Standardized Field Methods for the Characterization of Fractures in Subaerially Exposed Natural Rock Studied in the Context Surface Processes

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1. Introduction and Motivation

A wide range of geoscience studies employ crack characteristics observed in natural rock exposures to demonstrate the influence of fractures on processes like channel incision (Shobe et al., 2017), sediment size and production (e.g. Sousa, 2010), hillslope erosion (Neely et al., 2019), built environment degradation (Martinez-Martinez et al., 2013), landslide and rockfall hazards (Collins and Stock, 2016), groundwater and surface water processes (Maffucci et al., 2015) and vegetation (Aich & Gross, 2008). Here we employ the terms ‘fracture’ and ‘crack’ synonymously to mean visible, planar, *open* voids – with no evident lateral offset - at all scales, acknowledging that some fields of geosciences also include filled voids such as veins under the heading of these terms (e.g. Gudmundsson, 2011; Gomez and Laubach, 2006). Here we focus on open voids with the assertion that within the field of geomorphology open fractures are of interest because they directly influence subsequent water flow, erosion, or erodibility of any broken rock mass.

Although some rock crack characterization field methods exist in the context of structural geology, aquifer and reservoir characterization (e.g. Zeeb et al., 2013; Gudmundsson, 2011), they diverge significantly in their approaches and detail because they are largely developed for the particular application of each unique study. The methods for fracture quantification, particularly in the context of geomorphology, weathering and soil-based studies, vary wildly, and many studies lack specified decision-making criteria of sufficient detail to reproduce methods. For example, without a precise definition of what constitutes a measurable fracture, two people will inevitably measure different groups of features of the same rock!

The dearth of standardized methodology in quantifying fractures in the context of natural rock exposures and geomorphology research is in contrast with other components of Earth system field-based research like sedimentology or soil science. These disciplines have clear, standardized methods to acquire well-defined suites of data that constitute the “basic” data for characterizing their respective aspects of the Earth. Although numerous techniques for describing overall surface weathering of rock (e.g. related to roughness, ring vs. thud, or through non-destructive testing like Schmidt hammer (e.g. reviewed in Moses et al., 2014), within the geomorphology and weathering sciences no such common suite of data or methods has been defined or described that comprises an analysis of fractures beyond those that might typically be examined in a study of ‘joints’. It is in fact rare that studies of joints provide clear geometric criterion for choosing the fractures to measure – other than having several in parallel along scanlines (e.g. Ewan et al., 1983). Yet, environmental stresses also produce parallel fractures (McFadden et al., 2005; Aldred et al., 2016). Large-scale tectonic stresses inevitably combine with those of topography and the environment to contribute to the growth of all fractures as rocks are exhumed and approach Earth’s surface. Thus, here we argue that the difference between fractures defined as tectonically-induced ‘joints’ and those under the heading of ‘mechanical weathering’ cannot be fully decoupled.

With this abstract we introduce a proposed field guide that will leverage over 20 years of field-based crack-observation research (e.g. McFadden et al., 2005; Eppes et al., 2018) to: 1) define a standard suite of crack and rock data measurements that constitute “basic” field-based metrics to describe mechanical weathering in naturally exposed rocks and 2) detail best practices for collection of these data both from our experience and from existing studies. We limit the discussion here to field observations - cracks that can be observed with the naked eye or basic hand lens – and **we ask for feedback from PRF2022 conference attendees to help us make the field guide a practicable field tool for a broad audience.**

2. Guiding Principles and Concepts

Rocks fracture in response to the complex sum of all tectonic (Martel, 2006), topographic (Moon et al., 2020), and environment-related (Murton et al., 2006) stresses they experience. Importantly, if we assert most natural cracking to be subcritical in nature (e.g. Eppes and Keanini, 2017), climate matters twice– both in contributing to the stresses that the rock experiences, but also in contributing to the chemo-physical processes that actually break bonds at crack tips as cracks propagate. Thus all potential driving stresses – and variations in crack environment - must be considered in study design and site selection, similar to how all Factors of Soil Formation (Jenny, 1994) are considered in any soil science study.

