Introducing standardized field methods for fracture-focused surface processes research

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Abstract. Rock fractures comprise a key contributor to a broad array of Earth surface processes due to their direct control on rock strength as well as rock porosity and permeability. However, to date, there has been no standardization for the quantification of rock fractures in surface processes research. In this work, the case is made for standardization within fracture-focused research and prior work is reviewed to identify various key datasets and methodologies. Then, a suite of standardized methods is presented as a 'baseline' for fracture-based research in surface processes studies. These methods have been shown in preexisting work from structural geology, fracture mechanics, and surface processes disciplines to comprise best practices for the characterization for fractures in clasts and outcrops. These practical, accessible, and detailed methods can be readily employed across all fracture-focused weathering and geomorphology applications. The wide adoption of a baseline of data collected using the same methods will enable comparison and compilation of datasets among studies globally and will ultimately lead to a better understanding of the links and feedbacks between rock fracture and landscape evolution.

Short Summary. All rocks have cracks that can influence virtually every process acting on Earth's surface where humans live. Yet, scientists have not standardized their methods for collecting crack data. Here we draw on past work across geo-disciplines to show why standardization is important and propose a list of baseline data for fracture-focused surface processes research. We detail its rationale and the methods for collecting it. We hope its wide adoption will improve knowledge of rock fracture overall.

1 Introduction

Rock fracture in surface and near-surface environments plays a key role in virtually all Earth surface processes. The propagation of opening-mode fractures in universally occurs at or near the surface of Earth (e.g., within ~500 m - Moon et al., 2020), on other terrestrial bodies (Molaro et al., 2020), and at depth in the crust (e.g., Laubach et al., 2019). It epitomizes mechanical weathering and the development of 'critical zone architecture', i.e., the evolving porosity, permeability, and strength of near-surface rock (e.g., Riebe et al., 2021). For clarity and consistency herein, the use of the term fracture is limited to refer to any *open,* high-aspect ratio discontinuity in rock, regardless of its location (within a clast, or within shallow or deep bedrock), origin, or scale, acknowledging that veins or dikes (filled with secondary minerals) are also termed 'fractures' in many contexts. The term 'crack' is avoided because the wide-ranging semantics of the term can cause confusion when employed in interdisciplinary work across rock mechanics, structural geology, and geomorphology.

Fracture characteristics (e.g. size, number, connectivity, orientation) exert enormous influence on both rock mechanical properties (e.g., Ayatollahi and Akbardoost, 2014) and rock hydrological properties (e.g., Leone et al., 2020; Snowdon et al., 2021). Fractures therefore influence a wide array of natural and anthropogenic landscape features and processes including channel incision (e.g., Shobe et al., 2017), sediment size and production (Sousa, 2010; Sklar et al., 2017), hillslope erosion (e.g., DiBiase et al., 2018; Neely et al., 2019), built environment degradation (e.g., Hatır, 2020), landslide and rockfall hazards (e.g., Collins and Stock, 2016), groundwater and surface water processes (e.g., Maffucci et al., 2015; Wohl, 2008), and vegetation distribution (e.g., Aich and Gross, 2008). Additionally, the resultant physical properties of fracturing-produced sediment (i.e., clast size distribution, mass, porosity, etc.) control both hillslope and stream processes (e.g., Chilton and Spotila, 2020; Glade et al., 2019).

With fractures clearly central to so many surface processes, as well as non-academic concerns of hazard and infrastructure degradation, it is crucial to understand the factors that control surface and near-surface rock fracture attributes and rock fracturing rates and processes. To fully do so requires a large body of data quantifying fracture-related characteristics and phenomena in a variety of subaerial environments; however, to date, no standard field methods have been widely adopted to quantify fractures in the modern surface processes realm. Consequently, data collected across studies cannot be readily compared or coalesced. The purpose of this paper is to define an initial set of such standards by combining prior fracture methodology studies from other geoscience disciplines with those that have been developed, tested and refined during more than 20 years of field-based fracture observations for surface processes-related research (e.g., Aldred et al., 2015; Eppes and Griffing, 2010; Eppes et al., 2018; Eppes et al., 2010; Mcfadden et al., 2005; Moser, 2017; Shobe et al., 2017; Weiserbs, 2017).

Building on this combination of past work, this paper first defines the benefits of establishing a standard procedure for fracture-focused surface processes field research, describing how the authors' chosen methods outperform other approaches. This is limited to in-person field observations on sub-aerially exposed rock - i.e., fractures that can be observed with the naked eye or basic hand lens. Measurements of smaller fractures (e.g., those visible with microscopy) or of buried fractures (e.g., those visualized in boreholes or with indirect geophysical methods) are not directly described here. Also, methods for fracture detection using rapidly evolving automated analyses of remote data such as LiDAR, drone photography, or structure-from-motion are not described. These technologies hold great promise for expanding the scope of fracture measurements, but to date also hold numerous limitations. The methods outlined herein could be employed for the consistent validation of such data in the future.

The overall aim of this paper is to build: 1) a set of guiding principles applicable to all surface processes research involving rock fractures; 2) a list of fracture and rock data measurements that constitute "basic" field-based metrics; and 3) practical methods that comprise best practices for collection of these data. Unless otherwise specified, all methods may be applied to loose clasts or to outcrops. Also provided are some suggestions for data analyses and a demonstration of a real case example of how the proposed methods lead to reproducible results across users. By providing this compendium of fracture-focused field methods, the hope is to accelerate understanding of how a most basic feature of all rock – its open fractures – contributes to the processes and evolution of Earth's surface and critical zone.

1.1 The value of a standardized approach

Particularly within the fields of geomorphology and weathering sciences, no common suite of data, methods, or terminology has been defined or described that comprises an analysis of fractures. Although fracture characterization field methods exist in the context of structural geology and aquifer and reservoir characterization (e.g., Watkins et al., 2015; Wu and Pollard, 1995; Zeeb et al., 2013; Laubach et al., 2018), they diverge significantly in their approaches because they were largely developed for the specific application of each unique study or field of study. Furthermore, the terminology and methodology used to describe natural fractures across this existing research are largely limited to only those fractures loosely interpreted to be tectonically induced 'joints', and numerous published works fail to provide clear criteria, even for choosing which fractures to measure. This lack of consistency severely limits the ability of the geomorphic community to reproduce methods, or to combine, compare, or interpret different fracture datasets.

The development of consistent methods undergirds most quantitative Earth sciences. For example, the fields of sedimentology and soil science have clear, standardized methods to acquire what constitutes the "basic" data for their observations. Sedimentologists have long shared common metrics and methods for quantifying grain size, sorting, rounding, and stratigraphic records (e.g., Krumbein, 1943). Similarly, soil scientists share common methods, metrics, and nomenclature for describing soil profiles and horizons (e.g., Birkeland, 1999 Appendix A; Soil Survey Staff, 1999). The realization of the need for standard methods has also remained constant in laboratory-based rock mechanics over the last several decades, driving the American Society for Testing and Materials (ASTM) and International Society for Rock Mechanics (ISMR) to publish ongoing standards and methods papers (e.g., Ulusay and Hudson, 2007; Ulusay, 2015).

Standards like those mentioned above exist because workers have long recognized and reaped their benefits. Standardized methods can frequently lead to major step-change innovations when data are combined. For example, standardized soil methods allowed for 100 m scale mapping across the United States, enabling detailed human–landscape models that can aid in preserving vital soil resources (Ramcharan et al., 2018). In the field of rock mechanics prior to the 1950s, theoretical developments of rock failure and plasticity lagged behind other branches of geophysics and engineering, limited both by technology and, arguably more so, by lack of consistent methods. Methods for repeatable failure testing were then developed, largely in the groups led by Knoppf, Griggs, and Turner in the United States and Australia (Wenk, 1979). This standardization culminated in the landmark series of papers that comprised the observations driving 50 subsequent years of experimental rock mechanics (e.g., Borg and Handin, 1966; Handin et al., 1963; Handin and Hager, 1957, 1958; Heard, 1963; Mogi, 1967, 1971; Turner et al., 1954).

Here, a set of methods is proposed as a starting point for surface processes researchers so that a larger community of teams can begin to cross-pollinate their observations. It is necessary and expected that these methods will evolve as new needs and applications arise.

1.2 Development of the standardized fracture measurement approach

For the specific case of fracture-focused research, outside of geomorphology applications, the need for standardized rule-based methods has already been established. Within this prior body of research and, when considered in the context of surface processes problems, the methods proposed below have been shown to outperform other approaches. In one case example, study participants were asked to measure fractures with no particular instructions given for how to collect the data other than where to collect it. The wide variance in resulting datasets collected by different users led to the conclusion that, without common and clearly established measurement and selection criteria, fracture characterization is rife with subjective bias that severely impacts interpretations of results (Andrews et al., 2019). Then, based on post-data collection interviews and workshops, Andrews et al. (2019) scrutinized the source of the variance and provided a list of suggested best-practices that would serve to best eliminate the subjectivity of data collection that was leading to the bias. Forstner and Laubach (2022) and Ortega and Marrett (2000) further detail that many such issues arise, particularly from a lack of specificity with respect to identifying features to be measured.

In another case example, Zeeb et al. (2013) sought to determine how different sampling approaches lead to censoring bias of different fracture sizes from outcrop data by applying different sampling methods to artificially generated fracture networks that had known parameters. Analysis of data collected using scanline, window, and circular estimator methods revealed that the window approach resulted in the lowest uncertainty for most parameters and required the fewest measurements to provide representative datasets.

Incorporated here are the suggested best practices from the two case examples above as well as from other published methods research. Some methods are well attested to be reproducible in field studies. For example, field measurement ‘crack comparators’ are effective for measuring opening displacements particularly for sub-millimeter widths (e.g., Ortega et al., 2006). Other measurements such as length and connectivity may have low reproducibility (Andrews et al., 2019) owing to various observational and conceptual problems, including dependence on scale of observation (e.g., Ortega and Marrett, 2000). Above all, it is clear that reproducibility requires clear, rule-based criteria for all decision-making (Forstner and Laubach, 2022).

The chosen standardized methods are optimized for collecting outcrop- and clast-fracture data relevant to geomorphology. The methods described herein are germane to surface and near-surface (< 0.5 km) studies such as validating geophysical measurements, testing factors that influence fracture formation, or documenting links between fracture characteristics and topography or sediment production. These methods possibly differ from those of studies with other goals, such as using outcrops as guides (analogs) for deep (km scale) subsurface fractures. Such studies aim to distinguish mechanical and fracture stratigraphy, corroborate fracture patterns related to features (i.e., folds), obtain fracture statistics for discrete fracture models, or test efficacy of forward geomechanical fracture models. For these studies examining deeper deformation, mineral filled fractures may be more useful or appropriate than open fractures. Also, for these applications, near-surface and geomorphology-related fractures are considered “noise” and need to be omitted (e.g., Sanderson, 2016; Ukar et al., 2019). However, a major outstanding question is how this might be reasonably and accurately accomplished given the relatively sparse number of studies of fractures in the context of geomorphology.

2 Standardized methods: Guiding principles

2.1 Natural rock fracturing background

The design of any fracture-related study in the context of surface processes must arise from consideration of the variables that may influence the rates of fracturing and the characteristics of the fractures that form. When rock is proximal to Earth’s surface, those variables include factors related to Earth’s topography, atmosphere, biosphere, cryosphere, and/or hydrosphere. Here, a very brief overview is provided of some key rock fracture mechanics concepts behind these factors. Eppes and Keanini (2017) and Eppes (2022) provide more detailed reviews of rock fracture processes in the context of surface processes.

Rocks fracture at and near Earth’s surface in response to the complex sum of all tectonic (e.g., Martel, 2006), topographic (e.g., St. Clair et al., 2015; Moon et al., 2020; Molnar, 2004), biological (e.g., Brantley et al., 2017; Hasenmueller et al., 2017), and environment-related (e.g., Matsuoka and Murton, 2008; Gischig et al., 2011) stresses they experience. Fracturing can occur when stresses exceed the failure criteria (i.e., short-term material strength). More commonly, however, because critical stresses are only rarely reached in nature, fractures can also propagate *subcritically* at stresses as low or lower than 10% of the rock’s strength (see textbooks such as Schultz, 2019; Atkinson, 1987).

Overall, subcritical fracture propagation rates and processes are strongly dependent on stress magnitude, but they are *also* strongly influenced by the size of the fracture that is under stress, as well as the environmental conditions that impact fracture tip bond breaking (see fracture mechanics textbooks such as Anderson, 2005; or reviews such as Laubach et al., 2019). For single isolated fractures, stresses applied to the rock body are concentrated at fracture tips proportional to the length of the fracture (a concept embodied by the term 'stress intensity'), effectively increasing the stresses experienced directly in that location. The environmental factors known to impact subcritical rock cracking - in a manner separate from their influence on stresses - include vapor pressure, temperature, and pore-water chemistry (Eppes and Keanini, 2017; Eppes et al., 2020; Brantut et al., 2013; Laubach et al., 2019). Therefore, in the context of surface processes, climate matters twice for rock fracturing: 1) as it contributes to the stresses that the rock experiences, and 2) as it contributes to the chemo-physical processes that break bonds at fracture tips as they propagate subcritically.

Just as other common physical properties like tensile strength can be measured, rocks can be tested for their propensity to fracture subcritically by the measurement of subcritical cracking parameters such as the subcritical cracking index (e.g., Paris and Erdogan, 1963; Chen et al., 2017; Holder et al., 2001; Nara et al., 2012; Nara et al., 2017). These parameters influence both the rate of subcritical cracking in rock and the fracture characteristics (e.g., amount of fracture per area or fracture length as in Olson, 2004). In sum, natural rock fracturing is not necessarily the singular, catastrophic event as it frequently portrayed in surface processes research. Instead, it is likely dominantly a slowly evolving process progressing over geologic time and influenced by complex feedbacks between rock and fracture properties, as well as environmental, topographic, and tectonic factors.

2.2 Site selection and study design using a "State Factor" approach

Due to their influence on rock fracturing as described above, all potential driving stresses and variations in fracture environments must be considered in site selection and study design for any fracture-related research. Parent material, topography (and other loads), climate, biota, and time all potentially impact initiation and propagation of surficial fractures in rocks. Though this idea might generally exist in other fracture-focused research, in the field of soil geomorphology it has long been explicitly described as a 'State Factor' approach (e.g., Jenny, 1941; Phillips, 1989) to understanding progressive chemical and physical alteration processes. Thus, we propose that this well-vetted conceptual paradigm may be employed as a standard.

