Subaqueous Pumice:
From Formation to Deposits

by

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Declaration

This reading thesis contains no material which has been accepted for the award of any other degree or diploma in any tertiary institution, and to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference is made in the text of the reading thesis.

Signed

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Abstract

Pumice is vesicular volcanic glass and is produced from eruptions and found in eruption related deposits. Magma properties that influence pumice formation are the viscosity and volatile content, because these properties control bubble nucleation and growth. These properties also influence the dynamics of ascending magma and hence, the eruption style. Explosive eruptions occur by gas release from burst bubbles while effusive eruptions occur by low volatile content or passive volatile escape. For submerged vents, the hydrostatic pressure restricts volatile exsolution and vesiculation, and controls the styles of subaqueous eruptions. The behaviour of pumice clasts in water depends on the temperature and vesicularity of the pumice and clast size. Cold, coarse pumice can remain afloat for some time whereas hot, fine pumice sinks instantly by rapid water intake. Submarine gravity flows can transport pumice and hydraulic sort the material before deposition. Such flows have the potential to form many types of deposits with different textures. Pumice can settle from the water column into deposits after becoming water logged and sinking. Other pumice can remain afloat and be dispersed away form source by wind and water currents. Many deposits show characteristics from several different processes. Examples of submarine pumice deposits include the Shinjima Pumice, Yali Pumice, Josoji Formation and the products of the 1952-1953 Myojinsho eruptions.

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Chapter 1 Introduction

1.1 What is pumice?

Pumice is a highly vesicular froth-like volcanic glass (Lapidus & Winstanley 1990; McPhie et al. 1993; Whitham & Sparks 1986). It is common in explosive volcanic eruptions and found in pyroclastic deposits and volcanogenic sediments as an important constituent (Risso et al. 2002; Whitham & Sparks 1986). Pumice can form in any magma under certain conditions and the composition can range from felsic to mafic. Scoria is the term used for intermediate to mafic pumice (Lapidus & Winstanley 1990; McPhie et al. 1993). Pumice has the ability to float on water due to the low specific gravity of < 1000 kg/m^3 (Lapidus & Winstanley 1990; Whitham & Sparks 1986).

Pumice formation is quite dependent on many properties of the parent magma. Viscosity and volatile content affect the eruption style of a magma. These properties are important in the ascent of the magma during bubble nucleation and growth and can also influence each other.

Whether an explosive or effusive eruption will occur is dependent on fragmentation that is controlled by the viscosity, volatile content, bubble nucleation and growth and importantly the setting. The setting influences the factors that control the eruption process and therefore affects the eruption products.

The behaviour of pumice in a subaqueous setting depends on the temperature of the pumice and the clast size. Hot and cold pumice behave quite differently in the water column after eruption and the transport processes that can act are different. Pumice can be transported by volcaniclastic mass flows that travel down slope or else float for long periods of time. Pumice can settle from suspension after becoming water logged but floating pumice can be dispersed by wind and water currents.

Pumice-rich deposits are very common, especially in submarine volcanic successions. They have diverse origins so it is important to understand the main kinds of transport and depositional processes, and the characteristics of the deposits. In this review, the formation of pumice, with emphasise on important magma properties and eruption will be discussed. This will lead to the subaqueous transport and depositional mechanisms that can occur after eruption. Case studies of subaqueous pumiceous deposits will be used to relate observed textures to eruption and transport processes.

Chapter 2 Formation and Eruption

2.1 Magma properties that favour pumice formation

Whether or not an eruption will be explosive or effusive is based on the influence of the physical properties of a rising magma (Cas 1992; Cas & Wright 1987; Giordano et al. 2004). Magma physical properties include the composition, volatile content, viscosity, temperature and density; eruption rate, the amount of external water in the system and ambient pressure are also important (Cas 1992; Cas & Wright 1987; Giordano et al. 2004).

2.1.1 Viscosity

Viscosity is the consistency of a substance and is essential in magmatic and volcanic processes in controlling the transport mechanics that eventually governs the style of eruption (Cas 1992; Cas & Wright 1987; Giordano et al. 2004). An applied shear stress on a substance will produce a strain rate that is expressed as viscosity (Cas 1992; Cas & Wright 1987). In a magma history, the viscosity is subject to changes by crystals and gas bubbles presence, as well as uprise and pressure release processes and cooling (Cas & Wright 1987). The vesiculation rate can be affected greatly by viscosity prior to explosive fragmentation and eruption and can influence the form and mobility of lavas (Cas & Wright 1987).

Factors that influence viscosity include composition, temperature, solid (i.e. crystal) content, gas bubble content or vesicularity, dissolved volatile content and pressure (Cas 1992; Giordano et al. 2004). The viscosity of magma can be greatly influenced by the dissolved water content (Cas & Wright 1987).

2.1.2 Volatile content

Higher amounts of water in a certain magma will decrease the viscosity of that magma at fixed temperatures seen in Figure 2.1 (Cas & Wright 1987). Water can break Si-O-Si bonds and depolymerise a silicate melt (Cas & Wright 1987). Therefore, mafic rocks with less Si-O-Si bonds will not be affected by the lowering of viscosity by water content as much as would a silicic melt (Cas & Wright 1987).

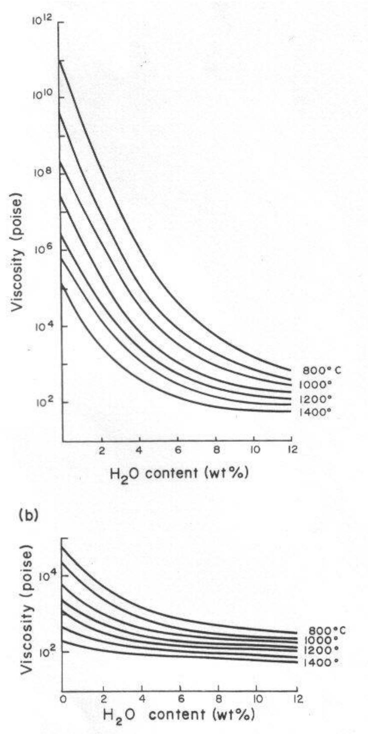

Figure 2.1: The effect of H_2O on the viscosity of (a) granitic and (b) basaltic melts at varying temperatures. (From Cas and Wright 1987).

The effect of volatiles on magma depends on the solubilities and abundances of the volatiles (Cas & Wright 1987). As well as water, chlorine and fluorine decrease the viscosity, especially for peralkaline compositions that have high contents of such volatiles (Cas & Wright 1987).

As temperature decreases and pressure increases, the magma water solubility will increase and it will decrease when the abundance of other volatiles increases (Cas & Wright 1987). Water solubility in a magma can be influenced by pressure (Cas & Wright 1987). Water exsolves from an ascending magma as the confining pressure decreases allowing crystallisation to occur that increases the magma viscosity and strength (Cas & Wright 1987). Explosive activity may be stopped by a low exsolved volatile content that increases the melt viscosity (Cas & Wright 1987). A decrease in volatile content, along with other factors can lead to the transition from one eruptive style to another and thus can form fall deposits or flow deposits (Borisova et al. 2005). Intense degassing in the volcanic conduit causes explosive eruptions compared to lava domes and flows that are extruded by slow degassing (Mourtada-

Bonnefoi & Laporte 2004).

2.1.3 Vesiculation processes

An ascending magma will experience pressure decreases that cause volatile exsolution (Cas & Wright 1987; Massol & Koyaguchi 2005). Bubbles will nucleate once a certain degree of supersaturation is reached (Massol & Koyaguchi 2005) as in Figure 2.2. A great amount of volatile supersaturation is required for a rhyolitic melt with 7% water to allow water bubble nucleation (Mourtada-Bonnefoi & Laporte 2004). High volatile supersaturation is needed in a melt for homogeneous nucleation to occur and less supersaturation is required for heterogenous nucleation on crystals and solid surfaces (Massol & Koyaguchi 2005).

