Chapter 1
Introduction and key concepts

Pyroclastic density currents are inhomogeneous mixtures of volcanic particles and gas that flow according to their density relative to the surrounding fluid (generally the atmosphere) and due to Earth's gravity. They can originate by fountain-like collapse of parts of an eruption column following explosive disintegration of magma and rock in a volcanic conduit, or from laterally inclined blasts, or from hot avalanches derived from lava domes. They can transport large volumes of hot debris rapidly for many kilometres across the ground and they constitute a lethal and destructive volcanic hazard. Ground-hugging pyroclastic density currents produce a buoyant counterpart, known as a phoenix cloud or cognimbrite ash plume, which can carry ash and aerosols into the stratosphere and so cause significant climatic perturbation. Most processes within pyroclastic density currents are impossible to observe and so are commonly inferred from the associated deposits.

Deposits of pyroclastic density currents

Deposits of pyroclastic density currents have been generally categorized, according to lithology and sedimentary structure, as ignimbrites, pyroclastic surge deposits and block-and-ash flow deposits. Ignimbrites typically are pumiceous and ash-rich. They predominantly comprise a poorly sorted mixture of pumice and lithic lapilli supported in a matrix of vesicle-wall-type vitric shards and crystal fragments. They may be loose and uncompacted, or partly to entirely densely indurated. Some show evidence of hot deposition (e.g. $T > 550^\circ\mathrm{C}$). They generally form low-profile sheets or fans, which can cover areas as large as 45 000 km$^2$, and they tend to bury or partly drape pre-eruption topography with marked thickening into topographic depressions. Ignimbrites can vary in thickness from centimetres to many hundreds of metres, and known examples range in volume from a few thousand cubic metres up to several thousands of cubic kilometres. Many show evidence, in a higher proportion of crystals in the ash-rich matrix than exists in the pumice clasts, that the parent current was originally very rich in fine ash, and that much of this fine ash was lost during transport and deposition. Ignimbrites commonly contain subordinate pumice-poor lithofacies, such as lithic breccias and scoria agglomerates. Although many ignimbrites at first sight appear to be mainly massive (i.e. non-stratified), close examination commonly reveals a wide range of sedimentary structures, including sharp to diffuse stratification, cross-stratification, splay-and-fade stratification, erosion surfaces and elutriation pipes, as well as various grading patterns, particle fabrics and soft-state deformation structures. In many cases such features grade laterally or vertically into truly massive, structureless lithofacies. Ignimbrite sheets and fans are frequently found to comprise the deposits of several pyroclastic density currents, together with closely associated pumice-ash and ash-fall layers. Somewhat better sorted and distinctly stratified layers, sometimes referred to as pyroclastic surge deposits, are normal subordinate lithofacies in ignimbrite successions. Characteristics of ignimbrites are reviewed by Smith (1960), Fisher & Schmincke (1984), Wilson (1986), Cas & Wright (1987) and Freundt et al. (2000). Block-and-ash flow deposits differ from ignimbrites in that they contain a large proportion of rather dense, poorly to moderately vesicular juvenile (lava) blocks with predominantly non-pumiceous ash of similar composition. They are generally of smaller volume than ignimbrites and are normally associated with lava domes.

The role of ignimbrites in ideas about pyroclastic density currents

Ignimbrites can contain a wealth of information about their parent pyroclastic density currents, but the transport and sedimentation processes are not well understood. Problematic issues, partly involving confused nomenclature, concern whether phenomena are discrete or intergradational, instantaneous or progressive. Early workers interpreted poorly sorted deposits and evidenced of transport over hills as indicating that the pyroclastic density currents were turbulent mixed, low-concentration suspensions that were many hundreds of metres thick (Murai 1961; Yokoyama 1974; Sheridan & Ragan 1976). The poor sorting and absence of fractional stratification in ignimbrites were interpreted by Fisher (1966) to indicate that pyroclastic density currents are density stratified, with basal particle concentrations sufficiently high to inhibit turbulence and sorting during deposition. Significantly, Fisher (1966) was an early exponent of progressive aggradation for ignimbrites, viewing their deposition as a sustained, incremental process. Subsequently, however, this view was largely abandoned, even by Fisher himself (e.g. Fisher 1979, 1990b), mainly because of the seminal works of G. P. L. Walker and R. S. J. Sparks and their colleagues, who introduced the influential paradigm of a standard ignimbrite flow-unit related to bulk evolution of an idealized pyroclastic flow. This flow was considered to be a high-concentration, poorly expanded and partially fluidized granular flow. It was envisaged as having an inflated fluidized head and a denser, laminar body that deflated during transport to form a semi-fluidized, high-yield strength plug that moved along on a basal shear layer. It was believed that the massive layer of the ‘standard ignimbrite flow-unit’ was formed when such a flow finally came to a halt en masse (Sparks et al. 1973; Sparks 1976; Sheridan 1979; Wright & Walker 1981; Freundt & Schmincke 1986; reviews by Carey 1991 and Francis 1993). The thickness of the massive layer formed in this way was thought to be roughly 75% of the thickness of the semi-fluidized flow (e.g. Wilson 1984; Francis 1993), and its vertical organization (e.g. coarse-tail grading) was thought to reflect the vertical structure of the current just before it halted en masse (Sparks 1976; Wilson 1984, 1986; Battaglia 1993; Sparks et al. 1997b).