Here, it is asserted that applying a State Factor approach to fracture research is relevant because fracturing processes are influenced by each of these factors, just as all other chemical processes acting on rock and soil. This is particularly true when the subcritical nature of rock fracture is considered (Sect. 2.1). Thus, all State Factors that could contribute to fracture propagation styles, and rates should be explicitly considered and controlled for as much as possible within the aims and scope of the research for any given site. These 'State Factors' - long categorized as they relate to overall soil development, of which physical weathering is a component (e.g., Jenny, 1941) - are equally applicable to fractures alone, and include climate (cl, both regional climate and microclimate), organisms (o, flora and fauna), relief (r, topography at all scales), parent material (p, rock properties) and time (t, exposure age or exhumation rate). For rock fracture, tectonics (T) should be added to this list, making cl,o,r,p,t,T.

Hereafter, the term 'site' refers to a single location of either a group of rock clasts or a group of outcrops, whereby all clasts or outcrops within the 'site' could be reasonably assumed to have experienced similar State Factors over their exposure history. For example, a site might comprise a single boulder bar on an alluvial fan surface or a single ridgeline with several outcrops. Once the specific State Factors (including the internal variability of each site) are identified for all the sites within a given field area, a series of sites can be selected whose State Factors are known and controlled for as much as possible. This enables a study of the influence of individual factors across the sites, i.e., fracture chronosequences, climosequences, toposequences, or lithosequences.

For rock fracture, it is important to understand how each cl,o,r,p,t,T factor may contribute both to stresses that give rise to fracturing, and/or to the molecular-scale processes that serve to subcritically break bonds at fracture tips (Sect. 2.1). Each has the potential to independently impact fracturing rates, styles, and processes. The following descriptions provide only brief examples of how each of the State Factors may influence rock fracture. To fully describe each of their influences on rock fracturing would comprise a textbook. The factors are listed in the cl,or,r,p,t,T order by traditional convention only. Assuredly, to date, there are insufficient data to propose a hierarchy of their influence on fracture characteristics in surface processes contexts.

2.2.1 Climate (cl)

Climate (cl) as a State Factor refers not just to regional mean annual precipitation or temperature, but also the local microclimate of a site, which may be influenced by site characteristics, such as runoff or aspect. The presence of liquid water increases the efficacy of water-related stress-loading processes like those related to freezing (Girard et al., 2013) or chemical precipitation of salts or oxides (e.g., Buss et al., 2008; Ponti et al., 2021). Moisture – particularly vapor pressure – can also serve to accelerate rock fracturing rates independent of any stress-loading (e.g., Eppes et al., 2020; Nara et al., 2017). Temperature cycling can produce thermal stresses (through differential expansion and contraction of both adjacent minerals as well as different portions of the rock mass, e.g., Ravaji et al., 2019), and can also influence rates and processes of fracture-tip bond breaking (e.g., Dove, 1995).

2.2.2 Organisms (o)

Organisms (o) refers to both flora and fauna - everything from overlying vegetation and large animals to roots and microorganisms, all of which may provide a source of rock stress and/or may influence water availability or chemistry. These relationships can be complex and unexpected. For example, tree motion during wind and root swelling during water uptake both exert stresses on rock directly (Marshall et al., 2021a). Organism density and type can impact rock water and air chemistry (Burghelea et al., 2015), both of which may impact the rates and processes of subcritical cracking (e.g., review in Brantut et al., 2013).

2.2.3 Relief (r)

In the context of State Factors, *relief (r)* refers generically to all metrics related to topography including aspect, slope, and convexity. Topography impacts the manifestation of both gravitational stresses. as well as tectonic stresses within the rock body (Molnar, 2004; Moon et al., 2020; Martel, 2006). The directional aspect of a particular outcrop or boulder face may also influence insolation and water retention, translating into differences in microclimate and vegetation and, thus, weathering overall (e.g., Burnett et al., 2008; West et al., 2014; Mcauliffe et al., 2022), including fracturing (e.g., West et al., 2014).

2.2.4 Parent material (p)

The *parent material (p)* factor in the context of a fracture study refers to the specific rock type(s) containing fractures (and potentially undergoing fracture) in the geomorphic environment. Rock varies in the types and dimensions of material present (e.g., sandstone, siltstone, shale, basalt, granite etc.) and the types and spatial arrangements of interfaces within the material (e.g., grain size, porosity, bedding, foliation). These properties directly influence the rates and styles of fracture propagation (Atkinson, 1987) due to both how they respond to stresses but also due to how they allow stresses to arise. Thus, they can all influence the rates and characteristics of fracture growth and susceptibility to topographic and environmental stresses. For example, different minerals are characterized by different coefficients of thermal expansion. As a result, rocks with different mineral constituents will be more or less sensitive to thermal stresses than others depending on the contrasts between adjacent grains. Rock mineralogy will also impact chemical processes acting at crack tips during subcritical cracking, as well as the overall susceptibility of the rock to chemical weathering.

Many (perhaps most) rocks contain fractures that formed prior to exposure, either due to deep seated tectonics and fluid pressure loads or to thermal and mechanical effect due to uplift towards the surface (English and Laubach, 2017; Engelder, 1993). In sedimentary rocks, fracture patterns (and, in some cases, fracture stratigraphy) vary with mechanical stratigraphy (e.g., Laubach et al., 2009) that can also influence near-surface fracture. In many instances, mechanical properties may be reflected in fracture stratigraphy, and vice versa. Schmidt hammer measurements are a useful, fast, and inexpensive field approach to documenting mechanical property variability (Aydin and Basu, 2005), however such measurements are impacted by weathering exposure age (Matthews and Winkler, 2022). The influence of fracture characteristics of the parent rock that may have formed in the deep subsurface are described in Sect. 2.2.6 “Tectonics”.

Additionally, here, parent material also refers to the size and shape of the clast or outcrop. For example, angular corners generally concentrate stresses more than rounded edges (Anderson, 2005). Also, clasts or outcrops of different sizes experience different magnitudes of thermal stresses related to diurnal heating and cooling (Molaro et al., 2017).

2.2.5 Time (t)

Time (t) likely plays a role in rock fracturing rates just as it does in chemical weathering, whereby outcrops found in slowly-eroding environments or clasts on old surfaces may be subject to different fracturing rates and processes (e.g., Rasmussen et al., in prep; Mushkin et al., 2014). Over time, rock mechanical properties can also change as weathering occurs (e.g., Cuccuru et al., 2012). Although the time factor has not been well-studied in the context of natural rock fracture, preliminary data suggest that it should be considered (Berberich, 2020; Rasmussen et al., 2021). Published surficial geologic maps or datasets of rock exposure ages or erosion rates (e.g., Balco, 2020) will provide such ‘time’ information.

2.2.6 Tectonics (T)

Finally, in a fracture-related study, *tectonic (T)* setting must also be considered as a State Factor. Fractures that have formed in the deep subsurface in response to tectonic forces inevitably become exhumed. Overall, tectonic fractures have traditionally been studied within the structural geology discipline, and that literature is extensive (e.g., reviews in Laubach et al., 2019; Laubach et al., 2018; Atkinson, 1987, Chapter 2). The tectonic history of rock can be maintained in its brittle structures over a wide range of past tectonic events, including its most recent exhumation and cooling. The resulting open or filled fractures depend on how deeply the material was buried, how rapidly uplifted, and the material properties (e.g., English and Laubach, 2017). Finally, the fact that the current tectonic setting can drive ongoing deformation has long been recognized (e.g., Hooke, 1972), and more recent work has highlighted that very low magnitude tectonic stresses can translate to fracture propagation in very near-surface bedrock, especially when interacting with local topography (e.g., Martel, 2011; Moon et al., 2020).

It is likely, though perhaps not widely appreciated, however, that tectonic fractures further increase in both number density (total number of fractures per area) and intensity (total fracture length per area) as they approach the surface and are propagated further by rock interactions with topographic and environmental stresses. There is a growing body of data pointing to such surface interactions (e.g., Marshall et al., 2021b; Moon et al., 2019; Moon et al., 2020; St. Clair et al., 2015), but overall, these differentiations are a topic ripe for further study. Pre-existing fractures may not always be easily separable from those formed or further propagated under geomorphological influence. Environmental stresses also produce parallel fractures (e.g., Aldred et al., 2015; Eppes et al., 2010; Mcfadden et al., 2005), as do those related to the morphology of the eroding landscape (Leith et al., 2014). For outcrops, and particularly for clasts where correlations with regional tectonic structures are not possible, microstructure analyses that examines fractures for diagenetic cements, fluid inclusions, or other similar features may provide insights into the tectonic origin of fractures.

Thus, in choosing study sites, consideration should be made of rock age, tectonic history and current tectonic setting (e.g., World Stress Map, Heidbach et al., 2018), as well as unambiguously tectonically-related structures such as dipping bedding planes, evidence of mineral deposits in the fractures, styolites, or ductile structures such as folds (Hancock, 1985; Laubach et al., 2019).

2.3 Bedrock outcrops versus deposited clasts

The fracture characteristics of outcrops have long been employed as proxies for subsurface fracture networks, and there is a reasonably large body of literature addressing these relationships and their potential pitfalls (e.g., Ukar et al., 2019; Al-Fahmi et al., 2020; Sharifigaliuk et al., 2021). However, as mentioned above, topographic and environmental stresses have likely both contributed to any sub-aerially observed fracture network. Thus, for studies that aim to isolate fractures associated with environmental stresses, measurements from clasts may be more useful than outcrops.

Clasts that have been transported by fluvial, glacial, or mass-wasting processes have experienced abrasion, and therefore, it is highly likely that pre-existing superficial fractures have been removed. Thus, clasts may be more reasonably considered ‘fresh’ than an outcrop with an unknown exhumation history, allowing clearer linkages between environmental exposure and observed fractures. This idea of “resetting” fractures within clasts through transport is supported by data showing clasts of identical rock type that have experienced more transport (i.e., rounded river rocks) having higher strength than those found in, for example, recent talus slopes (Olsen et al., 2020).

3 Selecting the clasts, outcrops, or rock surface locations that will comprise the fracture observation area

Carefully selecting the rock surface area(s) on which fractures will be observed and measured within a site is equally as important as selecting the site or the fractures themselves. Hereafter, the term ‘observation area’ refers to the specific portion(s) of rock surface(s) for which fractures are being measured. Observation areas may comprise the entire exposed surface of individual clasts, outcrops, or portions of either (Fig. 1). In the following sections, instructions for selecting these observation areas in the field are provided.

3.1 Establishing outcrop or clast selection criteria

Before observation areas can be identified, outcrops or clasts must be selected. The first step of that selection process is to establish criteria for determining which outcrops or surface clasts within the site are acceptable for measurement. Similar to site selection, variability in cl,o,r,p,t,T factors that may influence fracturing (temperature, moisture availability, rock shape, and rock type) should be controlled for as much as possible.

In general, characteristics of the clasts or outcrops that might impact mechanical properties, moisture, or thermal stress-loading should be most heavily considered. The 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 fracture rates and style characteristics. For example, perhaps only outcrops with no visible veins or dikes will be employed; or only outcrops greater than 1 m in height; or only north facing outcrop faces. Past work, for example, has focused on upward facing surfaces of outcrops or large clasts (e.g., Berberich, 2020; Eppes et al., 2018).

For loose clasts, only clasts of a particular size or rock type might be employed for measurement. For example, past work found that below approximately 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., 2015), clasts are more likely to have been moved or disturbed. Thus, these sizes were employed as a threshold for selection.

3.2 Non-biased selection of clasts or outcrops for measurement

Once criteria are defined, clasts or outcrops meeting those criteria must be chosen for the fracture measurements. A procedure similar to the well-vetted Wolman Pebble Count style transect (Wolman, 1954) should be employed to avoid sampling bias. For landforms with other geometries, a grid may be used instead of a transect line.

In either case, a tape transect or net grid is laid out on the ground at each site, and the clast or outcrop closest to specified intervals on the tape (or at the points of the grid meeting the criteria) is selected (Fig. 1a). The interval or grid spacing should be adjusted to the overall size and abundance of clasts or outcrops found on the surface. If there are relatively few meeting the criteria at a site, all within the site meeting the criteria can be measured.

A similar technique can and should be applied for selecting outcrops. For example, care should be taken to not be limited to the 'best' outcrops (cleanest and/or largest), since they likely are the least fractured. For locations where outcrops are within a few meters or tens of meters of each other and vegetation relatively sparse, a grid of a set dimension (e.g., 100 m) is overlain on aerial imagery, and the closest outcrop to each grid intersection meeting the outcrop criteria are selected (Watkins et al., 2015). For areas where outcrops are not visible in aerial imagery, a measured or paced transect can be employed where the user walks along a bearing and chooses the closest outcrop meeting the selection criteria at each interval, e.g., 30 paces.

In all of the above, transect locations and orientations should be selected following consistent criteria and being mindful of the State Factors cl,o,r,p,t,T. For example, all transects or grids might be placed uniformly along backslopes with a certain upslope distance from the crest; or along the latitudinal center or crest of a landform. Alternatively, the transect might be orientated perpendicular or oblique to a paleo-flow direction so that it is not constrained only to bars or swales. The coordinates and bearing of all transects or grids should be recorded, enabling tracking and avoiding repetition.

3.3 Observation areas comprising the entire clast or outcrop surface

The observation area for small clasts and outcrops can be their entire exposed surface. When clasts or outcrops selected for measurements are less than ~50 cm in maximum dimension, measurements can typically be readily made for all fractures visible on the clast or outcrop exposed surface.

No rocks should be moved during measurement. This non-disturbance practice is particularly crucial for maintaining Earth's geodiversity (Brilha et al., 2018) and preserving sites for future workers to revisit. Further, research examining acoustic emission localization of rocks naturally fracturing found that the large majority of fracture 'foci' were located in the upper hemispheres of boulders (Eppes et al., 2016). Thus, the potential insight gained by moving clasts does not warrant its damage to geoheritage.