During magma ascent, bubbles grow by decompression and diffusion of dissolved and coalescence water in the magma (Massol & Koyaguchi 2005). The magma rise velocity in the conduit and the rise of bubbles through the magma cause decompressional growth of bubbles (Cas & Wright 1987). Bubbles may nucleate several times in the conduit due to the high decompression rates that increase the nucleation rate (Massol & Koyaguchi 2005). A first nucleation event where the bubbles can reach final sizes could occur at great depths in the conduit as a result of ascent rate and nucleation rate (Mourtada-Bonnefoi & Laporte 2004). Fragmentation could be caused by late gas bubble nucleation in the higher conduit because a higher gas volume and internal pressure are present in the bubbles, possibly leading to the brittle transition (Massol & Koyaguchi 2005; Mourtada-Bonnefoi & Laporte 2004).

Three vesiculation events are thought to occur as three populations of vesicles are found in pumice (Whitham & Sparks 1986). The first stage occurs in the magma chamber, the second during ascent in the conduit and the last results from explosive eruption (Whitham & Sparks 1986). During the final event, the complete vesicle interconnectedness may occur when the pumice is thermally contracted or the glass is hydrated (Whitham & Sparks 1986). Another time the interconnectedness may occur is at an early stage when the external pressure decreases and the large excess pressure in the vesicles causes pumice and ash to form from the magma (Whitham & Sparks 1986). It is possible the vesicle interconnectedness is produced early in the magma and the process is completed later in the explosive eruption stage (Whitham & Sparks 1986).

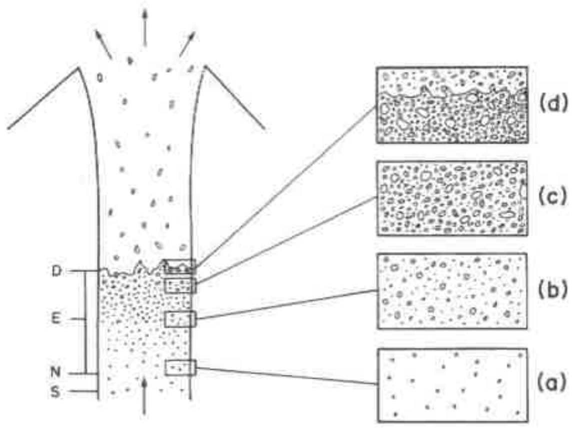

Figure 2.2: Gas bubble nucleation, growth and disruption sequence in an open vent magma column. S – gas saturation level. N – bubble nucleation level. E – bubble growth and exsolution interval. D – magma disruption level. A – early uninhibited bubble nucleation and growth. B – new nuclei form from continued growth. C – bubble saturated magma froth and growth ceases. D – bubbles burst as fragmentation surface engulfs the froth and moves down. (From Cas and Wright 1987).

2.2 Eruption

2.2.1 Explosive eruptions and fragmentation

Fragmentation determines whether an explosive or effusive eruption will occur (Massol & Koyaguchi 2005). Fragmentation may include volcanic explosions, autobrecciation of lava, quench fragmentation, epiclastic fragmentation and hydraulic fracturing (Cas & Wright 1987). Magma fragmentation is the process when slow moving laminar magma fragments into an intensely active and turbulent gas flow through breakage of bubbles and the release of compressed gas (Marti et al. 1999; Massol & Koyaguchi 2005; Zhang 1999). Magmatic pressure is greater than lithostatic pressure during fragmentation and the difference for rhyolites is much greater than that for trachytes (Polacci et al. 2004). Bubbles burst due to the difference in pressure between the atmosphere and the gas in the bubbles (Cas & Wright 1987).

The destruction of bubbles allows explosive escape and expansion of the gas from the vesiculated magma (Cas & Wright 1987; McPhie et al. 1993). Hot fragmented magma particles are transported with the released hot gas and thrust at high velocities from the vent (Cas & Wright 1987; McPhie et al. 1993). Phreatomagmatic eruptions are driven by the interaction of water and hot magma and involve the exsolution of water and carbon dioxide (Cas 1992; Lapidus & Winstanley 1990; McPhie et al. 1993). Phreatic explosions are eruptions of steam and country rock caused by the rapid conversion of superheated groundwater to steam, as a result of direct contact with dry magma (Cas 1992; Lapidus & Winstanley 1990; McPhie et al. 1993).

The particle type, size and morphology are controlled by the mode of fragmentation (Cas 1983). Sand sized crystals, fragments with shards, pumice, minor non-vesicular lithic fragments and ash are characteristic of subaerial eruptions (Cas 1983; Polacci et al. 2004). Subaerial and submarine eruptions can produce woody pumice or tube pumice (Marti et al. 1999). Bubble growth, stretching and shearing may occur together in the magma indicated from pumice textures (Marti et al. 1999).

2.2.2 Effusive eruptions and pumiceous lavas

An effusive eruption will result if volatiles escape or if a low volatile content occurs in the magma, therefore domes and lava flows will emerge (McPhie et al. 1993). When the yield strength is overcome by the applied shear stress then flow occurs (McPhie et al. 1993). Coherent and autoclastic facies are formed by lava flows (McPhie et al. 1993). The autobreccia is fragmented lava caused by cooling or high stress rates (McPhie et al. 1993). Domes and lavas can occur with co-magmatic explosively erupted pumice and ash deposits that form before effusive activity (McPhie et al. 1993). Silicic lavas and domes can have associated pumice, pumiceous lava and lava breccia as well as other facies (McPhie et al. 1993).

2.2.3 Pumice erupted under water

In silicic magmas, water is quite significant on the types of volcanic styles and products that will occur (Doyle & McPhie 2000). In a subaqueous setting the quenching of lavas and pyroclasts occurs quite rapidly between the hot magma and cold water (Cas & Wright 1987; Doyle & McPhie 2000). The hydrostatic pressure of the water column restricts exsolution and vesiculation in subaqueous explosive eruptions (Cas & Wright 1987; McPhie et al. 1993). The suppression of volatile exsolution with increasing water depth alters the vesicularity of lavas (Corsaro & Cristofolini 2000; Parfitt et al. 2002). The number of vesicles in the lavas could be used to estimate the eruption depth (Corsaro & Cristofolini 2000; Parfitt et al. 2002).

Silicic domes may not grow far from the feeder conduit in subaqueous settings due to rapid quenching and hyaloclastic brecciation (DeRita et al. 2001; Doyle & McPhie 2000). Subaqueous domes can also be associated with explosive phreatomagmatic activity (Cas & Wright 1987; McPhie et al. 1993).

Vesicular submarine lavas show that exsolution of volatiles can not provide enough energy to cause country rock failure or explosive activity (Cas 1992). The volatiles are kept in the flow, as the confining pressure is far too high for exsolution. Hence, compared to equivalent subaerial lavas, subaqueous lavas may have increased mobility and lower viscosity (McPhie et al. 1993). Also, at high ambient pressures a deep subaqueous eruption of highly vesicular magma will generate coarse pumice clasts (Kano 1996).

When magma vesiculation can occur, a explosive eruption will result and will produce a turbulent plume of hot gas and pyroclasts ejected from the vent into the water column at extremely high velocities (Kano et al. 1996). An eruption in shallow water can cause other phreatomagmatic or phreatic eruptions after the primary eruption by depressurisation of the vent that allows ambient water to flow into the vent (Kano et al. 1996).

Chapter 3 Submarine Transport and Deposition of Pumice

3.1 Pumice in water

The time taken for water to be absorbed by pumice to become water logged and then sink depends on the vesicle distribution and connectedness, density or vesicularity, volume and temperature (Whitham & Sparks 1986). Cold pumice can float for more than 1.5 years and steadily absorbs water slowly and ultimately sinks (Whitham & Sparks 1986). The time until the pumice becomes water logged can be weeks to months and larger pumice can take years (Whitham & Sparks 1986). The pumice clast size and vesicle interconnectedness are major influences for floating times of pumice (Whitham & Sparks 1986). For hot pumice, the density is lower than water but still will sink instantly due to the rapid intake of water (Whitham & Sparks 1986). Contraction of air and bubbling during cooling will cause the pumice to sink and also at a critical temperature, lower density pumice will sink (Whitham & Sparks 1986). The behaviours of hot and cold pumice could discriminate deposits by the amount of low-density pumice; a ‘hot’ deposit will have a higher proportion of low-density pumice than a ‘cold’ deposit (Whitham & Sparks 1986). Therefore, important sedimentation processes for subaqueous pumice on the seafloor include water settling and attrition (Whitham & Sparks 1986).