In the 1980s, the standard ignimbrite flow-unit paradigm was elaborated to account for features not previously considered, for example ‘ fines-depleted ignimbrite’ inferred to relate to interactions with substrate (Walker et al. 1980), ignimbrite veneer deposits inferred to derive from the ‘tail’ or ‘skin’ of a flow (Wilson & Walker 1982; Wilson 1986), pumice-rich basal deposits inferred to have been shot forward, or ‘ jetted’, out of the front of a current (Wilson & Walker 1982), low aspect-ratio ignimbrites inferred to record unusually energetic flows (Walker 1983) and stratified layers near the base of massive ignimbrites inferred to have formed from turbulent boundary layers beneath Bingham-type plug flows (Valentine & Fisher 1986).

More recently, ignimbrites have been treated as deposits from low-concentration currents (less than a few volume per cent (vol. %) solids) in which the particles are all fully supported by fluid turbulence virtually up to the point of deposition, which occurs progressively (e.g. Bursik and Woods 1996; Dade & Huppert 1996; Freundt 1999). These more recent models are quantitative and offer useful constraints on the possible transport behaviour of low-concentration pyroclastic density currents, and how they respond to topography. The models can reproduce some of the overall dispersal characteristics and thickness variations seen in ignimbrites, but as yet they have not succeeded in reproducing the variety and organization of ignimbrite lithofacies and sedimentary structures known from the field.

In 1992, in a paper principally concerned with ignimbrite welding and agglutination, we developed Fisher's (1966) idea that ignimbrites are deposited incrementally from density-stratified currents, the lowermost parts of which are of high concentration...
and predominantly non-turbulent (Branney & Kokelaar 1992). In support, we cited evidence from fabric studies, variations in lithofacies and welding characteristics, and the presence of compositional zonation within massive flow-units. We concluded that the massive layers generally aggregate progressively from the base upwards, rather than representing plug flows that halted en masse (Branney & Kokelaar 1992, 1994a, 1997; Kokelaar & Branney 1996). We proposed that the sedimentary processes occurred virtually irrespective of the concentration and transport mechanism(s) of overriding parts of the current, which may differ from current to current. The rate of aggradation might vary from slow to extremely rapid, and because the flow-unit is assembled progressively (through time) it cannot directly record the vertical structure of the current. Instead, the vertical structure of a flow-unit (deposit) records how the processes and conditions around a current’s basal flow boundary varied with time. This view of progressive aggradation of ignimbrites has been supported in some recent case studies (e.g. Capaccioni and Sarocchi 1996; Perrotta et al. 1996; Scott et al. 1996; Bryan et al. 1998a; Hughes & Druitt 1996; Duncan et al. 1998; Brown et al. 2003).

In this Memoir we develop a unified conceptual framework for the consideration of ignimbrite sedimentation, drawing on aspects of all of the above approaches. The emphasis is on ignimbrite sheets formed from intermediate to large-magnitude eruptions (1 km³ to >1000 km³); however, the approach also has implications for small-volume deposits that form from lava-dome collapses and from Vulcanian eruptions, and also for the stratified sequences, often referred to as ‘pyroclastic surge’ deposits, that form beyond the limits of block-and-ash flows or during phreatomagmatic explosivity.

We explore the idea that, whatever the concentration of the moving particle-gas mass, deposition is a sustained process (if sometimes only short-lived), and that the style of sedimentation must be governed by conditions and processes around the lower flow boundary of the pyroclastic density current. We investigate how changing conditions (e.g. particle concentrations and shear rates) and processes (e.g. segregation) around the lower flow boundary can account for the wide range of deposit types and their distribution. Each ignimbrite is unique, so, rather than attempt to interpret each known variation, we develop a conceptual framework involving intergradations of processes. In this framework the ‘standard ignimbrite flow-unit’ and the current it is inferred to have formed from constitute a particular case rather than the norm, just as a current in which transport is entirely at low concentrations constitutes another specific case. We relate vertical and lateral lithofacies distributions within ignimbrites to currents that can have various or changing source emissions, various durations and various clast-concentration profiles, and which are affected by topographies that evolve according to erosion and deposition.