3.4 Establishing 'windows' as the observation area for larger clasts and outcrops

When it is not feasible to measure every fracture on an outcrop or clast, the observation area may comprise predetermined 'windows' of representative decimeter- to meter-scale areas of the rock surface (Fig. 1b). This window selection method results in an accurate representation of fractures on an entire outcrop (e.g., Zeeb et al., 2013) and is least affected by subjective bias (Andrews et al., 2019). Other techniques that require measurements of all fractures that intersect a line (scanlines) are common and effective (Marrett et al., 2018; Hooker et al., 2009), but do not provide an observation area. Consequently, they do not capture all fracture orientations, they preclude calculations of fracture number density and fracture intensity (Sect. 6.1), and they complicate determination of rock properties. For areas with large outcrop exposures, circular scanlines combined with a window approach have proven effective (Watkins et al., 2015). Scanlines are also helpful in characterizing simple fracture clustering attributes. Here, a 'window' approach is outlined that can be employed regardless of outcrop size or fracture number density. An expansion of fracture length measurements – similar to that proposed by Weiss (2008) – is also detailed so that long fractures are not underrepresented (see Sect. 5.4.1 for length methods).

Importantly, the number and size of windows observed on each outcrop or at each site will depend on the typical number and size of fractures present on the surface of the rock (Sect. 4.2). Overall, it is preferable to strike a balance between window size and number so that during data analysis, variance can be quantified by comparing data collected between windows on the same outcrops and at the same site. More total observation area (more and/or larger windows) is required when fractures are fewer per area. The size of the area required for a representative quantification of fractures depends both on fracture average length and number density (e.g., Zhang, 2016). Here, an iterative approach is outlined for determining if sufficient area has been examined (Sect. 4.2), but other rules of thumb exist, particularly in the Rock Quality Designation Index literature (e.g., Zhang, 2016).

Choosing the placement of windows on the outcrop should entail a stratified random sampling approach. Just as for clast- or outcrop-selection, cl,o,r,p,t,T factors like aspect should be taken into consideration and controlled for as much as possible in the window placement strategy by, for example, only using upward facing surfaces. Then, window placement determination is made to avoid sampling bias and also edge effects. For example, if upward facing outcrop surfaces are to be characterized, then the total length and width of the face could be employed to align sufficient numbers of windows along even intervals of those measurements (e.g., for example, three windows whose centers are located along the center axis of the rock with even spacing between the edges and each box; Fig. 1b).

For the placement of each window, a simple cardboard template of the appropriate window size with a center hole can be employed to trace with chalk the window directly on the clast or outcrop. Then, all fracture measurements are made in the window(s). Each window should be numbered and photographed in the context of each outcrop or clast. Detailed photo-documentation and coordinates to 0.00000 dd are also recommended.

3.5 How many observation areas?

The number of clasts, outcrops, or windows required to measure sufficient fractures will vary with the study goals, site complexity, and the variables for which the data are being tested or controlled. Importantly, for each study, the required number of observation areas must be established based on the amount that is necessary to gain a statistically sufficient number of fracture observations to represent the rocks in question for that setting (Sect. 4.2). As yet, no rule-of-thumb can be employed, because there has not been sufficient standard fracture data collected to establish such a rule. Establishing such a rule of thumb is an illustration of the motivation of this paper, as well as an example of how it can be expected that the methods herein might evolve over time.

Rocks or outcrops with lower fracture number density (fewer overall fractures per area) will require that larger areas of their surface be examined in order to measure sufficient fractures for statistical significance (Sects. 3.4 and 4.2). Rocks or outcrops with significant variation in fracture patterns require sufficient observation to capture that variability. Thus, as an example only, in past work, when State Factors were carefully controlled for, relationships between rock material properties and rock fracture properties were evident from about three to ten meter-scale outcrops per rock type on ridge-forming quartz rich rocks (Eppes et al., 2018). However, until sufficient magnitude of datasets have been collected for a particular site, the amount of observation area must be established based on the number of fractures available uniquely at each study site.

4 Selecting fractures for measurement

4.1 Rules-based criteria for selecting fractures in surface processes research

The term ‘fracture’ is employed with a wide variety of meaning across the geosciences, potentially resulting in large variations in the range of features that two individuals might study on a single outcrop (Long et al., 2019). Therefore, it is crucial to employ clear and repeatable rules-based criteria (e.g., Table 1) for what constitute measurable ‘fractures’ within any fracture-related research. Failing to do so consistently results in a high variance of subjective bias that is more reflective of worker personality than of the variance in fracture of the outcrop (Andrews et al., 2019). Thus, consistency and documentation are required for deriving interpretable and repeatable results.

The proposed rules (Table 1) for determining which fractures to measure at any given field site were developed in the context of surface processes research and through iterations with numerous non-expert users (undergraduate students) to arrive at criteria that provided consistency in observations across users. Because surface processes are frequently and largely dependent both on rock erodibility and water within a rock body, the recommended criteria are applicable only to open voids, which are known to greatly impact both. Also, because other types of open voids like vesicles are common in rock, additional criteria includes that the open void must be planar in shape, bounded by parallel or sub-parallel sides (hereafter fracture or fracture 'walls'), with a visible opening that is deeper than it is wide. Fracture walls will pinch together at fracture terminations.

Voids that fit the shape criteria that are filled with lichens, dust, or other permeable material that can be readily brushed out with a fingernail or prodded with a needle should be included in the dataset. However, it is common for high aspect ratio voids in rock to have been filled with cemented mineral solids during intrusion and metamorphism, diagenesis, or weathering. Fractures, or portions of fractures containing these hardened cements, become the hydrologic and mechanical equivalent of solid rock. Therefore, these zones do not meet the defined 'open' criteria and should not be included in the fracture dataset. If such a solid secondary mineral cement forms a discontinuous "bridge" fully connecting the two walls of an otherwise open, planar void, the open length of the fractures on either side of the bridge would be treated as individual fractures. This type of fracture inclusion is common in many settings (see review in Laubach et al., 2019), so a yes/no indication of their presence may be added to the dataset.

Finally, additional proposed criteria include that the planar void must be continuously open (no 'bridges' of cemented mineral material or of rock) for a distance longer than 10 times the characteristic grain size dimension or 2 cm, whichever is greater. In most rock types, this translates to a 2 cm minimum cutoff for countable fractures (Fig. 2a; see Sect. 5.4.1 for measuring lengths). This proposed length threshold is based on three features. First, past work has demonstrated that deriving precise (repeatable) detailed information - other than length - for fractures <2 cm in length is challenging (e.g., Eppes et al., 2010). Second, temperature-dependent acoustic emission measurements (Wang et al., 1989; Griffiths et al., 2017) and theoretical arguments suggest that on single year time scales, fractures on single grain and smaller length scales exist in thermodynamic equilibrium, randomly opening and closing under constant redistribution of ubiquitous diurnal to seasonal thermal stresses within surface rocks. The approximate statistical mechanical 'rule-of-ten' states that well-defined equilibrium and nonequilibrium, continuum-scale properties, e.g., viscosity, density, stress and strain, each determined by myriad microscale random processes, are obtained on length scales approximately 10 times an appropriate molecular length scale, e.g., average atomic size or mean free path length between colliding (gas) molecules. This interpretation is consistent with recommendations for the number of grains the minimum diameter of a sample is for repeatable testing of continuous rock properties such as rock strength and elastic moduli (e.g., ASTM, 2017).

Last, and practically, the high abundance of fractures below this cutoff significantly increases the time required for fracture measurement. If these smaller fractures are of interest, they can be characterized with photographic analysis (not covered herein) or subjected to semi-quantification via an index (Sect. 5.2).

Importantly, in some applications, it may be appropriate that a larger minimum threshold in fracture length is chosen. However, in that case, fracture abundances in the rock will possibly dictate that significantly larger observation areas of the rock exposure need to be employed in order to obtain sufficient numbers of fractures to provide representative data (Sect. 4.2).

Regardless of the threshold length chosen for the study, two adjacent fractures separated by intact rock or bridges of cement are considered two fractures, even if at a distance they appear to be continuous (Fig. 2b). This practice results in repeatable measurement between multiple workers and provides the most accurate representation of past fracture growth and fracture connectivity in the rock body.

4.2 Determining how many fractures to measure

Most published fracture-focused studies provide no justification for the number of fractures they measure, begging the question - is the dataset representative of the rock body? However, it is a long-recognized concept in fracture and rock mechanics that fracture size distributions are highly skewed and characterized by scale-independent power law distributions (e.g., Davy et al., 2010; Hooker et al., 2014). Thus, the expected power-law distribution of fracture size can be leveraged in most cases to ensure that a representative fracture population has been measured in any given dataset (Ortega et al., 2006).

Here, it is recommend that to fully characterize the fractures for any site(s), outcrop(s), or feature(s) of interest, sufficient numbers of fractures should be measured such that a statistically robust power-law distribution (p-values <0.01) in fracture length is evident in the data. While other log normal, exponential, and Weibull distributions have been proposed for various fracture datasets (e.g., Baecher, 1983), employing these distributions depends on preexisting knowledge of the expected dataset. Thus, unless there is prior documentation of fracture distributions at a particular site, the power law distribution should suffice.

In practice, it is an iterative process to determine the number of fractures required for any given dataset; but generally, on the order of 10^2 fractures are required (e.g., Zeeb et al., 2013) to reach a representative distribution (Fig. 3). When sufficient numbers of fractures have been measured to result in such a distribution, then it can be assumed that the population of measured fractures is representative of all fractures on the rock, outcrop, or group of rocks/outcrops with certain features. For example, if the goal of a study is to test the influence of rock type on fracture width, enough fractures must be measured to allow for a power-law distribution of fracture lengths for *each* of the rock types. That population of fractures can then be considered representative of the given rock type, and statistics on other fracture properties like width can also be reasonably interpreted as representative.

An example of what that iterative process might look like is found in Fig. 3. In this example, all fractures were measured on the surface of 15-50 cm diameter granitic clasts selected along transects across both a modern wash bar (with few overall fractures per clast) and a ~6 ka alluvial fan bar (with many fractures per clast). For the modern wash, after 5, 30, or 50 clasts, a statistically significant power law distribution is not evident (Fig. 3). However, after 130 clasts, the fit of the power law falls below a p-value threshold of 0.01. Thus, measurements from around 130 clasts were necessary to fully characterize fractures for that particular site. In contrast, the threshold p-value is reached after only 5 clasts for clasts with high fracture number density on the mid-Holocene age site; however, with more clasts examined, more variables per clast can be analyzed in the data. Thus, in order to evaluate different variables (like clast size or shape), the iterative process would repeat, but limiting the analysis to fractures found on clasts meeting the criteria of interest. In this example, a total of 130 clasts per surface were measured, enabling several subsets of data to be examined in order to test the influence on a range of clast properties on fracture characteristics.

One notable exception to the scale independent power law rule of thumb may be if there are abundant fracture terminations in infilling material. In this case, the size of the fracture (as defined by Table 1) is dictated by the spacing of the filled material bridges. Thus, fracture sets in rocks that contain abundant varnish or secondary precipitates like calcium carbonate may not follow this rule.

5 Proposed baseline field data for fracture-focused surface processes research

Here, a basic suite of field data (Table 2) is described for all observation areas and all fractures. Table 3 contains a list of recommended field equipment to make the measurements. The list of data in Table 2 was developed with the goal of allowing the worker to fully analyze their fracture data in the context of variables known from the literature to influence or reflect fracture in exposed rocks. Workers may choose to measure only some of these data if, for example, they have controlled for a particular metric through site or clast selection. As overall knowledge of fractures in surface environments grows, the suggested set of measured variables should also change, just as, for example, the components of the simple stream power equation have evolved in fluvial geomorphology literature. The proposed fracture field methods list is also focused on direct 'observables' – without interpretation – that should apply universally across field areas. We readily acknowledge that additional items can and should be added to accommodate the needs of any specific study.

The metrics listed in Table 2 and the associated methods described below are designed to be applicable and translatable to both natural outcrops and individual clasts. While they may also be applicable to fractures found in quarries and road-cuts, such outcrops are prone to fracturing that has been anthropogenically induced by blasting, exhumation, and new environmental exposure (e.g., Ramulu et al., 2009; He et al., 2012).

5.1 The 'Fracture Sheet'

A data collection template is provided that comprises all the proposed standard data, allowing efficient, complete, and detailed recording of all parameters while in the field (e.g., a "fracture sheet", Fig. 4 with digital version provided in supplemental data). The fracture sheet can and should be modified to include additional parameters relative to any study. The template provided here is structured so that each observation area's information (e.g., that of each clast, outcrop, or window) shares a row with the first fracture measured. Then, subsequent rows are employed for additional measured fractures on the same observation area. Each observation area and fracture are assigned unique identifiers to enable unambiguous reference in subsequent data analysis. Employing a 'window' rather than an entire clast or outcrop as the observation area necessitates slightly different data collection, so two separate fracture sheets can be found in the supplement.

The fracture sheet provides a header space for site meta-data. Any observations that could elucidate the possible contributions of any State Factor (cl,o,r,p,t,T) acting at the site should be recorded (e.g., the vegetation or topography of the site). This header area should also be employed to note any and all criteria or conventions used throughout the study. For example, the use of any convention, such as right-hand rule for strike and dip measurements, should be noted in the header. The criteria employed to select clasts or outcrops (e.g., their size, composition, etc.) and the nature of the observation areas (e.g., only the north face of all clasts; or entire exposed clast surface for all outcrops) should also be noted.

5.2 The use of semi-quantitative indices

It is recommended that indices be employed for many observations following similar existing semi-quantitative methods commonly employed in both soil sciences (e.g., Soil Survey Staff, 1999) and sedimentology (e.g., rounding and sorting). The use of indices, rather than precise measurements, is especially appropriate for fractures and fracture characteristics given the natural variation between different rocks. Also, high numbers of small or discontinuous features on rock surfaces frequently precludes their accurate counting within a reasonable amount of time; for example, counting all fractures <2 cm in length.

Two particularly useful generic 'abundance' indices are defined here that are similar to those employed for quantifying the abundance of roots and pores in soils (Schoeneberger et al., 2012), whereby the quantity or coverage of specific elements or features is estimated within a specified area. For both, a 'frame' is employed whose size is dependent on the size of the feature being observed (Fig. 5). Features that are ≤0.5 cm are observed in 1 cm^2 frames; features >0.5 to <2 cm are observed in a 10 cm^2 frame; and features ≥2 cm are observed in a m^2 frame. Cut-out stencils of these sizes may be constructed and employed. The observer imagines randomly placing the 'frame' several times on any given portion of the observation area, noting the abundance of the feature of interest within the frame. The indices are based on the average value of abundance observed in any given such 'frame' across the entire area of observation (e.g., the entire clast, the entire outcrop, or the outcrop window).

