CONSERVATION AND MANAGEMENT OF ARCHAEOLOGICAL SITES
https://doi.org/10.1080/13505033.2022.2133790

Routledge
Taylor & Francis Group

Check for updates

Threshold of Weathering Needed for Fire to Erode Rock Art: Case Study of a Hohokam Petroglyph, Central Arizona, USA

Ronald I. Dorn[a] and David S. Whitley[b]

[a]School of Geographical Sciences and Urban Planning, Arizona State University, Tempe, AZ, USA; [b]ASM Affiliates, Tehachapi, CA, USA

ABSTRACT

A Sonoran Desert petroglyph panel experienced an intense wildfire event in July 2021 that eroded the entire surface, removing the Hohokam-style rock art. Field observations during sampling in 1995 indicated that the panel: (1) was coated with a heavy rock varnish, (2) had a 'fresh' visual appearance, and (3) had some granite-derived sand (angular grus) at the panel's base. Micron-scale back-scatter and nanoscale transmission electron microscopy of pre-fire samples revealed a minimal amount of decay (granite grussification): mainly minor grain-to-grain separation; minor internal dissolution; and a little feldspar grain cracking. Our basic finding is that even this minimal amount of grussification was enough to set the stage for the wildfire to erode the entire panel. Pre-fire micron-scale cracking may have enabled the fire's steep thermal gradient to spall the surface. Panel erosion was likely enhanced by pre-existing grain-to-grain porosity to facilitate further fire-induced granular disintegration. Pre-fire nanoscale dissolution within mineral grains, formed along crystal defects, provided a weakness that then led to grain cracking of quartz and other granitic minerals. The implication for the conservation of rock art on granitic panels is worrisome, but clear and simple: condition assessments need to indicate whether any granitic sand occurs at a panel's base. Given that many places experiencing climate change are also experiencing drought and enhanced risk from wildfire, the appropriate management recommendation would then be to remove all vegetation near the panel on a regular basis.

KEYWORDS
grus; mechanical weathering; petroglyphs; physical weathering; site management; sustainable practices

Introduction

A growing scientific consensus holds that the world is experiencing significant climatic change. The ongoing drought in southwestern North America, for example, may be the most severe such climatic event since 800 CE, with perhaps a fifth of this change resulting from anthropogenic effects (Williams, Cook, and Smerdon 2022; Williams et al. 2020). One manifestation of this change is an increase in the number, intensity, and distribution of wildfires. Between 1972 and 2018, for example, there has been a fivefold increase in the annual burned area within the state of California (Williams et al. 2019), with the global burnable area estimated to have doubled between 1979 and 2013 (Jolly et al. 2015). These

CONTACT Ronald I. Dorn ronald.dorn@asu.edu

figures link, in part, to longer annual fire seasons and the growing number of days reaching extreme fire indices levels (Goss et al. 2020; Zhuang et al. 2021). A recent United Nations report found that by 'the end of the century, the likelihood of catastrophic wildfire events will increase by a factor of 1.31 to 1.57. Even under the lowest emissions scenario, we will likely see a significant increase in wild events' (United Nations Environment Program 2022, 10).

One implication of increasing wildfires is a change in the threat to (and potential destruction of) archaeological sites. Although sites of all kinds are potentially at risk, rock art sites are especially endangered from wildfire. Rock art is landscape art, typically pictographs (paintings) or petroglyphs (engravings) placed on natural rock surfaces (Whitley 2005). The issue is global with recent scholarship examples including Australia (Franklin 2014; May et al. 2015), South Africa (Hall 2009) and Spain (Pozo-Antonio et al. 2018). Although sometimes equated with 'cave art', in our focus region of western North America rock art is more commonly found on open rock boulders and cliff faces. These contexts are often exposed to all of the elements, including wildfires.

The most common approach to rock art site management in North America has been passive preservation (Whitley 2001), following the logic that the sites have achieved a kind of natural equilibrium with their physical environment given that many of them have retained their integrity for hundreds if not thousands of years. Despite this tendency, site condition assessments reveal a host of different natural and anthropogenic processes that can damage or lead to the loss of rock art (Allen et al. 2011; Dorn et al. 2008; Fitzner, Heinrichs, and LaBouchardiere 2004; Groom et al. 2019; Loubser 2001; Pillans and Fifield 2013; Pope 2000; Sampietro-Vattuone and Peña-Monné 2021). In the past decade, awareness increased among rock art scholars that climate changes can directly or indirectly lead to rock art damage, particularly by wildfires (Carmichael 2016; Carmichael et al. 2018; Giesen, Mazel, et al. 2014; Giesen, Ung, et al. 2014; Huntley et al. 2021).

