CONDUIT, ERUPTION AND PLUME DYNAMICS
THROUGHOUT THE 28 – 29 MARCH 1875 ERUPTION
OF ASKJA VOLCANO, ICELAND

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ABSTRACT

Explosive eruptions exhibiting rapid and reversible shifts in eruption style and intensity within a single eruptive event are rare and, hence, very dangerous. The nature and reasons for such shifts are poorly understood, yet are critical to our ability to mitigate future volcanic hazards from these volcanic centers.

The 1875 rhyolitic eruption of Askja Volcano was characterized by intervals of sustained activity, yet also with abrupt shifts in eruption style. The combination of historical records, relative youth of the products, and preservation of both proximal and far distal deposits has presented an unparalleled opportunity to understand such shifts, in addition to further understanding of transport and deposition in wet and dry eruption plumes.

This dissertation project characterizes the products of each eruption phase and their dispersal, which has been used to calculate eruption parameters, such as volume, intensity and vent positions. The amalgamation of these data with quantitative studies of vesicles present in representative pumice clasts has resulted in a comprehensive understanding and evaluation of the relative roles of external factors and inherent characteristics of the magma which produced the 1875 eruptive activity.

All clasts from phases of the main eruption are microvesicular, and quantitative vesicle data suggest that similar deep processes of nucleation and growth occurred throughout the eruption. Subtle differences in vesicle textures suggest that the shallow conduit ascent history was slightly different between and within phases.

The shift between wet and dry phases was due to external factors, principally migration of the vent into, and out of, water sources. The transition between a wet
buoyant sustained phreatoplinian plume to collapsing column conditions was also due to external factors, vent widening and availability of water, during maintained high mass discharge rates.

The magma erupted during the phreatomagmatic phases of this eruption was a foam prior to both fragmentation and the interaction of external water. Future studies are required to understand the exact role of external water in driving the phreatoplinian eruption.

Fountaining from multiple separate vents was synchronous with sustained Plinian discharge during the climax of the 1875 eruption, and produced welded fallout deposits in two separate locations. The patterns of regional welding suggest that the accumulation rate and emplacement temperatures were critical controls. More localized welding, associated with meter-sized spatter bombs, appears unique to Askja, and I have termed it ‘Local welding’. The textures and distributions of these spatter bombs have important implications for magmatic source, conduit and eruption dynamics.

Proximal exposures up to 1 km from inferred vents have defined, for the first time, a proximal Seg-1 segment on semilog plots of thickness vs. area $\frac{v}{a}$ for each of the fall units, regardless of eruption intensity or style. This is attributed to ephemeral, premature and enhanced sedimentation from the jet and lower convective column margins.
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CHAPTER 1
INTRODUCTION

1.1 Background to the study

The short-lived powerful eruption of Askja volcano in 1875 has not been studied in detail since work conducted in the late 1970's, and early 1980's (Sigvaldason, 1968; Sigurdsson and Sparks, 1978a, b; Sigvaldason 1979; Sparks et al., 1981; Sigvaldason, 1982). These authors developed an initial petrological and volcanological framework for this eruption, which is expanded upon in this study. Certain key factors linked to this eruption have led to the large amount of information collected in my reexamination of the 1875 eruption: a) the minimal caldera collapse has facilitated study of proximal deposits in detail at distances up to 1 km from inferred vents; b) detailed historical records and drawings of the volcano made prior to, during and after the main eruption have constrained estimates of the eruptive phases, dispersal characteristics of the plumes, and vent configurations and timings; and c) the youth of this eruption resulted in low degrees of reworking and erosion of the deposits, which has made accurate volume calculations possible. These factors have facilitated formulation of many interesting and unique questions about volcanological processes for future studies, in addition to achieving the study objectives.

One example of the special properties of the 1875 eruption is that it features one of the 'type' examples of 'phreatoplinian' volcanism. This term, originally coined by Self and Sparks (1978) was used to describe powerful wet silicic eruptions. The 1875 eruption is the only historic example which was well documented and also features more proximal
deposits than the other ‘type’ examples, at Taupo. Although the interaction of magma and water is a common feature of many eruptions, very few historical examples exist for eruptions of high mass discharge rate. The diverse eruption and deposit characteristics of these ‘type’ examples is justification for further studies of this particularly hazardous eruption style (Table 1).

Table 1. Summary characteristics of ‘type’ phreatoplinian eruptions after Houghton et al., (2000) and Carey et al., (in review). Note the lack of time constraints for all except Askja 1875.

<table>
<thead>
<tr>
<th>Deposit</th>
<th>Aska-C</th>
<th>Hatepe Ash</th>
<th>Rotongaio Ash</th>
<th>Oruanui</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eruption</td>
<td>Aska 1875</td>
<td>Taupo 181 AD</td>
<td>Taupo 181 AD</td>
<td>Taupo 26ka BP</td>
</tr>
<tr>
<td>Volcano</td>
<td>Aska</td>
<td>Taupo</td>
<td>Taupo</td>
<td>Taupo</td>
</tr>
<tr>
<td>Style</td>
<td>sustained</td>
<td>episodic</td>
<td>episodic</td>
<td>episodic</td>
</tr>
<tr>
<td>water source</td>
<td>aquifer?</td>
<td>lake?</td>
<td>lake</td>
<td>lake</td>
</tr>
<tr>
<td>total eruption duration</td>
<td>~ 17 hours</td>
<td>unknown</td>
<td>unknown</td>
<td>unknown</td>
</tr>
<tr>
<td>phreatoplinian duration</td>
<td>~ 1 hour</td>
<td>unknown</td>
<td>unknown</td>
<td>unknown</td>
</tr>
<tr>
<td>total volume of eruption products</td>
<td>1.87 km$^3$</td>
<td>100 km$^3$</td>
<td>100 km$^3$</td>
<td>800 km$^3$</td>
</tr>
<tr>
<td>phreatoplinian volume</td>
<td>0.46 km$^3$</td>
<td>1.75 km$^3$</td>
<td>0.8 km$^3$</td>
<td>500 km$^3$</td>
</tr>
<tr>
<td>dispersal area</td>
<td>$10^3$ km$^2$</td>
<td>$10^3$ km$^2$</td>
<td>$10^3$ km$^2$</td>
<td>$10^6$ km$^2$</td>
</tr>
<tr>
<td>thinning rate ($B_0$)</td>
<td>6.7</td>
<td>4.5 - 5.5</td>
<td>2.9 - 5.0</td>
<td>18 - 148</td>
</tr>
<tr>
<td>limit to proximal exposure</td>
<td>&lt;1 km</td>
<td>~ 4 km</td>
<td>~ 4 km</td>
<td>unknown</td>
</tr>
<tr>
<td>historical records</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
</tbody>
</table>

Table 1 demonstrates the enormous range of physical and temporal attributes amongst the type examples: a) the volumes vary by three orders of magnitude; b) the dispersal varies by three orders of magnitude; c) durations can vary from as little as 1 hour to possibly months (Rotongaio Ash); and d) styles are either sustained or episodic.

The exposure of the 1875 Askja proximal deposits up to 1 km from the inferred vents has also led to two interesting areas of research: 1. The identification of welded fall deposits in unit D and inferences of the welding on eruption styles, number of vents and
vent location. In particular, the welded deposits have contributed greatly to our understanding and generation of a model of conduit and vent dynamics. 2. Enhanced premature sedimentation of particles from the jet and lower convective plume margins, which are currently unaddressed in eruption plume models. There were three major changes in eruption dynamics throughout the 17-hour-long main eruption, including rapid and reversible shifts in eruption style and intensity, fluctuations of the degree of external water interaction, and reversible changes between sustained buoyant plumes and collapsing columns.

The studies of the 1875 eruption presented within this thesis are a significant addition to the general understanding of volcanic process, not only providing unique examples of some eruptive phenomena, but also further developing our understanding of less well understood processes, most notably: a) welding processes of pyroclastic fall deposits; b) pyroclast transport and deposition from wet and dry plumes; c) causes and triggers of pauses, shifts in intensity and eruption style for powerful silicic eruptions; and d) the role of external water in phreatoplinian fragmentation.

1.1.1 Study Objectives

Study objectives are:

a) refining the chronology and timing of the eruption,

b) constraining tephra dispersal and plume dynamics for sustained wet and dry phases,

c) understanding processes of deposition in proximal fall deposits associated with powerful sustained eruptions,

d) defining controls on conduit and vent dynamics throughout the eruption,
Some of the specific issues that this study seeks to explore are:

1. Welded deposits: what processes are responsible for their formation? Where do they fit into the chronology of the main eruption? What does their nature suggest in terms of eruption styles and intensities and the number of associated vents and vent locations?

2. Mechanisms and rates of dispersal of tephra during each phase, as well as reassessment of the deposit volume and area of dispersal. An evaluation has also been made of inferred rates of deposit thinning and calculation of volume models, when proximal or distal data are missing.

3. Further understanding of wet and dry plume processes; transport and deposition of pyroclasts; thinning characteristics; changes in eruptive behavior, especially sustained vs. short-lived periods of instability as well as enhanced proximal accumulation of tephra.

4. The extent to which gradual and abrupt shifts in eruption style and intensity were driven by: a) by changes in the melt in the deep conduit; b) changing melt properties in the shallow conduit; and c) by external factors such as vent position/widening, fluctuating eruption intensities and/or water availability.

5. Relative roles of explosive magma/water interaction versus magma degassing on degree of fragmentation in the phreatoplinian phase.

1.1.2 Approaches

This study is a continuation of the physical volcanology work/research conducted on the 28-29 March 1875 event by Sigvaldason (e.g., 1979, 1982) and Sparks and co-
workers (e.g., Sparks et al., 1981 and references therein). The initial stages of this study included familiarization with the well-constrained stratigraphy initially established by Self and Sparks (1978), and developed further by Sparks et al., (1981). I modified the stratigraphy slightly, dividing the pyroclastic density current unit into three separate flow units, separating the Plinian unit into five separate sub-units, and also establishing the relative timing and stratigraphic position of the welded deposits located in the north of the present-day caldera. Once the proximal stratigraphy of the main eruption was established, I drew stratigraphic logs and measured bed thicknesses, collected both density and grain size samples, and measured largest lithic clasts and pumices at most of the 488 locations visited in the proximal, medial and distal areas. The results of these techniques are presented in a compilation of localities and data in appendices 1 - 13.

1.1.3 Askja volcano

Askja volcano is predominantly a basaltic center with rare powerful, high-intensity silicic eruptions. The general geology and structure of the Askja volcano was first described by Johnstrup (1877a, b) and later by Thoroddesen (1884, 1891, 1925) and then by a series of researchers throughout the 20th century (e.g., Spethmann, 1908, 1913; Reck, 1910; Bárðarson, 1926; Jónsson, 1941, 1942, 1945; Bemmelen and Rutten, 1955; Einarsson, 1962; Thorarinsson and Sigvaldason, 1962; Thorarinsson, 1963; Sigvaldason, 1968; and Rymer and Tryggvason, 1993). The first significant volcanological study of the 1875 eruption was conducted by Thorarinsson (1968) when he attempted to estimate the magma discharge and tephra volume produced by the main 1875 event. Sigurdsson and Sparks (1978a, b) suggested that the events of the Askja Fires 1874-75 comprise an example of a rifting episode characterized by lateral dyke injections from a shallow
magma chamber. Shortly thereafter, Sigvaldason (1979, 1982), Sigurdsson and Sparks (1981), and Macdonald et al., (1987) considered the petrological aspects of the 1875 products in a volcanological context. Studies by Self and Sparks (1978) and Sparks et al., (1981) concentrated on physical volcanological aspects of the eruption. The following is a summary of the nature and setting of this volcano, and a brief history of the eruptive activity related to the 1867 – 1876 volcano-tectonic event culminating in the powerful 1875 eruption – the focus of this study.

1.1.3.1 Geological setting

Askja volcano (also known locally as Dyngjufjöll) is the central volcano of the Askja volcanic system located in the Northern Volcanic Zone (NVZ) in Iceland (Fig. 1). Askja rises to more than 800 meters above its surroundings and hosts three calderas, the youngest of which (Óskjuvatn) formed in 1875 and is nested within the second-oldest, basaltic lava-filled Askja caldera (Fig. 2). Askja volcano was built by predominantly basaltic sub-glacial and sub-aquatic activity forming hyaloclastites and, to lesser extent, interglacial and Holocene (subaerial) basaltic lava flows (e.g., Sigvaldason, 2002 and references therein).
Figure 1: a) Askja volcanic system is located within the northern volcanic zone (NVZ) in Iceland. Box shows location of Figure 1b. b) Geologic setting of the Askja central volcano: Eruptive activity at this center is shown chronologically since 5000 yr BP. The tectonic fabric of the region is shown by the black lines indicating faults and fissures in the area.
Figure 2: Google Earth image of the Askja central volcano region in winter. The 1875 caldera is nested within the older caldera structure (~ 10 ka BP). The geology of the caldera region is divided between basaltic hyaloclastite in the east, and Holocene caldera-filling lavas in the west.
1.1.3.2 Chronology/history

Two powerful explosive silicic eruptions are known from Askja in Holocene times: the 1875 eruption and an earlier event that is not well constrained volumetrically or temporally. The 1867-1876 volcano-tectonic event is thought to be caused by large scale rifting, with earthquake and eruption activity along the Askja fissure system, most notably at Sveinagja and Fjárhólahraun, 40 and 5 km north of Askja, and Holuhraun, situated ~15 km south of the caldera (Sigurdsson 1978a, 1978b; Brandsdóttir, 1992; Sigvaldason et al., 1992; Thordarson et al., in prep). Early precursory deposits prior to the 28th – 29th March eruption include two basaltic phreatomagmatic tuff cones, one dacite lava, a rhyolitic fountain-fed lava and dike, and an obsidian-bearing small dacitic cone (Thordarson et al., in prep). Phreatic and basaltic activity continued after the main eruption into late 1876 (Sigvaldason, 1979; Sparks et al., 1981; Thordarson, unpubl. data). Post 1876, activity included both explosive and extrusive eruptions of basaltic magma in 1921-22, 1929, 1931 and 1961 (Sigvaldason, 1979; Sparks et al., 1981). Deformation data (tilt and GPS) show that Öskjuvatn has been continuously deflating over the last 20 years, and models suggest two Mogi point sources, at 3.0 and 16.2 km depth, thought to represent magma storage zones (Tryggvason, 1989; Sturkell et al., 2006).

1.1.3.3 The 28th – 29th March eruption

The pyroclastics of the Askja 1874-1875 sequence were originally divided into eight units by Self and Sparks (1978) and Sparks et al., (1981). In this scheme the formation of units A, E and F is correlated with weak intensity phreatic hydrothermal activity prior to and following the main phases (Units B, C, D). The current study has
defined five distinct intervals of magmatic activity with different intensities and styles (Fig. 3). The first unit (termed initial ash) is a very fine, white juvenile ash, which has a patchy distribution towards the east up to 10 km from vent, and represents a phase of phreatomagmatic activity prior to the main sustained eruption. It is uncertain whether (but likely that) this phase is temporally related to the main eruption or corresponds to the precursor period of intermittent phreatic, phreatomagmatic and magmatic activity referred to as Unit A by Sparks et al., (1981). The second unit (Unit B) corresponds to the initial phase of the main eruption, which began at 21:00 on the 28th March and lasted for ≥1 hour (Fig. 3). It is a widespread, well sorted, pumiceous subplinian fall (0.003 km$^3$ Dense Rock Equivalent DRE). The transition to the third unit (phreatoplinian unit C1) involved a substantial increase in eruption intensity characterized by sustained phreatomagmatic activity that lasted for 1 hour. Unit C1 (0.13 km$^3$ DRE) is a widespread, poorly sorted, very fine ash fall deposit that extends to Scandinavia. Pyroclastic density currents (unit C2) were produced in the wake of the buoyant phreatoplinian plume. The C2 deposit has a volume of 0.007 km$^3$ (DRE) and consist of three flow units, labeled here the lower (LC2), middle (MC2) and upper (UC2) units (Fig. 3). The C2 sequence became dryer with time. The final eruption unit of the main event is unit D, which is a widespread Plinian fall deposit with a volume of 0.21 km$^3$ (DRE). In the proximal environment it is divided into five distinct sub-units (D1 – D5, Fig. 3). Sub-units D1, D3 and D5 are widespread falls with thinning-half distances ($B_t$) of 3 - 4 km, which form a single layer outside the caldera. D2 and D4 are only dispersed locally, with linear $t_{1/2}$ distances in the range of 10s to 100s meters, or 1 to 2 orders of magnitude less than unit D, and form non-welded, more widespread equivalent to the welded deposits on the northern rim.
Figure 3: The stratigraphy of the main eruption. Phases B, C1, C2 and D are constrained by historical records as eruptive events on the 28th - 29th March 1875. The Initial Ash potentially represents a phreatomagmatic opening to the main eruption. Early and late phases represent precuratory and post-eruption events throughout 1874 - 1875.
The deposit characteristics of D2 and D4 suggest that they were produced by two separate periods of fountaining on multiple linear vents active simultaneously with the main Plinian eruption.

1.1.4 Historical observations

Historical records and drawings have been critical to our understanding of this eruption, the subsurface dynamics of the Askja volcanic system, and Icelandic volcanic systems in general. Of particular interest to this study are the descriptions made of the caldera regions both before and after the main eruption, as well as the timing and duration of tephra fallout from each phase (Appendix 12).

Earthquakes and eruption plume activity triggered the interest of farmers at Myvatn, 65 km north of Askja, which initiated an expedition in February 1875 to the caldera region. The farmers’ descriptions clearly document areas of volcanic activity and their associated products, areas of subsidence, locations and sizes of ponds of water and other landforms/structures observed within the caldera region. These descriptions outlined the morphology of the pre-1875 caldera region with which to compare the observations of the next expeditionary group, which arrived after the eruption in July 1875 (Watts, 1876).

These descriptions of the post-eruption caldera region have been the most rewarding in terms of integration with our physical volcanological data acquired throughout this study (Fig. 4a, 4b, 4c). The descriptions and drawings suggest that the magma was intruded as two elongated cross-cutting dikes along structural weaknesses within the 1875 caldera region.
Figure 4: Sketches of areas within the Askja caldera drawn after the main eruption.

a) Sketch made July 14, 1875 by Watts. This sketch was drawn in the southwest portion of the caldera looking toward the northeast.
b) Sketch drawn by Caroc, 1876. This sketch was drawn whilst in the northwest looking towards the east-southeast.
c) Caroc, 1876. Depression trends towards the southeast.
At the time of the eruption, eastern Iceland was predominantly an agricultural and sheep farming area. Thus the documented reports are derived from the observations of farmers in Eastern Iceland between 60 and 150 km north and east of Askja. The quality of the observations with regard to the eruption timing is remarkable. The following observations were made:

a) the weather at the time of the eruption; wind speed, direction and changes with time,
b) plume height and velocity,
c) type, size, color and duration of tephra fallout,
d) thickness of the final fallout deposits.

People in Scandinavia also experienced ash fall, and without knowing the source of the ash, documented thicknesses, mass per unit area and timing of ash fall (Fig. 5). These observations have facilitated the definition of the far distal field of the 1875 fallout, in addition to constraining the dispersal areas, plume velocity and direction over the Scandinavian landmass.

These observations have been critical to estimates of eruption intensity, durations and eruptive volumes, similarly to the highly explosive eruption of Vesuvius in 79 AD and Etnaean eruptions last millennium (e.g., Sigurdsson et al., 1985; Rosi et al., 1993; Branca and Del Carlo, 2004)

1.1.5 Methodology

Due to the contrasting nature of the studies conducted throughout this PhD period, numerous field and laboratory techniques were employed, which I now describe.

1.1.5.1 Field techniques

At each location, outcrops were cleared, holes were dug to expose the pre-1875
Figure 5: Isochron map drawn by Mohn in 1877. Mohn compiled descriptions of timing of tephra fall in Scandinavia resulting in a documentation of the dispersal of the ash plume as it travelled over the Scandinavian landmass.
surface and to permit good photography. Photographs were taken at every location for reference. In addition, stratigraphic logs were drawn. The welding study necessitated outcrop-scale sketches and focused sketches of particular areas of interest.

1.1.5.2 Maximum bomb measurements

The welding study required measurement of the distribution and size of the largest pyroclastic bombs that were ejected during episode D4. Lateral transects were made every 100 meters outboard of the northern caldera rim. On every E–W transect at regular intervals of 100 m, I measured the x, y and z axes of the largest bomb within a 20 x 20 m area. Such a large area was required due to the large diameters (> 10 m) of most of these bombs. The z axes were most difficult to measure accurately, as the lower surface of the bomb could not be observed. However some bombs had cracked on impact and it was then possible to measure to the base. Observations of cross sections of bombs on the caldera rim where the base was exposed showed that most bombs were pancake-shaped (i.e., low aspect ratio).

1.1.5.3 Grain size and componentry measurements

Grain size samples were collected from each fall deposit at most locations where sampling was possible. At least one representative sample was taken from each major unit. Sampling was initiated around the largest visible clast, which was extracted first. The weight of this coarsest clast was measured, and used to determine an appropriate size for a representative sample (<5 wt.%). All units were sieved and weighed in the field down to –4 φ (16 mm), and a representative split of the <16 mm fraction then taken to the laboratory for further analysis. Componentry was conducted on 1 sample from each
of the fall and pyroclastic density current sub-units to document and quantify the types of lithic components within each deposit.

1.1.5.4 Thickness/volume/intensity calculations

Isopach maps were constructed for the units B, C and D deposits and the thicknesses of the pyroclastic surge (C2) sub-units were also collected in the proximal environment. Volume and mass flux calculations were derived using both the thickness data and historical records. Maximum pumice and maximum lithic measurements were also taken for the fall deposits, derived by measuring the x, y and z axes of the five largest clasts. For subplinian and phreatoplinian deposits, an area of 1 x 1 meter was sampled to collect the largest clasts. Difficulties arose due to the fragile nature of the phreatoplinian/subplinian pumices, in addition to the lack of coarse (> ash size) phreatoplinian pumices. These data were used to construct isopleth maps, which were used for calculations of eruption column heights.

1.1.5.5 Density samples

At two proximal sections, ten samples were collected throughout the sub-units of the main eruption each containing at least 100 pumice clasts in the 16 to 32 mm size range. One sample was collected from the subplinian B deposits, two samples from the upper and lower phreatoplinian deposits, three samples from the pyroclastic density current deposits (1 from each flow unit) and six samples (D1, D2, lower D3, upper D3, D4 and D5) from the Plinian deposits. The bulk densities of these pumice clasts were measured using the techniques of Houghton and Wilson (1989) and converted to vesicularities using an average measured bulk density of 2350 kg m$^{-3}$. For the welding study, small pieces of rock were extracted using a hammer and a chisel. Care was taken
to get samples from restricted areas, because of the rapid nature of changes in welding intensity and density extending outward from the area of interest.

1.1.5.6 Studies of vesicles

From the distribution of densities per sample (plotted on histograms), I selected five to ten pumice clasts from each sample to represent the mode and low/high vesicularity tails. An image was collected from each by scanning the thin sections on a Hewlett-Packard flatbed scanner at 1200 dpi resolution (4.5x magnification), in order to collect the size data for the largest vesicles (2-5 mm). Eighteen backscatter electron images from each clast were taken on a JEOL-5900LV scanning electron microscope operating at a 20 kV accelerating voltage and 1 nA beam current. These images were processed to represent the vesicle size distributions (VSD), and the heterogeneities of the VSD at different scales (25x, 100x, 250x, 500x). Two-dimensional size distributions (Number per area, \( N_A \)) were then converted to volume distributions (number per volume, \( N_v \)) using the stereological conversion method of Sahagian and Proussevitch (1998). Vesicle number densities were also recalculated with reference to the melt volume (\( N_{m,v} \)) to avoid underestimating number densities of highly vesicular samples (after Klug et al., 2002). The Askja pumices have < 0.5% phenocrysts in them and no microlites (Sigurdsson and Sparks, 1978a, b), and thus their phenocryst abundances and size distributions were assumed to be negligible.

1.1.6 Structure of dissertation

This dissertation contains six chapters, four of which were written as papers for scientific journals. Each study presented within these latter chapters was designed to answer some of the key questions outlined at the beginning of this thesis. They
encompass three separate topics: tephra dispersal, eruption and plume dynamics; vesiculation and conduit dynamics; and welding processes and inferences for eruption dynamics (Fig. 6).

Chapter Two was divided into two separate papers and both will be submitted shortly to the Bulletin of Volcanology. The first paper presents deposit and dispersal characteristics of each fall unit and uses these data to constrain eruption intensity and volumes of each eruptive phase. Deposit characteristics and volumes were also calculated for the C2 pyroclastic density currents. Historical reports have also helped considerably in identifying eruptive phase duration and therefore intensity. This chapter also includes sections that test deposit-thinning models used to estimate volume when proximal or distal data are missing. The second paper in Chapter Two considers plume dynamics during wet and dry eruption styles that consequently led to enhanced proximal sedimentation and over-thickened proximal deposits.

Chapter Three will also be submitted shortly to the Journal of Volcanology and Geothermal Research. It is a study of the vesiculation of the magma erupted during the four phases of activity associated with the 28th – 29th March 1875 eruption. In particular, this chapter seeks to identify factors that control reversible shifts between ‘wet’ (phreatoplinian) and ‘dry’ (subplinian, Plinian) eruption processes, in addition to shifts between buoyant plume and collapsing column conditions. Are these shifts then related to processes in the shallow conduit, to external factors such as vent migration and widening, and/or the interaction of external water?

Chapters Four and Five are published in the Journal of Volcanology and Geothermal Research and describe in detail the welded deposits on the northern rim of the 1875 Askja
The welded deposits are located in the general stratigraphy. Two different processes of welding are identified and major implications for eruption dynamics, number of vents, vent configuration, and conduit dynamics throughout the Plinian phase are discussed.

Finally, Chapter 6 summarizes the main conclusions from these studies and presents some suggestions for areas requiring further work.

1.2 Background to techniques and concepts used within this study

1.2.1 Classification of explosive eruptions

Historically, most explosive eruptions around the world either were not observed or are poorly constrained by eyewitness accounts, which necessitates quantitative approaches based on measurable parameters linked to eruption products to describe and classify different types of eruptions. Initially Walker (1973) approached this task based on the deposit characteristics, dispersal (D, a proxy for intensity) and fragmentation index (F, a proxy for fragmentation efficiency). D is obtained by calculating the area over which a deposit thins to 0.01 of its thickness maximum; F is calculated as the percentage of a deposit finer than 1 mm at the point on the axis of dispersal where it crosses the 0.1 T_{max} (maximum thickness) isopach. Based on these parameters, Hawaiian, Strombolian, Surtseyan and Plinian styles were proposed, but subsequently more fields have been added to encompass the range of natural eruption styles (e.g., subplinian, phreatoplinian, Vulcanian, ultraplinian). More recently Pyle (1989) suggested two further approaches; the pyroclast half distance (B_c), defined as the radial distance at which the maximum clast diameter decreases by half, and the thickness half distance (B_t), which is the distance over
Figure 6: Cartoon illustrating the areas of research encompassed within this dissertation project. Chapter 2 is a study of plume dynamics, particle transport and eruption dynamics. Chapter 3 is a study of the vesiculation and conduit dynamics throughout the eruption. Chapters 4 and 5 are focused on the proximal welded deposits and the inferences for eruption dynamics.
which the deposit thickness halves.

1.2.1.1 Subplinian, phreatoplinian and Plinian eruptions

Highly explosive sustained eruptions are generally associated with high viscosity silicic magmas. However, rare examples exist of basaltic composition (e.g., Tarawera Plinian 1886 (Sable et al., 2006, Sable et al., in review); Etna Plinian 122 BC, Etna 2001 and 2002 subplinian events (Taddeucci et al., 2004 a,b; Andronico et al., 2005); Saksunarvatn 10300 BP,vatnaoldur 870 AD, and Viedivötn 1477 AD phreatoplinian events (Johannesdóttir et al., 2005; Larsen 2005). These types of eruptions generate buoyant convective plumes and widespread fall deposits with typical thinning half distances \( B_1 \) of kilometers (Pyle, 1989; Cioni et al., 2000). Mass discharge rates from \( 10^5 \) to \( 10^8 \) kgs\(^{-1}\) overlap between styles (Houghton and Gonnermann 2008). These eruptions show sustained and/or episodic behavior, and higher intensity or wet eruptions typically have periods of partial or total column collapse, producing pyroclastic flows or surges (Cioni et al., 2000; Wilson and Houghton 2000).

1.2.2.2 Summary of the other three 'type' phreatoplinian eruptions

The addition of the term 'phreatoplinian' to Walker's classification was based on four 'type' eruptions: Askja 1875 unit C1; Rotongaio and Hatepe ashes, 181 Taupo eruption; and the Oruanui tephra, 26 ka eruption of Taupo volcano (Self and Sparks, 1978). Although these eruptions are all 'phreatoplinian' in terms of the classification, these eruptions have extremely variable characteristics (e.g., volume, intensity durations, etc.). Here I describe briefly the three other 'type' phreatoplinian eruptions.

*Hatepe and Rotongaio ashes — Taupo 181 AD eruption*
The Hatepe and Rotongaio ashes are units 3 and 4 of the 181 Taupo eruption (Houghton et al., 1995). These are poorly sorted, very fine-grained deposits, and are both finely bedded (Smith, 1998). Both deposits show evidence of syn-eruptive formation of proximal dilute density currents, wet fall deposition and, in the case of the Rotongaio ash, syn-eruptive reworking of the deposits. The durations estimated for these phases are long, ranging from hours to days (Hatepe) and days to weeks (Rotongaio) (Smith unpub. thesis, 1998). The volumes calculated for the Hatepe and Rotongaio ashes are 1.75 and 0.8 km$^3$, and estimated intensities are $10^6$ and $10^5$ kgs$^{-1}$, respectively.

The interaction of magma with surface water from the early Lake Taupo was the source of external water throughout these phases (Smith, unpub. thesis, 1998). Textural analysis of the Hatepe phreatoplinian pumices suggest that the magma had already passed the peak of vesiculation prior to the interaction of magma and water (Houghton et al., 2003). The Rotongaio ash has a modal vesicularity and range much greater than the Hatepe phreatoplinian pumices and, taken together with textural analyses of bubble populations, suggests that the Rotongaio magma was significantly outgassed prior to the interaction of magma and water (Houghton et al., 2003).

*Oruanui 26 ka eruption – Taupo volcano*

The third example also comes from the Taupo volcano, however it was an order of magnitude more voluminous, producing ~ 500 km$^3$ of fall deposits and ~ 300 km$^3$ of ignimbrite (Wilson, 2001). These deposits are also fine-grained, with erosional breaks representing time breaks between phases. Phase durations estimated by Wilson (2001) range between weeks to months. A pre-existing Lake Taupo was also the source of water
throughout this highly explosive, long-lived eruption. No textural analyses of the pumices have been conducted at this time.

### 1.2.3 Magma ascent and explosive fragmentation

Explosive eruptions are powerful phenomena that have the potential to be very destructive, especially in settings near large population centers. In addition, volcanoes that exhibit shifts in eruption style throughout a single eruption are difficult to manage from a hazards perspective. For example, determining whether a volcano will produce a buoyant or collapsing column is critical, as the products will have different emplacement mechanisms, distributions from source, and therefore constitute different hazards. Two mechanisms can generate explosive eruptions: magmatic eruptions driven solely by the exsolution of magmatic volatiles, and phreatomagmatic eruptions, which are a result of magma/water interaction (e.g., Cas and Wright 1987). Here I discuss the requirements for powerful subplinian, phreatoplinian and Plinian eruptions.

#### 1.2.3.1 Changes in magma during conduit ascent

Factors that affect magma ascent and fragmentation include the intrinsic properties of the magma; pre- and syn-eruptive volatile contents, temperature, phenocryst content, melt composition, density and viscosity (e.g., Wallace et al., 1995; Costa, 2005; Pinkerton and Stevenson, 1992; Hess and Dingwell, 1996; Manga et al., 1998; Stevenson and Blake, 1998; Papale et al., 1998); in addition to aspects of flow behavior in the conduit (e.g., Jaupart, 1996; Papale et al., 1998; Denlinger and Hoblitt, 1999); and external influences such as conduit and vent dimensions and confining pressure etc. (e.g., Wilson and Sparks, 1978; Wilson, 1980; Sheridan and Wohletz, 1983; Barberi et al., 1989; Bertagnini et al., 1991).
**Volatile supersaturation and bubble nucleation**

Volatile contents of melts are highly dependant on pressure, and temperature to a lesser degree, (Blank et al., 1993; Mysen, 1977). In the magma storage region the most dominant species is water, with lesser amounts of CO$_2$ (Johnson et al., 1994; Wallace et al., 1995). The solubility of these species decreases with decreasing pressure, as the magma rises and hence volatiles will exsolve at some degree of supersaturation during ascent-driven decompression (e.g., Toramaru, 1990). Varying degrees of melt supersaturation will arise, depending upon the ascent rate, and the nature and abundance of the volatile species (Hurwitz and Navon, 1994; Mangan and Sisson, 2000; Gardner et al., 1999). Whether bubble nucleation occurs in equilibrium or disequilibrium manner will be a function of the inherent properties of the melt (i.e., availability of nucleation sites, volatile content, etc.), and the supersaturation pressure ($\Delta P$, the difference between the pressure at which dissolved volatiles are in equilibrium in the melt and the actual pressure of the supersaturated melt, e.g., Mangan and Sisson, 2000; Mourtada-Bonnefoi and Laporte, 2004). With rapid ascent, if the melt cannot nucleate and diffuse volatiles into bubbles at rates sufficient to keep the dissolved gas content equal to its equilibrium value, then high degrees of supersaturation will occur, bubbles will nucleate at high $\Delta P$ and result in a rapid change in magma properties (e.g., buoyancy, increase in viscosity, etc.), and degassing will be in a high degree of disequilibrium (Lyakhovsky et al., 1996; Mangan and Sisson, 2000; Mangan et al., 2004b; Gonnerman and Manga, 2005; Kaminski and Jaupart, 1997; Proussevitch et al., 1993). In contrast, if the rate of decrease in volatile solubility is equal to rate of decompression during ascent, then bubbles can nucleate and grow over an extended depth interval and the degassing system will remain
in equilibrium (Mangan and Sisson, 2000). A melt can switch between equilibrium and
disequilibrium degassing behavior in a response to abrupt changes of pressure, e.g., a
sudden decompression event (Lyakhovsky et al., 1996).

Classical nucleation theory predicts that the bubble nucleation rate will have a
very strong dependence on the supersaturation pressure (Hirth et al., 1970). The critical
supersaturation pressure required to trigger bubble nucleation is a function of melt
viscosity, volatile diffusivity and availability of nucleation sites. Experimentally,
supersaturations have been determined for different sets of conditions for rhyolitic melts,
leading to either homogeneous or heterogeneous nucleation. Homogeneous nucleation
occurs in the absence of preferred nucleation sites or at high rates of decompression
(Mangan and Sisson, 2000; Gardner et al., 1999). The supersaturation pressures required
for homogeneous nucleation in a phenocryst-poor rhyolite magma is $\Delta P > 120 - 150$
MPa, equivalent to approximately twice the equilibrium water concentration. Very high
decompression rates (0.25 – 1 MPa s$^{-1}$) are also necessary to achieve this supersaturation
pressure (Gardner et al., 1999). Experimentally-derived nucleation rates in rhyolite
magmas for $\Delta P = 120$ MPa are < 1 cm$^3$ s$^{-1}$; for $\Delta P = 130 - 150$ MPa are $10^3$ to $10^5$ cm$^3$ s$^{-1}$;
and for $\Delta P 160 – 175$ MPa are $10^6$ cm$^3$ s$^{-1}$ (Mangan and Sisson, 2000). Experimentally,
homogeneous nucleation triggered at high values of supersaturation ($\Delta P >120$ MPa)
results in bubble number densities of $10^7$ to $10^9$ cm$^{-3}$ (Mourtada-Bonnefoi and Laporte,
1999; Mangan and Sisson, 2000; Mangan et al., 2004a).

Heterogeneous nucleation occurs in the presence of nucleation sites, (e.g.,
microlites and phenocrysts), and occurs at lower values of supersaturation due to the
lower activation energy required (Sparks, 1994). Experimentally, heterogeneous
nucleation leads to equilibrium degassing, and bubble number densities of $10^5$ to $10^8$ cm$^{-3}$ are common (Hurwitz and Navon, 1994; Gardner et al., 1999).

**Bubble growth**

Once bubbles nucleate, the initial growth process will be the active diffusion of further volatile molecules into bubbles (Thomas et al., 1994; Lensky et al., 2004). The rate of diffusive bubble growth depends on volatile content, melt viscosity, diffusivity and decompression rate (e.g., Sparks, 1978; Lensky et al., 2004). Diffusion initially dominates expansion due to decompression and remains so for the majority of the ascent. However decompressive growth becomes increasingly important at shallower levels (e.g., Sparks, 1978).

**Bubble coalescence**

Analyses of pumice textures show very obvious signs that bubble coalescence is an important process during magma ascent, particularly in the shallow conduit when bubbles are close-packed, and ascent velocities and deformation rates are high (e.g., Klug et al., 1994; Cashman and Mangan, 1994). In silicic systems, coalescence is due to the thinning and rupturing of adjacent bubble walls (Cashman and Mangan, 1994). Bubble coalescence serves to reduce the number density of bubbles observed in textural analyses of pumice clasts. However, it is possible in studies of vesicularity to judge degrees of coalescence by bubble size, shape, spatial distribution/habit and wall thickness (e.g., Adams et al., 2006; Sparks, 1978).

**Outgassing**

Outgassing, the removal of bubble populations, is common for both silicic and basaltic systems, and occurs during degassing and magma ascent in all eruptions.
regardless of style, intensity or composition (e.g., Sparks, 2003). Gas escape relies on either buoyant rise of bubbles through a slower ascending or stagnant melt, or on the development of permeability. Experimental work on silicic magmas has suggested that the onset of permeability occurs at > 30% vesicularity, however for basaltic melts can begin as high as 70% given the right magma properties and ascent conditions (Klug and Cashman, 1994; Namiki and Manga, 2008). Permeability is highly dependant on magma ascent rate, and its ability to keep pace with degassing/ascent will control the extent of fragmentation and, thus, the product formed (ash vs. pumice) (Klug and Cashman, 1994).

1.2.3.2 Influence of changing external conditions

The final stages of magma ascent in the shallow conduit and eruption from the vent can also greatly affect the ensuing style and intensity of eruption (e.g., Wilson et al., 1980; Papale, 1999a; Jaupart, 1996; Sheridan and Wohletz, 1983, Barberi et al., 1989, Bertagnini et al., 1991). The most important factors are the decreasing rate of lithostatic pressure, geometry and changing dimensions of the shallow conduit and vent (e.g., Wilson et al., 1980), and the potential for interaction of the rising magma with a water source (Wohletz, 1986; Kokelaar, 1986; Büttner and Zimanowski, 1998; White and Houghton, 2000; Triglia et al., 2006).

Vent widening is common for large sustained eruptions, resulting in an increase in the mass discharge rate, but decrease in the exit velocity of the gas-particle mixture which is critical to buoyant plume development (e.g., Wilson et al., 1978). The interaction of external water with a vesiculating magma or hot fragmented gas-pyroclast mixture has a widely variable effect on eruption dynamics as outlined in section 1.2.3.4. The critical factor is the water:magma ratio and subsequently the density of the mixture.
as it exits the vent into the atmosphere (e.g., Wohletz, 1983, 1986). Shifts in this ratio can lead to dramatic changes in the eruption style, intensity, plume development and pyroclast transport (e.g., Koyaguchi and Woods, 1996).

1.2.3.3 Magma ascent and fragmentation during subplinian and Plinian eruptions

The necessary condition for sustained eruptions is that the system remains closed during degassing, i.e., the gas phase remains mechanically coupled to the magma (Sparks, 1978; Cioni et al., 2000; Cashman et al., 2000; Jaupart, 1996). The rapidly expanding mixture then accelerates upward as bubble overpressure increases (Melnek, 2000; Jaupart, 1996). To drive exit velocities of 100 – 400 m s⁻¹, typical of subplinian and Plinian eruptions, continued nucleation and coupled bubble growth are necessary precursors (e.g., Sparks, 1978; Papale, 1998). Fragmentation is assumed to occur when the volume fraction of bubbles reaches a threshold (typically 0.75, e.g., Sparks, 1978; Cashman et al., 2000), when the bubble overpressure is sufficiently large to rupture bubble walls (McBirney and Murase, 1970; Alidibirov, 1994; Zhang, 1999) by exceeding the tensile strength of the surrounding melt, or when the strain rate exceeds the structural relaxation rate of the magma, driving the melt through the brittle-ductile transition (Webb and Dingwell, 1990; Dingwell, 1996; Papale, 1999b).

1.2.3.4 Magma ascent and fragmentation in phreatomagmatic eruptions

Phreatomagmatic eruptions are driven by magma ascent through, and interaction with, an external water source (Morrissey et al., 2000; White and Houghton, 2000). The eruption style and intensity are affected by the thermal and physical states of both magma and water, in addition to the external environment in which the interaction takes place (Barberi et al., 1989; Bertagnini et al., 1991; White and Houghton, 2000). Thus, a
spectrum of phreatomagmatic eruption styles and intensities have been both observed and inferred from deposits.

Intrinsic properties of the magma include its temperature, viscosity, dissolved and exsolved volatile content and crystallinity, while the temperature, pressure and physical state of the water and its availability are important hydrological factors (e.g., Büttner and Zomanowski, 1998; White and Houghton, 2000; Morrissey et al., 2000). External water sources include groundwater at depth, seawater, geothermal fluid, crater lakes or snow/ice. Thus, the depth and environment of the interaction can vary from the surface to considerable depth (i.e., pressure) in the case of seawater and groundwater. The water:magma ratio is very important to the thermal efficiency of the interaction and the extent of fragmentation (e.g., Wohletz, 1983, 1986; Zimanowski et al., 1991; White, 1996; Büttner and Zimanowski, 1998). The thermal energy of the magma is transformed to mechanical energy resulting in high degrees of fragmentation and considerable kinetic energy with respect to magmatic fragmentation (e.g., Wohletz, 1983, 1986; Zimanowski et al., 1991). The greater the efficiency of mixing, the more mechanical energy is generated and the degree of fragmentation increases. Because the interaction can occur in the shallow conduit or vent region, deep magma ascent processes are likely to be similar to magmatic eruptions.

1.2.3.5 Changes in eruption style

Changes in eruption style and intensity can occur within minutes, hours, weeks or months and can be a result of changes in the factors relating to the magma supply at depth, changes in conduit flow regimes or variations in external factors, such as vent geometry, access of external water or water availability (e.g., Wilson, et al., 1978;
Wohletz, 1983; Sheridan and Wohletz, 1983; Pinkerton and Stevenson 1992; Hess and Dingwell, 1996; Papale et al., 1998; Manga et al., 1998; Stevenson et al., 1998; Denlinger and Hoblitt, 1999). Many eruptions involve shifts of eruption style and intensity. For Most typical are: a) a phreatomagmatic onset to the eruption, which is then followed by a magmatic phase (e.g., Vesuvius, 79AD); and b) a shift from a buoyant to collapsing column at the end of the eruption (e.g., Taupo 181AD). However, reversible shifts between phreatomagmatic/magmatic and buoyant/collapsing columns throughout an eruption remain poorly understood. Changing conditions within the magma chamber, the conduit and the vent will collectively influence the eruption dynamics and feedback mechanisms commonly exist between these processes such as coalescence.

1.2.4 Pyroclast transport and deposition

1.2.4.1 Plume transport

Strong eruption plumes are separated into three regions depending upon the particle transport regime (Fig. 7). When the hot gas-particle mixture exits the vent it is decompression-driven with a high vertical momentum upward at velocities commonly 100 – 400 m s\(^{-1}\) (Cioni et al., 2000; Sparks, 1986). This high-velocity injection into the atmosphere disturbs it in such a way that large turbulent eddies form on the jet margins, which allow the mixture to entrain and heat ambient air (e.g., Bursik et al., 1992; Sparks et al., 1997 and references therein). During this initial decompression-driven ascent (100 m – 4 km) it is critical that the jet entrains enough air such that the density of the mixture becomes less than that of the ambient atmosphere to form the buoyancy-driven convective column region of the plume (Bursik et al., 1992; Ernst et al., 1996). This region can extend into either or both the troposphere and stratosphere depending on
eruption conditions. At the point where the density of the plume equals the density of the atmosphere, the plume will begin to spread and form an umbrella cloud in directions dictated by the atmospheric conditions (Sparks et al., 1997 and references therein).

Models of the umbrella cloud region of dry eruption plumes have been long established and recent studies have begun to consider multiple particle sedimentation regimes operating at different levels within the convecting and jet regions of the plume (Neri et al., 2003; di Muro, 2004; Neri et al., 2007). Models of plume formation, particle transport and sedimentation in wet eruptions, however, are less fully understood, with only limited models described in the literature (e.g., Woods, 1993; Koyaguchi and Woods, 1996). This is due in part to the lack of historic phreatomagmatic eruptions, in particular large, intense eruptions, and hence the wet spectrum of eruption, transport and depositional processes remain poorly understood.