The first index scales from 0 to 4 and is applicable for 'countable' features of interest in the research like small fractures, fossils, or large phenocrysts. The index is: none – 0 (no visible features in any frame), few -- 1 (<1 feature on average), common -- 2 (≥1 and <5 features on average), very common -- 3 (≥5 and <10 features on average), and many -- 4 (≥10 features on average).

The second index scales from 0 to 5 and is employed for features that are not readily counted nor consistent in size (like lichen, varnish, fine grained mafic, or felsic minerals). In these cases, the index is based on the percentage of the rock surface covered by the feature: none – 0; very little – 1 (<10%); little – 2 (≥10 and <30%); common – 3 (≥30 and <60%); very common – (≥60 and <90%); and dominant – 5 (≥90%). A percentage estimator (Fig. 6) should always be employed to assign the index categories – even experienced field workers are subject to 'quantity bias'.

5.3 Measuring rock characteristics

The following rock characteristics should be measured for each observation area – each clast, outcrop, and/or window – that is employed in a study. Some fracture characteristics not captured in individual fracture measurements are also included. In particular, fracture connectivity and fracture spacing should be measured after all individual fractures within the observation area have been identified and measured.

5.3.1 Clast, outcrop, or window dimensions

Rock – or outcrop – size, aspect, and slope can impact stress-loading through, for example, thermal stress distribution (e.g., Molaro et al., 2017; Shi, 2011). Or, for instance, natural outcrop height has been linked to its exposure age and/or erosion rates (e.g., Hancock and Kirwan, 2007). The dimensions of the clast, outcrop, or window employed for fracture observations are also required for calculations of fracture number density and intensity (i.e., the number/length of fractures per unit area; see Sect. 6.1).

The length and width of planar 'windows' are measured directly. If a window 'bends' across multiple faces of the rock surface, then separate length and width measurements should be made for each face with a distinct aspect. These areas are then added together for fracture number density and intensity calculations.

The vast majority of rock clasts and outcrops found in nature have 'cuboid' forms (Domokos et al., 2020). Thus, length, width, and height of individual clasts or outcrops may be reasonably employed to calculate the exposed surface area (see Sect. 6.1 for calculations). If clasts or outcrops are well-rounded, spherical or half-spherical surface areas can be employed, depending on burial.

For all dimension measurements regardless of rock shape, metrics are measured as point-to-point orthogonal measurements. Length is measured parallel to the longest axis. Width is measured on the widest extent that is perpendicular to length, and height is measured vertically from the uppermost surface of the rock down to the ground surface. If a through-going fracture splits the rock into two pieces that remain *in situ*, it should still be considered one rock and measured accordingly. If a clast or outcrop is spheroidal in shape, that should be noted for future surface area calculations.

For site preservation, and to minimize geoheritage and environmental impacts, rocks should not be moved from their natural state; therefore, the height measurement of a highly embedded rock will only represent the height of the exposed rock surface above the ground. A metric derived to estimate the degree to which clasts are exposed versus embedded is provided in Sect. 5.3.8.

5.3.2 Sphericity and roundness

Sphericity and roundness from standard sedimentology practices (e.g., Krumbein and Sloss, 1951) provide metrics for rock shape. Shape can influence stress distribution in a mass and, therefore, rock fracture. For example, generally, corners tend to concentrate stresses, and 'corner fractures' are a recognized phenomenon in fracture mechanics (e.g., Kobayashi and Enetanya, 1976). Thus, this metric has been included as one to be measured both for outcrops and for clasts.

Sphericity refers to the length by width ratio, or elongation, of the clast or outcrop, whereas roundness is a measure of angularity (Fig. 7). The roundness and sphericity designation for the square on the chart in Fig. 7 most closely matching the dominant shape of the entire clast or outcrop should be noted (ex. r-SR; s-SE). If a more precise rock shape analysis is needed, a modified Kirkbride device can be used to quantitatively measure rock roundness (see Cox et al., 2018 for device modifications and methodology).

5.3.3 Grain size

Mean grain size can impact numerous fracture and stress characteristics including the proclivity for granular disintegration (Gomez-Heras et al., 2006), fracture toughness (Zhang et al., 2018), initial fracture length, thermal stress disequilibrium (Janio De Castro Lima and Paraguassú, 2004), and bulk elastic properties (Vazquez et al., 2015). The mean grain size should be visually estimated by comparing the dominant size of individual grains or mineral crystals to a standard grain size card. This size can be reported as one average value for all minerals, or different values for different suites of minerals (e.g., felsic vs. mafic), depending on the lithological assemblage(s) of the observation area(s).

5.3.4 Fabric and fracture filling

Here, the term 'fabric' is employed to refer to any preexisting (prior to weathering) primary or diagenetic planar, linear, or randomly oriented anisotropies within the rock comprising the outcrop or clast of interest. Fabric is most commonly observed as fossils or lithological bedding planes in sedimentary rocks and as crystal horizons or foliation structures in igneous or metamorphic rocks. Also, all rocks can have diagenetic mineral deposits within parts of otherwise open fractures or contain fully filled veins and dikes.

Finding mineral deposits in open fractures points to a deeper origin. Rock fabric can impart anisotropy that influences rock strength, fluid flow, and fracturing clustering, rates, and orientations (e.g., Nara and Kaneko, 2006; Zhou et al., 2022). Thus, any visible fabric type, as well as the strike(s) and dip(s) (or trend(s) and plunge(s)) of each parallel or subparallel set should be noted in the fracture sheet for each observation area. By collecting these data, it can be determined by comparing orientations the extent fractures in the dataset are influenced by these fabrics.

5.3.5 Fractures <2 cm in length

Fractures <2 cm in length can comprise a significant portion of all fractures on a given rock exposure, particularly in coarse crystalline rock types (e.g., Alneasan and Behnia, 2021). Thus, it is recommended that an index is recorded, using an observation 'frame' (see Sect. 5.2) that quantifies the abundance of fractures less than 2 cm in length (hereafter 'small fractures').

The approximate number of small fractures visible each time the 'frame' is moved should be observed. A rough average of all theoretical frames should be taken, and the categories in Fig. 5 should be used to assign an abundance. For example, if there are generally either zero or one small fracture in any given 10 x 10 cm frame, the abundance would be "1" – i.e., few, <1 per unit area.

5.3.6 Granular disintegration

Granular disintegration refers to evidence of *active* loss of individual crystals or grains due to fracturing along grain boundaries (i.e., sedimentary particles or igneous or metamorphic crystals). This feature is observed on the rock surface as individual grains or small clusters of grains of the rock that can be brushed away by hand. Granular disintegration is commonly observed in coarse igneous, metamorphic, and sedimentary rocks, and over the long-term leads to the accumulation of sediment comprised of individual crystals or small clusters of a few crystals on the ground surface (Eppes and Griffing, 2010; Isherwood and Street, 1976; Gomez-Heras et al., 2006).

This disintegration comprises the complete separation of intergranular fractures. Because the fractures that comprise granular disintegration are typically too small to be readily measured in the field, however, its presence is assumed when loose grains are present on the rock surface. The worker should mark affirmatively (circling the 'G' on the Fracture Sheet) if there is evidence of granular disintegration on the rock surface of observation. If more detail is desired, an abundance index (e.g., Fig. 5) may be employed to quantify what percentage of the surface of observation contains loose grains.

5.3.7 Pitting

Pitting is the occurrence of small holes or fissures that form on the rock surface due to granular disintegration or to preferential chemical weathering of certain mineral types, typically feldspars and micas in silicate rocks. Pitting is distinct from granular disintegration as it is not necessarily 'actively' occurring – i.e., pitting can exist without loose grains on the rock surface. It is included here as a rock property because of its possible linkage to intergranular fracturing. Furthermore, measuring the extent and depth of pitting due to chemical weathering has long been employed as a relative age dating tool in Quaternary geology applications (Burke and Birkeland, 1979).

Pitted surfaces form as individual grains become weathered and fall out or are dissolved; or, for soluble rocks like carbonates, as entire rock regions are dissolved**.** Pitting can either be quantified as present/absent (circling P on the fracture sheet) or as a quantity index (Figs. 4 and 5).

5.3.8 Clast exposure

This metric is used to record to what degree individual clasts appear to be exposed above the ground surface. Individual clasts are known to weather and erode from the upper rock surface down until they become 'flat' rocks at the ground surface (e.g. Ollier, 1984). Surface exposure can be estimated as the amount and shape of a boulder's exposed surface that is currently not covered by loose sediment, vegetation, or other material. This exposure is grouped into four categories: 0 - the clast is sitting above the ground, and its sides curve downward toward the ground surface almost meeting; 1 - the clast is partially covered, with sides curving downward toward the ground surface but not meeting; 2 - the clast is "half" covered, with sides projecting roughly vertically into the ground surface; 3 - the clast has only one upward facing side visible at the ground surface. In a field study, a correlation test on data from 300 boulders revealed a positive correlation of 0.66 between the indices and the fraction of boulder embeddedness (in vertical length) (Shaanan et al., 2022).

5.3.9 Lichen and varnish

Lichens and other plant life can act to push rocks apart during growth (Scarciglia et al., 2012), but have also been shown to strengthen rocks through infilling of voids or shielding from stress-inducing sunlight (Coombes et al., 2018). It is noted that lichen are living organisms that would be killed by removal. In order to determine if a lichen-coated lineation is in fact a measurable fracture (see Sect. 4.1), a needle or straight pin may be employed to poke through the lichen into the possible void of the fracture.

Rock varnish (oxide staining that can appear as a dark gray/black or orange coating on rock and typically contains Fe or Mn oxides) is well-documented to evolve over time. The extent of varnish cover has been employed frequently as a relative-age indicator, particularly in arid environments (e.g., Mcfadden and Hendricks, 1985; Macholdt et al., 2018). Thus, variations in varnish across the rock face can provide evidence of loss of surface material through *in situ* fracturing.

Lichen and varnish can come in many forms and be difficult to distinguish from each other and from primary rock minerals, hiding in fractures, pitting holes, and atop mafic crystals. So, careful consideration of the types of lichen and varnish that may be found in field sites and close inspection with a hand lens is recommended. A fresher exposure of the rock surface can help in the identification of lichen and varnish relative to the natural rock composition and color. Due to the geodiversity impact, however, such exposures should not be made with force.

The quantity of lichen and varnish (secondary chemical precipitates deposited on the subaerial rock surface) visible on the rock observation surface are separately estimated using a visual percentage estimator (Fig. 6) and a quantity index is assigned (Fig. 5; Sect. 5.2).

5.3.10 Collecting samples for microfracture analyses

Rock microfractures (those not visible with hand lens in the field) play a central role in contributing to rock strength, anisotropy, and subsequent macrofracturing processes (Kranz, 1983). It is beyond the scope of the field-based methods presented herein to describe microfracture measurement and analysis, which continues to evolve (e.g., Griffiths et al., 2017; Healy et al., 2017). Instead, suggestions for rock sampling and placement of thin-section billets are provided.

Thin-section analysis of microfractures is a time-consuming process, particularly when considering the per-capita rock volume examined. It is therefore extremely important to select rock or portions of rock that are precisely the rock type of interest. For loose clasts, an entire clast can be sampled and a thin-section billet processed in the lab. For larger clasts and bedrock, a smaller portion must be extracted. By sampling pieces that are already naturally detached, or nearly detached, fracturing that arises due to chiseling or hammering is avoided.

For both clasts and outcrops, the natural orientation of the sampled rock (its horizontal and azimuthal directions) should be marked on the specimen. The sample should be photographed prior to removing from its location. It is essential to ensure all permitting is in place prior to sampling.

Similar to clast or outcrop selection, care must be taken when considering the location within the rock that the thin-section billet will be cut. Because microfracture strike and dip can be influenced by environmental, gravitational, and tectonic forces, both the depth and orientation of the billet should be noted and controlled for as appropriate for all samples compared within a single study.

5.3.11 Fracture connectivity

Fracture connectivity has long been recognized as being key to rock strength and fluid flow (e.g., Rossen et al., 2000; Long and Witherspoon, 1985), and presumably contributes to rock erodibility given that fractures must intersect for rock to erode. There is a large body of literature that addresses fracture connectivity and how to measure it (e.g., Berkowitz, 2002; Barton et al., 1993; Healy et al., 2017; Sanderson and Nixon, 2018), especially in the context of reservoirs and rock quality index studies. As yet, fracture connectivity has been little studied in the context of surface processes, but likely holds high potential given its relationship to water access and to erodibility. Here, the focus is on a simple, rules-based observation of fracture intersection ‘nodes’ (e.g., Barton and Hsieh, 1989; Manzocchi, 2002; Forstner and Laubach, 2022; Sanderson and Nixon, 2018) that comprise the basis for fracture network connectivity assessment (e.g., Andresen et al., 2013).

After all fractures within each observation area have been identified and measured (Sect. 5.4), all fracture links within the observation area should be counted and recorded by noting their relationship to other fractures (Fig. 8): dead end (I-node), crossing (X-node), and/or abutting without crossing (Y-node). Numbers of nodes per area can then be used as a proxy for fracture connectivity. If fracture connectivity is of particular interest for the research, rules-based ‘contingent mode’ (C-node) intersections may also be added (Forstner and Laubach, 2022). An example of a C-node rule might be if fractures >100 mm in length terminate within 10 mm of another fracture, its termination would be a c-node. Another C-node definition could comprise intersection relations where visible connected traces are sealed with secondary minerals. These c-nodes may be important when there are ambiguous at-depth relationships between fracture terminations (e.g., Fig. 2b).

5.3.12 Fracture spatial arrangement

In addition to overall fracture density and intensity, the arrangement of fractures in relation to each other (e.g., evenly spaced, random, clustered in space) can impact loci of rock mass weakness, fluid flow, and landscape morphology. Laubach et al. (2018) is a special edition of the Journal of Structural Geology devoted to spatial arrangement of fractures. The mathematical analysis of clustering is beyond the scope of this field guide, however, measuring one-dimensional fracture spacing along scan lines can be used in many such calculations (Corrêa et al., 2022; Marrett et al., 2018).

Following similar methods as those used for locating windows (Sect. 3.4), lines should be established across the center of observation area, perpendicular to each other in order to capture different orientations of fractures. A tape is then laid across the lines, and, beginning with the edge of the observation area as distance 0, the distance along the tape of each fracture is noted, as well as the "Crack ID" already established for that fracture on the Fracture Sheet. If fractures are marked with chalk, this is an easy process. In that way, the size of each fracture and its adjacent spacings is noted. Fracture arrangement is scale dependent. These spatial arrangement data can go on the back of the Fracture Sheet.