Climate variability and climate changes set the stage for wildfires by enhancing natural swings between wet periods followed by extreme drought (Collier and Webb 2022; Dai, Zhao, and Chen 2018; Post and Knapp 2020; Todhunter, Jackson, and Mahmood 2020). This creates an abundance of fuel that then becomes tinder dry. Invasive grass species are another key factor in western North American wildfires. The Sonoran Desert of Arizona, for example, did not experience extensive wildfires naturally (Humphrey 1963; McDonald and McPherson 2013; Narog, Koonce, and Cocoran 1995; Shyrock, Esque, and Chen 2015). Even though lightning strikes occur in the region during the North American monsoon summer season, sparse vegetation cover naturally inhibited the spread of fires in this region (Humphrey 1963; McDonald and McPherson 2013; Narog, Koonce, and Cocoran 1995; Shyrock, Esque, and Chen 2015). This changed with the invasion of exotic annual grasses such as *Bromus tectorum* and *Bromus madritensis ssp. Rubens*, altering natural grass/fire cycles (Aslan et al. 2021; Brooks and Pyke 2001). Native scrub replacement by invasive grasses produces abundant fine fuels followed by increasing frequency of large fires (D'Antonio and Vitousek 1992). Furthermore, after fires, invasive grasses typically thrive, leading to a fire regime that did not previously exist naturally (Brooks and Pyke 2001).

Archaeologists are aware of how rock properties and rock surface weathering impacts and interacts with rock art (Fillatre et al. 2021; Lacanette et al. 2013; Meiklejohn et al., 2009; Walderhaug 1998), as well as stone monuments (Hosono et al. 2006). Archaeologists interested in the effects of fire on rock art have long been worried about the implications of wildfire on rock art conservation (Kelly and McCarthy 2001). Some of the rock art literature highlights specific case studies of fire damage (Figueiredo, Paupério, and Romão 2021; Knight 2020; Sefton 2011), and many study the processes by which fire erodes rock surfaces (Ryan et al. 2012; Tratebas, Cerveny, and Dorn 2004) as a mean to develop more effective management strategies (Giorgi and Tacon 2019; Lambert and Welsh 2011; Nhamo 2018; Pozo-Antonio et al. 2020; Pozo-Antonio et al. 2018).

Geomorphologists interested in how fire interacts with rock surfaces have long recognised that rock decay (weathering) before a wildfire promotes the erosion of rock surfaces (Allison and Bristow 1999; Allison and Goudie 1994; Birkeland 1984; Blackwelder 1927; Buckman, Morris, and Bourman 2021; Dorn 2003; Dragovich 1993; Emery 1944; Esposito et al. 2013; Goudie, Allison, and McClaren 1992; Ollier 1983; Shakesby and Doerr 2006; Shtober-Zisu et al. 2018; Shtober-Zisu et al. 2015; Shtober-Zisu and Wittenberg 2021a, 2021b; Swanson 1981; Yatsu 1988). The presence of moisture within the weathered pores spaces in the rock can also worsen a rock's response to heat from a wildfire (Mol and Grenfell 2022). The engineering literature also recognises the role of pre-fire rock decay in enhancing fire-related erosion of granitic building stones (Dionisio et al. 2021) and naturally fractured granite (Ding, Wang, and Cheng 2022).

The specific research question explored here is whether even a limited amount of natural rock decay (weathering) in seemingly 'fresh' (hard rock) granitic rock art panel can lead to panel loss during a wildfire (Pozo-Antonio et al. 2020). This paper focuses on a case study where we have before and after samples, in which a petroglyph's granitic host rock was exposed to a wildfire event that took place in July 2021 in central Arizona, USA. The host granite bedrock seemed fresh during sampling in 1995, with the sort of 'ring' when pinged with a rock hammer (under the pecked joint face and far away from the rock art) that is typical of hard granite. Still, the area around the panel's base had some accumulation of grus (angular sand composed of the same mineral as the bedrock granite), indicating that the bedrock must have experienced some degree of 'grussification'—a term meaning granite weathering that leads to granular erosion (Anovitz et al. 2021; Dorn, Mahaney, and Krinsley 2017; Hayes et al. 2020; Hoskin and Sundeen 1985; Isherwood and Street 1976; Neely and DiBiase 2020; Rahmntara and Krawczyk 2022; Wakatsuki et al. 2007).