2.1 Site selection and study design – a tried and true 'state factor' approach

We recommend employing the well-vetted weathering 'State Factor' approach (Jenny, 1994) when considering the design for any mechanical weathering study, whereby all factors that contribute to weathering and fracture must be considered and controlled for in so much as possible, prior to comparing data between sites. These factors have long been categorized (e.g. Jenny, 1994) as climate (cl, both regional climate and microclimate), organisms (o, flora and fauna), relief (r, topography at all scales), parent material (p, lithology) and time (t, exposure age, or exhumation/erosion rate). For mechanical weathering, tectonics (t) should be added to this list – making cl,o,r,p,t^2. For rock fracture, it is important to understand how each cl,o,r,p,t^2 factor may contribute *both* to stresses that give rise to cracking, *and* to the molecular-scale processes that serve to subcritically break bonds at crack tips (e.g. Eppes et al., 2020; Eppes and Keanini, 2017). Each has the potential to independently impact the rates, styles and processes of crack propagation.

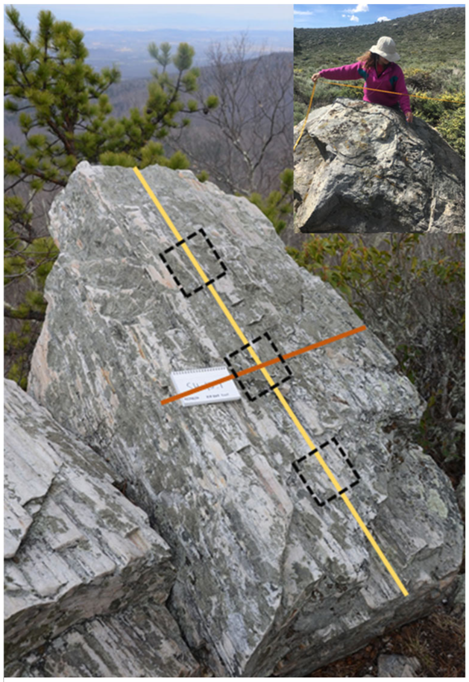

Figure 1. Example of establishing a non-biased set of locations for measurements of cracks within 'windows' on a large outcrop or boulder. A simple method is to bisect the length and width of the surface of measurement, and locate 'windows' at even increments within the length.

3. Methodological Premises

3.1 Outcrops versus Clasts

If researchers choose to focus on in situ bedrock, tectonic, topographic and environmental stresses have likely contributed to the observed fracture network – including those related to erosion rates (Leith et al., 2014). Thus, for studies that aim to isolate fractures associated with environmental stress, measurements from clasts may be more useful. Clasts that have been transported by fluvial, glacial, or mass-wasting processes sufficiently to abrade away pre-existing superficial fractures may be more reasonably considered 'fresh', than an outcrop with an unknown exhumation history. This idea of fracture "resetting" within clasts by transport is supported by data showing clasts of identical rock type that have experienced more transport (i.e. rounded river rocks) have higher strength than those found in, for example, talus slopes (Olsen et al., 2020).

3.2 Outcrop or Clast Selection Criteria

Once a specific site is selected, criteria must be developed for identifying which outcrops or surface clasts within the site will be employed for measurement. In general, characteristics of the boulders or outcrops that might impact mechanical properties, moisture or thermal stress-loading are those that should be most heavily considered – given their ubiquitous potential influence on all subaerial cracking, regardless of other sources of stress-loading (e.g. salt precipitation or freezing). In past work, for example, we have focused on upward facing surfaces of outcrops or large clasts (e.g. Eppes et al., 2018). For loose clasts, perhaps only clasts of a particular size or rock type might be of interest, noting that below about 5 cm diameter in semi-arid and arid environments (Eppes et al., 2010), and 15 cm in more temperate environments with vegetation (Aldred et al., 2016) the long-term stability of the positioning of the clast on the surface becomes questionable. Rock type properties that should be considered when developing selection criteria include not only heterogeneities like bedding or foliation, but also grain size and mineralogy, all of which can influence cracking characteristics.