3.2 Submarine pumiceous gravity currents

Turbidity currents, fluidised beds, grain flows and debris flows are varieties of gravity flows (Fiske et al. 1998; Lowe 1982). A classification based on whether the flow is laminar or turbulent was suggested by Lowe (1979b) and Nardin et al. (1979) (Lowe 1982). Pumiceous gravity flows can be directly triggered by explosions, other gravity flows, storms, seismic activity, subaerial or subaqueous fallout, collapse of an eruption plume as well as suspension processes (Allen & McPhie 2000; Choux et al. 2004; Fiske et al. 1998; Kano 1996; Kano et al. 1996; Rinaldi & Venuti 2003). The interaction of hot pyroclastic flows with water and the resultant mass-flow processes can be seen in Figure 3.1.

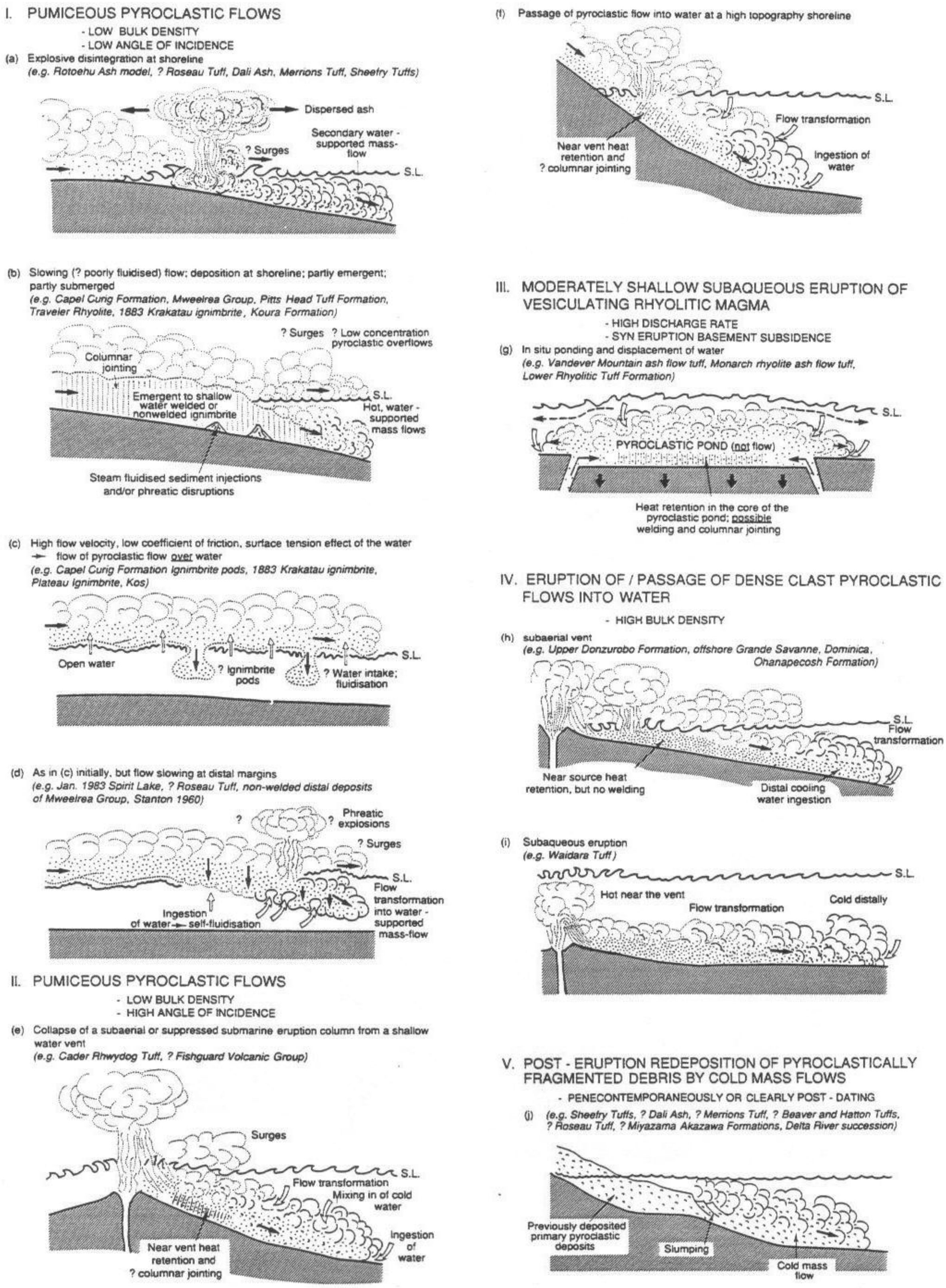

Figure 3.1: Representation of scenarios in which hot pyroclastic flows interact with cold water and the possible resultant mass-flow processes. (From Cas and Wright 1987).

Segregation processes occur during transport and deposition from source in gravity flows due to the varying size and density of solid particles (Choux et al. 2004; Rinaldi & Venuti 2003). During segregation, the buoyant components such as pumice are moved toward the top of the flow supported by turbulence while gravity influences dense components like lithic clasts to be suspended at the base region (Calder et al. 2000; Choux et al. 2004; Rinaldi & Venuti 2003).

During down-slope transport, large shear stresses can build up that erode the substrate and deposit the lithic clasts within the base of a deposit (Kano 1996). Ambient water can be entrained in the gravity flow head causing flow inflation that decelerates the flow and deposits the load (Kano 1996). Hot pumice can move down slope in such gravity flows and with the absorption of water, can become denser and break up due to grain collisions or strain induced by thermal stress (Kano 1996).

The grading in a pumiceous deposit can be determined by the stratification of grain size and density in a gravity flow (Choux et al. 2004). Experiments show a reverse to normal vertical grading of pumice-like particles can result from a two component subaqueous flow (Choux et al. 2004). Ignimbrites have reverse grading which is caused by floatation of large pumice in a very high density suspension (Choux et al. 2004). The final deposit densities are similar to the gravity flow densities that are represented by pumice density within the flow (Calder et al. 2000).

3.3 Submarine pumiceous water-settled fallout

After an subaqueous explosive eruption, a plume of larger hot pumice clasts can ascend by buoyancy and thermal convection (Kano et al. 1996). The hot and large pumice clasts can be buoyant for some time and be dispersed with ash after eruption by thermal convection and surface currents (Allen & McPhie 2000; Kano et al. 1996; Rinaldi & Venuti 2003). A steam carapace can form around large hot pumice clasts that prevent water intrusion and contribute to the buoyancy of the clasts (Allen & McPhie 2000; Kano et al. 1996; Whitham & Sparks 1986). Before becoming water logged, the large pumice blocks can be buoyant for long times due to the temperature or vesicularity of the pumice (Rinaldi & Venuti 2003; Whitham & Sparks 1986). Also, dense components can sink immediately to form a normal graded pumice lapilli and block deposit depleted in ash (Kano et al. 1996). This can be covered later by pumice clasts that have taken some time to water log and sink (Allen & McPhie 2000; Kano et al. 1996; Rinaldi & Venuti 2003). The settling of pumice and ash from the water column can occur continuously after water saturation (Allen & McPhie 2000; Kano et al. 1996; Renaldo & Venuti 2003). Fallout from subaerial eruption columns can produce dilute submarine density currents of finer grained material that can flow down slopes and form strongly bimodal pumice-lithic deposits (Fiske et al. 1998).