The ideas in this Memoir draw both on the extensive literature that documents ignimbrite lithofacies (e.g. granulometry and fabrics) and on the results of modelling and experimental research into turbulent pneumatic and hydraulic particle transport, granular flow, stratified flow, fluidization and the settling behaviour of non-shearing polydisperse suspensions (references cited in text). We also draw attention to phenomena that remain poorly understood. The hope is that this Memoir will facilitate the interpretation of ignimbrites, and help to stimulate further field observation, laboratory experimentation and numerical simulation. The development of pyroclastic density current models that can predict, and be validated by, moderately detailed lithofacies data is crucially important for the investigation of volcanic hazards and the mitigation of associated risks.

**Key concepts**

Meaningful analysis of ignimbrites entails integration of four key concepts concerning pyroclastic density currents. (1) Pyroclastic density currents are inherently inhomogeneous in both time and space, for example with respect to velocity, concentration, capacity and rheology, so that processes within them change both temporally and spatially. (2) Depositional mechanisms are fundamentally influenced by conditions and processes near the lower flow boundary, so that the lithofacies architecture of an ignimbrite essentially records temporal and spatial variations there. (3) Diverse clasts are supported and segregated in various ways so that, for example, adjacent clasts in a deposit may have had differing spatial origins and transport histories. (4) Processes and conditions near a current’s depositional flow boundary can differ fundamentally from those higher in the current. These concepts are developed in the following sections.

**Current steadiness and uniformity**

It is important to distinguish between variations of a current that occur temporally with respect to a fixed location (the Eulerian reference frame) and variations of a current that occur spatially with respect to a point that moves with the current (the Lagrangian reference frame). A current is steady where material passes a fixed location with a constant velocity (dashed line in Fig. 1.1A) and direction; that is, in the Eulerian reference frame the current is invariant and acceleration is zero. Conventionally, for one-phase fluids and for low-concentration particulate currents, steadiness refers to velocity. However, with high-concentration particulate currents, other parameters also affect transport and deposition, and it is useful to apply the term ‘steady’ with a specification: for example, steady velocity, steady competence, steady capacity, steady mass flux and even steady composition (in the sense of the hydraulic properties of the particle population) or temperature. Steady flow denotes temporal invariance of all parameters. There are three main types of unsteadiness: waxing is when a parameter at a fixed location increases with time, waning is when one decreases, and quasi-steady is when a parameter fluctuates only slightly over some constant value with limited consequences (Fig. 1.1A).

Many researchers (e.g. Walker et al. 1995) have considered pyroclastic density currents to be, in effect, of single-surge type (Fig. 1.1A): that is, an individual short-lived (highly unsteady) pulse that waxes rapidly and then begins to wane almost immediately (such as the rapidly transient current formed from the May 1980 Mount St Helens blast; Druitt 1992). Clearly, all pyroclastic density currents have finite duration and thus all are inherently unsteady, but pyroclastic fountaining eruptions (Sparks et al. 1997a; Fig. 2.1B and C) may sustain pyroclastic density currents for periods up to several hours or more, which may include periods of quasi-steady flow (Fig. 1.1A) interspersed with periods of less steady flow. Bursik & Woods (1996) propose that the largest ignimbrites are from eruptions sustained for 10⁴-10⁵ s, and they also suggest that most deposition occurs from quasi-steady flow. Significant waxing and waning of a current during an eruption may result, respectively, from dilution of a conduit and/or vent and from the progressive depletion of volatiles in the magma chamber and conduit by eruptive withdrawal.

