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# Fractional changes in elemental mass (Ω) and relative variation curves: Unravelling elemental mass redistribution patterns within the regolith

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ABSTRACT

Within the arid climate of southern California, USA, we uncovered through trenching a granodioritic-tonalitic corestone, a partially encircling fractured rind, and an overlying Ah2 horizon composed of sandy soil. Using the geometric mean of chemical data derived from an adjacent erosionally exhumed corestone as a proxy for unweathered bedrock, the compositional linear trend derived from weathering was calculated. Average weathering intensities (*t*-values) and 95% confidence intervals are as follows: uncovered corestone = 0.56 (±0.13), inner fractured rind = 0.93 (±0.08), outer fractured rind = 1.5 (±0.05), and Ah2 = 1.7 (±0.09).
Ti was used as a reference frame for calculating Ω, the modeled fractional change in a given elements mass. Resulting relative variation curves plotted on 10 bivariate graphs, where the x-axis represents *t*-values and the y-axis is Ω, show that with the exception of $P_2O_5$, samples from each of the above textural groups, cluster and plot closely about the 10 relative variation curves. The clustering and ordering of samples analyzed from the uncovered corestone, inner rind, outer rind, and Ah2 horizon about the relative variation curves suggests that weathering of the section of regolith uncovered by trenching occurred in an orderly and sequential manner as the result of increasing pH and decreasing surface area for fluid/rock reactions. Mass balance calculations are consistent with the modeled relative variation curves, and the weathering of plagioclase to smectite and kaolinite, and biotite and chlorite to vermiculite.



## 1. Introduction

Since initial publication of von Eynatten et al. (2003) and von Eynatten (2004), several studies focusing on the chemical evolution of the regolith have utilized the mathematical and statistical techniques advocated by the above authors to model compositional linear trends in three-part compositions, as for instance, the often used sub-composition formed from molar A, CN, and K values (e.g., Girty et al., 2013, 2014; Parizek and Girty, 2014; Heath et al., 2015; Purcell et al., 2015). In such compositions, A is the percentage of molar $Al_2O_3$ in the sum of molar $Al_2O_3$, $CaO^*$, $Na_2O$, and $K_2O$. CN and K are calculated in a similar manner, except that the denominator for CN is the sum of molar $CaO^*$ and $Na_2O$ values, and for K is molar $K_2O$ values. $CaO^*$ signifies that molar CaO values were corrected for the presence of apatite as follows: $CaO^* = CaO - 3.3P_2O_5$ (McLennan, 1993). Thus, $CaO^*$ represents that part of the total CaO associated with the silicate minerals only. No carbonates were present in samples analyzed from the study site, and as a result, a correction for their presence was not necessary.

The results of past efforts at evaluating orderly appearing changes in regolith compositions in A-CN-K space have resulted in the identification of biotite, plagioclase, and illuviation controlled compositional linear trends (Girty et al., 2013; Carrasco and Girty, 2015; Purcell et al., 2015; Heath et al., 2015). Though the first study to model compositional linear trends in higher dimensions, such as the 11-part major element compositions that are commonly included in chemical studies of the regolith was by von Eynatten et al. (2003), these authors focused primarily on the plagioclase-dominated weathering trend originally identified in three-dimensional A-CN-K space by Nesbitt and Young (1984). In this paper, we present the results of our study of a section of regolith that developed from the weathering of the La Posta pluton, a Cretaceous (~94 Ma), largely granodioritic to tonalitic pluton (Clinkenbeard and Walawender, 1989), located in southern California, USA, within an arid climate (Fig. 1). The specific question that we attempt to address is *Can modeling of compositional linear trends in higher dimensional space be used to identify and quantify systematic changes in element redistribution patterns in regolith developed from unweathered granodioritic to tonalitic bedrock?* As documented below, for the site that we studied, modeling compositional linear trends in higher dimensional space yielded significant insight into how elemental mass was systematically

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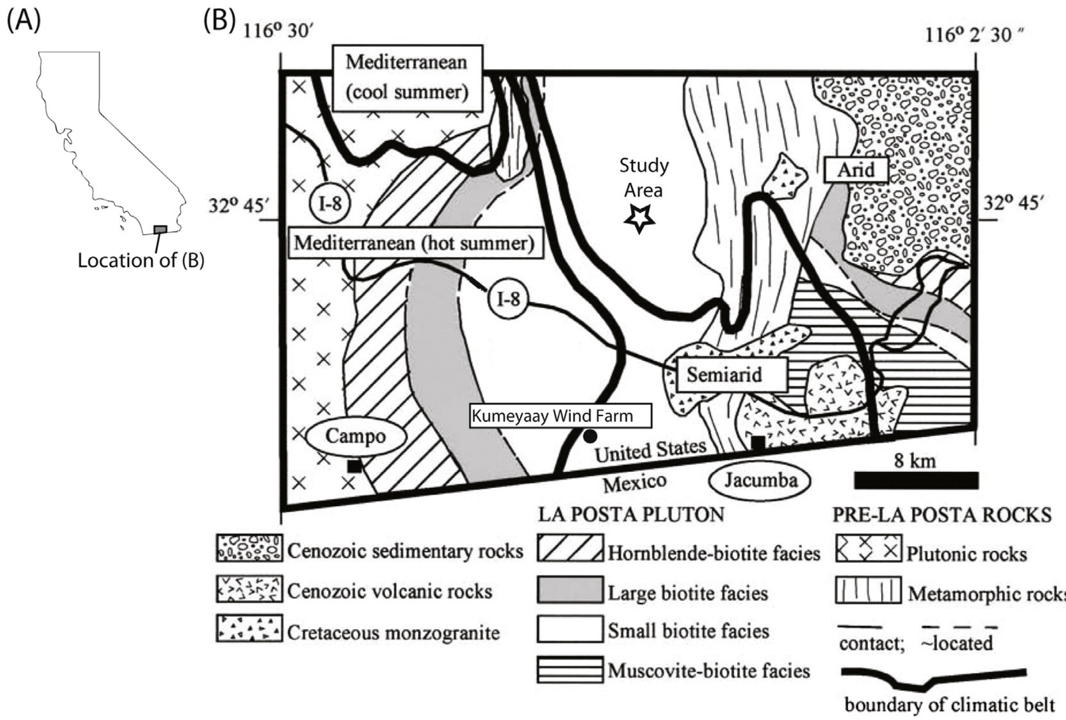