3.4 Ocean and wind currents

Felsic pumice with densities of <1000 kg cm^{-3} are known to remain afloat after eruption and travel for months to years (Bryan et al. 2004; Risso et al. 2002; Whitham & Sparks 1986). Prevailing wind and ocean currents can transport pumice over 20 000km (Bryan et al. 2004; Risso et al. 2002). Sea-rafted pumice can be the only indicator of submarine explosive eruptions in remote areas (Bryan et al. 2004; Shane et al. 1998). The distribution of the pumice can be used to understand large-scale ocean current patterns and transport rates (Bryan et al. 2004; Risso et al. 2002; Shane et al. 1998). Pumice rafts can transport biota that can become attached and that may be biologically harmful to certain areas of the world (Bryan et al. 2004; Shane et al. 1998). Also, bones, trees and even humans can be transported on such rafts of pumice (Bryan et al. 2004). It was thought that the coastal pumice can be used to correlate coastal sequences but problems arise with this approach (Shane et al. 1998). Pumice washed up on coastlines can become dehydrated and recover floating potential before being swept out by large tides (Bryan et al. 2004). Therefore, pumice can be extensively reworked in coastal environments and dispersed great distances far from the origin (Bryan et al. 2004; Shane et al. 1998).

Chapter 4 Case Studies of Submarine Pumiceous Deposits

Most subaqueous pumiceous deposits are not formed by one single process. Several, if not all the processes described in the previous chapter can be responsible for the formation of subaqueous pumiceous deposits. In this chapter, examples of subaqueous pumiceous deposits are used to relate the textures observed to the eruption and transport processes.

4.1 Shinjima Pumice

Kano, Yamamoto and Ono 1996 have carried out work on the Shinjima Pumice and this section is based on that work. Shinjima Island appeared in 1780 north of Sakurajima volcano in SW Japan by subaqueous eruptions and emplaced several thousand years ago (Kano et al. 1996).

The rhyolitic Shinjima Pumice is a 40 m thick pumice lapilli tuff within the Shinjima Island sedimentary succession and was deposited in water of 60-140 m deep (Kano et al. 1996). Overlying unconformably above the Shinjima Pumice is thinly interbedded pumice lapilli tuff, tuff and tuffaceous siltstone that show cross-lamination, convolutions and upward-cuspate intrusions (Kano et al. 1996). Pumice-bearing mudstone lie above these units as well as the Moeshima shell bed and pumice and ash fall deposits (Kano et al. 1996). Tuffaceous sandstone to mudstone turbidites and interbedded pumice lapilli tuff and tuff are below the Shinjima Pumice (Kano et al. 1996) (Fig 4.1).

The components of the Shinjima Pumice besides pumice include minor crystals, glass shards and rare obsidian and hard black mudstone clasts (Kano et al. 1996). Present in the pumice unit are structures including parallel to wavy diffuse stratification formed by pumice clast alignment and poorly defined beds of 1-10 m thickness (Kano et al. 1996). The unit is well sorted and each bed contains bimodal populations of pumice lapilli and ash made of crystals and shards of pumice and glass (Kano et al. 1996).

The larger blocky and elongate to equant pumice clasts have tube vesicles and are subrounded due to abrasion during eruption (Kano et al. 1996). Fractures common on the pumice are similar to contraction cracks formed by thermal stresses building up in water during cooling of lavas and bombs (Kano et al. 1996). The abundance of vesicles, glass and crystals do not change, meaning on eruption into water, crystallisation and vesiculation had ended (Kano et al. 1996). The smaller, elongate to equant ash pumice clasts are present with shards of blocky, curved or platy glass (Kano et al. 1996). Curviplanar surfaces interpreted as brittle fractures from quenching or shock formed by phreatomagmatic eruptions cut vesicle walls (Kano et al. 1996). Overall, the bimodal size distribution of different density pumice is believed to form from hydrodynamic behaviour differences in subaqueous eruption plumes (Kano et al. 1996).

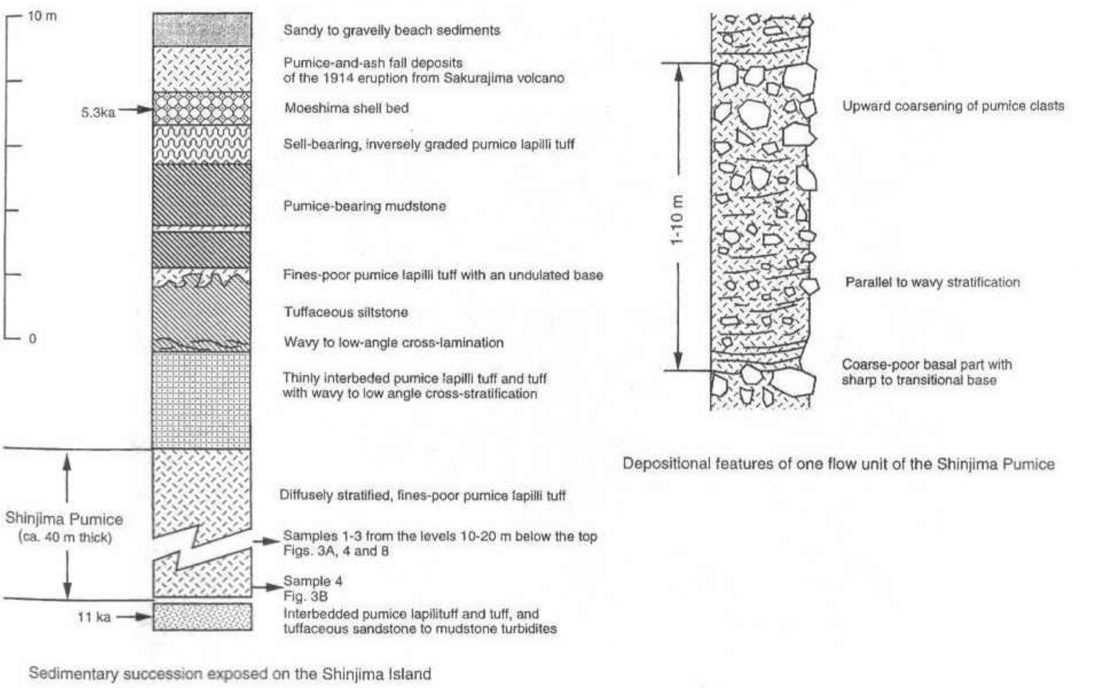

Figure 4.1: Sedimentary succession exposed on Shinjima Island and depositional features of one flow unit of the Shinjima Pumice. (From Kano et al. 1996).

The Shinjima Pumice was emplaced directly from subaqueous eruptions onto the Aira caldera floor by subaqueous volcaniclastic turbulent mass flows (Kano et al. 1996). The eruption was caused by magma vesiculation and some magma-water interaction, as shown by differences in pumice clast size and by the presence of glass shards and curviplanar surfaces on vesicles (Kano et al. 1996). The eruption occurred at a shallow level, indicated by the rarity of lithic clasts, and the sediments were wet and unconsolidated (Kano et al. 1996).

At eruption, high-velocity gas-supported pumiceous eruption plumes were forced into ambient water and, through turbulent mixing, collapsed as water-logged mass-flows (Kano et al. 1996) (Fig. 4.2). During early eruption, only clasts denser than water and small amounts of fine pumice can fall out, settling by grains at a time after moving by traction on the slope forming a stratified fine-grained deposit (Kano et al. 1996). At later stages, larger pumice clasts begin to fall out that were caught in the turbulent mass, causing an upward coarsening above the lower stratified fine-grained deposit (Kano et al. 1996). The Shinjima Pumice is depleted in fine ash because the convective plume created by the eruption kept the ash entrained due to the small falling velocity (Kano et al. 1996). The ash was dispersed away with hot coarse pumice clasts by thermal convection and surface currents (Kano et al. 1996). In a short time, a mass-flow deposit would form after numerous explosions from a large and dense, turbulent suspended pumiceous mass (Kano et al. 1996).