Spatial variability of a current at any instant, such as a change in velocity at a break of slope, is described in terms of non-uniformity. Uniform currents (spatial acceleration ubiquitously equals zero) do not exist naturally, but parts of some pyroclastic density currents may approach uniformity, particularly where channelled. Non-uniform, or ‘varied’, flow results from slope changes, sedimentation, elutriation, clast abrasion and breakage, interaction with substrate and air ingestion. Hydraulic jumps and downcurrent changes between turbulent and laminar flow (flow transformations of Fisher 1983) are types of non-uniformity. We use accumulative and depletive, respectively, to refer to downcurrent increases and decreases in a parameter (e.g. velocity) of a non-uniform current (after Koeller & Branney 1995). A pyroclastic density current is accumulative where, for example, an adjacent deposit mass advances as a result of flow convergence or flow down a steepening slope. It is depletive where...
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Fig. 1.1. Steadiness and uniformity in pyroclastic density currents. (A) Current velocity, $u$, versus time, $t$, at a fixed geographic location. In high-concentration currents velocity, $u$, may be replaced by concentration, competence or some other parameter. Pyroclastic density currents may vary from highly unsteady single-surge types (left) to more sustained currents (right) that wax and wane and may include periods of quasi-steadiness. (B) Velocity–time–distance ($x$) diagram for a sustained but unsteady, depletive pyroclastic density current (modified from Kneller & Branney 1995). The heavy arrow shows the deceleration of an individual parcel of fluid in the current; it may decelerate, thus causing deposition, even when the current velocity waxes. (C) Thirteen different types of pyroclastic density current classified according to their steadiness and uniformity, with consequences for grading in deposits. Currents 1–3 are waxing depletive; 4 is waxing uniform; 5 is waxing accumulative; 6 is steady accumulative; 7–9 are waning accumulative; 10 is waning uniform; 11 is waning depletive; 12 is steady depletive; and 13 is steady uniform (autosuspending). Note that the so-called standard ignimbrite flow-unit results from only currents in field 11. The classification considers only one spatial dimension (i.e. the downcurrent dimension). Most natural pyroclastic density currents migrate from one field to another, defining an evolutionary pathway across the diagram; for example, they wax then wane, and they modify the topography and hence change their uniformity by deposition and/or erosion. Grain sizes in graded sequences are subject to availability at source or within material previously deposited and then eroded by the current. Modified from Kneller & Branney (1995).

for example, it decelerates as a result of flow down a lessening (concave) slope or by spreading radially across flat ground. Progressive infill or erosion of topography, and destruction or burial of vegetation, will cause the non-uniformity of a current to vary. As with steadiness, types of non-uniformity also can involve parameters other than velocity (e.g. competence, concentration).

Previously, ignimbrite emplacement has been considered in terms of deceleration of entire currents, but it is useful to consider the behaviour of individual local ‘parcels’ of fluid, that is, of pyroclasts plus gas. A lithic clast that has been only just fully supported in a current will tend to settle, and ultimately deposit, if the parcel of fluid in which it occurs undergoes negative net acceleration. The net acceleration experienced by a local parcel of fluid is known as the substantive acceleration, and is given by the vector relationship:

$$\frac{\Delta u}{\Delta t} = \frac{\partial u}{\partial t} + u \nabla u.$$  \hspace{1cm} (1.1)

where $u$ is the local downcurrent velocity, $t$ is time and $x$ is downcurrent distance. $\partial u/\partial t$ is temporal acceleration at a fixed geographical location (zero for steady currents) and $\partial u/\partial x$ is spatial downcurrent acceleration (zero for uniform currents). The equation shows that waning velocity ($\partial u/\partial t < 0$) is not a prerequisite for deposition (Kneller & Branney 1995; cf. Kieffer & Sturtevant 1988). A waning current can erode if it is sufficiently accumulative: for example accelerating down a convex slope or converging into a channel. Such currents are simultaneously decelerating in one sense (Eulerian reference frame) and accelerating in the other (Lagrangian reference frame). Conversely, in steady or even waxing density currents, clasts can experience spatial decelerations (Fig. 1.1B) and may tend to deposit: that is, where the current is depletive ($\partial u/\partial x < 0$), such as where it fans out across a plain. Hence, for any density current, use of the terms acceleration and deceleration without stating the reference frame is ambiguous and best avoided by using waxing, waning, accumulative and depletive.

See Tritton (1988). Useful insight can be gained by considering the simplification to one-dimensional flow, given by:

$$\frac{du}{dt} = \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x}.$$  \hspace{1cm} (1.2)
Figure 1.1C classifies 13 conceptual types of pyroclastic density current according to their uniformity and steadiness. The classification is a considerable simplification, especially because it ignores vertical and transverse variations of currents. The ‘standard ignimbrite flow-unit’ (Sparks 1976) was generally assumed to have been deposited very rapidly during waning and depletive flow of a single-surge type current. Such a current is type 11, and is only one of the 13 conceptual types. Most pyroclastic density currents involve behaviour that would, in this conceptualization, involve migrations within and between some of the fields; for example changing vent emission or unsteady eruptive fountain collapse would register in migrations vertically across Fig. 1.1C, different migrations within and between some of the fields; for example changing vent emission or unsteady eruptive fountain collapse involve behaviour that would, in this conceptualization, involve migrations vertically across Fig. 1.1C, and a particular reach of a current affected by modifications to substrate and topography during emplacement would migrate in some sideways direction across the fields. Even this highly simplified conceptualization, which takes velocity to be the sole control on deposition, shows that a sustained pyroclastic density current may deposit and erode intermittently, and at varying rates at different locations, according to changes in vent emissions and changes in topographic slope. Thus we should expect diversity in the nature and organization of lithofacies within ignimbrites.