5.4 Individual fracture characteristics

The following properties are measured for each fracture found within the observation area that meets all the fracture selection criteria listed in Table 1. In order to keep track, it is useful to mark fractures with chalk within the observation area after you have made their appropriate measurements.

5.4.1 Length

Fracture length is measured for the entire surface exposure length of the fracture; i.e., around corners and up and down rock topography (Fig. 2a). Measurements can be made with flexible seamstress tape to follow the curve of a fracture's exposure on the rock surface. Length is only measured where there is an open void (Fig. 2b; Sect. 4.1), because to measure across bridges of secondary cemented material or rock would be to infer future fracture propagation that has not yet occurred. By only measuring the open portion of voids, the user avoids arbitrary interpretation of possible behavior. Thus, if a seemingly continuous fracture (Fig. 2b, left inset) is in fact separated by bridges of solid rock (Fig. 2b, right inset), then these should be measured as two different fractures and their lengths should terminate at the rock bridges. The inset in Fig. 2b reveals four fractures possibly meeting all Table 1 criteria. If two fractures intersect in x- or y-nodes (Fig. 8), each fracture is defined by its own distinct strike, and the full length of the full open fracture with that strike is measured (e.g., the length of segments ab and cd in Fig. 8).

Importantly, when using a 'window' approach to rock observation area, both the total length of the fracture extending beyond the window, as well as the total length within the window, should both be recorded. The latter is employed in fracture intensity calculations (Sect. 6.1); the former provides representative information about all fracture lengths on the rock being measured.

5.4.2 Width

Fracture aperture widths (hereafter, 'widths') can impact both the strength and permeability of rock. Generally, they scale with fracture length and, thus, can possibly reflect the innate subcritical cracking parameters of the rock (Olson, 2004). Fracture widths typically vary along their exposure and pinch out at fracture tips. Determining an average or representative width within a single fracture can thus be somewhat arbitrary and subject to bias. Locating the widest aperture is less subject to bias and can also provide information about fracturing processes. Also, the center of the open fracture is an objectively repeatable location, and also where the fracture might be expected mechanistically to be the widest. However, given that this relationship can become complicated as fractures fill or branch, it is recommended here that recording fracture width both at the midpoint of the measured length of the exposed fracture be consistent as well as recording its maximum width along its exposure.

Both measurements should only be made in regions of the fracture where fracture walls are parallel or sub-parallel (e.g., green arrows in Fig. 9), avoiding locations where fracture edges have been obviously rounded by erosion or chemical weathering, or where large pieces have been chipped off or are missing (e.g., red arrows in Fig. 9). If it is unclear if a portion of the fracture has chipped off (e.g., orange arrow in Fig. 9), a notation can be made and employed later to eliminate potential outliers in the dataset. Fractures greater than about 3 mm in width can be easily measured by inserting the back-blades of digital calipers into the widest opening of the fracture. For narrower fractures, a logarithmically binned ‘crack comparator’ (Fig. 7) is recommended (Ortega et al., 2006), whereby the line on the comparator most closely matching the fracture aperture is chosen.

5.4.3 Strike and dip

Fracture orientation (i.e., strike and dip) is a function of the orientation of existing anisotropy within the rock and the orientation of the principle stresses that drove its propagation. Fracture orientations are commonly related to tectonic forces; however, both gravitational and environmental stresses can also be directional (e.g., St. Clair et al., 2015; Mcfadden et al., 2005). When fractures are growing at subcritical rates, they can lengthen through a series of ‘jumps’ that link parallel or subparallel smaller fractures. The following suggestions are for research aimed not at characterizing these small mm-cm scale heterogeneities, but rather identifying major stresses and heterogeneity in the entire rock body.

Fracture orientation is measured with a geological compass or similar tool that has both azimuthal direction and inclinometer functionality. When measuring strike and dip of fractures, it is important to visualize how the fracture plane intersects the rock surface, as if slipping a sheet of paper into the ‘file folder’ of the fracture. For larger fractures, weathering and erosion may have resulted in loss of rock along the upper edge of the fracture, so it is imperative to measure the angle at the interior of the fracture where its walls are parallel (Fig. 9) to avoid measuring instead the angle of the eroded face.

Fractures grow until they intersect other fractures and/or branch. If fractures appear to intersect or branch (i.e., two connected planar voids with noticeably different orientations joined by a sharp angle), their lengths should be measured separately as well as their orientations (e.g., two strikes and dips) as previously mentioned. For fractures that meander around mm-cm scale heterogeneities like phenocrysts or fossils, the overall trend is measured. A 1 to 10 rule of thumb can be used whereby, as long as the ‘jog’ in the fracture orientation is <1/10 of the fracture length, it is not measured.

Fracture tip propagation direction may also slowly change as the orientation of external stresses or internal stress concentrations change withing the rock mass. For curvilinear fractures, the average orientation can be measured, as the orientation of the non-curved plane whose ends are defined by the ends of the fracture. Alternatively, the fracture curvilinear plane may be subdivided into roughly linear planes and each orientation measured. If this latter approach is taken, the intersection should be marked as a node, and two lengths recorded. It is important to note which method was employed and to remain consistent for all measurements.

There are numerous commonly-employed conventions for measurements of strike and dip. If the worker is consistent and clear in the use of their preferred convention and in the presentation of their data, any are acceptable. If the worker has no such prior habits, record strikes as an azimuthal orientation from 0-359 degrees, and dip angle as an angle deviation from horizontal of 0-90 degrees. For dip direction, a convention such as the "right-hand rule" should be employed whereby the dip direction is always known from the orientation of the strike alone. For example, the right-hand rule states that the down-dip direction is always to the "right" of the measured and recorded strike when the observer is facing the same direction of the strike. Therefore, the strike that is recorded is the one whereby the dip direction is always +90 degrees clockwise (to the right) from the strike direction.

5.4.4 Fracture parallelism

Noting the parallelism of the fractures can help to better understand the origins of the population of fractures at a site. Parallelism is common because fractures often follow rock heterogeneities or anisotropies such as bedding, foliation, veins, or even the rock surface. Fractures in a single bedrock outcrop or clast are also commonly parallel because they have formed due to external stress-loading with a consistent orientation (e.g., those related to tectonics or directional insolation). Thus, noting parallelism may help to distinguish the origins of fractures, though not always. For example, 'surface parallel fractures' (e.g., Fig. 2a) - commonly referred to as exfoliation, sheeting joints (e.g., Martel, 2017), or spalling – vary dramatically in scale and can have origins related to several different factors including tectonic-topographic interactions (Martel, 2006), chemical weathering and volumetric expansion (Røyne et al., 2008), and thermal stresses related to insolation (e.g., Lamp et al., 2017; Collins and Stock, 2016) and fire (e.g., Buckman et al., 2021).

In the fracture sheet, features to which the fracture is parallel should be documented. A visual inspection will suffice for most applications, but for applications where more precision is needed, the fracture may be considered parallel if the strike and dip of a fracture is within +/-10° of the orientation of the feature (the rock's long axis, its fabric, or its outer surface). A fracture may be parallel to more than one feature in the rock. Categories may be added as necessary for rocks with other repeating features unique to the field site (fossils; veins, etc.).

5.4.5 Sheet height

Surface parallel fractures naturally detach 'sheets' of rock between the fracture and the rock surface ('h' in Fig. 2a**).** The thickness of these sheets may be of interest for understanding the size of sediment produced from the fracture or for understanding the stresses that produced the fracture. Sheet height is measured using calipers at the location of the maximum height of the sheet and is only used for surface parallel fractures. To limit these measurements to those that have likely formed in situ as related to the current morphology of the rock, a rule of thumb is to only measure those 'sheets' that would result in removal of <10% from the outer surface of the rock downward into the dimension(s) of the rock face(s) to which they are perpendicular.

5.4.6 Weathering index

Rock fracture is ultimately a molecular scale bond-breaking process; so, when fractures propagate, they initially form a razor-sharp lip or edge. Over time, these edges naturally round through subsequent chemical and physical weathering, erosion, and abrasion (e.g., regions of the red arrows in Fig. 9). Following similar research that has demonstrated time-dependent changes in rock surface morphology due to such weathering processes (e.g., Shobe et al., 2017; Gómez-Pujol et al., 2006; McCarroll, 1991), we established an index of relative degree of such rounding along a fracture edge to be noted in the fracture sheet:

1: fresh with evidence of recent rupture (flakes/pieces still present, but not attached)
2: sharp, no rounded edges anywhere
3: mostly sharp with occasional rounded edges
4: mostly rounded edges with occasional sharp edges
5: all rounded edges

6 Suggestions for data analyses

For initial data exploration, normal cross-plots, or quantile-quantile plots, as well as standard correlation analysis may be applied to rock and fracture data. For categorical data, normal analytical techniques (histograms, discrete correlation analysis, etc.) can be applied. As with all heavy-tailed data, the median is preferred over the mean value to understand a characteristic value—though power distributed data generally does not have a characteristic dimension. Standard statistics such as mean, variance, skewness, and kurtosis all remain valid to explore and evaluate the datasets.

To understand fracture length and fracture width data, it is key to first recognize that, with the exception of studies such as in rocks with fractures with uniform spacing and bedding-controlled widths (Ortega et al., 2006), the data will have a heavy-tailed distribution, such as lognormal, gamma, or power law. As mentioned above, of these, strong observational and theoretical evidence suggests that fracture size is most commonly power law distributed (e.g., Bonnet et al., 2001; Davy et al., 2010; Hooker et al., 2014; Ortega et al., 2006; Zeeb et al., 2013), i.e.,

$$\boldsymbol{n(b) = Ab^{-\alpha}} \quad (1)$$

where b is the fracture dimension (length or width) of interest, n is the number of fractures with dimension d, and A and α are constants. When log-transformed, Eq. (1) becomes

$$\boldsymbol{\log\big(n(b)\big) = \log(A) - \alpha\log\,(b)} \quad (2)$$

which has led many practitioners to fit Eq. (2) by linearly binning the data in n, then log-transforming the data and fitting the resulting data with a linear regression. This has proven to lead to significant bias in estimates, $\hat{\alpha}$, of the power law exponent (Bonnet et al., 2001; Clauset et al., 2009; Hooker et al., 2014) and is not recommended despite its common usage.

Two straight-forward approaches have been shown not to have biases, or misestimates of the exponent α. 1) The following is based on Clauset et al. (2009). First, the exponent can be found from the cumulative distribution of the dimensions, C(b), or number of fractures with dimension greater than b, i.e.,

$$\boldsymbol{C(b) = \int_b^{b_{\max}} n(b)db} \quad (3)$$

Where b_{max} is the maximum size of the fracture dimension (e.g., maximum length or width). The cumulative power law distribution has the form

$$C(b) \propto b^{1-\alpha} \tag{4}$$

It is common to denote 1-α as c. To find α (or c), the dimension data is logarithmically binned. In other words, the dimension data is binned on a logarithmic (1, 10, 100, …) frequency scale, and then log-transformed. At this point, linear regression techniques can be applied to estimate α and assess uncertainty. However, in all cases, uncertainty estimates such as R^2 will overestimate the certainty for such log-transformed data; but at least the estimate of α is unbiased.

2) Another method to find α from a data set of fracture dimensions is to use the maximum likelihood estimator (MLE) given by

$$\hat{\alpha} = 1 + N\left[\sum_{i=1}^{N} \ln\left(\frac{b_i}{b_{min}}\right)\right]^{-1} \tag{5}$$

where $\hat{\alpha}$ is the estimate of the exponent in (1), b_i is the dimension of the ith fracture, b_{min} is the minimum valid fracture dimension (see below) and N is the total number of samples (Clauset et al., 2009; Hooker et al., 2014). The MLE estimate has the advantage of an accurate estimate of standard error, σ, given by

$$\sigma = \frac{\hat{\alpha}-1}{N} + O\left(\frac{1}{N}\right). \tag{6}$$

Clauset et al. (2009) showed that both the logarithmically-binned cumulative distribution and the MLE estimator produce unbiased estimates of the exponent. For all empirical power law distributions, there is a scale; in this case b_{min}, below which power law behavior is not valid. This can be visually assessed by plotting Eq. 2 with logarithmically binned n. The interval between b_{min} and b_{max} where the slope is linear is where the power law is valid (Clauset et al., 2009; Ortega et al., 2006), and Clauset et al. (2009) presents a formal method to find b_{min} and b_{max}. Hooker et al. (2014) use a chi^2 test to evaluate the goodness of fit, which is simpler than the p-tests of the Kolmogorov-Smirnov statistic proposed by Clauset et al. (2009).

6.1 Fracture number density and fracture intensity

Here, following large portion of fracture mechanics literature and for clarity, the term ‘fracture number density’ is employed to refer to the number of fractures per unit area (e.g., # fractures/m^2), and the term ‘fracture intensity’ to the sum length of all fractures per unit area (e.g., cm/m^2). However, it is crucial to note that these terms are frequently defined differently and in inconsistent ways across disciplines and even within disciplines (e.g., Barthélémy et al., 2009; Narr and Lerche, 1984; Ortega et al., 2006; Dershowitz and Herda, 1992). It is imperative that workers clearly define their usage in each work.

In the suggested use herein, the ‘area’ refers to the surface area of observation area. For fractures measured in ‘windows’ (Sect. 3.4), the length of fractures only *within* the window is used, and the area of the window (e.g., 10 cm x 10 cm) for the calculations. For loose clasts and outcrops, the appropriate calculation of surface area will depend on the shape and angularity of the rock. For most rocks, calculations for the surface area of the exposed sides of a rectangular cuboid (L*W + 2*(L*H) + 2*(W*H)) are appropriate.

6.2 Circular data

Standard 'linear' statistics cannot be employed for circular data. Instead, circular statistical and plotting software can be used for the visualization and analysis of strike and dip data. The statistics employed by such software is typically based on established circular statistical research methods (e.g., Mardia and Jupp, 1972; Fisher, 1993). The following statistics are useful in reporting strike and dip data.

The Mean Resultant Direction (a.k.a. vector mean, mean vector) is analogous to the slope in a linear regression. Circular variance can be quantified using either a Rayleigh Uniformity Test (for single mode datasets) or a Rao Spacing Test (for datasets with multiple modes), whereby p-values <0.05 indicate non-random orientations. If p-values for these tests are below a threshold (e.g., <0.05), then data are considered non-uniform or non-random.