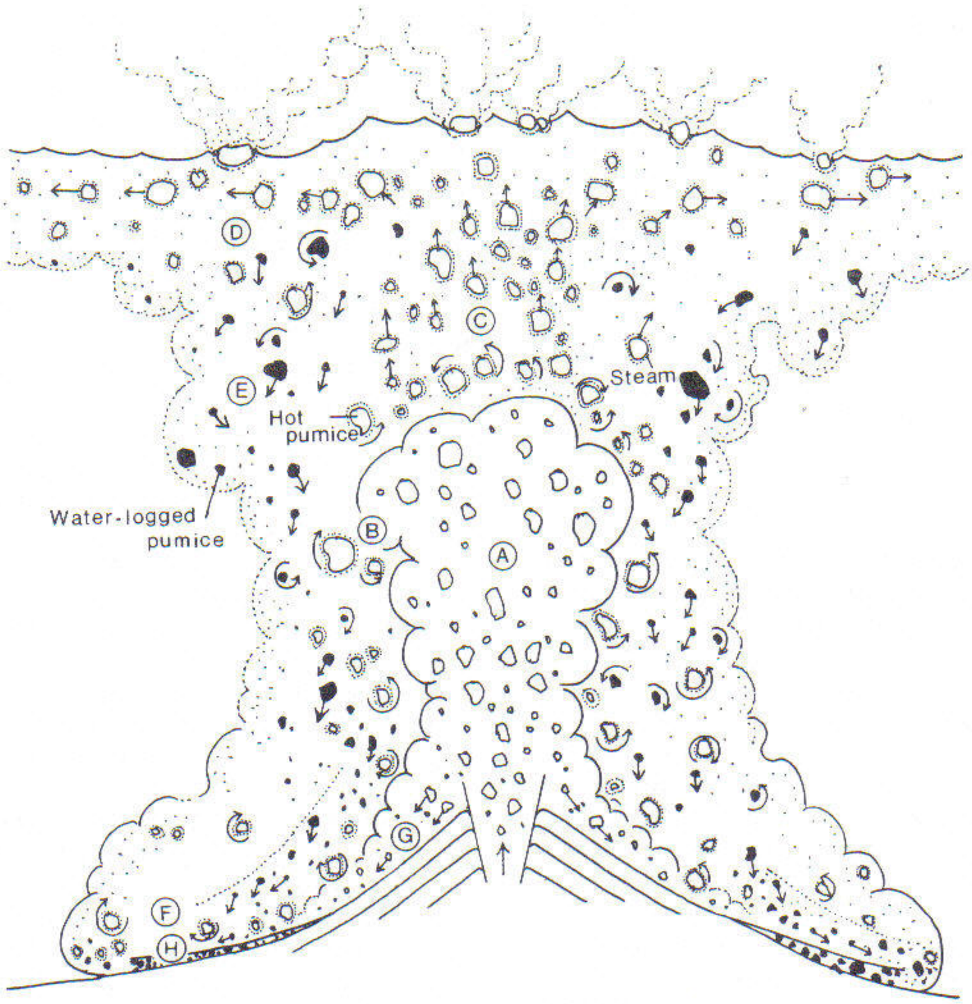

Figure 4.2: A model of subaqueous pyroclastic eruption and emplacement for the Shinjima Pumice. During eruption the vent may widen and subside. A – gas supported pumiceous eruption plume. B – mixing zone of plume and water. C – pumiceous plume. D – pumice clasts and fine ash component cloud. E – water logged pumice clasts and other dense material fallout. F – gas and water logged mass flow. G – gas supported hot pyroclastic flow. H – pumice deposit. Not to scale. (From Kano et al. 1996).

4.2 Yali Pumice

The Yali pumice breccia lies in the eastern Aegean at Yali Island in Greece and is a Quaternary submarine rhyolitic pumice succession (Allen & McPhie 2000). The succession covers 2.8 km^2 on 60-100 m high, steep cliffs with 10-15^o dipping beds (Allen & McPhie 2000). The pumice itself is angular to subrounded and is pebble, cobble and boulder in size (Allen & McPhie 2000). The stratigraphy of the Yali pumice breccia can be seen in Figures 4.3 and 4.4.

The beds of loose pumice clasts are accompanied by a minor fine ash matrix and are moderate to well-sorted and other components such as basement lithic clasts and dense juvenile clasts are quite rare (Allen & McPhie 2000). The pumice occurs as 4 different types including white aphyric pumice, speckled porphyritic pumice, grey pumice and non-vesicular to poorly vesicular speckled or grey clasts (Allen & McPhie 2000). All types are rhyolitic to dacitic in composition (Allen & McPhie 2000). The vesicles present in these types are either uneven in texture or tube vesicles, and the Yali pumice clasts are mainly finely vesicular (Allen & McPhie 2000).

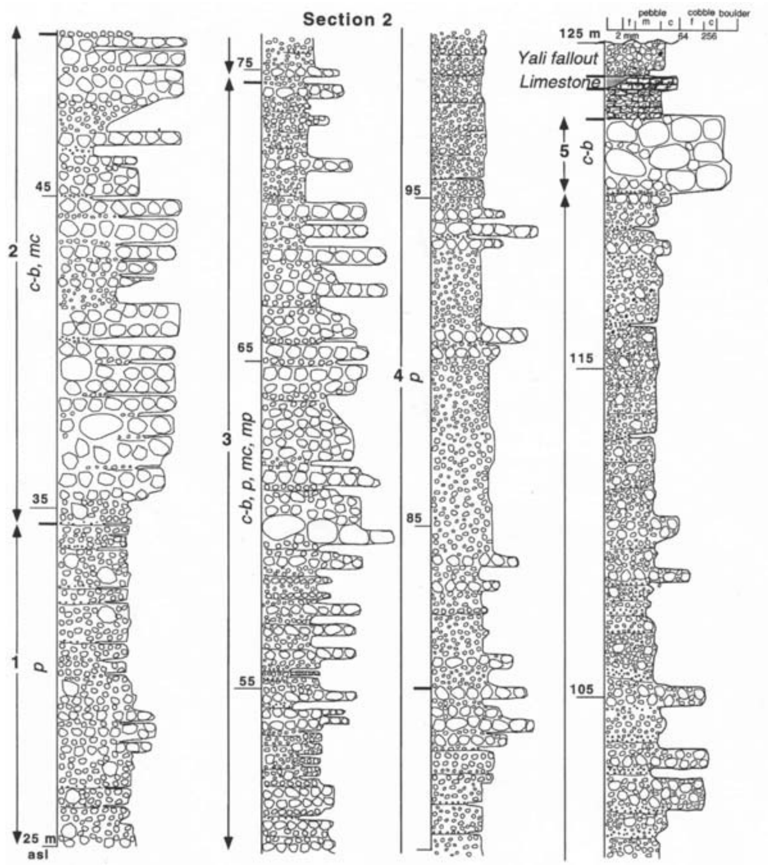

Figure. 4.3: Stratigraphic log through the Yali pumice breccia at section 2. The section comprises five units 10-15 m thick. Each unit is dominated by a single, or combination, of lithofacies. p: Dominated by pebble facies, with distinct planar (unit 1), or diffuse (unit 4), stratification. c-b, p, mc, mp: Interbedded cobble-boulder, pebble and mixed facies (unit 3). c-b: Dominated by cobble-boulder facies (unit 5). Fossiliferous limestone. Bioclastic sandstone and associated units, together with the Yali subaerial fallout occur at the top of the section. (From Allen & McPhie 2000).

Quenched margins and internal polyhedral joints are present on the prismatic cobble-sized and boulder-sized pumice clasts that form massive and tabular, well sorted, grain-supported medium to very thick beds (Allen & McPhie 2000). These beds contain no lithic clasts or matrix (Allen & McPhie 2000). The blocky pebble-sized and granule-sized clasts are polyhedral, angular to subrounded, and form beds that are wedge-shaped and massive to diffusely stratified (Allen & McPhie 2000). Curviplanar surfaces on the clasts cut vesicle boundaries and the clasts have no quenched margins (Allen & McPhie 2000).