Plumes associated with large magmatic eruptions

As the hot gas-pyroclast mixture exits the vent, the main mass of the plume expands and becomes buoyant, and the transport mode changes from a jet with momentum to a buoyancy-driven convective column. The buoyancy of the mixture depends on the exit velocity, temperature of the ascending suspension and the efficiency of heat transfer from the hot gas and particles to the entrained air (Woods, 1988; Wilson et al., 1978). Within the umbrella cloud, the size, density, and shape of a clast will determine its terminal velocity, which will control how far it will be carried prior to its release (Bonadonna and Phillips, 2003; Sparks et al., 1997 and references therein).
Figure 7: Schematic cartoon of a typical Plinian plume. Decompression-driven ascent after fragmentation drives the upward momentum of the gas-pyroclast mixture in the jet. The entrainment and heating of air is critical to the buoyancy of the plume. If the density of the plume becomes less than that of the ambient atmosphere, the plume will become buoyant. Collapsing column conditions will prevail if the density criteria is not met. The convective column region will extend up to the point of neutral buoyancy, where it will spread laterally as a gravity current, according to the wind conditions. Diagram modified after Cioni et al. 2000.
Plumes associated with large phreatomagmatic eruptions

Numerical models of phreatoplinian or wet eruption plumes are not well-constrained due to the complexity in the nature and timing of the interaction of magma and water, uncertainties associated with establishing the water:magma ratio and its fluctuations with time, as well as the state of the water at the time of the interaction and during plume transport (Woods, 1993; Koyaguchi and Woods, 1996; Triglia et al., 2006). Studies conducted by Koyaguchi and Woods (1996), and Woods (1993) have shown that magma-water interaction affects plume dynamics dramatically, but varies depending on the water:magma ratio and the resulting density and temperature of the pyroclastic mixture (Koyaguchi and Woods, 1996).

Specific conditions with respect to the physical state of both the magma and water have to be met to result in buoyancy of wet eruption plumes. When hot magma, hot exsolved gases and cold water mix and explosively fragment the melt, the temperature of the magmatic phases significantly decreases, as some or all of the water vaporizes, increasing the volumetric abundance of gas in the resulting mixture (e.g., Morrissey et al., 2000; White and Houghton, 2000). For thermally efficient magma-water interaction, the volumetric expansion of the external water into vapor during explosive fragmentation will rapidly lower the density of the erupted mixture and increase the potential for buoyant rise (Koyaguchi and Woods, 1996).

Early plume models postulated that small quantities of water (<15% by mass) have only a minor effect upon plume dynamics (Woods, 1993). Later models suggest that if the mass of incorporated surface water is small (<10 %) then the density and temperature of the erupting mixture decreases and the minimum exit velocity for which a
buoyant plume can develop decreases (Koyaguchi and Woods, 1996). Experimental modeling of the interaction of a hot, fragmented gas-particulate mixture with external water, and the resultant secondary fragmentation have not been documented in the literature.

_Sedimentation from the jet and lower convective column margins_

Currently eruption plume models do not account well for sedimentation from the lower convective column margins and jet region of plumes (excluding ballistics). Existing models of the jet region associated with sustained high intensity eruptions show turbulent eddies at the margins, which thereby allows entrainment of air and sedimentation of large particles (Ernst et al., 1996; Sparks et al., 1997 and references therein). In these models finer clasts are re-entrained by the margins of the rising plume. However, studies of proximal deposits at Novarupta and Tarawera (Fierstein et al., 1997; Houghton et al., 2004 and Sable et al., 2006), and as a result of this study, the 1875 fall units have provided qualitative observations of rapidly-thinning near-source deposits, and used quantitative data such as thinning rates as verification of the existence of different sedimentation regimes for clasts that do not enter the upper portions of the convective plume. Thus, a small fraction of the total mass of clasts sediment from the gas thrust region and lower margins of the convective plume. Descriptions of two recent sub-Plinian eruptions (Asama 1783 and Oshima 1986) suggest that the deposits also have a region of proximal over-thickening (e.g., Sumner, 1998; Yasui and Koyaguchi, 1998).

Although quantitative models have not been developed for sedimentation from the lower convective column and plume margins, conceptual models have been described
based upon observations of these regions (Clarke et al., 2002) and the deposit characteristics (e.g., Sable et al., 2006, Houghton et al., 2004). The conceptual model developed for the 1912 Novarupta ejecta ring and 1886 Tarawera proximal deposits assumes a curved velocity profile of magma ascending in the conduit, which is extended into the jet, such that the particles at the sides of the jet have less momentum, and sediment prematurely from the margins of the jet (Fierstein et al., 1997; Houghton et al., 2004; Sable et al., 2006). In contrast, during the Oshima 1986 and Asama 1783 eruptions, proximal over-thickening is thought to be due to sedimentation from both the high plume and from lower elevations on the margins of the column (e.g., Sumner, 1998; Yasui and Koyaguchi, 1998).

Enhanced proximal sedimentation during wet eruptions has not been observed and due to the lack of documentation for over-thickened proximal deposits of these eruptions, conceptual or quantitative models have not been developed. Models of wet eruption plumes (Koyaguchi and Woods, 1993) have emphasized the delicate balance between buoyant plume formation versus collapse, for eruptions involving water. The likely higher density of the erupting mixture in addition to the velocity profile and thus inherent instability of wet plumes would favor enhanced sedimentation proximal to vent.

1.2.4.2 Lateral transport in the context of Plinian and phreatoplinian volcanism.

Pyroclastic density currents are a common product of both small and large scale eruptions and can be produced simultaneously with a sustained buoyant plume via partial collapse (e.g., Phase C1, Askja 1875; Taupo Plinian, Wilson and Walker, 1984), or as a result of total column collapse following changing conditions in the magma chamber, conduit or vent (e.g., Phase C2 Askja 1875; Pinatubo 1991, Rosi et al., 2001).
The production of volumetrically minor pyroclastic density currents forming synchronously with Plinian activity has been well documented for large eruptions (>10^8 kg s^-1) and believed to be a result of slight fluctuations in eruption intensity coupled with instabilities of the plume margins (e.g., Taupo 181 AD, Wilson and Walker, 1984; Vesuvius 79AD, Sigurdsson et al., 1985, Cioni et al., 1992). Pyroclastic density current phases are also very common at the end of an eruption, as a response to changing magmatic or external conditions, such as depletion of magmatic volatiles (Wilson, 1980), or vent widening (Wilson et al., 1980).

In phreatomagmatic eruptions, pyroclastic density currents are fairly ubiquitous due to the increased density of the water-rich eruption mixture, as well as, temporal and cross-conduit heterogeneities of the mixture of liquid water, steam and particles, which result in unstable column conditions. Although common, there is extreme diversity in the characteristics of density currents produced during phreatomagmatic eruptions. For example, the Rotongaio and Hatepe phreatoplinian phases produced dilute density currents synchronously with fall deposits (Smith, unpub. thesis, 1998), and during the Oruanui eruption, large volume high particle concentration flows were erupted both synchronously with, and separately from, fall deposits (Wilson, 2001). The Askja 1875 pyroclastic density currents are pyroclastic surges, which are radially-distributed basal, turbulent, low concentration particulate mixtures of ash, pumice, lithics, gas, steam and/or liquid water. Base surges produced historically have been both hot and cold (e.g., Taal 1865; Moore, 1967; Ukinrek maars 1977; Self et al., 1980), depending upon the water-magma mass ratio.
1.2.5 Welding

1.2.5.1 Welding in pyroclastic rocks

The descriptions in the literature of welding in pyroclastic deposits have mostly been related to welding of pyroclastic flow or ignimbrite deposits. The welding processes for welded flow, and welded fall and spatter deposits are different due to the inherent characteristics of the eruption and transport systems, including for example, temperature, grain size, and the emplacement mechanism. Welded fall deposits appear to be rare, as few examples are documented in the scientific literature (e.g., Sparks and Wright, 1979; Wolff and Wright, 1981; Turbeville, 1992). However, welded fall deposits are common products of many modern volcanoes where proximal regions are preserved and cover a wide range of magma compositions; including peralkaline (e.g., Pantelleria, Stevenson et al., 1997; Mayor Island, Stevenson et al., 1993); basaltic (e.g., Karhunen, 1988; Calderone et al., 1990) and silicic (Sparks and Wright, 1979; Duffield, 1987; Hackett and Houghton, 1985).

1.2.5.2 Process of welding in pyroclastic fall deposits

A definition of welding often used in the scientific literature is as follows; the sintering together of hot, glassy pyroclastic fragments and their flattening under compactional load at temperatures above the glass transition temperature (e.g., Smith, 1961; Cas and Wright, 1987; Quane and Russell, 2005). Welding in fall deposits is the cumulative influence of a) the inherent properties of the magma; melt viscosity and yield strength (which are dependant on temperature and composition); b) parameters pertaining to the eruption style (e.g., fountaining), emplacement temperature and accumulation rate; and c) topographic slope, load pressure and wall-rock lithic clast content. The welding
process reflects the accumulation of hot, plastic pyroclasts, which form layers of agglutinated to incipiently welded pyroclasts. Welding intensifies with higher accumulation rates, greater compactional loads and the influence of topographic slope, which will incur changes in the physical state of the pyroclasts, such as plastic flattening and deformation. Changes in physical properties such as a reduction of primary porosity and increases in density accompany welding and have been used as quantitative measures of welding intensity (e.g., Quane and Russell, 2005).

The key factors promoting welding of fall deposits have been discussed in the scientific literature, but have been not uniformly agreed upon by authors. Sparks and Wright (1979) and Head and Wilson (1989) have suggested that accumulation rate is the critical factor, through covering and insulating clasts quickly and hence slowing cooling rates. However, Head and Wilson (1989) also highlight that clast temperature on landing is another important factor, which is a function of both clast size and flight time. Thomas and Sparks (1992) postulate that grain size is the most important factor in facilitating welding based on their numerical modeling of clast cooling times. Recently Capaccioni and Cuccioli (2005) modeled cooling rates of particles during ballistic transport and deposition and also proposed that grain size is a critical factor in promoting welding or agglutination. Quane and Russell (2005) promote deposit thickness as a key factor, as it increases load pressure and slows heat loss.
CHAPTER 2
Tephra dispersal, eruption and plume dynamics of
wet and dry phases of the 1875 eruption of Askja Volcano

Abstract
The 1875 rhyolitic eruption of Askja volcano was the most powerful silicic eruption to have been well-documented in Iceland. Eye-witness chronologies coupled with examination of very proximal exposures and historical records of distal deposit thickness data provides an unparalleled opportunity for study of Plinian and phreatoplinian eruption and plume dynamics. The ~17 hour-long main eruption was characterized by abrupt and reversible shifts in eruption style; e.g., from 'wet' to 'dry' eruption conditions and transitions from fall to flow activity. The onset of the main eruption began with a 'dry' subplinian phase (B), followed by a shift to a very powerful phreatoplinian 'wet' eruptive phase (C1). A shift from sustained 'wet' activity to the formation of 'wet' pyroclastic density currents followed, the C2 pyroclastic density currents becoming dryer with time. Severe ground shaking accompanying a migration in vent position and the onset of the highly intense 'dry' Plinian phase (D). Each of the fall units can be modeled using the segmented exponential thinning method (Bonadonna et al., 1998), and three to five segments have been recognized on a semilog plot of thickness vs. area$^{1/2}$. Very proximal deposits (> 1 km from vent) of the B and C1 phases have facilitated the identification of a new very steep proximal segment, termed Seg-1, which we infer to represent particles sedimenting principally from the jet and lower margins of the convective column. The availability of very proximal and far-distal thickness data in addition to detailed
observations taken during this eruption has also enabled very accurate calculations of eruption parameters such as volumes, intensities and eruption column heights. This comprehensive dataset has been used here to calculate the bias of volume calculations when proximal and distal data are missing, and to evaluate power-law and segmented exponential thinning methods using more limited datasets.

1.0 Introduction

The 1875 eruption of Askja volcano, Iceland, was one of very few eruptions to include both phreatoplinian and Plinian phases, and represents the only historical ‘type’ example of phreatoplinian volcanism (Self and Sparks, 1978). During this eruption, abrupt shifts between subplinian, phreatoplinian, pyroclastic surge and Plinian activity occurred; representing abrupt changes in eruption style (wet vs. dry) and eruption regime (fall vs. surge). Well-preserved very proximal and far-distal fallout deposits coupled with documented historical accounts taken prior to, during, and immediately after this eruption have provided a large dataset to develop two different topics:

a. greater accuracy of the 1875 eruption parameter calculations and inferred vent locations active during this eruption, and;

b. contrasting modes of transport and sedimentation from wet and dry plumes.

The dispersal data define very proximal over-thickened deposits for all of the fall phases, regardless of wet or dry eruption styles, which have implications for the transport and sedimentation regimes of these intense eruption plumes, and sustained plumes in general. This complete data set also enables us to evaluate shifting vent positions and mass discharge rates. Studies of these deposits provide a valuable dataset on which further
transport and deposition models of wet and dry eruption plumes can be developed in addition to considerations of proximal sedimentation regimes of highly intense eruptions.

1.1 Location and geological setting

Askja central volcano (locally known as Dyngjufjöll) is situated in the North Volcanic Zone (NVZ), which delineates the divergent plate boundary in north Iceland (Fig. 1). The Askja volcanic system, in which the central volcano sits, is 10 – 15 km wide and 100 km long. The 45 km$^2$ central volcano Askja rises to more than 800 meters above its surroundings and hosts three calderas, the 2nd-oldest of which (Askja) is 7 x 7 km wide and is almost completely in-filled with post-glacial basaltic lava (Sigvaldason, 2002). The 1875 eruption, which is the subject of this paper, formed the youngest caldera which is 3 x 4 km in diameter, and is today filled by Lake Öskjuvatn (Fig. 2a). Askja volcano was largely built by basaltic sub-glacial and sub-aquatic activity forming hyaloclastites and to lesser extent interglacial and Holocene (subaerial) basaltic lava flows (Sigvaldason 1979; 2002). Two powerful explosive silicic eruptions are known from Askja in Holocene times, the 1875 eruption and an older event, which is not well constrained volumetrically or temporally. Throughout postglacial times, activity at Askja has been vigorous with a number of basaltic eruptions on ring fractures surrounding the caldera rim, as well as flank eruptions (Fig. 2a) (Thordarson et al., in prep). The most recent activity appears to be controlled by lithospheric extension producing an en echelon array of north-northeast to south-southwest fissures that cut the main caldera ring fractures (Fig. 2a) (Brandsdóttir, 1999). The 1875 eruption and caldera formation occurred during a rifting episode along the entire volcanic system with eruptions at Askja volcano. Early
precursory activity within Askja prior to the 28th – 29th March phase includes eruptions that produced two basaltic phreatomagmatic tuff cones, two dacite lavas and a dike, and an obsidian-bearing small dacitic cone (Fig. 2b) (Thordarson et al., in prep). The pre- and post main eruption activity also included extrusion of basaltic lava further out on the fissure swarm, most notably at Sveinagjá and Fjárhólahraun, 40 and 5 km north of Askja and Holuhraun situated ~15 km south of the caldera (Fig. 1: Sigurdsson 1978a, 1978b; Brandsdóttir, 1992; Sigurdsson, 1978a, b; Thordarson et al., in prep).

Phreatic and basaltic phreatomagmatic activity continued after the main eruption well into 1876 (Sigvaldason, 1979; Sparks et al., 1981; Thordarson, unpublished data). Post 1876, activity includes both explosive and extrusive eruptions of basaltic magma in 1921-22, 1929, 1931 and 1961 (Sigvaldason, 1979; Sparks et al., 1981). All the pyroclastic vents that were active during the March 28th – 29th, 1875 eruption sequence are located within the present day Lake Öskjuvatn.

1.2 28th – 29th March 1875 eruptive sequence

The pyroclastics of the Askja 1874-75 eruption were divided into six units (A - F) by Self and Sparks (1978) and Sparks et al., (1981). In this scheme, the formation of units A, E and F are correlated with weak phreatic or hydrothermal activity prior to and following the main phases (units B, C1, C2 and D). Magmatic eruptive activity of the main eruption, beginning on 28th March, had four distinct intervals of different intensity and style (Fig. 3). The eruption began with a subplinian phase (unit B), followed by a phreatomagmatic fall phase (unit C1). Dilute density currents (unit C2) were emplaced
Figure 1: Geologic setting of the Askja volcano: The Askja central volcano is located on the Askja volcanic system in the North Volcanic Zone (NVZ). Sveinagjá, Fjárhóla and Holuhraun fissures located to the north and south of the Askja volcano are sites of effusive basaltic eruptions associated with the Askja volcano-tectonic episode in the 1870's (Thordarson et al. in prep). The dispersal areas of significant, and minor 1875 tephra fallout across East Iceland are shown.
Figure 2: (a) Map of the Askja volcano, including sites (black) of explosive and effusive basaltic volcanism post-dating the 28th - 29th March 1875 event. The volcano features two separate areas of contrasting geology; a mostly subglacial hyaloclastite formation that surrounds the Askja caldera, and the Holocene basaltic lavas that partly in-fill the caldera. The bounding faults of the Askja caldera are shown and their position on the eastern side prior to March 1875 is highlighted by the orange-shaded area. Note that the post 1875 activity is focused on this eastern sector of the Askja caldera fault margins, except for those situated on ring fractures of the younger Óskjuvatn caldera. The 1924-29 basaltic lava flow field issued from a SW-NE trending fissure on the southern flank of the volcano and is aligned parallel to the regional trend of the fissure swarm outside of the volcano. (b) Reconstructed map of the Askja volcano prior to the March 28th - 29th event, showing the known vent sites of precursory activity in yellow. These sites are situated on the old Askja caldera marginal faults (in red) as well as ring fractures that circumscribe the Óskjuvatn caldera. These structural weaknesses were also exploited post 1875 during caldera collapse to eventually define the Óskjuvatn caldera.
after the phreatoplinian fall but were largely confined to the caldera. The final phase was characterized by a Plinian eruption (unit D). In detail, the Plinian phase in the proximal area can be separated into five distinct sub-units with contrasting dispersal, grain size and componentry (Fig. 3). D1, D3 and D5 are widely dispersed sub-units and cannot be singly identified outside of the caldera, where they merge, forming unit D with thinning half (t½) distances of 3 - 4 kilometers. D2 and D4 thin and fine more rapidly with radial thinning half distances 1 to 2 orders of magnitude less (10s to 100s of meters) and are associated with fountaining from separate vents that were synchronous with Plinian activity (Carey et al., 2008a).

2. 28th - 29th March 1875 deposits
The 1875 deposits are well exposed along the caldera rim and particularly towards the east along the dispersal axis (Fig. 4). At the time of the eruption, thick snow cover was present in the proximal and medial areas. The 1875 deposits accumulated on this snow, and were subject to local reworking. The annual thick snow cover and seasonal melting in the highlands surrounding Askja has subsequently led to high degrees of erosion and reworking in the proximal environments, and especially on the volcano. In addition, there is also some evidence for syn-eruptive mass failure and slumping of C1 and C2 tephra in the most proximal exposures. However, true primary thicknesses are well preserved in many places, especially in topographic lows. This is particular true for unit B and C deposits which were protected by Plinian fall D, and these exposures provide a very good control on proximal stratigraphy. In the medial to distal areas, historical records highlight that there was very bad weather conditions two days after the eruption and the deposits
were eroded and reworked significantly; tephra was eroded from topographic highs and deposited in lows, which necessitates very careful interpretation of the medial/distal data.

**Initial Ash**

A white, very fine-grained ash underlies the subplinian deposits, however it is patchily distributed in the medial area.

**Unit B**

The first distinct magmatic unit of the 28th - 29th March eruption sequence is a subplinian coarse fall deposit which is reversely graded, well sorted and has a maximum thickness of 56 cm at the most proximal site situated about 950 meters downwind from the inferred source vent. The pumices typically range from fine to coarse lapilli with rare bombs up to 15 cm in diameter (Figs. 5a, 5b). Lithic clast abundance in the unit B deposit ranges from 5 – 25 modal % and decreases systematically with distance from vent. The lithic clasts are predominantly non- to poorly vesicular obsidian fragments (80 modal wt.%); grey basaltic lava fragments and red-oxidized hyaloclastite are minor components. The Unit B pumice fall deposit has a narrow east-directed dispersal and forms a tephra sheet extending out to ~50 km from the source, however did not reach inhabited areas in east Iceland. This unit is capped by the very fine phreatoplinian ash fall deposit of unit C1 (see below), which infiltrates the interstices of the coarse B pumice fall deposit in all areas.
Figure 3: The stratigraphy of the deposits formed in the main eruption (28th - 29th March 1875). This stratigraphy has been adapted from Self and Sparks (1978) and Sparks et al. (1981). The C2 pyroclastic surge deposits have been split into three flow units (lower, middle and upper), and the Plinian unit D deposits subdivided into five separate sub-units as defined in Carey et al. (2008a).
Figure 4: Photograph of the northeastern side of the caldera, view to east along the dispersal axis. Note in the foreground the alternating white-grey stratigraphy of unit D on the peninsula. White C2 pyroclastic surge and C1 phreatoplinian ash lie underneath. The ash mantles the faulted and downthrust blocks to the left, which have dropped due to caldera collapse after the 1875 eruption. X1 and X2 are locations of the deposits shown in Figure 8.
Figure 5: Photographs of unit B in medial locations. Note how unit B is reversely graded at both sections. It has a salt and pepper texture due to the abundance of obsidian and basaltic lava fragments in addition to minor grey micro-vesicular clasts (Tape measure is 32 cm for scale). In Figure 5b, a very fine dark hydrothermally altered unit A ash is present above the pre-1875 snow and ice. Partial thicknesses of unit C lie above, unit B, however unit D is completely removed. Tool is 30 cm for scale.
**Unit C1 Fall**

Unit C1 is a phreatoplinian fall deposit consisting of very fine, pale grey, uniformly massive ash (Figs. 6a, 6b, 6c). In the medial-distal area, it is inferred that C2 ash overlies C1, and collectively is simply referred to as unit C. This unit has a maximum thickness of 228 cm along the southeast sector of the Óskjuvatn caldera. Similar meter-scale thicknesses are maintained at proximal sites to the north, east and west of the caldera. In the most proximal sites within three kilometers of the vent, C1 contains sporadic lenses of sub-angular to sub-rounded pumice lapilli as well as single-grain-thick trains of lapilli-sized pumices. Grain size analyses conducted by Sparks et al., (1981), suggest that 99 wt% of this deposit is < 1 mm. In many of the medial and distal locations the ash is vesiculated with mm-sized cavities but accretionary lapilli are rare. Lithic clasts within this unit occur predominately in the ash-size fraction, however rare >1 cm in diameter lithic clasts are also present in the deposit at the most proximal sites. The lithic population has a modal abundance of < 5 wt.% and consists predominately of obsidian shards together with minor abundances of basaltic lava fragments. Unit C is widely dispersed to the east-northeast, extending over eastern Iceland and Scandinavia (Sparks et al., 1981). The most distal sites within Iceland at ~150 km from the source vent have a thickness of 5 mm whereas in Scandinavia, 1200 to 1500 km away, very fine submillimeter ash fall was reported. In the proximal area, unit C1 is overlain by C2 dilute density current deposits (Figs. 6a, 6c), however outside the caldera, clasts from Plinian fall unit D impact into and sit upon unit C.
C2 dilute density current deposits

Following the C1 phreatoplinian fall deposits, three major intervals of pyroclastic surge deposition occurred, these have been named lower, middle and upper C2 (Fig. 3). These three phases varied in intensity and degree of water involvement with time. The first dilute density current deposits (LC2) are extremely ash-rich, with poorly sorted fine to medium lapilli lenses, lacking well-sorted fine to coarse pumice lenses and often heavily erode C1 in the proximal area. The MC2 dilute density current deposits are also extremely ash-rich, however well-sorted fine to coarse pumice lenses are common, and these currents often erode LC2 and C1 deposits (Figs. 7a, 7b). The upper C2 (UC2) deposits have well-defined bedsets, a higher abundance of well-sorted, pumice lenses, which are fines-poor and contain rounded coarse lapilli. The UC2 bedforms have longer wavelengths, higher amplitudes and also erode underlying deposits (Figs. 7a, 7b). Bedform directionality of all C2 deposits point to radial transport from a vent now situated within the north-central part of Öskjuvatn. All of the dilute density current deposits were largely confined to the older caldera, with minimal runout via the lower topography in the southwest portion of the older caldera walls.

Unit D Fall

The Plinian fall deposits are the final erupted products of the main eruption (Figs. 8a, 8b). In the proximal area, the widespread Plinian D1, D3 and D5 sub-units define a trend of reverse grading with increasing median grain size of -3.2, -5.3 and -6.1 phi respectively at our type locality (Carey et al., 2008a). Inman (1952) sorting values ($\sigma_0$) of these sub-units range from 1.6 to 2.5 (Carey et al., 2008a). In the medial area, the D1, D3 and D5 sub-units are amalgamated into a single inverse-graded, moderately sorted fall unit (0.6 – 1.4;
Inman, 1952) and hereafter simply referred to as unit D. A weak two-fold subdivision in the medial/distal areas is superimposed on the overall trend of reverse grading, and identified based on lithic abundance. The lowermost part contains approximately 5 - 10 modal% lithic clasts that are dominantly obsidian and basaltic lava fragments. The upper part is comparatively lithic-poor, with lithic abundances < 5 modal wt.%, dominantly obsidian with minor basaltic lava fragments and rare granophyre.

Distal deposits of Plinian fall up to 150 km from vent, are moderately well sorted (0.15 - 1.1; Inman 1952) and are up to 2.0 cm-thick at the most distal Icelandic location along the dispersal axis. In Scandinavia, 1100-1500 km from Askja, reported thicknesses of freshly fallen ash from the phreatoplinian and Plinian phases range from 3 mm to 0.3 mm (Nordenskiöld 1876), however we are unable from the historical reports to discriminate the relative contribution from units C and D.
Figure 6: Photographs of unit C1. (a) Photograph of C1 and C2 in a proximal-caldera outcrop. The C1 phreatoplinian fall unit is at the base and contains discrete lenses of fine lapilli. There are two major erosional unconformities visible in this outcrop as indicated by dashed lines. The first is the erosion of C1 due to the erosive lower C2 surge currents. The second is the erosion of lower C2 deposits by middle C2 surge currents. Tape measure is 80 cm for scale. (b) C1 at the same location resting on pre-1875 snow/ice. Note the lenses of fine lapilli which are laterally discontinuous.
Figure 6: Photograph of unit C1. (c) Outcrop ~400m radially from the caldera margin (tool is 30 cm for scale).
Figure 7: Photographs of outcrops on the Öskjuvatn caldera margin, exemplifying the current bedforms of the C2 pyroclastic surge deposits. (a) Lower C2, Middle C2, Upper C2 deposits. See text for details. (b) Full outcrop-scale picture where deposits in Figures 6a and 6b are located. This outcrop displays all pyroclastic surge flow units, and the erosive unconformities are visible. All C2 flow units exhibit similar directions of transport towards the left of picture. Unit D is above. Shovel is 1 meter for scale.
Figure 8: Photographs of the unit D deposits which are located at X1 and X2 on Figure 4. (a) This photograph (at location X1; Figure 4) shows all five sub-units of D. D2 and D4 are related to a separate series of vents that were erupting in weaker fountaining fashion (Carey et al. 2007a, b). The grain size of the D1, D3, D5 deposits becomes coarser with time, so that D5 comprise the coarsest ejecta. (b) D1, D2, D3 along with scatter of D4 and D5 bombs at location X2, Figure 4.
3.0 Distribution and thickness of the depositional units

All fall units erupted during the main eruption over a ~17 hour period on 28\textsuperscript{th} – 29\textsuperscript{th} March 1875 were transported to the east, although each had slightly different dispersal direction. The dispersal of the subplinian fall B is to the northeast, but its deposition is entirely confined to the highlands above the rural communities in eastern Iceland. The fall deposits of the phreatoplinian and Plinian phases (C and D) are more widely dispersed and the thicknesses of the C and D fall were reported by the inhabitants of eastern Iceland as well as Scandinavia (Nordenskiöld, 1876; Thorodssen, 1913, 1925; Thorarinsson, 1963). This information was used by Mohn, (1878) to draw an isochron map of the Askja 1875 plume dispersal as it traveled from Askja and over Scandinavia (Fig. 9). This isochron map, in addition to quantitative thickness and isomass measurements of tephra fall at sites in Scandinavia (Nordenskiöld, 1876), and analysis of the prevailing wind pattern during that season, has allowed us to constrain the distal isopachs of both phases in the far-distal field (Mohn, 1878). The isopach data presented here are constructed using and constrained by four sets of data:

1. Deposit logs, measurements of deposit thickness and maximum clast size at 488 new sites across eastern Iceland, including documenting sites of zero thickness. Care was taken to measure primary thicknesses in multiple pits at one location and preferably in topographic lows, where deposits were at primary thicknesses.

2. New bulk deposit density measurements for the tephra of units C1 and D along the dispersal axis.

3. Collation of documented/reported ‘in situ’ thickness measurements of the March 29\textsuperscript{th} 1875 deposit in eastern Iceland made at the time of the eruption (Phases C1
and D) (Thordarson et al., in prep). These data are complemented by our own observations and thickness measurements of the deposits at the same sites allowing us to calculate compaction factors.

4. Collection and analysis of reliable observations, including deposit thickness and mass per unit area data, of the March 28th - 29th 1875 deposits obtained from contemporary descriptions in Norway and Sweden compiled by Nordenskiöld (1876) and Mohn (1878) immediately after the eruption.

**Integrating the historical and modern thickness data**

First, at the 488 new localities that were visited in 2004-2006, we have logged and described the Askja March 28th – 29th deposit and measured unit thicknesses. Second, the distal measurements of thickness made in Scandinavia at the time of the eruption, have been adjusted from the measured uncompacted thickness to compacted values using a compaction ratio of 0.5. This compaction ratio is obtained by comparing thickness measurements taken shortly after the eruption in the medial and distal fields in Iceland and reported in the historical accounts, with our own thickness measurements at the same locations in 2005 - 2006. Some issues arose with the historical Scandinavian data because of the syn-and post-eruptive reworking recorded by the observers. Consequently, many reported measurements are clearly over-thickened. For this reason, we have given emphasis to three isomass measurements made where tephra was collected over extended and undisturbed measured areas. Our third approach to integrate thickness data was to use historical accounts where thin ash fall was observed but could not measured to establish a "visual trace isopach". Finally, the presence or absence of known 1875 ash shards in peat bogs through Norway, Sweden, Germany and the Faeroe Islands define a "detected limit"
isopach. The visual trace isopach has an assigned equivalent thickness value of $10^{-3}$ mm, based on the recorded outer limit for four historical Plinian and subplinian eruptions, particularly the visual trace measured for the 17 June 1996 eruption of Ruapehu volcano, New Zealand (Bonadonna and Houghton, 2005). The detected limit reflects where ash particles have been currently detected and is a true outer limit to the 1875 ash fall. We have assigned an equivalent thickness value of $10^{-4}$ mm, which is obtained from calculations of number of ash particles (20 - 40 microns) identified within a known volume of organic material documented in northern Germany, Sweden, and Norway (Persson, 1971; Oldfield et al., 1997; van den Bogaard et al., 2002; Boygle, 2004; Pilcher et al., 2005).

The historical reports and distal thickness measurements in Scandinavia do not discriminate between the products of the phreatoplinian and Plinian plumes, and thus it is impossible to constrain robustly the individual thicknesses of C and D tephas. At the most distal point in Iceland, where thickness measurements of C and D tephra were collected, the ratio of unit C to unit D ash was approximately 1:3. Therefore this ratio has been adopted in partitioning the ash fall in the far-distal fields in Scandinavia.
Figure 9: Isochron map drawn by Mohn in 1877, documenting the timing of the phreatoplinian/Plinian plume as it progressed across the Atlantic and over the Scandinavian landmass. Mohn compiled descriptions of the timing and nature of the tephra fall in Scandinavia and was able to demonstrate a southward deflection of the plume over Scandinavia and towards northern Germany.
**Subplinian unit B.**

The subplinian fall began at 9 pm on 28 March, when “a pitch black column of smoke was seen rising from Askja and was visible for only one hour due to the approaching darkness (Thoroddsen, 1913, 1925). The tephra fall from phase B was dispersed over the highlands to the east of Askja, reaching up to 50 km from source. Consequently, its dispersal is only constrained by modern observations (Fig. 10a). The proximal to distal isopachs of the subplinian fall of unit B, as shown on Figure 10a, define a narrow dispersal to the east-northeast which is extremely attenuated in the proximal to medial areas, as defined by the 50 - 5 cm isopachs. Isopachs of 2 and 3 cm thickness extend up to 34 km downwind from vent and are also extremely narrow. The 2, 1 and 0.5 cm isopachs in the distal areas spread increasingly wider, both crosswind and downwind and the latter shows the greatest crosswind expansion (Fig. 10a).

**Phreatoplinian unit C**

Analysis of historical accounts indicates an onset of the phreatoplinian C1 eruption was around 5:30 am on 29th March and lasted for approximately 1 hour (Thordarson et al., in prep). According to the historical accounts the dispersal of the phreatoplinian plume was to the east-northeast by strong winds (~ 20 ms⁻¹) in the upper atmosphere and involved fallout of a “wet, sticky gray ash” in medial to distal areas (e.g., Thoroddsen, 1913, 1925). Preserved thicknesses of ash from this phase are most likely to be primary, due to its wet adhesive nature and the fact that it was almost immediately covered by Plinian pumice fall from the following phase. The proximal, medial and distal isopachs of the phreatoplinian phase have distinctly different geometries (Fig. 10b). In the proximal area, the 200, 100, 50 and 25 cm isopachs have near-circular to ellipsoidal shapes (Fig. 10b).
There is an attenuation of the 20 and 10 cm isopachs toward the northeast, and on a cross-axis transect at approximately 12 km from source, the 5, 2.5, 1 and 0.5 isopachs show drastic radial expansion, whereas the 20 and 10 cm isopachs are narrow. The 0.1 cm isopach is extremely attenuated towards the northeast and east. The far-distal isopachs curve southward over Scandinavia, indicating a sharp deflection to the south as the plume traveled over the landmass (Fig. 10c).

**Plinian unit D**

After approximately a 30 minute pause in tephra fall in eastern Iceland, reports from mid-eastern Iceland (Jökuldalur, 62 km east of Askja) indicate a renewed phase of pumice fall (Thoroddsen, 1913, 1925). A summary of the historical reports indicate that ash fall began and stopped significantly later at localities farther to the south, suggesting a southward shift of the main dispersal axis with time (Thoroddsen, 1913, 1925). The medial to distal isopachs of the Plinian phase are much wider in a cross-transport direction than those of other eruptions at similar distances (e.g., Mt St Helens; Saran-Wojcicki et al., 1981), which may be accounted for by such a southerly migration of the wind direction throughout the D phase (Fig. 10d). In the proximal region, the 300, 200, 100 and 50 cm contours are all strongly ellipsoidal to the east of the Óskjuvatn caldera (Fig. 10d). In the medial and distal areas, the 20, 10, 5, 2 and 1 cm isopachs are also strongly ellipsoidal towards the east, but show crosswind expansion. In the very distal area the isopachs trend eastwards before turning south over Scandinavia and extending as far as northern Germany (Fig. 10e).
Figure 10: Isopach maps of the units B, C, and D fall deposits. Isopachs are given in centimeters. (a) The unit B deposits are elongated and distributed towards the east in the proximal/medial area. However, more distally unit B has been distributed towards the north east. (b) The unit C isopachs in the proximal environment are circular, but become elongated when the deposit is <20 cm in thickness. The isopachs show a northeastern dispersal. Unit C has a thickness of 0.5 cm on the east coast of Iceland. (c) Far-distal isopach map of unit C. The deflection described by Mohn (1877) fits with data from inhabitants within the dispersal area. (d) Isopach map for unit D. The proximal isopachs are elongated toward the northeast/east. (e) The far-distal isopachs of unit D.
Peat bogs in the Faeroe Islands, British Isles and Scotland show no signs of 1875 tephra and constrain the detected limit isopach (Fig. 10e) (Persson, 1971; Oldfield et al., 1997; van den Bogaard et al., 2002; Boygle, 2004; Pilcher et al., 2005).

### 4.0 Clast size distribution

The maximum sizes of pumice and lithic clasts within each unit of the 1875 deposits were measured at each location by measuring and averaging the three long axes of five clasts.

**Subplinian unit B**

In the proximal area, pumice clasts to 100 mm and lithics of 20 mm in diameter are found up to 1 km from the inferred vent. The 100, 75 and 50 mm proximal pumice isopleths are very elongate with narrow cross- and upwind extents (Fig. 11a). A similar but even narrower trend is observed for the 10 mm lithic isopleth (Fig. 11b). The medial to distal pumice isopleths (20, 10, 5 mm) are much more expanded than their proximal counterparts. The medial lithic isopach is, however, do not exhibit this expansion until approximately 4 km from vent, as shown by the 10 mm isopleth. In terms of dispersal, the lithic isopleths show a migration from an easterly axis (10 mm) to a northeasterly direction (7.5, 5, 2.5 mm), which is not observed in the pumice isopleths (Figs 11a, 11b). A similar trend observed in the pumice and lithic isopleth data is the northeasterly dispersal direction shown by the smaller isopleths in the medial and distal fields, which migrate to a more northerly trend.
Figure 11: Isopleth maps of units B, C, and D. Measurements are given in millimeters. The outlines of the dispersal areas are shown. The $x$, $y$, and $z$ axes of the five largest pumices and lithics at every site were measured. (a) and (b) maps showing the maximum pumice (MP) and maximum lithic (ML) isopleths for unit B. (c) and (d) unit C isopleth maps showing the dispersal of the largest pumice and lithic clasts. (e) and (f) isopleth maps of the unit D deposits. Note the angularity of the southern arm of the 50 mm MP and 5 mm ML isopleths. These observations together with field work suggest that severe erosion in this sector has taken place.
**Phreatoplinian unit C**

Pumice isopleths (70 and 50 mm) in the proximal and medial areas are narrowly ellipsoidal, only expanding more significantly cross wind at approximately 9 km downwind from inferred vent (Fig. 11c). The proximal lithic isopleths (>10 mm) mirror those of the pumice. However they are more strongly ellipsoidal, with the exception of the most proximal isopleth (70 mm) which is circular (Fig. 11d). Medial pumice isopleths (20 and 10 mm) show a cross-wind expansion and northward migration which is mirrored in the lithic isopleths (7.5, 5, 2.5 mm). Distal pumice (5, 2.5 mm) and lithic isopleths (1 mm) are expanded greatly crosswind and show a more northward trend than those of the proximal-medial isopleths. These trends together with the isopach data suggest a westerly wind direction for lower elevations which then becomes more southerly with increasing plume height.

**Plinian unit D**

The isopleth dispersal maps show complex geometries throughout the proximal to distal areas. In the proximal area, the lithic and pumice isopleths are initially circular but become ellipsoidal with increasing distance from vent (Figs. 11e, 11f). The 500 mm pumice isopleth and 50 mm lithic isopleth reflect a northeastern dispersal direction that becomes more eastward for smaller isopleths. With exception of the 50 mm pumice isopleth and 5 mm lithic isopleth, the medial to distal isopleths follow a eastward to slight northward dispersal direction, with greater crosswind expansion with increasing distance from vent (Figs. 11e, 11f). In comparison to the earlier phases of this eruption, the pumice and lithic isopleths in proximal to distal areas are wider cross wind, and less ellipsoidal, and there is more expansion in the isopleths closer to vent. The southward
migration of the wind throughout Plinian tephra fall probably accounts for the expanded medial/distal isopleths in comparison to other phases.

5.0 Eruptive parameters

5.1 Volume calculations

Volume of a tephra fall deposit is the key parameter in terms of establishing the magnitude and intensity of an eruption. Calculations of volume for medium to large scale eruptions is generally difficult for preservation reasons, for example due to the absence of thickness data in the proximal region (e.g., \(< 4 \) km from vent for Taupo 181 AD; Smith and Houghton, 1995a, b) and/or in the distal field, e.g., due to tephra dispersal over the ocean (e.g., Quizapu, 1932, Hildreth and Drake, 1992; Hudson, 1991, Scasso et al., 1994). The 1875 eruption is unique in that proximal exposures up to 1 km from vent are accessible and far-distal thickness data are available from \(10^{-2}\) to \(10^{-5}\) cm. The dispersal of tephra in Iceland has well-constrained proximal to near-distal isopachs for each phase (< 150 km east of vent) and data from sites in Scandinavia and Germany uniquely constrain the far-distal field of tephra dispersal (1100 km to 2000 km from source). Thus, this eruption permits the relationship between thickness and dispersal area to be accurately quantified. Each of the fall units have been plotted on a semi-log plot of thickness vs. area\(^{1/2}\), after Pyle (1989), to identify thinning trends (Fig. 12). We use both exponential thinning and power-law methods to compare and contrast volume calculations of each fall unit of the 1875 eruption.
Figure 12: Semilog plots of thickness vs. square root of area within the isopach for the 1875 fall units. The inset shows the proximal thinning characteristics of each of the phases. Note the steeply sloping nature of the most proximal segment and the segmented nature of each fall unit.
5.1.1 Exponential thinning

Numerous studies of thickness vs. area$^{1/2}$ relationships for medium to large scale eruptions show that the volume of a fall unit cannot be approximated by simple exponential thinning and that the thinning relationship is better approximated by two or more segments on a plot of semi-log thickness vs. area$^{1/2}$ (e.g., Quizapu 1932, Hildreth and Drake, 1992). Fierstein and Nathenson (1992) and Pyle (1990) derived equations to calculate volumes based on two exponentially thinning segments with one inflection point. Where more than two segments can be defined, a more general formula was proposed by Bonadonna and Houghton (2005):

\[
V = \frac{2T_{10}}{k_1^2} + 2T_{10} \left[ \frac{k_2BS_1 + 1}{k_2^2} - \frac{k_3BS_1 + 1}{k_1^2} \right] \exp\left(-k_1BS_1\right) \\
+ 2T_2 \left[ \frac{k_3BS_2 + 1}{k_3^2} - \frac{k_3BS_3 + 1}{k_2^2} \right] \exp\left(-k_2BS_3\right) \\
+ 2T(n-1) \left[ \frac{k_nBS_{(n-1)} + 1}{k_n^2} - \frac{k_{(n-1)}BS_{(n-1)} + 1}{k_{(n-1)}^2} \right] \exp\left(-k_{(n-1)}BS_{(n-1)}\right)
\]

(1)

Where $T_{10}$, $k_n$, and $BS_n$ are the intercept, slope and break in slope of the line segment $n$. The $n$ values (number of segments) for the Askja deposits range are 3 (subplinian), 4 (Plinian) and 5 (phreatoplinian).

On semilog plots of thickness vs. area$^{1/2}$, the 1875 fall units are best approximated by three to five exponential line segments (Fig. 13) and thus we have used the method of Bonadonna and Houghton (2005) to calculate fall volumes based on these segments for
Figure 13: Definition of segments for semilog plots of thickness vs. area^{1/2} for each of the fall units. The volumes of each segment are shown next to figures (a), (c) and (e). The segments are also indicated in figures (b), (d) and (f) which show expanded views of the more proximal areas of each graph. (a) and (b): Unit B can be approximated with three segments. (c) and (d): Unit C can be separated into five segments. (e) and (f): Unit D can be approximated by four segments. Note the steeply sloping most proximal segment for all fall units.
Table 1: (a) Total volume estimates for the Askja 1875 fall units calculated using the segmented exponential and power-law thinning models. The deposit data in each case were best approximated by the exponential thinning model, except in the case of unit B, where a power-law fit to the data gave the identical volume. (b) Break in slope (Bs) distances from vent between segments (i.e. 1 – 2 etc.) are listed for each of the 1875 fall units.

<table>
<thead>
<tr>
<th>Unit</th>
<th>First segment</th>
<th>Second segment</th>
<th>Third segment</th>
<th>Fourth segment</th>
<th>Fifth segment</th>
<th>Exponential total</th>
<th>Power law total</th>
<th>Integration limits</th>
<th>B (km)</th>
<th>C (km)</th>
<th>R²</th>
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<tr>
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<td>0.001</td>
<td>0.002</td>
<td>0.011</td>
<td>——</td>
<td>——</td>
<td>0.014</td>
<td>0.014</td>
<td>0.0004</td>
<td>45</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>Unit C</td>
<td>0.07</td>
<td>0.12</td>
<td>0.1</td>
<td>0.27</td>
<td>0.0001</td>
<td>0.45</td>
<td>0.47</td>
<td>0.027</td>
<td>1300</td>
<td>0.95</td>
<td></td>
</tr>
<tr>
<td>Unit D</td>
<td>0.08</td>
<td>0.4</td>
<td>0.9</td>
<td>0.0001</td>
<td>——</td>
<td>1.37</td>
<td>2.33</td>
<td>0.03</td>
<td>1300</td>
<td>0.88</td>
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<th>Bs (km)</th>
<th>Bs (km)</th>
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<td>1-2</td>
<td>2-3</td>
<td>3-4</td>
<td>4-5</td>
</tr>
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<tr>
<td>Unit C</td>
<td>2.5</td>
<td>4.2</td>
<td>31</td>
<td>633</td>
</tr>
<tr>
<td>Unit D</td>
<td>2.8</td>
<td>27</td>
<td>591</td>
<td>——</td>
</tr>
</tbody>
</table>
each of the fall deposits. The number of segments, their respective volumes and breaks in slope for each fall unit are listed in Table 1a, 1b.

