



Residual regolith derived from the biotite-controlled weathering of Cretaceous tonalite–quartz diorite, Peninsular Ranges, southern California, USA: A case study

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ABSTRACT

Though K-feldspar-free tonalite and quartz diorite are common plutonic rocks in exhumed continental-margin magmatic arc rocks around the globe, how they weather has not been extensively studied. We therefore undertook an investigation aimed at understanding how an approximately 6-m thick section of residual regolith (saprock and overlying Alfisol) developed from Cretaceous K-feldspar-free tonalite and quartz diorite at Santa Margarita Ecological Reserve, southern California, USA. We analyzed three samples of soil, 10 of saprock, and 10 of corestone for their major, trace, and rare earth element compositions. Thin sections of each major textural group also were studied and point counted. Common XRD techniques were used to determine clay mineralogy. Three samples of soil and five of saprock were analyzed for their pH.

Within the saprock, an extensive network of cracks was likely produced by the volumetric expansion that accompanied the conversion of biotite to vermiculite. Migrating near neutral fluids responsible for this conversion resulted in a loss of K mass and affected several trace elements that are commonly found in biotite, but with the exception of an interval between 177 and 270 cm, left most other major, trace, and rare earth elements (REE) little affected. Within the 177 to 270 cm interval, at a depth of 208 cm, relative to the immobile framework, incongruent leaching of plagioclase by acidic solutions, resulted in the losses of Si, Al, Ca, Na, Pb, Sr, and Ga mass. In contrast, more neutral solutions added heavy REE (HREE) and Y mass at 177 to 237 cm depths, while acidic solutions removed REE and Y mass at 270 cm depth. In the soil, acidic solutions attacked plagioclase, biotite, and apatite leaching and removing, relative to the immobile framework, Ca, Na, Mg, K, and P mass. In addition, the dissolution of apatite resulted in depletions in HREE and Y mass. None of the elemental mass removed from the soil accumulated in the directly underlying saprock, and must have been removed from the near vertical plane of sampling.

Within the saprock, the above changes are mostly the result of near neutral pH water/rock interactions occurring within a warm and dry Holocene climate. Identified changes in elemental mass, other than those associated with the conversion of biotite to vermiculite, are localized and are likely the result of the paths taken by fluids with differing pH moving through the complex network of cracks. Any model purporting to describe the evolution of residual regolith must explain such natural complexities.

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1. Introduction

Regolith is defined as: “... the layer or mantle of fragmental and unconsolidated rock material, whether residual or transported and of highly varied character, that nearly everywhere forms the surface of the land and overlies or covers the bedrock” (Bates and Jackson, 1987). Residual regolith, the primary topic of this paper, develops on and from crystalline basement rocks, as for instance the intrusive rock

series (e.g., Le Bas and Streckeisen, 1991; Borrelli et al., 2014; Letto et al., 2015; Perri et al., 2015).

Nesbitt and Young (1984) documented the chemical effects of a plagioclase-dominated weathering trend developed in residual regolith within the now classical Toorongo weathering profile of SE Australia. Residual regolith within the Toorongo profile is developed on a Paleozoic granodiorite in the highlands of eastern Victoria about 100 km east of Melbourne. At this locality, climate is moderate with average temperatures ranging from -5°C to 10°C in the winter to 25°C to 30°C in the summer. Annual precipitation rates are approximately 1500 mm (Nesbitt and Markovics, 1997). Based on their mineralogical and chemical studies, along with experimental laboratory data, Nesbitt and Young (1984) demonstrated through use of the A–CN–K ternary diagram that

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plagioclase altered more quickly than did potassium feldspar. In such diagrams, A is the proportion of molar Al_2O_3 in the sum of A, CN, and K. CN and K are calculated in a similar manner, except that the numerator for CN is the sum of molar CaO^* and Na_2O , and for K is molar K_2O . CaO^* signifies that molar CaO values are corrected for the presence of carbonates and apatite. For this work, calcite was not present, and as a result corrections were made only for apatite ($\text{CaO}^* = 3.33 * \text{P}_2\text{O}_5 - \text{CaO}$). Molar proportions are the weight percent of each major oxide divided by its formula weight (Nesbitt, 2003). In A-CN-K space, the plagioclase-dominated alteration trend over much of its length was characterized by depletion of molar CaO^* and Na_2O relative to Al_2O_3 , and little to no change in molar K_2O , indicating that CaO^* and Na_2O are preferentially removed from plagioclase during regolith development (Nesbitt and Young, 1984). Only after plagioclase weathering has gone to near completion does K-feldspar weathering and the loss of molar K_2O become apparent.

In contrast to the alteration pattern exemplified by the Toorong data, the biotite-dominated weathering trend identified by Girty et al. (2013) occurred in saprock derived primarily from a Cretaceous tonalite located within the Santa Margarita Ecological Reserve (SMER), southern California, USA. The Mediterranean climate at SMER is characterized by annual temperatures ranging from 11.0 °C to 11.7 °C in the winter and 20.0 °C to 23.6 °C in the summer, and an average annual precipitation rate of approximately 336 mm (Weather Currents, 2014). Though small amounts of K-feldspar were present in the tonalite (<2%), the above authors interpreted the loss of molar K_2O relative to molar CaO^* , Na_2O , and Al_2O_3 to be the direct result of the removal of K from the interlayer position of biotite as it was converted to vermiculite. Such a process has been documented and discussed by many others (e.g., Nettleton et al., 1970; Bisdom et al., 1982; April et al., 1986, 2004; Dixon and Weed, 1989; Dixon and Schulze, 2002; Jolicoeur et al., 2000; Wilson, 2004; Aspandiar and Eggleton, 2006; Eggleton, 2008; Harraz and Hamdy, 2010; Perri et al., 2012, 2015; Girty et al., 2013; Borrelli et al., 2014; Parizek and Girty, 2014; Carrasco and Girty, 2015; Purcell et al., 2015).