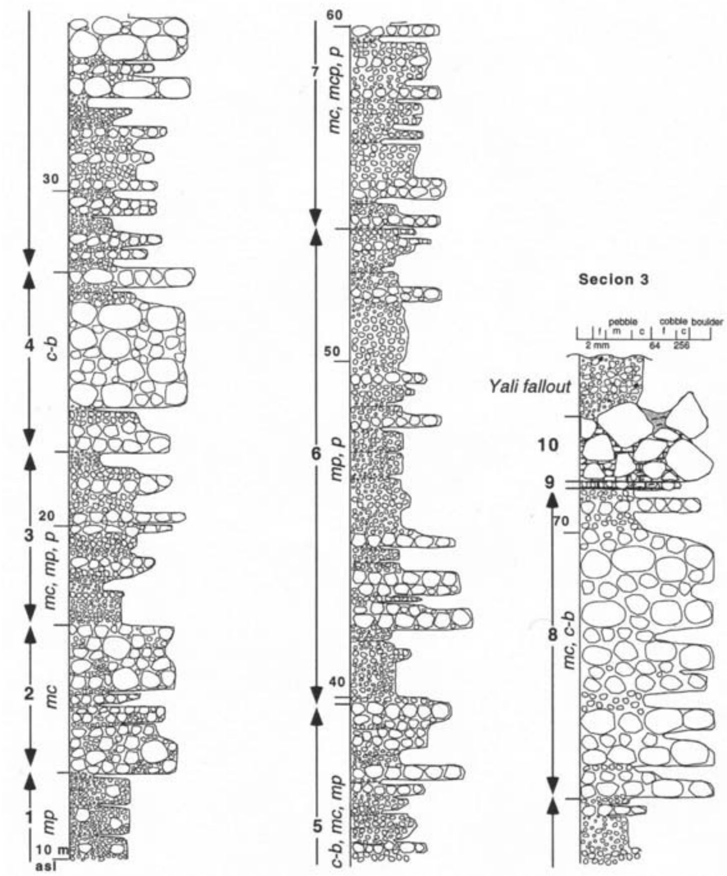

Figure. 4.4: Stratigraphic log through the Yali pumice breccia at section 3. The Yali pumice breccia comprises eight units that are mostly less than 10m thick. mp: dominated by mixed pebble-dominant facies which is weakly planar stratified (unit 1). mc: Dominated by mixed cobble-dominant facies which is also weakly planar stratified (unit 2). mc, mp, p: Interbedded mixed facies and pebble facies (units 3,7). c-b: Dominated by cobble-boulder facies (unit 4). c-b, mc, mp: Interbedded cobble-boulder and mixed facies (unit 5). mp, p: Interbedded mixed pebble-dominant facies and pebble facies (unit 6). mc, c-b: pebble bed (unit 9) and talus breccia of blocks of carbonate-cemented pumice (unit 10) that are overlain by limestone, bioclastic sandstone and the subaerial Yali fallout. (From Allen & McPhie 2000).

The cobble-boulder facies formed by water settling from suspension of large pumice clasts (Allen & McPhie 2000). The clasts were hot and have quenched margins (Allen & McPhie 2000). The pumice pebble beds are suggested by the grain size and sorting to have originated as fallout (Allen & McPhie 2000). Resedimentation of waterlogged, cohesionless pumice by submarine gravity flows formed the bedforms seen in the pebble granule facies (Allen & McPhie 2000). To explain the mixture of clast sizes, resedimentation of the pebble and cobble boulder facies and large pumice clasts settling from suspension occurred concurrently (Allen & McPhie 2000).

In formation of the Yali pumice breccia, the rhyolite dome vesiculated (Allen & McPhie 2000) as seen in Figure 4.5. Brecciation of the carapace occurred by cooling contraction and continued effusion (Allen & McPhie 2000). Phreatomagmatic explosions and submarine lava effusion processes such as spalling and quenching created the large amount of pumice clasts (Allen & McPhie 2000). After release, the large and hot pumice blocks were buoyant in the water column and cooled slowly internally while the surfaces quenched quickly (Allen & McPhie 2000). Both the explosive and effusive processes were important interchangeably in formation of the bed structures (Allen & McPhie 2000). The pumice clasts were formed by the spalling or explosive fragmentation of the vesicular carapace of felsic lava domes (Allen & McPhie 2000). Other intense explosions and disintegration of suspended hot clasts created polyhedral pumice clasts (Allen & McPhie 2000).

The water logged pumice pebbles settled by suspension and were remobilised from large unstable masses by gravity flows moving down slope initiated by sudden events (Allen & McPhie 2000). Some the gravity flows carried lava and lithic clasts too dense to be suspended in water and were deposited closer to source and were thicker while all the other deposits were formed some distance from the source (Allen & McPhie 2000). The depletion of the ash component occurred by separation from coarser material by rising heated seawater plumes and then carried away to be deposited elsewhere by water and possibly wind currents (Allen & McPhie 2000). The larger floating pumice cobble-boulder clasts became water logged and sank after being dispersed a short distance from the source (Allen & McPhie 2000). The clasts formed either the mixed facies produced from gravity flows or the tabular beds formed from settling (Allen & McPhie 2000).

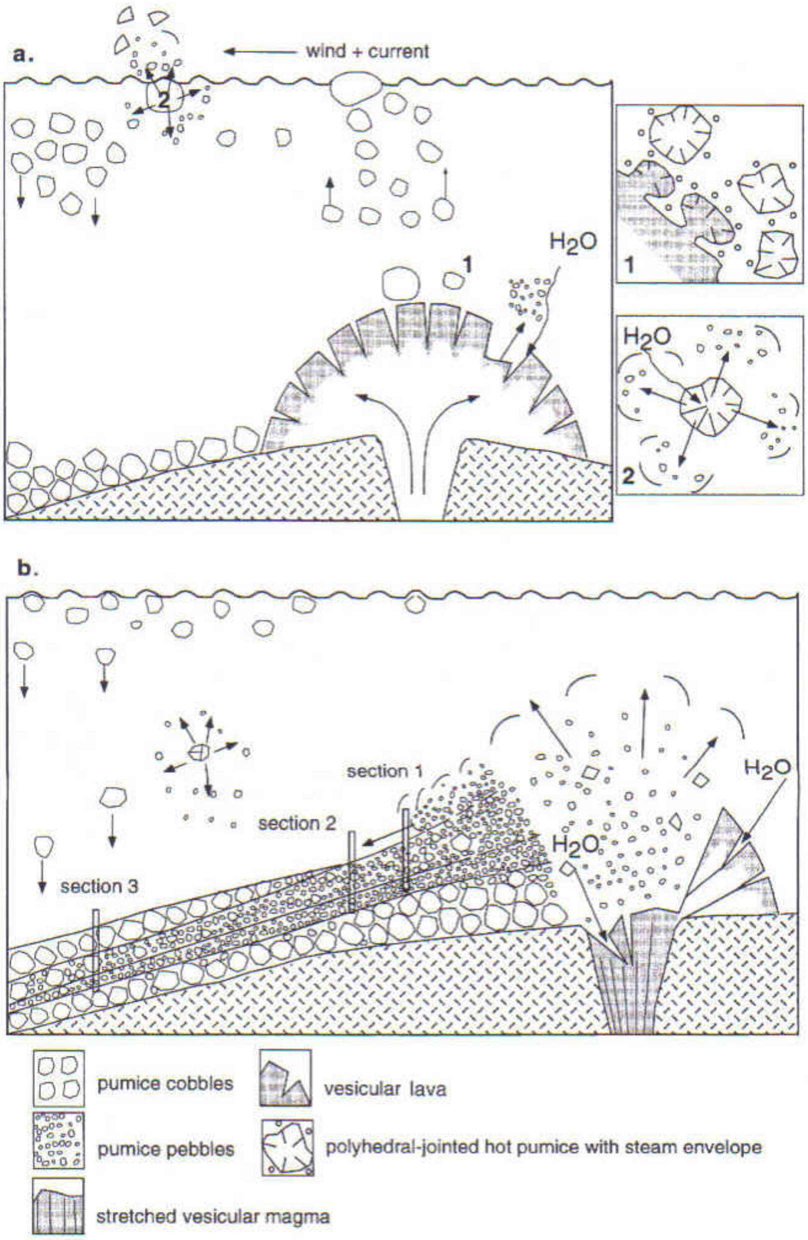

Figure. 4.5: The eruption, transport and depositional processes thought to have formed the Yali pumice breccia. The eruption includes effusive and explosive activity. A – During effusion, a volume of tens of cubic metres of lava was extruded on the seafloor. The outer carapace vesiculated and fragmented. 1 – Large pumice clasts with quenched surfaces (some more than 1m) spalled from the vesicular carapace and to the levels of neutral buoyancy. The clasts were transported a short distance by water and wind currents and then settled from being water logged. 2 – Some coarse clasts exploded as steam formed by water absorption into the hot interior. B – Probably phreatomagmatic explosive activity caused an unstable small pumice clast apron to form that became constantly resedimented down slope by gravity flows. (From Allen &

McPhie 2000).

