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Cinder Cone Degradation

Introduction

Scoria cone degradation can be studied by applying a handful of active erosion and transport processes called “diffusion modeling” to determine the approximate age of an individual cone based on some basic site measurements like height and slope. Using measurements from a field of scoria cones in Northern Arizona called the San Francisco volcanic field; several cones of unknown dates of origin were surveyed. Data collected included the height and slope along a chosen transect, as well as visual observations like grain size, biological activity and hydrologic evidence such as rills and channels. These field measurements were supplemented with ArcGIS data based on available digital elevation models and Google Earth images. Figure 1 displays an overview of the scoria cone field using an overlay of DEM with a slope analysis. In this area there are four cones with previously known ages, and multiple cones of unknown ages. Using the data extrapolated from first four cones with known ages, and applying the diffusion modeling with the active erosion and transport processes, this study attempts to interpolate the dates of the three cones of unknown age.

Processes

To attempt an estimation of the age of unknown scoria cones, there are two main types of diffusion that are discussed herein, linear diffusion and non-linear diffusion. The simplest mathematical form of the diffusion process is $q_s = kx^mS^n$ (Equation 1), where q_s represents the soil flux, k is a constant that represents the cohesiveness of the soil or the efficiency of the process, x^m is the distance from the divide, and finally S^n represents the slope of the hillside. Using this equation, the linear diffusion case sets m=0 and n=1, so the angle of the slope is the primary driver in this first condition. This linear process of soil diffusion down a slope results in a hillside that migrates into the ultimate shape of a convex parabola. Physical examples of linear diffusion drivers are rain-splash, freeze-thaw effects, burrow holes from small animals, and finally tree-throw. Each of these processes has a long term net effect of moving soil down slope and is represented in the landscape by hillsides with a smooth convex parabolic shape (Figure 2).

Using the linear diffusion model, the assumption has been made that the maximum slope of a scoria cone possibly gives a direct relationship to the age of the cone, and will be discussed further in the next section.

Non-linear processes are continually undermining the linear processes, complicating the analysis. Non-linear processes are represented mathematically using the same diffusion equation, with m=1 and above, and n=2. This creates forms in the landscapes that display straight slopes near the angle of repose, or concave gullies. When material on a hillside is at rest above the angle of repose, eventually the internal friction will give way in dry ravel events, or more dramatic rock falls or landslides. These events bring the material back to its natural angle of repose, and it typically will display a straight section of slope, not the parabolic shape that the slow creep of linear diffusion creates (Figure 3). A more extreme non-linear process of erosion is hydrologic in nature, whether it is rills, gulleys, or rivers. At the point when enough surface area can focus rainfall runoff into a channel, this will carve a concave gash into the landscape (Figure 4). This dramatically competes with the convex, parabolic nature of linear soil creep. This competition between linear and non-linear will prove challenging when using linear diffusion to determine the age of a cinder cone as the sudden rock slides and gully washing of a rain event will hinder the linear soil creep from creating the natural parabolic shape. This will affect the expected pattern of gradually decreasing maximum slopes of a hillside over time, and will be discussed further in this report.

Cinder Cone Morphology

Over time, both the morphology and the active processes of a cinder cone changes in a predictable pattern. Figure 5a through 5d shows four time steps in the erosion of a typical cinder cone over time. Beginning with Figure 5a, the young cinder cone would display a definite straight section which is set by the angle of repose. This angle for a typical cinder cone has been measured to be about 33 degrees from the horizontal. At this point, the cinder cone would display evidence of non-linear transport with landslides and dry ravel along the straight section. There would be poorly sorted cinders along the straight slope and landslide lobes with large cinder boulders at the base of the cone. The cone also exhibits some evidence of linear transport, as the top of the cone erodes and sediment transport begins to move down the straight section. There would be no evidence in the straight section of hydrologic erosion, although there may be some rills at the top of the concave portion of the deposition zone. Evidence of hydrologic erosion is typically absent from the main body of the cone at this stage due to the high infiltration of the cinders which are loosely consolidated. Only after some time has passed where linear processes break down the cinders into smaller grain sizes, ultimately decreasing the infiltration rate, will the cone generate enough overland flow to experience hydrologic effects.

In the next time step Figure 5b – Intermediate #1, linear processes begin to dominate and round out the top of the cone into the parabolic shape. The parabolic shape occurs in the erosion zone and is transported along the shortening straight section until it is deposited in the concave section at the base of the cone. This deposition zone displays deeper layers of strictly colluvium as the young cone has been eroded primarily by landslides and dry ravel, but upper layers of the deposition zone show more colluvium based on evidence of bioturbation, and some vegetation. Further down the slope in the deposition zone, alluvium deposits begin to appear. The breakdown of the cinders into small grains and soils begin to decrease infiltration rate and runoff begins to erode small rills and gulleys in the gentler slopes around the base of the cone.