If biotite-dominated weathering is common in the regolith, then it should be prevalent and perhaps dominant in the weathering of completely K-feldspar free plutonic rocks such as tonalite, quartz diorite, diorite, and gabbro. We therefore undertook a study focused on an approximately 6-m thick exposure of regolith derived from the weathering of a biotite-amphibole tonalite-quartz diorite. The specific study site is located at SMER, and is underlain by an 108 Ma Cretaceous pluton that has been mapped as gabbro by Tan and Kennedy (2000) and Kennedy and Tan (2007) (Fig. 1). However, petrologic work by students at San Diego State University indicates that the pluton varies in composition from gabbro to quartz diorite to low-quartz tonalite (Martinez, 2007; Johnson, 2008; Earl, 2008; Page, 2010) (Fig. 1). Significantly, K-feldspar-poor to K-feldspar-free plutonic rocks like those studied during this investigation make up a significant proportion of the highly dissected Cretaceous magmatic arc that extends the length of the Peninsular Ranges of southern California, USA, and Baja California, Mexico (e.g., Gromet and Silver, 1987; Todd et al., 1988; Kimbrough et al., 2015). In addition such rocks are common components in belts of exhumed plutonic rocks around the globe (e.g., Le Bas and Streckeisen, 1991). Consequently, how such rocks weather is worthy of some study.

In the following sections we first discuss the general setting and climate, and then the analytical methods used in this study. Subsequently, we provide the results of our petrology and clay mineralogy studies. Lastly, we apply compositional linear modeling and mass balance relationships to assess how elemental mass has been modified throughout the section of sampled regolith.

2. Setting

The approximately 6-m thick vertical section of regolith sampled and analyzed during this study is exposed along the northern bank of

a tributary of the Santa Margarita River at N 33° 26' 1.2" longitude and W 117° 11' 13.7" latitude (Fig. 1). At this location, the exposed section of regolith occurs at the base of a slope with an approximately 12% grade.

The tributary to the Santa Margarita River transects a hilly, rolling transport-limited landscape (Taylor and Eggleton, 2001) covered by variably eroded Alfisols (rhodoxeralfs) of the Las Posas Series (Web Soil Survey, 2014). The Las Posas Series supports annual grasses, forbs, chamise, flat-top buckwheat, and black sage, and is commonly used for dryland pasture and grain along with irrigated citrus and truck crops (Knecht, 1971).

Though the current climate at SMER is characterized as Mediterranean, a number of observations indicate that the sampled section of regolith may have developed over a long period of time. For example, although the exact timing of the down cutting of the Santa Margarita River and its tributaries is uncertain, geochronologic data derived from river terraces suggest that Los Flores Creek, the next major drainage to the north, formed during the world wide sea level drop 24,000 to 8000 years ago (Fig. 1) (Pearl and Waters, 1999). If the Santa Margarita River and its tributaries existed at this time, then it is likely that the drop in base level resulted in their entrenchment. Such an interpretation implies exhumation and exposure during the Pleistocene. However, an even earlier history cannot be ruled out (Girty et al., 2013). In short, the weathering patterns established in this study likely reflect changes within the regolith over a broad time frame that is at least 24,000 to 8000 years in duration. During this time interval, the climate of the Peninsular Ranges likely experienced cooler and wetter climates within the Younger Dryas event, 10.5 ka years ago, and during Heinrich events H_2 and H_1 , 21.0 ka and 14.5 ka years ago respectively, but was otherwise generally dry and warm throughout the Holocene (Bell et al., 1998).

3. Methods

3.1. Field sampling

In this paper, we utilize the term saprock when referring to in situ slightly weathered bedrock in which <20% of the weatherable minerals are altered (Anand and Paine, 2002). At the sampling site, saprock is friable and disaggregates readily under mild hand pressure. In contrast, saprolite, though not present in the section of regolith that we studied, refers to weathered bedrock in which >20% of the weatherable minerals are altered. Spheroidal to ellipsoidal enclaves of unweathered bedrock enclosed in saprock are referred to as corestones.

Within the approximately 6-m thick section of regolith and corestone investigated during this study (Fig. 2), large corestones with diameters between 0.5 and 1.0 m are prominent in the lower 3.2 m. Above this 3.2 m depth only two small corestones <0.3 m in size are visible, and the capping Alfisol is approximately 1.0 m thick. Within the studied section of regolith saprock and soil samples were collected at approximately 50 cm vertical intervals (Fig. 2), soil samples were collected from depths of 26 cm to 57 cm and saprock samples were collected from depths of 78 cm to 369 cm. Corestone samples were collected near the base of the outcrop between 340 cm and 471 cm depths. Prior to collecting three soil and 10 saprock samples, the face of the outcrop was cut back at least approximately 30 cm (Fig. 2). Using a chisel, approximately 200 g samples were removed from the outcrop and placed into clean plastic containers. Ten, approximately 100 to 300 g samples of corestone, were collected using a gas powered drill and a 5 lb sledge hammer from three separate ellipsoidal bodies of corestones exposed in the lower 3.2 m of the studied section of regolith. Note that only one of these corestones is visible in Fig. 2.

3.2. Thin sections and point counting

Following sampling for geochemical work, between 200 and 400 g of epoxy was poured into five small approximately 1000 cm^3 basins

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