5.1.2 Power-law thinning

Several deposits (e.g., Ruapehu, 17 June 1996) show a good fit to a power-law thinning relationship (Bonadonna and Houghton, 2005). The power-law relationship is also theorized to be more applicable than exponential thinning when there is significant fine ash in the plume, as exponential thinning tends to underestimate the volumes of such deposits (Bonadonna and Houghton, 2005; Bonadonna et al., 1998). Using the method described in Bonadonna and Houghton (2005), with $B$ and $C$ integration values (distance of calculated maximum thickness and downward limit of significant volcanic cloud spreading respectively) calculated for each 1875 fall units, the volumes have been obtained (Fig. 14; Tables. 1a, 1b).

5.2 Rates of thinning

Following Pyle 1989, the parameter $B$, which describes the rate at which a deposit thins, has been calculated for each exponential segment based on individual isopach maps from each unit (Fig. 10) and the semilog plot of thickness vs. $area^{1/2}$ (Fig. 13) and the data are summarized in Table 2. The implications of the $B$, values will be discussed in section 7.11.
Figure 14: Power law thinning relationships for semilog plots of thickness vs. area $^{1/2}$. This model is well-suited to unit B (a), but fails to model accurately the medial and distal thinning trend of the unit C and D deposits (b) and (c), even though 13 - 16 isopachs can be defined for each fall unit.
Table 2: Thinning half ($B_t$) distances for each segment in units B, C and D.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Segment</th>
<th>Segment name</th>
<th>$B_t$ (km)</th>
</tr>
</thead>
<tbody>
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<td>B</td>
<td>first</td>
<td>Seg-1</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>second</td>
<td>Seg0</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>third</td>
<td>Seg1</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>first</td>
<td>Seg-1</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>second</td>
<td>Seg0</td>
<td>6.7</td>
</tr>
<tr>
<td>C</td>
<td>third</td>
<td>Seg1</td>
<td>7.1</td>
</tr>
<tr>
<td></td>
<td>fourth</td>
<td>Seg2</td>
<td>44.4</td>
</tr>
<tr>
<td></td>
<td>fifth</td>
<td>Seg3</td>
<td>67.4</td>
</tr>
<tr>
<td>D</td>
<td>first</td>
<td>Seg0</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>second</td>
<td>Seg1</td>
<td>5.3</td>
</tr>
<tr>
<td></td>
<td>third</td>
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<td>37.2</td>
</tr>
<tr>
<td></td>
<td>fourth</td>
<td>Seg3</td>
<td>67.4</td>
</tr>
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</table>

5.3 Mass discharge rates

Detailed historical reports (Thordarson et al., in prep) have enabled mass discharge and volumetric discharge rates for each of the 1875 phases to be calculated. Durations for each of the phases are constrained approximately by historical reports: the subplinian column was observed for an hour, phreatoplinian ash fall in the medial/distal areas continued for 1 hour, followed by 5-6 hours of Plinian ash fall. Mass and volumetric discharge rates for each phase of the 1875 pyroclastic fall deposition are listed in Table 3, in addition to the estimated rates during the pyroclastic surge phase. Approximating the duration of the subplinian phase as 1 hour with a calculated volume of 0.0143 km$^3$ yields
<table>
<thead>
<tr>
<th>Deposit</th>
<th>Column height (km)</th>
<th>MDR (kg s⁻¹)</th>
<th>VDR (m³ s⁻¹)</th>
<th>DRE (km³)</th>
<th>Volume (km³)</th>
<th>Time (hours)</th>
<th>Total mass (kg)</th>
<th>Bc (km)</th>
<th>Bt (km)</th>
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<tr>
<td>Subplinian</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Vesuvius sub plinian</td>
<td>17-21</td>
<td>3-6 x 10⁻⁷</td>
<td>0.07</td>
<td>11</td>
<td>49.9 x 10⁹</td>
<td></td>
<td></td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>2 Furnas L2</td>
<td>12.5</td>
<td>4 - 6 x 10⁻⁵</td>
<td>0.0206</td>
<td>0.067</td>
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<td></td>
<td>78.4 x 10⁹</td>
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<td></td>
</tr>
<tr>
<td>3 Furnas L3</td>
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<td>5-8 x 10⁻⁵</td>
<td>0.0327</td>
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<td>3.1</td>
<td></td>
<td>74.8 x 10⁹</td>
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<td></td>
</tr>
<tr>
<td>4 Hekla 1970</td>
<td>16</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td>2</td>
<td>2</td>
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<tr>
<td>5 Hekla 1991</td>
<td>11.5</td>
<td></td>
<td>0.02</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>6 Mt St Helens 25th May</td>
<td>12.8</td>
<td></td>
<td>2.6 x 10⁻³</td>
<td>0.0001</td>
<td>0.5</td>
<td></td>
<td></td>
<td>3.4</td>
<td>2.6</td>
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<tr>
<td>7 MSH june 12</td>
<td>14</td>
<td>2.7 x 10⁻⁶</td>
<td>0.0078</td>
<td>0.017</td>
<td>4.5</td>
<td></td>
<td>0.45 x 10¹¹</td>
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<td>14.8</td>
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<tr>
<td>Askja 1875 B</td>
<td>8 (a)</td>
<td>2.6 x 10⁻⁶</td>
<td>3.9 x 10⁻³</td>
<td>0.004</td>
<td>0.014</td>
<td>1</td>
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<td>Phreatoplinian eruptions</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 Rotongaio ash (Taupo 181 AD)</td>
<td>10⁻⁵</td>
<td>0.8</td>
<td>2.1</td>
<td>days to months</td>
<td>2.9-4.9</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>9 Oruanui (Taupo 26 ka)</td>
<td>10⁻⁶</td>
<td>0.7</td>
<td>1.8</td>
<td>weeks to months</td>
<td>12.6-110</td>
<td></td>
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<tr>
<td>10 Hakone, Japan 13000 BP</td>
<td>16</td>
<td></td>
<td>1.1 x 10⁻¹³</td>
<td>1.5-3.3</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Askja 1875 C</td>
<td>22.8 (b)</td>
<td>6.8 x 10⁻⁷</td>
<td>1.2 x 10⁻⁵</td>
<td>1.04</td>
<td>0.45</td>
<td>2</td>
<td>4.8 x 10¹¹</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>Plinian eruptions</td>
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<td></td>
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<tr>
<td>11 Vesuvius 79 AD (grey)</td>
<td>32</td>
<td>1.5 x 10⁻⁵</td>
<td>2.1</td>
<td>9.5</td>
<td>6.1 x 10⁻¹²</td>
<td>4.2</td>
<td>7.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 Huaynaputina 1600 stage 1</td>
<td>34-46</td>
<td>2.8 x 10⁻⁵</td>
<td>8.8</td>
<td>20</td>
<td>2.1 x 10⁻¹³</td>
<td>8.34 (MP)</td>
<td>6.5</td>
<td>50.5</td>
<td></td>
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<tr>
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<td>23-26</td>
<td>0.7-1.0 x 10⁻⁵</td>
<td>2.1</td>
<td>8.8</td>
<td>60</td>
<td>4.8 x 10⁻¹²</td>
<td>22</td>
<td>18.6</td>
<td></td>
</tr>
<tr>
<td>13 Novarupta 1912 episode 2</td>
<td>22-25</td>
<td>0.6 - 2 x 10⁻⁵</td>
<td>1.99</td>
<td>4.8</td>
<td>combined</td>
<td>4.8 x 10⁻¹²</td>
<td>22</td>
<td>18.6</td>
<td></td>
</tr>
<tr>
<td>13 Novarupta 1912 episode 3</td>
<td>17-23</td>
<td>0.2 - 0.4 x 10⁻⁴</td>
<td>1.66</td>
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<td>hours</td>
<td>4.0 x 10⁻¹²</td>
<td>18.6</td>
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<tr>
<td>14 Quizapu 1932</td>
<td>25-32</td>
<td>1.5 x 10⁻⁵</td>
<td>4.05</td>
<td>9.5</td>
<td>19-25</td>
<td></td>
<td>5.4</td>
<td>62.4</td>
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<td>15 Mt St Helens 18th May</td>
<td>19</td>
<td>1.9 x 10⁻⁷</td>
<td>1.1</td>
<td>0.24</td>
<td>9.1</td>
<td>6.3 x 10⁻¹¹</td>
<td>3.3</td>
<td>28.6</td>
<td></td>
</tr>
<tr>
<td>16 Hudson 1991</td>
<td></td>
<td></td>
<td>3.3</td>
<td>3.3</td>
<td></td>
<td></td>
<td>34.4</td>
<td>34.4</td>
<td></td>
</tr>
<tr>
<td>Askja D</td>
<td>26 (a)</td>
<td>2.5 x 10⁻⁷</td>
<td>3.5 x 10⁻⁷ (peak)</td>
<td>0.213</td>
<td>1.37</td>
<td>6</td>
<td>5.0 x 10¹¹</td>
<td>1.1</td>
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a mass discharge rate (MDR) of $2.6 \times 10^6 \text{ kgs}^{-1}$ and volumetric discharge rate (VDR) of $3.9 \times 10^3 \text{ m}^3\text{s}^{-1}$ (Table 3). The phreatoplinian fall phase with a known duration of 1 hour has a MDR of $6.8 \times 10^7 \text{ kgs}^{-1}$ and VDR $1.2 \times 10^5 \text{ m}^3\text{s}^{-1}$ (Table 3). The duration of pyroclastic surge emplacement is assumed to be the observed time between the two enclosing fall units (unit C and D). If we assume the two-hour long cessation of fall equates to the maximum time over which the C2 density currents could have been emplaced within the caldera, then a minimum MDR of $2.3 \times 10^6 \text{ kgs}^{-1}$ and VDR of $3.9 \times 10^3 \text{ m}^3\text{s}^{-1}$ are calculated (Table 3). The Plinian phase continued for approximately 5 - 6 hours according to a synthesis of reports from eastern Iceland. Assuming this duration, the time-averaged MDR for the phase is $2.5 \times 10^7 \text{ kgs}^{-1}$ and the VDR is $6.9 \times 10^4 \text{ m}^3\text{s}^{-1}$ (Table 3). Our synthesis of historical records suggests the time of peak Plinian discharge was four hours, resulting in a maximum discharge rate of $3.5 \times 10^7 \text{ kgs}^{-1}$ and VDR of $9.5 \times 10^4 \text{ m}^3\text{s}^{-1}$.

5.4 Comparison with other eruptions.
Combinations of dispersal with other eruptions of similar style (Fig. 15) show how each of the 1875 fall units fit into the global scale/picture of eruption intensity. In terms of mass discharge rates, the 1875 Plinian phase with a peak discharge rate of $3.5 \times 10^7 \text{ kgs}^{-1}$ is of comparable size to some of the more well-known eruptions such as Mt St Helens 1980 ($1.9 \times 10^7 \text{ kgs}^{-1}$; Carey and Sigurdsson, 1985) (Fig 15; Table 3). In comparison to the other 'type' phreatoplinian eruptions from the Taupo Volcanic Zone, the Askja phreatoplinian phase appears to be a mid-intensity member of the group ($10^5$-$10^6 \text{ kgs}^{-1}$; Smith, unpublished thesis, 1998).
Figure 15: Semilog plots of thickness vs. area $^{1/2}$ for each of the fall units, together with the dispersal trends for other eruptions of similar type. (b), (d) and (f) are expanded proximal equivalents to emphasize the proximal thinning trends in each case.
The mass discharge rate of the Askja subplinian phase \((2.6 \times 10^6 \text{ kgs}^{-1})\) sits in the field of the 20th century eruptions of Hekla volcano \((10^5 \text{ kgs}^{-1} \text{ to } 10^6 \text{ kgs}^{-1} ; \text{Thorarinsson and Sigvaldason, 1972;} \text{ Gudmundsson et al., 1992;} \text{ Höskuldsson et al., 2007})\), and also that of the May – June 1980 eruptions of Mt St Helens \((\sim 2 - 3 \times 10^6 \text{ kgs}^{-1} ; \text{Sarna-Wojcicki et al., 1981})\) (Fig. 15; Table 3).

5.5 Column height

A common method used to calculate column heights of eruptions is based on fining of clast size - where the height of the eruption column can be estimated by the rate at which clast size decreases cross wind (e.g., Pyle 1989, Carey and Sparks, 1986). Here we apply these methods to estimate and compare column heights for the phases of the 1875 eruption. According to Pyle (1989), the neutral buoyancy height of the eruption column can be estimated by the rate at which the clast size decreases. In all three units of the main 1875 eruption, one to two segments are observed on a semilog plot of clast diameter vs. area \(^{1/2}\) (Fig. 16). A simple linear fit to the data is precluded by steep proximal segments for each unit, and we have used more distal segments for our calculations. \(H_b\) (neutral buoyancy height) can then be used to approximate \(H_t\) (total column height), by the empirical relationship \(H_b/H_t \sim 0.7\) (Sparks, 1986). The potential of low-density pumice to be influenced by wind advection is very high and therefore we use the slope of distal segments of the maximum lithic clasts. This method gives \(H_b\) and \(H_t\) values of (unit C) = 23, 33 km and (unit D) = 26, 37 km respectively (Table 4).
Figure 16: Semilog plots of clast diameter vs. area $1/2$ displaying the maximum pumice (MP) and maximum lithic (ML) data for each 1875 unit in comparison to other eruptions. All of the Askja fall units plot in the lowermost portion of their respective fields. However, only limited datasets were available for other eruptions. Using the method described in Pyle (1989), column heights were estimated using the ML plot.
Table 4: Estimated column heights for each of the 1875 fall units using the methods of Pyle (1989) and Carey and Sparks (1986).

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<td>km</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$H_b$</td>
<td>$H_t$</td>
</tr>
<tr>
<td>B</td>
<td>16</td>
<td>22</td>
</tr>
<tr>
<td>C</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>D</td>
<td>26</td>
<td>26</td>
</tr>
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</table>

Complexities arise when estimating column height for the distal segment of the initial subplinian phase (Fig. 16b) as calculated column heights are unreasonably low for an eruption of this volume and intensity. This is dominantly due to the lack of distal primary deposits. Thus we have used the intermediate segment to apply this calculation of column height, giving $H_b$ and $H_t$ values of (unit B) = 16 and 22 km.

The method of Carey and Sparks (1986) was applied to the isopleth data for lithics found within the subplinian and Plinian fall deposits. It could not be applied to the phreatoplinian deposits due to the high degree of fragmentation of the lithic components, which are uniformly fine-ash particles. Column heights for the subplinian and Plinian phases calculated using this method are 8 km and 26 km respectively (Table 4).

We feel that the methods of Pyle (1989), and Carey and Sparks (1986) give the most reasonable estimations of column heights, i.e., the subplinian plume rising to 8 km, phreatoplinian plume to 23 km and Plinian plume to 26 km (Tables 3, 4). Historical accounts converge on column heights of 27 - 30 km for the phreatoplinian and Plinian columns (Thorodssen, 1913, 1925; Thordarson et al., in prep).
5.6 Vent position

Vent locations for each phase of the eruption are located within the present-day lake, however using descriptions and drawings made weeks-to-months after the main eruption, knowledge of the structural weaknesses in the caldera region, dispersal data and deposit characteristics, we are able to infer fairly accurately where vents were located. Historical records written in February, 1875, prior to the main eruption, (Thorodssen, 1913, 1925) document precursory activity occurring in the east and southeastern margin of the region. In addition, a small pond had formed in a depression in the north-central area of the present-day lake, fed from groundwater. Observations made after the main eruption document a triangular depression, with three fracture swarms which extended from the centre of the depression: one to the southeast, one to north and one to the west-northwest (Fig. 17; Watts, 1876; Johnstrup, 1877, 1876). The subplinian deposits contain basaltic lithic and hyaloclastite particles and the narrow cross-wind widths of the isopach and isopleth data suggests that this vent was located near the eastern-most side of the present day lake, i.e., at the time at the contact of the hyaloclastite walls of the Askja caldera and the caldera-filling basaltic lavas (Fig. 17). This location lies within the NW-SE trending fault swarm and is the eastern-most vent position throughout the eruption.

The isopachs and isopleth data for the phreatoplinian C phase are difficult to interpret in terms of a precise vent location due to the location of the present-day lake and the circular nature of the proximal isopachs. Due to the wet nature of the dilute density currents, we infer that they were erupted from a geographically similar location as the phreatoplinian vent. Flow directions from the dilute density currents suggest that the vent location is in the central-north region of the present day lake, which is within the north of
the Askja caldera marginal fault (in red) (Fig. 17). Descriptions of the pre-eruption depression coincide with this location.

Sharp unconformities between the C2 and Plinian deposits clearly suggest that ground shaking between these phases was very intense. The lower sub-unit of the Plinian deposits has the highest abundance of lithic clasts, suggesting that the initial phase of this eruption was one of vent opening. Preliminary componentry data also suggests that the Plinian vent was located within the basaltic lava-covered area. Plinian dispersal characteristics and the abundance of large meter-sized lithic basaltic lava and pumice bombs on the northwest side of the caldera and meter-sized pumice bombs on the south of the southern caldera mountains suggests a vent location to the south and west of the inferred source of the phreatoplinian and pyroclastic surge phase (Fig. 17). The contemporary drawings made of the depression and gas plumes also suggest that this vent location was in the mid-southern extent of the old caldera fault region.

Minor weaker explosive activity was synchronous with the Plinian phase and produced intensely welded deposits in the southwest and northern regions of the Öskjuvatn caldera. Based on the observations described above, and the dispersal characteristics of the welded deposits (Carey et al., a,b 2008), it appears that these vents were at the peripheral extensions of two structural weaknesses, one along the southern extent of the caldera fault, and the other at the northwest extent of the NW-SE trending fault (Fig. 17).
Figure 17: The present day form of Öskjuvatn caldera (dashed line). Also shown is the early developing shape of the Öskjuvatn caldera in 1876 as reconstructed by Jónsson (1942) based on descriptions made in 1876 by Johnstrup (1877). Their observations document a triangular depression, with three fracture swarms: one to the southeast, one to north and one to the west-northwest (Watts, 1876; Jóhnstrup, 1877, 1876). The 'small pond' of water they describe in their reports was located at the junction of these two depressions. B, C and D, are our inferred vent positions: W the locations for fountaining vents during the D phase. The older Askja caldera marginal fault is shown in red.
6.0 Discussion

6.1 Background on transport and deposition from wet and dry plumes

Studies dating from the late 1980's have recognized that fall deposits typically do not follow a simple exponential thinning model (e.g., Pyle 1989; Hildreth and Drake 1992; Fierstein et al., 1992, Houghton et al., 2004). Instead, the thinning curves had discrete segments and breaks in slope with distance from source, e.g., Hudson 1991 (Scasso et al., 1994), Novarupta 1912 (Houghton et al., 2004), Quizapu 1932 (Hildreth and Drake, 1992, Bonadonna et al., 1998) and Mt St Helens 1980 (Bonadonna et al., 1998). The proximal, medial and distal segments were named \( \text{Seg} 1 \), \( \text{Seg} 2 \) and \( \text{Seg} 3 \) by Bonadonna et al., (1998). The segmentation was attributed to different sedimentation laws for different particle sizes in proximal, medial and distal regimes. Hildreth and Drake (1992) noticed that the deposits of Quizapu 1932 had a very steep proximal segment and interpreted this as a consequence of a change in sedimentation mechanism. Bonadonna et al., (1998) suggested that this steep proximal segment (which they called \( \text{Seg} 0 \)) represented sedimentation from the upper convective plume margins of particles which did not enter the umbrella cloud.

6.2 Rates of thinning \( (B_t) \) and breaks in slope \( (B_s) \)

Thinning rates \( (B_t) \) and breaks in slope \( (B_s) \) have been calculated for each segment of the 1875 units (Tables 1b and 2). In addition to segments 0 through 3 described by Bonadonna and Houghton (2005), we recognize a further extremely proximal segment characterized by \( B_t \) values of 0.3 and 0.4 for subplinian and phreatoplinian phases respectively (Figs 13b, 13d, 13f; Tables 2, 5).
These $B_i$ values, irrespective of style or intensity, are approximately an order of magnitude less than the $B_i$ values described for the 'type' Seg0 of the Quizapu 1932 deposits (Table 5), and yet are an order of magnitude larger than those calculated for low-moderate intensity cone-forming deposits (e.g., Sable et al., 2006). We will refer to this segment as Seg-1. This segment must be related to a proximal sedimentation regime not described by existing models for high intensity eruptions and linked to sedimentation from low elevations on the jet/column. Data from the ejecta ring of the Novarupta 1912 (Houghton et al., 2004) and Tarawera 1886 (Sable et al., 2006) proximal cone-forming deposits also have $B_i$ values which are of the same order of magnitude as the subplinian and phreatoplinian Seg-1 (Table 5). These proximal deposits were described, by Houghton et al., (2004) and Sable et al., (2006), as products of early sedimentation from the jet and lower convective plume margins, which then leads to proximal overthickening.

Thinning data from the literature make it clear that Seg-1, and even Seg0 may not have been recorded for some historical eruptions. For example, for the Hudson 1991 deposit, the first break in slope on a log T vs. area$^{1/2}$ plot occurs at about 19 km from vent, which is too far from the volcano to be explained by transition from the column margin to the umbrella cloud sedimentation (Seg0 to Seg1), which typically takes place at < 30 % of column height (Bonadonna and Phillips, 2003). Similarly the 1980 eruption of Mount St Helens 1980, has a first break in slope at 27 km (Bonadonna et al., 1998).
Table 5: $B_i$ values of the most proximal segment for the Askja 1875 fall units and other selected eruptions, where multiple segments can be identified on a semilog plot of thickness vs. area$^{1/2}$. Eruptions with cone-forming deposits are also listed for comparison. The Askja subplinian and phreatoplinian phases have $B_i$'s in the same order of magnitude as other cone-forming eruptions.

<table>
<thead>
<tr>
<th>Deposits</th>
<th>style</th>
<th>most proximal segment $B_i$ (km)</th>
</tr>
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<tbody>
<tr>
<td>Askja 1875 B</td>
<td>subplinian</td>
<td>0.3</td>
</tr>
<tr>
<td>Askja 1875 C</td>
<td>phreatoplinian</td>
<td>0.4</td>
</tr>
<tr>
<td>Askja 1875 D</td>
<td>Plinian</td>
<td>1.1</td>
</tr>
<tr>
<td>Hekla 1970</td>
<td>subplinian</td>
<td>2</td>
</tr>
<tr>
<td>Hudson 1991</td>
<td>Plinian</td>
<td>3.1</td>
</tr>
<tr>
<td>Quizapu</td>
<td>Plinian</td>
<td>1.1</td>
</tr>
<tr>
<td>Kilauea Iki</td>
<td>Hawaiian</td>
<td>0.2</td>
</tr>
<tr>
<td>Ruapehu 1996</td>
<td>subplinian</td>
<td>0.2</td>
</tr>
<tr>
<td>Tarawera 1886 proximal cones</td>
<td>Plinian + Strombolian-style</td>
<td>0.02 - 0.25</td>
</tr>
<tr>
<td>Novarupta ejecta ring</td>
<td>Plinian</td>
<td>0.3</td>
</tr>
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The breaks in slope between the 1875 first and second segments occur at radial distances between 900 m to 2.8 km radial distance from vent, which is up to an order of magnitude closer to source than the initial break in slope of the Quizapu 1932 deposits (7.3 km).

6.3 Theory and examples of proximal over-thickening

The initial models for dry eruption plumes assumed that significant sedimentation of particles (excluding ballistics exiting from the jet) started at the plume corner, where the erupted mixture passes from vertical transport in the convective column to lateral
transport in the umbrella cloud (Sparks et al., 1997 and references therein). More comprehensive models were later developed adding a second depositional regime where sedimentation of only coarse particles is possible from the turbulent margins of the convective column margins with re-entrainment of all particles finer than ~ 1 cm (Bursik et al., 1992; Ernst et al., 1996). These models do not account for the lapilli-rich overthickened, cone-forming proximal deposits that were described at Tarawera (Sable et al., 2006), Novarupta (Houghton et al., 2004) or the ultra-proximal fall deposits of the 1875 fall units ($B_i$'s $< 1$). Descriptions of two recent subplinian eruptions (Asama 1783 and Oshima 1986) also suggest that they also have a region of proximal over-thickening (Sumner, 1998; Yasui and Koyaguchi, 1998). In addition, the 1996 subplinian eruption of Ruapehu has a proximal segment with a $B_i$ value in the same order of magnitude as observed for the Askja subplinian phase (Table 5) (Houghton, unpublished data) which suggests similar proximal over-thickening.

6.3.1 Sources of proximal over-thickening of the dry 1875 fall units

To develop a model for proximal over-thickening of dry eruptions, we summarize the models developed for other examples, together with descriptions of historical eruptions, where very proximal sedimentation is documented from the lower portions of the jet and lower convective plume margins.

The model developed for the 1912 Novarupta 'ejecta ring' advocates a parabolic velocity profile in the Plinian jet, so that ejecta at the jet and lower convective column margins exit at lower velocities than the core (Fierstein et al., 1997; Houghton et al., 2004). A model for proximal over-thickening was suggested by Sable et al., (2006) for the Tarawera 1886 eruption, based on the model for the 1912 Novarupta 'ejecta ring'. This
model also assumes a curved velocity profile in the conduit, which is extended into the jet, such that the particles at the sides of the jet have less momentum, and sediment prematurely from the margins of the jet. In contrast, during the Oshima 1986 and Asama 1783 eruptions, proximal over-thickening is thought to be due to sedimentation from both the high plume and from lower elevations on the margin of the column (e.g., Sumner 1998; Yasui and Koyaguchi 1998).

Recently Clarke et al., (2002) described transport dynamics of the jet and lower convective column regions of the plume for non-sustained vulcanian eruptions that were observed at the Soufrière Hills volcano at Montserrat during 1997. They describe opaque veils and overhanging vortices extending from the main jet and lower convective column margins at low elevations from which tephra fallout occurred close to vent and was commonly swept up in the ensuing pyroclastic density currents. Numerical models developed by Clarke et al., (2002), with inputs specific to the vulcanian eruptions at Soufrière Hills, have simulated the formation of veils and described them as vortex phenomena centrally located around the source vent where particles move in a clockwise direction. The numerical simulations describing particle transport directions and size within this inner region of sedimentation showed downward and outward particle trajectories close to vent, and were observed to form within seconds after the explosion.

Although the mechanism of eruption, gas/particle and juvenile/lithic ratios are inherent to short-lived vulcanian explosions, we suggest that this type of sedimentation may be common also during higher intensity sustained eruptions.

We propose that, in high intensity eruptions, short-lived fluctuations of mass flux, coupled with the heterogeneous distribution of erupted particle sizes above the
fragmentation surface drive unsteadiness in the lower portion of the plume. Consequently, unsteady conditions in the jet and probably lower convective plume margins likely gives rise to sedimentation of particles having different velocities and, as observed in numerical models by Clarke et al., (2002), with complex trajectories. This unsteady behavior of only the very margins of the jet facilitates the premature sedimentation of particles of all grain sizes from heights of a few kilometers, rather than only those large clasts considered as ballistic. In this model, the bulk of the erupted mass is not affected by these marginal instabilities and rises through the jet to feed the convective plume. The proximal over-thickened deposits of the dry 1875 phases with small to intermediate $B_i$'s are then a mixture of particles sedimented from the upper portions of the convective regions and principally from the margins of the jet and lowermost portions of the column.

6.3.2 Sources of proximal over-thickening for the 1875 wet fall unit

Although over-thickening of proximal deposits has been described for Plinian eruptions (e.g., Fierstein et al., 1992, Houghton et al., 2004, Sable et al., 2006), they have not been previously described for phreatomagmatic or phreatoplinian deposits. Two other 'type' phreatoplinian examples from the Taupo 181 AD eruption do not have proximal deposits exposed at less than 4 km from vent, but do show some over-thickening in the most proximal exposures at 4 kilometers (Smith and Houghton, 1995a,b).

The $B_i$ value for Seg-1 of the 1875 phreatoplinian phase is similar to that of the subplinian phase and the proximal segments of Tarawera 1886 and Novarupta 1912 deposits (Table 5). Proximal Seg-1 extends to an equivalent distance of ~2.5 km which is reasonable given the location and circular nature of the proximal unit C isopachs. In
addition to the mechanism described for dry plumes, two further mechanisms are possible for phreatomagmatic plumes and these singly or together may push the outer limit of the over-steepened region further outward. To account for this over-thickening, we present here the proximal characteristics of the phreatoplinian deposits. The deposits of the proximal phreatoplinian fall contain minor lenses associated with weak, dilute density currents. Very few particle aggregates have been found in proximal, medial or distal areas. Although particle aggregates are not widely observed within the Askja phreatoplinian deposits, sedimentation of dry aggregates has been documented during many historical eruptions (e.g., the 1980 Mt St Helens and 1932 Quizapu eruptions; Sorem, 1982; Dartayet, 1932; Lunkenheimer, 1932) and it is considered that most fine-grained particles fall from plumes as aggregates (Gilbert and Lane, 1994). At Mt St Helens and Quizapu these aggregates fell from the umbrella cloud at distances from as little as 12 km, to greater than 300 km from vent. During wet eruptions accretionary lapilli have been observed to fall at much closer distances to vent (2 – 5 km) during phreatomagmatic eruptions (e.g., Sakurajima volcano, Japan; Gilbert and Lane, 1994). Accretionary lapilli have also been observed in the Initial Ash of the 181 AD Taupo eruption at distances of ~ 4km from source (Houghton, unpubl. data). The formation and sedimentation of particle aggregates close to vent suggests that they could form and be displaced from the vertical convecting column.

Talbot et al., (1994) described dilute density currents within the deposits of the Hatepe Plinian phase, which were distributed in tongue-like lobes extending from the inferred vent. These dilute density currents are described as short-lived events, driven by partial column collapses, but with low velocities (< 25 ms⁻¹) thought to be due to slight
fluctuations of the mass discharge rate, thereby affecting the water-magma ratio. Other historical eruptions have also documented phases of dilute density current deposition during sustained buoyant eruption columns where the common factor was some degree of magma:water interaction (e.g., Vulcan Rabaul, 1937, McKee et al., 1985). It is not possible to correlate the coarse cross-bedded lenses of pumice observed in the Askja phreatoplinian ash, and furthermore they have not breached the higher caldera topography, suggesting similarly to be emplaced by low velocity, dilute density currents. The lack of both thick sequences of dilute density current deposits and particle aggregates within phreatoplinian unit C in the proximal environment, do not account for the degree of over-thickening in this proximal environment.

To account for the degree of over-thickening of the Askja phreatoplinian deposits represented by Seg-1 in the semilog thickness vs. area^{1/2} graph, we suggest that two synchronous processes were occurring: First, that there were significant plume instabilities due to fluctuations in mass flux and therefore water:magma ratio, which produced minor dilute density current deposits shed from the jet and lower convective column margins, in addition to significant premature sedimentation of fine ash. Second, that the fine grain size of the phreatoplinian ash induced particle aggregation to occur and was a key factor in premature sedimentation of the phreatoplinian ash in the proximal environment. However as they are rarely observed, we suggest that these aggregates disintegrated on deposition.

The occurrence of over-thickened phreatomagmatic (Rabaul) and phreatoplinian deposits (Taupo and Askja) suggests that over-thickened proximal deposits may be common products of both small and large phreatomagmatic eruptions, driven by the high density
and thus inherent instability of 'wet' plumes (Koyaguchi and Woods, 1996). The delicate balance between buoyant plume formation vs. collapse for eruptions involving water favors complex intercalations of fall and dilute density current deposits either due to total or partial column collapse, but a lack of well-preserved proximal fall deposits for other wet eruptions, in particular the high intensity end-members, has led to few analogue case studies.

6.4 Wet eruption plume dynamics during the phreatoplinian phase

The formation of buoyant plumes occurred three times during this eruption, the high intensity sustained phreatoplinian C plume was preceded and followed by low and high intensity dry plumes. The proximal isopachs have different dispersal geometry in wet and dry phases; the phreatoplinian proximal isopachs are circular around a north-central location focused in the present-day lake, whereas the proximal isopachs from the dry phases are elongated, suggesting that even lower portions of the dry convective plumes were significantly affected by the wind. The circular nature of the phreatoplinian proximal isopachs shows the inability of low level winds to affect the wet plume and thus the wet plume had much greater upwind and crosswind penetration than the dry plumes of the surrounding phases.

In an attempt to constrain the amount of water within the phreatoplinian plume, we use historical reports and field observations of the deposits;

a. The phreatoplinian fall deposits are very fine-grained deposits with >99 % of the erupted material less than 1 mm in diameter (Sparks et al., 1981);
b. The absence of bedding and presence of thin lenses of lapilli within the phreatoplinian deposits;
c. Rare preserved particle aggregates in the proximal environment;
d. Vesiculated ash textures in medial/distal areas (~5 – 150 km from vent), note historical reports stating that the weather conditions were dry.
e. Historical accounts clearly indicate that the C1 tephra that fell in inhabited areas was wet and sticky.

The combination of our field observations (a), (b) and (c) suggest that throughout the duration of phreatoplinian volcanism, there was a high efficiency of fragmentation, only minor fluctuations of the discharge rate and that the water-magma mass ratio was fairly optimal in terms of efficiently converting external water into steam. The production of very fine ash (a) and rare preserved proximal aggregates (c) suggests that initially there was relatively little liquid water within the convective plume. Under these conditions it is likely that wet aggregates with high preservation potential were not formed, and possibly only dry or Sorem aggregates with little preservation potential were formed but disintegrated on deposition. Observations (d) and (e) suggest that as the plume became older and colder, condensation of H₂O vapor may have led to liquid water within the umbrella cloud.

6.5 Calculating tephra-fall volumes based on power-law and exponential thinning

The low intensity subplinian B phase of the eruption produced a deposit for which nine isopachs could be constrained, and power-law and exponential thinning methods give similar calculated volumes (Table 1a). Similar to the Ruapehu 1996 subplinian deposit
described by Bonadonna and Houghton (2005), the resolution of the power-law trend constrained by the large number of tightly-spaced isopachs together with the rapidly thinning nature of the deposit, leads to the power-law method being a valid method to calculate volumes.

The more widespread deposits from the Plinian and phreatoplinian phases also yield large datasets (13 and 16 isopachs respectively). Close to source the deposits are moderately-well described by a power-law trend that fails, however, to constrain the distal data (Figs. 14b, 14c). The entire datasets can only be adequately modeled by a segmented exponential thinning trend with four to five segments (Figs. 13b, 13c). The problem for both datasets lies in the distal field.

There are significant challenges in accurately using deposit data in thinning models to calculate volumes. In terms of the collection of data, it is important not only to constrain many isopachs, but also to have consistent intervals of isopach contours. An irregularity of contour spacing may lead to apparent deviation in thinning trend, in particular when using a power-law model.

The diversity of common processes operating in volcanic plumes will also present a challenge for deposit thinning models. The process of particle aggregation which occurs very commonly in plumes, can shift a power-law trend of thinning based on the particle Reynolds number described in numerical models, to a segmented exponential thinning trend (Bonadonna and Phillips, 2003) (e.g., 1980 Mt St Helens and 1932 Quizapu eruptions; Sorensen, 1982; Carey and Sigurdsson, 1982; Dartayet, 1932; Lunkenheimer, 1932). In addition, plume margin instabilities which are also common features of both dry, but particularly wet eruptions will inherently lead to the production of pyroclastic
density currents (e.g., Hatepe Plinian phase, Taupo 181 AD. Talbot et al., 1994; Vulcan, Rabaul, 1937, McKee et al., 1985; and Ukinrek Maars, Alaska 1977, Self et al., 1980) and the net effect is an over-thickening of the proximal deposits.

Secondary pyroclast transport after deposition is a natural process, however timescales are typically accelerated due to the alpine and harsh weather environments surrounding volcanoes. Manville et al., (2000) documents in detail the rapid rate and complexity of tephra-snow-water interactions and remobilization processes of primary deposits geographically, and with time (presently up to 12 years) at Ruapehu volcano after the subplinian eruptions of 1995 and 1996.

The region of 1875 tephra fallout is characterized by rain, snow and windy conditions, in combination with seasonal melting/freezing cycles. Hence, in the 133 years since this eruption, the degree of reworking and particularly erosion is expected to be high. Each of the processes described above was probably occurring either throughout, and after the eruption and it is difficult to assess the relative roles of each. Recent eruptions (<100 years) where the deposits are well preserved, deposited predominantly on land, and/or documented immediately, are more likely to follow the idealized power-law thinning trend defined by numerical models (e.g., Ruapehu volcano, New Zealand; Bonadonna and Houghton, 2005). However pre-historical eruptions are likely to be eroded and/or reworked and thus may be more suited to the application of a segmented exponential thinning method (e.g., Novarupta, 1912; Houghton et al., 2004).
6.6 Comparison of full data set with that of incomplete data sets where distal or proximal data are missing – using both power-law and exponential thinning methods

The Askja 1875 fall units have well constrained very proximal and far-distal thickness measurements and are thus particularly well-suited for comparison of volume calculations involving missing distal or proximal data, which is often the case for high intensity caldera-forming eruptions. In the following examples we simulate two separate scenarios; first, a situation analogous to the deposits of the Taupo 181 AD eruption, where Plinian and phreatoplinian deposits are not exposed less than 4 km from the inferred vent locations and thus no proximal data is available. Secondly, a theoretical case, in which there is no exposure of the 1875 deposits outside of Iceland (i.e., greater than 150 km from Askja caldera). For the subplinian scenario, we consider an option where no deposits observed at distances greater than 15 km from vent which is often the case for example for historical subplinian falls at Etna volcano (e.g., Branca and del Carlo, 2005).

Exponential thinning models applied to the 1875 units without proximal data < 4 km from vent produced volumes that were 99%, 87% and 105% of the actual volumes for the subplinian, phreatoplinian and Plinian units respectively (Figs 18a, 19a, 20a; Table 6). There was also a predictable reduction in the number of required exponential line segments of unit C to four. A power-law fit to the same data set produced volumes that were 92%, 89% and 84% of the actual volumes respectively (Figs 18b, 19b, 20b; Table 6).
Table 6: Volumes using the segmented exponential thinning model for each of the 1875 fall units, and comparisons to calculated volumes when proximal and distal data are missing using both power-law and segmented exponential thinning models. When the exponential thinning model is used on incomplete datasets, the number of recognized segments (listed in the left column) is typically reduced.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Volume (km$^3$)</th>
<th>% of actual volume</th>
<th>No. segments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Exponential model without proximal data</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit B</td>
<td>0.0142</td>
<td>99.3</td>
<td>3</td>
</tr>
<tr>
<td>Unit C</td>
<td>0.39</td>
<td>86.7</td>
<td>4</td>
</tr>
<tr>
<td>Unit D</td>
<td>1.49</td>
<td>105.0</td>
<td>4</td>
</tr>
<tr>
<td><strong>Power law model without proximal data</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit B</td>
<td>0.0131</td>
<td>91.7</td>
<td></td>
</tr>
<tr>
<td>Unit C</td>
<td>0.40</td>
<td>89.3</td>
<td></td>
</tr>
<tr>
<td>Unit D</td>
<td>1.15</td>
<td>83.8</td>
<td></td>
</tr>
<tr>
<td><strong>Exponential model without distal data</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit B</td>
<td>0.0030</td>
<td>21.0</td>
<td>2</td>
</tr>
<tr>
<td>Unit C</td>
<td></td>
<td>42.4</td>
<td>3</td>
</tr>
<tr>
<td>Unit D</td>
<td>0.61</td>
<td>44.5</td>
<td>3</td>
</tr>
<tr>
<td><strong>Power-law model without distal data</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit B</td>
<td>0.0060</td>
<td>42.0</td>
<td></td>
</tr>
<tr>
<td>Unit C</td>
<td>0.32</td>
<td>72.1</td>
<td></td>
</tr>
<tr>
<td>Unit D</td>
<td>1.88</td>
<td>128.5</td>
<td></td>
</tr>
<tr>
<td><strong>Actual volumes</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit B</td>
<td>0.0143</td>
<td>100.0</td>
<td>3</td>
</tr>
<tr>
<td>Unit C</td>
<td>0.45</td>
<td>100.0</td>
<td>5</td>
</tr>
<tr>
<td>Unit D</td>
<td>1.37</td>
<td>100.0</td>
<td>4</td>
</tr>
</tbody>
</table>
Figure 18: Semilog plots of thickness vs. area shown for the Unit B deposit, in two different scenarios: (a) and (b) no proximal data <4 km from vent; (c) and (d) no distal data >150 km from vent. Both segmented exponential (c) and (a) and power-law thinning models (b) and (d) are shown for comparison. Both models were unable to calculate accurate volumes when distal data were missing, resulting in very inaccurate calculations in (c) and (d). When proximal data were missing, both models calculated fairly accurate volumes, shown in (a) and (b). The segment number is shown.
Figure 19: Semilog plots of thickness vs. area\(^{1/2}\) shown for the Unit C deposit, for two different scenarios: (a) and (b) no proximal data <4 km from vent; (c) and (d) no distal data >150 km from vent. Both methods could not approximate the volume well where distal data is not available. However, the power-law method (d) was more accurate than the exponential method (c). In absence of proximal data, both methods resulted in similar values and slightly underestimate the true volume (a) and (b). The segment number is shown.
Figure 20: Semilog plots of thickness vs. area^{1/2} shown for the Unit D deposit, in two different scenarios: (a) and (b) no proximal data < 4 km from vent; (c) and (d) no distal data > 150 km from vent. Without distal data, the power-law method overestimates the volume, however the segmented exponential method severely underestimates the volume. Without proximal data, the power-law method underestimates the volume, and the segmented exponential thinning model slightly overestimates the volume. The segment numbers are shown.
Without the distal data sets, segmented exponential thinning produced volumes that were 21%, 42% and 45% of the actual volumes for the subplinian, phreatoplinian and Plinian units respectively, and a reduction of segments by one for each unit (Figs 18c, 19c, 20c; Table 6). A power-law fit without the distal data produced volumes that were 42%, 72% and 129% of the actual volumes respectively (Figs 18d, 19d, 20d; Table 6).

6.6.1 Summary

In summary, both the segmented exponential thinning and power-law methods generally underestimated the volume of the deposits when either proximal or distal data were not available. Both methods are only slightly sensitive to a poor record of proximal exposure but that loss of distal data has a drastic effect on volume calculations.

When proximal data (< 4 km) were missing, both techniques calculated the volume to within 17% of the true value. The exponential thinning model provided fairly good approximations of the true volume except for the Askja C phreatoplinian phase, because of significant proximal over-thickening with ~16% of the volume in the first segment (< 4 km). It appears that for units B and D, missing proximal data had a minor effect (+/- 5%). Using the power-law model, the loss of the proximal data for each of the units reduced the value of maximum thickness ($T_0$), and the $R^2$ fit, leading to an underestimation of the volume. The choice of power-law or exponential thinning models when proximal data are missing must be evaluated based on the remaining most distal data (i.e., degree of caldera collapse). It appears that a segmented exponential thinning model would best if; a) only few data are missing and b) there is no proximal over-thickening suspected.
When distal data were missing, the degree of underestimation using the segmented exponential method was a function of the volume represented in the last segment. For example, losing the two last distal segments for unit C and final segment of unit D, represents thicknesses of <0.5 and <2cm of tephra respectively, which are large components of the total volume (similarly with unit B, the distal segment is < 3cm-thick). If minimal distal ash is lost (e.g., 18 May 1980 Mt St. Helens tephra fall), exponential thinning is a good approximation. The power-law method is always difficult to apply when the distal data are missing. This is predominantly due to the difficulty extrapolating the thinning trend into the distal field and the fact that the volume calculation is very susceptible to the integration limits of C (observed distance of plume spreading). For reasonable limits of C, based on the artificially-constrained data (i.e., without distal data), the power-law method both greatly underestimated (unit B and C) and greatly overestimated (unit D) the volumes (Table 6).

This dataset broadly supports the studies conducted by Bonadonna and Houghton (2005) where a power-law thinning model is considered to be better suited to deposits for which distal data is missing, especially if it is possible to constrain the limit of downwind spreading of the umbrella cloud via satellite imagery. This method could also be applied in a setting where the approximate size/intensity of the eruption can be approximated, to interpolate the thinning trend into the distal field, and thus calculate an approximate volume. However there are some caveats to using the power-law method to estimate volume when data are missing; Firstly, if the intermediate data points cannot adequately define the zone of curvature for the power-law fit, (as also shown in Bonadonna et al., 1998) then this method would be extremely unreliable. Secondly, if the eruption is
prehistoric, then the choice of integration limit of maximum distance downwind of significant plume spreading \((C)\) will be problematic. However, ash shards in drill core, such as the 1875 ash found throughout Scandinavia and northern Germany may define the integration limit \((C)\), enhancing the reliability of the power-law method.

### 7.0 Conclusions

Our study focused on the dispersal characteristics of the main phases of the 1875 eruption of Askja volcano, and this, together with detailed historical observations, permits interpretations based on two major themes; first, transport and depositional characteristics of wet and dry eruption plumes and second, implications of the dispersal characteristics for eruption dynamics. The combination of very proximal and very far-distal data for this eruption has supplied a very detailed dataset which enabled us to test the validity of the segmented exponential thinning model for each of the 1875 fall units, make very accurate calculations of eruptive volumes and evaluate the bias of the volume data when proximal or distal data are missing.