The cone represented in Figure 5c – Intermediate #2 is now dominated by linear diffusion processes as it has completely lost its straight section. The convex parabolic shape through the erosion zone directly transitions into the concave deposition zone. The maximum slope is decreasing over time, as are the infiltration rates due to decreasing rock size and the increase in vegetation. This increases runoff and the deposition zone displays more evidence of rills and channels carved in to the apron of the cone. Direct evidence of caliche in this region of a similar cone with this shape was observed in the field study.

The final stage of the cone is displayed in Figure 5d – Old Cinder Cone. This cone still displays the parabolic shape determined by linear soil creep processes, although the curve is much larger, and to the naked eye may appear almost flat. The area displays high amounts of vegetation such as tall grasses and burrow holes from ground dwelling animals. The grain sizes are much smaller which decreases infiltration further. The low maximum angle and decreased infiltration allows for hydrologic erosion processes to dominate the area. Direct field observations on a similar cone showed high drainage density with deep gullies and channels with layers of caliche. The shape of the cone has made an interesting transition, as the erosion zone has actually moved beyond the original cone cinders into the colluvium deposits at depth. Over time both the linear soil creep and hydrologic erosion processes will erode this cone down completely.

Interpretation

Diffusion modeling provides some tools to estimate the ages of cinder cones, but the range of variables complicates the problem. Figure 6 shows several cones plotting with their Average Slope versus Time. All the cones create a general trend that appears to be slowing over time. The average slope is decreasing over time, but it decreases at a rate that is also decreasing. This demonstrates that the cones are eroding at a decreasing rate. The decreasing rate of erosion obscures the age of the cone as diffusion modeling assumes a uniform erosion rate. The actual date of the cone would be older than its projected age based on the average slope.

Figure 7 is a plot of both the Linear Diffusion Curve and the four cones of known age on a chart of Maximum Slope versus Time. The parameters chosen greatly affect the diffusion curve and how it predicts the age of an unknown cone. For example, Figure 7 sets the original height of the cone at 200m based on the current height of a young cone, and a k factor of 0.1. This k factor is a typical rate for desert cones in the southwest United States. The youngest cone lands on the curve, but the older cones fall below the curve. If the initial height is revised to 150m, then the curve adjusts down to line up with the maximum slope of the older cones. Alternatively, changing the k factor of 0.1 to a faster rate of erosion of 0.2, the curve again falls in line with the maximum slope of the existing cones. This implies that either the older cones were originally much smaller than the youngest cone, or there are more erosion processes than just diffusion acting on the cones. The older cones are more heavily impacted by hydrological, non-linear processes. Younger scoria cones that are primarily eroded by linear diffusion would be more in-line with the diffusion modeling. As the cone is older, that projection would be more difficult to line up. In order to estimate a more accurate date of older scoria cones, it would be necessary to observe the entire cone, and look for any and all evidence of non-linear erosion patterns. Linear diffusion modeling is a helpful place to start in aging the cone, but adding in a correction for non-linear processes could help adjust the age projection more accurately.