The Rayleigh statistic is based on a von Mises distribution (i.e., a normal distribution for circular data) of data about a single mean (i.e., unimodal data). Therefore, for multi-modal data, the variance might be high, but nevertheless, the data might be non-uniform. The Rayleigh Uniformity Test calculates the probability of the null hypothesis that the data are distributed in a uniform manner. Again, this test is based on statistical parameters that assume that the data are clustered about a single mean.

Rao's Spacing Test is also a test for the null hypothesis that the data are uniformly distributed; however, the Rao statistic examines the spacing between adjacent points to see if they are roughly equal (random with a spacing of 360/n) around the circle. Thus, Rao's Spacing Test is appropriate for multi-modal data and may find statistical significance where other tests do not.

8 Case example

To demonstrate the consistency of results that might be achieved across users, we provided minimal training (one demonstration with some minor oversight of initial work) to four groups of two students each. The fifth pair of workers included a scientist who had logged over 500+ hours of experience using the standardized methods. Each of the five groups followed the methods to measure the length and abundance of fractures on boulders (15-50 cm max diameter) on the same geomorphic surface (a 6000-year-old alluvial fan in Owens Valley California, comprised of primarily granitic rock types). Each group followed the methods described herein for rock and fracture selection and measurements. As such, the results from each group (Fig. 10; Data Supplement) could be compared not only for fracture selection and measurements, but also for observation area selection – a key component of collecting data that is representative of a particular site.

We find that the data collected by each of the groups for fracture length, number of fractures per rock, and rock size are statistically indistinguishable by student t-test (all pairs of p-values > 0.1; Fig. 10; Data Supplement). Also, there is no consistent difference between measurements made by the novice groups and that of the trained group. The mean fracture lengths from the four novice groups novice group (37±23 mm to 59±51 mm) span across that of the mean collected by the well-trained group (42±22 mm; Supplement), as do the number of fractures per rock (2±2 to 6±8 for novice groups compared to 3±3 for trained group). With only one exception (fracture length for Group 1), variance between groups does not range by more than a factor of 3 in any of the data – a common rule of thumb for the threshold of 'similar' variance between small datasets. Overall, especially given the relatively small size of the datasets (~10-20 rocks and ~40-60 fractures each), this comparison suggests that the results using the standardized methods are reproducible, even with novice workers with minimal training.

9 Conclusions

The methods proposed herein comprise a ‘first stab’ at standardization of field data collected in rock fracture research surrounding surface processes and weathering-based geologic problems. The outlined methods comprise best practices derived in large part from existing work in the context of structural geology and fracture mechanics. They also comprise general guidance and nuances developed from experiences (and mistakes) over the last two decades of fracture-focused field research applied to geomorphology and soil science. It is our hope that providing these rules-based, detailed, accessible, standardized procedures for gathering and reporting field-based fracture data will open the door to rapidly building a rigorous galaxy of new datasets as these guidelines and methods become more widely adopted. In turn, they may enable future workers to better compare and merge fracture data across a wide range of studies, permitting future refinements of our understanding of rock fracture and in the methods themselves. Compiling such a standardized global dataset is the best hope for fully characterizing the role and nature of fractures in Earth surface systems and processes.

10 Author Contributions

MCE spearheaded the evolution of the development of the guiding principles and methods described herein as well as writing of the manuscript. JA, SB, MD, SE, FM, SP, MR, and US all participated extensively in field campaigns during which the methods were developed and refined, and they contributed to editing of manuscript and editing and development of figures. MM, AR and RK contributed to the development of theoretical statistical analyses practices that are outlined in the document and the editing of the manuscript.

11 Competing interests

The authors declare that they have no conflict of interest.

12 Data Availability

All data presented in the manuscript are available in the Supplement.

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Figure Captions

Fig. 1. Images illustrating the selection of observation areas for clasts and outcrops. A. Photograph of a transect established for clast selection. Black dot: predefined transect interval location on the tape. Red dot: clast that does not fit the predefined clast selection criteria (e.g., it is too big). Green dot with red circle: clast that fits criteria but is further away from the interval point that the clast with the green dot. Green dot: closest clast to the transect interval that meets the selection criteria. B. Annotated photograph showing an idealized placement of 'windows' (dashed black squares) on a bedrock outcrop. Outcrop dimensions are measured and the windows are placed using predetermined selection criteria. In this example, the windows are equally spaced along the centerline of the long-dimension of the upward-facing side of the outcrop.

Fig. 2. A. Example of the measurement of a surface exposure length (L; yellow line) of a fracture meeting the criteria in Table 1. The 'h' refers to the location where sheet height would be measured for this surface parallel fracture. B. Example of fractures that may appear to be a single fracture (left), but upon close examination are in fact multiple fractures intersecting and/or separated by rock (right inset). Arrow points to the location of the inset image on the main image. Compass in the foreground for scale.

Fig. 3. Example histograms and statistics of fracture length data measured on the exposed surfaces of clasts 15-50 cm max diameter. Upper row are data for clasts found on a modern ephemeral stream boulder bar. Clasts overall have very low fracture number density. Lower row are data for clasts on an ~6 ka surface where fracture number density is much higher. Note that it takes about 100 clasts to arrive at a statistically significant power law distribution for the Modern Wash clasts, but only 5 rocks for the rocks with higher fracture densities. Producing histograms interactively as data is collected can help establish how many observation areas are necessary for a given site.

Fig. 4. Reduced size image of an 8.5" x 11" 'fracture sheet' to be employed in the field to increase efficiency and to reduce 'missing' data. Sheet templates for both clasts and outcrops that can be modified are provided in Data Supplement as well as a data-entry template.

Fig. 5. Visual aide for estimating the abundance of "countable" rock features – including fractures. An index of 0-4 is assigned depending on the abundance of features within an average of any given observation area (ex: 10 x 10 cm) on the clast or window being examined. The area of observation is defined by the size of the features being measured. A 10 cm x 10 cm square is used for estimating the abundance of 'fractures < 2 cm' defined as fractures with lengths of >0.5 cm but < 2 cm (see section 5.2 for details of how to use the index). For features ≤0.5 cm, a 1 cm x 1 cm area would be employed and for features ≥2 cm, a 1 x 1 m area.

Fig. 6. A visual percent estimator (modified from Terry and Chilingar, 1955). Estimator should be employed in every estimate of percentages. See section 5.2 for using the estimator to assign a percent coverage index to features that are not countable or vary in size (e.g., lichen coverage, fine mafic minerals, etc.).

Fig. 7. **Inset:** Roundness and sphericity chart – modified from Krumbein and Sloss (1951). **Roundness:** A = angular; SA = subangular; SR = subrounded; R = rounded; WR = well-rounded. **Sphericity:** S = spherical; SS = subspherical; SE = sub-elongate; E = elongate. **Edges:** fracture comparator whereby the width most closely matching the fracture aperture is noted. Note: a to-scale pdf is available in the Data Supplement, however, owing to printing and publication scaling, it is highly recommended to calibrate the comparator prior to using it in the field.

Fig. 8 Depiction of types of fracture intersection nodes. I-nodes comprise fracture terminations with no connections. Y-nodes are abutting fractures that do not cross. X-nodes are fractures that cross. C-nodes are 'contingent nodes' defined by the user. In this example the rule is related to the distance between I-nodes. For #1, the distance is wider than the criteria, so the terminations are designated as I-nodes. For #2, the distance is within the limits, and the 'connection' is designated as a C-node.

Fig. 9. Examples of aperture transects that are appropriate for measurement of fracture aperture widths (green) and transects where there is evidence that the fracture walls have been eroded or chipped and therefore should not be employed for a width

measurement (red). In cases where it is not clear if erosion or chipping has occurred (orange), a note can be made for the fracture width to possibly eliminate outliers during data analysis.

Fig. 10. Box and whisker plots of case example data collected by five different pairs of workers on the same geomorphic surface. “x”s mark the means. Groups 1-4 were novice workers. Group 5 comprised one experienced worker. A. Fracture lengths B. Fractures per rock C. Clast length

Table 1. List of proposed rule-based criteria for defining measurable fractures

The answer to the following questions must be 'yes' for all measured fractures. Measure <u>all fractures meeting these criteria</u> within the observation area.	**<u>NOTES</u>**
• Is the feature a lineament longer than it is wide? • Does the lineament contain open space bounded by walls? • If the lineament is not open, can the infilling material (ex: dust and lichens) be readily scraped out? • If the lineament is open or after the material has been scraped out, is the opening deeper than it is wide <u>and</u> bounded by ~parallel walls? • Is the open portion of the lineament ≥2 cm (>10 grains) in length (without interrupting bridges of rock or cemented infilling material)?	Do not measure: • Spherical pores/vesicles. • Lineaments, or portions of lineaments, with solid mineral infilling/cement. • Ledge edges or linear etchings. • rock bridges between fractures

Table 2. List of proposed data to collect for the rock observation area and for all fractures ≥2 cm in length

Rock Observations	**Individual Fracture Observations**
• Dimensions of the observation area (e.g. clast, outcrop, and/or window length, width, height) • Rock type • Grain size • Mineralogy % (minimally felsic vs. mafic) • Sphericity of exposure • Roundness of exposure • Fabric description, strike, and dip (e.g. vein, foliation, bedding) • Granular Disintegration • Pitting • Lichen and Varnish • Fracture Connectivity • Fracture Spacing	• Length (surface exposure length measured with a flexible tape) • Aperture width: center and maximum widths measured with calipers and/or comparator • Strike 0-360º (right-hand rule preferred) • Dip 0-90º • Parallelism (note features parallel to the fracture such as fabric, rock faces) • Sheet height (the thickness of what would be the detached spall or sheet of rock above a surface parallel fracture) • Weathering Index

Table 3. List of field equipment

Required	**Recommended**
• Hand lens (large, 10x) • Grain size card • Fracture comparator (for fracture widths) • Flexible seamstress tape measure (with mm) • Calipers (mm 0.0 to 150) • Brunton or similar compass • Roundness and sphericity chart • Visual percentage estimator • Fracture sheets	• Camera with macro lens • Chalk for marking measured fractures and windows • Safety pin or needle for fracture exploration • Cardboard cutout frames for windows • Small white board or chalk board for including observation area ID in photos