Proximal exposures within \(> 1 \text{ km}\) from inferred vents have permitted us to conduct a detailed study of proximal deposition and transport in wet and dry plumes. We have identified very proximal over-thickening for each of the units of the main phases, regardless of style or intensity. For subplinian and phreatoplinian phases, the degree of over-thickening is greater than for the Plinian phase and is represented by a newly recognized segment, \(Seg-1\), on semilog plots of thickness vs. area\(^{1/2}\). The \(B_1\) values of \(Seg-1\) for these phases are less than \(Seg0\) for the 1932 Quizapu eruption, greater than those observed for cone-forming lower intensity basaltic eruptions, and similar to those
of the Tarawera 1886 proximal cones, and the 1912 Novarupta ‘ejecta ring’. SegO is thought to be related to sedimentation of particles from the upper eruption column margins, and we propose that Seg-1 for the dry subplinian phase is related to sedimentation from heights of a few kilometers, principally from the jet and lower convective plume margins. For the wet phreatoplinian phase, we propose that two processes were occurring simultaneously: transient dilute density currents coupled with premature sedimentation of fine ash. Our study suggests that heightened accumulations of particles of all grain sizes close to vent will occur for high intensity eruptions, regardless of wet or dry eruption styles. However, caldera collapse following large Plinian eruptions is very common and removes very proximal deposits, which hold important keys to eruption and eruption plume dynamics. A further ~500 radial meters of caldera widening would have destroyed the proximal exposures at Askja and we postulate that very proximal sedimentation during higher intensity eruptions are more common than documented in the literature. This dataset will supply input for the next phase of wet eruption plume models in addition to refinement of models concerning sedimentation from the unsteady jet and lower convective column margins.
CHAPTER 3
Abrupt shifts between wet and dry phases of the
1875 eruption of Askja Volcano: microscopic evidence for macroscopic dynamics

Abstract
The eruption of Askja in 1875 was a powerful eruption with intervals of sustained activity, yet also with abrupt shifts in eruption style, e.g., from dry to wet fall, from buoyant to collapsing column conditions, and sharp fluctuations of eruption intensity throughout its duration. Deep ascent processes, including decompression, bubble nucleation and early growth, were similar among the four main phases, regardless of wet or dry, buoyant or collapsing column conditions. Uniformly high vesicle number densities suggest that magma degassing throughout the eruption was a highly disequilibrium process with very high nucleation rates; Power law distributions of the subpopulations of small bubbles on cumulative number density plots suggest continuous nucleation of bubbles. Shallow processes of bubble growth and magma ascent were at times decoupled from deep ascent processes; at the onset of each phase, the erupted magma appears to have a mature vesicle signature, suggesting extended residence times in the shallow conduit, irrespective of decompression or magma ascent rate. Throughout a phase, the textural and density data suggest more uniform conditions of ascent and shallow degassing. Two pauses in the eruption are accompanied by shifts in vent position. We suggest that magma during this eruption was intruded in an elongated dike-like fashion and vent migrations between phases led to the eruption of magma that had slightly greater residence time and hence more mature textures. The major yet reversible
shifts between ‘dry’ or magmatic and ‘wet’ or phreatomagmatic eruption styles were driven by changing external conditions—the migration of the vent into and out of water sources, rather than by changes of mass flux. The shift between buoyant phreatoplinian wet plume conditions to the production of wet density currents was a function of vent widening during the high intensity phreatoplinian phase, thereby decreasing the exit velocity of the wet mixture. In terms of the role of external water in the phreatoplinian phase, our qualitative textural observations and quantitative suggests that the magma was a foam prior to fragmentation, however presently cannot resolve the exact role of the external water.

1. Introduction

Shifts between eruption styles, eruption intensities and degrees of interaction with external water are common features of high intensity silicic eruptions (e.g., Vesuvius 79AD, Sigurdsson et al., 1985; Hekla 1104 AD, Larsen et al., 1977; Taupo 181 AD; Houghton et al., 1995). Eruptions will exhibit a phreatomagmatic opening (e.g., Vesuvius 79AD, Sigurdsson et al., 1985; Taupo 181 AD, Houghton et al., 1995; Kaharoa 1305 AD, Nairn et al., 2003) and/or a shift from fall to flow conditions at the end of an eruption (e.g., Vesuvius 79 AD, Sigurdsson et al., 1985; Pinatubo 1991, Rosi et al., 2001; Taupo, 181 AD, Houghton et al., 1995). However, sharp fluctuations of eruption intensity and abrupt and reversible shifts between magmatic and phreatomagmatic styles, or fall and flow activity within sustained eruptions are far less systematic and hence, far more dangerous. Are such shifts driven by (i) conditions in the magma chamber, (ii) conduit dynamics, (iii) external factors, or some combination of these? Vesicularity studies of
Pumice have already been shown to provide a window into conduit dynamics, in particular the relative roles of nucleation, growth, coalescence and collapse of vesicles in the conduit in ‘driving’ explosive eruptions (e.g., Klug et al., 2002; Adams et al., 2006; Houghton et al., 2003; Sable et al., in press). External factors such as conduit and vent geometries, inferred from field mapping and componentry, also have a strong influence on eruption dynamics (e.g., Wilson et al., 1980; Mitchell, 2005), particularly on the mass discharge rate and eruption regime (e.g., Taupo 181 AD, Kaharoa 1305 AD, Furnas 1630, Azores; Cole et al., 1995). However the triggers for such abrupt shifts in style or intensity and the relative roles of external and internal factors remain poorly understood for many eruptions.

In this study, we examine in detail the products of four contrasting phases of different intensity and style during the sustained 1875 eruption of Askja volcano. Our study focuses on changes occurring within the conduit and vent environment both between, and within, single phases.

We aim to address the following questions through studies of vesicle populations and vesicularities of representative pumice clasts: First, were abrupt shifts in eruption style caused by changing conditions of magma ascent or were external factors such as vent geometry important? Second, what mechanisms drove fluctuations of eruption intensity on scales of minutes to hours? Third, were there any pauses in the eruption with time, and what were there causes?
1.1 Geological setting

Askja is the central volcano of the Askja volcanic system situated in the northern Volcanic Zone (NVZ) in Iceland which delineates the divergent plate boundary in north Iceland (Fig. 1). The volcanic system is 10 – 15 km wide and 100 km long, and the central volcano hosts three calderas, the second oldest (~ 10 ky) of which is 7 x 7 km wide and almost completely in-filled with post-glacial basaltic lavas (Fig. 2). The youngest caldera Óskjuvatn, is 3 x 4 km in size and formed after the powerful rhyolitic main phase of the eruption on 28th – 29th March, 1875. Post-glacial eruptive activity at Askja has produced extensive basaltic eruptions on ring fractures surrounding the older caldera, in addition to flank eruptions (Sigvaldasson, 1979, 2002; Thordarson et al., in prep). The young activity appears to be controlled by lithospheric extension producing an en echelon array of north-northeast to south-southwest trending fissures that cut the main caldera fault and ring fractures (Brandsdóttir, 1992). Precursory eruptive activity is associated with the rifting episode: at Sveinagjá and Fjárhólahraun, 40 and 5 km north of Askja, Holuhraun situated ~15 km south of the caldera in addition to minor explosive and effusive eruptions along ring fractures and structural faults within the caldera (Fig. 1: Sigurdsson 1978a, 1978b; Brandsdóttir, 1992; Sigurdsson, 1978a, b; Thordarson et al., in prep). Post-1875 events also include both explosive and effusive eruptions of basaltic magma in 1921-22, 1929, 1931 and 1961 (Sigvaldasson, 1979; 2002) (Fig. 2). All the pyroclastic vents that were active during the March 28th – 29th 1875 sequence are located within the present-day Lake Óskjuvatn (Carey et al., in review).
Figure 1: Geologic setting of the Askja volcano: The Askja central volcano is located on the Askja volcanic system in the North Volcanic Zone (NVZ). Askja Volcano is the central volcano of the Askja volcanic system, which is 15 wide x 100 km long. Sveinagjá, Fjárhóla and Holuhraun were sites of basaltic effusive eruptions associated with the Askja volcano-tectonic episode in the 1870's. The dispersal areas of 1875 tephra fallout across East Iceland is shown (0.33 km3 dense rock equivalent (DRE) after Carey et al., in review).
Figure 2: Map of the Askja volcano, including sites (black) of explosive and effusive basaltic volcanism post-dating the 28th - 29th March 1875 event and known vent sites of precursory activity in yellow. The volcano features two separate areas of contrasting geology; a mostly subglacial hyaloclastite formation that surrounds the Askja caldera (purple), and the Holocene basaltic lavas that partly in-fill the caldera (dark grey). The bounding fault of the Askja caldera is shown its position on the eastern side prior to March 1875 is highlighted by the red-shaded area. Note that most of the pre- and post 1875 activity is focused on Askja caldera fault margin, except for those situated on ring fractures of the younger Óskjuvatn caldera. The diagonal line across the 1875 Óskjuvatn caldera is later referred to in Figure 18.
1.2 Eruption Summary

On March 28th 1875, the eruption of Askja began and lasted for approximately 17 hours, depositing tephra (0.33 km$^3$ dense rock equivalent DRE) over eastern Iceland, Scandinavia and northern Germany (Sparks et al., 1981; Carey et al., in review). This eruption also produced 0.01 km$^3$ (DRE) of dilute density current deposits which were mostly confined to the caldera region. Many farms in Jökuldalur (≈ 50 km east of Askja) had to be abandoned after the eruption. The main eruption began at 9 pm with a subplinian phase that had a duration of approximately one hour. This phase produced a reversely graded, coarse pumice fall deposit. Underlying this layer at many proximal/medial locations is a thin very fine pumiceous ash that may reflect a brief phreatomagmatic opening to the main eruption. After a ~ nine hour pause in activity, a wet intense phreatoplinian phase began from a separate vent to the north west of the subplinian vent and lasted for ~ one hour (Thordarson et al., in prep; Carey et al., in review). This abrupt shift in style and intensity marks the first sharp change in eruption dynamics. A sustained phreatoplinian column produced fall deposits with minor dilute density current deposits confined within the caldera and attributed to slight fluctuations in eruption intensity and water-magma ratio (Carey et al., in review). After the phreatoplinian phase, farmers in eastern Iceland observed a two hour-long pause in activity between the phreatoplinian and Plinian fall (Thordarson et al., in prep), however in the proximal environment dilute density currents were emplaced. This abrupt shift from wet sustained buoyant plume conditions to a collapsing column is the second major change in eruption dynamics. The pyroclastic density currents are inferred to have originated from the phreatoplinian vent and their characteristics change with time,
becoming ash-poor and well-sorted, with bedforms that have increasing wavelengths and amplitudes. Strong seismicity then accompanied a second shift in vent location and the onset of the main Plinian phase characterized by a sustained high eruptive plume which lasted for approximately five to six hours (Carey et al., in review). The beginning of this final phase marks the third major shift in eruption dynamics in the main eruption.

1.3 Eruption stratigraphy

Initial studies conducted by Self and Sparks (1978), recognized that this eruption was one of few that included a wet, highly intense phase for which they coined the phrase ‘phreatoplinian’. Self and Sparks (1978) proposed an initial stratigraphy of the products from the main, pre- and post eruptive events based on the proximal products, dividing the entire stratigraphy into eight units. Four of these units were produced during the main eruption on March 28\textsuperscript{th} – 29\textsuperscript{th} 1875. Sparks et al., (1981) developed the framework for the eruption with studies of the proximal, medial and distal areas in Eastern Iceland, in addition to integrating historical records of the eruption. Further studies conducted by Carey et al., (2007a) adapted the original stratigraphic nomenclature of Sparks et al., (1981) but divided the dilute density current deposits (C2) into three main flow units and identified five sub-units within the Plinian unit D (Fig. 3).

1.4 Deposit characteristics

The March 28\textsuperscript{th} – 29\textsuperscript{th} 1875 deposits are well exposed along the caldera rim, and fall units are dispersed toward the east (Sparks et al., 1981; Carey et al., in review). The first unit B
Figure 3: The stratigraphy of the deposits formed in the main eruption (28th - 29th March 1875). This stratigraphy was originally adapted from Self and Sparks (1978) and Sparks et al. (1981) with revision by Carey et al. (2008a). Ten samples were taken from these four units for vesicularity studies (as shown by grey brackets).
is a subplinian fall deposit (0.004 km$^3$ DRE), with a more limited dispersal than the following fall phases. Dispersal characteristics and isopach data are presented in Carey et al., (in review). This unit is a well-sorted pumice fall deposit with a lithic content of up to 25 modal wt%, comprising basaltic lava, hyaloclastite and obsidian fragments.

The phreatoplinian fall deposit C1 directly overlies the subplinian fall deposit and is dispersed over eastern Iceland and extends to Scandinavia (e.g., Sparks et al., 1981; Carey et al., in review). Grain size analyses conducted by Sparks et al., (1981) suggest that 99 wt% of this deposit is < 1mm. The dilute density current deposits of C2 were emplaced following the cessation of phreatoplinian fall and are largely confined to the caldera region. Carey et al., (in review) observed three flow units within the C2 deposits in the proximal area based on the abundance of ash, presence of well-sorted lapilli beds, and bedform wavelength, angle and amplitude. Subsequently these have been named lower (LC2), middle (MC2) and upper (UC2), adhering to the original Sparks et al., (1981) nomenclature. In the proximal region, the D Plinian deposits can be divided into five separate sub-units; D1, D2, D3, D4 and D5. D1, D3 and D5 are widespread, with thinning half-distances ($B_1$) of 3 – 4 km, whereas the D2 and D4 deposits have $B_1$ values one to two orders of magnitude less (10s to 100s of meters; Carey et al., 2007a). These more locally dispersed sub-units were inferred to have been produced by separate vents further to the north that had a fountaining eruption style (northern W on Figure 4) (Carey et al., 2007a, b). In the medial and distal environments, D1, D3 and D5 merge into a single reversely graded fall unit (unit D). The Plinian D deposits are also dispersed over eastern Iceland and extend over to Scandinavia (Sparks et al., 1981; Carey et al., in review).
Figure 4: Present form of Öskjuvatn caldera (dashed line) and also shown is the early developing form of the caldera in 1876 as reconstructed by Jónsson (1942) based on descriptions made in 1876 by Johnstrup (1877, in white). Observations document a depression, with three fracture swarms: one to the southeast, one to north and one to the west-northwest. The 'small pond' of water observed was located at the junction of thee fracture swarms. B, C and D are our inferred vent positions; W, the locations for fountaining vents active during the D phase (Carey et al., 2007a, b). The older Askja caldera marginal fault is shown in red and the areas of contrasting geology as shown in Figure 2.
1.5. Summary of eruption dynamics

The wealth of historical drawings and descriptions made prior to, during and after the main eruption have led to an extra source of important information that is rarely available to volcanologists working on other historical eruptions. These observations, together with modern techniques used to calculate deposit volumes, and eruption intensities etc, allowed Carey et al., (in review) to estimate durations and constrain fairly accurately the chronology and intensities of each phase of the eruption. In addition, field observations and deposit characteristics also help to constrain eruption process. These combined datasets have all been considered in the following discussion of eruption dynamics.

1.5.1 Changes in eruption intensity

This eruption is characterized by three sharp, abrupt and reversible shifts in eruption intensity and here we summarize each change in eruption dynamics, in terms of field characteristics and intensity data Carey et al., (in review) (Table 1).

1.6 Vent location and timing

Vents active throughout the main eruption are presently located within Lake Öskjuvatn. Observations made after the main eruption document a triangular depression with three fracture swarms extending outwards from the centre of the depression: one to the southeast, one to north and one to the west-northwest (Fig. 4; Watts, 1876; Johnstrup, 1877, 1876). Studies conducted by Carey et al., (in review) defined the vent locations within this depression (Fig. 4).
Table 1: Summary table of eruption characteristics of the four phases of the main 1875 eruption taken from Carey et al., (in review). Mass discharge rates (MDR) and volumetric discharge rates (VDR) are shown.

<table>
<thead>
<tr>
<th>Eruptive phase</th>
<th>sub-unit</th>
<th>Duration</th>
<th>MDR</th>
<th>VDR</th>
<th>Deposit description, changes within phases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plinian D</td>
<td>D5</td>
<td>5.5 hours</td>
<td>$2.5 \times 10^7$</td>
<td>$6.9 \times 10^4$</td>
<td>Vent opening phase, sustained throughout duration reverse grading suggests increasing intensity with time</td>
</tr>
<tr>
<td>Plinian D</td>
<td>UD3</td>
<td></td>
<td>$3.5 \times 10^7$ (peak)</td>
<td>$9.5 \times 10^4$</td>
<td></td>
</tr>
<tr>
<td>Plinian D</td>
<td>LD3</td>
<td>peak 4 hours</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plinian D</td>
<td>D1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PDC C2</td>
<td>UC2</td>
<td>2 hours</td>
<td>$2.3 \times 10^6$</td>
<td>$3.9 \times 10^3$</td>
<td>Episodic changes of mass flux, dilute density currents spread radially from a point source. Currents become dryer with time, suggesting decreasing influence of water</td>
</tr>
<tr>
<td>PDC C2</td>
<td>MC2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PDC C2</td>
<td>LC2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phreatoplinian C1</td>
<td>UC1</td>
<td>1 hour</td>
<td>$6.8 \times 10^7$</td>
<td>$1.2 \times 10^5$</td>
<td>Vent opening phase, short-lived instabilities of plume margins due to minor fluctuations of mass flux and magma-water ratio</td>
</tr>
<tr>
<td>Phreatoplinian C1</td>
<td>LC1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subplinian B</td>
<td>B</td>
<td>1 hour</td>
<td>$2.6 \times 10^6$</td>
<td>$3.9 \times 10^3$</td>
<td>Vent opening phase, sustained throughout duration increase in intensity with time</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The subplinian vent was located within the NW-SE trending fault swarm and is the eastern-most vent position throughout the eruption (B on Figure 4). The proximal phreatoplinian circular isopleth and isopach data were difficult to interpret to define a vent position due to the inability of the wind to affect the wet plume (Carey et al., in review). However the wet nature of the dilute density currents suggests that they were erupted from a geographically similar position to the vent producing the wet phreatoplinian ejecta (C on Figure 4). The directionality of the density currents points to a central north region in the present-day lake, which is within the upper portion of the old caldera fault region. Descriptions of a small pre-existing pond of surface water are also coincident with this location. Sharp unconformities between the pyroclastic density currents and the Plinian deposits suggest severe ground shaking in between these two phases. Componentry and dispersal data of unit D deposits suggest a vent location in the mid to southern extent of the old caldera fault region (D on Figure 4) (Carey et al., in review).

1.7 Chemistry

Petrological and geochemical studies of the 1875 deposits were conducted by Sigvaldasson (1979), Sigurdsson and Sparks (1978a, b) and Macdonald et al., (1987). The bulk of the magma erupted during the main phase ranged in silica content (whole rock SiO₂: 68 – 75 % and glass SiO₂: 70 – 75 %), however no patterns of changing silica content with time were observed. The phenocrysts are typically < 1mm, unzoned and subhedral to round, and contain common inclusions of pale brown rhyolite glass (Sigurdsson and Sparks, 1978b). Geothermometry studies by Sigurdsson and Sparks
(1978b), suggest crystallization temperatures of 990 – 1050 °C. Mineral to liquid phase relations indicate crystallization in water saturated conditions (P_{H_2O}) = 500-1000 bars, corresponding to saturated water content of 3 wt%. The petrological data have been interpreted to indicate pre-eruptive injection of fresh basaltic magma into the crustal chamber beneath Askja, heating and partly mixing with an existing rhyolite body at the top of the chamber, thereby leading to the climactic eruption on 28th – 29th March 1875 (Sigurdsson and Sparks, 1978b).

2.0 Methods

At two proximal sections, ten samples were collected throughout the stratigraphy of the main phase, each containing at least 100 pumice clasts in the 16 to 32 mm size range. One sample was collected from the unit B deposits, two samples from the upper and lower C1 deposits, three samples from C2 and four samples from D (Fig. 3). Care was taken not to collect samples from the D2 and D4 sub-units, due to contamination by pumices from other vents (Carey et al., 2008a, b).

The bulk densities of these pumice clasts were measured using the techniques of Houghton and Wilson (1989) and converted to vesicularities using an average bulk density of 2350 kgm\(^{-3}\) based on density measurements of 1875 rhyolitic obsidian. The distribution of densities per sample was binned and plotted on histograms so that individual clasts could be chosen for microtextural studies. We selected 5 - 10 pumice clasts from each sample representing the mode and low/high vesicularity tails. The largest clasts were chosen to attain the maximum thin-sectional area, and were cut in a plane along the longest axis. Care was taken not to thin section pumices with elongated
(or tube-like) vesicles. The lowest magnification images (4.5x) were collected by scanning the thin sections on a Hewlett-Packard flatbed scanner at 1200 dpi resolution to collect and include the largest vesicles in the analyses. Eighteen backscatter electron images from each clast were taken on a JEOL-5900LV scanning electron microscope operating at a 20 kV accelerating voltage and 1 nA beam current. These images were then transformed into binary images in order to measure bubble diameters in two dimensions (on image magnifications of 4.5x, 25x, 100x, 250x, 500x). Two-dimensional size distributions (Number per unit area, $N_A$) were then converted to volume distributions (number per volume, $N_V$) using the stereological conversion method of Sahagian and Proussevitch (1998). Vesicle number densities were also recalculated with reference to the melt volume ($N^m_V$) to avoid underestimating nucleation densities of highly vesicular samples (after Klug et al., 2002). The Askja pumices have < 0.5% phenocrysts in them and no microlites (Sigurdsson and Sparks, 1981) and thus crystal abundance and size distributions were assumed to be negligible.

3.0 Results

3.1 Clast textures

Clasts in each of the samples (B, L1, UC1 etc.) collected throughout this eruption were separated into two end-member groups; clasts that had an elongated fabric, i.e., consisting of stretched tube vesicles (tube pumices) and clasts that had no fabric, i.e., with a heterogeneous assortment of bubble sizes and equant, broadly elliptical shapes (equant pumices) (e.g., Pollacci et al., 2001, 2003). Generally samples had < 30 wt% of tube
pumices, however for the final C1, two pyroclastic density current (MC2, UC2) and final D samples (D5), percentages increased to between 41 and 74 wt% (Table 2).

**Table 2**: Textural and density data for each sample taken from the 1875 eruption deposits. The number and wt% of tube vs. equant pumices in each sample are listed, in addition to the mean, average of the three minimum and average of the three maximum clasts. The grey shaded samples are observed to have higher abundances of tube pumices than samples at the onset of a phase.

<table>
<thead>
<tr>
<th>Eruptive Phase</th>
<th>sub-unit</th>
<th>equant no.</th>
<th>tube no.</th>
<th>equant wt%</th>
<th>tube wt%</th>
<th>mean density kgm$^{-3}$</th>
<th>3 min kgm$^{-3}$</th>
<th>3 max kgm$^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plinian D</td>
<td>D5</td>
<td>31</td>
<td>69</td>
<td>26</td>
<td>74</td>
<td>580</td>
<td>270</td>
<td>1130</td>
</tr>
<tr>
<td>Plinian D</td>
<td>UD3</td>
<td>69</td>
<td>31</td>
<td>73</td>
<td>27</td>
<td>350</td>
<td>210</td>
<td>620</td>
</tr>
<tr>
<td>Plinian D</td>
<td>LD3</td>
<td>70</td>
<td>30</td>
<td>72</td>
<td>28</td>
<td>330</td>
<td>190</td>
<td>600</td>
</tr>
<tr>
<td>Plinian D</td>
<td>D1</td>
<td>81</td>
<td>19</td>
<td>79</td>
<td>21</td>
<td>400</td>
<td>190</td>
<td>730</td>
</tr>
<tr>
<td>PDC C2</td>
<td>UC2</td>
<td>53</td>
<td>47</td>
<td>53</td>
<td>47</td>
<td>320</td>
<td>190</td>
<td>570</td>
</tr>
<tr>
<td>PDC C2</td>
<td>MC2</td>
<td>42</td>
<td>58</td>
<td>33</td>
<td>66</td>
<td>320</td>
<td>150</td>
<td>640</td>
</tr>
<tr>
<td>PDC C2</td>
<td>LC2</td>
<td>78</td>
<td>22</td>
<td>79</td>
<td>21</td>
<td>330</td>
<td>120</td>
<td>890</td>
</tr>
<tr>
<td>phreatoplinian C1</td>
<td>UC1</td>
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<td>32</td>
<td>58</td>
<td>41</td>
<td>310</td>
<td>180</td>
<td>680</td>
</tr>
<tr>
<td>phreatoplinian C1</td>
<td>LC1</td>
<td>73</td>
<td>27</td>
<td>73</td>
<td>27</td>
<td>380</td>
<td>220</td>
<td>740</td>
</tr>
<tr>
<td>subplinian B</td>
<td>B</td>
<td>79</td>
<td>21</td>
<td>81</td>
<td>19</td>
<td>340</td>
<td>170</td>
<td>590</td>
</tr>
</tbody>
</table>

### 3.2 Clast density and vesicularity

The samples collected throughout the stratigraphy are all extremely unimodal in comparison to other Plinian eruptions, with very narrow ranges of clast density (total range 200 – 1200 kgm$^{-3}$; 41-92 % vesicularity) and low density modal peaks (300 – 600 kgm$^{-3}$; 75-87 %) (Fig. 5a; Table 2). The unit B sample is unimodal with a mean density of 340 kgm$^{-3}$ (85 %) and a very narrow range of density values (160 – 610 kgm$^{-3}$; 74-93 %). The transition between subplinian and phreatoplinian phases (after a ~9 hour-long
pause) is marked by a widening of the range of density values (220 – 850 kgm$^{-3}$; 63-91 %; Fig. 5b) and a slight increase in the mean density (380 kgm$^{-3}$; 84 %) but a similar modal density (Fig. 5a; Table 2). Within the phreatoplinian phase, the mean density decreases to 310 kgm$^{-3}$ (87 %) and the range of density values decreases dramatically, with the narrowest distribution of density of the entire eruption (160 - 440 kgm$^{-3}$; 81-93 %; Fig. 5b) . The transition to the pyroclastic density current phase is marked by a broadening of the density range (180 - 1100 kgm$^{-3}$; 53-92 %), but similar mean density values (330 kgm$^{-3}$, 86 %). Throughout the pyroclastic density current phase, the range of density values decreases, skewed to lower density clasts (180 – 620 kgm$^{-3}$; 74-92 %; Fig. 5b), the mean density decreases slightly (320 kgm$^{-3}$; 86 %), however the modal density remains similar (Fig. 5a; Table 2). The switch to Plinian activity is marked in the clast density data by an increase in the range of clast density, skewed to higher density clasts (250 - 740 kgm$^{-3}$ 69-89 %), coupled with an increase in mean clast density (400 kgm$^{-3}$; 83 %) . The middle two samples of the Plinian phase have lower mean densities (330 and 350 kgm$^{-3}$; 85-86 %) than the lower and upper samples of this phase (400 and 580 kgm$^{-3}$; 75-83 %) (Fig. 5b; Table 2).

**Interpretation**

The ten density samples collected have very similar narrow unimodal peaks at relatively low densities (Fig. 5a). On a global scale, the narrow unimodality of these samples is unique, and for comparison representative histograms of Plinian and Phreatoplinian phases of the 181 AD Taupo eruption are shown here (Fig. 6; Houghton et al., 2003). This narrow unimodality suggests that the magma ejected in each phase of the 1875
Figure 5: a) Clast density histograms from each of the 10 samples identified in Figure 3. For comparison of density histograms between consecutive phases, the final sample from the phreatoplinian (UC1) and pyroclastic density current (UC2) phases are shown twice. The stars show where representative clasts were taken from for qualitative textural analyses. The black star is the location of the pumice clast used in the quantitative analyses for each sample. The selected sample is very representative of the bulk of the magma erupted at that time, due to its location for most samples on the modal peak, in addition to the narrow unimodality of most clast histograms. Note the similarity of clast histograms from the wet phreatoplinian and dry Plinian samples.
Figure 5: b) Sample density distribution vs. normalized stratigraphic height for ten samples collected throughout the main eruption stratigraphy. The mean, average 3 minimum and average 3 maximum density clasts have been plotted for each sample, in addition to one standard deviation of the mean density. Note at the onset of a phase, a greater mean and range of clast densities skewed to higher values and also a reduction of the range of clast densities as a phase progresses. The exception is the final Plinian sample, which represents the end of the eruption.
Figure 6: Clast density histograms of the Askja 1875 and Taupo 181 AD phreatoplinian phases (Rotongaio and Hatepe ashes). The Askja phreatoplinian samples are uniquely unimodal with respect to the Taupo phreatoplinian examples, which have clast densities skewed to much higher values.
eruption was exceptionally uniform, and that within and between phases, processes were broadly similar. Exceptions are the histograms representing each onset of a new phase, which have broader distributions than those following within the same phase (Fig. 5a). In all three examples (C1, LC2 and D1) the distributions broaden due to an influx of higher density clasts (Figs. 5a, 5b). These trends suggest that the magma erupted at the onset of every phase had a slightly different and somewhat more diverse history. Within phases, the range of clast densities and unimodality of the density distributions both narrow. This trend suggests increasingly uniform conditions of vesiculation with time (Figs. 5a, 5b). The exception provided by the final Plinian sample (Fig. 5a) is very important. It shows the broadest span of density data with the mode displaced significantly (Figs. 5a, 5b). This has important implications for increasing heterogeneity and maturity of the magma in the closing stages of the eruption.

3.3 Vesicle data

3.3.1 Qualitative observations

Observations of vesicle textures are key to understanding roles of the vesiculation process and relative timescales of ascent and degassing (e.g., Cashman and Mangan, 1994; Mangan and Cashman, 1996). Here we describe key features of selected pumice clasts in every unit, including vesicle size, shape and habit for every unit of this eruption. Due to the narrow unimodality of the clast density histograms, all clasts were chosen to represent the bulk of the magma erupted and hence were selected from the modal density range.

Subplinian unit B
Pumice textures from the subplinian phase are relatively uniform among samples and are characterized by zones of highly coalesced intermediate sized bubbles (75 – 175 µm) with round or concave walls and coarse (> 175 µm) bubbles that have polylobate and convoluted shapes reflecting coalescence (see 100x unit B image in Fig. 7). This population of coalesced bubbles is often clustered into domains separated from one another by zones characterized by small (5 – 25 µm) round bubbles. Bubble walls range between 1 and 13 µm thick (predominantly 6 - 13 µm).

**Phreatoplinian unit C1**

Upper and lower samples were collected from the phreatoplinian unit to characterize both the onset and final stages of this highly explosive phase. There are significant contrasts in pumice textures between the previous unit B subplinian sample and the early phreatoplinian sample (LC1) erupted ~ nine hours later. The LC1 sample has a much more numerous population of small round 5 – 25 µm bubbles, often clustered around neighboring large coalesced polylobate bubbles, and similar abundances of intermediate-sized coalesced bubbles which show either round shapes or have concave walls (Fig. 7). Bubble wall thicknesses range from 1 to 13 microns, but are predominantly 8 -13 µm thick. The UC1 sample has a higher abundance of 5 – 25 µm bubbles, which are round and distributed evenly around larger bubbles (75 – 250 µm) (Fig. 7). Larger bubbles commonly have irregular sharply concave shapes and broken, round retracted bubble walls. Regardless of bubble size and abundance, bubble walls are thick with respect to all previous samples ranging between 3 and 18 microns, but predominantly 8 - 14 µm.

**Pyroclastic density current phase C2**
Figure 7: Scanning electron microscope images of representative pumices of the ten samples collected throughout the deposits of this eruption. The magnifications of each image are shown at the bottom of this figure. The glass is white, and the bubbles are black in each image.
The transition between phreatoplinian fall and lower C2 density current phases is recorded in pumice textures by a decrease in the complexity of bubble shape, a decrease in the abundance of small bubbles, and an increase in the number of intermediate-sized bubbles. Bubble wall thicknesses are slightly less, ranging from 2 to 10 µm (Fig. 7). Textures in the MC2 sample is very different from the LC2 sample; Two distinct textures are observed in images; a texture characterized by intermediate to coarse bubbles that are polylobate or have concave walls, with very few small bubbles and relatively thin walls (2 – 8 µm); and a texture dominated by small round bubbles with thick bubble walls (5 – 10 µm) (see 250x image in MC2; Fig. 7). The textures of the UC2 sample is distinct from all earlier pumices, dominated by homogeneously distributed intermediate to coarse bubble sizes that are predominantly round to sub-round, and bubble walls that have extremely variable thicknesses. Coalescence textures, such as very thin convoluted walls, are common, in addition to smaller elongated bubbles aligned along the edges of much larger coalesced bubbles.

*Plinian phase D*

The transition to the Plinian phase is extreme as seen in pumice textures. The major differences between UC2 and D1 pumice textures include: increase in abundance of both small round bubbles and coarse coalesced bubbles with concave walls or polylobate shapes; development of coalescing bubble trains at the expense of the round intermediate-sized bubbles; a general increased thickness of bubble walls (8 – 15 µm); and the separation of smaller and larger bubbles into domains observed at all magnifications (Fig. 7).
The LD3 pumice textures are homogeneous with abundant small to intermediate-sized bubbles, which are round to sub-angular, and minor coarse bubbles with irregular shapes. Bubble walls are thinner than those of the earlier pumices, but are variable, ranging from 2 to 15 µm thick (Fig. 7).

The UD3 pumice textures have an increased abundance of small bubbles and show zones characterized dominantly by small to intermediate sized round bubbles with 2 - 10 µm thick walls, and zones of clustered intermediate to coarse bubbles with thin bubble walls (2 - 5 µm), which are round to sub-angular (Fig. 7). The D5 sample has similar textures to those of the LD3 and UD3 pumices described above. However, the zones of intermediate to coarse bubbles dominate, the coarse bubbles are larger and extend to very coarse bubbles (> 2mm), and the abundance of small bubbles has decreased significantly (Fig. 7). Pumice trains are common and there is a slight elongation fabric to the pumice textures.

**Interpretation**

Pumices from Unit B show moderate-high degrees of coalescence, and the lack of small bubbles is suggestive of a mature bubble population, i.e., one reflecting extended time for vesiculation. Pumice textures of clasts within the early phreatoplinian phase (LC1) have much higher numbers of smaller bubbles than the preceding phase (B), but lower degrees of coalescence as shown by a decrease in the median diameter, suggesting less time for vesiculation and residence time than the subplinian magma (Table 3). Pumice textures change significantly within the phreatoplinian phase; bubble wall thickness increases significantly, small bubbles dominate pumice textures, with relatively few intermediate-sized coalesced bubbles, and bubble shapes at all size ranges become complex and
irregular with concave walls. This combination suggests a complex ascent history for the late-stage phreatoplinian magma.

The transition to the pyroclastic density sample (LC2) is shown by an increase in both the large coalesced bubbles and continued high abundances of small bubbles. MC2 textures have similar populations of bubbles to LC2, but have larger domains dominated by large numbers of very small to small bubbles. UC2 textures are dominated by intermediate to large coalesced bubbles and thick bubble walls, suggesting high degrees of coalescence and some bubble collapse. The LC2 and MC2 textures are much different from those of UC2, and suggest that the early magma had a shorter residence time than later within that phase. The early Plinian textures (D1) have a bimodal bubble population with discrete populations of round bubbles and polylobate large coalesced bubble trains. Bubble walls are generally thick but variable from 5 to ~20 µm. This bimodal bubble size distribution implies a complex history of magma ascent. The textures observed in the two middle Plinian samples (LD3 and UD3) show a progression to a heterogeneous assortment of bubble size and bubble wall thickness. The dominance of intermediate-sized bubbles with predominantly round shapes and persistence of small round bubbles in both LD3 and UD3 pumices suggest fairly uniform conditions of fast magma ascent, and relatively little time in the shallow conduit for large-scale bubble coalescence. The textures in the final Plinian sample (D5), including large polylobate bubbles, bubble trains and relatively few small bubbles suggest that there was time available for advanced coalescence in the shallow conduit.
Table 3: Table of quantitative vesicle parameters for the 1875 deposits. Eighteen images were processed for each unit.

<table>
<thead>
<tr>
<th>Eruptive phase</th>
<th>sub- unit</th>
<th>Density kgm(^{-3})</th>
<th>Vesicularity %</th>
<th>(N_{A}) total cm(^{-2})</th>
<th>(N_{V}) total cm(^{-3})</th>
<th>(N_{V}^{m}) total (no/cm(^{3})/cm)</th>
<th>size range (microns)</th>
<th>Median (microns)</th>
<th>No. included</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plinian D D5</td>
<td>580</td>
<td>77.6</td>
<td>1286</td>
<td>1.6E+08</td>
<td>7.1E+08</td>
<td>3.5 E+7</td>
<td>4 - 4883</td>
<td>316</td>
<td>1233</td>
</tr>
<tr>
<td>Plinian D UD3</td>
<td>350</td>
<td>85.2</td>
<td>1549</td>
<td>2.0E+08</td>
<td>1.4E+09</td>
<td>3.7 E+7</td>
<td>4 - 3665</td>
<td>180</td>
<td>1547</td>
</tr>
<tr>
<td>Plinian D LD3</td>
<td>330</td>
<td>88.1</td>
<td>901</td>
<td>1.2E+08</td>
<td>1.0E+09</td>
<td>1.8 E+7</td>
<td>4 - 3833</td>
<td>200</td>
<td>943</td>
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<td>1121</td>
<td>2.0E+08</td>
<td>1.3E+09</td>
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<td>4 - 2766</td>
<td>350</td>
<td>1471</td>
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<td>320</td>
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<td>1.3E+08</td>
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<td>350</td>
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<td>225</td>
<td>1793</td>
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<td>843</td>
<td>1.1E+08</td>
<td>9.0E+08</td>
<td>5.5E+7</td>
<td>4 - 2755</td>
<td>360</td>
<td>1882</td>
</tr>
</tbody>
</table>

DRE value used 2350 kgm\(^{-3}\) to calculate vesicularities. \(N_{A}\) total is the number of vesicles per unit area.

\(N_{V}\) total is the volumetric number density of vesicles referenced to the whole clast.

\(N_{V}^{m}\) total is the volumetric number density of vesicles referenced to melt only. \(n\) is the population number density.
3.3.2 Quantitative vesicle data

We have examined quantitative vesicularity data from 21 clasts, each of which was taken from the unimodal density peaks identified in Figure 5a.

**Total number densities**

Number densities for the Askja samples are very uniform regardless of eruption style or intensity and despite the diversity of vesicle textures described in section 3.3.1 (Table 3). The initial and final samples (subplinian B and Plinian D5) have number densities that are slightly lower than those of the remaining eight samples of the main phase. Within the remaining samples, number densities range from only 1.0 to $2.1 \times 10^9$ cm$^{-3}$ compared to, for example, $1.4 \times 10^8$ to $3.9 \times 10^9$ cm$^{-3}$ for the 79 AD Vesuvius eruption (Gurioli et al., 2005), or $3.7 \times 10^8$ to $3.5 \times 10^{10}$ cm$^{-3}$ for the 6900 BP Mt Mazama eruption (Klug et al., 2002). The samples of the phreatoplinian phase (C1) have number densities of 1.5 and $2.1 \times 10^9$ cm$^{-3}$; pyroclastic density current samples (C2) show a progressive decrease in number densities from $2.4 - 2.0 - 1.1 \times 10^9$ cm$^{-3}$; Plinian samples (D) (with exception of the final sample D5) are very uniform, with numbers between 1.0 and $1.4 \times 10^9$ cm$^{-3}$.

**Vesicle size distributions**

Vesicle size distributions (VSD’s) can be used to assess the changes in rates of nucleation, growth and coalescence, throughout an eruptive sequence. The vesicle size distributions are shown for all representative clasts, grouped by phase (Fig. 8). These graphs are natural log plots (In) of population density (no. vesicles/mm$^3$/mm) versus equivalent vesicle diameter. With conditions of steady-state nucleation and growth, growth rate is independent of vesicle size and results in exponential size distributions.
Figure 8: Vesicle size distributions (\( \ln(n) \) vs. \( L \)) for all representative pumices, which have been grouped into phases. All of these samples show one curved segment suggesting non-steady state conditions of nucleation and growth, which is similar to that observed for other silicic powerful eruptions (e.g. 6900 BP Mt Mazama, Klug et al. 2002; Vesuvius 79 AD, Gurioli et al. 2005).
which would plot as single straight line segments (Mangan and Cashman, 1996). Size data for each of the measured clasts of this eruption are remarkably non-linear and decline as one curved segment, similar for example, to those observed for the phreatoplinian clasts of the 181 AD Taupo eruption (Houghton et al., 2003), and the Mount Mazama pumices (Klug et al., 2002).

The size distribution of vesicles are also examined by log plots of $N_{m_v}(>L)$ versus $L$, where $N_{m_v}(>L)$ is the melt-corrected number density (No./cm$^3$) of vesicles greater than diameter $L$. Linear trends on these graphs indicate power law relationships between these two parameters, which is always observed for powerful silicic eruptions (i.e., Cashman and Klug, 1995; Adams et al., 2006; Klug et al., 2002) and in samples of basaltic composition (e.g., Gaonac’h et al., 1996; Sable et al., in press). Each of the Askja clasts plot as two or three separate segments that define power-law relationships (Fig. 9). For all phases, the first segment representing the smaller bubble population defines a best-fit line with slopes (i.e., exponents) between 1.6 and 2.1 ($R^2$ values > 0.99) (Fig. 9; Table 4). All clasts have at least one additional linear segment, with best-fit lines with exponents of 2.3 to 5.1 (Table 4). The final pyroclastic density current sample (UC2) has an extra segment, representing coarse bubbles, with an exponent of 4.4, and the transition between the two occurs at 500 µm (Table 4). The power-law distributions with 2 - 3 discrete segments suggests multiple bubble populations.
Figure 9: Log plots of $N_m^v (> L)$ vs. $L$ (the melt corrected number density (No./cm$^3$) of vesicles greater than diameter $L$) from all representative samples. The first segment for all samples is shown in pink, and the power law exponent also in pink; The second segment and power law exponent is shown in blue; the third segment (UC2 only) and power law exponent is shown in green. $R^2$ values for each of these fits is > 0.99.
Table 4: Power law exponents of individual segments as shown on plots of N_{mv} (>L) vs. L for each pumice sample. The bubble diameter at which the two populations (i.e., two power-law segments) intersect (i.e., 1 – 2) is listed in microns.

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<th>Eruptive phase</th>
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Vesicle volume distributions

Vesicle volume distributions (VVD’s) also support the suggestion that all clasts have multiple bubble populations. The advantage of VVD’s (where volume fraction is plotted against vesicle equivalent diameter) is that the relative contribution of each bubble size fraction to the total population can be clearly identified. This is particularly useful with polymodal samples, as well as for assessing relative contributions of nucleation, growth, coalescence processes, and for comparison with other samples. The subplinian (B) pumice has a weakly polymodal VVD, with a dominant mode at 720 µm, while weak subordinate peaks exist at 15 and 80 µm (Fig. 10). This pumice has a predominance of
bubbles in the very narrow 250 µm to 1.25 mm size range, and unlike all other samples taken from this eruption, no tail of coarse bubbles greater than ~ 1.25 mm.

The transition between the subplinian (B) and phreatoplinian phases (LC1) is marked in the VVD’s by a similar modal peak at 720 µm, but with significant secondary peaks at vesicle diameters of 200 µm, and between 2 and 5 mm (Fig. 10). There is a much broader total range of bubble sizes, with a greater population of smaller bubbles < 125 µm. The upper phreatoplinian clast (UC1) also has similar populations of small and coarse bubbles, however, the higher bubble number density reflects a much larger population of bubbles < 50 µm (Fig. 10). This pumice has a unimodal peak in the main bubble population at 200 µm, no peak at 720 µm and a reduced abundance of very large vesicles extending to 5 mm.

The transition between the phreatoplinian (UC1) and pyroclastic density current phases (LC2) is characterized by similar broad ranges of bubble size; however, there is a shift in the main bubble population to slightly coarser sizes and an increase in bubbles > 1.25 mm (Fig. 10). This is reminiscent of the earlier transition between the subplinian and phreatoplinian phases. The MC2 pumice has a much broader mode at smaller bubble diameters and a more sharply defined coarse subpopulation of bubbles over 1.25 mm. The UC2 pumice has a much different vesicle volume distribution in comparison to all other pumices except for the first subplinian clast. It is highly unimodal with a much coarser mode at ~ 400 µm and a lack of large bubbles > 1.25 mm (Fig. 10). The transition from pyroclastic density current (UC2) to Plinian phases (D1) is the type example of a phase transition; with a shift from a narrow, relatively unimodal VVD dominated by intermediate sized bubbles (UC2) to a broader bi- or tri-modal VVD in D1 (Fig. 10).
Figure 10: Vesicle volume distributions (volume fraction vs. vesicle equivalent diameter) for all representative samples of this eruption. Vesicle number densities calculated for each sample are also shown top left of each graph, and two vertical lines are shown for comparative purposes between samples. Note at the onset of a new phase, a distinct population of coarse bubbles > 1.25 mm.
The D1 clast has a coarse bubble subpopulation that is more pronounced than observed in any other example, with the exception of the final Plinian sample (D5). Clasts in the Plinian phase (with exception of D5) have broad ranges of bubble sizes, however, with time smaller bubbles become more significant especially with regard to the coarse tail (Fig. 10). The VVD of the final Plinian pumice (D5) is similar to the D1 pumice and shows bimodality, with a coarse modal peak (~5 mm), a principal broad mode at 250 µm, and a marked decrease in the relative abundance of small bubbles (Fig. 10).