By comparing samples from the petroglyph panel collected in 1995 with those collected in July 2021 immediately after the Tiger Fire, we were able to test the hypothesis that a wildfire can completely erode the surface of a bedrock petroglyph panel – even bedrock that did not seem very weathered prior to the wildfire. We next explain the study area, present methods, our results, and then we discuss the implications of our findings in the context of prior scholarship.

Study Area

The first author visited a rock art site in 1995, in the far northern Sonoran Desert of central Arizona, that experienced the Tiger Fire in July 2021 (Figure 1). The 1995 visit included then-USA Bureau of Land Management archaeologist Connie Stone and three individuals from the Yavapai Nation, as well as other observers. After some discussion and observation of the petroglyph sampling technique, the first author was asked to collect samples from an engraving about 15 centimetres long. Following standard procedures presented in Dorn et al. (2012), samples were also collected from the natural surface surrounding the

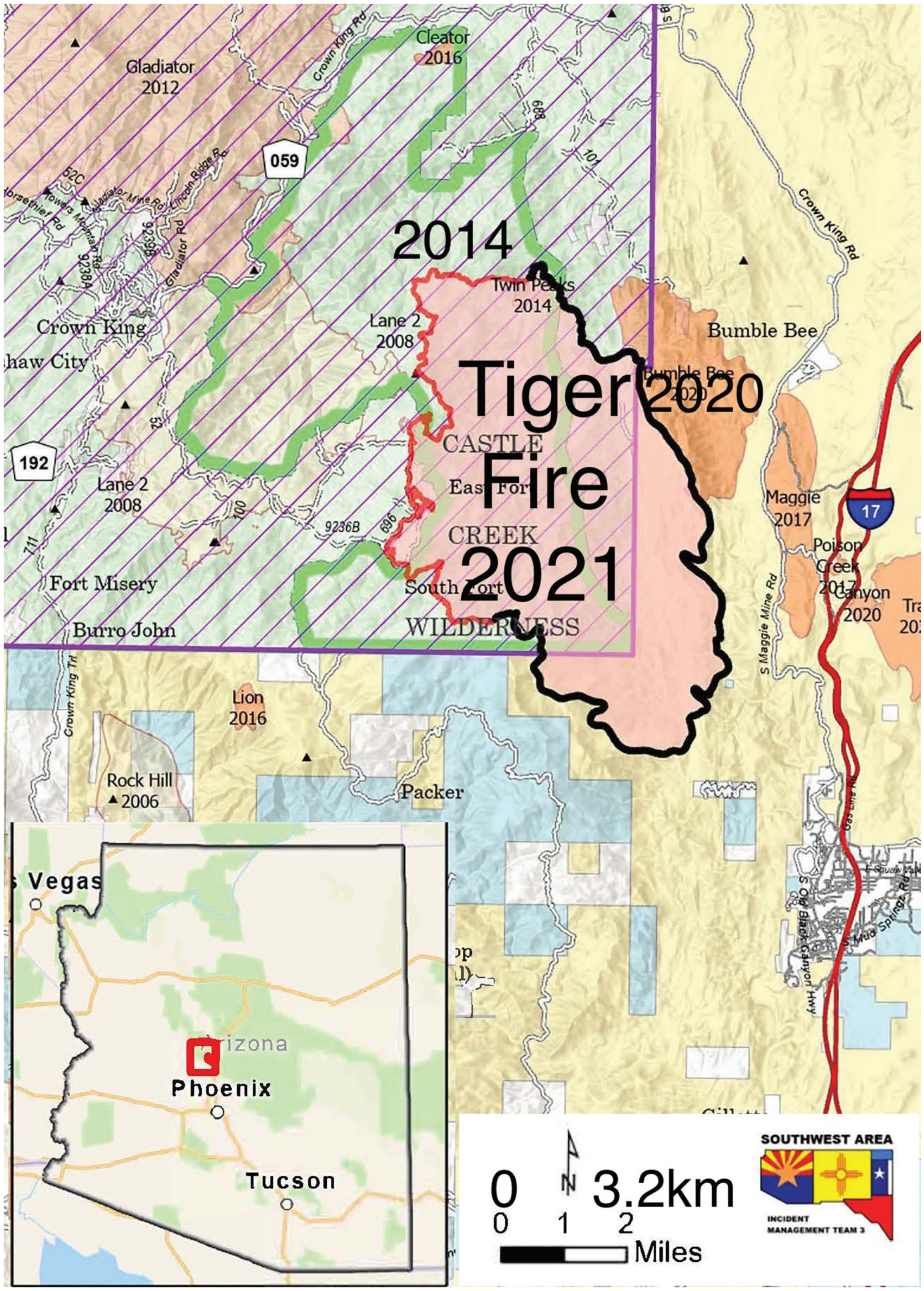

Figure 1. Tiger fire public information map from 14 July 2021, superimposed on land ownership. Located between interstate-17 to the east and the Bradshaw Mountains to the west, the petroglyph site was subject to a 2014 wildfire, but not a 2020 wildfire. As is appropriate and by convention, the exact location of the rock art site is left vague. The map was modified from the public domain version at: https://inciweb.nwcg.gov/incident/map/7595/0/115349.

petroglyph to serve as a comparison. The samples were archived until funding could be obtained to conduct analyses required to measure the petroglyph's age. The samples were not analysed, however, until the engraved boulder's surface completely eroded away during the Tiger Fire.

The rock type hosting the petroglyph is a slightly metamorphosed granite that was described as a 'foliated granite' by Phillip Anderson (Reynold et al. 2017). The petroglyph carved into the granite was a Gila-style (Wright and Bostwick 2009) Hohokam engraving produced by direct percussion (Figure 2). This type of image is typically called 'Pipette' (Bostwick 1998). The area around the petroglyph site contained pieces of Prescott Grayware shards (Stone 2015). The first author was asked to keep the specific site confidential, but the location was within