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The effect of fractures on weathering of igneous and volcaniclastic sedimentary rocks in the Puerto Rican tropical rain forest

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Abstract

Just as microscopic observations show that minerals dissolve quickly at sites where defects intersect the water-crystal interface and dissolve slowly at zones of perfect lattice structure, weathering rates also vary across a landscape. Specifically, at landscape scale, dissolution (weathering) occurs faster where defects (fractures) intersect the land surface, and slower in unfractured zones. In the rain forest of Puerto Rico, for example, we used ground penetrating radar to document how deep fracture zones allow meteoric waters to accelerate weathering in the Luquillo Mountains. The mountains comprise a metamorphic aureole complex where a quartz diorite pluton intruded into volcaniclastic sedimentary country rock. In the only watershed that has incised deeply into the quartz diorite (Río Icacos), water infiltrates slowly through areas without deep fractures and penetrates more deeply into fractured zones that criss-cross the landscape. These deep fracture zones contain weathered granular material, spheroidally weathered corestones, and waters with higher Si concentrations, [Si]. In the areas between fracture zones, the flowpaths are shallower, intersecting only weathered granular material and perhaps a single corestone, and are characterized by lower [Si]. In contrast, in the volcaniclastic sedimentary rocks, fractures are distributed more homogeneously. Penetration of water in those rocks is thus more homogeneous at the landscape scale. Weathering controlled release rates of Si were estimated using residence times of surface and groundwater based on tritium concentrations, [^{3}H]. The Si weathering release rates are higher for waters that have penetrated to deeper depths as expected if fractures accelerate weathering at depth by providing both preferential hydrologic flowpaths and access to highly soluble Si-containing mineral phases.

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Keywords: weathering; fractures; groundwater; dissolved silicon; tritium; Luquillo Mountains

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1. Introduction

The Luquillo Mountains comprise a metamorphic aureole complex formed when quartz diorite intruded into volcaniclastic country rock. Weathering and erosion of the complex has been the focus of study for many years[1,2]. Of particular interest are the catchments of the i) Río Icacos that has cut through the overlying sedimentary rock, the hornfels-facies aureole, and into the quartz diorite, and ii) the Río Mameyes which mostly has incised the volcaniclastic sedimentary rocks. Weathering of the igneous pluton is characterized by formation of spherical corestones (spheroidal weathering) while weathering of the volcaniclastics produces angular corestones. Previous research has established that subvertical features, presumably fracture sets, allow meteoric water access into the quartz diorite[3]. Here, we present groundwater chemistry and geophysical measurements to assess the architecture of flow in the Quebrada Guaba sub-catchment of the Río Icacos watershed, and in the Bisley sub-catchment of the Río Mameyes watershed. Geophysical observations document the physical structure of these two watersheds on different lithologies while water chemistry focused on groundwater wells throughout the Luquillo Mountains provides context for small scale variations in groundwater residence time and Si release rate.

2. Methods

Surface water and a seep were sampled in and adjacent to the Quebrada Guaba drainage (Río Icacos watershed), and groundwater was sampled from wells in the Río Icacos and Río Mameyes watersheds. Quebrada Guaba was chosen because it is the site of numerous previous studies of weathering and groundwater and is located within 100 m of cored saprolite and bedrock taken from well LGW1. Water at Guaba discharges mostly from void spaces between corestone-filled gullies. Dissolved silicon in water samples, [Si] (±2–5%), was measured by inductively coupled plasma atomic emission spectroscopy. Data are only presented for samples collected when discharge at the Río Icacos stream gauge had been less than the median discharge the day before and the day of sampling. At each site, one sample was analyzed for tritium [^{3}H] by helium ingrowth[4]. Data are presented in tritium units (TU; equivalent to one tritium atom per 10^{18} hydrogen atoms). The radioactive decay equation is used to calculate mean residence time (MRT) for water samples assuming a constant input of [^{3}H] in precipitation ranging from 1.01–1.25 TU since the early 1990s. Age estimates derived from this range of input values were calculated assuming both piston flow (PFM) and an exponential (EM) distribution of flow lines[5].