The bimodal to polymodal shapes of the VVD’s result in contrasts in slope on cumulative volume percent plots (Fig. 11). The slope of the curve reflects the narrowness of the bubble size distribution; steep slopes indicate narrow size distributions and its position reflects the median bubble size. Sub-populations of bubbles that reflect different process (of nucleation and growth) have different slopes on these plots (Fig. 11a, b, c, d). The subplinian sample (B) has a smooth curve with a gentle slope and no breaks in slope, indicating a single broad population of bubbles (Fig. 11a). The upper phreatoplinian sample (UC1) is steeper than that of the lower phreatoplinian sample (LC1), but has a lower median bubble size of 158 µm, in comparison to 225 µm (Fig. 11b; Table 3). The three pyroclastic density current samples (C2) show the greatest range of median vesicle sizes of the entire eruption; the two later samples (MC2, LC2) have steeper slopes, i.e., narrower size distributions, than that of the sample representing the onset of that phase (LC2) (Fig. 11c). Median vesicle sizes are much lower for the first two clasts with values of 180, 112 and 350 µm respectively (Table 3). The Plinian clasts are, perhaps predictably, more uniform yet show greater complexity, as all samples show sharp breaks in slope at vesicle diameters greater than ~450 µm (Fig. 11d). LD3 and UD3 samples
Figure 11: a, b, c, d) cumulative volume percent plots for the modal density clasts, which have been grouped here into phases. Median diameters for each sample have been calculated from these graphs and are listed in Table 3. e) and f) samples from the onset and end of phases have also been grouped and shown here. Note the diversity of samples reflecting the end vs. onset of a phase.
have smaller median diameters, reflecting more bubbles <125 µm than the early and late Plinian samples (D1 and D5) (Table 3).

From a different perspective we have plotted samples representing the onset and end of phases on the cumulative volume graphs in Figure 11e and 11f. Interestingly, the samples representing the onset of each phase are less diverse and have a greater volume% of large coarse bubbles (>630 µm), with the exception of the sample representing the end of the Plinian phase (D5). In addition, there is more variation in median vesicle sizes and curve shapes at the end of a phase, reflecting the variable state of vesiculation in the final stages of each phase.

4.0 Interpretations:

4.1 Conduit processes throughout the eruption

Here we consider conduit processes over two depth ranges, arbitrarily defining deep as where processes of nucleation and free growth of bubbles are dominant and shallow as the depth interval where coalescence of bubbles becomes significant.

4.1.1 Implications for deep ascent processes

The narrow unimodality of density/vesicularity amongst the 1875 pumices suggests that the magma ejected in each phase of the eruption was exceptionally uniform, and that within and among phases, processes and rates of early ascent, nucleation and free growth of bubbles were similar.

The range of vesicle number densities among the Askja samples is fairly narrow with respect to those calculated for other eruptions listed in Figure 12.
Figure 12: Vesicle number density vs. discharge rate (i.e., eruption intensity) for all Askja 1875 samples together with those calculated for other eruptions including, Mt Mazama 6900 yr BP (Klug et al., 2002); Vesuvius 79AD (Gurioli et al., 2005); Novarupta 1912 (Adams et al., 2006); Taupo 181 AD, (Houghton et al., 2003); Mt St Helens (Klug and Cashman, 1994). Vesicle number densities for the Askja Plinian samples are nested within the field of other powerful large silicic eruptions, similarly to the Askja phreatoplinian samples. The Taupo phreatoplinian examples have a lower vesicle number density and lower discharge rate than those of the Askja phreatoplinian pumices.
Similarly to the density data, this narrow range strongly suggests that the history of deep ascent, decompression, supersaturation and nucleation was almost identical throughout the 1875 eruption. The samples from the beginning and end of the eruption (B and D5 respectively) have the lowest number densities, which we attribute below to a greater influence of bubble coalescence.

Experimental results for silicic melts show that homogeneous nucleation, at high values of supersaturation ($\Delta P > 120$ MPa) results in number densities of $10^7$ to $10^9$ cm$^{-3}$ (Mourtada-Bonnefoi and Laporte, 1999; Mangan and Sisson, 2000; Mangan et al., 2004). This degree of supersaturation equates to decompression rates of $0.25 - 1.0$ MPa s$^{-1}$ (Gardner et al., 1999) and the volatile requirements of these silicic melts in the absence of nucleation sites were $> 5$ wt% H$_2$O and $> 600$ ppm CO$_2$ (Mourtada-Bonnefoi and Laporte, 1999; Mangan and Sisson, 2000). Number densities of $10^6$ to $10^8$ cm$^{-3}$ are more common for heterogeneous nucleation (Hurwitz and Navon, 1994; Gardner et al., 1999).

High vesicle number densities in the 1875 pumices are strongly suggestive that the magma underwent homogeneous bubble nucleation at relatively high degrees of volatile supersaturation in a manner analogous to the eruptions of Mount Mazama 6900 BP (Klug et al., 2002), Mount St. Helens 1980 (Klug et al., 1994), and Novarupta 1912 (Adams et al., 2006) (Fig. 11). The lack of efficient nucleation sites, low H$_2$O content and probable low CO$_2$ content, suggest that homogeneous nucleation was the dominant mechanism, and subsequent degassing was at a high degree of disequilibrium.

The wide range of bubble sizes in the Askja pumices, down to 5 µm, strongly suggests that bubble nucleation was an extended process continuing even after the bubble-bubble interaction and coalescence affecting larger bubbles. There is some evidence supporting
this from the bubble size distributions: Power law exponents for vesicle populations reflect the processes contributing to bubble growth (Gaonac'h et al., 1996; Blower et al., 2001, 2002). The 1875 samples have multiple segments on log plots of $N_{m,v}(>L)$ vs. $L$ (Fig. 11), suggesting that different processes influenced different subpopulations among the bubbles. The initial line segments characterizing the smallest bubbles have exponents between 1.6 and 2.2, (Fig.9; Table 4). Blower et al., (2001, 2002) showed numerically that exponents $\sim 2$ reflect continued nucleation and free growth of bubbles.

4.1.2 Implications for shallow ascent processes

We suggest, for the majority of the 1875 melt, that mid- and late- stage coalescence became a dominant process affecting the Askja magma. This process was superimposed on continued bubble nucleation and can account for the multiple linear segments identified on log plots of $N_{m,v}(>L)$ vs. $L$ (Fig. 9), the broad peaks obvious on the VVD’s (Fig. 10) and also the generation of a coarse tail of bubbles also observed on the VVD’s. The breaks between power-law segments at 30 – 50 µm on log plots of $N_{m,v}(>L)$ vs. $L$ suggests that coalescence probably influenced vesicle growth for all bubbles $> 30$ µm and became a primary growth process from that point on. This is also observed in the sample images, where at these typical sizes individual bubbles begin to interact and often form bubble trains and larger irregular-shaped bubbles (Fig. 13). The second segments on the Askja cumulative number density plots have exponents $> 2$ suggesting the overprint of coalescence on continued nucleation (Gaonac’h et al., 1996). In particular the subplinian (B), final phreatoplinian (UC1), middle pyroclastic density current sample (MC2) and Plinian LD3 sample have the highest exponents for this second segment (5.1, 3.5, 3.3 and 3.3 respectively).
Figure 13: Four images from representative clasts taken on the scanning electron microscope at 500x magnification. The glass is white and the vesicles are black. The measurements shown are in microns. Bubble diameters are typically between 30 and 50 μm prior to high degrees of bubble coalescence between intermediate-sized bubbles. These interactions usually form large-very large bubble trains and polylobate bubbles, changing the form of the VVD and form breaks in slope on cumulative number density plots (see Figure 9).
Furthermore images of these samples show high degrees of coalescence with highly irregular and amoeboid-shaped vesicles that preserve the dimensions of the smaller original constituent bubbles (Fig. 7). The final pyroclastic density current sample (UC2) shows very advanced coalescence, very thin wavy bubble walls and wide bubble-poor domains (Fig. 7). This sample has a third linear segment with a power law exponent of 4.4, also suggesting late stage growth dominated by run-away coalescence (Fig. 9; Table 4). The most distinctive samples in this respect occur at the start and end of the main eruption (B and D5 respectively).

The narrow unimodality and low modal densities of the initial subplinian phase data suggest very uniform ascent conditions throughout this phase (Fig. 5a; Table 2). The coarse median bubble size (360 µm) together with the polymodal VVD with a dominant modal peak at 720 µm suggests that coalescence was a dominant process, skewing the modal and median bubble size towards coarser values (Fig. 7, Table 3). Slower rates of magma ascent during this phase appear to have increased the relative role of coalescence and driven bubble number densities down.

The final sample of the Plinian phase (D5) is unlike most other samples of this eruption. It has the lowest bubble number density, high median bubble size (316 µm), large coalesced bubble trains and high mean clast densities (580 kg m⁻³; Table 2). These data suggest that nucleation, decompression and ascent rates declined in the final stage of this eruption, which facilitated greater residence times in the shallow conduit and hence high degrees of coalescence and partial outgassing.
4.1.3 Changes in shallow magma ascent between phases

The pumices erupted at the very start of phases C1, C2 and D are characterized by a combination of a significant increase in the subpopulation of large bubbles > 800 µm as well as a greater range of clast densities. These observations suggest that the magma first erupted in phase C1, C2 and D had a different shallow ascent history with respect to that discharged late in phase B, C1 and C2. However, the data are not compatible with the simple model that each of these phases began with arrival of a new pulse of magma with limited residence time in the shallow conduit and hence restricted opportunity for bubble coalescence. Instead they suggest that the early erupted magma in C1, C2 and D1 was slightly more influenced by bubble interaction and coalescence than magma erupted late in these phases, the reasons and implications are discussed below.

Studies conducted by Carey et al., (in review) suggested three separate vent locations that were active throughout the eruption, centered upon the depressions indicated in Figure 4, which mimic NE-SW and SE-NW-trending structural faults (Fig. 4). We suggest that the magma was intruded in cross-cutting elongated dike-like bodies centered on the NE-SW-trending Askja caldera marginal fault, and in a SE-NW-trending structural fault (Fig. 4). Magma was able to reach shallow depths beneath any given portion of the vent system significantly before the onset of activity at that vent. The first magma erupted after the opening of a newly located vent (e.g., early C1 or D1 times) reflects this mechanism, with extended residence times than magma erupted during the peak discharge of that phase (Fig. 14a).
Figure 14: (a) At the onset of phreatoplinian and Plinian phases, magma with greater residence time in the conduit is erupted first (darker red), followed later by gas-rich magma (bright red). (b) During the phreatoplinian (C1) phase (1 hour), continued high ascent rates, water availability and vent widening facilitated a change from buoyant to collapsing column conditions. Throughout this period, magma with greater residence time at the margins of the conduit was removed. (c) At the end of the pdc and Plinian phases, decreases of mass flux facilitated magma to stagnate on the conduit margins, prior to degassing-induced pauses in the eruption.
The vent active during C2 time is interpreted to be located coincident with the phreatoplinian vent (Carey et al., in review), and did not establish its own vent. At the onset of this phase however, we see the greatest range of clast densities, a coarse population of bubbles similar to those observed at the onset of other phases and large, very complex bubbles with thick walls. The shift from buoyant plume to collapsing column conditions appears not to be a result of a decrease in the mass flux and/or change of the water-magma ratio, as the bubble number densities (a proxy for decompression rate) are actually higher within the C2 phase (Table 3). Instead, we suggest that vent widening in the phreatoplinian phase changed exit conditions and led to the change in transport regime. This mechanism can also account for the incorporation of magma with longer residence times from adjacent conduit and dike areas (Fig. 14b).

4.1.4 Changes in shallow magma ascent within a phase

Limited changes are observed in the clast density/bulk vesicularity and VVD data within phases. Throughout the C1 phreatoplinian phase, we see an increase in the bubble number density through time, coupled with a decrease in the median size of the vesicles, and a decrease in the range of clast densities (Tables 2, 3). This trend is suggestive of higher rates of decompression as the driving mechanism for changing rates of bubble nucleation during magma ascent (Mangan and Sisson, 2000). However, shallow processes of ascent must have been different; there is an obvious switch in clast textures to a population of irregular distorted bubble shapes with thick bubble walls, despite an increase in the small bubble populations (Figs. 8, 12). These shapes must suggest greater residence time of the majority of the magma despite higher decompression rates and decoupling of deep vs. shallow ascent processes. Considering that the generation of dilute
density currents is the next progression of this eruption despite higher decompression and ascent rates of the magma, we suggest that this final phreatoplinian sample represents the beginning of vent widening (Fig. 14b). Magma that was residing in the adjacent dike had slightly longer residence times, and vent widening at the end of this phase led to the eruption of this magma and a shift from sustained buoyant to collapsing column conditions.

In the C2 pyroclastic density current phase, there is a trend with time of fluctuating median diameter and a non-uniform trend of vesicle volume distribution with a decrease in bubble number densities. In addition, there is an increase in the wt% abundance of tube pumices (47 - 66 wt%), that are moderately to highly vesicular (83 % modal vesicularity). We suggest that the decreasing decompression rate, together with the episodic nature of the pyroclastic density current phase (C2) led to highly variable conduit conditions; including periods of slowed or stalled ascent in the shallow conduit which facilitated variable degrees of bubble coalescence and collapse, and potentially, at times, a reduction in the effective radius of the conduit. The final sample collected from this phase has an additional third linear segment representing coarse bubbles (Fig. 9; Table 4) and we suggest that this sample represents extended residence times in the conduit available for run-away coalescence and minor collapse between eruptive pulses.

In the final D Plinian phase, there is a complex trend, slight fluctuations of bubble number density (with exception of the final Plinian sample D5) and smaller median bubble sizes and ranges of clast densities in LD3 and UD3 samples of this phase (Table 3). The highest number density and lowest median bubble size occurs in the third Plinian sample (UD3), suggesting that although early and late magma ascent conditions were
fairly similar throughout this phase, the highest intensity of this phase correlates to the sample UD3.

4.3 Pauses associated with the eruption

From eyewitness accounts there appear to have been two pauses throughout this eruption; the first between the subplinian (B) and phreatoplinian (C1) phases and second, at the end of the eruption (Carey et al., in review). Our limited microtextural data are based on a single subplinian sample which cannot demonstrate any change in the erupting magma that may have triggered this pause. Higher resolution sampling and textural analysis throughout the subplinian (B) deposits is required.

The end of the eruption, characterized by the final Plinian (D5) sample has a much lower vesicle number density with high degrees of coalescence and shearing (Table 3), suggesting a degassing-induced end to the eruption (Fig. 14c).

Our analyses also suggest that there was a pause between pyroclastic density current (C2) and Plinian (D) phases; this transition was preceded by decreases of vesicle number density (i.e., decompression and magma ascent rates), and pumice textures record progressively higher degrees of coalescence and shearing (Table 3). These observations support a degassing-driven pause between these two phases (Fig. 14c).

4.4 Role of external water in highly explosive sustained wet volcanism

4.4.1 Role of external water in the phreatoplinian phase C1

In addition to early and late processes of nucleation, growth, coalescence and collapse that affect the vesicularity characteristics, could external factors such as the interaction of water influence texture contrasts between wet and dry phases?
4.4.2 Extent of vesiculation of the magma prior to fragmentation

The density histograms of the Askja phreatomagmatic phases (C) are highly unimodal (Fig. 5a). Mean, modal and ranges of these clast vesicularities are also very similar to those of the earlier dry subplinian (B), and later Plinian (D) phases, suggesting that melt involved in the phreatomagmatic phases had vesiculated to the same extent as that ejected in the 'dry' eruptive phases (Table 3). The vesicle number densities in both the 1875 phreatomagmatic and Plinian phases are also very similar and, finally, the vesicle volume distributions all have similar broad ranges, from small 4 µm up to 5 mm bubbles (Fig. 10). These observations suggest that the processes of nucleation at depth, decompression and ascent rates were similar between wet and dry phases of the 1875 eruption. Throughout this study, there has been no evidence that vesicle nucleation and growth was terminated prematurely during the phreatoplinian and pyroclastic density current phases.

4.4.3 Comparison to two other ‘type’ phreatoplinian eruptions – Hatepe and Rotongaio ashes, Taupo 181 AD eruption

The phreatoplinian (C1) phase of this eruption is one of four ‘type’ examples of this style of volcanism. Vesicularity studies have been conducted on two other ‘type’ examples: the Hatepe and Rotongaio ashes, units 3 and 4 of the 181 AD eruption of Taupo volcano, New Zealand (Houghton et al., 2003). A comparison of clast vesicularity between the 1875 and Taupo 181 AD phreatoplinian phases shows that the 1875 wet phase has a narrower density range, tighter unimodal distribution and lower density values than the two Taupo wet phases (Fig. 6). Vesicle number densities from the Askja phreatoplinian samples have a narrow distribution between 1.5 and $2.1 \times 10^9$ cm$^{-3}$, which are greater than
those of the Hatepe and Rotongaio phreatoplinian samples (5 – 9 x 10^8 cm^-3; 1 – 3.5 x 10^8 cm^-3, respectively; Houghton et al., 2003).

The model proposed by Houghton et al., (2003) for the Taupo phreatoplinian phases, similarly based on clast density, pumice textures, vesicle size and number density was that the Hatepe phreatoplinian magma had reached and advanced through the peak of vesiculation prior to the interaction of external water which quenched and halted the vesiculation process (Fig. 15). In the case of the Rotongaio magma, vesiculation textures were strongly suggestive that the magma had passed the peak of vesiculation and had a protracted outgassing history prior to the external water interaction. Based on the vesiculation data, textures and observations above, it is clear that the 1875 phreatoplinian phase underwent fragmentation at an earlier stage in its degassing/outgassing history (Fig. 15). Instead, the magma erupted during this phase was definitely at the peak of vesiculation prior to the involvement of external water.

6.0 Conclusions

The 1875 eruption of Askja volcano is an excellent case study for examining conduit and vent dynamics, in particular shifts in eruption regime and transitions between wet and dry styles of activity. Historical observations and drawings, together with newly constrained dispersal, deposit geometry and deposit characteristics (Carey et al., in review), suggest multiple vent locations that were aligned in two cross-cutting weak structural zones, NNE - SSW and NW - SE. We suggest that the magma erupted was intruded in a dike-like fashion along these two structural zones. External influences, including changing vent position, vent widening, and availability of external water, appear to be first-order
Figure 15: A schematic of the progression of vesiculation with time and the inferred points of fragmentation (denoted by thick arrows) for the Askja 1875 and Taupo 181 AD phreatoplinian phases, based on vesication data presented in the text and in Houghton et al., (2003). The clast textures and quantitative data suggest that the Askja phreatoplinian magma was definitely a foam and potentially already fragmented prior to the interaction of magma and water. Similar observations and data suggest that the Hatepe phreatoplinian magma had passed the peak of vesiculation and was outgassing prior to the interaction with external water. More extreme degrees of outgassing are inferred for the Rotongaio magma prior to interaction with external water. Scale bars on images are 50 microns.
influences facilitating rapid and reversible shifts in eruption styles. The initial shift from dry subplinian to wet phreatoplinian fall was facilitated by an increase in the eruption intensity coupled with a shift of vent location into an existing water source and area of high water availability. The vesicle number densities increase throughout this phase; however, clast textures become increasingly complex, indicating a greater role and extended timescale for coalescence. We suggest that increased magma ascent rates and vent widening at the end of this phase facilitated incorporation of magma with longer residence times from adjacent portions of the dike system. The most complex and mature textures of all studied samples are from this period. The switch from wet sustained fall to wet density currents is superimposed on a continuous trend of inferred increasing decompression and magma ascent rates, suggesting that vent widening rather than a reduction of mass flux was responsible for this change in plume dynamics. The clast textures and density data also support this interpretation. Throughout the density current phase, the vesicle number densities decrease, however the deposit characteristics of the currents suggest lower degrees of water interaction with time. These combined observations suggest that at the end of the pdc phase, the availability of water had greatly reduced at a time when magma flux was also declining. Pumice clast textures at the end of this phase suggest high degrees of coalescence and minor collapse, and support a degassing-induced pause in the eruption. The shift in eruption style from wet pyroclastic density currents to dry Plinian fall was due to both a shift in vent position out of the water source, and an increase in magma ascent rates. The end of this eruption is recorded in the pumice clast textures by an increase in the degree of coalescence and minor bubble collapse, once again suggesting a degassing-induced halt to the eruption.
One important observation brought about by microscopic studies of pumice clasts of this eruption, is that degassing processes during deep and shallow magma ascent were decoupled within and between phases. At depth, nucleation and initial growth stages of growth were similar; however, with continued ascent, shallow controls on degassing, changing vent position and vent widening severely affected the pumice clast textures and densities. The deposit characteristics together with textural observations of phreatoplinian pumice clasts suggest that the magma was a foam prior to the interaction of water. Future studies are planned to examine the role of magma-water interaction for fragmentation during this wet sustained phreatoplinian phase.

Acknowledgements

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CHAPTER 4

Contrasting styles of welding observed in the
proximal Askja 1875 eruption deposits I: Regional welding

Abstract

Welded fall deposits on the northern caldera rim at Askja volcano are associated with the Plinian phase of the 1875 eruption. Two welding units occur within the proximal Plinian fall centered on stratigraphic sub-units which, where non-welded, are poorly sorted and ash-rich with high abundances of fluidal and needle-like ash particles. Welding has formed due to two discrete processes;

a) the sintering of hot ash and lapilli which forms the two distinct units that are laterally continuous on distance scales of tens of meters (termed ‘regional welding’), and

b) creation of welding halos enclosing large, dense, discrete, non- to poorly vesicular spatter bombs that are up to nine meters in diameter (termed ‘local welding’). This paper is concerned with the nature of regional welding and the companion paper (this issue) focuses on the phenomenon of local welding. Three case studies documenting the range of welding patterns observed in regional welding are presented here. Vertical and lateral profiles of welding intensity, together with the deposit characteristics reveal that welding could only occur when the accumulation rates were sufficient and that grain size and thickness are second order factors facilitating welding. Rapid and reversible shifts in both thickness and welding grade are observed on a ~ 10 meter scale laterally along the caldera rim suggesting considerable unsteadiness of the transport regime, which promoted localized fluctuations of the accumulation rate. The welded deposits prompt re-
examination of both the dynamics of the Plinian phase of the 1875 eruption and the
distribution of source vents. The dispersal of the welding units is not compatible with
deposition from the full height of the Plinian plume. Similarly to the ultra-proximal
deposits of Novarupta or Tarawera, these clasts probably fell from heights of hundreds of
meters to < 4 kilometers, retaining sufficient heat to weld after deposition. The E-W
elongated distribution of the welded units is also not compatible with a single vent, and
favors several vents that were in a fountaining phase, and located adjacent to the northern
rim.

1. Introduction
Here we describe rhyolitic welded fall deposits from the 1875 eruption of Askja volcano.
Welded deposits are located in three separate regions of the caldera; the south west corner
and along the northern rim. The welded deposits on the northern rim are the focus of this
paper (Fig. 1) and are unmistakably fall deposits, due to their mantling character and
grain size characteristics. Welding at this location takes two forms; a) the sintering of hot
ash and lapilli, which is then overprinted by b) welding halos enclosing large, dense,
discrete spatter bombs up to nine meters in diameter. This paper is concerned with a) and
a companion paper (Carey et al., 2008) describes b).
Figure 1: The northern rim of the 1875 caldera in the foreground, now filled by Lake Öskjuvatn. The mountainous background is the western margin of the main Askja caldera. Note the position of Viti phreatic crater, used as a reference point throughout the text, and the peninsula, with 2 orthogonal faces. The welded deposits are red-colored distributed on the northern rim.
1.1 Welding in pyroclastic rocks

Welded air fall deposits appear to be rare, as few examples are documented in the scientific literature (e.g., Sparks and Wright, 1979; Wolff and Wright, 1981; Turbeville, 1992) - most examples of welded deposits are associated with ash flow tuffs (Kamata et al., 1993; Quane and Russell, 2005; Sheridan and Wang, 2005). This literature describing welded air fall is generally restricted to deposits formed during mildly explosive eruptions resulting in locally dispersed pyroclastic ejecta and restricted to the proximal environment < 2 km from vent (Hackett and Houghton, 1985, Karhunen, 1988). Welded air fall deposits however are common products of many modern volcanoes in proximal regions and cover the full range of composition. Fall welded deposits of peralkaline composition (e.g., Pantelleria, Stevenson et al., 1997; Mayor Island, Stevenson et al., 1993) and welded basaltic spatter deposits (e.g., Karhunen 1988; Calderone et al., 1990) appear to be dominant and few examples of welded calcalkaline silicic air fall deposits have been documented (Sparks and Wright, 1979; Duffield, 1987; Hackett and Houghton, 1985). Examples range from basaltic through rhyolitic magma compositions and the best documented examples include the Thera and Therasia tuff from Santorini (dacite) (Sparks and Wright, 1979) and the Pinnacle ridge tuff from Ruapehu volcano (andesite) (Hackett and Houghton, 1985). The Askja 1875 welded fall deposits were identified and briefly described by Sparks and Wright (1979).

The process of welding of pyroclastic deposits has previously been described as the sintering together of hot, glassy pyroclastic fragments and their flattening under compactional load at temperatures above the glass transition temperature (e.g., Smith, 1961; Cas and Wright, 1987; Quane and Russell, 2005). Two important controls on
welding are melt viscosity (which is dependant on temperature and composition) and lithostatic load (thickness of the deposit). Other parameters that control the final degree of welding in air fall deposits are eruption style (e.g., fountaining), emplacement temperature, accumulation rate, the composition of the magma, rate of crystallization, slope and lithic clast content. During the welding process, accumulation of hot, plastic pyroclasts forms layers of agglutinated to incipiently welded pyroclasts. Welding intensifies with higher accumulation rates, and under the compactional load of overlying tephra, changes will occur in the physical characteristics of the pyroclasts, such as plastic flattening and deformation of pyroclasts. Physical properties such as a reduction of primary porosity and increases in density accompany welding and can be used as quantitative measures of welding intensity (Quane and Russell, 2005).

The problem posed by all welded fall deposits is determining the conditions under which airborne ejecta can remain significantly hot during flight to weld and compact after deposition. The welding process is influenced by numerous depositional processes together with the inherent thermodynamic properties of the ejecta and deposit. Previous authors (e.g., Sparks and Wright, 1979; Head and Wilson, 1989) have suggested that accumulation rate is the critical factor, by covering and insulating clasts quickly and hence slowing cooling rates. In addition, Head and Wilson (1989) highlight that clast temperature on landing is another important factor, which is a function of both clast size and flight time. Thomas and Sparks (1996) completed a theoretical study combining estimates of clast cooling times with deposition rates from a Plinian column to postulate that grain size appeared to be the most important factor in facilitating welding. Recently Capaccioni and Cuccoli (2005) modeled cooling rates of particles during ballistic
transport and deposition. These authors have also proposed that grain size is a critical factor in promoting welding or agglutination. Another key factor is deposit thickness which increases load pressure and slows heat loss and hence will promote higher degrees of welding (Quane and Russell, 2005).

1.2 General setting of Askja volcano

The central volcano Askja is situated on the southern sector of the Askja volcanic system and has been active for >200,000 years (Fig. 2) (Sigvaldason, 2002). It is the locus of activity on the system and rises to more than 800 meters above its surroundings, capped by the composite Askja caldera, which incorporates the nested 1875 Óskjuvatn caldera (Fig. 1). Two explosive silicic eruptions are known from Askja in Holocene times, the 1875 eruption and a ~10 ka event which has been estimated to be close to an order of magnitude larger (DRE volume 1.2 km³; Sigvaldason, 2002). Askja is composed predominantly of basaltic hyaloclastites, pillow lavas erupted during subglacial times, and subaerial post-glacial lava flows which have partially filled in the main caldera. Nestled within this larger construct is the 230 meter-deep Óskjuvatn caldera, covering an area of 15 km². This structure formed during the 1873-1875 Askja volcano-tectonic episode due to post-1875 downfaulting and ring fracture collapse and is now occupied by Lake Óskjuvatn (Sigvaldason, 1979). Throughout postglacial times, activity at Askja has been vigorous with a number of basaltic eruptions on ring fractures surrounding the caldera rim. The recent activity appears to be controlled by lithospheric extension producing an en echelon array of north-northeast to south-southwest fissures on which are superimposed the main caldera ring fractures (Fig. 3).
Figure 2: Map of northeastern Iceland showing the volcanic systems of the Northern Volcanic Zone (NVZ) in red and the locations of associated central volcanoes shown with black triangles. Sveinagja, 40 km north of Askja is the site of the precursory effusive event, producing 0.3 km$^3$ of basaltic lava which occurred between February and March 1875. Holuhraun, ~15 km south of Askja is a second site of basaltic precursors. Map modified from Sigvaldason, (2002).
Figure 3: Schematic map of the Dyngjufjöll central volcano, showing the main Askja and the nested 1875 (lake-filled) calderas. Tectonic lineaments form a cross-cutting pattern defined by SE-NW and SSW-NNE faults (white lines in figure). Eruptive activity in the Dyngjufjöll complex has predominantly occurred on these lineaments. Pre- and post-1875 basaltic activity has also occurred along ring faults that surround the 1875 caldera and main caldera rims (in red). Post-1875 lavas in black. Diagram modified from Sigvaldason (2002).
Post 1875 activity includes both explosive and extrusive eruptions of basaltic magma in 1921-22, 1929, 1931 and 1961 (Sigvaldason, 1979; Sparks et al., 1981).

Prior to the 1874-1876 volcano-tectonic episode, precursory activity began perhaps as early as 1867 (Thordarson et al., in prep). Precursory activity that began in 1874 was due to rifting along the entire volcanic system, with eruptions at Askja central volcano, Sveinagjá 40 km north of Askja and Höluhraun, ~15 km south of Öskjuvatn on the fissure swarm (Fig. 2, Sigurdsson, 1978a, b; Sigvaldason, 1979; Sparks et al., 1981, Thordarson et al., in prep). Following the explosive subplinian-phreatoplinian-Plinian eruption in March 1875, post-eruption activity lasted into 1876 and included the phreatic creation of Víti crater on the northern rim of Öskjuvatn and continued weak phreatic activity in the southeast corner of Öskjuvatn (Sigvaldason, 1979; Sparks et al., 1981).

1.3 Previous work

The 1875 eruption produced a number of distinctive pyroclastic units, including non-welded subplinian, phreatoplinian and Plinian fall and pyroclastic surge deposits together with welded deposits erupted during the Plinian phase (Sparks and Wright, 1978; Sigvaldason, 1979; Sparks et al., 1981). Askja 1875 welded deposits have been previously described by Self and Sparks, (1978), Sigvaldason, (1979), Sparks and Wright, (1979) and Sparks et al., (1981). Sparks and Wright (1979) describe two 1875 welded tuffs, located on the northern and southwestern rim of Öskjuvatn and formed during the main phase of the eruption in 1875, together with two welded fall deposits of Santorini. Sparks and Wright (1979) describe briefly the welded northern rim deposits but focus upon the welded deposits in the southwestern sector of the 1875 caldera.
1.4 The 1875 Askja eruption

The Askja pyroclastic deposits have been divided into six units (A-F) by Sparks et al., (1981). These units have been correlated with explosive activity between 1875 and 1876. The deposits of the main phase on 28 - 29 March, 1875 (Units B, C, D), comprise three distinct magmatic units, with a trend of fluctuating eruption intensity. These products were dispersed towards the east and cover a combined area of 628,000 km². Unit D is a very coarse grained, well sorted Plinian fall and is undeniably associated with the main fallout from the eruption. The welded deposits on the northern rim of the caldera are associated with the Plinian D phase of the eruption and are the focus of this paper.

2. The non-welded northern D deposits: stratigraphy and dispersal

The grain size, sorting, color and lithic abundances of non-welded sub-unit D deposits are often obscured when the deposits become welded. Here we describe these features and stratigraphic divisions within the non-welded deposits, to supply a framework to understand welding process.

2.1 Stratigraphy

The proximal unit D deposits, where non-welded, are separated into five sub-units, recognized to first order, by the alternating white and grey-brown coloration of each sub-unit (Fig. 4). Less striking but more reliable indicators of the stratigraphic boundaries between sub-units are shifts in grain size and componentry.

We recognized that the grey-brown-colored D2 and D4 sub-units are coarse grained, poorly to very poorly sorted deposits with a higher abundance of ash than the D1/D3/D5
sub-units (20-30 modal %) and contain abundant fluidal ash particles. The non-welded characteristics have been used first to define and then to map stratigraphic boundaries between sub-units. The definition of five sub-units has enabled close stratigraphic correlations between sites and dispersal calculations within this proximal environment. The best area to quantify each sub-unit is immediately southeast of Viti crater, where a broad peninsula forms two orthogonal faces with continuous exposure of all the D sub-units (Fig. 5). Circumferential (NW-SE) outcrops and the peninsula (SW-NE) outcrops provides an opportunity to observe changes in thickness, grain size and componentry in a downwind-upwind transect (circumferential) and a crosswind (radial) transect (Fig. 5). On the downwind traverse, the D sub-units are largely non-welded except for the local influence of spatter bombs. On the cross wind traverse, the welding state of the deposits and the abundance of outsized spatter bombs in D2 and D4 increases significantly to the southwest, towards the tip of the peninsula. We measured ten sections on a NW-SE transect along a lower bench 50 meters from the current lakeshore. A further four sections were measured on a NE-SW radial line along the upper bench of the caldera rim (Fig. 5). The following volcanological attributes of each sub-unit are defined below from those sections where welding is not present.
Figure 4: The non-welded unit D stratigraphy with underlying unit C pyroclastic surge deposits, photograph taken at a proximal section on the peninsula (X1 in Fig. 5). Note the color change between darker locally dispersed D2 and D4 deposits versus the lighter widespread D1, D3 and D5 sub-units. The boundaries between D1-D2 and D3-D4 are sharp, in contrast to the boundaries between D2-D3 and D4-D5.
Figure 5: Photograph of the peninsula near Viti, view to the west. The 1875 deposits mantle the peninsula and the alternation of light and dark sub-units of unit D is obvious. The northern rim is visible in the background. The SW-NE radial transect of four sections points into the lake, while the circumferential transect is the face perpendicular to this. Note the X1 is the section shown in Figure 4.
2.1.1 Sub-unit D1.

Sub-unit D1 is the initial product of the Plinian D phase. It is a continuous layer around the caldera margin, however it cannot be distinguished from D3 when sub-unit D2 is absent. D1 is a white, coarse grained, poorly bedded, well sorted deposit consisting of highly to very highly vesicular pumice. The components are medium to coarse pumice lapilli and subordinate angular ash-sized shards. The lithic component is dominantly angular obsidian fragments; in abundance up to ~ 8 modal%. Bulk density measured in the field for the D1 sub-unit is 285 kg m$^{-3}$.

2.1.2 Transition between D1 and D2.

The transition between D1 and D2 is recognizable due to a sharp decline in abundance of lithic clasts, an increase in maximum grain size, and the substantial increase in abundance of matrix, comprising predominately of fluidal juvenile clasts in the ash-sized fraction. D2 is typically darker in appearance; however, we also recognize a darkening of some D1 clasts, such that one single clast can have a cream-colored lower part and a dark brown upper part. This darkening phenomenon we interpret to be caused by oxidation from hot overlying D2 material.

2.1.3 Sub-unit D2.

Sub-unit D2 is the lower of the two dark brown to grayish-black sub-units. It is consistently poorly to very poorly sorted and comprises fine to coarse lapilli and pumice bombs within a matrix of grey/brown ash, including fluidal particles, shards and needles. The matrix is fine to coarse ash and generally comprises 20 – 25 modal% of the sub-unit but reaches a maximum of 40 modal%. Four different lithic clast types are present, obsidian, granophyre, basalt and red-oxidized hyaloclastite clasts, and the total lithic
abundance is consistently < 2 modal%. The vesicularity of the pumice clasts is variable, although most are highly to very highly vesicular. Where it is thickest, we can define three parts within sub-unit D2. The lower part is dominated by dark grey clasts, and has high abundance of the ash-sized matrix (20 – 25 modal%). The middle part has a combination of dark and white to yellow/brown pumice clasts. The dark grey clasts dominate in the ash and block fractions and the abundance of the ash matrix is reduced to approximately 15 – 20 modal%. The white/cream/yellow clasts are not homogenous in color and can vary in one individual clast. The uppermost part is similar to the lowermost part in terms of components and ash matrix. Bulk density of the D2 sub-unit is 321 kg m$^{-3}$.

2.1.4 Transition between D2 and D3 sub-units.

The exact transition between grey-brown-colored D2 and cream-colored D3 is difficult to identify due to the high abundance of brown/yellow oxidized clasts at the transition zone of the D2 and D3 sub-units. However an abrupt decrease in abundance of fluidal particles and ash content over no more than 5 cm presents an obvious marker.

2.1.5 Sub-unit D3

The proximal D3 deposits are widely dispersed, and merge with the D1 and D5 sub-units when D2 and D4 are missing, and together can be traced outside the caldera towards the east to form the bulk of the medial/distal fall unit that fell over eastern Iceland and Scandinavia. It is a white, clast-supported, coarse grained pumice lapilli and bomb deposit, which is moderately well sorted. The pumices are mostly highly vesicular with a very minor proportion of clasts that have breadcrusted exteriors. The sparse matrix (< 10 modal%) within this sub-unit is dominantly pumice shards and fragments. The lithic
clasts are predominantly obsidian, basaltic lava and granophyre fragments. The D3 sub-unit has a bulk density of 258 kg m$^{-3}$.

2.1.6 Transition between D3/D4

This transition is always sharp and linear. The distinction between D3 and D4 is straightforward, marked by a large and abrupt increase in maximum grain size, linked with increases in the abundance of matrix and appearance of fluidal ash-sized clasts. We do not observe any ‘mixed layer’, containing both light and dark clasts.

2.1.7 Sub-unit D4

Where non-welded, this sub-unit is a very poorly to poorly sorted layer, with abundant coarse bombs up to 80 cm in diameter. It is poorly bedded and contains up to 30 modal% ash matrix, which includes shards, needles and fluidal ash particles. The lithic clast content within this layer is low, ~0-2 modal%, and includes obsidian and granophyre lithic clasts. Juvenile clasts are highly to very highly vesicular pumice; approximately 20% of these clasts have very highly elongated vesicles and shiny blue exteriors. The bulk density of this sub-unit is 548 kg m$^{-3}$.

2.1.8 Transition between D4/D5

Similarly to the transition between sub-units D2 and D3, the D4/D5 transition is also difficult to identify on an outcrop scale due to the high abundance of brown/yellow oxidized clasts at the transition zone. The finer characteristics such as increase in lithic clast content and decrease in both the abundance of ash and fluidal ash components are better indicators of this transition.
2.1.9 Sub-unit D5

D5 is a poorly sorted sub-unit of fine to coarse pumice lapilli within an ash matrix (< 10 modal%), with abundant coarse bombs resting on the upper surface. The matrix comprises white fine to coarse ash, including pumice shards, and fibrous fragments. The lithic content is approximately 10 – 15 modal%, the second highest after D1, and comprises fragments of obsidian, granophyre, basalt lava and red-oxidized hyaloclastite. This sub-unit cannot be clearly delineated from D3 where D4 is no longer present. The bulk density of this sub-unit is 282 kg m⁻³.

2.2 Geometry and dispersal

The proximal deposits within the caldera are distributed in an elongated ellipse centered on lake Öskjuvatn and components of the proximal stratigraphy (sub-units D1, D3 and D5) merge into the widely dispersed medial Plinian D fall towards the east and northeast beyond the phreatic crater Víti (Fig. 6). In comparison, the dark sub-units D2 and D4 have a much more restricted dispersal, confined solely to the proximal environment along the northern rim of Lake Öskjuvatn (Fig. 6). The combined area of non-welded and welded D2 and D4 sub-units cover an area of 2.3 km², to be compared with an area of 4919 km² within the 2 cm isopach for the widespread Plinian D fall. Approximately 950 meters east of the Víti crater, D4 becomes a discontinuous layer and a further 200 meters away dark clasts and bombs are no longer present at this level in the stratigraphy. D2 follows a similar pattern, 1.3 km from Víti this layer is no longer continuous and at a further 300 meters, D2 clasts are absent. At this point, D1, D3 and D5 cannot be distinguished one from another. For this reason we plot the combined thickness of these
units in Figure 7, which clearly shows the sharper downwind decline in thickness of D2 and D4 with respect to the enclosing sub-units. In this region the downwind linear thickness half-distances are: 5.9 kilometers for the combined D1+D3+D5 sub-units; 310 meters for the lower dark sub-unit D2; and 70 meters for the upper dark sub-unit D4. The light-colored sub-units are thus one to two orders of magnitude greater in dispersal than the dark-colored sub-units. In addition, D2 has a downwind dispersal five times greater than D4. D2 is also more widely dispersed crosswind than D4 as shown on a plot of radial linear thickness half-distance (Fig. 7).

2.3 Grain size and componentry

In order to quantify grain size of proximal deposits from the main Plinian phase, samples were collected from a section on the peninsula where all the deposits are entirely non-welded (site X1 on Figs. 5 and 6). This site was chosen as it represents the proximal grain size of each sub-unit and is the most proximal section where all sub-units can be observed. Grain size samples were taken from each sub-unit and the weight of the largest clast was measured and used to determine an approximate size for a representative sample. All sub-units were sieved and weighed in the field down to -4 φ (16 mm) and a representative split of the <16 mm fraction was taken to the laboratory for further analysis. Proximal grain size results for each sub-unit are shown in Table 1. The median grain size of the sub-units shows a coarsening with stratigraphic height.
Figure 6: Aerial photograph of the 1875 caldera with the outline of the distributions of the locally (D2 +D4) and widely dispersed (D1+D3+D5) sub-units. The white 1875 tephra is draped upon the basaltic hyaloclastite range from the northeast to southwest. To the north and west are the main caldera-filling lavas. Post-1875 activity is colored red, with the date when it was erupted. Note that the post-1875 activity is focused on ring fractures around the 1875 caldera. X1 is the location of samples taken for grain size analysis for each sub-unit.
Figure 7: Plot of downwind and crosswind thinning for the widespread Plinian sub-units (D1+D3+D5) versus the locally dispersed sub-units (D2+D4). The D2 sub-unit is more widely dispersed downwind than its D4 counterpart. Downwind thinning half-distance for D1+D3+D5 is 5.2 km, and the values for D2 and D4 are 312 and 70 meters respectively. The crosswind thinning half-distances for D2 and D4 are 45 and 33 meters respectively.
There is a three times increase in median grain size from D1 to D2, and smaller changes of medial grain size between other sub-units (Table 1). In terms of sorting, the dark sub-units D2 and D4 have Inman sorting values ($\sigma_q$) between 3.2 and 2.5 and are poorly sorted. D1 is also poorly sorted (2.5) and D3 and D5 are better sorted (1.6 and 2.1 respectively). Relative to 'dry' fall deposits in Walker (1971), the D2 and D4 samples, while still unimodal, show significantly poorer sorting. Similar samples documented by Walker (1971) show $\sigma_q$ values dominantly between 0.7 and 2.0.

Table 1: Table of median diameter ($Md_\varphi$) and Inman sorting coefficients ($\sigma_q$) for each sub-unit within the unit D deposits. Note the increase of median grain size with time and the poor sorting of D1, D4 and especially D2. In comparison the D3 and D5 sub-units which contribute mostly to the widespread Plinian fall are better sorted.

<table>
<thead>
<tr>
<th>sub-unit</th>
<th>$Md_\varphi$</th>
<th>$\sigma_q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>-3.2</td>
<td>2.5</td>
</tr>
<tr>
<td>D2</td>
<td>-4.7</td>
<td>3.3</td>
</tr>
<tr>
<td>D3</td>
<td>-5.3</td>
<td>1.7</td>
</tr>
<tr>
<td>D4</td>
<td>-5.9</td>
<td>2.5</td>
</tr>
<tr>
<td>D5</td>
<td>-6.1</td>
<td>2.1</td>
</tr>
</tbody>
</table>

3. The welded D deposits

3.1 Background to study of the welded D deposits

The welded deposits described here are restricted to the northern caldera rim. Proximal to the northern rim welding is most intense and decreases in intensity non-uniformly outward. Smaller areas of welding are also observed near Víti and on the peninsula. The fundamental nature of the welding process and its characteristics are similar for each of
these regions. Here we describe the nomenclature used for the observed degrees of welding and the techniques applied during this study.

3.2 Nomenclature for describing welded air fall pyroclastic deposits

In the literature, the nomenclature used for describing welded pyroclastic rocks and the degree of welding varies for welded ignimbrites (e.g., Sheridan and Ragan, 1976; Quane and Russell, 2005) and welded fall deposits (e.g., Sparks and Wright, 1979; Wright, 1980). For fall deposits, the terminology also varies for spatter deposits versus welded fall deposits of predominantly pumice (Sparks and Wright, 1979; Karhunen, 1988). Recently Quane and Russell (2005) have proposed a quantitative classification of welding intensity for ignimbrites, based on physical attributes of bulk density, porosity, uniaxial strength, and measurements of clast dimensions. Here we outline a similar classification scheme for describing welding intensity, from non-welded to densely welded, for the Askja air fall deposits (Table 2). These terms for welding intensity are based on measurable attributes of both clasts and matrix. Clast flattening, shape, vesicle geometry and vesicularity were observed, together with matrix cohesiveness, texture and vesicularity.