4.3 Josoji Formation

The Early to Middle Miocene Josoji Formation occurs north of Etomo at Shimane Peninsula, Japan, and contains a 15-16 m thick subaqueous rhyolitic volcaniclastic mass-flow deposit known as the Tayu Volcaniclastic Bed E (Kano 1996). The components are lapilli to block sized pumice, glassy clasts with no to poor vesicularity, and ash and lithic clasts (Kano 1996).

The Tayu Volcaniclastic Bed E is divided into 4 layers. Layer 1 is a poorly to moderately sorted normally graded lithic breccia (Kano 1996). The base is mainly sharp, apart from upward cusps showing rapid water escape during deposition (Kano 1996). The sub-angular to angular lithic clasts are lapilli to block in size and include rhyolite, shale and sandstone (Kano 1996). A tuff breccia lies over the first layer and is distinguished by the sudden reduction in lithic clasts, which are rhyolite, pumice and shale clasts (Kano 1996). In layer 2 are groupings of coarse pumice clasts that form parallel to wavy stratifications and shale blocks that are tabular to lenticular are mainly parallel to the pumice clasts (Kano 1996). Interbedded pumice-rich and pumice-poor layers form the 2.5-3 m thick layer 3 that has a transitional contact with layer 2 (Kano 1996). The abundance of the lithic clasts and the size of the pumice clasts both decrease suddenly (Kano 1996). The pumice in the pumice-rich layers is lapilli size and parallel to bedding while the pumice is ash size in the depleted layers (Kano 1996). Layer 4 has ash sized plagioclase and pumice shreds and minor lithic clasts and is well-stratified and sorted (Kano 1996). The base of layer 4 is sharp and laminae within the layer are locally hummocky cross-stratified (Kano 1996).

Layer 1 formed from a gravelly high-density turbulent flow with the grading a result of fallout from the suspension load due to density and size (Kano 1996) (Fig. 4.5). Large shear stresses created the basal folding and shale blocks were torn up and carried by these stresses produced in the flow (Kano 1996). The shear stresses also formed the shale clast groupings in layer 2 (Kano 1996). The textures in layer 2 is developed as the flow head collected ambient water or topography changed (Kano 1996). Separation of the gravity flow will occur with inclusion of ambient water as the dense lower flow continues forward while the upper flow slows down (Kano

1996). This process could repeat numerous times as the sediment supply and water entrainment may be not be continuous but also crossing of flow heads or lobes and unsteady eruptions can also be involved in creating such textures (Kano 1996). Layer 3 was formed from the remaining lithic-poor, pumiceous turbulent flow and deposited rapidly through traction and suspension (Kano 1996). The pumice-rich and pumice-poor layers could form like layer 2 or by intense current pulses (Kano 1996). The deposition of layer 4 can be compared to sand turbidites and the cross stratification could be formed by waves moving along a dense underflow and the less dense and thicker overlying turbulent flow.

Phreatomagmatic explosions and explosive lava collapse or vesiculation of magma may have caused the eruption that produced the volcanic material in the beds (Kano 1996) (Fig. 4.5). A pumiceous quenched crust forms on the lava due high water pressure suppressing escape of volatiles (Kano 1996). Pressure build up and release leads to explosion of the pumiceous zone, forming pumice clasts (Kano 1996). The coarser clasts are found as fallout while other clasts remain hot and become buoyant and can be dispersed away (Kano 1996). The eruption plume should be low and wide, caused by the high ambient pressure, and would rapidly collapse to form a water logged mass-flow (Kano 1996).

High temperature emplacement did not occur for the Tayu Volcaniclastic Bed E and shale rip-up blocks, load clasts and water-escape structures establish the depositional setting as subaqueous (Kano 1996). The lower parts of the deposit are massive and poorly sorted with an upper parallel and stratified division (Kano 1996). Upward in the bed, there is an overall fining, lithic clast depletion and concentration of pumice, compared with depletion of fine ash components in the bed (Kano 1996). The mass-flow was fluidised and expanded, allowing sorting of the material by sedimentary processes (Kano 1996). Kano (1996) suggests the origin of the Tayu Volcaniclastic Bed E was syn-eruptive (Fig. 4.6). The interpretation is based on the absence of fossils, normal sediments, abraded clasts and thick, coarse pumice debris piles at the believed source (Kano 1996). The presence of homogeneous clasts and the intense internal shear within the unit is evidence for the syn-eruptive origin (Kano 1996).

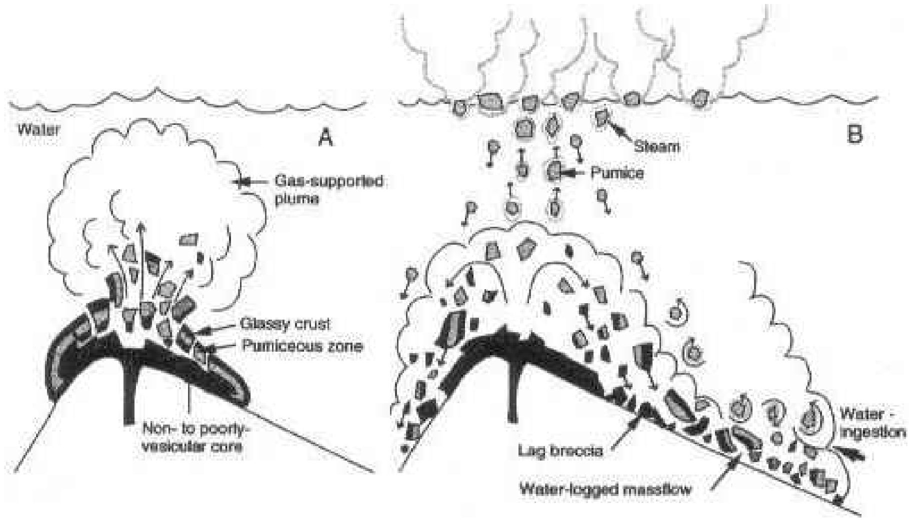

Figure. 4.6: A model for the Tayu Volcaniclastic Bed E. A – subaqueous explosion of lava. B – Generation of coarse mass flow. Not to scale. (From Kano 1996).

4.4 The 1952-1953 Myojinsho Eruption

The shallow submarine Myojinsho volcano erupted from 1952-1953 and is located 420 km south of Tokyo (Fiske et al. 1998). Ancient submarine silicic successions are analogous to the deposits of Myojinsho but in ancient deposits little is understood about the relationships between deposits and processes, the source vent location and volcanic cone construction (Fiske et al. 1998).

During 1952-1953, hundreds of phreatomagmatic explosions occurred subaerially and subaqueously, creating vast areas of floating pumice from the vesiculated magma (Fiske et al. 1998). Pumice lapilli and even some clasts up to a metre were observed during the eruption period and the fact that the larger clasts were still buoyant means that the clasts cooled in air preventing absorption of water and sinking (Fiske et al. 1998). Wind currents separated the floating pumice from the tephra that was dispersed by ocean currents due to differences in the currents (Fiske et al. 1998). Lapilli and ash were observed being dispersed as discoloured plumes in the water that gave temperature anomalies (Fiske et al. 1998). Other than water-saturated pumice and remobilised material, autoclastic fragments and clasts from explosive fragmentation, quench shattering and dome emplacement and disintegration are present in the deposits (Fiske et al. 1998).