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FIGURE 1

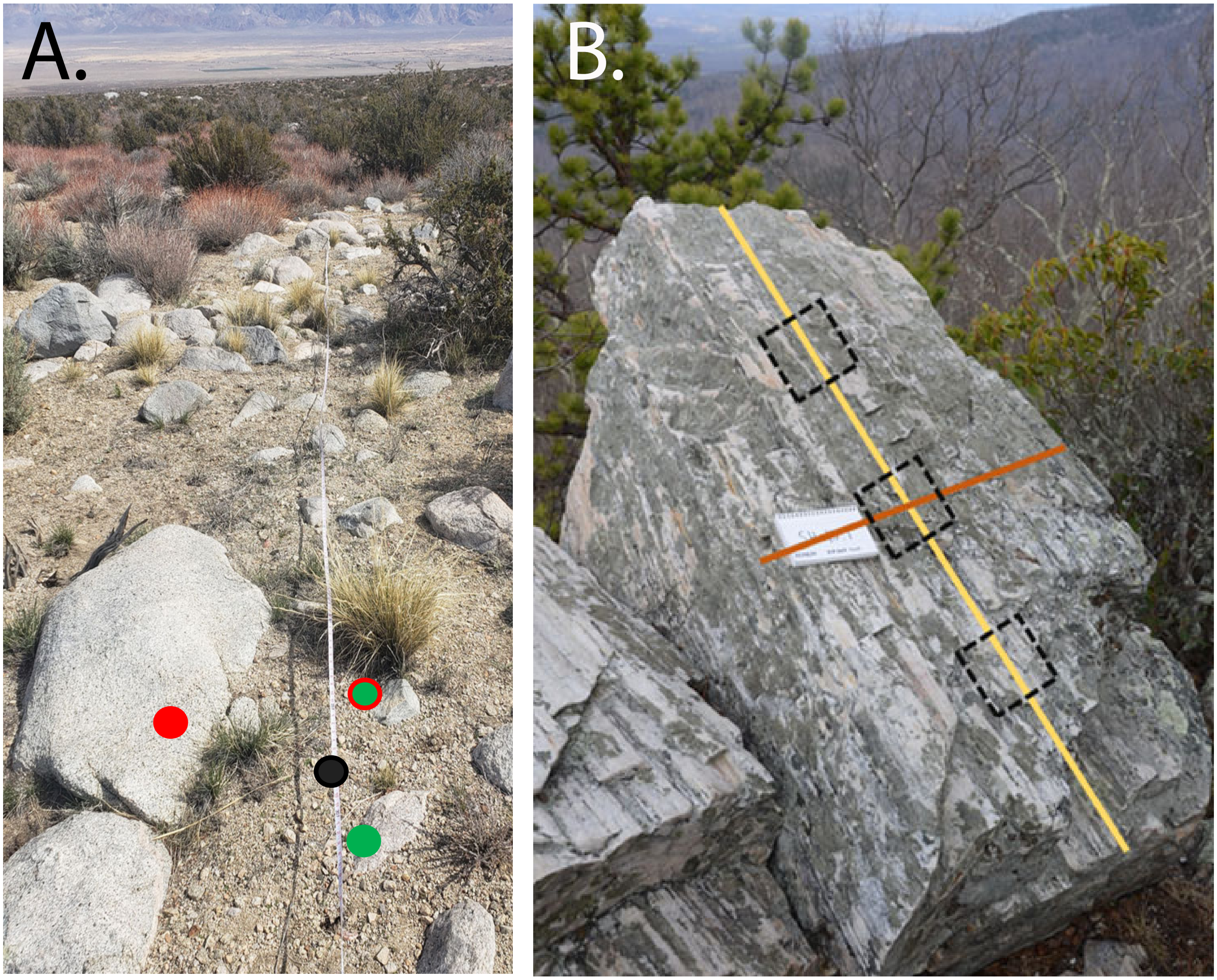


FIGURE 2

FIGURE 3

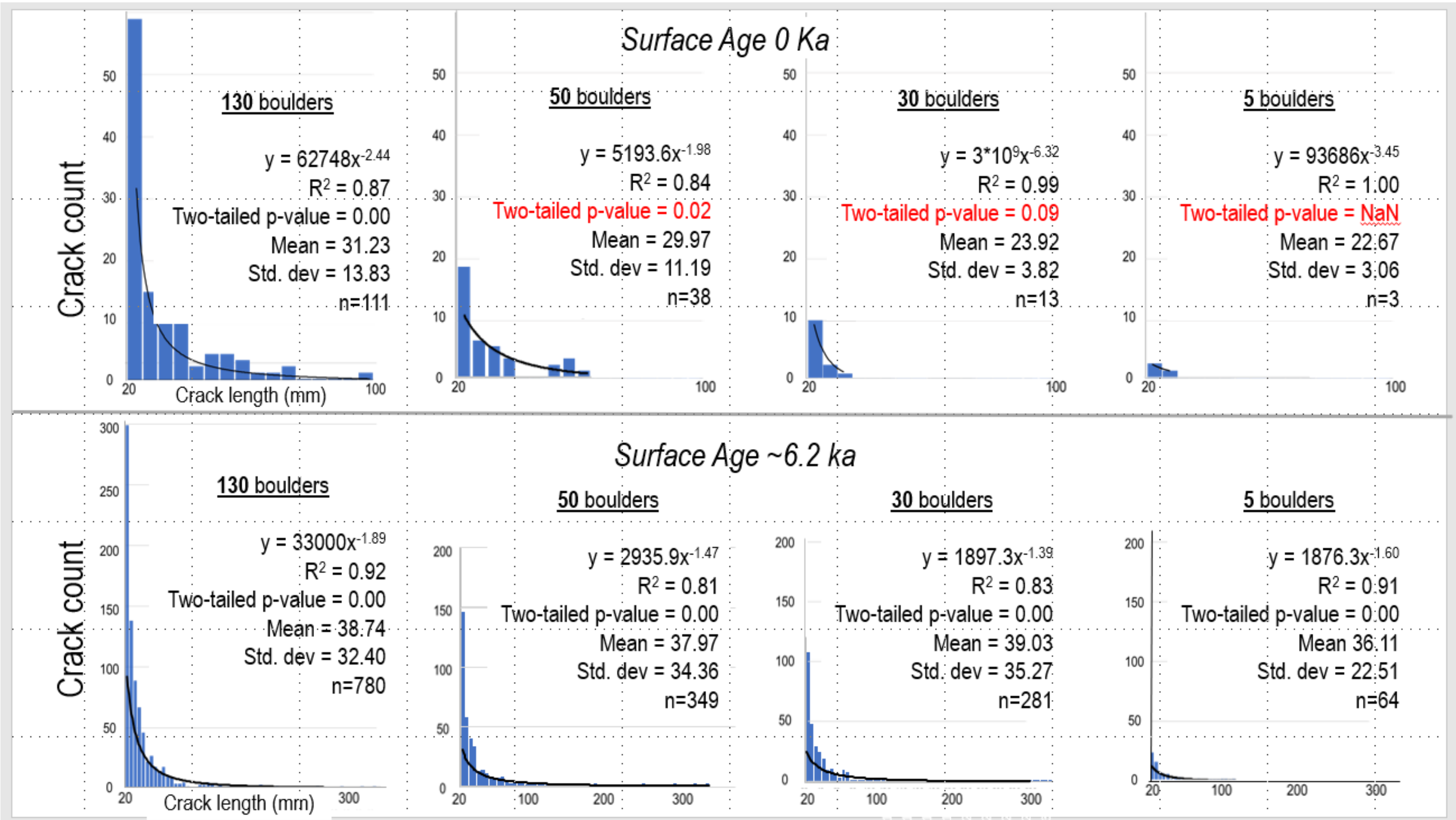


Fig. 3

FIGURE 4

Name(s) & Date:
Site Name:
GPS Cooridnates:
GPS Projection:
Orientation conventions:
Declination:

Criteria for Clast/Outcrop selection:

Portion observed (eg. All exposed, north face only, etc.):

Relevant Cl, O, R, P, T,T observations:
Vegetation-type & percent of each:
open ground cover (%):
Surface Slope:
Other:

ID & Rock Type	Avg. Grain Size (mm)	spheri-city/ round-ness	Minerology	Length (cm)	Width (cm)	Height (cm)	Exposure	Cracks <2 cm	GD & Pit	Lichen	Varnish	Fabric Type	Fabric Strike (°)	Fabric Dip (°)	Crack ID	Crack Parallel to	Mid Crack Width (mm)	Crack Max Width (mm)	Crack Length (mm)	Crack Strike (°)	Crack Dip (°)	Sheet Ht. (mm)	Weathering Index	Notes
		s- r-					0 1 2 3	0 1 2 3 4 5	g p	0 1 2 3 4 5	0 1 2 3 4 5	F S B V O				S F L							1 2 3 4 5	
		s- r-					0 1 2 3	0 1 2 3 4 5	g p	0 1 2 3 4 5	0 1 2 3 4 5	F S B V O				S F L							1 2 3 4 5	
		s- r-					0 1 2 3	0 1 2 3 4 5	g p	0 1 2 3 4 5	0 1 2 3 4 5	F S B V O				S F L							1 2 3 4 5	
		s- r-					0 1 2 3	0 1 2 3 4 5	g p	0 1 2 3 4 5	0 1 2 3 4 5	F S B V O				S F L							1 2 3 4 5	
		s- r-					0 1 2 3	0 1 2 3 4 5	g p	0 1 2 3 4 5	0 1 2 3 4 5	F S B V O				S F L							1 2 3 4 5	
		s- r-					0 1 2 3	0 1 2 3 4 5	g p	0 1 2 3 4 5	0 1 2 3 4 5	F S B V O				S F L							1 2 3 4 5	
		s- r-					0 1 2 3	0 1 2 3 4 5	g p	0 1 2 3 4 5	0 1 2 3 4 5	F S B V O				S F L							1 2 3 4 5	
		s- r-					0 1 2 3	0 1 2 3 4 5	g p	0 1 2 3 4 5	0 1 2 3 4 5	F S B V O				S F L							1 2 3 4 5	
		s- r-					0 1 2 3	0 1 2 3 4 5	g p	0 1 2 3 4 5	0 1 2 3 4 5	F S B V O				S F L							1 2 3 4 5	
		s- r-					0 1 2 3	0 1 2 3 4 5	g p	0 1 2 3 4 5	0 1 2 3 4 5	F S B V O				S F L							1 2 3 4 5	
		s- r-					0 1 2 3	0 1 2 3 4 5	g p	0 1 2 3 4 5	0 1 2 3 4 5	F S B V O				S F L							1 2 3 4 5	
		s- r-					0 1 2 3	0 1 2 3 4 5	g p	0 1 2 3 4 5	0 1 2 3 4 5	F S B V O				S F L							1 2 3 4 5	
		s- r-					0 1 2 3	0 1 2 3 4 5	g p	0 1 2 3 4 5	0 1 2 3 4 5	F S B V O				S F L							1 2 3 4 5	
		s- r-					0 1 2 3	0 1 2 3 4 5	g p	0 1 2 3 4 5	0 1 2 3 4 5	F S B V O				S F L							1 2 3 4 5	
		s- r-					0 1 2 3	0 1 2 3 4 5	g p	0 1 2 3 4 5	0 1 2 3 4 5	F S B V O				S F L							1 2 3 4 5	
		s- r-					0 1 2 3	0 1 2 3 4 5	g p	0 1 2 3 4 5	0 1 2 3 4 5	F S B V O				S F L							1 2 3 4 5	
		s- r-					0 1 2 3	0 1 2 3 4 5	g p	0 1 2 3 4 5	0 1 2 3 4 5	F S B V O				S F L							1 2 3 4 5	
		s- r-					0 1 2 3	0 1 2 3 4 5	g p	0 1 2 3 4 5	0 1 2 3 4 5	F S B V O				S F L							1 2 3 4 5	
		s- r-					0 1 2 3	0 1 2 3 4 5	g p	0 1 2 3 4 5	0 1 2 3 4 5	F S B V O				S F L							1 2 3 4 5	
		s- r-					0 1 2 3	0 1 2 3 4 5	g p	0 1 2 3 4 5	0 1 2 3 4 5	F S B V O				S F L							1 2 3 4 5	
		s- r-					0 1 2 3	0 1 2 3 4 5	g p	0 1 2 3 4 5	0 1 2 3 4 5	F S B V O				S F L							1 2 3 4 5	
		s- r-					0 1 2 3	0 1 2 3 4 5	g p	0 1 2 3 4 5	0 1 2 3 4 5	F S B V O				S F L							1 2 3 4 5	
		s- r-					0 1 2 3	0 1 2 3 4 5	g p	0 1 2 3 4 5	0 1 2 3 4 5	F S B V O				S F L							1 2 3 4 5	
		s- r-					0 1 2 3	0 1 2 3 4 5	g p	0 1 2 3 4 5	0 1 2 3 4 5	F S B V O				S F L							1 2 3 4 5	
		s- r-					0 1 2 3	0 1 2 3 4 5	g p	0 1 2 3 4 5	0 1 2 3 4 5	F S B V O				S F L							1 2 3 4 5	
		s- r-					0 1 2 3	0 1 2 3 4 5	g p	0 1 2 3 4 5	0 1 2 3 4 5	F S B V O				S F L							1 2 3 4 5	
		s- r-					0 1 2 3	0 1 2 3 4 5	g p	0 1 2 3 4 5	0 1 2 3 4 5	F S B V O				S F L							1 2 3 4 5	
		s- r-					0 1 2 3	0 1 2 3 4 5	g p	0 1 2 3 4 5	0 1 2 3 4 5	F S B V O				S F L							1 2 3 4 5	
		s- r-					0 1 2 3	0 1 2 3 4 5	g p	0 1 2 3 4 5	0 1 2 3 4 5	F S B V O				S F L							1 2 3 4 5	

Cracks <2 cm: Evidence of microcracks <2 cm long. 0 = 0; 1 = <1/dm^2; 2 = 1-5/dm^2; 3 =5-10/dm^2; 4=≥10/dm^2

GD & Pit: G = positive **e**vidence of granular disentigration (loose grains) **P** = pitting evident

Crack Length defined as total exposed length of the crack; equivalent to a surface exposure length NOT a 'caliper' length.

Fabric type: f=foliation; **s**=fossils; **b**=bedding; **v** = vein or dyke **o**=other

Lichen&varnish: 0 = 0%, 1=>0and<10; 2=>10 and<30; 3=>30 and<60; 4 = >60 and <90; 5 =>90

Avg. Grain Size = representative size of grains throughout the boulder

Parallel: S = surface, F = fabric, L = long axis of clast or outcrop

Sheet Ht = the height of the spall or exfolation resulting from a surface-parallel crack; n/a for other cracks

Crack Parallel to: S: Surface, F: Fabric (joints, bedding); L = long axis

weathering Index:

0 = no crack (step)

1: fresh with evidence of recent rupture (flakes/pieces)

2: sharp, no rounded edges anywhere

3: mostly sharp with occasional rounded edges

4: mostly rounded edges with occasional sharp

5: all rounded edges

NOTE: 0, or 1 must have clear evidence of a recent break: i.e. small pieces left

Exposure

use angle of the boulder at the ground

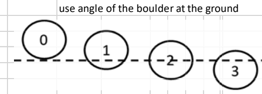


FIGURE 5

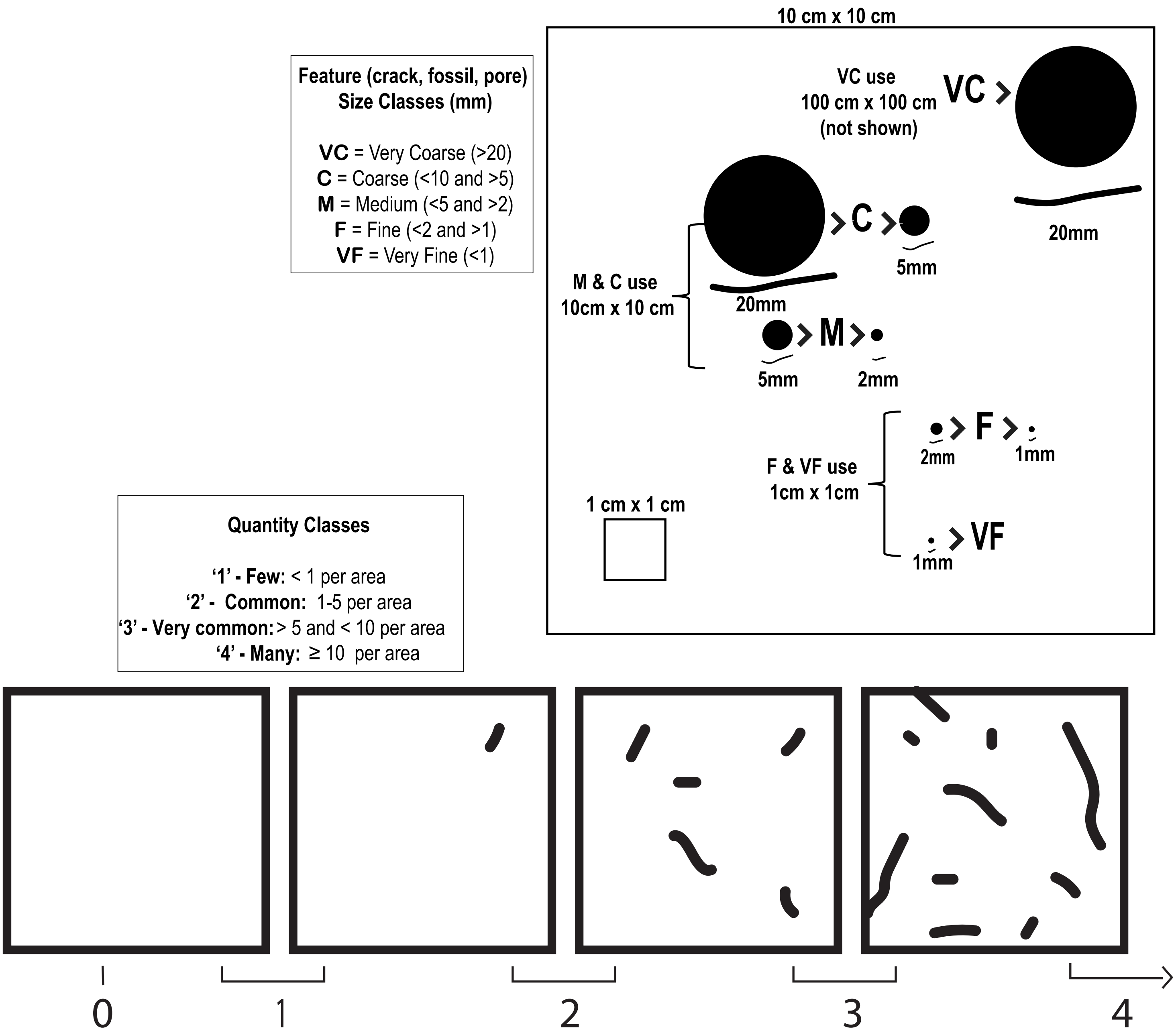

Feature (crack, fossil, pore)
Size Classes (mm)
VC = Very Coarse (>20)
C = Coarse (<10 and >5)
M = Medium (<5 and >2)
F = Fine (<2 and >1)
VF = Very Fine (<1)
10 cm x 10 cm
VC use
100 cm x 100 cm
(not shown)
VC
20mm
C
5mm
20mm
M & C use
10cm x 10 cm
M
5mm
2mm
F
2mm
1mm
F & VF use
1cm x 1cm
VF
1mm
1 cm x 1 cm
Quantity Classes
'1' - Few: < 1 per area
'2' - Common: 1-5 per area
'3' - Very common: > 5 and < 10 per area
'4' - Many: ≥ 10 per area
0
1
2
3
4