When it is not feasible to measure every crack on an outcrop or large clast, data collection within predetermined “windows’ – small areas defined on a rock’s surface (Fig. 1) - has been demonstrated to result in the most accurate representation of fractures on an entire outcrop – as opposed to more commonly employed scanline method (e.g. (Zeeb et al., 2013). When clasts are being used for measurements, the well-vetted Wolman Pebble Count transect may be employed for clast selection in order to avoid sampling bias.

3.3 How many rocks? How many cracks?

In further considering the number of sites to examine, or the number of outcrops or boulders within each site, the extent to which each factor must be controlled for must be considered. In general, the number of boulders or outcrops characterized will vary with the study goals, site complexity, and the variables being tested or controlled. In past work, when tectonics, climate, relief and organisms were carefully controlled for, relationships between rock material properties and rock cracking properties were evident from about 3-10 outcrops per rock type (Eppes et al., 2018). Around 50 clasts per rock type appears to produce statistically meaningful results, but 100 clasts per site or rock type allows for more careful examination of crack size distributions. Sufficient numbers of cracks should be measured for any site, outcrop(s) or feature of interest such that a power-law distribution in crack length is evident in the data - generally on the order of 10^2 cracks are required (e.g. Zeeb et al., 2013).

3.4 The use of semi-quantitative indices

We have established indices for various observations following a model of similar existing semi-quantitative methods commonly employed in both soil sciences (e.g. Soil Survey Staff, 1999) and geology (e.g. rounding and sorting). The use of indices, rather than a precise measurement, is especially appropriate for cracking features, given the natural variation between different rocks, and the daunting number of measurements that would be required to accurately quantify, for example, something like total number of very small cracks. One particularly useful index is ‘few, common, many’ whereby the average number of an object within any given area of a designated size across the rock face or window is noted.

4. Proposed Suite of Standard Measurements

4.1. Rock Measurements

To fully interpret rock cracking information, rock information is also required. We propose a suite of standard rock metrics – with details for describing them that will be provided in the final field guide - that should always be recorded for each location (window or clast) where cracks are measured (Table 1). This list is based on rock characteristics known from the literature to influence cracking in exposed rocks, and/or that are needed for certain standard crack morphology calculations. Some cracking characteristics not captured in individual crack measurements are also included. This list can – and should – be added to if other variables are of interest or relevance for the specific research question or study area.

4.2. Crack Measurements

We propose a suite of crack metrics – with details for measuring them to be provided in the final field guide - that should always be recorded for each visible crack (open, planar longer than it is wide) >2 cm in length (Table 1). This 2 cm cutoff is based on our experience whereby precise measures of metrics cannot be reliably obtained on smaller cracks. Furthermore, all such cracks – including small ones – inevitably influence surface processes. The list of measured crack features can – and should – be added to if other variables are of relevance for the specific research question or study area.

5. PRF2022 – Feedback requested.

We readily acknowledge that there is a broad range of workers who have been making field observations of fractures much longer than us. We want this field guide to be 1) practicable for covering the collection of all ‘basic’ data related to rock fracture and importantly 2) of sufficient detail and thus replicable by any reader so that measurements made following its directions might be compared across studies. We welcome any feedback you may provide towards those aims.

Table 1. List of Proposed Standard Observations for the observed rock area and for all cracks >2 cm in length

Rock Observations	Crack Observations
Area of observation Rock Type Grain Size Mineralogy % (minimally felsic vs. mafic) Sphericity of Exposure Roundness of Exposure Fabric Description: stike, dip, type (i.e. vein, foliation, bedding) Evidence of Granular Disintegration: define an index Evidence of Pitting: define an index Lichen or Varnish: %	Length: surface exposure length measured with a flexible tape Width: most dominant width as measured with crack comparator or calipers Strike: right hand rule preferred Dip: 0-90 degrees Parallelism: Note features parallel to crack (fabric, rock faces) Weathering characteristics: an index of rounded edges where 1 = entirely sharp, fresh edges; 2=mostly sharp edges, some rounding; 3 = mostly rounded edges, some sharp; 4= entirely rounded edges “Sheet Height”: the thickness of what would be the detached spall or sheet of rock, If crack is surface parallel and it were to detach the rock surface

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