3.3 Methods

At each section photographs were taken together with sketches and a detailed stratigraphic log describing thickness, color, ash content, grain size, sorting, lithic abundance and degree of welding. When recording the thickness of regional welding along the northern rim and peninsula, measurements were taken only in places where
there were no spatter bombs in the immediate area (~1 meter in either direction to avoid the thermal overprinting by these bombs). The welding state was recorded at every location where the thickness was measured.

**Table 2:** Nomenclature used in descriptions of welding intensity of the Askja 1875 welded deposits. For each welding grade, attributes of both clasts and matrix are described.

<table>
<thead>
<tr>
<th>Welding grade</th>
<th>Attributes of welding</th>
</tr>
</thead>
<tbody>
<tr>
<td>densely</td>
<td>glassy matrix, no obvious pyroclastic texture</td>
</tr>
<tr>
<td></td>
<td>no void space between clasts</td>
</tr>
<tr>
<td>moderately</td>
<td>no void space between clasts, matrix texture</td>
</tr>
<tr>
<td></td>
<td>no longer apparent, eutaxitic textures</td>
</tr>
<tr>
<td>slightly</td>
<td>clasts sintered together, however clastic texture</td>
</tr>
<tr>
<td></td>
<td>still apparent, void space present</td>
</tr>
<tr>
<td>tack</td>
<td>loose, unconsolidated with void space</td>
</tr>
<tr>
<td>no welding</td>
<td>loose, unconsolidated</td>
</tr>
</tbody>
</table>

3.3.1 *Clast aspect ratio and density.*

The welding intensity of pyroclastic deposits can be quantified by changes in fabric and texture as well as measurements of physical properties such as clast aspect ratio, density and porosity. These properties can vary both vertically and laterally.

*Aspect ratio:* Aspect ratio measurements were made from five clasts at each site which appeared most representative of the general clast population. The X and Y axes were measured perpendicular to each other and the degree of welding was noted, together with descriptions of clast morphology (spatter vs. pumice).
Density sampling: Bulk rock density samples were taken from the welded deposits with a chisel and hammer. Care was taken to collect samples over very narrow intervals that represented a specific grade of welding intensity. Spatter bombs, if present in the field sample, were removed from the laboratory sample so not to bias the data towards high density values.

3.3.2 Calculations of deposit pre-welded thickness

To investigate the effect of pre-welding thickness on welding intensity we collected density samples from each welding zone at every section, assumed values for the bulk density of non-welded material and applied the following expression to determine pre-welding thickness from the reduction in density:

\[ L_0 = L_w \left( \frac{\rho_w}{\rho_0} \right) \]

Where \( L_0 \) is the original thickness, \( L_w \) is the present thickness, \( \rho_w \) is the density of the sample and \( \rho_0 \) is the bulk density of non-welded material.

We calculated a bulk density of non-welded D4 material based on the percentages of components in the basal non-welded D4 layer and using an average density value for the constituent pumice clasts, derived from density measurements of 100 clasts in the 16 mm size fraction from an adjacent D4 deposit.

Our mixture comprises the following: 48% pumice lapilli with a pumice density of 357 kg m\(^{-3}\), 30% ash with a bulk density of 1100 kg m\(^{-3}\), 20% interstitial pore space in open void spaces between lapilli and 2% lithic clasts with a density of 2350 kg m\(^{-3}\) to result in a non-welded D4 bulk density of 548 kg m\(^{-3}\).
3.4: Diversity and nature of welding – General

A key feature of the northern welded D2 and D4 deposits is rapid changes in welding state, which can be observed along horizontal distances of less than 100 meters. We have identified two distinctly different processes which led to welding; i) relatively uniform compactional adhesion and sintering of ash and lapilli, and ii) local flattening and heating of the matrix by large discrete spatter bombs which range in size up to 9 meters and decrease in abundance radially outboard of the caldera rim. The focus of this paper is the first style of welding, termed regional welding. However for clarity, we wish to introduce here the second style of welding which we call local welding (Fig. 8). Local welding is described fully, with case studies in Carey et al., 2008b. Regional welding is defined by consistent intensities of welding (irrespective of proximity to large clasts), which are maintained on distance scales of at least tens of meters. Regional welding at the northern rim involves comparatively uniform adhesion and weak flattening of ash and lapilli to yield mostly tack-and-slightly welded deposits. Only rarely have we observed moderately welded material. Within regional welding we observe clasts with flattening ratios of 1:2 to 11:1 but commonly values are between 2:1 and 5:1. Densities taken from regionally welded samples yield results between 650 kg m$^{-3}$ and 1620 kg m$^{-3}$. This style of welding is somewhat simpler to interpret than local welding (Fig. 8). Local welding is due to large discrete spatter bombs impacting into, compressing and supplying heat to an asymmetrical halo of surrounding material, which then undergoes softening, flattening and sometimes even rheomorphic flow. This material may have been previously non-
Figure 8: Photograph illustrating both types of welding observed in the 1875 welded deposits - regional welding and local welding. Regional welding forms a continuous protruding welded bench, which has been deformed due to the arrival of meter-sized spatter bombs. Local welding is easy to identify due to its close proximity to spatter bombs. At this site the thickness of regional welding is approximately 30 cm, whereas the locally welded deposits concentric around the large spatter bomb are 55 cm-thick, and formed at the expense of formerly non-welded D3+D4 material. This spatter bomb in the foreground is ~ 1.9 meters x 95 cm.
welded (e.g., parts of sub-unit D3 in proximity to spatter bombs) or may have had some component of regional welding.

3.5 Welding units
We have devised a welding nomenclature to represent the two welded units we observe in the field. These welding units are centered upon but not limited to sub-units D2 and D4. Thus the welding units are not coincident with stratigraphically defined sub-units and we name them W1 and W2, centered on D2 and D4 respectively. At a limited number of sections, W1 falls entirely within D2 and W2 within D4; however at most sections W1 can encroach into D1 and/or D3 and W2 into D3 and/or D5. This nomenclature exists independent of the styles of welding that have contributed to the welding. For example, W1 can reflect purely regional, regional and local (Fig. 8), or less commonly, simple local welding (Fig. 8).

4. Regional Welding
4.1 Documentation of background welding- vertical and lateral changes
4.1.1 Distribution of non-welded D2 and D4 deposits
The sub-units on which welding is centered, D2 and D4, have a much more restricted dispersal than the Plinian D1, D3 or D5 deposits, and have contrasting dispersals (Figs. 5, 7). In particular, D2 extends further to the south east along the caldera margin than D4, but does not extend as far to the east. D4 does not extend as far west along the northern caldera rim as D2 (Figs. 9a, b).
4.1.2 Lateral distribution of W1 and W2 regional welding

Regional welding is common to both welding units; however, these units and their associated non-welded equivalents (D2 and D4) have contrasting distributions (Figs. 9a, b). In particular the distribution of W2 is slightly skewed to the west with respect to W1. The extent along the northern rim of regional welding is approximately the same for the two units; however the area covered is less for W2, mainly a more limited radial extent.

Welding unit 1

W1 is centered on the central-west portion of the northern caldera rim (Fig. 9a). The lateral extent is approximately 1.15 km along the rim and its radial range outward of the rim is, at maximum, 50 meters. The area covered by this welding unit is 0.18 km². At the eastern but particularly at the western limit of this welding unit, we observe patchy non-continuous welding (Fig. 9a). Welding can develop and vanish over lateral distances of ~10 meters with non-welded D2 material intervening. At the eastern end, we observe ~50 meters of such discontinuous welding, prior to a gap of ~100 meters of non-welded material before continuous welding appears again. At the western end we observe discontinuous welding for 240 meters, for intervals from ~10 meters to 50 meters. There appears to be no pattern in the frequency or length of these welded intervals.

Welding unit 2

W2 is focused on the central and eastern portions of the northern caldera rim (Fig. 9b) and its extent along the northern rim is 1.24 km. It overlaps with W1, so that at many sections along the rim, both regionally welded W1 and W2 are present (Figs. 9a, b). The area covered by W2 is 0.20 km². At the eastern margin of W2, there is a discontinuous
Figure 9a, b: The northern caldera rim, with the outlines of the distribution of non-welded D2 and D4 sub-units (green) and welded W1 and W2 units (red). The graph underneath is geo-registered with the aerial photo, showing the grade of welding and its thickness in centimeters for particular regions on the northern caldera rim. D2/W1 is shown in (9a) and D4/W2 is shown in (9b). Numbers refer to sections described in the text. The diameter of Viti crater is approximately 190 meters, for scale. These graphs together show the lateral changes of degree of welding and thickness for the welding units. Note the simpler pattern of welding for the W2 unit with two thickness maxima. The W1 welding unit is more complicated with reversals of welding grade and significant thickness changes over very short lateral intervals. Viti crater is shown in black. Note the contrasting dispersals of non-welded D2 and D4.
zone of welding that extends outwards for a further 115 meters (Fig. 9b). Stratigraphic sections described in case study 1 (section 4.2), are within this zone. This eastern discontinuous zone is much greater than the analogous discontinuous zone on the western margin. This western discontinuous zone extends for only 85 meters and is defined by only two zones of welding that are 20 – 40 meters wide.

4.1.3 Lateral changes in thickness

In both welding units, we observe rapid changes in thickness over short lateral distances (Figs. 9a, b). We have made thickness measurements for strictly regional welding of both units along their entire lateral extents. We avoided areas where spatter bombs influenced the welding pattern.

Welding unit 1

W1 has two thickness maxima; the eastern maximum is between 760 and 890 meters from Víti and the western maximum is between 1100 and 1310 meters from Víti (Figs. 9a, b). Both have thickness maxima of 30 cm (Fig. 9a). On a range of scales, thickness and welding maxima appear to be decoupled. At the onset of continuous welding from the east, W1 shows a steady increase in thickness to the first maximum of 30 cm without an increase in the grade of welding. Within the interval of the thickness maximum, the welding grade does increase from tack to slight welding. Between the eastern and western thickness maxima, there is a significant decrease in thickness of the unit, which does not correlate with the observed changes in welding grade. To the west of the western maximum, W1 decreases rapidly and discontinuous zones of slight and tack-welding begin. These discontinuous zones show a general decrease in thickness with distance to
the west, but values can vary by up to 20 cm over very short lateral distances of tens of meters.

**Welding unit 2**

W2 shows a uniform increase in thickness with small fluctuations over a distance scale of ~100 – 200 meters to reach thickness maxima of 30 cm at distances of 550 to 610 meters and 860 to 1050 meters to the west of Víti (Fig. 9b). These thickness maxima correspond to the maxima in welding grade; however the maximum welding grade extends over a much greater distance than the thickness maxima. West and east of the thickness maxima, there is a gradual decrease of thickness paralleled by a decrease in the welding grade.

**4.1.4 Lateral changes in maximum welding grade**

Along the northern rim, there are non-systematic shifts in welding intensity, with rapid and reversible shifts over short lateral distances.

**Welding unit 1**

The maximum welding grades for W1 follow a systematic increase from tack-welding at the margins of the welding unit to slight to moderate welding grades in central portions of the unit (Fig. 9a). The onset of welding at the eastern end of W1 is consistently tack-welding as opposed to the western end where the regional welding is variable and patchy with alternating intervals of tack and slight welding present. Slight and tack-welding are equally common throughout the unit and it is common to see lateral reversions of welding grade. The maximum for welding grade is between 1160 and 1200 meters west of Víti. The transition to this welding maximum is sharp. A change laterally from tack to moderate welding occurs on an east to west traverse over < 10 meters, without a change in thickness. To the west of the W1 welding maximum, slight welding of the deposits
continues for 290 meters, in both laterally continuous and discontinuous intervals. Two other intervals of slight welding occur at 800 and 890 meters and 950 to 1050 meters. The western interval corresponds to an increase in thickness of the W1 unit, while the other exhibits no correlation. Across the discontinuous zone, there is a gradual drop in maximum welding intensity towards the west.

**Welding unit 2**

W2 has a much simpler welding pattern. From the east, there is a gradual increase of welding grade from tack to slight welding (Fig. 9b). This tack-welded zone lasts for 340 meters and the ensuing slight welding zone continues for a further 650 meters. The zone of slight welding overlaps with the two 30 cm thickness maxima despite a drop of thickness to 20 cm in between. There is a much more restricted and discontinuous zone of tack-welding on the western portion of W2.

**4.1.5 Changes of grain size along the northern rim**

Grain size was recorded along the northern rim in an attempt to identify whether the increases in welding grade correspond to changes in grain size. These observations suggest that local changes in grain size lead to changes in the welding state. We consider this possible correlation in grain size and welding grade, and the smaller scale fluctuations in welding intensity in more detail via three case studies which describe the lateral onset of W2 regional welding, and welding maxima for W1 and W2 respectively.

**4.2 Case study 1: The lateral onset of regional welding**

The exposures along the northern rim record both the western and eastern onsets of regional welding for the W1 and W2 units. Regional welding of the W1 and W2 units is laterally displaced such that regional welding of W2 begins before the onset of W1.
welding on an east to west traverse. The opposite is true in the west; the onset of W1 occurs prior to W2. In addition, the onset of welding on both margins of W1 and W2 is typically patchy and discontinuous over distances scales of tens of meters. Here we describe the onset of regional welding of the W2 unit on the eastern side as an example of this phenomenon.

W2 welding is first present on the north eastern sector of the northern rim, 80 meters west of Viti. We have logged W2 at five locations along a 57-meter traverse to show lateral changes in thickness and degree of welding (Fig. 10). The lateral coverage of regional welding is patchy and non-uniform in terms of increases in both unit thickness and/or welding intensity. East of section 1 welding is absent and within 10 meters to the west of section 5, regional welding becomes essentially continuous over lateral distances of 30 – 40 meters. The welding recognized along this traverse is strictly regional and related to the adhesion and sintering together of lapilli and ash particles in the absence of heat contributions from large spatter bombs.

4.2.1 Section 1

At the easternmost section (1) the D4 layer including W2 is 60 cm-thick (Fig. 10). It can be separated into a non-welded basal layer, a welded unit (W2) and an upper non-welded layer. The basal non-welded layer of D4 (17 cm) is brown to black in color, moderately to poorly sorted; the ash matrix is dominated by juvenile fluidal ash particles including ash shards and needles comprising 40%.
Figure 10: Five sections measured at the eastern margin of W2. Note the fluctuations in the degree and thickness of welding over short lateral distances. Grey tones represent different degrees of welding in W2. The letters next to the sections represent the assigned welding grades as defined in the field: non-welded (nw), tack-welded (tw) and slightly welded (sw). The letters in green denote the non-welded stratigraphic nomenclature.
Above this layer, W2 is 17 cm-thick, has an abundant ash matrix (up to 30%) with diverse ash particles including fluidal clasts. W2 can be separated into two zones based on welding intensity, varying up to 10 cm in thickness along strike. The lower 7 cm is tack-welded, i.e., clast edges are lightly sintered together but there is no deformation of the clasts (density = 1130 kg m$^{-3}$; AR 1:1 – 3:1). The upper 10 cm is slightly welded and the edges of clasts adhere and the fragments are slightly deformed but the matrix texture is still apparent (density = 1470 kg m$^{-3}$; AR 2:1 to 5:1). Above this zone is a non-welded, matrix-rich top that is 20 cm-thick.

4.2.2 Section 2

Section 2 is 20 meters to the west of section 1 (Fig. 10). D4 is ~35 cm-thick, and is a poorly sorted, matrix-supported deposit that is non-welded throughout with clasts up to 6 cm and fluidal and needle-shaped ash particles which sometimes make up 25 – 30 modal% of the entire layer. The transition between D4 and D5 is well defined, but the occasional coarse D4 bomb protrudes through D5, which is ~15-20 cm-thick and comprises coarse ash to medium lapilli that are predominantly (~75%) light in color, in a coarse ash matrix comprising of pumice shards.

4.2.3 Section 3

The non-welded base to D4 is 19 cm-thick at section 3 (Figs. 10, 11). The W2 unit is 29 cm-thick with a similar abundance of ash matrix to that of lower D4; however, median grain size increases with height. W2 can be separated into three zones. The lower zone is 8 cm-thick and slightly welded (density 1470 kg m$^{-3}$) with an abundant red oxidized ash matrix and fine lapilli up to 2 cm in diameter. Clasts are slightly elongate (AR 2:1 to 4:1) but with mostly equant vesicles. The middle zone (11 cm) is also slightly welded (density...
950 kg m\(^{-3}\)) and red oxidized with abundant ash matrix and coarse lapilli up to 8 cm in diameter. This zone has a slightly greater degree of lapilli-flattening than the lower zone with aspect ratios between 3:1 and 6:1. The upper tack-welded zone (10 cm) consists of coarse ash, fine to coarse lapilli and bombs up to 12 cm in diameter, which are lightly sintered, with clast aspect ratios generally less than 2:1 (density 840 kg m\(^{-3}\)). On top of W2 is a scatter of 10 – 80 cm pumice clasts (D4 +/- D5) which has been stripped of original matrix and now consists of ragged lapilli and bombs infiltrated by Viti mud.

4.2.4 Section 4

D4 is non-welded throughout section 4 (Fig. 10). D4 is 31 cm, matrix-supported (~35 modal%), and is poorly sorted. Particles range from fine ash to rare 8 cm clasts but more typically to 2 - 4 cm. The transition between D4 and D5 is conspicuous with a sharp decline in abundance, and a color change, of the ash components, and an increase in median grain size.

4.2.5 Section 5

At section 5, D4 and W2 have a combined thickness of 69 centimeters (Fig. 10). W2 is 35 cm and divided into three zones. The two lower zones (in total 17 cm) are slightly welded and well delineated from the lower non-welded D4, due to a sharp transition of welding intensity and smaller clast sizes (Fig. 12). The slightly welded zones (densities 1490 kg m\(^{-3}\), 1250 kg m\(^{-3}\)) are red-oxidized and the lapilli are only slightly elongate (AR 2:1), and the matrix texture is clear. The upper unit is tack-welded (density 1030 kg m\(^{-3}\); AR 1:1 – 2:1) and features a red oxidized matrix.
Figure 11: Section 3 at the eastern onset of welding of the W2 unit. The boundary between D3 and D4 (a) can be easily recognized by the color change and sharp increase in ash within the matrix of D4. The vertical sharp onset of slight welding at this section (b) is also easy to recognize due to the protruding red oxidized bench. The transition between slight (sw) and tack-welding (tw) is shown at (c).
Figure 12: The lower portion of section 5. Note the fine grain size of D4 (a) which also includes fluidal ash-sized particles and the sharp onset of slight welding allowing the deposit to form a protruding welded bench (b). Tool is 25 cm for scale.
Table 3a: Table of the welded and calculated pre-welding thicknesses for each zone within sections 1 – 5. Using a calculated bulk density (548 kg m\(^{-3}\)) for the original non-welded D4 material and density measurements collected from each welded layer, the pre-welding thicknesses were calculated.

<table>
<thead>
<tr>
<th>measured thicknesses (cm)</th>
<th>section 1</th>
<th>section 2</th>
<th>section 3</th>
<th>section 4</th>
<th>section 5</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0</td>
<td>0</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>tack-welded</td>
<td>18</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>slightly welded</td>
<td>7</td>
<td>11</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>8</td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>tack-welded</td>
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<td>0</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>non-welded D4</td>
<td>34</td>
<td>31</td>
<td>19</td>
<td>35</td>
<td>17</td>
</tr>
<tr>
<td>total (cm)</td>
<td>69</td>
<td>48</td>
<td>54</td>
<td></td>
<td></td>
</tr>
<tr>
<td>total welded (cm)</td>
<td>35</td>
<td>29</td>
<td>17</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

pre-welding thickness (cm)

| upper non-welded D4       | 0         | 0         | 20        |           |           |
| tack-welded               | 34        | 15        | 0         |           |           |
| slightly welded            | 16        | 19        | 27        |           |           |
| slightly welded            | 27        | 21        | 0         |           |           |
| tack-welded               | 0         |           | 14        |           |           |
| non-welded D4             | 34        | 19        | 17        |           |           |
| total (cm)                | 111       | 31        | 75        | 35        | 78        |
| total welded (cm)          | 77        | 56        | 41        |           |           |

welded thickness change (cm) 42 27 24
% pre-welding thickness 62 64 69

Table 3b: Density values (kg m\(^{-3}\)) from zones in sections 1 – 5 used for calculations of the pre-welding thicknesses from sections 1 through 5. Sections listed in geographical order.

<table>
<thead>
<tr>
<th>welded zone</th>
<th>section 1</th>
<th>section 2</th>
<th>section 3</th>
<th>section 4</th>
<th>section 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>upper non-welded</td>
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<td>1030</td>
<td>840</td>
<td></td>
<td></td>
</tr>
<tr>
<td>tack-welded</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>slightly welded</td>
<td>1250</td>
<td>950</td>
<td></td>
<td>1470</td>
<td></td>
</tr>
<tr>
<td>slightly welded</td>
<td>1490</td>
<td>1470</td>
<td></td>
<td>1130</td>
<td></td>
</tr>
<tr>
<td>tack-welded</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>lower non-welded</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.2.6 Welded and non-welded thickness

The density measurements and pre-welded thicknesses of these five sections are summarized in Tables 3a, 3b respectively. The combined thickness of non-welded and welded D4 deposits in the welded sections range between 48 and 69 cm, whereas the non-welded sections have a more restricted thickness of D4 deposits, ranging from 31 to 35 cm.

There is no systematic trend of changing thickness of individual zones, irrespective of which zones are included in the comparison. For example, the thickness of the non-welded basal D4 layer is non-uniform with distance along the traverse; the combined thickness of non-welded and welded deposits is also not uniform with distance and finally, it is difficult to correlate the thickening of the non-welded D4 part to the thicknesses of the probable D4 deposits in the welding sections. The thickness of the non-welded D deposits above the welding unit also varies between sections. At the westernmost sections, there is <10 cm of material above the welding unit. At section 1 however, there is ~20 cm of non-welded material above the welding unit. This must reflect in part, the incorporation of D5 material into the welding unit.

At two of the welded sections (3 and 5), there is a sudden onset of welding to a slightly welded grade without an intermediate tack-welded zone. The absence of such a transitional tack-welded zone suggests the onset of welding was triggered by an abrupt shift in conditions at the time of onset of welding rather than attainment of some critical value of loading. The sharp increase in welding grade is not coincident with changes of grain size or thickness. The observations suggest that an abrupt increase in accumulation rate could potentially be the key factor leading to onset of welding. Within D4, the
vertical onset of welding is not accompanied by an increase in clast size, in fact generally there is a local decrease in grain size. Thus we infer that grain size is, at best, a second order factor facilitating welding and that potentially other factors such as local variations in accumulation rate and thickness of the overlying material may be more significant factors.

4.3 Case study 2: high W2 regional welding grades at section 6
Regional welding in the W2 welding unit is observed to fluctuate in both intensity and thickness along the northern rim. At the site of our second case study (section 6) we observe the W2 welding unit forming a prominent ledge, which extends to the east and west of this section. This location falls within the second, or western, welding grade maximum for W2 (Fig. 9b). We use this section first to characterize the patterns and intensities of the W2 welding maxima on the northern rim, and second to contrast the welding characteristics of a welding maximum with those of the onset of welding. The thickness of W2 is variable (2-17 cm) over a lateral distance of ~2 meters, however this welding unit is always present with no reversals back to purely non-welded material. The upper and lower boundaries of this unit are sharp, with abrupt contacts to an underlying non-welded lower D3 layer and an overlying zone of larger D5 clasts with sintered bases. The density values for regionally welded W2 are the highest collected from 10 sections measured along the rim. A measured profile at section 6 (profile III in Carey et al., 2008) is 17 cm-thick, consisting of a basal 10 cm that is slightly welded, and an upper 7 cm of tack-welded material (Fig. 13). Non-welded D4 material is 9 cm-thick at the base. Density measurements in the slightly welded zone are 1550 and 1620 kg m\(^{-3}\). In the tack-
welded zone, a sample yields 1120 kg m$^{-3}$. Average aspect ratios from the slightly welded deposits are only slightly larger than tack-welded deposits, 2.6:1 vs. 2.4:1. Within the welding unit there does not appear to be any systematic changes in grain size either vertically or horizontally along strike.

We have calculated the pre-welded thickness of the W2 unit. The present day total D4 thickness of section 6 (~ 26 cm) is only 49% of the inferred original thickness prior to welding, which represents a significant volume reduction (Tables 4a, 4b). The density measurements collected from this section are the highest of the whole dataset collected from W2 on the northern rim, despite its only moderate pre-welding thickness (52 cm).

4.4 Case Study 3: high regional W1 welding grades at section 7

Section 7 is located approximately 101 meters to the west of section 6 (Figs. 9a, b). This location falls within one of the welding maxima (moderate welding) for W1 (Fig. 14; Tables 5a, 5b). We use this case study to characterize the patterns of the welding maxima in W1 and to compare the welding maxima present in W1 and W2. W1 extends as a continuous unit to the east and the west of section 7, with minimal thickness variations. The upper and lower contacts between W1 and non-welded material are fairly sharp and the high degrees of tack-welding in W1 allows it to protrude as a bench.

At the base there is 5 cm of non-welded D2 material, then W1 comprises five welded zones overlain by non-welded D3 deposits. The lowermost tack-welded zone (10 cm) has a density value of 1090 kg m$^{-3}$. 

200
Figure 13: Stratigraphic section and photograph of section 6 from W2: This profile was taken through the W2 unit at a welding maximum.
**Figure 14:** Stratigraphic section and photograph of section 7 from W1: This profile represents the welding maxima in W1.
Table 4a: Table of the welded and calculated pre-welding thicknesses for each zone within section 6. Using a calculated bulk density for the original non-welded D4 material (548 kg m$^{-3}$), and density measurements collected from each welded layer, calculations of the pre-welding thicknesses were made.

<table>
<thead>
<tr>
<th>measured thicknesses (cm)</th>
<th>section 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>tack-welded</td>
<td>7</td>
</tr>
<tr>
<td>slightly welded</td>
<td>10</td>
</tr>
<tr>
<td>non-welded</td>
<td>9</td>
</tr>
<tr>
<td>total (cm)</td>
<td>26</td>
</tr>
<tr>
<td>total welded (cm)</td>
<td>17</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>original thickness (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>tack-welded</td>
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<tr>
<td>slightly welded</td>
</tr>
<tr>
<td>non-welded</td>
</tr>
<tr>
<td>total (cm)</td>
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<tr>
<td>total welded (cm)</td>
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</table>

<table>
<thead>
<tr>
<th>thickness change (cm)</th>
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</thead>
<tbody>
<tr>
<td>26</td>
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<tr>
<th>% original thickness</th>
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<tbody>
<tr>
<td>50</td>
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</table>

Table 4b: Density values (kg m$^{-3}$) used for the pre-welding calculations of section 6.

<table>
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<tr>
<th>welding grade</th>
<th>density kg m$^{-3}$</th>
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<tbody>
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<tr>
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<td>1585</td>
</tr>
<tr>
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<td>548</td>
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</table>
Table 5a: Table of the welded and calculated pre-welding thicknesses for each zone within section 7. Using a calculated bulk density for the original non-welded D4 material (548 kg m$^{-3}$) and density measurements collected from each welded layer, calculations of the pre-welding thicknesses were made.

<table>
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<th>measured thicknesses (cm)</th>
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<tr>
<td>non-welded</td>
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<td>tack-welded</td>
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<td>11</td>
</tr>
<tr>
<td>moderately welded</td>
<td>3</td>
</tr>
<tr>
<td>tack-welded</td>
<td>10</td>
</tr>
<tr>
<td>non-welded</td>
<td>5</td>
</tr>
<tr>
<td>total (cm)</td>
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<tr>
<td>total welded (cm)</td>
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</table>

<table>
<thead>
<tr>
<th>pre-welding thickness (cm)</th>
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<td>5</td>
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<tr>
<td>slightly welded</td>
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<tr>
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</tr>
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<td>tack-welded</td>
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<tr>
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<tr>
<td>total (cm)</td>
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<tr>
<td>total welded (cm)</td>
<td>60</td>
</tr>
</tbody>
</table>

| thickness change (cm) | 31 |
| % original thickness  | 55 |

Table 5b: Density values (kg m$^{-3}$) used for the pre-welding calculations in section 7.

<table>
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<th>density kg m$^{-3}$</th>
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<tr>
<td>tack-welded</td>
<td>590</td>
</tr>
<tr>
<td>slightly welded</td>
<td>1340</td>
</tr>
<tr>
<td>moderately welded</td>
<td>1620</td>
</tr>
<tr>
<td>tack-welded</td>
<td>1090</td>
</tr>
<tr>
<td>non-welded</td>
<td>548</td>
</tr>
</tbody>
</table>
It is overlain by a 3 cm-thick moderately welded zone with a density value of 1610 kg m$^{-3}$, and the average aspect ratio of lapilli in this zone is 4.9:1. It is overlain by a 10.5 cm-thick slightly welded zone (1340 kg m$^{-3}$, AR = 3.1:1) grading sharply into 5 cm of tack-welded zone (590 kg m$^{-3}$ AR= 1.5:1). At this section, the present day thickness of W1 is 38.5 cm which, compared with the calculated pre-welding thickness of 69.8 cm, represents ~ 55% of the original thickness (Table 5a).

Section 6 has a greater bulk reduction in volume than section 7 despite its smaller pre-welding thickness (52 vs. 70 cm) and lack of moderately welded deposits.

5.0 Interpretation

5.1 Summary characteristics of the welded and equivalent non-welded deposits

W1 and W2 are not restricted to the welding of purely coarse ejecta, but often comprise dominantly fine ash to medium lapilli. This has implications for eruption and emplacement mechanisms, in particular eruption styles, eruption temperatures and source vents. Irrespective of welding grade, the northern proximal exposures have the following features in common;

i) the welding grade can change over a short vertical interval without an obvious change in grain size.

ii) the onset of regional welding is usually sharp from underlying non-welded D2 or D4 deposits, often marked by an overhanging welded bench.

iii) generally tack-welded deposits characterize the top of the welding unit.

iv) the top of W2 is not necessarily coincident with the top of D4, and D5 bombs and clasts often penetrate into the welding unit.
v) WI typically encroaches into original non-welded D3.

vi) the onset of welding is not coincident with an increase in grain size at all of the welded sections; instead at sections like 1, 3, and 5 there is actually a local reversal and decrease in the mean grain size.

5.2 Comparisons between WI and W2

5.2.1 Vertical changes in welding density

The case studies have shown similar values for clast aspect ratio and density data in the two welding units. However, the moderate welding grades observed in WI are not observed in W2. We speculate that higher accumulation rates provide the insulation and heat retention required to achieve these moderate grades and is the dominant facilitating factor. However, a secondary role of loading, and hence insulation by the overlying D3 deposits potentially could have facilitated higher welding grades in WI. For case studies 2 and 3, the highest density measurements collected were from the mid-upper portion of the WI and W2 units. One difference between the welding maxima of WI and W2 is the relative shift to higher degrees of welding; i.e., at section 7 there is a sudden shift within the welding unit (between tack-welded and moderate welding) versus the less abrupt shift in W2 at the boundary between non-welded D4 and slightly welded W2. The WI welding grades and densities are all higher than for W2; however, the overall reduction in volume is not greater than W2.

5.2.2 Lateral changes in welding density

The two welding units show very different aerial distributions for thickness maxima and welding grade (Figs. 9a, b). WI has a more complex pattern, with reversible changes in
thickness and welding along the region of continuous welding. In W1, the zones of higher welding grade are approximately correlated with increases in thickness of the unit; however, in two areas, X2 and X3 (Fig. 9a), the thickness of the unit can decrease to 20 cm without any change in welding grade. The sharp onset of moderate welding from tack-welding whilst maintaining a similar thickness is also interesting. In addition, the discontinuous western fringe to W1 can vary in thickness by up to 20 - 30 cm, and still maintain a similar welding grade. These factors together would suggest that the accumulation rate is the critical factor leading to increases of the welding grade. The short distances over which welding grade can change without changes in thickness would also suggest unsteadiness in the transport regime, leading to localized fluctuations of the accumulation rate.

5.2.3 Physical changes accompanying welding

Volume loss during welding is accommodated by reduction of pore space in the deposit, both densification of the matrix and subsequently pumice clast flattening. The physical changes of density and pumice clast aspect ratios therefore can be compared with calculated reductions of original non-welded thickness.

In case study 1, we observe the highest flattening ratios within the slightly welded deposits at sections 1 and 3; however, the highest density measurements collected were from sections 3 and 5. The reduction in volume was greatest for sections 1 and 3. Case study 2, representing the W2 maxima, has similarly high values of density for slightly welded deposits, but it also has the smallest clast aspect ratios of all the case studies. The reduction of volume was the greatest at this section. Case study 3 had high densities and moderate aspect ratios, and the reduction in volume was intermediate between case
studies 1 and 3. Thus it appears that in the 1875 regional welded deposits, aspect ratio is not a uniformly reliable indicator of either the onset or degree of welding and that the majority of the volume loss was accommodated by a reduction of pore space and densification of the matrix. At Askja, regional welding is principally a function of variable degrees of compaction and densification of the matrix.

5.3 Relationship between original thickness and welding grade

The original thicknesses of the welded sections in each case study does not seem to affect either a) the maximum welding grade attained, b) the maximum value of measured density or c) the highest aspect ratios of pumice. In addition, the maximum density and aspect ratios measured in each of the sections is in the mid to upper portion of the sections. This combination of thorough observations from seven sections suggests that welding was facilitated by other factors than simply loading.

In W1, the thickness maxima correspond with increases in welding grade from tack to slight welding (Fig. 9a). In addition the western thickness maximum corresponds with the zone of most intense welding (moderate welding) between 1160 and 1200 meters from Viti. However in between these two maxima, we also see another lateral welding grade increase from tack to slight welding, with no obvious correlation to an increase in thickness. Table 6 describes the thickness variability for each welding grade observed in the continuous welding zone.

In W2, the onset of the slight welding from the eastern margin corresponds exactly to an increase in the thickness of the welding unit (Fig. 9b). However, as was the case for W1, the thickness can vary by +/- 10 cm on a local scale and there is no significant change in
welding grade. Table 7 describes the thickness variability for each welding grade observed in the continuous welding zone.

Table 6: Welding grades associated with the W1 and W2 welding units and the corresponding thicknesses observed for each welding grade.

<table>
<thead>
<tr>
<th>welding unit</th>
<th>degree of welding</th>
<th>thickness range</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>tack-welding</td>
<td>0 - 30 cm</td>
</tr>
<tr>
<td></td>
<td>slight welding</td>
<td>10 - 30 cm</td>
</tr>
<tr>
<td></td>
<td>moderate welding</td>
<td>20 - 30 cm</td>
</tr>
<tr>
<td>W2</td>
<td>tack-welding</td>
<td>0 - 20 cm</td>
</tr>
<tr>
<td></td>
<td>slight welding</td>
<td>20 - 30 cm</td>
</tr>
</tbody>
</table>

5.3.1 Implications

These data suggest that there is at best a broad relationship between welding grade and thickness. However, these data are more compatible with a scenario where local fluctuations in accumulation rate over short distance and time scales are the dominant factor. If the accumulation rate fluctuates such that some areas receive short-lived higher deposition rates, the observed broad relationship between welding grade and thickness could result.

5.4 Inferences from the patterns of welding

5.4.1 Sharp vertical changes in welding grade

The abrupt vertical change from non-welded to slightly welded grades within all W1 and some W2 sections, without a significant thickness of the overlying material, would suggest that the higher intensities are being induced by a process other than loading. In
the 1875 regionally welded deposits, we commonly recognize sharp vertical changes of welding grade (e.g., section 4.2). Jumps in welding grade occur in both units, but at contrasting points in the welding profiles. In W1 the jump is from tack to moderately welded, i.e., within the welding unit, whereas in W2 the shift is from non-welded to slightly welded without intervening tack-welding. This has implications for the timing within D2/W1, D4/W2 of increases of the accumulation rate. In D2 times, the initial accumulation rate must have been sufficient to facilitate low grades of welding prior to a sudden increase where moderate grades of welding were possible. In D4 times, the initial accumulation rates did not permit welding to occur. We suggest that rapid vertical changes in welding grade equate to shifts in intensity within each phase. The highest density samples were collected from the middle and upper zones of the W2 unit. Therefore in the absence of a significant thickness of D4 material above the slightly welded zone (< 7 cm original thickness) it appears that the pre-welding thickness at section 6 did not have a significant effect on the final welding grade. All case studies also show that shifts in welding grade do not coincide with shifts in grain size.

5.4.2 Rapid and reversible lateral changes

It appears from case study one, where there are no obvious lateral shifts in grain size and a poor correlation of pre-welding thickness and welding grade, that thickness and grain size are not first order factors leading to the onset of welding. It seems instead that changes in eruptive conditions led to short-lived and local changes in the accumulation rate at some sections, which then led to both higher welding grades and greater thicknesses. What is interesting is that these fluctuations of accumulation rate are very localized; non-welded and welded sections can exist within less than 10 meters of each
other. This discontinuous pattern of welding onset over such short lateral distance scales, without increases in either grain size or total thickness suggests that heat loss was faster at some sections than others. This can be adequately explained by the lateral variability of the accumulation rate throughout the period of deposition. These fluctuations occurred on very localized scales (<10 meters) and must be explained in terms of processes of pyroclast transport, which also has implications for the eruption style. The welding maxima case studies (2 and 3) show less lateral variability in welding grade or thickness than seen for case study 1.

6. Discussion

6.1 Comparisons with other welded deposits

The 1875 welded deposits are quite distinct in terms of their inherent properties and the physical patterns of welding observed. Here we show five regional welded profiles from the 1875 welded deposits, and compare these with three welded fall deposits of Santorini and Mayor Island (Sparks and Wright, 1979; Houghton et al., 1985) and four profiles through well-known welded pyroclastic flow deposits (Fig. 15) (Sheridan and Ragan, 1976; Kamata et al., 1993; Quane and Russell, 2005; Sheridan and Wang, 2005).
Figure 15: Graphs of normalized density ($\rho / \rho_{\text{DRE}}$) vs. normalized stratigraphic height. Graph on right represents density profiles through welded fall deposits. Five profiles through the Askja 1875 welded deposits are in orange and three other welded fall deposits are from Santorini (Thera = red squares, Therasia = red diamonds) (Sparks and Wright, 1979) and the Ruru Pass (red triangles) (Houghton et al., 1985). Graph on left shows four density profiles from welded flow deposits taken from the literature: Bishop Tuff (blue triangles) (Sheridan and Wang, 2005), Bandalier Tuff (blue rectangles) (Russell and Quane, 2005), Wineglass Welded Tuff (blue circles) (Kamata et al., 1993) and Ito Tuff (blue diamonds) (Sheridan and Ragan, 1976). Note the contrasting profiles between welded fall and flow deposits; in addition, the Askja profiles are displaced to lower density values with respect to the other fall deposits.
The 1875 welded deposits have an almost symmetrical profile on graphs of normalized stratigraphic height vs. normalized density ($\rho/\rho[\text{DRE}]$) (Fig. 15). In detail, the trend to higher density values is very uniform between profiles with a gradual increase to a central zone characterized by stable welding values, but with curves slightly displaced from one another in terms of absolute welding intensity (density) (Fig. 15). The uppermost portion of each profile is different between samples. In other welded fall units plotted in Fig. 15, the vertical profiles are generally similar with exception of Ruru Pass, which is the thickest of the welded fall deposits described here (7 meters). However, the other fall units have higher densities than the 1875 profiles, almost consistently by 10 – 25 % (Fig. 15). Welded pyroclastic flow profiles in comparison are dissimilar to those of the 1875 or other welded falls. The density values are much more uniform over the entire thickness, in contrast to welded fall deposits which show greater shifts in density values within a single section (Fig. 15). In addition, the welded flow deposits shown here and repeatedly commented on in the literature have their highest grades of welding in the lower third of the deposit, reflecting the enhanced role of loading (Sheridan and Ragan, 1976; Quane and Russell, 2005; Sheridan and Wang, 2005).

In terms of welding process, each of the fall units appears to require attainment of a critical rate of accumulation for welding to begin. The non-uniformity of the mid to upper portions of each section varies probably due to the heterogeneity of the welding material’s characteristics (grain size, sorting, pyroclast temperature, etc.), and also the variability in factors such as accumulation rates. The layer-by-layer aggradation of fall material inhibits the formation of stable conditions of heat transfer, cooling and loading.
This is the primary contrast with processes of welding and compaction in pyroclastic flow deposits.

**6.2 Factors governing regional welding in the 1875 deposits**

At all sites where we have studied W2, the welding patterns are similar: the onset of welding is characterized by slight welding grades some distance above the base of the stratigraphic unit; commonly, the highest density sample collected from each section is from the middle to upper parts of the unit. These observations, together with the rapid lateral shifts between welding grades regardless of overlying thickness in both W1 and W2, suggest that loading was not a first order factor facilitating welding during the 1875 eruption.

The three case studies from the northern rim strongly suggest that local accumulation rate is the dominant factor facilitating regional welding during both periods of welding. The similarities in the patterns of welding and density measurements taken from W1 and W2 maxima suggest similar general shifts in eruptive conditions during the two depositional periods (with second-order local fluctuations in rate of clast accumulation producing local variability in welding grade). Each unit experienced a rapid increase in mass flux of deposited material leading to higher accumulation rates and a jump in welding intensity. The switch in relative position of these jumps in welding grade has simple implications for the relative timing of the increase in the accumulation rate. However in contrast to the conditions during the emplacement of W2, the accumulation rate throughout D2/W1 deposition must have been sufficient enough to produce tack-welding.
6.3 Implications for eruptive style

6.3.1 Inferences from clast dispersal

The dispersal data for the D2 and D4 deposits are incompatible with their being derived from the full height of the 1875 eruption plume, estimated to be 26 km by Carey and Sparks (1986), as the thickness half distances for proximal Plinian falls of this intensity are typically 1 - 4 km (Pyle, 1989, Houghton et al., 2000). For comparison, thickness half distances for historical Strombolian and Hawaiian deposits are typically several tens of meters (Houghton et al., 2006). Thinning half-distances for D2 and D4 are of the order of 100-200 meters, the only pyroclastic fall units of comparable geometry are those described by Houghton et al., (2004) for the 1912 Novarupta eruption and Sable et al., (2006) for the 1886 Tarawera eruption. In both cases the authors inferred these units to have incorporated large volumes of material shed by fountaining parts of the jet phase of eruption plumes, from heights of probably 1 - 4 km.

The comparison with Novarupta and Tarawera also permits some speculation about the positioning of the vents responsible for D2 and D4. The Novarupta exposures occur between 250 meters and 1.5 km from vent (Fierstein et al., 1997; Houghton et al., 2004). The Tarawera deposits form a series of half cones between 500 and 600 meters from the center of the 1886 craters. This is strong indirect evidence that the vent or vents responsible for D2 and D4 were probably within 1 km of the modern northern caldera rim. The E-W elongate geometry of both units is also difficult to reconcile with their resulting from eruptions from a single point source.
6.3.2 Inferences from clast cooling times

Cooling time calculated from Hort and Gardner (2000) for 2 cm pumices is 150 seconds and for a 5 cm clast 10 minutes. If D2 and D4 clast assemblages, with their high abundance of ash matrix are to retain sufficient heat to weld on deposition, the cooling times are much less than 2 minutes. This implies three things; first a high eruption temperature, second that the clast assemblage must not be in the air for an extended period and last, that the material must be covered quickly (high accumulation rates preventing heat loss). The transport time for 2 mm pumice shards falling at their terminal velocity from heights of 5 km is approximately 40 - 50 seconds (Wilson, 1972). Considering that the matrix of D2 and D4 subunits consists of between 20 – 40 % ash, these particles must have fallen from heights much less than 5 km, probably << 2 kilometers.

6.3.3 Variation of eruption intensity with time

It is difficult to assign intensities to the D2 and D4 fountaining vent(s). The sharp boundary between D1/D2 and D3/D4 observed in non-welded deposits (Fig. 4) suggests that the shifts in eruptive conditions were relatively sharp and the fountaining activity dominated the proximal environment in D2 and D4 times. However, in each instance, accumulation rates and, by inference, mass discharge rates were insufficient to immediately promote welding. The implication is thus that in both phases the intensity of activity increased with time. The pattern of welding intensity with time in W1 is also suggestive that maximum accumulation rates occurred relatively late in D2 times. Samples from the upper middle portion of welded W2 yield the highest densities
suggesting high intensities at this time. The weakly defined upper boundaries to D2 and D4 suggest that the fountaining activity declined steadily over some finite period.

6.3.4 Stability and directionality of the fountains/jets

Section 4.1 illustrated the extreme lateral variability in pre-welding thickness of the original non-welded D4 deposits (up to a 45 cm change in vertical height over a 6 m distance). The irregular thickness data and the lack of a continuous pattern of increasing welding intensity at the eastern and western margins of the welding units suggests that on short lateral scales of a few tens of meters, accumulation rates varied considerably. We consider that this can only be associated with considerable variability in the pyroclast sedimentation rate either through episodicity or directionality of the fountains. This scenario is explored in detail in the companion paper (Carey et al., 2008b).

