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Compaction profiles of ash-flow tuffs: Modeling versus reality

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ABSTRACT

Density profiles of 4 ash-flow deposits in Oregon and Idaho are simulated using the model of Riehle et al. (1995) to calculate heat flow, degassing, and compaction. The deposits are all <45 m thick and most have well defined density reversals and lack substantial alteration or vapor-phase deposition. Model results are made to closely match the measured profiles of 3 simpler deposits by making the assumptions that density reversals represent cooling breaks between ash flows or that subtle density inflections at the base of the profiles are cooler surge deposits. The first assumption is supported by a fossil fumarole pipe truncated at a density inflection, and the second by foreset bedding at the base of the deposit. Deposit temperatures within each unit of thermally stratified deposits are assumed to be homogeneous.

The Rattlesnake Tuff—a more complex ignimbrite sheet—was sampled at 3 distal sites near to one another, a medial site, and 4 proximal sites. Model results of distal profiles are similar despite more than twofold variation in thickness and comprise 3 early deposits having emplacement temperatures of 724–732 °C, followed by two hotter deposits (785–790 °C), and a cooler capping deposit of about 735 °C. One distal site has an inferred surge deposit at its base. Density reversals simulated as cooling intervals all range from 3 to 10 days. Correlated cooling intervals agree to within a factor of two, however, the duration of a cooling interval cannot be precisely hindcast owing to potential complications by rainfall or accumulation of chilled airfall ash. Thus, the seemingly wide range of model results for the cooling intervals is perhaps not surprising.

Proximal profiles have more density reversals implying more deposits than the distal profiles. They also have greater overall compaction and consequential loss of detail in the density profiles. Some earlier deposits have model temperatures of 736–757 °C and may correlate with the lower distal deposits; at one site these are overlain by two hotter deposits (790–796 °C) and a cooler capping deposit (745 °C) that are almost surely correlatives of the upper distal deposits. Some sites have additional, early hotter deposits and one site has an uppermost deposit that is the coolest of all model deposits. Thus a picture emerges of thermally stratified, near-source flows during early eruptive activity and more far-travelled flows during later eruptions. Shards analyzed by Streck and Grunder (1997) show a compositional range and corresponding magma temperatures of 795–880 °C, which is permissive of thermally layered deposits and implies cooling during fallback and travel of 50–100 °C.

Rare textural evidence for internal flow boundaries, as well as our consistent model results among multiple sites despite variation in deposit thickness, support the assumption that density reversals represent partial cooling breaks. If so, then modeling of density profiles can provide important evidence for how large ignimbrites are constructed. Sheridan and Wang (2004) also report stratigraphically consistent results by modeling density reversals in distal Bishop Tuff as cooling breaks. Our results contrast with those of Wilson and Hildreth (2003), who concluded that density reversals in the proximal Bishop Tuff do not represent cooling breaks but instead are evidence for thermally heterogeneous deposits. It may be that the proximal Bishop Tuff is not amenable to modeling due to its great thickness (100–200 m) and deposition on steeply dipping, rugged terrain, factors which would likely cause turbulent flow, obscure subtle stratigraphic details of flow boundaries, and complicate resulting compaction zonation.

1. Introduction

Systematic variation of density or porosity in vertical sections of ash-flow deposits is mainly the result of differential compaction of viscous glass shards following deposition. The primary variables that

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control compaction of ignimbrites were known by the 1950s (e.g. Fenner, 1948; Boyd and Kennedy, 1951; Smith, 1960a,b) to be temperature and total load pressure and to a lesser extent, gas content. Early compaction profiles (e.g. Ross and Smith, 1961, p. 47) hinting at the interplay amongst these variables show density increasing downwards (porosity decreasing) in response to increasing load pressure, then a density reversal below the center of the deposit reflecting rapid cooling at the base. The basal reversal clearly indicates that compaction is a rate-controlled process, else density would simply increase linearly to the bottom; instead, cooling at the base raises the viscosity of the shards sufficiently to overcome greater load pressure.

Compaction experiments by Friedman et al. (1963) provided the first systematic, quantitative constraints on the controlling variables. Their results enabled Riehle (1973) to calculate the theoretical shape ideal density profiles should have for different initial thicknesses and emplacement temperatures. A secondary factor was the length of cooling between successive ash flows whose cooling histories interacted; Riehle (1973) constrained the amount of compaction at the contact between two such compound cooling units but could not handle more complicated cases of 3 and more interacting deposits. However, by adopting a finite-difference scheme to solve for combined cooling and gas outfluxing, Riehle et al. (1995) were able to calculate compaction for multiple compound deposits. As an example of the application of the model profiles, Riehle et al. used 4 measured profiles from the Matahina Ignimbrite; each of these profiles seemed to have correlatable density reversals, implying that the deposit comprises several ash flows having partial cooling breaks measured in days to weeks.

