initiates on slopes of 15° or less. This is also indicated by laboratory experiments (e.g., McLeod et al., 1999; Freundt, 2003).



(After Francis and Howells, 1973; Cas and Wright, 1987)