Figure 1: San Francisco Volcanic Field - Slope Map

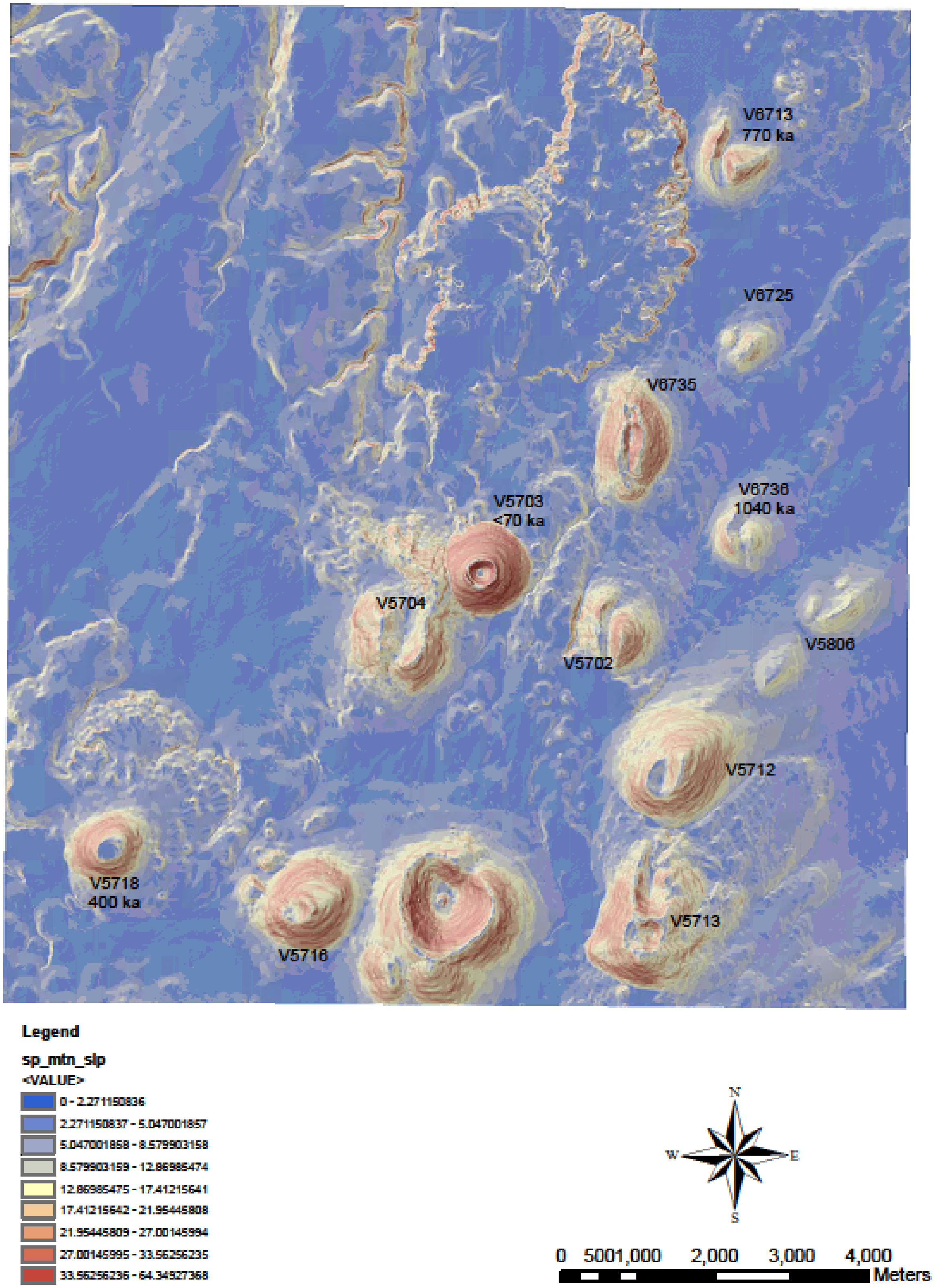


Figure 2: Parabolic Shape

Figure 3: Landslides and debris lobes at base of hillside

Figure 4:

TOP: Channel with caliche layers

BOTTOM: Rill carved into the slope from hydrologic processes

Figure 5a: Young Cone

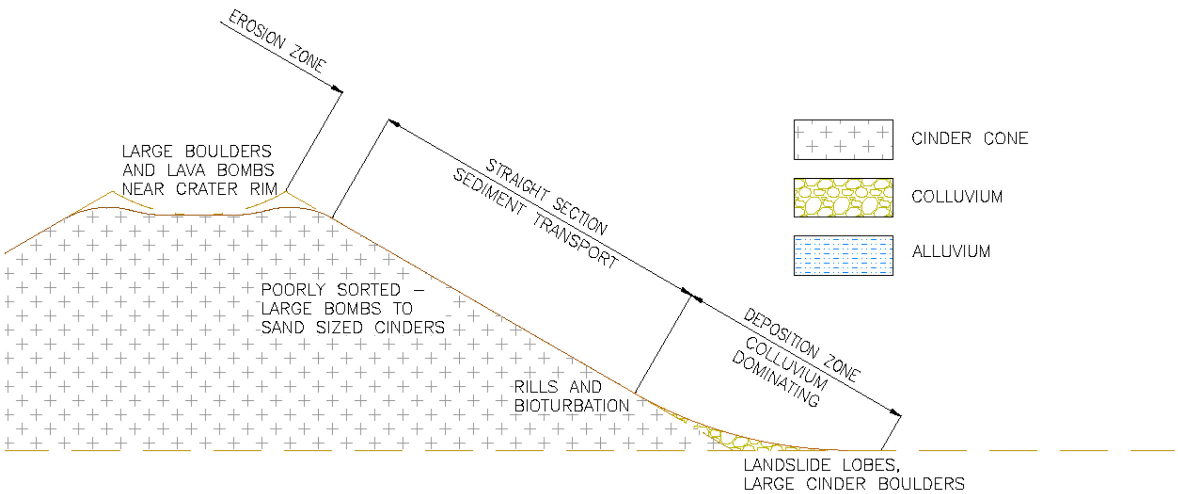


Figure 5b: Intermediate Cone #1

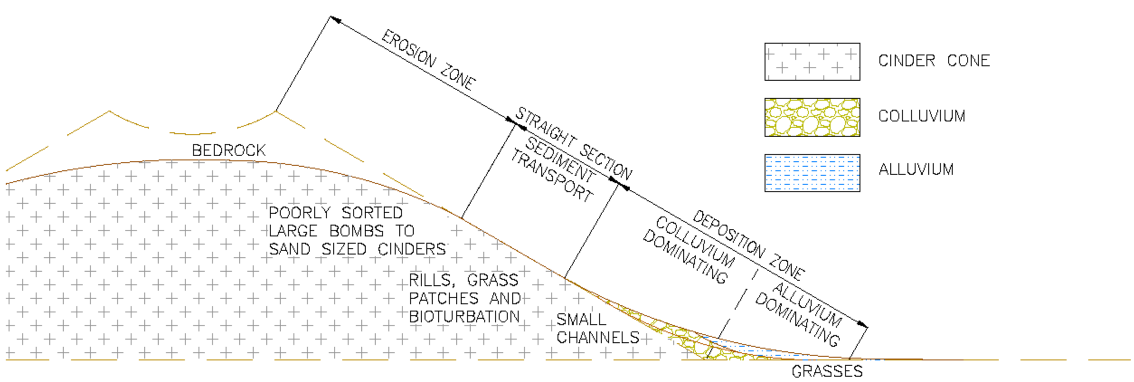


Figure 5c: Intermediate Cone #2

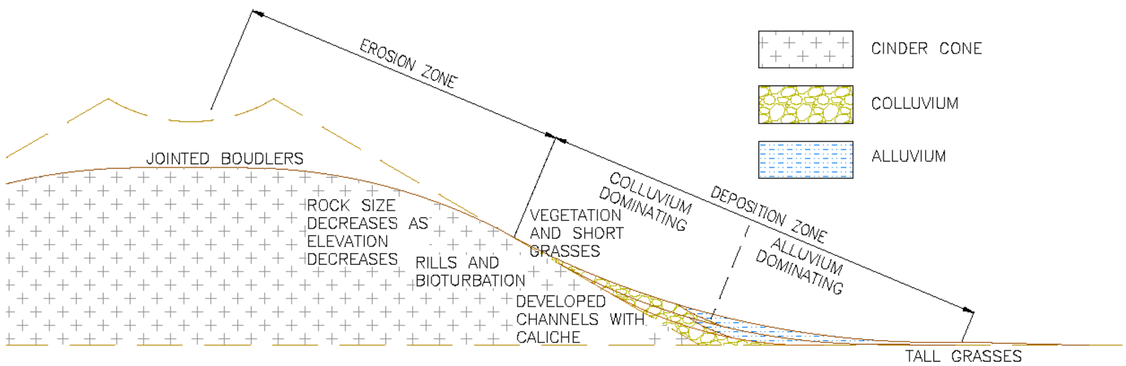


