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Effects of illuviation on the petrology and chemistry of tonalitic saprock

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ABSTRACT

In order to characterize the petrological and chemical effects of illuviation, we collected 14 samples from an ~6.7 m high tonalitic corestone (tor) and 17 samples of saprock from an adjacent ~65 cm deep trench extending laterally ~1.5 m. Based on thin section observations, all saprock samples are characterized by a network of transgranular and intergranular cracks filled or lined with illuviated clay. The silicate mineral framework has been weakly to mildly weathered, and as a result, biotite has been partially transformed into vermiculite and mixed-layer biotite/vermiculite. Plagioclase has been weakly weathered to a dusting of smectite and hornblende has been weakly weathered to Fe- or Mn-oxyhydroxide, or both. The weathering of biotite at the 95% confidence level translates into a 6 ± 4% loss of K mass. In contrast, the weathering of plagioclase resulted in no statistically significant loss of Ca or Na mass. At the 95% confidence level, 38 ± 5% loss of Ba mass is likely due to the weathering of biotite.

The above effects of eluviation contrast markedly with the statistically significant additions of Si, Al, Fe, Mn, Ti, Sc, Cr, Cu, Rb, Y, and Yb mass produced by illuviation. Such additions at the 95% confidence level translate into an overall statistically significant 12.5 ± 3.6% increase in bulk mass. The above increases in elemental and bulk mass are a reflection of eluvial processes operating in the overlying section of regolith removed by erosion. Within that overlying section, kaolinite; minute particles of biotite, hornblende, and ilmenite; and ions derived from leaching of these mineral were suspended into downward percolating fluids.

On centered p(A)-p(CN)-p(K) ternary diagrams, illuviation resulted in a well-defined compositional linear trend anchored by the geometric mean of the corestone samples and the projected composition of kaolinite at the p(A) apex. Notably, this trend is unlike that documented for biotite-controlled and plagioclase-controlled weathering.

1. Introduction

Weathering profiles derived from granitic rocks commonly grade upward from unweathered granite into saprock, saprolite, and soil (Nesbitt et al., 1997; Nesbitt and Markovics, 1997). The unweathered granitic basement is fractured to varying degrees and in the overlying weathering profile is represented by ellipsoidal to spheroidal unweathered enclaves referred to as corestones. Such bodies generally become smaller and sparser upwards, and often project above the land surface as tors. Of the weatherable minerals <20% are altered in saprock. In saprolite >20% are affected by chemical weathering (Anand and Paine, 2002; Graham et al., 2010).

Girty et al. (2013) showed that the weathering of granitic rocks commonly follows either biotite- or plagioclase-controlled compositional linear trends in centered molar A–CN–K compositional space (Fig. 1). As described in a later section of this paper, A–CN–K compositions are derived from the molar proportions of Al_2O_3, $CaO^* + Na_2O$, and K_2O, and are useful in tracking the alteration of common, weatherable minerals such as plagioclase and biotite. They speculated that the biotite-controlled compositional linear trend dominated in the weathering of K-feldspar absent or poor granitic rocks such as tonalite, quartz diorite, quartz gabbro, diorite, and gabbro. In contrast, the plagioclase-controlled compositional linear trend was thought to be more prevalent during the weathering of K-feldspar rich rocks such as granodiorite and granite (e.g. Nesbitt and Markovics, 1997; Nesbitt and Young, 1984, 1989). As illustrated in Fig. 1, the former trend is characterized by a loss of K mass while the latter reflects the loss of Ca and Na mass. Such losses are the result of the transformation of biotite to hydrobiotite, vermiculite, or mixed-layer biotite/vermiculite, and the incongruent leaching of Ca and Na mass as plagioclase is converted to mixed-layer illite/smectite or smectite. A wide range of petrological, chemical, experimental, and theoretical data support these general ideas (e.g., Bornyasz et al., 2005; Busenberg and Clemency, 1976; Dove and Elston, 1992; Drever, 1988; Garrels and Christ, 1965; Girty et al., 2014; Graham et al., 2010; Holdren and Speyer, 1985, 1987; Isherwood and Street, 1976; Kendrick and Graham, 2004; Nesbitt and Markovics, 1997; Nesbitt and Young, 1984, 1989; Nesbitt et al., 1980, 1997; Nesbitt, 1979;

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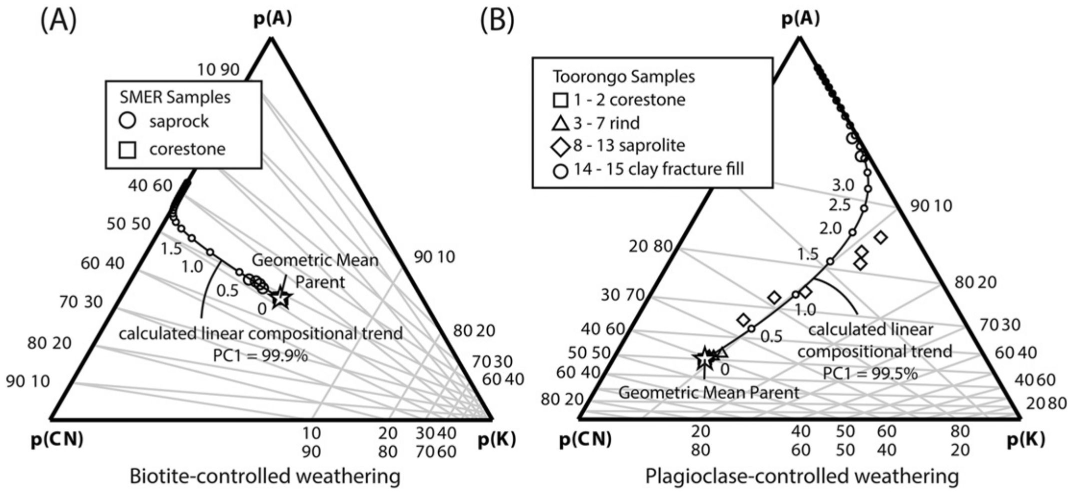

Fig. 1. (A) Example of a biotite-controlled weathering pattern derived from tonalitic regolith. Data are from Girty et al. (2013). SMER = Santa Margarita Ecological Reserve. (B) Example of plagioclase-controlled weathering pattern derived from granodioritic regolith. Data are from Nesbitt and Young (1984, 1989).

