WEATHERING RIND AGE CALIBRATION OF SANTA BARBARA, CALIFORNIA DEBRIS FLOWS
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1. INTRODUCTION
On January 9th, 2018, a debris flow devastated Montecito, California. The damage from the flow resulted in 23 deaths, and 246 destroyed and 167 damaged buildings (County of Santa Barbara, 2018). Since the wildfire potential appears to be increasing in Southern California as the climate warms and dries, the risk of debris flows is likely to increase and expand in this and similar regions, as wildfire and debris flows are closely linked (Kean et al., 2011; Keller et al., 2019). Given this information and the damage from the 2018 event, the community fears the possibility of another event in the near future. Understanding how events like this happen in the future is best understood in terms of their behavior in the past. As it stands, the recurrence interval of large-scale debris flows in Santa Barbara and the surrounding areas is currently unknown despite evidence of them in nearly every canyon in the county. This evidence occurs as large boulder fields, as seen in areas like Rocky Nook Park, as well as boulder levees along the banks of streams that flow out of the canyon mouths and into the city. Knowledge of the timing of the repeated incidence of these past flows will give insight into the evolution of the modern environment and improve the risk assessment of debris flow hazards moving forward.

In order to gain a better understanding of Santa Barbara debris flow recurrence, weathering rinds on the in-situ boulders of debris flow deposits were measured as an indication of the age of the events that created these deposits. A weathering rind is an identifiable layer that has undergone more weathering than the material beneath it (Burbank and Anderson, 2012). The thickness of this layer is an indication of the extent of mineral oxidation and reaction below the surface of a clast (Gellatly, 1984). This thickness increases over time, making it an effective tool for determining the relative age of surficial deposits. When matched with an independent absolute age dating method, empirical best-fit models can be created to quantify the rate of rind thickness development for particular climates and lithologies (e.g. Colman and Pierce, 1981; Knuepfer, 1988; Sak et al., 2004). In doing so, weathering rind analyses have been used as a low-cost strategy to enhance absolute dating methods or provide age estimates when other dating methods cannot be applied. For our purposes, weathering rinds were measured in conjunction with radiocarbon analysis of charcoal found in the fine-grained matrix of the debris flow deposits to calibrate the growth rate of weathering rinds of the debris flow boulders in Santa Barbara County. Upon this calibration, the weathering rind thickness can be used as an independent chronometer, allowing for the interpretation of the recurrence history of debris flows and an overall better understanding of the general geomorphic history of the area.

2. GEOLOGIC & CLIMATIC SETTING
Due to the north-south shortening associated with the nearby left-step in the San Andreas Fault, the Santa Ynez Mountains above Santa Barbara are a rapidly uplifting (1 to 2 mm/yr), east-west oriented feature of the
Santa Barbara Fold Belt (Gurrola et al., 2014). The rapid uplift and incision of this area, combined with wildfire and intense precipitation, have resulted in the formation of a series of fans fed by the deposits of high-magnitude debris flow dominated from the surrounding landscape (Keller et al., 2015).

The stratigraphy of the Santa Ynez mountains consists of east-west striking strata that steeply dip to the south. The lithologic units are Eocene to Miocene aged interbedded layers of sandstone and shale (Dibblee and Ehrenspeck, 1986). Due to the compositional and grainsize similarities of all the boulders of the debris flow deposits, we hypothesize that the boulders originate from the Coldwater Sandstone and Matilija Sandstone units of these layers, both of which are massively bedded, marine arkosic sandstones (Norris, 2003; Dibblee and Ehrenspeck, 1986).

Since our study area is restricted to a relatively small area, spanning about 40 km² and an elevation change of about 200m, we can assume the same climatic conditions have been acting upon the different deposits. The current climate of Santa Barbara is considered Mediterranean. Chinn (1981) found no variation in the rate of rind development within the range of altitudes, aspects, and conditions within their study area, therefore we assume that microclimate conditions are averaged out, and therefore are not a significant influencer of rind growth in Santa Barbara.