kilometres of the Euler Site, a Hohokam masonry pueblo occupied between 1200 CE and 1400 CE (Stone 2015). Although basalt and sandstone rock types often host petroglyphs in western North America, rock art panels commonly occur on granitic rock types that are abundant in the Sonoran Desert (Bostwick 1998; Stone 2015) and such places as the Sierra Nevada in California (Whitley 1987) and in many other locations globally (Pozo-Antonio et al. 2018; Pozo-Antonio et al. 2020).

As noted above, the Sonoran Desert within Arizona, including the study site, did not experience extensive wildfires prior to the invasion of non-native grasses (Humphrey 1963; McDonald and McPherson 2013; Narog, Koonce, and Cocoran 1995; Shyrock, Esque, and Chen 2015). Prior to the invasion of European grasses, if a patch of desert caught fire, areas would burn here and there in a mosaic-type pattern. Invasive grasses, however, generate mats of dried material that result in much larger burn areas (Wentz et al. 2001). Fires in grasslands, furthermore, spread and burn more rapidly than in many other environments, making containment and suppression more difficult.

Figure 2. Pre-fire image of the lost petroglyph, contextualised by the position of the bedrock granite in a landscape burned by the July 2021 Tiger Fire. The burned vegetation consists of charred remains of palo verde (*Cercidium*) and catclaw (*Acacia*). The other Sonoran Desert plants (e.g. creosote bush) were completely burned. The Pipette engraving was about 15 centimetres long, visible because percussion removed the surrounding darker rock varnish and exposed the lighter-colored weathering rind of the granite.

The extreme 2021 drought conditions in central Arizona also impacted desert scrubs such as creosote bush (*Larrea tridentata*), jojoba (*Simmondsia chinensis*), crucifixion-thorn (*Canotia holacantha*), bur sage (*Ambrosia dumosa*), brittlebush (*Encelia farinosa*), and ocotillo (*Fouquieria sp.*), making them more flammable. Small trees, including species of palo verde (*Cercidium*), some catclaw (*Acacia*), and mesquite (*Prosopis)* added to the fuel load at the study site. Given that all of the woody plants burned to the level seen in Figure 2, the fire could have been quite hot. However, we did not make measurements of the intensity or duration of the fire at the rock art panel, and we know of no such measurements made for other rock surfaces during the July 2021 fire.

