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# Unravelling the development of a spheroidally weathered diorite-gabbro, Santa Margarita Ecological Reserve, Peninsular Ranges, southern California, USA

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A B S T R A C T

Within Santa Margarita Ecological Reserve (SMER), southern California, an ~108 Ma diorite-gabbro pluton has weathered spheroidally resulting in the formation of concentric rindlets, i.e., a rindlet zone, around an unaltered ellipsoidal core of the parent rock. To our knowledge little is known about how spheroidal weathering is produced in Mediterranean climates like that characteristic of portions of the Peninsular Ranges. Hence, we undertook a detailed study aimed at determining the textural and chemical changes associated with the spheroidal weathering of the diorite-gabbro pluton.

The parental spheroidally weathered corestone is characterized by a hypidomorphic-granular texture, and consists primarily of plagioclase, amphibole, and biotite, along with minor amounts of pyroxene and quartz. Within the corestone, sericite, and uncommonly, calcite and chlorite, replace plagioclase. The latter mineral also infrequently replaces portions of amphibole and biotite. Such alteration products are derived from sub-solidus deuteric alteration of the pluton.

XRD clay mineral analysis of the 13 rindlets indicates the presence of mostly kaolinite and vermiculite, and a far lesser volume of green smectite. Thin section study of rindlet samples suggests that vermiculite is derived from the weathering of biotite, the most extensively altered mineral in the rindlet zone. Such alteration is paralleled by statistically significant losses of K mass across the rindlet zone. In addition, statistically significant losses of Ca and Na mass across the rindlet zone, likely reflect conversion of sericite to kaolinite. In contrast, the absence of statistically significant losses of Mg, Fe, and Mn over most of the rindlet zone, implies that fluids were mostly oxidizing, and that any Mg leached from amphibole was likely fixed within smectite, while leached Fe and Mn precipitated out as oxides or oxyhydroxides. Though calcite was present in the corestone, its absence in the rindlets indicates that fluids were sufficiently acidic to dissolve and remove it.

Previous studies have shown that spheroidal weathering occurs when volume expansion produced by a positive ΔV of reaction builds up internal elastic strain energy in the rock. For example, this type of reaction occurs when iron oxidizes within biotite resulting in an expansion of d(001) from 10 Å to 10.5 Å, or when biotite is transformed into vermiculite leading to an expansion of d(001) from 10 Å to 14 Å. Data presented here suggest that the conversion of biotite to vermiculite, and the resulting positive ΔV produced the spheroidal fracturing of the corestone at SMER. Hence, these and other data discussed in this paper suggest that the weathering of biotite is the primary driving force in the formation of spheroidally weathered corestone in the Mediterranean climate of the Peninsular Ranges.

## 1. Introduction

Though our understanding of how various types of granitoids respond to chemical and physical weathering has advanced considerably over the last decade (e.g., Taboada et al., 1990; Sequeira Braga et al., 2002; Begonha and Sequeira Braga, 2002; Bornyasz et al., 2005; Martins et al., 2012; Campodonico et al., 2014; Borrelli et al., 2014; Perri et al., 2015, 2016; Mazurier et al., 2016), the processes responsible for spheroidal weathering in Mediterranean climates has received little attention. Spheroidal weathering is defined as a form of chemical and physical weathering that affects fractured bedrock and results in the formation of concentric layers encircling or partially encircling unweathered enclaves of bedrock (e.g., Chapman and Greenfield, 1949; Ollier, 1971; Ferry, 1984; Sarracino and Prasad,

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1989; Fletcher et al., 2006; Buss et al., 2008; Røyne et al., 2008). In this paper, concentric layers will be referred to as rindlets, a set of rindlets bound by through going fractures as bundles, and the entire group of bundles as a rindlet zone.

Fletcher et al. (2006) modeled the spheroidal weathering of a quartz diorite within the hot and tropical environment of the Rio Icacos watershed, Puerto Rico. Their 1-D model coupled physical and chemical processes and showed how diffusion-controlled chemical weathering could generate elastic stresses that drive the concentric fracturing pattern characteristic of spheroidal weathering. Within the same watershed, Buss et al. (2008) later demonstrated that the primary mechanism of fracturing within the quartz diorite was the oxidation of iron within biotite. This process produces positive volume changes ($\Delta V > 0$) that in turn lead to a buildup of internal stresses that eventually lead to brittle failure, and as a result, a fracture delimiting the boundaries of a new rindlet.

The model proposed by Fletcher et al. (2006), and its subsequent modification by Buss et al. (2008), assumes a hot and wet tropical climate, and the concomitant ready availability of oxidizing fluids. Would such a model work in a drier setting like that characteristic of the Peninsular Ranges, southern California, USA, where precipitation is far more variable and typically restricted to winter months? To address this question, we studied a spheroidally weathering biotite-hornblende gabbro-diorite located at N33°26′54.15″ longitude and W117° 10′14.98″ latitude, in the Santa Margarita Ecological Reserve (SMER) within a Mediterranean (hot summer) climate. In and around SMER, average annual precipitation is ~39 cm and the average annual temperature is ~17 °C (Fig. 1) (Weather Currents, 2014). At the study site, the spheroidally weathered ellipsoidal corestone is derived from an ~108 Ma diorite-gabbro (Johnson, 2008), and forms part of a complexly fractured and spheroidally weathered section of regolith overlain by sandy loam (~34 cm thick) (Picasso, 2015) (Fig. 2). The long dimension of the spheroidally weathered corestone is 33 cm whereas its short dimension is 23 cm.