Parizek and Girty, 2014; Reuss and Johnson, 1985; Wahrhaftig, 1965; White et al., 2001; Yokoyama and Matsukura, 2006).

Eluviation, i.e., the suspension of particles and ions into downward percolating fluids, is the primary mechanism controlling the weathering trends shown in Fig. 1 (Nesbitt et al., 1997; Nesbitt and Markovics, 1997). As a variety of reactions between the downward moving fluids and the enclosing silicate mineral framework occur, suspended particles are deposited and ions are adsorbed or exchanged as illuviation takes place (e.g., Birkeland, 1999; Garrels and Christ, 1965). How such additions affect the compositions of tonalitic saprock is the focus of this paper. In the following pages we provide petrologic and clay mineralogic data to frame the context of our study, and then evaluate the effects of illuviation utilizing the chemical index of alteration and classical molar A–CN–K relationships (e.g., Nesbitt and Young, 1984, 1989). We then use the non-central principal component analytical technique of von Eynatten et al. (2003) to derive and assess the statistical significance of the centered A–CN–K compositional linear trend that explains much of the variation in saprock samples produced by illuviation. In light of these results, changes in elemental and bulk mass are then evaluated. Work reported here suggests that illuviation results in a unique linear compositional trend that is unlike that produced by biotite- or plagioclase-controlled weathering. All uncertainty boundaries cited in this paper are at the 95% confidence level.

2. Site characteristics

The study site is located at 33° 31′ 2.00″ N and 116° 54′ 24.67″ W, ~0.9 km SE of Roundtop, a small but prominent hill located within the USGS Sage 7.5′ quadrangle (Fig. 2). Located along the margin of the Pacific plate and within the structural block lying between the San Jacinto fault to the east and the Elsinore fault to the west (Fig. 2), the landscape in and around the study site contains many exhumed to partially exhumed corestones. Some corestones are precariously balanced on pedestals and have been used to map the effects of ground shaking during earthquakes (Brune et al., 2006). Using ^{10}Be cosmogenic dating, a precariously balanced rock near Roundtop was estimated to have been exposed ~35,000 years ago (Rood et al., 2012). Such results are consistent with the idea that much of the regolith of the Peninsular Ranges, including that at the study site, may have been exhumed during the late Pleistocene when pluvial conditions dominated the region (Grant Ludwig et al., 2009), but do not rule out the likely possibility of an even older genesis.

Gauging from the nearest comparable weathering stations, the climate in and around the region enclosing the study site is classified as Mediterranean with temperatures ranging from ~8 °C to 28 °C and an average annual precipitation of ~27 cm to 31 cm (Western Regional Climate Center, 2014). Vegetation includes chamise, brome, California sagebrush, Ceanothus, manzanita, purple tussockgrass, squirreltail, and fescue (Wachtell, 1978).

3. Methods

3.1. Field

Hornblende-biotite tonalite of the Cretaceous Coahuilla Valley pluton (Morton and Kennedy, 2005; Sharp, 1967) underlies the study site (Fig. 2). The ellipsoidal corestone sampled during this study extends ~6.7 m above a land surface characterized by sparse vegetation and ≤36 cm of eroded Entisols (Typic Xerorthents) composed of rocky sandy loam (Wachtell, 1978) (Fig. 3). It therefore follows that for the corestone to be exposed at its current level at least ~6.7 m of regolith had to be removed by erosion. Fourteen samples were removed from the NE side of the corestone using a gas powered drill. Using a hammer and chisel, 17 saprock samples were extracted from an ~1.5 m long trench extending perpendicular to the interface between corestone and saprock at depths between ~36 and ~65 cm. After extraction of saprock samples for geochemistry, a low viscosity resin was poured into the trench and allowed to solidify overnight. The artificially impregnated saprock was then collected and returned to the laboratory for thin section study. A saprock sample for clay analysis was collected from the northern wall of the trench at ~44 cm depth at a distance of ~1.2 m from the interface between saprock and corestone.

3.2. Thin sections and point counting

Representative samples of saprock (n = 5) and corestone (n = 9) were cut into thin section billets. Both sets of thin sections were chemically stained with sodium cobaltinitrite ($Na_3Co(NO_2)_6$) to distinguish K-feldspar from plagioclase. The mineralogy and crack characteristics in each thin section were determined by identifying the mineral or textural feature at 300 regularly-spaced points at a grid spacing of ~1.5 mm. Resulting data are presented in Tables 1 and 2 and reflect the percentages of points landing on each mineral or textural category.

3.3. Clay mineralogy

The <2 μm fraction was separated from the representative saprock sample following procedures outlined in Moore and Reynolds (1997). From this fraction, a sample was Mg-saturated and transferred to a slide using the Millipore transfer-filter method described in Moore