Ground penetrating radar (GPR) uses a transmitting antenna (Tx) to generate a high-frequency electromagnetic wave (EMW) that penetrates the subsurface and is returned to a receiving antenna (Rx) as a sequence of reflections from interfaces[6]. The velocity of this EMW is primarily controlled by the relative dielectric permittivity (ε_r) of the subsurface media, a property strongly dependent on the geological material properties such as water content. Lack of reflections at certain depth may be due to either a lack of interfaces (i.e. unfractured, homogenous material), or signal attenuation. In turn, signal attenuation occurs because of energy losses with depth or conduction losses related to changes in electrical conductivity. Therefore, EMW do not propagate efficiently through materials such as clays with high cation exchange capacity, CEC (e.g. smectite and vermiculite)[7]. Porous material with high CEC clays dissipate most of the EMW energy as heat, attenuating the signal and showing a dramatic reduction in depth of penetration[8]. If a material is magnetic, the signal also attenuates quickly[6].

Surveys were measured using 100 MHz unshielded antennas. Trace spacing was 0.2 m, with sixteen stacks per trace, and a sampling time window ranging of ~900 ns. Velocities at each site were determined from additional common midpoint surveys. Data were processing included: a) a “dewow” filter over a 10ns time-window; b), application of a time-varying gain; c) a bandpass filter; and d) a static correction. Surveys were completed along a transect in Río Icacos intersecting LGW1 and along one in the Bisley catchment intersecting two boreholes.

3. Results

Monitoring of groundwater wells throughout the Luquillo Mountains from 2012–2016 demonstrates variation in [Si] greater than analytical precision (Table 1). Both [Si] and [^{3}H] in groundwater are depth dependent (Figure 1).

Common offset GPR profiles collected in the two watersheds can be compared with observations from boreholes at the study sites (Figure 2). The Bisley boreholes are characterized by an alternating sequence of fractured rock and regolith which yields a laterally continuous GPR profile that extends to ~12–14 m depth. In comparison; there is significant lateral variability in the Río Icacos profile (Figure 2b). Areas with very weak reflections correspond to saprolite overlying relatively shallow bedrock, (e.g., at the LGW1 well), and are interspersed with vertical zones of enhanced reflections that extend to at least 16 m depth, such as those between 120–130 m and 145–160 m.

Table 1. Dissolved Silicon and Tritium Concentrations for Groundwater samples in the Luquillo Mountains, Puerto Rico

Sample Description			[Si]			[^{3}H]		MRT*		
name	type	depth (m)	n	(μM)	1σ	(TU)	err	min.	max.	pref.
Quebrada Guaba[†]	stream	0	10	307	19	1.01	0.04	0.0	4.3	1.6
Guaba slide[†]	seep	0	22	310	32	0.96	0.04	0.7	5.4	2.6
LGW1	well	6	40	253	12	0.82	0.04	3.5	9.4	6.1
LGW2B	well	16	24	342	24	0.92	0.04	1.5	6.4	3.5
LGW2C	well	18	41	391	25	0.94	0.03	1.1	5.9	3.1
EP1	well	35	24	583	31	0.80	0.05	4.0	10.1	6.8
Caimitillo[#]	well	51	7	623	20	0.81	0.04	3.7	9.6	6.3
Palo Colorado[#]	well	54	5	708	34	0.84	0.04	3.1	8.8	5.6
Aviary[#]	well	77	3	763	22	0.60	0.04	9.1	19.5	15.0

*Mean Residence Time (MRT) in years, calculated using a range of values for precipitation (1.01–1.25 TU), and using both PFM and EM. The preferred age was calculated for an initial tritium concentration of 1.1 TU using the exponential model (EM).

[†] Plotted as Guaba seeps/streams in Figure 1.

[#] Plotted as USFS Mam in Figure 1.

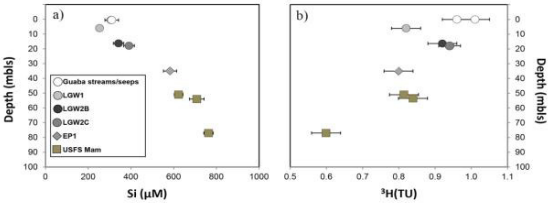

Figure 1. (a) Average [Si] as a function of depth, and (b) [^{3}H] as a function of depth for groundwater and surface water in the Luquillo Mountains. Both [Si] and [^{3}H] can be interpreted as a function of depth; the relative differences in these values for a given sample allow estimation of Si release rate.