Flow density and velocity changes during down-slope transport would create turbidity currents, fluidised beds, grain flows and debris flows, all collectively called submarine pyroclastic gravity flows for the Myojinsho deposits (Fiske et al. 1998) (Fig. 4.7). These had little influence from wind and water currents (Fiske et al. 1998). The upper slopes of the volcano deposit formed from dilute subaerial fallout that entered the water column and became dense fallout that formed vertical density currents (Fiske et al. 1998).

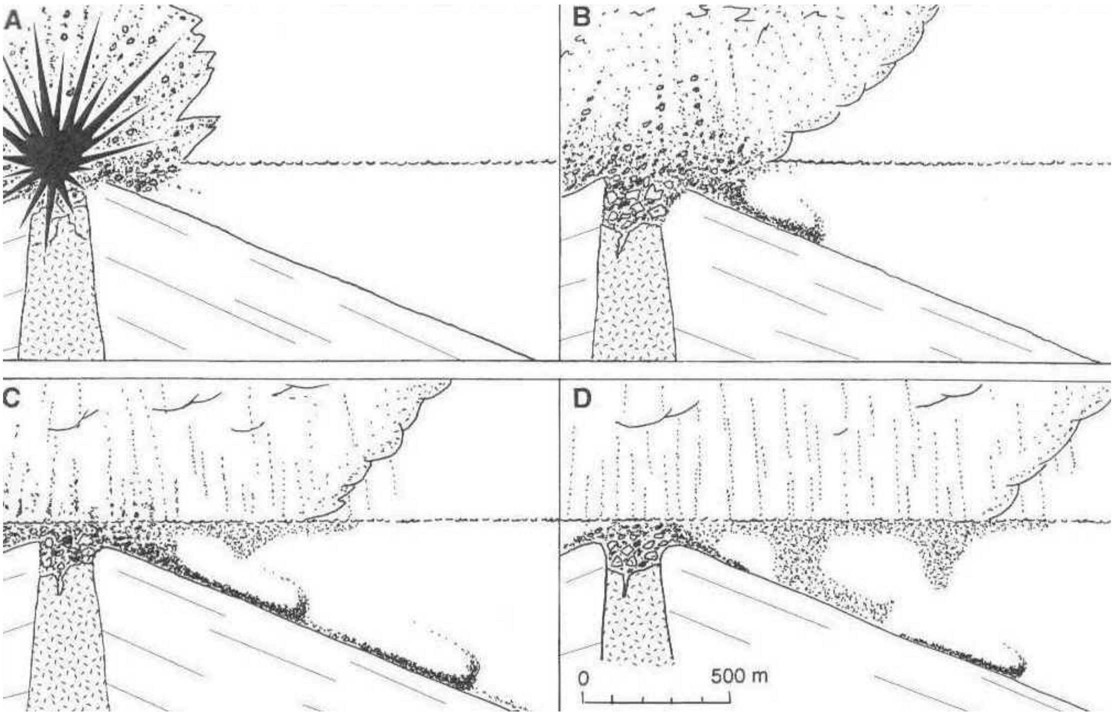

Figure. 4.7: Interpreted transport and deposition of tephra at Myojinsho, 1952-1953. A – The growing dome is shattered by an explosion forcing debris upward into the air and sideways into the water. B – Clasts with high terminal velocities (V_T) fall quickly on the slopes of the volcano and submarine gravity flows form. C – Continual fallout of high V_T pyroclasts form more gravity flows. Subaerial fallout of lower V_T pyroclasts form particle hyper-concentrations in a near surface layer. Gravitational instabilities begin to form inverted plume-like vertical density currents. D – Vertical density currents descend to the volcano slopes through 400 m of water and deeper. (Fiske et al. 1998).

Chapter 5 Conclusions

The formation of pumice is dependent on the certain properties of the magma. Viscosity, volatile content and vesiculation processes are important for the ascent of the magma and can govern the eruption styles that can occur. The volatile content refers to the dissolved gases in the melt and water is a quite important factor on the eruption process as it breaks Si-O bonds and lowers the viscosity (Cas & Wright 1987). Eruption styles can be controlled by the decrease of volatile content in the melt (Borisova et al. 2005). Bubble nucleation results from the magma reaching supersaturation, and diffusion and decompression allow bubble growth (Massol & Koyaguchi 2005; Mourtada-Bonnefoi & Laporte 2004). Three vesiculation events occur forming the vesicles in pumice. The first stage, occurs in the magma chamber, the second during ascent in the conduit and the last results from explosive eruption (Whitham & Sparks 1986).

Explosive magma fragmentation is the process where magma fragments into a turbulent gas flow through breakage of bubbles and the release of compressed gas from bubble destruction (Cas & Wright 1987; Marti et al. 1999; Massol & Koyaguchi 2005; McPhie et al. 1993; Zhang 1999). Crystals, shards, pumice and minor non-vesicular lithic fragments and ash are characteristic of subaerial eruptions (Cas 1983; Polacci et al. 2004). Volatile escape or a low volatile content will produce effusive activity creating domes and lava flows (McPhie et al. 1993). Coherent and autoclastic facies are formed by domes and flows and also associated pumice, pumiceous lava and lava breccia (McPhie et al. 1993).

Exsolution and vesiculation in subaqueous explosive eruptions are suppressed by the overlying hydrostatic pressure of the water column (Cas & Wright 1987; McPhie et al. 1993). Due to the pressure as well as rapid quenching, silicic domes are not able to flow far from the feeder conduit and are subject to quench brecciation (DeRita et al. 2001; Doyle & McPhie 2000). Explosive eruptions will result from magma vesiculation producing a turbulent plume of hot gas and pyroclasts (Kano et al. 1996). Coarse pumice clasts can form and be preserved at high ambient pressures in a deep subaqueous eruption of highly vesicular magma (Kano 1996).

The time for pumice to absorb enough water to become water logged and then sink depends on the vesicle distribution and connectedness, density, volume and temperature (Whitham & Sparks 1986). Cold pumice slowly absorbs water and can float for long periods of time (Whitham & Sparks 1986). Hot pumice is lower in density than water but sinks instantly due to the rapid intake of water (Whitham & Sparks 1986).

Submarine pumiceous gravity flows include turbidity currents, fluidised flows, grain flows and debris flows (Fiske et al. 1998; Lowe 1982). Segregation during transport and deposition is important in the hydraulic sorting of material and also important in the textures of resultant deposit. Large hot pumice clasts can ascend by buoyancy and thermal convection before sinking from being water logged. Fallout can produce dilute density currents that can flow down slopes and form strongly bimodal pumice-lithic deposits (Fiske et al. 1998). Large cold pumice that is carried away after eruption can be transported vast distances by wind and ocean currents. Pumice can wash up on coastlines, become dehydrated and recover floating potential and can be reworked on coastlines and be dispersed far from origin (Bryan et al. 2004; Shane et al. 1998).

A single transport and deposition process does not form one deposit; many or all the processes discussed can be involved. The Shinjima pumice of SW Japan is a 40 m thick pumice lapilli tuff (Kano et al. 1996). Magma vesiculation and magma-water interaction caused the explosive fragmentation that lead to the formation of subaqueous volcaniclastic turbulent mass flows (Kano et al. 1996). The Yali Pumice of Greece is a Quaternary submarine pumice succession with beds of moderate to well sorted loose pumice clasts and fine ash matrix (Allen & McPhie 2000). The material originated form phreatomagmatic explosions and vesicular submarine lava effusion and deposited by settling and resedimentation by subaqueous gravity flows that sorted the material. The Josoji Formation of Japan contains a 15-16 m thick subaqueous volcaniclastic mass-flow deposit called the Tayu Volcaniclastic Bed E (Kano 1996). The bed is divided into 4 layers that all represent different components and transport and deposition processes. Phreatomagmatic explosions and vesiculation of magma caused the eruption producing the volcanic material (Kano 1996). Both water settling and syn-eruptive mass-flows formed the deposit. From 1952-1953, the shallow submarine Myojinsho volcano erupted 420 km south of Tokyo (Fiske et al. 1998). Floating pumice was observed during this time as well as lapilli and ash plumes in the water. The eruptions are thought to have formed submarine mass-flows on the deeper flanks of the volcano.

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