**Fig. 1.** (A) Map of California with field area highlighted. (B) Map showing climatic zones and location of study area at 32°45′1.91″ N, 116°16′27.7″ W. Note that the study area lies within an arid environment and within the small biotite facies of the La Posta pluton.
(Modified from Girty et al. (2003)).

redistributed within the studied section of regolith. Subsequent mass balance calculations quantified elemental mass gains and losses, and generally support the modeled trends.

## 2. Setting, climate, and general field characteristics

The study site, located at 32°45′1.91″ N and 116°16′27.7″ W, at an elevation of ~1150 m (Fig. 1), is positioned within a ~10 m wide area lying between two large corestones at the top of a ridge trending 310°. The mean annual precipitation in and around the study site is 37.7 cm. The average annual minimum temperature is ~7.2 °C, and the average annual maximum temperature is ~24.4 °C (Weather Underground, 2016). Though these values are characteristic of an arid climate (Eidemiller and Finch, 1972), geochronologic data from near Jacumba, located ~16 km to the SE of the study site (Fig. 1), suggest that regolith development may have extended over a lengthy period of time. For example, at the Jacumba site, Bell et al. (1998) used rock-varnish microlamination and cosmogenic $^{36}$Cl dating techniques to show that corestone exhumation occurred about ~10.5 ka to ~23.6 ka ago. During this time interval, the climate of the Peninsular Ranges likely experienced cooler and wetter periods during Heinrich events $H_2$ and $H_1$, 21.0 ka and 14.5 ka years ago respectively, and within the Younger Dryas event, ~10.5 ka years ago, but was otherwise generally dry and warm throughout the Holocene (Bell et al., 1998).

Over the above time interval, data and observations described in Bell et al. (1998) imply that prior to exhumation, bedrock was broken into blocks by multiple sets of more-or-less orthogonal joints. As water penetrated along the joint system, spheroidal weathering converting the rectangular to square joint-bounded blocks to ellipsoidal to spheroidal corestones enveloped in saprock and saprolite. As the system evolved through the Pleistocene and Holocene, erosion removed the weaker saprolith leaving behind a surface cluttered with exhumed corestones.

At the study site, the primary geomorphic feature is a partially erosionally exhumed ellipsoidal granodioritic-tonalitic corestone extending ~2.0 m above the surrounding land surface (Fig. 2A, B). A sub-spherical ~0.8 m high corestone occurs adjacent to the SE margin of the larger corestone. A trench beginning at the base of the larger ellipsoidal corestone, and extending 140° for ~2.15 m and then 228° for ~0.6 m revealed a buried sub-spherical shaped mass composed of granodiorite-tonalite with long and short horizontal dimensions of at least 1.5 m and 1.0 m, respectively (Fig. 2A). A fractured rind partially encircles and parallels the shape of the granodiorite-tonalite mass uncovered by trenching and is characteristic of corestone undergoing spheroidal weathering (e.g., Chapman and Greenfield, 1949; Ollier, 1971). Two soil horizons designated from lowest to uppermost, Ah2 and Ah1, lie above the uncovered corestone and fractured rind (Fig. 2C). Soil horizon designations follow the recommendations of the World Reference Base (2014).

The fractured rind is ~10–20 cm thick (Fig. 2C). It grades through a decrease in crack density into the more massive interior of the corestone uncovered by trenching. The outer parts of the fractured rind often contain cracks infilled with material derived from the overlying Ah2 horizon, and, in general, are weaker and more friable than the inner parts.

Both the fractured rind and uncovered corestone are stained an orange-red color, and vary from mildly to very friable. In addition, under various degrees of mild hand pressure, samples from both regolith components disaggregate readily into coarse sand to pebbly sized fragments. Such responses, along with thin section observations described in Section 4.1, are characteristic of saprock (Anand and Paine, 2002; Graham et al., 2010).

The light brown (10 yr-3/4), 1.5 to 2.0 cm thick, Ah1 horizon extends completely across the top of the uncovered corestone, fractured rind, and Ah2 horizon (Fig. 2A). In the field, laminations within the Ah1 horizon are characterized by alternating sandy and pebbly lenses, millimeters in thickness. Polished and resin-impregnated slabs of the Ah1 horizon show bulbous and elongate cylinder-like darker colored and finer grained material disrupting the laminations. Such features are likely of biogenic origin (Stoops, 2003).

The contact between Ah1 and Ah2 is sharp at the scale of the outcrop, but on close inspection is highly irregular and bioturbated (Fig. 2C). Within the walls of the trench, Ah2 is dark brown (10 yr 5/4) and