7. Conclusions

The case studies described above show that regional welding was possible during this sustained eruption only during periods of fountaining of ejecta from elevations well below the postulated height of the convective plume. However, accumulation rates had to reach a critical point at which significant heat retention could occur. Deposition along the entire northern rim was subject to an abrupt shift in eruptive conditions promoting jumps in welding state during both D2 and D4 times. Considering that the highest welding grades within W1 and W2 can occur with only $\sim < 10$ cm of tack-welded material above, loading was not a determinant factor and high emplacement temperatures should also be considered as a first order control on welding. On a finer scale, changes in maximum welding grade on distance scales of tens of meters imply second order fluctuations in
accumulation rate which we link to instability of the fountaining jets. The process of
welding in the 1875 deposits led to only moderate welding grades and much lower
intensities than those described for other welded fall and flow deposits. The limited
duration of the fountains and the progressive accumulation of the deposit did not permit
higher grades of welding as observed in pyroclastic flows, which are rapidly emplaced
and cool as a single isothermal unit.

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CHAPTER 5
Contrasting styles of welding observed in the
proximal Askja 1875 eruption deposits II: Local welding

Abstract

As an alternative to classical welding models of fall deposits due to the progressive accumulation of hot tephra which then weld, we describe here welded deposits on the northern 1875 caldera rim of Askja volcano that have welded due to the influence of hot, discrete spatter bombs impacting into and supplying heat to a halo of surrounding tephra. This style of welding we term ‘local welding’ in contrast to ‘regional welding’ which is described elsewhere (Carey et al., 2008a). Locally welded deposits are associated with the rhyolitic Plinian phase of the 1875 eruption of Askja volcano. Two distinct welding units (W1 and W2) are interbedded with Plinian fall on the northern caldera rim, and grade outwards to weakly dispersed non-welded fall. Spatter bombs are found in both welding units but vary in their characteristic sizes and internal features. In the W1 unit simple bombs with homogeneous internal characteristics up to ~ 60 cm in diameter are found. In the W2 unit, large discrete spatter bombs with complex internal features range up to 9 meters in diameter.

We describe here two case studies showing the effects of a) single small spatter bombs; b) multiple small spatter bombs and c) large discrete spatter bombs varying in size. Vertical and lateral profiles through welding zones reveal that the primary controls on local welding are the availability of supplied or added heat and the loading capacity of the spatter bomb. Local welding grades are much higher than that of regional welding, as
the combined effects of heat, compaction and insulation can provide suitable conditions which lead to dense welding and, proximal to the spatter bomb, rheomorphic flowage. If heating and loading exceed the critical requirement for welding, porosity loss via matrix welding and vesicle collapse occurs to a point where further strain must be accommodated as shearing and ductile flowage. The spatter bombs are found only within the weakly dispersed welding units and are the final erupted products of each fountaining phase. Their low viscosities are evident by their deformation on impact and fluidal forms, and hold some important clues to eruption dynamics in the shallow conduit and vent regions.

1. Introduction

In the literature welding is generally associated with either welded ignimbrites, such as the Bishop Tuff (Smith, 1961; Ragan and Sheridan, 1972; Riehle et al., 1995; Sheridan and Wang, 2005) or, less commonly, welded fall deposits of weak to moderate intensity (Hackett and Houghton, 1985; Sumner, 1998). Most literature on welded fall deposits focuses on agglutination of spatter derived from fluid magma, such as in basaltic fire fountaining eruptions (Wolff and Sumner, 2000; Sumner et al., 2005). However welding of more viscous magmas is a common feature of near-vent facies for some eruptions (e.g., Asama and Shiotani volcanoes, Japan, Yasui and Koyaguchi, 2004; Kano et al., 1997). The welding of fall deposits is defined by the sintering, flattening and adhesion of clasts to form a cohesive deposit. Loading by overlying tephra is also an important factor that promotes welding in this setting. There are necessary pre-requisites for welding, for example short durations of particle transport from fragmentation to deposition, thereby
preventing excessive cooling, and high accumulation rates to ensure that clasts are covered quickly, thus slowing cooling (e.g., Smith, 1961; Sparks and Wright, 1979; Head and Wilson, 1989; Thomas and Sparks, 1992). Other important factors may also include grain size and total thickness of the deposit (e.g., Thomas and Sparks, 1992). Coarser clasts do not lose as much heat via radiative and convective cooling as smaller clasts in a given time interval and, so may have residual heat available to begin the welding process. Large deposit thicknesses allow the welding tephra to thermally equilibrate and maintain a quasi-equilibrium temperature for longer periods, allowing it to cool as a single unit. In addition, the overburden of tephra supplies a load to the underlying deposits, thereby compacting and increasing the degree of welding (e.g., Cappaccioni and Cuccioli, 2005). One type of welding not previously described in the literature is more localized welding caused by large, hot, discrete meter-sized spatter bombs with high heat capacities, which supply heat to the surrounding deposit, and insulate underlying tephra from heat loss while providing a compactional load. The combination of an external source of heat plus enhanced loading increases the time available over which clasts can deform and flatten, thus increasing the welding grade. Here we describe this style of welding observed within the Askja 1875 rhyolitic welded fall deposits on the northern caldera rim.

1.1 Background to the 1875 welded deposits
The welded deposits of the 1875 eruption are associated with the climactic Plinian D phase. The deposits of this phase are divided into five distinct sub-units with alternating characteristics. D1, D3, D5 are the sub-units with a clear Plinian dispersal and these deposits are generally non-welded. The D2 and D4 sub-units are less widely dispersed
and are also distinct in terms of their appearance, textural characteristics and spatial
distributions (see Carey et al., 2008a). Two welding units and local concentrations of
welding-inducing spatter bombs are centered on, but not limited to, D2 and D4
respectively. Thus the welding units are not coincident with stratigraphically defined sub-
units and we name them W1 and W2, centered on D2 and D4 respectively. This
nomenclature exists independent of the styles of welding that have contributed to the
welding. For example, W1 can reflect purely regional, regional and local, or local
welding (Carey et al., 2008a). The Sparks and Wright (1979) study on welded air fall
tuffs included a description of welded deposits at Askja; however, their paper focused on
a welded apron located on the southwest rim of the 1875 caldera. They observed physical
mixing of rhyolite and basaltic components and suggested that superheating of the silicic
component probably contributed to welding.

1.2 Current study

This paper together with Carey et al., 2008a documents welding processes of rhyolitic
proximal fall deposits from the 1875 eruption of Askja volcano. Carey et al., (2008a)
describe a sintering of hot ash and lapilli to form two distinct tack-to-moderately welded
units that are laterally continuous on distance scales of hundreds of meters. The distinctly
different style of welding described here is termed local welding. We describe the
features of local welding via two case studies, chosen to illustrate the influence of hot
spatter bombs on the surrounding deposits. Together, the two papers a) allow us to
identify key factors that have led to the patterns of welding that we observe and b)
provide us with key insights into welding processes and their implications for eruption dynamics throughout the Plinian D phase of the 1875 eruption.

1.3 Background to welding due to the influence of coarse spatter bombs
Welding due to the influence of spatter bombs is readily generally very easy to recognize in the 1875 deposits, because of the distinctive appearance of the spatter bombs and generally very high welding grades. The spatter bombs impact into and supply heat to a halo of surrounding tephra that then compacts, softens and deforms, sometimes to an extreme extent where the spatter bombs are meter-sized. In addition, the high density of these spatter bombs means that they have high heat capacity - this then allows a large quantity of heat to be dissipated slowly into the matrix and thereby greatly increasing the cooling time for the bulk deposit. In some regions along the northern caldera rim, there are very high number densities of these spatter bombs, which can range up to 9 meters in diameter and thus provide a very efficient heat source for the welding mechanism.

2. General characteristics of the welded deposits
2.1 The diversity of welding processes
Local welding is due to large discrete spatter bombs compressing and supplying heat to an asymmetrical halo of surrounding dominantly ash-to-lapilli sized tephra. The tephra surrounding these spatter bombs shows evidence of softening and often flows rheomorphically. The large heat capacity and mass of the largest spatter bombs can also add significantly to the degree of welding of under- and overlying tephra. In the 1875 deposits, the tephra affected by local welding can be initially non-welded or have some
component of regional welding prior to local welding. The welded halos of tephra surrounding the spatter bombs are concentrically but asymmetrically zoned from a highly welded interior to a less welded exterior. The tephra underneath spatter bombs is generally more highly welded than the tephra above them - this is due to the combined effects of heat-transfer and compaction versus purely heating. The fiamme/clast aspect ratios and bulk densities of the tephra surrounding spatter bombs are significantly greater than values obtained from non-welded and regionally welded tephra, confirming that the local welding grades are much higher than those of regional welding (Carey et al., 2008a). Commonly immediately adjacent to spatter blebs we observe densely welded areas, with fiamme having 8:1 – 30:1 clast aspect ratios and density values are as high as 2000 kg m\(^{-3}\). In comparison, the densities measured for regional welding range from 770 to 1610 kg m\(^{-3}\) (Carey et al., 2008a).

2.2 Nature of the spatter bombs

The internal characteristics of spatter bombs allow us to define two distinct classes: simple spatter bombs (Figs. 1a, b) and composite spatter bombs (Figs. 2a, b). The simple spatter bombs have homogenous, black, dense interiors, which are either non-vesicular or poorly vesicular with sparse equant mm-sized bubbles. The composite bombs are generally larger than the simple spatter bombs and are either wholly dark grey to black, or color-composite from bright orange to black. They also feature multiple vesicular domains, separated by regions of glassy dense rock, which appear to invade the vesicular domains. The vesicular domains have vesicularities ranging from 35 to 70 % and sometimes include coalesced gas blisters up to 30 cm in diameter. These composite
bombs also contain isolated lithic clasts up to 10 cm. Included lithic clasts of granophyre are typically granular and fragile, whereas hyaloclastite lithics are commonly contact-metamorphosed to form a dense hard rock with a brittle fracture. Within the D2 deposits we observe predominantly simple spatter bombs, with <5 modal% composite spatter bombs. In the D4 deposits, the reverse is true, with ~ 80 modal% of the spatter bombs of the composite type. In outcrops, margins of most of the spatter bombs are easily identified by the presence of halos of enhanced welding grade. The size range of these spatter bombs spans at least 2 orders of magnitude. The D2 spatter bombs are commonly 2 – 50 cm in length with aspect ratios that range from 2:1 to 8:1. The D4 spatter bombs are an order of magnitude larger in maximum size, ranging from ~2 cm to 9 meters and have aspect ratios between 2:1 and 26:1. The exterior surfaces of these bombs can only be observed adequately from spatter bombs that penetrate the top of the 1875 Plinian fall. Commonly the D4 bombs have fluidal, fusiform or ribbon shapes and some bombs have been observed with fluted tail-like projections (Fig. 3a). The spatter bombs have deformed to variable degrees on landing. Common to both of the spatter types are bombs that have fluidal surface morphologies in addition to flattened “pancake” shapes (Fig. 3b). Some 243 spatter bombs associated with sub-unit D4 are exposed on the surface of the 1875 fall deposit and give a wider range of shape data than those bombs seen in outcrop- with an average aspect ratio of 5:1 and a range of 1:1 and 26:1.
Figure 1: a) A simple spatter bomb with a homogenous poorly vesicular interior, comprising predominantly mm-sized vesicles with rare cm-sized bubbles. In plan view, this bomb is disc-shaped with fluted edges, demonstrating the ductile, fluid nature of the spatter bomb. b) A second example of a simple spatter bomb with a dense and homogenous interior. This bomb is extremely dense and very poorly vesicular. In contrast to the one shown in Figure 1a, it underwent brittle deformation as it landed.
Figure 2: a) A composite spatter bomb showing vesicular domains with abundant cm-sized coalesced vesicles and a gas blister, separated by dense, poorly vesicular glassy stringers. Post-depositional cooling fractures have formed. b) A second example of a composite spatter bomb. Domains of high vesicularities are also separated by glassy zones that often give the spatter bomb a bimodal texture. Note in Figures 2a and 2b that the vesicles are mostly round and not flattened, suggesting ongoing post-depositional degassing.
Figure 3: a) A spatter bomb located ~ 150 meters north of the northern Ōskjuvatn caldera rim. The spatter bomb has a 'pancake' shape with dimensions 4.8 x 3.9 x 1.3 meters. It cracked upon impact exposing its internal texture. This bomb and others, typically have three internal zones; a very coarse and highly vesicular interior which grades outwards into a glassy and moderately vesicular zone and an outer pumiceous carapace that often has tail-like structures and flutes. Shovel is 95 cm for scale. b) A fluidal-shaped spatter bomb featuring a tail-like structure. The core/interior (black) of the bomb contains moderately vesicular and dense, glassy regions, whereas the outer carapace (brown) is pumiceous.
2.3 Distribution of the spatter bombs

The distribution of spatter bombs is restricted to within 600 meters of the northern caldera rim and laterally for a distance of 1900 meters from 170 to 2070 meters east of Viti (Fig. 4). The radial distribution is different for the D2 bombs and the D4 bombs. D2 bombs are less radially distributed (\(-<100\) meters) whereas D4 bombs are dispersed radially up to 600 meters from the caldera margin. The aerial distribution of D4 spatter bombs is, in fact, wider than that of the W2 welded deposits, the non-welded D4 deposits and the Plinian D3 deposits. Between 100 and 600 meters from the rim, spatter bombs can therefore sit directly upon non-welded Plinian D3 tephra, and greater than 600 meters, the spatter bombs sit directly upon pre-1875 intra-caldera basaltic lava flows. D4 spatter penetrates the top of the D5 deposit permitting us to draw a map showing the distribution of spatter bombs associated with D4 (Fig. 4).

Figure 4 shows the location of bombs in four volume categories: \(<1\) m\(^3\) in yellow symbols, 1-5 m\(^3\) in orange, 5-10 m\(^3\) in red and >10 m\(^3\) in black. As expected, there is a general decrease in the size of bombs with distance from the caldera. In addition, there are also three discrete fingers or lobes of more widely dispersed coarse ejecta (outlined by white dashed line). These coarse lobes are not based on the occurrence of one or even two coarse bombs but are concentrations of multiple large bombs, each of which has at least one bomb with a volume >10 m\(^3\). The middle lobe extends farthest to the north, but the flanking lobes have the coarsest ejecta. We now describe the detailed characteristics of local welding of the matrix by such bombs with reference to two case studies, 104 meters apart at sections 6 and 8 (Fig. 4).
3. Case study 1: Section 6

The first site is of particular interest because it features unequivocal examples of both styles of welding; regional and local. At section 6, high concentrations of spatter bombs of diverse sizes provides a unique opportunity to observe and assess the effects of a) large m-sized spatter bombs, b) isolated smaller cm-size spatter bombs, and c) concentrations of abundant small spatter bombs on regionally welded tephra. Furthermore, it also allows us to make some general inferences as to the relative effects of local and regional processes of welding and compaction.

3.1 General overview of Section 6

At section 6, three large meter-sized spatter bombs dominate the outcrop and are present within W2 (Fig. 5). Continuous tack- to slight regionally welded W1 and W2 units laterally extend between these large spatter bombs and contain isolated cm-sized spatter bombs, with less pronounced overprints upon the regional welding. Vertically W1 and W2 can be separated by up to 78 cm of non-welded and red-oxidized D3 tephra. Beneath W1 is 12 cm of non-welded D2 (dark grey/black) and 5 cm of D1 (white) tephra, which is underlain by white ash-rich pyroclastic surge deposits of Unit C.
**Figure 4:** A map showing the northward distribution of spatter bombs associated with the sub-unit D4. The X, Y, Z axes of the five largest spatter bombs exposed at the surface were measured at 100 meter intervals and each point represents the largest individual volume of a spatter bomb in m³. Yellow dots represent spatter bombs with volumes < 1 m³, yellow squares 1 - 5 m³, red triangles 5 - 10 m³, and black squares > 10 m³. The outer limit to bombs > 1m³ is outlined by the white dashed line. Graph below indicates the degree of regional welding (W2) and its relative thickness along the northern caldera rim.
3.2 Local welding at section 6

Local welding at this location is observed in 2 different settings; (a) 1 - 2 cm-thick halos around small spatter bombs, within a regional welding unit (Fig. 5 in yellow), and (b) wider and more intense welding zones (up to 2 meters wide) that surround large spatter bombs and encroach into over- and under-lying previously non-welded material (Fig. 5 in red).

3.2.1 Local welding associated with single small spatter bombs

Spatter bombs are generally smaller within W1 than W2; however, they have had a similar effect on the welding profile. Bombs less than 15 cm in diameter (e.g., sb4, sb5, respectively in Fig. 6), in both W1 and W2 produce very thin halos, typically <1 cm-thick of higher welding grade than the surrounding tephra. This is demonstrated by the comparison of profiles through W1 and W2 (profiles II and IV; Fig. 6), where regional welding predominates, but is overprinted by local welding induced by single small spatter bombs. The background regional welding grade for W1 is typically tack-welding throughout its entire thickness (e.g., profile I). Density measurements from upper middle and lower parts of this zone yield values between 1000 and 1140 kg m⁻³ and clasts within this unit have an average aspect ratio of 1.5:1 (Table 1). Adjacent to profile I, approximately 1.1 meters to the east, is profile II. W1 is 26 cm-thick (Fig. 6) and is dominantly tack-welded throughout its thickness; however, a spatter bomb (sb4) with the dimensions 19 x 6 cm sits at 10 – 15 cm from the base and is surrounded by a thin halo of moderately welded tephra extending < 2 cm into the surrounding tack-welded deposits.
Figure 5: A photograph and annotated drawing of the structures at section 6, where regional and local welding can be observed at the same location. Areas of regional welding are shaded in yellow on the annotated drawing. Regional welding is observed to be continuous on lateral scales of tens of meters and extends further to the east and west of this section. The W1 welding unit is 20 - 30 cm-thick and characterized by tack to slight welding grades, although local increases to moderate welding grades are observed in 1 - 2 cm-thick halos around small spatter bombs 10 - 20 cm in diameter (blue). Underneath W1 are the non-welded D1 (white) and D2 (dark grey) deposits lying above ash-rich pyroclastic surge deposits of phase C (white). The W2 welding unit (red oxidized) is between 5 and 20 cm-thick and is predominantly tack-welded. Large spatter bombs at this section are indicated by sb1, sb2 etc. Adjacent to the spatter bomb (sb5) the tephra becomes slightly welded. Regions shaded red represent areas where local welding induced by the large spatter bombs is overprinted on regional welding. Insets represent areas of detailed study, considered later in the text. Under sb1 (inset A), local welding, and minor contributions from W2 regional welding, have contributed to the welding profile underneath. This area is separated from the W1 welding unit by non-welded, red oxidized D3 deposits and is zoned from proximal dense welding to tack-welding. Under sb3 (inset B), minor contributions from regional welding together with local welding have resulted in a welded profile 25 - 45 cm-thick and zoned from inner proximal moderate welding to tack-welding. This zonation includes a rapid decrease in welding grade from moderate to slight and the majority of the thickness is tack-welded. Beside sb1 (inset C), local welding occurs of former non-welded Plinian D3 deposits. Non-welded D3 deposits between sb1 and sb3 represent the standard thickness of Plinian fall without welding or compaction. In comparison this thickness must have been partially reduced in the welded regions underneath the spatter bombs. Tape measure is ~ 1 meter long.
Figure 6: A close-up view of the regionally welded benches between the spatter bombs sb1 and sb3 at section 6, with enhanced welding around spatter bombs sb4 and sb5. Four profiles represent regional and local welded deposits from each welded unit. The spatter bombs (sb4, sb5) are outlined in white. Density measurements (A-L) and aspect ratios are summarized in Table 1. Density (blue) and aspect ratio (green) plots have been made for each profile. Spatter bombs in the stratigraphic sections are shaded black. Note the similar welding grade for W1 and W2, despite a factor of two difference in thickness. The thickness of non-welded, but red oxidized D3 is ~ 78 cm. Density and aspect ratio values are given in Table 1 (samples A-L).
Table 1: Density measurements taken from profiles at section 6.

<table>
<thead>
<tr>
<th>Section</th>
<th>Sample Name</th>
<th>Density [kg m⁻³]</th>
<th>Aspect Ratio</th>
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<td>b</td>
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<td>am</td>
<td>1120</td>
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Density measurements for the adjacent tack-welded zone range from 920 to 980 kg m$^{-3}$. A sample from the halo yields a density measurement of 1800 kg m$^{-3}$. Aspect ratios taken in this halo average 2.5:1, whereas those taken within the welded unit range between 1.5:1 and 1.8:1.

Regional welding within W2 generally has tack-to-slight welding grades. Profile III is 17 cm-thick, consisting of a basal 10 cm, which is slightly welded, and an upper 7 cm, which is tack-welded. Coarse D4 and/or D5 clasts lie on top of this profile and have tack-welded bases where they are in direct contact with W2. Density values in the slightly welded zone are between 1550 and 1620 kg m$^{-3}$. In the tack-welded zone, a single sample yielded 1120 kg m$^{-3}$. Average aspect ratios from the slightly welded deposits are only slightly higher than those from tack-welded deposits, 2.6:1 vs. 2.4:1. Two meters to the east, at profile IV (Fig. 6), W2 is 19 cm-thick and there is a 42 x 18 cm spatter bomb (sb5, Fig. 6). This bomb sits within the slightly welded zone and the halo surrounding this bomb remains slightly welded but at an enhanced grade, suggested by higher density values (1500 kg m$^{-3}$) and aspect ratios (2.1:1) compared to that of the surrounding regionally welded deposits (density = 1220 kg m$^{-3}$) with aspect ratios (1.7:1 to 2.1:1). A density sample from the lower tack-welded unit yields 1510 kg m$^{-3}$, which conflicts with the lower aspect ratio data and probably reflects a noticeably higher lithic content.

3.2.2 Discussion of welding associated with single small bombs

At this location, the W1 and W2 regionally welded units are overprinted by local welding induced by isolated small internal spatter bombs, and show contrasts in terms of the resulting welding patterns. First W1 remains tack-welded throughout with the exception of a spatter bomb in W1, which produces a thin halo of moderate welding (profiles II +
IV: Fig. 6). There is no transition between tack-welding and moderate welding and no compaction of the underlying tephra. In contrast, the W2 unit has a higher overall regional welding grade but the halo surrounding the spatter bomb is also slightly welded (profile IV; Fig. 6). The W2 bomb examined here is larger than the one measured in W1 suggesting that the availability of heat from the bombs is not just a simple function of size but is also a function of their exact emplacement temperature.

3.2.3 Local welding induced by high concentrations of small spatter bombs

The examples described above demonstrated that isolated small spatter bombs have limited overprint on regional welding as the halos of enhanced welding are < 2 cm-thick zones around the bomb margins. There is minimum modification to the regional welding patterns. However, locally both welding units, W1 and W2 contain local high concentrations of small spatter bombs and here we examine their impact upon the regional welding pattern.

The best example of this phenomenon at section 6 is within W1 in and around profile VI, located ~ 40 cm to the west of sb1 (Fig. 7). Two 15 - 20 cm bombs and abundant smaller spatter (3 - 8 cm) that have induced local welding (profile VI; Fig. 7) overprints on regional welding. At profile V, taken 3.3 meters farther to the west, W1 contains no spatter bombs and the observed welding is of a pure regional nature (Fig. 7) and we use this section for comparison. Profile VI (33 cm) features five distinct zones (Fig. 7). At the bottom is a 4 cm-thick non-welded D2 base, followed via a sharp transition by a 6 cm-thick tack-welded part (990 kg m⁻³) (AR = 2:1), then a 13 cm-thick zone of slightly welded tephra (1420 kg m⁻³) (AR = 3.3:1) containing a high concentration (~60 %) of small spatter bombs with moderately welded halos. This sequence is overlain by a 3 cm-
thick zone of slightly welded tephra (1450 kg m$^{-3}$) (AR = 2.2:1) and a 7 cm-thick final tack-welded zone (890 kg m$^{-3}$) (AR = 1.6:1), which defines a trend of decreasing welding intensity. Profile V is divided into 4 zones (Fig. 7). The non-welded D2 base is 6 cm thick, followed by a sharp transition to a 9 cm-thick tack-welded zone (1260 kg m$^{-3}$) (AR = 2:1). It grades into a 7 cm-thick zone of slightly welded tephra (1500 kg m$^{-3}$) (AR = 2.1:1) representing the highest welding grade in the section. The sequence is capped by 4 cm of tack-welded tephra (1000 kg m$^{-3}$) (AR = 1.2:1).

3.2.4 Discussion of welding related to high concentrations of small spatter bombs

Our observations imply that the presence of abundant small spatter bombs had an impact on the extent of welding adjacent to the bombs, but did not enhance the welding grade significantly. Increasing abundance of small spatter increased the thickness of slightly welded tephra from a regionally welded thickness of 6 cm to a thickness of 17 cm, at the expense of the surrounding tack-welded deposits, and overlying originally non-welded D3 tephra (Fig. 7). This resulted in a total thickness increase for W2 of 7 cm. The similarity of the density measurements for the slightly welded zones in each section suggests that the abundance of spatter did not significantly increase the density. In addition, in profile VI, the densities of the moderately welded halo surrounding the bomb and the surrounding slightly welded tephra are essentially identical. These observations combined suggest that with only minor amounts of loading from these small spatter bombs, the densities did not increase significantly.
Figure 7: Photograph of the westernmost sector section 6, showing the position of profiles V and VI within the W1 welding unit. The distance between the two profiles is ~1.6 meters. Profile V is situated within the regionally welded W1, whereas profile VI was taken where the unit has high concentrations of small spatter bombs that produced local welding. Density (blue) and aspect ratio (green) profiles are shown adjacent to the stratigraphic logs. The spatter bombs are shaded black. Note the red orange oxidation of the non-welded D3 sub-unit (situated above W1), which was originally white/pale grey. Measured density and aspect ratio values are given Table 1.
3.3 Welding associated with large spatter bombs

At section 6, the presence of three meter-sized spatter bombs provides the additional opportunity to identify and separate the effects of a) heat and variable amounts of compaction due to loading (beneath the bombs and reflecting changes in size of bomb), and b) heat only (tephra laterally adjacent to the bombs). Three locally welded regions are shown on Fig. 5 as insets A, B, C, developed about sb1 and sb3. The most conspicuous effect of the bombs is the encroachment of welding into otherwise non-welded D3 fall (Fig. 5). Away from these bombs, the thickness of non-welded Plinian D3 fall (78 cm) between W1 and W2 correlates well with measured Plinian fall thickness measured elsewhere on the northern rim. Adjacent to the largest spatter bombs, the thickness of non-welded tephra is drastically reduced in thickness as local welding zones develop at the expense of surrounding original non-welded fall.

3.3.1 Local welding beneath large spatter bombs (due to heat and loading):

Here we look at the effects of two isolated large spatter bombs (of different sizes) on the underlying deposits.

Profile VII - welding underneath sb1

The largest spatter bomb at section 6 (2.4 x 1.4 meters in cross section) is associated with W2 and has induced local welding of the underlying D3 deposits (inset A; Fig. 5). Non-welded D3 tephra is still present between the locally welded W2 and regionally welded W1 units. Profile VII is based on density measurements from seven samples and systematic clast aspect ratio measurements across the locally welded zone underneath sb1. The profile shows a steady decrease in welding intensity outward from sb1, at the top of the profile, towards the non-welded D3 deposits at the base, defining densely,
moderately, slightly and tack-welded zones. The densely welded zone extends for 37 cm from the top of the profile. It is a glassy zone containing black, non-vesicular flattened ghost-like clasts ranging in length from 0.5 to 2 cm, fine-lapilli-sized lithic clasts, and vesicular medium lapilli with rounded edges (Fig. 8). Three samples (T, U, V; Fig. 8) were taken from 9, 15 - 21 and 30 - 35 cm below the spatter bomb and have density values of 2020, 1870, and 1730 kg m\(^{-3}\). Aspect ratio values show a gradual downward decrease, ranging from 5.7:1 at the top to 4.9:1 near the base of the densely welded zone.

The underlying moderately welded zone is 14 cm-thick (37 to 51 cm depth under sb1) and features elongated lapilli-sized clasts with rounded margins in a homogenous, glassy, grey matrix. Two density samples (W and X; Fig. 8) at 40 – 44 and 46 - 51 cm depth have values of 1503 and 1420 kg m\(^{-3}\), respectively. Aspect ratios of flattened clasts range from 4.2:1 to 3.2:1. Sample Y at ~ 60 cm in the underlying slightly welded zone has a density value of 1550 kg m\(^{-3}\) and clast aspect ratios in this zone range from 3.2:1 to 3:1. The tack-welded zone (sample Z at 63-66 cm depth) has a density value of 1270 kg m\(^{-3}\) with an average clast aspect ratio of ~2.4:1. This welding profile yields the highest density values in the collection of samples considered in this study (Table 1). The average density for this profile is 1700 kg m\(^{-3}\), which in comparison to the average bulk density of ~250 - 300 kg m\(^{-3}\) for the non-welded Plinian deposits represents a ~ five-fold increase in the deposit density (Carey et al., 2008a). The rate of decrease of density with distance from the spatter bomb is 12 kg m\(^{-3}\) per centimeter. The sharp shift from the slightly welded tephra (sample Y) to the tack-welded tephra (sample Z) corresponds well with field observations of a sharp boundary separating the domains of flattened and non-
Figure 8: Inset A from section 6 showing the measured density and aspect ratio data from profile VII, situated between the spatter bomb sb1 and the non-welded part of sub-unit D3, visible at the base of the photo. Note the contrast in vesicularity between coarsely moderately vesicular bomb (sb1) and the dense glassy welded zones. The brownish-red domains with round edges beneath sb1 are ghost-like remnants of bomb-sized clasts. The dashed line is the basal surface of sb1 and labels t, u, v etc. are density samples. Tape measure is 80 cm. Density and aspect ratio measurements are given in Table 1.
flattened pumice. Clast aspect ratios mimic the change in the density data and in general show a steady decrease in values with depth. The exception is the interval between samples U and V, which features a sharp shift in clast aspect ratio from 4:1 to 3:1.

Profile VIII – welding beneath sb3

Profile VIII is immediately below sb3, which is the second-largest spatter bomb at section 6 and situated 2.4 meters to the east of sb1 (inset B; Fig. 5). In cross section, the spatter bomb is 185 cm x 76 cm. The profile (VIII) was taken ~10 cm to the right of a granophyre lithic clast which is 10 cm in diameter. We identify three welding zones underneath sb3 with a combined thickness of 28 cm. It is separated from the W1 unit by 38 cm of non-welded D3 deposits, which is only a portion of its original thickness because of the encroachment of regionally welded W1 and locally welded W2. Immediately underneath sb3 is a moderately welded zone, 5 - 7 cm-thick (Fig. 9), which thins to 1 cm above the before-mentioned lithic clast. It is characterized by a grey/black glassy matrix and orange to black 2 to 8 cm-long non-vesicular fiamme, which are flattened with an average aspect ratio of 6.8:1. The density of this zone is 1700 kg m⁻³. The underlying slightly welded zone is 6 - 7 cm-thick and has a density of 1370 kg m⁻³. It can be distinguished from the upper zone by a more discernable matrix texture and lower clast aspect ratios (~3.3:1). The lowest, tack-welded zone is 20 cm-thick and has density ranging from 970 to 1050 kg m⁻³, for samples collected from the upper and lower portions of the zone. The pyroclasts within this zone have aspect ratios from 1.9:1 to 1.8:1 and the matrix texture is clearly discernable. The tephra immediately beneath sb3 reaches only a moderate welding grade and is followed by a sharp decrease in welding.
Figure 9: Inset B from section 6, showing the density and aspect ratio data for profile VIII underneath sb3. The spatter bomb (sb3) contains dm-size domains of macroscopic vesicles, which are a strong contrast to the non-vesicular nature of the moderately welded tephra adjacent to the spatter bomb. With distance outward from the margin of the bomb, the original tephra textures gradually become more apparent. Labels aa, ab etc. are density samples. Tape measure is 30 cm long. Density and aspect ratio values are given in Table 1.
intensity with depth. The rate of decrease of density with depth is 26 kg m\(^{-3}\) per centimeter. The average density of the welded zone below sb3 is 1050 kg m\(^{-3}\) or 3.5 times greater than the non-welded D3 deposits.

*Comparisons of welding profiles underneath the two spatter bombs*

The most obvious difference in the welding pattern and intensity of the tephra beneath the two large spatter bombs considered here are the steeper density and aspect ratio gradients with depth below sb3, compared to that of sb1. This is expected because of the size difference between the two bombs, sb1 is approximately two times larger than sb3.

3.3.2 *Local welding laterally, due to contribution of heat from the spatter bombs.*

The welding influence of the spatter bombs is not limited to the tephra beneath the spatter bombs, but also extends to the deposits beside and above the bomb (inset C; profile IX; Fig. 5). Clearly, this welding is solely induced by heat transfer laterally and upwards from the bomb and not influenced by forces generated by impact and loading. Thus, profile IX provides us with an excellent opportunity to study quantitatively the effects of heat transfer alone on the process of local welding.

Profile IX extends laterally from the margin of the bomb through moderately, slightly, tack and non-welded D3 deposits over a distance of 70 cm and contains 9 samples (Fig. 10). The welded tephra was originally non-welded D3 Plinian fall, which outside the welded halo has the Plinian characteristics observed elsewhere, including framework support, with 2 to 25 cm lapilli (predominantly in the 2 - 4 cm size range) and 10 - 15 modal% ash shards. At the margin of the spatter bomb there is a rheomorphic zone, which is 0 – 4 cm wide and has a density of 1740 kg m\(^{-3}\) (sample ae; Fig. 10). Over the
Figure 10: Inset C at section 6, showing profile IX through the welded tephra adjacent to spatter bomb sb1. The density profile is similar to that of profile VIII, in that it shows a sharp initial decrease to values approaching non-welded values. However, the range in density values is similar to that observed at profile VII, in that the highest density value adjacent to sb1 is twice that obtained for the most distal sample. Although the aspect ratio values are low compared to profiles VII and VIII (see Figs. 8 and 9), the profile shows a parallel trend which corresponds reasonably well with the change in density with distance from sb1. Another noteworthy feature is the increase in matrix cohesiveness towards sb1. Density and aspect ratio values are listed in Table 1.
next 25 cm (samples af – ai; Fig.10), the density decreases gradually outwards from 1820 to 990 kg m\(^{-3}\) (~30 kg m\(^{-3}\) per centimeter), and remains relatively uniform at 990 - 1120 kg m\(^{-3}\) for the remainder of the welded halo. The density data are in fairly good correlation with the aspect ratio data; however, there is a more rapid decrease in aspect ratio that initiates an earlier transition to a stable value (sample ai at 26 cm from origin) compared with the density changes (sample aj at 37 cm from origin). From sample ai outward the aspect ratio remains between values of between 1.1:1 and 1.3:1, which are similar values to those obtained for non-welded D3 Plinian fall that typically ranges from 1:2 to 2:1.

3.3.3 Discussion of welding related to single large spatter bombs

Heat, compaction and insulation are properties which facilitate welding of the deposits surrounding spatter bombs. Addressing the patterns of welding observed underneath the spatter bombs due to the contributions from heat and compaction, we see, at both sections, a more rapid decline in the aspect ratios than the densities. This suggests that the flattening of the clasts has a critical heat requirement that is only achieved close to the clast. If the critical heating requirement is not met, then significant flattening cannot occur. Density reflects the combination of pumice flattening and matrix compaction, and the timescales of heating, softening and welding are faster in finer-sized tephra due to an increased surface area to volume ratio. Heating effects thus extend further outward in the matrix and the density data reflect this. It appears that density is a more sensitive measure of the welding grade due to the combined effects of heat and compaction. Also it seems that heat and compaction are both required to flatten clasts and reach dense welding grades.
A comparison of welded profiles from underneath the spatter bombs (profiles VII and VIII; Figs. 8, 9) shows some interesting features. The rates of density and aspect ratio decrease are less for the larger spatter bomb which also has the highest density and aspect ratio found in the entire study. This is most likely due to the increased load, high heat capacity and strong insulating properties of the largest spatter bomb, facilitating long-term release of a larger quantity of heat and heat retention in the underlying deposits. Heat transfer out of the spatter bombs also appears to be an efficient mechanism to weld the surrounding deposits. However, some degree of insulation is needed to retain this heat and keep the deposit at a temperature near the glass transition. The welding grades we have observed in profile VIII underneath sb3 (Fig. 9) range from moderate welding (very proximal to bombs – 1 to 2 cm) to tack-welding. In a lateral profile (IX; Fig. 10) extending away from sb1, aspect ratios have identical values to non-welded D3 tephra, and it is clear that aspect ratio data cannot be used as a proxy for welding intensity when there is a lack of compaction-induced strain. However, density measurements provide a more reliable analysis of welding grade. Welding in this particular case study was facilitated by insulation as the D4 spatter bomb was deposited deep within D3 tephra and thus was insulated on deposition.

In summary, the spatter bombs appear to require a critical emplacement temperature and size to produce the flattening and compaction of the surrounding pyroclasts required to achieve high degrees of welding (dense welding and rheomorphism). In addition, high grades of welding at the sides and top of the bomb can only occur when the welding material is insulated, thereby preventing high rates of heat loss.
4. Case Study 2: Section 8

In the previous case study at section 6, we examined the effects of local welding as they vary with the size and abundance of spatter bombs. It addressed factors that promote welding, such as heat and compaction, and examined local welding associated with a) a single spatter bomb; b) multiple small spatter bombs and c) large meter-sized spatter bombs. In this case study we contrast local welding effects in- and adjacent to W1 and W2. Section 8 is 104 meters to the east of section 6 in a region where the abundance of spatter bombs is significantly higher. In both welding units we see a 30 - 50% increase in the local abundance of spatter, but with similar sizes of spatter bombs to those in the previously described section 6. Over a lateral distance of 25 meters, we have chosen four profiles (8-a, 8-b, 8-c, 8-d; Figs. 11a, b, c); each profile provides insight into the effects on regional welded tephra with contrasting superimposed contributions from local welding (Figs. 11a, b, c). These four profiles also allow us to contrast the W1 and W2 welding units. Each section is between 1.72 and 2.00 meters-thick and we divide W1 and W2 into zones (e.g., W1-a, W1-b and W2-a, W2-b, respectively) based on welding grade, grain size and componentry.

4.1 General overview of the profiles at section 8

At 8-a, there is one large (sb6) and several smaller spatter bombs (Fig. 12). The tephra throughout the entire section has been thermally oxidized to yellow, orange, brown and
Figure 11a, b, c: At section 8, four profiles were measured along this 24 meter-long, east to west traverse, to show lateral variability in local and regional welding. Section 8-a is the least welded section while section 8-d is extremely welded and forms a protruding bench. Note the abundance of spatter bombs (black) in the upper portions of each profile, outlined in Figure 11b. Note the contrast in both size and abundance of spatter bombs from east to west. At the west of this section, W1 and W2 merge to become a single welded bench. Each of the stratigraphic profiles from section 8 are shown with their corresponding density (blue) and aspect ratio profile (green). The spatter bombs have been labeled according to the text. Each zone in the stratigraphic section is labeled (W1 or W2) and its relative position (A to E). The zones have each been shaded and non-welded tephra is white. Tack-welded, slightly welded etc. have been labeled tw, sw etc. on this, and the following figures. Moderately and densely welded zones have rounded clasts drawn within them to represent significant changes in original clast properties. Spatter bombs are drawn in white in the stratigraphic logs and their positions marked by name in the photographs (Figs. 12, 13, 14, 15). Density samples taken through each of the logs have been labeled 1 - 55 and the values are given in Table 2.
dark grey colors. W1 and W2 are present at this location as two discrete units separated by a significant thickness (78 cm) of non-welded D3 fall. Profile 8-b is 10 meters west of 8-a, and is considerably more welded due to the influence of two large spatter bombs (sb7, sb8; Fig. 13) in W2. W1 is regionally welded, with no significant spatter within 2 meters laterally.

W2 has a high degree of welding, encroaching significantly into D3. Profile 8-c is characterized by a large spatter bomb on the top of this section (70 x 35 cm in cross section) and numerous dm-sized spatter bombs in both welding units (Fig. 11b) which increase the intensity and extent of welding in both W1 and W2 (Fig. 14). Non-welded D3 is at a reduced thickness due to the encroachment of W1 and W2. Profile 8-d (Fig. 15) is 6 meters west of 8-c and represents the extreme example of local welding at section 8. At this location all D sub-units have welded together to form a composite W1/W2 bench that protrudes above the C pyroclastic surge deposits. This profile has been divided into six welding zones with three major spatter bombs. Abundant smaller spatter bombs are present, particularly in the lower 35 cm and upper 55 cm. The largest spatter bomb, with dimensions of 280 x 50 cm, has flattened significantly and extensively welded the originally non-welded D3 tephra.

4.2 Background regional welding at section 8.

At this location the high concentration of spatter bombs makes it difficult to observe the effects of background regional welding in areas unaffected by local welding. We see background regional welding for W1 at 8-b (Figs. 11a, b) but large spatter bombs are
Figure 12: Profile 8-a, at the eastern end of this location is 1.95 meters-thick and W1 and W2 are present as discrete units. W1 has been split into five zones and spatter is concentrated in W1-c, corresponding to upper D2. Zones W1-a and W1-b are also formerly non-welded D2 deposits, whereas zones W1-d and W1-e were non-welded sub-unit D3 deposits. The W2 unit is split into three zones. Zones W2-a and W2-b, represent regional welding and zone W2-c has contributions from local and regional welding. The spatter bomb at the top of this profile (sb6) is a simple bomb and is 90 x 45 cm.
Figure 13: Profile 8-b is 10 meters to the west of profile 8-a. W1 at this location is regionally welded with no influence of spatter. The W2 unit has been separated into five zones and has two spatter bombs within it (sb7, sb8). The non-welded sub-unit D3 deposits have been significantly thinned (15 cm vs. 78 cm) due to the encroachment of both W1 and W2. Density samples (12 - 24) are labeled in black boxes and the values are given in Table 2. Note the coarse vesicularity and moderate vesicularities of sb7 relative to the surrounding welded deposits. Both of these bombs appear to be composite bombs, and within sb6, dense rounded particles from former clasts have been incorporated into the spatter bomb.
Figure 14: Profile 8-c is the third profile on an east to west traverse, both W1 and W2 are present and have contributions from regional and local welding. W1 has been divided into five zones and the middle zone (W1-c) has abundant spatter within it (~60 modal%). This spatter-rich zone has increased the thickness of W1 greatly by welding surrounding originally non-welded D3 tephra from above. W2 has been separated into three zones, (W2-a to W2-c) and W1-c has a concentration of spatter bombs within it (~85 %). Density samples and aspect ratio measurements were taken from each welded zone and the values are given in Table 2. The tape measure is 1 meter long.
Figure 15: The westernmost profile of this traverse is 8-d, and it is the most intensely welded of the four profiles and on the northern rim of the caldera. Welding units W1 and W2 have merged to form a single welded bench that protrudes from the underlying pyroclastic surge deposits. Spatter bombs (sb10, 11) are related to D4-time deposition and has welded former non-welded D3 tephra, which is no longer recognizable at this location. Above sb10 are three zones (W2-a to W2-c) and W2-c has abundant spatter within it (~ 80 modal%). Note the lithic clast and a relic pumiceous clast in sb10, shown by a white outline. Density measurements were taken through the welded units and are given in Table 2.
associated with W2 at all four sections and we find pure background welding of W2 only in the lower portion of W2 at 8-a. At 8-a (Figs. 11a, b), regional welding of W2 reaches tack- to slightly welded grades with density values between 1210 kg m\(^{-3}\) and 1600 kg m\(^{-3}\) (Fig. 12; Table 2). Regionally welded W1 is represented at 8-b (Fig. 13).

The W1 deposits range between tack and slight welding, and the density values range between 650 kg m\(^{-3}\) and 930 kg m\(^{-3}\). An interesting feature of the W1 welding unit is the alternation between tack- and slightly welded deposits. This is probably a function of fluctuations in accumulation rate (Carey et al., 2008).

### 4.3 Local welding of W1

At all profiles apart from 8-b, local welding is superimposed on regional welding grades to produce enhanced degrees of welding. At 8-a and 8-c, local welding reflects the influence of abundant decameter-sized spatter bombs; at 8-d we see the added influences of 3 larger bombs (Figs. 12, 14, 15). At all of these three sites, dm-sized spatter is concentrated in the middle portion of the welding units. The W1 unit extends significantly into formerly non-welded upper D2 and the original non-welded D3 sub-unit and less into the D1 sub-unit.
Table 2: Density measurements taken from profiles 8-a, 8-b, 8-c, 8-d at section 8.

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8-a: The spatter concentration is confined to the original D2 sub-unit, identified by the higher abundance of matrix and finer grain size of lapilli in slightly welded zones (W1-a, W1-b, W1-d) above and below this spatter-rich zone (W1-c) (Fig. 12). If we look in detail at the exact position of spatter it lies within the upper third of the D2 sub-unit. W1-a and W1-b consistently have finer grain size and high ash abundance (~ 15 - 25 modal%). Based on grain size, W1-d appears to be a combination of formerly non-welded D2 tephra and D3 tephra, whereas W1-e is tack-welded and is comprised totally of former non-welded D3 tephra. A sudden change to high density values (samples 1 and 2: 880 – 1550 kg m⁻³) precedes the spatter-rich sub-unit (W1-c) containing the highest density values (samples 3, 4, 5: 1830 -1710 -1690 kg m⁻³; Table 2). In the overlying welded zones, there is a more gradual decrease in density over a greater vertical distance (samples 6, 7: 1200 – 760 kg m⁻³). Aspect ratios mimic the density data, with a sudden increase to higher values (1.5:1 to 3.3:1) followed by a gradual decrease in value (5.3:1 to 1.6:1).