Chemical exchanges and mineral dissolution processes acting on rocks cause the rinds to form, but the extent of the rind thickness is limited by the permeability of the rock and the dissolution reaction rates acting upon them (Reeves and Rothman, 2014). Therefore, the thicknesses are mainly a function of lithology and climate. The uniform climatic and lithologic factors of the study area make the comparison of the weathering rind thickness between deposits more feasible. This allows the assumption that the growth rate of the rinds in the different deposits has been constant through time.

3. Methods

3.1 Weathering Rind Measurements

The boulders of the Montecito flow deposits have no weathering rinds. As such, we assume that the movement down the canyon removes any previously accumulated weathering rinds, thereby “resetting the clock” and limiting any effects of inheritance moving forward. This permits the measurement of the weathering rind thickness to be considered a proxy for the time since the last distal movement of the boulder.

The weathering rind thicknesses were collected by making 20 measurements on a sample set of boulders at each debris flow deposit site. Care was taken in sampling to avoid boulders with obvious signs of recent disturbance or non-natural movement (i.e. for building or development purposes). Additionally, sampling was biased toward measurements on larger boulders (>1m on the intermediate axis) to assure that other processes, such as river transport, were not responsible for the transportation to their measured location.

Rind measurements were taken along the edge of an intact piece of weathering rind, adjacent to where a piece of rind had flaked off, exposing the unweathered rock beneath. The thickness of the rind was measured using digital calipers with a precision of 0.01 mm to the top of the to the parent rock, normal to the boulder surface. In some cases, the boulder was cracked in such a way that the
weathering rind thickness was measured using the color contrast between weathered and unweathered rock. In this case, the prominent red color due to the increased concentration of immobile oxides relative to the unweathered parent rock depicts the thickness to be measured. Figure 1 illustrates these two methods of weathering rind measurement in photos A and B, respectively.

Geospatial data of each measured boulder was taken using a Trimble Geo 7X handheld device.

3.2 Charcoal Collection and Analysis

Charcoal and other organic material inclusions within the debris flow deposits were collected for radiocarbon dating. Because wildfire and debris flows are so closely coupled, it can be assumed that the charcoal within the fine-grained matrix of the flow deposits originate from a wildfire event close enough in time to the debris flow to accurately approximate the age of the event (Kean et al., 2011). However, due to the possibility of recycling of previous wildfire material, the ages will represent a maximum potential age. Charcoal samples were collected by first digging a few inches into the unconsolidated matrix surrounding the boulders. From behind this cleared material, a bulk sample of material was collected. This material was then placed in a series of sieves to remove any pebbles or silt and clay sized particles. Stainless steel forceps were used to extract any charcoal pieces found in the remaining material. These samples were sent to the DirectAMS laboratory in Bothell, WA for radiocarbon analysis using an accelerator mass spectrometer. The ages received from this analysis will be correlated with the average weathering rind thicknesses of the respective debris flow deposit site.

3.3 Secondary Data

In conjunction with these thickness measurements, some additional secondary measurements were collected. These include hardness, roundness, and color data. These measurements were made on the same boulders as the weathering rind thickness measurements. Hardness was measured using a Schmidt Hammer, an instrument that measures the rebound of a spring-loaded mass impacting the surface of a sample. The hammer hits the sample at a defined energy and the rebound is dependent on the hardness of the sample. The rebound value (R) can be used to determine the materials compressive
strength. This (R) value can then be transformed into (N/m²) using empirical correlations. Roundness was estimated by comparing the boulders to the Krumbein (1941) roundness chart. Finally, color was taken by comparing that of the boulders to a Munsell Soil Color Chart.

4. RESULTS

4.1 Weathering Rind Data

After compiling the greater than 5,000 weathering rind thickness measurements and taking the mean of each set of measurements per site, there is a definite distribution of thicknesses throughout the deposits in Santa Barbara (Fig. 2). The weathering rind thickness measurements appear to fall in three subgroups, labeled as thin, intermediate, and thick. These represent debris flow deposits of relatively younger, intermediate, and older ages, respectively. The thin weathering rinds range in average thickness from 4.156mm to 4.627mm, intermediate range from 5.673mm to 8.310mm, thick range from 9.343mm to 10.761mm. These ranges were broken up using the Jenks Natural Breaks Classification system, a method designed to minimize the deviation from the class mean while maximizing the deviation from the means of the other groups.