Vegetation at the study site is dominated by a Chaparral plant community including Mountain mahogany (*Cercocarpus betuloides*), Coast live oak (*Quercus agrifolia*), California sagebrush (*Artemisia californica*), California buckwheat (*Eriogonum fasciculatum*), Black sage (*Salvia mellifera*), Chamise (*Adenostoma fasciculatum*), and Chaparral yucca (*Hesperoyucca whipplei*), along with various genera of the grass family (Lightner, 2011; Picasso, 2015).

## 2. Field setting

Within the outcrop investigated during this study, a hierarchical set of fractures are well developed. If early formed fractures represent a free surface, i.e., a surface of no cohesion or strength, then later formed fractures cannot propagate across them (Bohn et al., 2005; Twiss and Moores, 2007). Using this principle as a guide, in Fig. 2, the relative ages of fractures are shown with decreasing line width, and each fracture set is labeled, from oldest to youngest, 1 through 5. Notably, the 5 sets of fractures appear to have formed sequentially, and subdivide the outcrop into 15 polygonal subdomains, each characterized by a spherical or partial-spherical fracture pattern surrounding or partially surrounding a corestone. An additional 3 subdomains along the base of the outcrop studied during this investigation are incompletely exposed.

As shown in Fig. 2, the earliest fractures tend to be longer than later fractures and are assigned to sets 1a and 1b. The former set strikes between N04E and N19E, and dips 74–85° NW and SE, whereas those assigned to the latter set strike between N21E and N51E and dip 50–53° NW. Notably, at some locations fractures assigned to set 1a abut against fractures assigned to 1b, but at other locations fractures assigned to 1b abut against those assigned to 1a. Such observations imply that the two sets formed contemporaneously and are therefore conjugates. Though this set of fractures may have formed from tectonic stresses generated during uplift and exposure of the Peninsular Ranges batholith, as described below the hierarchical nature of fracture sets 2 through 5 are indicative of locally generated stresses. The most likely source of such stresses is volume changes caused by chemical weathering (Røyne et al., 2008; Jamtveit et al., 2009).

Following development of fracture sets 1a and 1b, the N79E striking, 35° NW dipping fracture of set 2 developed (Fig. 2). This fracture meets fractures of set 1a at T-junctions; i.e., at an ~90° angle. Fractures striking between NS and N42W and dipping between 21° and 57° E or NE are assigned to set 3 (Fig. 2). They tend to meet fractures of set 1b at T-junctures. In contrast, fracture set 4 strikes ~N61E and dips ~88 SE. Intersections of fractures belonging to sets 3 and 4, also tend to meet at T-junctions. Fracture set 5, the youngest set in the studied outcrop, is represented by one NW striking moderately NE dipping fracture that is confined to the spheroidally weathered corestone that is the focus of this study (Fig. 2).

The above pattern of fracture development and spheroidal weathering is characteristic of reaction-induced hierarchical fracturing (Røyne et al., 2008; Jamtveit et al., 2009). In such systems, fractures of differing generations tend to intersect at angles close to 90° (T-junctions) resulting in polygons dominated by four-sided domains (Bohn et al., 2005; Jamtveit et al., 2009). Within this context, fluids percolating through the time transgressive fracture network focus weathering intensity on the angular corners of intersecting fractures. Thus, rindlet zones like the one sampled during this study reflect spallation and rounding of the angular corners of blocks produced by intersecting fracture networks generated by local stresses driven by reaction induced positive volumetric changes (Fig. 2) (Røyne et al., 2008).

## 3. Field methods

A large section of the corestone (~800 g) was removed with a hammer and chisel. Subsequently, this large fragment was subdivided into four parts for thin section and chemical analysis.

A large section of the SW part of the rindlet zone was removed carefully from the outcrop using a chisel and hammer (Figs. 2 and 3). Fractures within the sampled rindlet zone are either long and through going or short and confined to areas bounded by the long through going fractures. The long and through going fractures control the dominate fracture anisotropy of the rindlet zone, and either extend completely or at least half-way across the sampled rindlet zone (Fig. 3). They are therefore referred to as bundle bounding fractures. Each bundle bounded by a long and through going fracture is labeled from outermost to innermost I through V (Fig. 3). In a similar manner, long and through going fractures are labeled 1 through 5. At the macroscopic and microscopic scales, there is no evidence for shearing during development of either bundle bounding fractures or shorter fractures confined to individual bundles; hence, they are largely or entirely Mode I extensional cracks (Twiss and Moores, 2007).

As noted in the previous section of this paper, if early formed fractures represent a free surface, then later formed fractures cannot propagate across them (Twiss and Moores, 2007). Using this idea, a relative order of timing can be approximated for the 5 bundle bounding fractures. For example, fracture 2 did not propagate across fracture 1 and as a result, it must have formed after fracture 1 (Fig. 3). Similarly, fracture 3, the innermost boundary of bundle III, did not propagate across fracture 2; thus, it is younger than fracture 2. Though similar evidence is not available for fractures 4 and 5 which bound bundles IV and V, the position of these bundles within the inner part of the sampled rindlet zone closest to the corestone (Fig. 3), implies that they formed relatively late in the history of the sampled rindlet zone (e.g., Fletcher et al., 2006; Buss et al., 2008). The above observations suggest that the bundle bounding fractures propagated sequentially inward over time. In contrast, shorter fractures occur entirely within each bundle and do not extend across bundle bounding fractures (Fig. 3). They therefore must have occurred after bundle formation. They appear to reflect a mechanism that allowed fluids to access the internal parts of