Methods

Individuals with stewardship over a petroglyph that request sampling usually wish to observe the sampling process on natural surfaces, typically rock surfaces away from a rock art panel. Once questions are asked and answered, and permission given, petroglyph samples are collected using a tungsten-carbide needle, prying out millimetre-scale pieces that are already loose. Samples are also collected from adjacent natural rock surfaces next to the engraving to serve as control. Since no funding was available to process the samples further, they were archived in glass vials until the Tiger Fire event of 2021.

Once the area was re-opened a few days after the fire, the first author revisited the location (Figure 2). The bedrock surface hosting the engraving had completely eroded away. No evidence of a petroglyph existed, and no rock varnish remained on the boulder surface. The first author then re-collected samples from the original location of the petroglyph and also from the original location of the adjacent control surface, as well as 10 other locations across the former panel.

One petroglyph sample chip from the 1995 sampling was prepared for varnish micro-lamination (VML) dating. The basis for VML dating is that major climatic changes alter the layering pattern found in the rock varnish that forms on top of petroglyphs found in drylands. Wet periods produce manganese-rich layers that appear darker in thin sections. Drier periods produce manganese-poor layers that appear orange or yellow if extremely dry. The method was developed by Tanzhuo Liu of Columbia University (Liu 2022), who made calibrations of the varnish layers using independent age control (Liu 2003; Liu and Broecker 2007, 2008a, 2008b, 2013). Liu's Holocene calibration (Liu and Broecker 2007) was verified independently for the Sonoran Desert (Dorn 2014). The method has been subject to blind tests in both geomorphic research (Marston 2003) and in rock art research (Whitley 2013).

The VML dating method is not precise for several reasons. VML ages are minimums, because varnish formation post-dates the process that exposed the surface to varnishing – in this case, the making of the petroglyph. Also, age estimates are in ranges between the key wet climatic intervals. In this case, the key wet-period bracketing events in the late Holocene are the Little Ice Age black layers called WH1 (wet Holocene 1) that formed between 350–650 yr BP and WH2 (wet Holocene 2)—a Medieval Warm wet event around 900 yr BP (Liu and Broecker 2007).

In order to understand the impact of pre-existing grussification on the response of a petroglyph panel to wildfire, it is important to obtain an understanding of prior weathering in the host foliated granite rock – all prior to when the engraving was made. To obtain a broader perspective of inherited weathering in the area, samples were also collected from a roadcut in the region that is the same foliated granite. The roadcut contains classic examples of core stones surrounded by grus. Five samples were collected along a transect from the grus into the centre of a core stone (or heartrock) to understand natural variability in the 'inherited' grussification of a petroglyph surface. The different samples were impregnated with epoxy in the field in order to preserve *in situ* relations.

We employed different electron microscope techniques to characterise the rock decay of the material collected in 1995 and then after the Tiger Fire in 2021. Sample preparation involved placing a rock chip in epoxy with an orientation normal to the subaerial rock surface. The epoxy and the rock chip were polished with smaller and smaller grit sizes, ending up with a 0.1 μm aluminium paste. Back-scattered electron (BSE) detectors generated images of polished surfaces where brightness reflects the average atomic number (Krinsley et al. 2005). In some cases, rock decay had progressed to the point where chunks of mineral material broke lose during polishing, providing 3D BSE perspectives that image atomic number and also topography. Also, high resolution transmission electron microscopy (HRTEM) (Krinsley, Dorn, and Tovey 1995) was used to generate nanoscale images. Both BSE and HRTEM imaging approaches employed energy dispersive spectroscopy (EDS) to provide elemental chemistry of individual granitic minerals (Reed 1993).

Results

Varnish Microlamination Dating

The minimum age for the Hohokam-style Pipette engraving (Figure 2) is between 650 yr BP and 900 yr BP (Figure 3). This age is consistent with what is known about temporal variability in this style (Bostwick 1998). It is also consistent with the age of a nearby Hohokam masonry pueblo estimated to have been occupied from 1200 CE to 1400 CE (Stone 2015).