Figure 5d: Old Cone

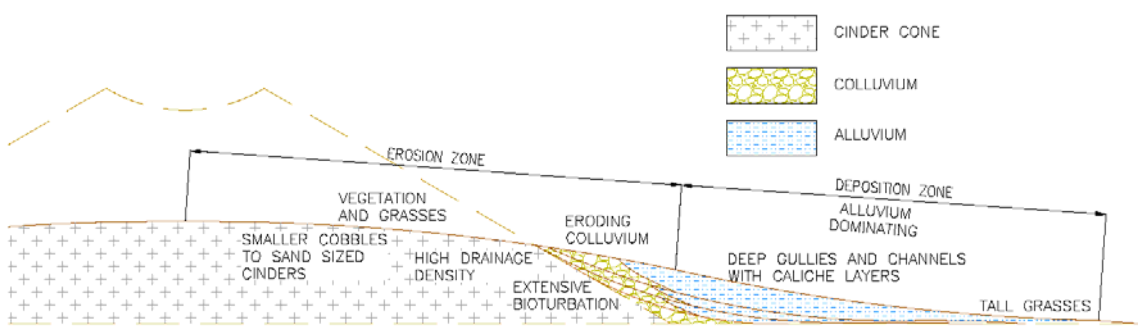


Figure 6: Average Slope vs Time

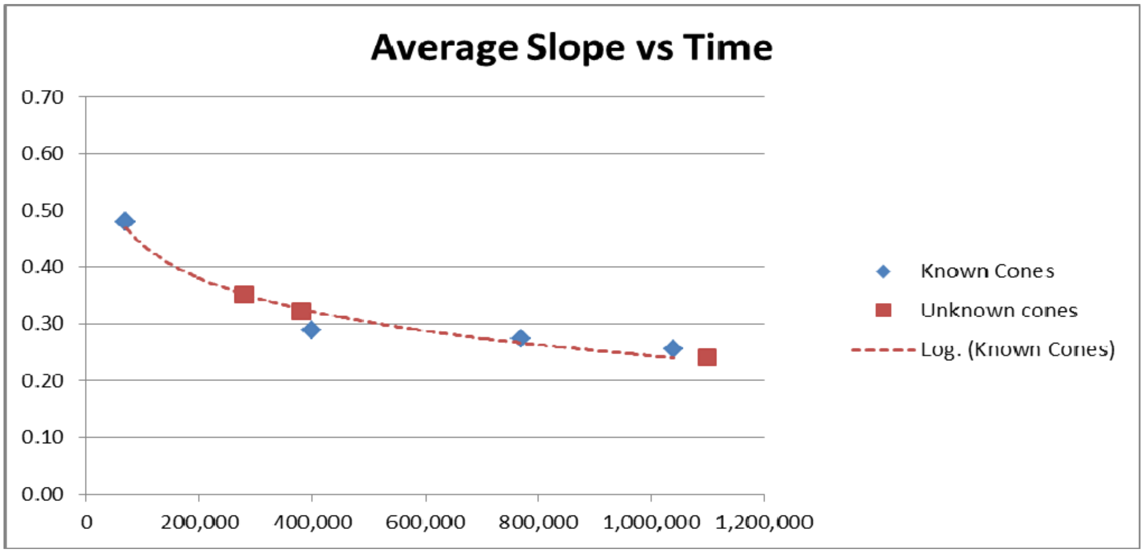
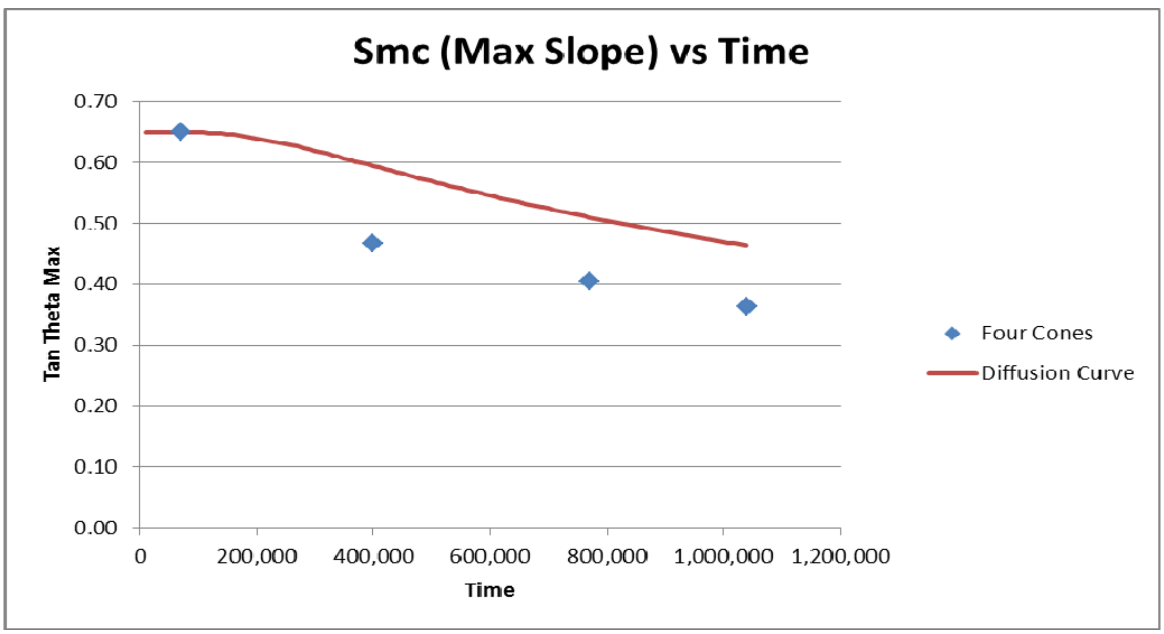


Figure 7: Max Slope vs Time



Parameters	
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