Cooling, degassing and compaction of rhyolitic ash flow tuffs: a computational model

Abstract Previous models of degassing, cooling and compaction of rhyolitic ash flow deposits are combined in a single computational model that runs on a personal computer. The model applies to a broader range of initial and boundary conditions than Riehle's earlier model, which did not integrate heat and mass flux with compaction and which for compound units was limited to two deposits. Model temperatures and gas pressures compare well with simple measured examples. The results indicate that degassing of volatiles present at deposition occurs within days to a few weeks. Compaction occurs for weeks to two to three years unless halted by devitrification; near-emplacement temperatures can persist for tens of years in the interiors of thick deposits. Even modest rainfall significantly chills the upper parts of ash deposits, but compaction in simple cooling units ends before chilling by rainwater influences cooling of the interior of the sheet. Rainfall does, however, affect compaction at the boundaries of deposits in compound cooling units, because the influx of heat from the overlying unit is inadequate to overcome heat previously lost to vaporization of water. Three density profiles from the Matahina Ignimbrite, a compound cooling unit, are fairly well reproduced by the model despite complexities arising from numerous cooling breaks. Uncertainties in attempts to correlate in detail among the profiles may be the result of the non-uniform distribution of individual deposits. Regardless, it is inferred that model compaction is approximately valid. Thus the model should be of use in reconstructing the emplacement history of compound ash deposits, for inferring the depositional environments of ancient deposits and for assessing how long deposits of modern ash flows are capable of generating phreatic eruptions or secondary ash flows.

Key words Ignimbrite · Pyroclasts · Compaction · Tufts · Matahina Ignimbrite

Introduction

Essential characteristics of dispersion and compaction of ash flow tuffs

Zirkel (1876) described pumice samples from Utah and Nevada as 'welded together'; Iddings thought in 1909 that fallen pyroclasts could remain hot enough to weld. However, the pyroclastic origin of large ignimbrite sheets was not fully recognized until a mechanism was understood by which pyroclasts could be dispersed while conserving magmatic heat.

Anderson and Flett (1903) and LaCroix (1904) observed pyroclastic flows of the 1902 eruptions of Mont Pelee and deduced that gas was essential for the mobility of both the basal avalanche of incandescent particles and the overriding cloud. Griggs (1922) and Fenner (1923) inferred that the 'indurated sand flow' deposit in the Valley of Ten Thousand Smokes was formed of hot fragments that had compacted after emplacement in 1912. These workers realized that the pyroclastic particles themselves are sources of gas. However, Perret's (1935) emphasis that ash flows are two-phase mixtures that remain partly gas charged during travel downslope was an especially important insight that led eventually to the analogy of ash flows with the industrial process of fluidization (Reynolds 1954; McTaggart 1960). Largely because of the observations at Mont Pelee, it became accepted that even widespread, densely compacted deposits had been dispersed as pyroclasts (e.g. Marshall 1931; Gilbert 1938; Fenner 1948).
After deposition from a fluidized flow, ash is subject to compaction by its own weight. In their classic works, Smith (1960a) and Ross and Smith (1961) elucidate how thickness, temperature and volatiles affect deformational compaction. Zonal variation of the degree of compaction reflects mainly the initial temperature and environmental parameters that governed the rate of cooling (Smith 1960b). Peterson (1961, 1979) shows that pumice fragments are increasingly flattened downward in response to the weight of the overlying deposit. Ragan and Sheridan (1972) found that the foliation of the Bishop Tuff is due exclusively to vertical (that is, uniaxial load) compaction. Directional structures such as lineations or folds (e.g. Schminke and Swanson 1967) indicate that a horizontal component of deformation can occur in some ash sheets by down-valley flowage after initial emplacement. Such horizontally directed deformation is beyond the scope of this paper, which is concerned solely with vertical compaction under lithostatic pressure.

Quantitative compaction studies

Empirical relations among bed expansion, grain size distribution and gas outfluxing velocity are known for industrial fluidized systems (e.g. Takahashi et al. 1984). In ash flows, however, both outfluxing and grain size distribution fluctuate (Wilson 1980, 1983), so the state of expansion throughout specific ash flows is difficult to reconstruct precisely. Densification of fluidized systems during declining gas flow — called deflation — has been well studied by engineers (e.g. Richardson 1971). Deflation of ash deposits proceeds by both grain packing and particle deformation. Experiments to deform ash have typically begun with deflated samples, a well-defined initial condition, but one that ignores deflation.

Friedman et al. (1963) were the first to experimentally determine the rates of deformational compaction of naturally occurring rhyolitic ash under various conditions. They quantify a relationship between stress and the rate of change of porosity and show how compaction slows as porosity decreases. Compaction is also slowed by the increase in ash viscosity during devitrification (Guest and Rogers 1967). Richle (1970, 1973) uses an empirical fit of Friedman et al.'s compaction rates to model the interaction of temperature and thickness in governing the compaction of simple and compound cooling units. Kono and Osima (1971) use a theoretical relationship between glass viscosity and porosity to simulate the compaction of simple cooling units. Bierwirth (1982) experimentally compacted anhydrous rhyolitic ash and fits the strain rates by an Arrhenius function of temperature.

Present study

Neither Richle nor Kono and Osima allow for varying fluid pressures during degassing of an ash deposit. Miller (1990) was the first to calculate transient gas pressures in outfluxing deposits, but it has remained to include the effects of transient gas pressure on ash viscosity and effective load in compaction models. We combine previous computational models of cooling, degassing and deformation, and improve the results by simultaneously calculating temperature, gas pressure and porosity in small time increments. Our model simulates any number of deposits in compound cooling units, deposits >80 m thick and chilling by water at the top and bottom of an ash deposit. The compaction results for thin, simple cooling units are broadly similar to Kono and Osima's despite major differences in methodology and do not differ much from Richle's. To model thick or complicated deposits, however, an integrated model such as ours seems essential.

A numerical model of cooling, outfluxing and compaction has several potential uses. (1) As is shown later, environmental parameters can be inferred or at least constrained for well-preserved ash deposits by simulating the observed compaction zonation. Such parameters include the emplacement temperature and timing of eruptions based on cooling intervals between emplacement units. (2) A model provides a predictive tool for evaluating the hazards associated with secondary ash flows or phreatic explosions in modern ash deposits such as those at Mount Pinatubo (Torres et al. in press). (3) Model compaction profiles provide idealized standards that can serve to emphasize the role of other processes such as localized deposition, fumarolic outgassing or devitrification.

Computational model

Our computational model (hereafter, 'the model') is a Fortran program that combines Miller's (1990) model of cooling and degassing with Richle's (1970, 1973) model of deformation. In brief, an ash deposit is assumed to be a mixture of glass particles and gas that cools by conduction in the vertical, outgases by advection to the atmosphere and compacts by deforming under the stress of its own weight less the pressure of interstitial gas. Gas pressure declines with degassing or cooling and increases as porosity decreases. Advection is inconsequential to overall cooling because less than 1% of the heat content of the deposit is in the gas phase (Richle 1973). The model with documentation is available on disk for PC (Miller and Richle 1994). The minimum hardware requirements are a 286 processor, a math co-processor and a printer.

Parameters governing cooling and outgassing

The algorithm we use to calculate the combined one-dimensional transport of mass, heat and momentum of a variable-density fluid in a porous medium is a modification of the finite-volume method of Issa (1985). Conditions for numerical stability are prescribed by Patan-