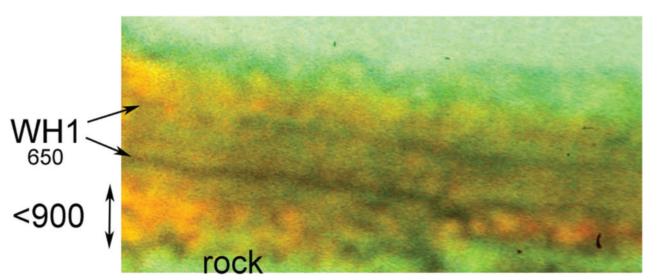

Figure 3. Varnish microlamination thin section of varnish formed on top of the Pipette engraving. The WH1 (wet Holocene 1) set of black layers is the Little Ice Age signal. As is typical for Hohokam-age engravings, there is no WH2 layer present between WH1 and the underlying rock surface of the engraving. Thus, the VML age is bracketed between 650 yr BP and 900 yr BP. The varnish thickness ranges between 11 μm on the left and 8 μm on the right.

Electron Microscope Observations

A roadcut in the region of the sampled petroglyph provided insight into the range of rock decay that can be seen in the same foliated granite rock type as the petroglyph. The idea behind analysing classic spheroidal weathering of foliated granite core stones surrounded by grus (Figure 4) is to provide a qualitative view of a range of grussification in the area.

The five samples collected along a 1.5 m-long transect from thoroughly grussified granite sand (Figure 4(a)) to the centre of a rock-hard corestone (Figure 4(e)) identified in Figure 4. The interior of the core stone is most similar to the panel sample collected before the Tiger Fire. The transect A-E corresponds with the BSE images in Figure 4(a-e). At the most decayed end of the transect, grussified sand (held in place by field-impregnated epoxy) displays substantial space separating grains – many of which show abundant internal porosity (Figure 4(a)). The interior of fresh-looking core stone shows the most grain-to-grain contact and the least amount of internal grain porosity (Figure 4(e)). The three sampling positions in between reveal a gradient of decreasing porosity towards the interior of the core stone. The summary finding is that all analysed samples displayed some degree of grussifiction in the form of grain-to-grain separation and internal grain porosity – even the interior of a core stone.

Samples of the engraved boulder collected in 1995 prior to the Tiger Fire show some grussification. The least amount of porosity was found in a sample collected 1 m away from the engraving (Figure 5(a)), covered by rock varnish. The most observed porosity occurred next to a lichen inside the petroglyph (Figure 5(b)). Lichen-generated acids

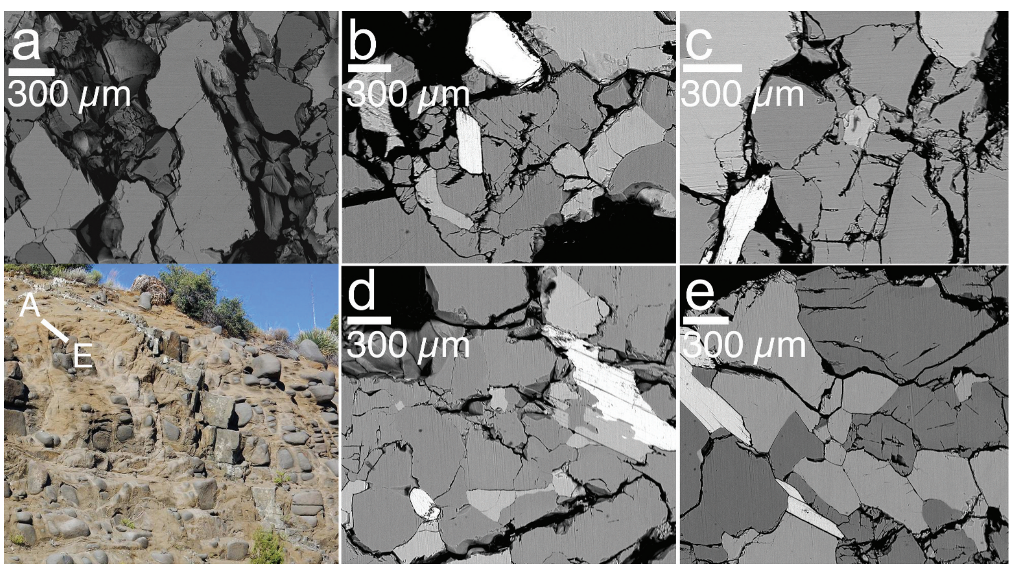

Figure 4. Road cut exposure of the same granite rock type as the studied petroglyph panel but showing the rock decay status as being classic core stones separated by grussified material. Samples collected along a 1.5 m a-to-e transect (from rotten granite to the fresh-looking interior of a core stone) and imaged by back-scattered electron microscopy reveal a qualitative change in grussification from high porosity and internal grain decay (a) to just some porosity along some grain-to-grain boundaries (d and e). The condition of the engraved boulder is most similar to image e, found near the interior of core stone.