8-b: Is regionally welded with no obvious spatter.

8-c: Within this profile, W1-c is spatter-rich (Fig. 14). This central W1-c zone of moderate welding, induced by the high abundance of dm-sized spatter, is surrounded by a thinner halo of less welded tephra at its lower margin (W1-a and W1-b) relative to the upper welding zones (W1-d and W1-e). Density measurements from W1-a and W1-b increase gradually upwards (840 – 1070 kg m⁻³). The density of the W1-c spatter-rich zone ranges between 1590 and 1760 kg m⁻³. The overlying tephra shows a much more gradual decrease in density (1540 – 1040 kg m⁻³) than the tephra below spatter rich W1-c. The aspect ratio data shows that the lower zones (W1-a, W1-b; samples 1 and 2) have
slightly higher values (1.8:1 – 2:1) than the upper zones (W1-d and W1-e; samples 6, 7, 8, 9; Table 2) with values of 1.6:1 to 1.7:1.

8-d: W1 is slightly to densely welded and the abundant spatter of variable size in this section leads to difficulties in separating the W1 and W2 units, and the effects of regional versus local welding (Fig. 15).

4.3.1 Discussion of implications of the properties of the W1 welding unit

At sites 8-a and 8-c, the welding profiles are simpler than that of 8-d. At both sections there is a central spatter-rich zone with approximately 60 % spatter (W1-c) and we observe that the thickness of the welded tephra above this zone is greater than that below. The greater thickness of welded tephra above the spatter zones is due to the efficiency of upward convective heat transfer. At both sections there is a gradual decline in density from W1-c to overlying and underlying tephra, and aspect ratios generally mirror the density trends. Profile 8-c shows a more rapid decrease in aspect ratio than density. Observations of ductile deformation in the W1 unit (Fig. 16) suggest that when the spatter was deposited the matrix was sufficiently hot to undergo this deformation. The tephra underneath the large lithic clast is moderately welded, similarly to above and beside the clast. This demonstrates that the strain induced by impact is probably not a first-order factor facilitating welding.

4.4 Local welding in W2

The most obvious difference in characteristics between the W1 and W2 welding units is the increase in the size of spatter in W2 and hence the radii of the surrounding halos of
Figure 16: Lithic clast impacted into the W1 unit. This lithic clast impacted into the W1-c spatter-rich zone and the tephra responded by deforming in a ductile fashion. This spatter-rich zone must have been sufficiently hot at the time of lithic impact to deform in this manner. The grade of welding underneath the impacted lithic clast is similar to that of the surrounding welding zone.
local welding. Large spatter bombs are present at the top of the W2 unit in every profile and some profiles have abundant dm-sized spatter bombs in the upper third of the W2 unit with variable shapes and sizes.

8-a: A ~45 cm spatter bomb rests on W2 (sb6, Fig. 12). The effect of sb6 is quite minimal on the welding grade, with very little density difference between the lower (1110 kg m\(^{-3}\)) and upper (1210 kg m\(^{-3}\)) tack-welded zones (Fig. 1lc).

8-b: The degree of welding of the W2 unit is significantly greater within this profile than that of 8-a (Fig. 13). We recognize five welding zones in the unit (W2-a to W1-e) within this profile (Fig. 11c) with a substantially sized, flattened spatter bomb (sb7, Fig. 13) on top of W2 (185 x 52 cm) and one 20 cm below within W2 (sb8, 60 x 38 cm). In addition, W1-e has a significant percentage of 5 to 18 cm-sized spatter bombs absent in W2 at 8-a. Thus the W2 unit has a complex welding profile (Fig. 1lc) due to abundant spatter bombs at different levels. Under this spatter-rich zones, in formerly non-welded D3, there is a rapid decrease in density from W2-d to W2-a. The aspect ratio data however show a more gradual reduction of value.

8-c: W2 can be separated into three zones (W2-a to W2-c) based on welding, grain size and particularly componentry as the uppermost zone has a significant population of dm-sized spatter (~60 modal%). This zone is 45 cm-thick and there is a large spatter bomb (70 x 35 cm) on the top of this profile (sb9; Fig. 14) which has flattened significantly on impact (Fig. 14). The density of the tephra remains fairly constant for the first 3 samples (37, 36, 35: 1480, 1460, 1250 kg m\(^{-3}\) respectively; Table 2) under the spatter bomb (Fig. 1lc) with a significant decrease to the fourth sample (34: 720 kg m\(^{-3}\)), whereas the aspect
ratio data show a more rapid reduction in value (37-36: 3.2:1 to 1.7:1). The aspect ratio is potentially higher in the W2-c zone because of the abundance of spatter in the unit.

8-d: Here W2 is the best example of complexity associated with local welding and the abundance of large spatter bombs (sb10, sb11; Fig. 17). The complexity in this section led us to look at the immediate influence of the larger spatter bomb (sb10) on adjacent non-welded D3 tephra. We took four samples laterally left of sb10 and two samples from above sb10 to examine the effects of lateral versus upward dissipation of heat.

4.4.1 Lateral profile at location 8d

As previously observed at section 6, welding without compaction can occur laterally away from spatter bombs. At section 8-d, we also observe welding laterally adjacent and above sb10 (Fig. 17). Immediately adjacent to the bomb, pumices are elongate in a vertical orientation and tephra has markedly higher welding grades, suggesting either displacement and flowage from beneath the bomb after its emplacement or a welded rim formed prior to ejection of the bomb (Fig. 17). Observations of welding intensity show a shift from moderate welding immediately adjacent to the bomb outward to slight welding. Four density measurements were made (Table 2) and the calculated density decrease (excluding the high density rim of sb10), from inner to outer samples (37 cm) is 15 kg m^{-3} per centimeter.

4.4.2 Vertical upwards profile

A vertical profile was taken above the spatter bomb through previously non-welded D3 deposits. The material immediately above sb10 is slightly welded and remains at that grade, until the spatter-rich layer is reached (W2-c). Physical observations of the slightly welded material passing laterally and vertically from the spatter bomb reveal that the
matrix texture is slightly more cohesive close to the spatter bomb. Two density samples were collected in the slightly welded area, one at 5 cm above the bomb (sample 43) and the other a further 5 cm away (sample 44). The density values are summarized in Table 2 and reveal a rate of density change of 22 kg m\(^{-3}\) per centimeter.

4.4.3 Implications from the W2 welding unit

Spatter zones in the upper third of the W2 unit show density values similar to those in the W1 welding unit. Aspect ratios, however, appear to show less flattening, but mirror the density data well. We note that spatter bombs, regardless of size, can have a range of effects on the substrate on which they land. For example sb6 at 8-a, has had very little effect on the tack-welded tephra immediately underneath it. In comparison, sb9 at 8-c, approximately the same volume although flattened (hence presumably hotter), has had a significant effect on the deposits underneath. This suggests considerable heterogeneity in terms of viscosity, temperature and heat capacity of the depositing spatter bombs.

The comparison of lateral and vertical profiles adjacent to sb10 at 8-d (Fig. 17) shows that a slightly greater amount of heat is transferred to the tephra above the heat source than laterally to the side. This has implications for the lateral and vertical extent of the welding unit. In areas of pure local welding with no input from regional welding, spatter
Figure 17: Lateral and vertical profiles taken adjacent to and above sb10 at section 8-d. Density samples are shown as black squares and their values are given in Table 2. Four samples were taken laterally away from sb10, and 2 samples were taken above sb10 but below the W2-c spatter-rich zone.
bombs must almost be adjacent to one another to form a continuous welded bench (<< 1 meter). This is a useful field tool to detect the presence of regional welding in areas with large spatter bombs.

5. Timescales and rheology of welding

When hot pyroclastic deposits are emplaced, welding and compaction occurs via sintering and adhesion of hot glassy particles and loading and deformation created by the overlying tephra (e.g., Smith, 1961; Sparks and Wright, 1979). Measurements of physical characteristics such as particle oblateness and density (which are proxies for strain) therefore allow us to understand the accumulation of strain throughout the welding and compaction process (e.g., Quane and Russell, 2005; Russell and Quane, 2005).

There are two types of strain;

a) reduction of the deposit thickness through shortening and the loss of porosity (volume strain) and;

b) shear strain and plastic ductile flowage of the material (conservation of volume).

(Quane and Russell, 2005; Russell and Quane, 2005)

Under the conditions of pure volume strain all the strain is accommodated by volume loss and therefore particle oblateness is a measure of total strain, assuming that all the particles were initially equant (e.g., Russell and Quane, 2005). Under these conditions, there is a 1:1 relationship between strain (calculated from density measurements) and particle oblateness. Under the conditions of conservation of volume, all the strain must be accommodated by deformation of the material – a fixed value of strain requires particles
Figure 18: Oblateness derived from measurements of flattened pumice lapilli versus normalized density for samples that have undergone welding due to heat and compaction (in red and blue) and samples that have welded due to heat only (yellow). Oblateness and normalized non-welded bulk density for D3 and D4 deposits are plotted on the same graph (from Carey et al. 2008). Values of oblateness for samples that have welded due to heat and load increase linearly with normalized density. Note the disparity in density and oblateness between samples with similar degrees of welding.
Figure 19: Oblateness versus normalized density ($\rho/\rho_{DRE}$) for welded samples that have either welded due to both heat and load (local welding- in red) or intrinsic heat (regional welding- in yellow). D2, D3 and D4 non-welded values have been added to the graph for comparison. See text for explanation.
Figure 20: Oblateness versus normalized density ($\rho/\rho_{DREI}$) for welded samples due to either intrinsic heat (regional welding in blue) or inherited heat (inset C samples in yellow). The intrinsically-welded samples (blue) show higher values of oblateness at given density values than the inherited heat samples.
to show greater oblateness because the volume is conserved (e.g., Russell and Quane, 2005).

The purpose of this section is to understand which mechanisms operated (and their relative timing) and resulted in the patterns of welding we observe in the 1875 welded deposits. Figures 18, 19 and 20 show the relationship between particle oblateness derived from measurements of flattened pumice lapilli and the normalized density. Oblateness is calculated by combining lengths \(a\) and heights \(c\) of flattened lapilli as \(1-(c/a)\). Density is normalized by dividing the measured welded densities by the dense rock density \(\rho/\rho_{DRE}\). We use a DRE density value of 2350 kg m\(^{-3}\), assumed for a rhyolitic magma composition.

### 5.1 Oblateness and density changes

#### 5.1.1 Some limitations of the approach

Unlike welded pyroclastic flow deposits which cool as a single unit, welded fall deposits are thermally heterogeneous, emplaced at rapidly changing accumulation rates, and thus inherently much more difficult to model. Thus we present here general trends and list the potential reasons for the scatter observed in the data.

- a) The non-welded pumices are not equant and in non-welded fall deposits pumices can be aligned either with the largest axis vertically, or (the majority) with the long axis horizontally. Therefore the starting values of oblateness can be very variable.
b) The deposits as originally emplaced were probably not isothermal - clasts of different sizes follow different transport paths and thus may have been deposited together but at different depositional temperatures.

c) Some scatter in the densely welded samples may be due to the difficulty identifying extremely flattened fiamme when they have ghost-like textures, so that less flattened clasts may have been chosen unintentionally.

d) Some of the deposits affected by spatter may have already had some component of regional or local welding; others did not.

e) The grain size and (original non-welded) bulk densities may have been slightly different due to the addition of a large clast, changing lithic or ash contents.

5.1.2 Differences between heat + loading (Insets A and B) vs. heat without significant loading (Inset C)

Figure 18 illustrates the variation in oblateness and normalized density from samples collected from a) profile VII at section 6 – high degree of loading and heating from a large bomb (red symbols, see Fig. 8); b) profile VIII at section 6 – smaller degree of loading and heating from smaller bomb (blue symbols, see Fig. 9) and; c) profile IX at section 6 – heating only, along a lateral profile away from the largest spatter bomb in original D3 non-welded tephra (orange symbols, see Fig. 10). The samples that have undergone welding due to heating and loading effects (red and blue) show a linear trend of increasing oblateness and density with increasing welding intensity. The red samples are displaced to slightly higher density values and/or have lower aspect ratio values with respect to the blue samples (Fig. 18).
The orange samples representing welding due to pure inherited heat (profile IX) show a trend of increasing density without significant changes of the oblateness (Fig. 18). This is probably due to the lack of loading associated with these samples taken from lateral profiles away from a spatter bomb together with insufficient time to heat the larger lapilli to a plastic state and thus oblateness largely reflects original emplacement aspect ratios.

In Figure 21, we show our interpretation of the evolution of the welding process in fall deposits and its signature on physical characteristics of density and pumice flattening. There are basically three processes to consider:

a) initial matrix compaction and elimination of open intraclast pore space;

b) shrinkage and flattening of the vesicles in the pumice, further reducing the porosity and facilitating pumice flattening;

c) flowage and shearing of the welded material.

We define three segments on the graphs which reflect the progressive onset of these processes. Along segment A, welding is characterized by matrix compaction with only minor flattening and shrinkage of pumices and so the segment shows a relatively flat trend on the plot of oblateness versus density. Segment B is dominated by flattening and collapse of vesicles leading to a marked increase in the oblateness of lapilli, further densification of the matrix probably accompanies this shift. Line segment C reflects the situation where virtually all original pore space is lost but rheomorphic flowage results in very high degrees of pumice stretching (Fig. 21). Our data suggest that most of the local welded samples fall on line segments A and B, and rheomorphic flow was only possible very close to the largest spatter bombs.
Figure 21: Cartoon showing contrasting patterns of welding development for locally welded samples subjected to heat transfer and loading, versus pure heat transfer. The former samples define three line segments with increasing welding intensity defined by dominantly compaction and elimination of pore space in the matrix (A), an increased role for flattening and shrinkage of pumice (B) and rheomorphic flow (C). The latter follows a trend that is essentially a continuation of line segment A. See text for further explanation.
5.1.3 Comparison of loading + heating effects vs. regional welding

The increase in density of samples taken from areas where loading and heating were responsible for welding (red symbols, Fig. 19) generally correlates simply with the welding grade assigned physically in the field with the exception of one point. However, the regionally welded samples (blue symbols) show much more variation in both oblateness and density and have markedly overlapping fields.

The trend generated by samples which have been influenced by both heating and significant loading from spatter bombs (in red) display an initially gentle slope that then steepens at normalized density values greater than \(\sim 0.60\) (Fig. 19). This point correlates with the boundary between slight and moderate welding grades. At lower values of normalized density there are no significant changes in oblateness and this must relate to an initial welding period where the matrix compacts and welds with only limited flattening of the pumices (strain dominantly due to volume loss). The change in slope at densities of 0.60 suggests a change in the mechanism of strain accommodation (Fig. 19). We suggest that this shift correlates with a move from pure welding of the matrix to the beginning of strain being accommodated by flattening of pumices with minor additional loss in pore space of the matrix.

In the samples that have undergone regional welding purely due to the influence of intrinsic heat in the clast assemblage (blue symbols, Fig. 19), we see a general trend of increasing oblateness with welding intensity. However, oblateness values are lower than those of heat and load-induced local welding (red symbols, Fig. 19), and there is more scatter in the data for a given density. For example, five tack-welded samples with normalized density \((p/p_{[DRE]})\) values between 0.33 and 0.36 have oblateness values
between 0.11 and 0.4. This deviation stems from the deviation in original non-welded oblateness and reflects original alignment of the now welded particles. For a given oblateness, normalized density values vary significantly (e.g., at oblateness values of ~0.4). The densification of the samples without increases of oblateness must relate to the initial welding period where the matrix welds, without the flattening of vesicles within the pumices (strain due to volume loss).

5.1.4 Intrinsic heat vs. inherited heat

Fig. 19 contrasts the nature of the welding due to intrinsic heat (regionally welded samples, e.g., W1 at profile 8b etc.) with samples affected by added or ‘inherited’ heat from the spatter bombs without loading (inset C samples; Fig. 10 and section 8-8d; Figs. 11a, b, c). These welding processes are different in terms of welding potential, and this must have major consequences for the resulting welding profile. Presumably the tephra with intrinsic heat was already capable of welding and compacting in the absence of any influence from spatter. In comparison, the samples from originally non-welded tephra laterally adjacent to spatter bombs represent tephra that was too cool to weld as a result of intrinsic heat (mostly because clasts were derived from, and cooled efficiently in, the high D3 Plinian plume) and in addition, the D2 and D4 welding tephra has a high abundance of ash, in contrast to the D3 Plinian tephra which is much better sorted.

The regionally welded samples (blue symbols, Fig. 20) show the broader linear relationship between particle oblateness and density with some scatter in the data, the reasons which were described previously in section 4.1.2. These samples in response to intrinsic heat, show a welding trend implying a combination of matrix compaction together with a finite amount of flattening of pumice (Fig. 20). In comparison, the
samples that have been affected by introduced heat (orange symbols, Fig. 20) show a near horizontal trend of progressive increase of density with very small changes of particle oblateness, essentially a continuation of segment A in Fig. 21. The contrast lies in the inherent original thermodynamic properties prior to welding. Pumice lapilli in the regionally welded D2 tephra were probably hotter than the ash matrix that enclosed them when welding commenced. The enhanced values of oblateness at increasing but low densities must suggest some early component of pumice flattening and thus individual D2/D4 lapilli must be very close to glass transition temperatures. In comparison, pumice lapilli in the Plinian D3 tephra subsequently heated by the spatter bomb were originally cooler/cold, and significantly more time is required to heat the lapilli relative to the ash fraction with its larger surface area-volume ratio. Therefore one would predict that those parts of the welding process involving flattening of the lapilli would be delayed or completely suppressed in the case of local welding without enhanced loading. This suggests that initial depositional temperature rather than rate of heat loss/efficiency of insulation is a first order factor for the locally welded deposits.

5.2 A comparison to the patterns of strain described in welded ignimbrites

Although the physical process of accommodating strain through welding and compaction may be similar between deposits of fall and flow origin, the trends for change in total strain with stratigraphic height/depth observed in pyroclastic flows appear completely dissimilar (Fig. 22; e.g., Quane and Russell, 2005; Russell and Quane, 2005).
Figure 22: Graph of normalized density ($p/p_{DRE}$) vs. normalized stratigraphic height for Askja 1875 welded fall deposits (in red and orange) and welded pyroclastic flow deposits taken from the literature (in blue): Bishop Tuff (Sheridan and Wang, 2005), Bandelier Tuff (Russell and Quane, 2005), Wineglass Welded Tuff (Kamata et al., 1993) and Ito Tuff (Sheridan and Ragan, 1976). Assuming all welding compaction is due to the removal of pore space, $p_n$ values can be used as a proxy for strain in pyroclastic welded deposits. Five 1875 regional welding profiles are shown together with three local welding profiles. Note the contrasting profile shapes of welded 1875 fall deposits and those of the welded flow deposits. In addition, note the contrasting profile shapes of local welding due to heat only (profile IX) and due to heat and load (profiles VII and VIII).
This is due to the contrasts in the thermal history of each emplacement mechanism. Pyroclastic flows are emplaced very rapidly in a thermally efficient manner, allowing the deposit to cool as a single unit and therefore the relationship between welding and compaction largely reflects the changing extent of loading throughout the welding unit (Sheridan and Wang, 2005). This permits systematic changes in particle oblateness and density with stratigraphic height/depth, with the development of maximum welding state relatively low in the stratigraphy. The 1875 welded deposits are more complex on the outcrop scale because welding has been produced under conditions of both fluctuating accumulation rate and varying degrees of external heating and loading by large spatter bombs. The spatter bombs are heterogeneous in terms of a source of both heat and loading and therefore add further complexity.

6. Discussion and interpretation

6.1 Spatter

6.1.1 Characteristics and size

Spatter in the rhyolitic 1875 deposits has a diverse set of characteristics, some of which are similar to those of spatter originating from basaltic fire fountains (Sumner et al., 2005), but others that are unique to the 1875 deposits. Similarities include: the diverse range of densities observed, the fluidal fusiform shapes, and flattening/deformation on impact. Differences include: the complex internal textures observed in many 1875 bombs, lack of secondary spattering, coarseness of the 1875 ejecta, which range over nearly 2 orders of magnitude, and finally contrasts in erupted 1875 spatter when comparing the D2 and D4 deposits. An overwhelming abundance of simple spatter
bombs with respect to composite bombs seen in D2/W2 is the exact reverse in D4/W2 deposits. This observation must hold some important clues to eruption dynamics in the shallow conduit and vent regions.

6.1.2 Contrasts in spatter bombs within W1 and W2

In the 1875 deposits the most obvious differences in the W1 and W2 spatter bombs are the internal textures and size. In W1, the spatter bombs are predominately simple spatter bombs with a size range of 5 to 50 cm with smooth margins, lacking any remnant of a pumiceous or brittle carapace. In W2, simple and composite spatter bombs are both common, but composite bombs dominate, and the size range extends up to 9 meters in diameter. Spatter bombs commonly have fluidal and pancake shapes; flattening ratios measured from bombs greater than 1 meter in diameter suggest that the interiors have a sufficiently low viscosity to deform plastically and hence must be at temperatures above the glass transition. Many smaller spatter bombs in both welding units lack flattening suggesting extreme thermal heterogeneity of the erupted bombs. This must relate particularly to the conditions in the shallow conduit, vent and erupted jet. The coarsest bombs (cubic meters in volume) lose minimal heat in being transported through the air prior to deposition suggesting that the contrasting morphology of these bombs reflects thermal heterogeneity in the shallow conduit.

6.1.3 Position of spatter within the stratigraphy

Spatter is concentrated in the upper third of each welding unit and is associated with two phases, each of which simultaneously produced pumiceous D2 and D4 deposits. As established by Carey et al., (2008a), the eruption phases of D2 and D4 had sudden onsets and gradual declines in activity. The spatter appears to be related to the end of each
phase. In addition, the nature of non-welded D2 tephra (Carey et al., 2008a) shows that there were 2 periods of rapid deposition at the onset and closing stages of D2 time.

6.1.4 Geographic distribution of W1 and W2 spatter

In addition to the smaller size of the W1 spatter bombs, their distribution is distinctly more limited than their W2 counterparts (< 100 meters versus ~ 600 meters). Travel distance is related to many factors including density, size, ejection angle and most importantly, eruption velocity. A more focused study on the distribution of the spatter bombs and implications for eruption dynamics will be the subject of a separate paper.

6.2 Welding

6.2.1 Factors governing local welding

The two primary controls that a spatter bomb exerts on local welding are its heat and loading capacities. These factors approximately scale with the size of the spatter bomb, except in cases where we have observed brittle fracture and no deformation on landing of large spatter bombs which obviously did not have high emplacement temperatures. In terms of heating, the thermal conductivity of the dense spatter bombs is low and larger spatter bombs will supply heat continuously to the surrounding deposits for a longer time period. After the initial heating period, the tephra immediately adjacent to the bomb will attain a quasi-equilibrium temperature and any remaining heat in the spatter bomb will dissipate more slowly resulting in extended timescales of cooling, facilitating further compaction and flattening in the deposit. Compaction is also related to the size (loading) of the spatter bomb; the greater the load (at the critical welding temperature), the greater the degree of flattening of the matrix material and hence higher welding grades.
As we have seen in profiles VII, VIII and IX, at section 6 (Figs. 8, 9, 10), the combined effects of heat, compaction and insulation can provide suitable conditions for dense local welding and, proximal to the bomb, rheomorphic flowage. These welding grades are unattainable in the 1875 regionally welded deposits. It appears that the combination of compaction and heat is the primary factor that facilitates high degrees of welding. In a comparison of profiles VII and VIII (under bombs of different sizes), the density and aspect ratio data show that a critical bomb size (i.e., loading) is needed to produce dense grades of welding. Profile IX at section 6 also shows that heating alone cannot form these high welding grades, except immediately adjacent to the spatter bomb.

6.2.2 The local welding process

The physical property measurements track the strain accumulated during welding and compaction. As discussed in section 4.1, there is a linear relationship between oblateness and density for locally welded samples that have been affected by both loading and heating from overlying spatter bombs (Figs. 18, 19). Strain is accommodated initially by volume loss of the deposit. In Figure 19a, there is a segregation of data points between oblateness values of 0.55 and density values of ~0.60. This is presumably the field where strain can no longer be accommodated by matrix volume loss, and so flattening of the pumiceous lapilli and matrix clasts occurs. Local welding due to contributions of heat alone is observed to weld the matrix of the deposit; however, the heat supplied laterally is not enough to begin to soften and collapse the vesicles leading to high grades of welding (with the exception of the region within a few mm to 1 cm of the spatter bomb).

6.2.3 Contrasts between regional and local welding
Regional welding grades commonly range from tack to moderate welding grades; however, tack to slight welding is dominant. In comparison, local welding can induce dense welding and the necessary flattening ratios for this welding grade are achieved by the compaction associated with loading by coarse spatter bombs. The thicknesses of regionally welded deposits are predictably less than locally welded deposits. The maximum thickness of regional welding is dictated by accumulation rate, the duration of deposition, and the need for thermal insulation. In contrast, local welding is able to weld original non-welded tephra in a halo concentrically around a spatter bomb and in extreme cases, can weld the entire D deposit thickness. Lateral variations in zone-thickness are more rapid for local welding than regional welding due to the dependence on heat originating from the spatter bomb and the inefficiency of lateral heat transfer.

7. Implications of welding for a model of eruption dynamics

The welded and non-welded deposits on the northern rim suggest that deposition during the Plinian phase in the northern proximal environment at Askja included 2 elements: i) rain-out of clasts from the upper margins of a sustained Plinian column arising from a centrally located source vent, and ii) episodic contributions from a separate northern source area that displayed jetting/fountaining styles of eruption. The pattern of the welding and spatter bomb distribution suggests multiple vents operating at any one time throughout the fountaining-dominant phases (D2 and D4).

The two periods of fountaining activity from the northeastern source each began with a sudden onset and an intense period of eruption and deposition. In the first fountaining phase (D2), the discharge rate was not sustained, and appears to have decreased slightly
towards the middle of its duration only to increase to discharge rates similar to those of the initial opening period (Carey et al., 2008). At the end of both fountaining phases, enhanced eruption of spatter appears to be synchronous with the decline of discharge rate. The decline of activity during the end of the D2 phase was gradual and the fountaining jets were more or less continuous. In contrast the high abundance of very dense spatter in the upper D4 deposits suggests that more of the magma had significantly degassed in the final stages, and we speculate that more episodic, directed vent clearing explosions of dense magma resulted in the coarse population of spatter bombs being ejected to distances far beyond the D2 depositional area.

8. Conclusions
The unusual proximity of the welded deposits on the northern rim to source vents at Askja has permitted study of ultra-proximal exposures of complex welded deposits erupted synchronously with portions of the main Plinian activity. There were major contributions from different source vents that were in a markedly different eruption style. Welding on the northern rim is a function of the fountaining style of eruption, high but locally variable proximal deposition rates, and the presence of the hot, dense spatter material that was erupted at the end of each fountaining phase. The patterns of regional welding suggest that accumulation rate was the most important factor facilitating this style of welding. In addition, the distribution of regional welding in the deposit along the northern rim suggests that more than one fountaining vent was operational throughout the formation of the deposit and that the fountains had considerable instability and directionality. The patterns of local welding suggest that emplacement temperature and
the size of the spatter bomb are first order factors in combination with the initial degree of regional welding.

We have presented case studies of both regional and local welding which document the welding characteristics and patterns associated with welding due to a) intrinsic heat only and b) inherited heat from spatter bombs of contrasting size and abundances. The welding process responsible for regional welding is initially similar to that of local welding, however the volume is never reduced to the point where strain becomes accommodated by shearing. In locally welded deposits where heating and loading are both above the critical requirement for welding, porosity loss via matrix welding and vesicle collapse occurs to a point where strain must be accommodated by shearing and ductile flowage.

The low viscosity of spatter bombs erupted from the fountaining vents is evident from their flattening on impact, common fluidal forms and welding of the surrounding deposits. Similarly to Sigurdsson and Sparks (1978b) and Sparks et al., (1981), we postulate that the 1875 rhyolitic magma was superheated due to the injection of basaltic magma into the shallow magma chamber beneath Askja volcano. This facilitated welding and decreased the viscosity to the extent that spatter could be transformed into fluidal shapes during flight through the air and then subsequently deforming on landing.

In summary, in terms of contributions of each factor to local welding, a comparison of the lateral profiles and profiles taken under bombs of different sizes reveals several important conclusions:

i) Without compaction due to loading, dense welding is not possible (except in rare cases extremely proximal to spatter bombs).

ii) The size of the bomb will affect the degree of compaction.
iii) Insulation either by the spatter bomb or surrounding matrix is required to reach high welding grades.

iv) Efficient convective heat transfer above the spatter bombs is likely to weld deposits above the bomb to a greater degree than those laterally adjacent.

As observed throughout this study (e.g., section 8-d) it is difficult to predict the extent to which a specific spatter bomb will have affected the surrounding deposits. This is due to the abundance of spatter in the surrounding area, the heterogeneity of bomb temperatures, and finally the variable role of regional welding.

Local welding is a valuable key to understanding factors that contribute to welding and hence parent eruption style, behavior, number of vents and vent locations. The dispersal pattern of dense spatter gives insight into the transport regimes of the spatter-producing phases. This, together with a comprehensive study of the complex internal characteristics and textures of spatter bombs, will be a key to further understanding eruption dynamics in the vent and shallow conduit throughout the D phase.

At many volcanoes, significant caldera collapse after large Plinian eruptions, especially eruptions with ignimbrite-forming phases, is likely to obscure evidence for ultra-proximal deposits, which hold important keys to eruption dynamics. Limited caldera collapse at Askja has enabled us to examine proximal deposits and infer eruption, transport and deposition mechanisms in addition to identifying multiple source vents operating synchronously and with two completely different eruption styles. A further ~ 500 meters of caldera widening would have destroyed the proximal exposures, perhaps leading to the interpretation of a single Plinian eruption mode during this phase of the 1875 eruption.
We suspect that welded deposits in the ultraproximal regions of Plinian eruption centers are more common than documented in the literature.

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CHAPTER 6
CONCLUSIONS

6.1 Conclusions for the 1875 eruption

Magma ascent histories

The study of vesiculation and conduit dynamics demonstrated that the 1875 magma erupted throughout the main eruption had very similar deep magma ascent histories of bubble nucleation and diffusive growth, and only slightly different shallow conduit histories between phases (decompressive-growth and coalescence of bubbles). Studies of the vesicle populations have shown that fragmentation occurred when the magma was at the peak of vesiculation during every phase, regardless of eruption style or intensity.

Causes of abrupt shifts between wet and dry eruption styles

The two abrupt shifts between wet and dry eruption styles were a function of shifts in vent position, into and out of a source of external water. This is an interesting conclusion, as the shifts in vent position were over reasonably short distances (~1 km), and thus the geology and structure of the caldera region was a major influence on the location of the water source and hence, the eruption dynamics. Superimposed on these major shifts in style, were fluctuations of eruption intensity. Vesicle data presented within chapter three, suggest two degassing-induced pauses in the eruption. Complex coalesced bubble shapes with size distributions skewed to larger bubbles and comparatively large decreases in the vesicle number densities suggest a pause at the end of the pyroclastic density current phase, and a final pause at the end of the Plinian phase, representing the
end of the eruption. Historical records highlight an approximately nine hour pause between subplinian and phreatoplinian phases. However, the resolution of our sampling from the subplinian phase does not allow assessment of the reason for this pause. Volcanic centers that have a history of multiple source vents, or fissure-like intrusions of magma are perhaps susceptible to such abrupt and reversible shifts in eruption dynamics.

**Causes of shifts between buoyant and collapsing column conditions**

The late phreatoplinian and early pyroclastic density current pumices have complex vesicle shapes suggesting greater timescales for coalescence in the shallow conduit despite increased magma ascent rates, as inferred from higher vesicle number densities (a proxy for decompression and magma ascent rate). The combination of these two observations suggests that variations in eruption intensity and therefore changes of the magma-water mass ratio were not responsible for the shift from buoyant to collapsing column conditions. Instead I suggest that vent widening during the high intensity phreatoplinian phase caused a trend of decreasing exit velocity at the vent, which reduced the ability of the already wet mixture to become buoyant. This mechanism also accounts for the evacuation and eruption of slowed or stalled, highly coalesced magma from the adjacent dikes. In contrast, the more gradual shift from wet to dry dilute density currents appears to be a function of lower availability of external water.

**Styles of welding at Askja**

Welded silicic fall deposits are rare, particularly in the context of sustained, intense eruptions, and yet the 1875 eruption produced two geographically separate
welded fall deposits. These two deposits are also unusual amongst welded deposits in the complex styles of welding observed. Chapters four and five identified and documented two styles of welding on the proximal northern deposits: regional and local welding.

**First order controls on welding**

First order factors leading to high degrees of welding have been widely debated in the literature (e.g., Head and Wilson, 1989; Thomas and Sparks, 1996; Capaccioni and Cuccoli, 2005). Numerical models of cooling rates of tephra developed by Thomas and Sparks (1996) suggested that grain size is the major factor. However, other studies (e.g., Sparks and Wright, 1979; Head and Wilson, 1989) suggest that accumulation rate is critical. Emplacement temperature and accumulation rate appear to be dominant factors that facilitate higher degrees of regional welding at Askja.

Local welding developed around large dense juvenile bombs currently appears to be unique to the 1875 Askja deposits. First order controls on the degree of local welding appear to be both loading and the high emplacement temperature and/or heat capacity of the spatter bombs.

**Implications of welding for eruption dynamics**

The proximal northern welded deposits at Askja are remnant deposits of fountaining activity from multiple source vents active twice during the Plinian phase. The patterns of regional welding suggest that during both D2 and D4 times, multiple fountains were approximately aligned in an E-W array, north of the Plinian vent and often inclined, leading to local fluctuations in accumulation rate. Such synchronous
Plinian and low fountaining activity is rare and must require special properties of the magma, such as different volatile contents, chemistry etc, in addition to vent and conduit conditions (e.g., degree of conduit fracturing as pathways for degassing etc.).

A comparison of segmented exponential thinning and power law models

Thinning trends and volume calculations of each of the 1875 deposits are believed to be highly accurate due to the availability of data from both very proximal and very distal deposits. Thus, this comprehensive data set was used to assess the bias of the exponential and power law thinning models when proximal or distal data are missing.

Both methods approximated the volume well when proximal data were missing. However, if over-thickening is expected, then the value of $T_0$ (maximum thickness) used in the power-law model will be underestimated, as will be the volume calculation. When distal data were lacking, both models were severely challenged in terms of accurate volume calculations. It appears that the power-law method is best if intermediate points can define the curvature of the power-law fit, and that the limit of maximum plume spreading can be defined either historically (i.e., Askja 1875), observed remotely (i.e., Mt St Helens 1980), or distal ash shards can be found in ice/sediment cores (i.e., Quizapu 1932).

Enhanced proximal sedimentation

The combination of deposit characteristics, eruption parameters and historical records have collectively led to the identification of a new proximal segment on volume semilog plots of thickness vs. area$^{1/2}$ for two of the three 1875 fall units (Seg-1). This
segment and seg0 represent variable, but high degrees in apparent over-thickening of the proximal deposits, suggesting significant volumes of ejecta were shed from the jet and lower convective column margins during both magmatic and phreatomagmatic sustained high intensity phases. Representative sorting characteristics for proximal deposits have been demonstrated (table x; Chapter x) that the very proximal ejecta are poorly sorted with variable size distributions and therefore not solely limited to ejecta considered as ballistic.

Over-thickening has been described previously in two other dry magmatic Plinian deposits (e.g., Novarupta 1912, Fierstein, 1997, Houghton et al., 2004; Tarawera 1886, Sable et al., 2006), but has currently not been accounted for by particle transport and sedimentation models. The conceptual model of premature sedimentation of ejecta due to velocity gradients across the conduit extending into the jet developed by Houghton et al., (2004) and Sable et al., (2006) appears to be valid for the dry phases of the Askja 1875 eruption.

There are currently no descriptions or documentation of over-thickened proximal phreatoplinian and phreatomagmatic deposits. On the basis of the deposit characteristics and literature on particle sedimentation (e.g., Bonadonna and Phillips 2003; Gilbert and Lane, 1994) we have developed a conceptual model of enhanced proximal sedimentation during the phreatoplinian phase.

In our model, premature fallout of ash is derived in two ways; associated with minor instabilities of the jet and lower convective column margins, leading to firstly particle-laden veils extending from the erupting column; secondly to dilute density currents. Currently our model does not include ash sedimentation as aggregates as they
are rare in the Askja phreatomagmatic deposits. There is a high possibility that future phreatomagmatic eruptions may deposit greater accumulations of wet tephra in proximal regions than expected. The observations made in this study justify considerable effort be focused on the integration of premature proximal sedimentation in future tephra fall hazard models.

6.2 Future work

The onset of the eruption

It is necessary to conduct a vesiculation study on the deposits of the subplinian phase at greater resolution to understand the onset of the main eruption. A study at such resolution will also help to identify the nature and cause of the ~9 hour pause between the subplinian and phreatoplinian phases.

Broader studies: Eruptions commonly have an eruptive event of lower intensity prior to the climactic phase. Integrating vesiculation studies with chemical analyses of early ejecta may provide a more comprehensive forecast of an impending eruption.

Conduit geometry/processes responsible for concurrent but contrasting eruption styles

The welding studies presented within this thesis cannot constrain the reasons for the two periods of lower fountaining simultaneous with a Plinian high intensity eruption. Preliminary observations of vesicle textures of D2 and D4 clasts show large, highly coalesced bubbles, and similarly to the Plinian clasts, a crystal-poor groundmass. These textures and the diverse nature of the two synchronous, yet diverse eruption styles suggest that the histories of magma ascent and degassing were very different. Three
possibilities to explain these contrasting styles are: i) the magmas are derived from the same deeper silicic magma source, but at shallow levels magma is separated into different pathways and undergoes different patterns and rates of degassing; ii) the magmas are derived from different magma source regions with variable volatile contents and separate conduits; or iii) within the deep conduit, stalled magma was able to degas significantly prior to its ascent.

Chemically and texturally homogeneous magmas were erupted in contrasting styles during the Tarawera 1886 eruption (Sable et al., in press). Steep edifice and vent geometries with significant influx of both lithic and juvenile material into the vent would dampen the momentum of the pyroclast mixture after fragmentation and has been suggested as a potential reason explaining the diverse eruption styles (Sable et al., in press; Carey et al., 2007). Thus, a possible fourth mechanism exists involving a highly fractured, steep-walled vent with significant influx of both juvenile fountain ejecta and lithic material.

The shift from pyroclastic density current to Plinian phases was accompanied by intense seismicity and appearance of fountaining vents. The alignment of vents and inclination of fountains at times, suggest that it is feasible that this fountaining-vent area was highly fractured. This would facilitate mechanisms (iii) and (iv); a highly fractured vent/conduit area which provides pathways for gas escape derived from deeper magma degassing and, iv) a structurally weak and open vent area.

A combined study including magma chemistry, melt inclusion studies, vesiculation and microtextures of spatter and clasts erupted during D2 and D4 times will
identify similarities between fountaining and Plinian magmas and will constrain degassing processes.

Broader studies: It is critical to understand the nature of changes that produce such diversity of eruption styles. Did the changes originate within the magma through degassing and vesiculation processes? Or were the changes brought about by external factors, such as high degrees of conduit fracturing or re-orientation of the near surface stress field and formation of complex fracture patterns (e.g., shallow feeders)? Other silicic eruptions with similar deposits potentially hold a clue to understanding the relative roles of each.

Implications for conduit and eruption dynamics based upon spatter bombs

The large spatter bombs associated with local welding are interesting from a physical welding perspective, but also for their implications for the shallow conduit and vent dynamics, and the conditions under which they were expelled from vents. The spatter bombs are present in both sub-units associated with fountaining activity and have external textures that suggest they deformed during transport in the air and on impact. In addition, their internal textures resemble low viscosity lava, with a pumiceous crust, denser, low vesicularity viscoelastic region, and a central highly vesicular interior with coarse round bubbles. These features suggest that the rhyolitic spatter had a lower viscosity than typical calc-alkaline rhyolite magmas and that degassing could continue once the spatter was deposited. In addition, many spatter clasts are composite, with faint rounded outlines of smaller juvenile vesicular clasts and angular lithic clasts within them.

These observations suggest that the vent(s) were wide and open and that ejecta
could be recycled prior to incorporation in the D2/D4 deposits. The observations made here would suggest that mechanism (iv) described above was a highly probable situation in which there was significant influx of previously erupted material into the vent. A macroscopic study of the spatter bomb textures in combination with chemical, melt inclusion and microtextural analyses will help to identify the role of mechanisms (i) through (iv) above.

Conclusions from spatter bomb distribution

A numerical study of the distribution of spatter bombs on the northern rim of the caldera can be used to calculate the range of ejection velocities from the fountaining source vent(s). This information will be critical to develop a model of source vent and shallow conduit conditions (i.e., required over-pressures, etc.) that will add to our model of eruption mechanisms for fountaining eruptions throughout the Plinian phase.

Role of external water in highly explosive sustained wet volcanism

It is critical to the understanding of this eruption to identify the source, location and the nature of the external water involved in the phreatomagmatic phases. Pre-eruption historical records do not state that there was a significant body of water present within the caldera region. Currently a hydrological groundwater study of the Askja caldera region is underway at the University of Edinburgh, to examine the possibility of groundwater as the source of the external water. In addition, a microscopic study (SEM) of clast surface textures, identifying hydro-fractures and other morphological evidence of
water-magma interaction will be critical to identify the role of the external water in the wet phases.

**Development of future plume models**

*Broader studies:* The most recent and comprehensive models simulating the multiphase dynamics of gas-pyroclast mixtures produced by explosive eruptions has been developed by Augusto Neri and his working group at the University of Pisa, Italy (di Muro, 2004, Neri 2007). Their PDAC-2D code has been applied mainly to the simulation of collapsing columns and associated pyroclastic flows. However, this code has been applied also to the simulation of transient sedimentation and Vulcanian explosion dynamics (Clarke et al., 2002). In this case, the code was used to link the unsteady conduit dynamics of Vulcanian explosions to the resulting dispersal of volcanic ejecta.

The ability of the model simulations to quantify the mass of pyroclasts of different size forming the various regions of a collapsing or buoyant plume is critical when trying to interpret the deposits and style of an eruption. Eruptions with over-thickened proximal deposits suggest unsteady or quasi-steady behavior of the emergent gas-pyroclast mixture leading to transient or continual instabilities of the eruption jet and lower convective column regions.

Further development of models, integrating unsteady conditions of conduit flow (after fragmentation) and in the emergent mixture are now necessary to begin to understand enhanced and premature sedimentation of mass in proximal regions. Such models need to combine code for the steady transport of mass through the core of the jet
phase into the convective plume with short-lived, unsteady sedimentation of tephra from sectors on the margin of the jet and lower plume.

Testing future plume models

Future plume models will require vigorous testing with field data. Askja is an important source of input data but further study needs to be conducted on the Askja proximal fallout deposits, in addition to locating other eruption deposits that have overthickened proximal deposits and/or are phreatomagmatic. Further thickness data but also extensive grain size studies are required as a comprehensive grain size study was not part of this project. In terms of Askja 1875, further thickness measurements and grain size samples need to be collected in the proximal region, to constrain the quantity and grain size of the ejecta that prematurely sedimented out of the jet and lower convective plume margins. Grain size samples have been collected for all fall units in the medial and distal areas in eastern Iceland and these will be processed in the future to aid in understanding transport and sedimentation of wet and dry plumes in the more distal regions.

Data from recent eruptions from Askja need to be combined with observations of transport and sedimentation processes in new sustained magmatic and/or phreatomagmatic eruptions. Such observations will enhance our current conceptual model, and provide a source of field data for future numerical model validation.

Viscosity of the 1875 magma

Sigurdsson and Sparks' (1978b) study of the petrological aspects of the 1875 magma derived rhyolitic magma compositions between 69 and 76 wt.% SiO₂. Mineral to
liquid phase relations indicate crystallization at $P_{H_2O} = 50-100$ MPa, which they suggest corresponds to a saturated water content of 3 wt%. Their work on the mineral phases also suggested high magmatic temperatures of the order $990 - 1050 \, ^\circ C$.

Their observations and petrological conclusions are very important to the eruption dynamics. Such a low viscosity and high temperature of the 1875 magma would have important consequences for the eruption and plume dynamics of the eruption. Some of which include:

* Limited phenocryst/microlite nucleation and growth:
  - Homogeneous nucleation style is likely in high temperature melts due to lack anisotropies in the melt.
  - Growth and coalescence would not be impeded by phenocrysts, thus forming permeable networks of bubbles. The fragmentation threshold is strongly dependent on porosity; high Increased thermal energy would be available for mechanical fragmentation in phreatomagmatic activity
  - More thermal energy would be available for efficient heating of ambient atmosphere and driving plume buoyancy
  - Greater buoyancy may lead to greater plume heights and more widespread dispersal

Knowledge of the physical properties of the 1875 magma will be critical for future modeling of volcanic processes and interpretation of experimental studies. An additional study of the precursory eruption deposits (in particular the rhyolitic dikes and lavas) will
also be useful in understanding the roles of volatile content versus conduit ascent history in facilitating this magma to erupt in variable fashion.
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