FIGURE 6

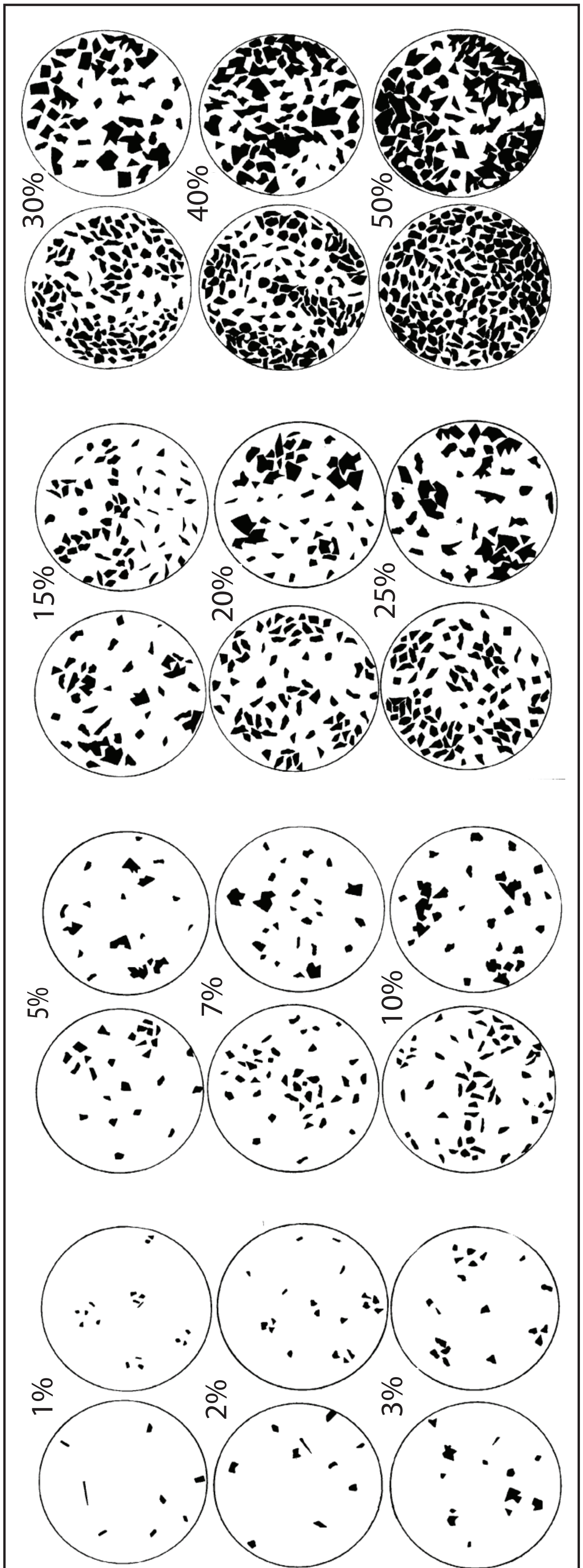
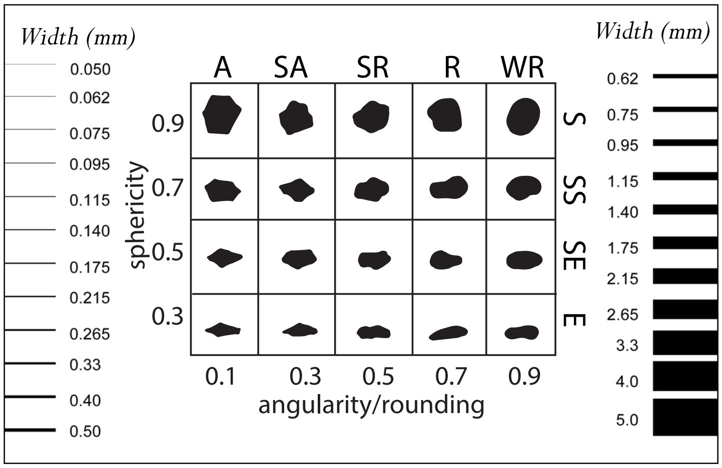


FIGURE 7



note to copy-editor: this figure should be published to scale when the document is viewed at 100%

FIGURE 8

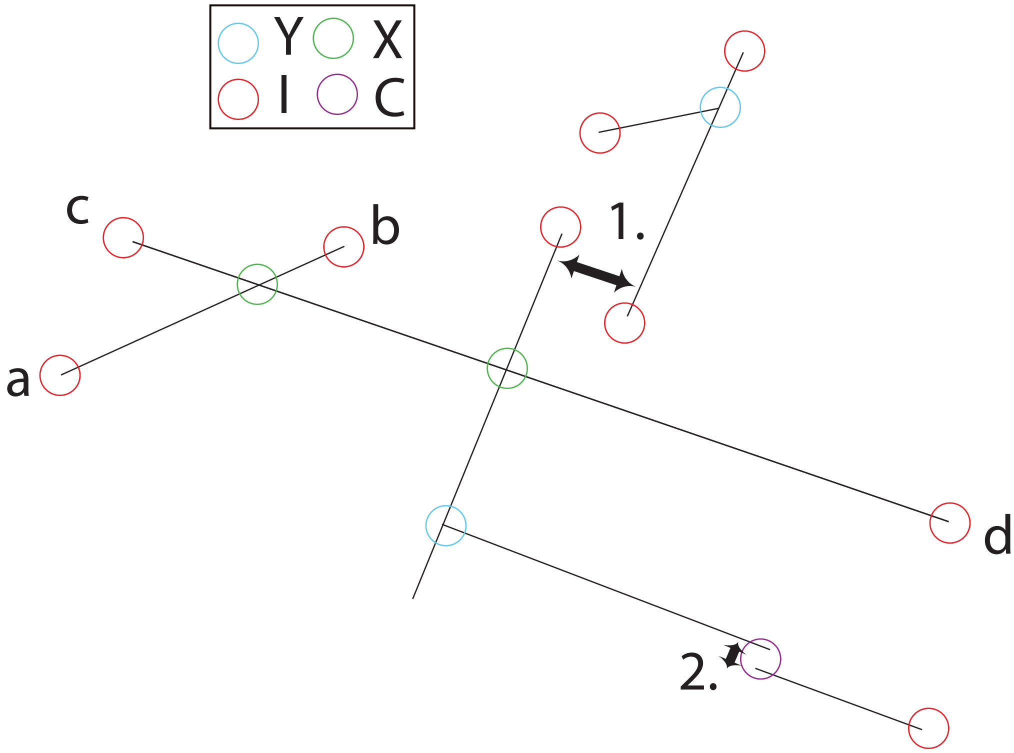


FIGURE 9

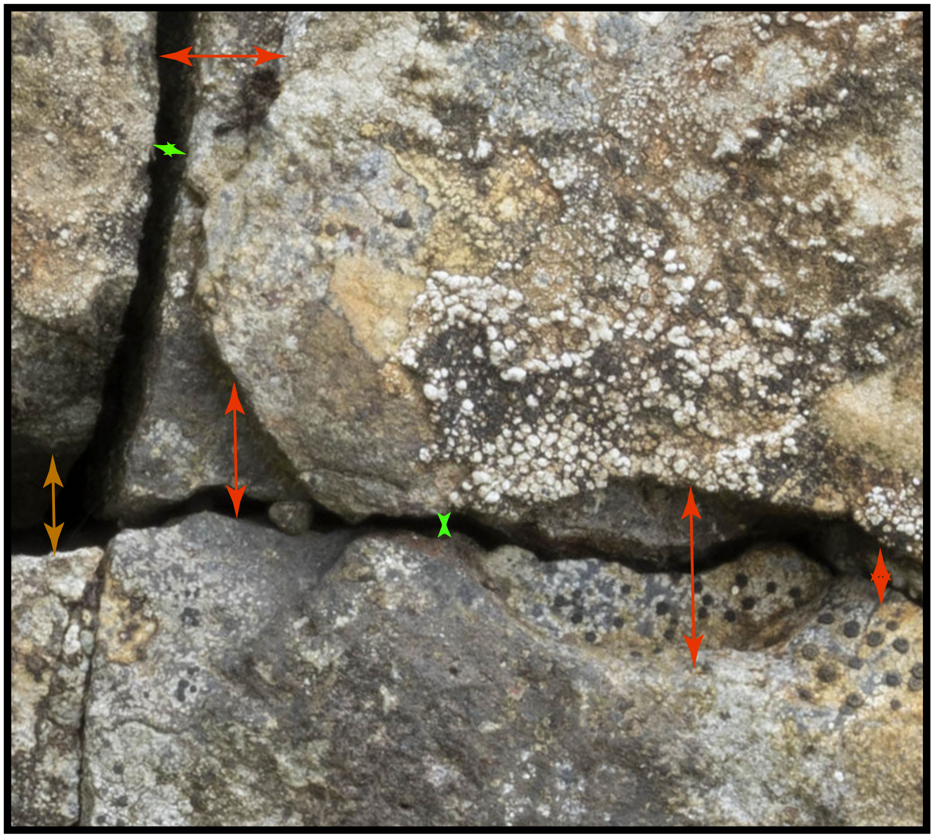
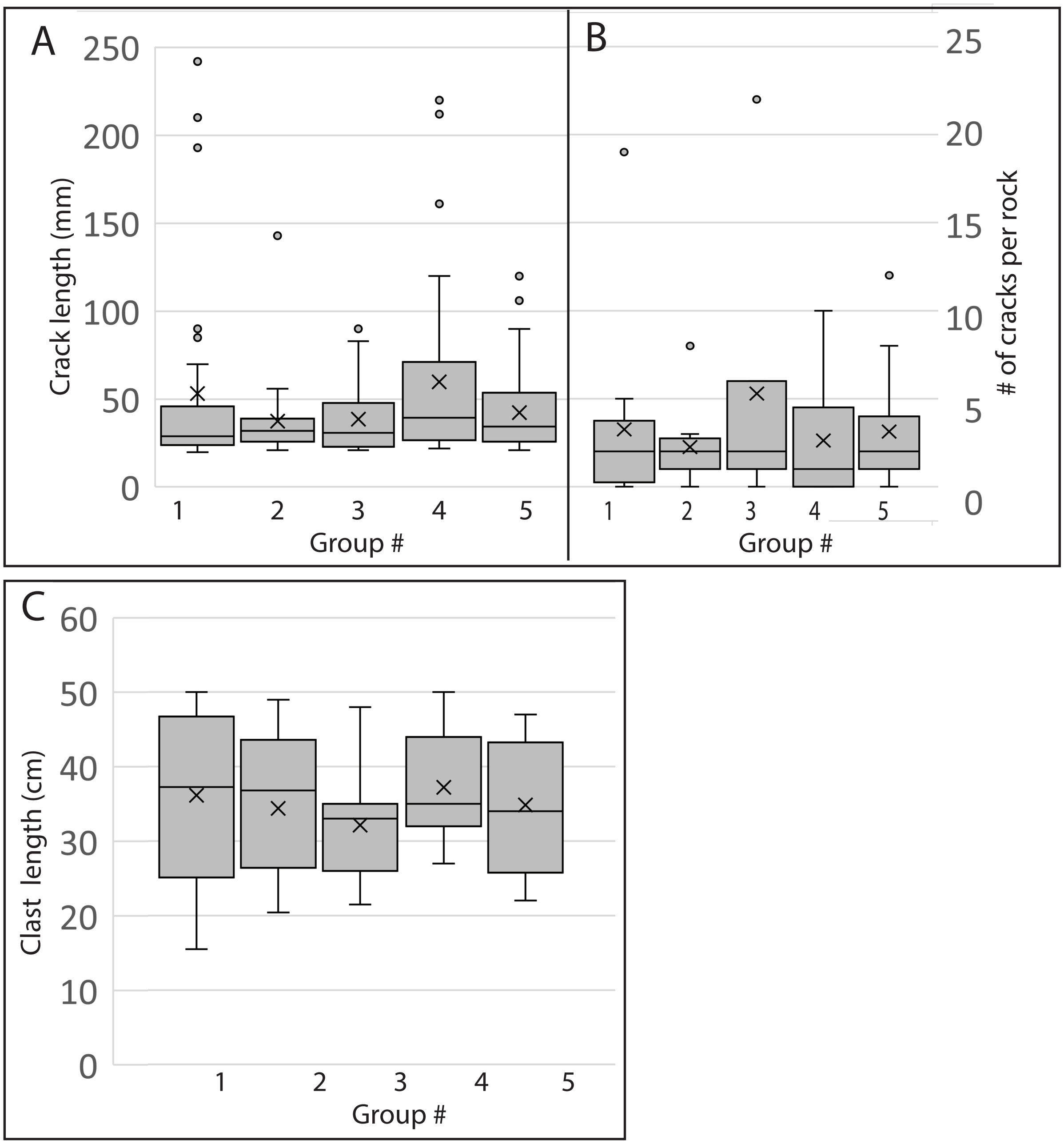


FIGURE 10



A
250
200
150
100
50
0
Crack length (mm)
1
2
3
4
5
Group #
B
25
20
15
10
5
0
# of cracks per rock
1
2
3
4
5
Group #
C
60
50
40
30
20
10
0
Clast length (cm)
1
2
3
4
5
Group #