Figure 3 shows the geographic spread of the sites where weathering rind thicknesses were measured. Each group of circles is a site. Each individual dot is a boulder within that site on which measurements were made. The color of the circle is based on the average of the 20 thickness measurements that were taken on
The thickness ranges for the thin, intermediate, and thick categories are slightly different for this figure due to the average per boulder in a given site being used rather than the average for the entire site. These categories were depicted using the Jenks Natural Breaks Classification system. This figure illustrates how sites of similar thickness, and therefore age, appear to cluster around similar geographic areas.

4.2 Radiocarbon Analysis Results

At this time, charcoal samples are still being dated at DirectAMS. Figure 4 represents an idealized version of the hypothesized calibration curve of age vs weathering rind thickness. It is hypothesized that the growth rate will decrease with increasing deposit age.

5. DISCUSSION

5.1 Following Flow Paths with Weathering Rinds Thicknesses

The predominate path that past debris flows took to their depositional locations can be traced using the geographical locations of boulders with weathering rinds of similar thickness. Or, similarly, similar weathering rind thicknesses along an area could show the dominant flow path of multiple episodes of debris flows around the same general time period. For example, sites 1, 4, and 3 follow...
a path down Mission Canyon (Fig. 3). Without dates, we cannot say whether these are from the exact same event, but at least, it can be assumed that they originate from event(s) of a similar age, following a path down Mission Canyon.

Additionally, weathering rind thickness could give insight into how dominate paths of debris flow have changed over time and the general tectonic history of the area. For example, for sites 15, 16, and 17, deposits with thicker weathering rinds, therefore relatively older ages, show a path that crosses what is now Mission Ridge (Fig. 3). Mission Ridge is a growing anticline with an uplift rate of about 1m/ka, with a present local relief of 100m and is part of the Mission Ridge fault system of Santa Barbara (Keller et al., 2015). It can be inferred that the flows that created the deposits at these sites happened in events prior to the beginning of the uplift of this ridge. In contrast, sites 1, 4, and 3, sites that all fall into the thin weathering rind category, are farther to the west. This decrease in rind thickness, therefore flow age, moving from east to west could be representative of westward propagation of Mission Ridge. Furthermore, this could be interpreted as the present debris flow risk being lower in the region of sites 15, 16, and 17 and increases toward the west.

5.2 Decreased Rind Development Rate through Time

Rind growth appears rather linear from site to site (Fig. 2). However, when considering the hypothesized ages of the respective deposits, this is not the case. As seen in the idealized graph of the weathering rind thickness vs time (Fig. 4), the rate of development decreases through time. Chinn (1981) found there is a power law relationship between weathering rind thickness of sandstone boulders in New Zealand and the age of those boulders. Gordon and Dorn (2005) suggest that reduced humidity levels within the deeper parts of a clast could result in a decreased weathering penetration depth, thereby decreasing the weathering rind development through time. An alternative hypothesis is that weathering rind development may still progress into the rock but simultaneous microerosions are occurring on the outermost
parts of the rinds such that the apparent thickness is lower than it would be otherwise (Gordon and Dorn, 2005). As such, once the radiocarbon analyses are complete, the sites with thinner rinds, therefore younger, will have better defined ages than those with the intermediate and thicker rinds.

6. Conclusions
We can better understand the age, therefore, recurrence of past debris flow events, by utilizing this inexpensive dating method. Expanding our understanding of the mechanisms of the past can provide insight into the frequency of large events in the future. Additionally, these techniques may give insight to the geomorphic history of the area on a broader scale, which could allow for better assessment of present day hazards.

7. Future Work
Moving forward, weathering rind thicknesses will be measured at 3-5 more debris flow deposit sites. Additionally, most of the remaining time will be spent procuring samples for radiocarbon analysis. Once these samples have been analyzed, the correlation between weathering rind thickness and absolute age can be better synthesized, allowing us to place an age on the sites where charcoal is not readily available. Following this, we will have a better control on the recurrence of Santa Barbara debris flows. More statistical analyses will be done to test whether different sites are considered to be from the same population, allowing us to assume they are from the same, or nearly same, aged event.

References


Krumbein, W.C., 1941, Measurement and Geological Significance of Shape and Roundness of Sedimentary Particles: v. 11, p. 64–72.