Lower flow-boundary zones: sites of segregation and variable deposition

The lower flow boundary of a pyroclastic density current is the surface between the current and its substrate. During deposition, the flow boundary must lie at the top of the aggrading deposit and each clast undergoing deposition must cross it. We propose that ignimbrite lithofacies mainly record processes and conditions in a loosely delineated flow-boundary zone that includes the lowermost part of the current, the boundary and the uppermost part of the forming deposit (Fig. 1.2). This zone rises relative to the former substrate as the deposit progressively aggrades (Fig. 1.2A).

The nature of the flow-boundary zone, and the rate of progressive aggradation, must vary according to the current velocity, concentration and rate of supply of particles to the flow-boundary zone (the latter is linked to spatial and temporal changes in the capacity of the current). The stratification and sorting characteristics of an ignimbrite lithofacies are largely determined by the particle concentration and velocity profiles across the flow-boundary zone from which the lithofacies aggrades. In later chapters we consider four contrasting types of flow-boundary zone, while emphasizing that each type may be continuously intergradational into another. In one type of flow-boundary zone the clast concentration in the uppermost part of the deposit is much greater than the concentration of the lowermost levels of the current, so that the concentration and velocity profiles both have a marked step (double inflection) at the flow boundary (Fig. 1.2B). Tractional planar stratification and low-angled cross-stratification require such a flow-boundary zone type, with a high shear intensity close to the flow boundary and a marked rheological contrast across it, so that clasts are able to move freely. In another type of flow-boundary zone the clast concentration of the poorly compacted top of the forming deposit grades up into a high concentration and slowly shearing lowermost part of the current, so that the rheologies of the materials immediately above and just below the flow boundary are similar (Fig. 1.2C). This in case tractional movement and segregation are dampened, and the aggrading deposit acquires less stratification and becomes massive if traction is almost entirely inhibited. In consideration of this latter case, it is useful to define deposit as the particle mass that has zero downcurrent velocity, irrespective of its packing density. The aggrading deposit may continue to compact and degas, with segregation of gas-coupled fine ash (elutriation), and it may allow large dense lithic clasts to sink through it. However, once any part of the deposit starts to move downcurrent, it becomes part of the current, by definition.

Ignimbrite architecture: a record of flow-boundary zone evolution through time and space

We use architecture to refer to the overall structure of an ignimbrite: that is, its distribution, thickness variations, and the internal arrangement of lithofacies, ‘time surfaces’ and any internal or bounding scour surfaces, and the relations of these features to
topography and substrate type. A lithofacies describes part of the deposit with a distinctive set of characteristics (e.g. granulometry, stratification, fabric anisotropy and/or composition). As pyroclastic density currents evolve in both time and space, consequent variations in conditions and processes in the flow-boundary zone determine where and how different lithofacies are formed. Thus, the vertical arrangement of lithofacies within an ignimbrite sheet records unsteadiness in the flow-boundary zone, and the horizontal variations record non-uniformity within the flow-boundary zone. Because lithofacies reflect processes and conditions in the flow-boundary zone, they do not directly record bulk properties of the overriding current. Thus, as a first step toward inferring the behaviour of an entire current, one must first interpret each lithofacies in terms of the flow-boundary zone processes (see Table 7.1) and then analyse the vertical and horizontal lithofacies sequences across an ignimbrite sheet to determine how the flow boundary evolved overall through time and space. Ideally, an aim should be to analyse the architecture of an entire ignimbrite sheet. This is because, even though an ignimbrite may locally exhibit an apparently simple vertical organization (e.g. one that could be interpreted in terms of waning-flow-dominated deposition from a single-surge current), its overall architecture might exhibit complexities that indicate more sustained and complexly evolving currents, including switches in runout direction (e.g. Cole & Scarpati 1993; Branney & Kokelaar 1997; Wilson & Hildreth 1997; see Chapter 6).