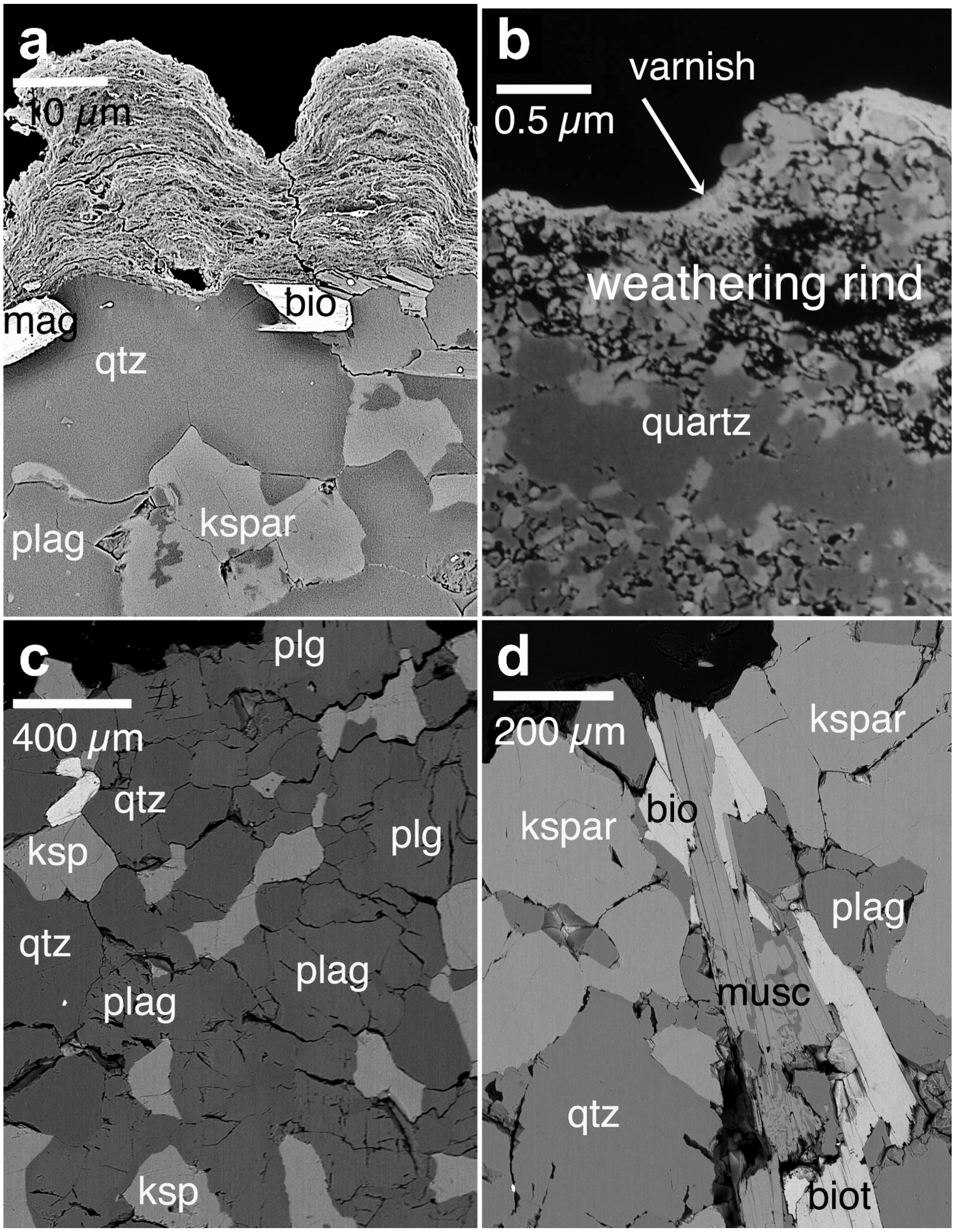

Figure 5. Electron microscope BSE images of the natural surface of the panel (image a), a sample from the engraving that was adjacent to lichen growth (image b), and samples of the interior of the bedrock collected from a rock face that was not engraved (images c and d). Mineral abbreviations are qtz (quartz); plg or plag (plagioclase); ksp or kspar (orthoclase); bio or biot (biotite); musc (muscovite); and mag (magnetite). The minerals were identified by EDS analyses.