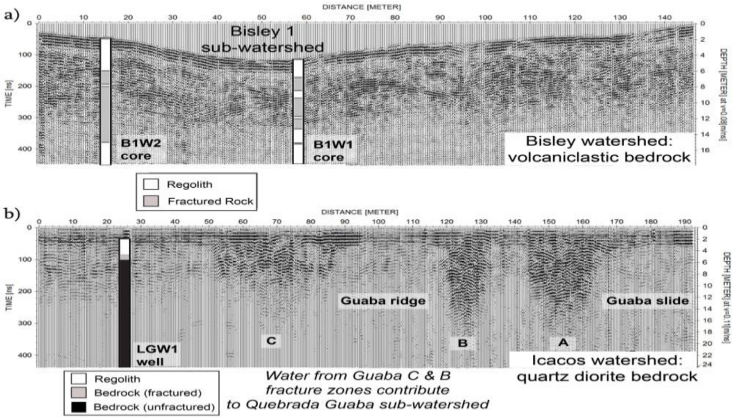

Figure 2. GPR reflector records measured in Bisley (a) and Icacos (b) catchments. Each transect intersected boreholes as shown, allowing direct comparison of drilled material with GPR observations. Material from the LGW1 borehole is described in other work[9]; as is material from the Bisley boreholes[3]. Here, “regolith” refers to granular weathered material. In panel (b), it can be seen that LGW1 is in close proximity to both the Quebrada Guaba stream site and the Guaba slide seep site, as well very close to the well-studied Guaba ridge site[1]. The close proximity of these study sites (Table 1) to each other demonstrates that the deviation from the large scale patterns shown in Figure 1 occurs at a small spatial scale, and is directly related to the presence of fractures zones and their hydrological and geochemical importance in subsurface weathering systems.

4. Discussion

In the Icacos profile (Figure 2b) we interpret the zones of deep reflectors with sharp vertical boundaries as fracture zones bounded by unfractured (non-reflecting) bedrock. Field observations show that granular weathered material is often washed out of the top 5 meter of the fractured zone, perhaps enhancing reflections in those areas. In Bisley the reflector record documents a more laterally continuous distribution of fractured material, granular material (labelled “regolith”), and bedrock. These observations provide context for interpreting water chemistry.

Using mean residence times (Table 1); we estimated simple downward vertical velocities to range from 4.6–9.8 m/year for all wells except LGW1. This well, sited on an interfluve between deeply weathered fracture zones (Figure 2b), intersected saprolite and weathered rock with only unfractured bedrock below ~6 meters[9]. The vertical velocity for water in this well is ~1m/year, consistent with published infiltration rates of the quartz diorite saprolite[1]. Rates of release of Si into groundwater based on MRT span the range of 41–192 µM/year. The highest rate occurs in Quebrada Guaba which discharges water from corestone-filled valleys (developed in fracture zones) and has the highest measured [^{3}H]. The slowest rate occurs <100 m away in the LGW1 well which has the lowest measured [Si] concentration. It is known that Si-containing minerals are largely removed from the quartz diorite-derived regolith[1]. As our data indicate, simple soil-saprolite-bedrock weathering profiles are incapable of accounting for the high [Si] fluxes from the Río Icacos watershed. Instead, we suggest that fracture zones provide rapid hydrologic flowpaths that access soluble Si-containing minerals. As such, these fracture zones are loci of high Si release rates from rock.

5. Conclusions

Fracture zones in quartz diorite are widely spaced but are loci of rock weathering, promoting rapid water transit and high weathering rates and formation of spheroidal corestones. Fractures in the volcaniclastic rocks are more regularly distributed, interconnecting with bedding planes in these sedimentary rocks to promote relatively homogeneous weathering at the landscape scale. The volcaniclastic fracture-dominated media also does not show the strong anisotropies exhibited by the fractured quartz diorite. Fractures accelerate weathering in the Luquillo Mountains and the architecture of the fractures controls the distribution of weathering rates and [Si] in natural water.

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