The interpretation of cooling breaks was challenged by Wilson and Hildreth's (2003) study of compaction variation in the Bishop Tuff. These authors state that some intercalated zones of density minima in the Bishop Tuff "do not coincide with or represent cooling breaks at all" and they conclude that therefore, the density variations must represent emplacement of hotter material mixed with cooler material. Moreover, early density profiles (Marshall, 1935; Gilbert, 1938; Boyd, 1961; Ross and Smith, 1961; Sheridan, 1970) lack detail because of wide sample spacing; most seem to comprise one or at most, two deposits. Thus interpretation of the significance of multiple density reversals, especially where subtle, has been troubling for those who assume that ignimbrites are deposited nearly instantaneously. Boundaries of individual flows (deposits) comprising an ignimbrite sheet may be marked by fall deposits, truncations of fumarole pipes, or concentrations of pumice blocks (e.g. Wilson and Hildreth, 2003). However, as noted by Lipman et al. (1966, p. 11), "depositional breaks are particularly difficult to locate within zones of dense welding". Most fall deposits within the Bishop Tuff are only few cm thick, are laterally discontinuous, and are obscured by compaction. Thus, density reversals typically have no accompanying sedimentologic evidence for their origin. Moreover, Wilson and Hildreth had no independent means to quantitatively estimate duration of breaks even if real, except to infer that intercalated fall deposits represent a "significant time break". They concluded that "a demonstrable time break may not be accompanied by significant changes in the properties of the ignimbrite whereas other parts show that clearly defined changes in ignimbrite properties may lack any evidence for a significant time break..." In short, by their estimation it is all but impossible to identify true flow boundaries with certainty, and in any case, density reversals cannot be interpreted as cooling during temporary cessation of deposition.

Wilson and Hildreth conducted their study in the Owens Valley Gorge, where the Bishop Tuff was emplaced on steeply sloping paleotopography: 900 m of fall over some 30 km of runout. Subsequently, Sheridan and Wang (2004) modeled density profiles of the Bishop Tuff that were measured in Adobe Canyon, where the tuff was emplaced on a surface of low relief. Each of their dozen profiles has one to 3 density reversals and the profiles are generally similar to one another, lending confidence that the reversals are correlatable stratigraphic horizons. When modeled as cooling breaks, the duration of the breaks implied by the reversals range from 5 to 40 days and emplacement temperatures range from 570 to 676 °C and have a slight decrease with distance from source. These are reasonable values assuming cooling with transport several tens of kilometers from source. Moreover, interpretation of density reversals in the Bishop Tuff as cooling breaks as long as 1–2 years is supported by studies of the origin of the cryptoperthites (Snow and Yund, 1988). These two studies together cast serious doubt on Wilson and Hildreth's assertion that density reversals cannot represent cooling breaks.

If density reversals do in fact indicate cooling breaks between ash flows, then density profiles can provide important evidence about the anatomy of ignimbrite deposits despite the paucity of visual evidence for flow boundaries. The question is, are large caldera-forming ignimbrites ever constructed piecemeal with depositional hiatuses? The tuff in the Valley of 10,000 Smokes has several flows "emplaced in quick succession *but separated sufficiently in time (minutes to hours)*... that compaction promoted channeling of later flows..." (Hildreth, 1987, p. 681; italics added). Tambora in 1815, one of the largest historic eruptions, had several Plinian eruptions over a 5-day period, followed by as many as 7 ash flows in a 24-hour period (Sigurdsson and Carey, 1989). Deposits of such volcanic-arc eruptions are, however, small in volume ($\leq$50 km^3) compared with the largest pre-historic deposits, the details of whose depositional history can only be inferred. The Kidnappers ignimbrite, a 450-km^3 Pleistocene deposit in New Zealand, comprises "at least 2 flow units separated...by a few cm of fall material" (Wilson et al., 1995). The Pleistocene Bandelier Tuff in New Mexico consists of an upper and lower member, each >100 km^3 and separated by 380,000 years (Spell et al., 1996). "The complexity of the deposits [of the upper member] indicates that the eruptions spanned more than a few days...erosional features within the deposits leads us to estimate that somewhat less than 10 years is a realistic figure..." (Smith and Bailey, 1968, p. 637). A detailed, proximal density profile of the upper member (Riehle, unpub. data) indeed has many density reversals, some of which are marked by lithic concentrations or by thin beds of cross-bedded ash. In view of the difficulty of recognizing subtle textural differences at flow boundaries after compaction, then, we suggest that it may be more likely than not that large-volume ignimbrite deposits consist of multiple flow units emplaced over periods of many hours to as much as a few years.

Other uncertainties about the interpretability of complex density profiles remain. Does devitrification prematurely halt compaction? Is the basal density of typical ash deposits solely a factor of load pressure and conductive cooling, or do other processes such as ground-layer deposition (Branney and Kokelaar, 1992) or dynamic compaction against pre-eruption topographic highs during flow (Chapin and Lowell, 1979) obscure simple compaction? Does vapor-phase mass transfer alter primary compaction profiles? We address these issues at appropriate places in the following report.

2. This study

In view of the stark contrast between conclusions reached by Wilson and Hildreth (2003) and those of Sheridan and Wang (2004), we felt a model study of other ash-flow deposits, focusing on thin deposits on paleotopography of low relief, might yield some worthwhile insights. In this paper, we first report on thin, relatively simple cooling units and examine whether the compaction model can closely reproduce their density profiles. We then follow with profiles of a complex Miocene ash-flow tuff, the Rattlesnake Tuff of eastern Oregon. Our approach is that, although a unique model solution may not be obtainable from a single profile, the systematic correlation of model results amongst multiple, distal and proximal deposits should lend confidence the model.