enhanced dissolution of the rock, creating a porous weathering rind that was covered and case hardened (Dorn, Mahaney, and Krinsley 2017) by a thin layer of rock varnish (Figure 5(b)). Samples collected from the interior of the bedrock show images of some porosity developed between grain boundaries and across grains that appears most similar to the interior of the core stone (Figure 4(e)).

Samples collected in 1995 and then a few weeks after the Tiger Fire in 2021 from approximately the same location on the boulder reveal what happened to the petroglyph (Figure 6). The rock varnish was mechanically removed when the petroglyph was made, seen in an angular unconformity (Figure 6(a)) with post-petroglyph varnish on top. Then, after the fire, there is no evidence of the original varnished surface (Figure 6(b)).

The bedrock surface of the panel had its surface completely removed/eroded by the effects of the fire, taking the panel with it. Samples taken from the bedrock surface that was exposed by the fire reveal three general patterns of rock decay. Figure 7 illustrates examples of grain cracking of different minerals. Figure 8 shows the development of flakes with separation somewhat parallel to the surface of the rock. Figure 9 shows the development of multiple fractures underneath the surface that will lead to future flaking, all within the upper 2 mm of the sampled rock surface. Note that no rock varnish occurs in any of the images in Figures 7–9. This is because the entire surface of the panel eroded away due to the fire. Just how many millimetres or centimetres of erosion took place in response to the fire is not known.

Internal cracking of grains (Figure 7), the development of a surface-parallel fracture (Figure 8), and the development of multiple surface-parallel fractures (Figure 9) are

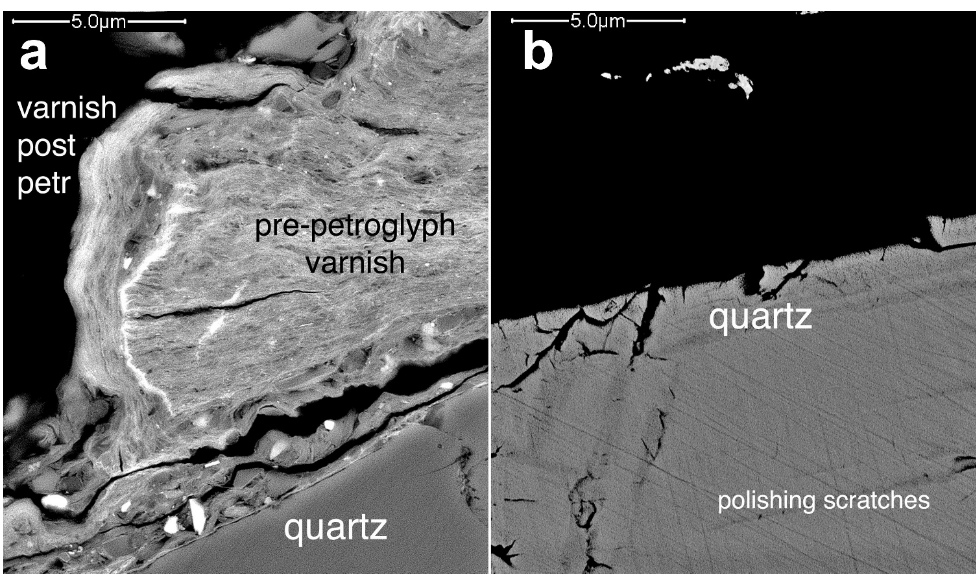

Figure 6. Complete removal of a petroglyph revealed in before and after BSE images of an edge of the Pipette engraving. The before-fire image a shows the percussion that removed the original varnish, and then more varnish developed along the unconformity after the engraving was made. The after-fire image b shows cracked quartz; the micron-scale fractures could have been the result of the fire's intense heating. The lineations seen in image b are due to an imperfect job of polishing during sample preparation.

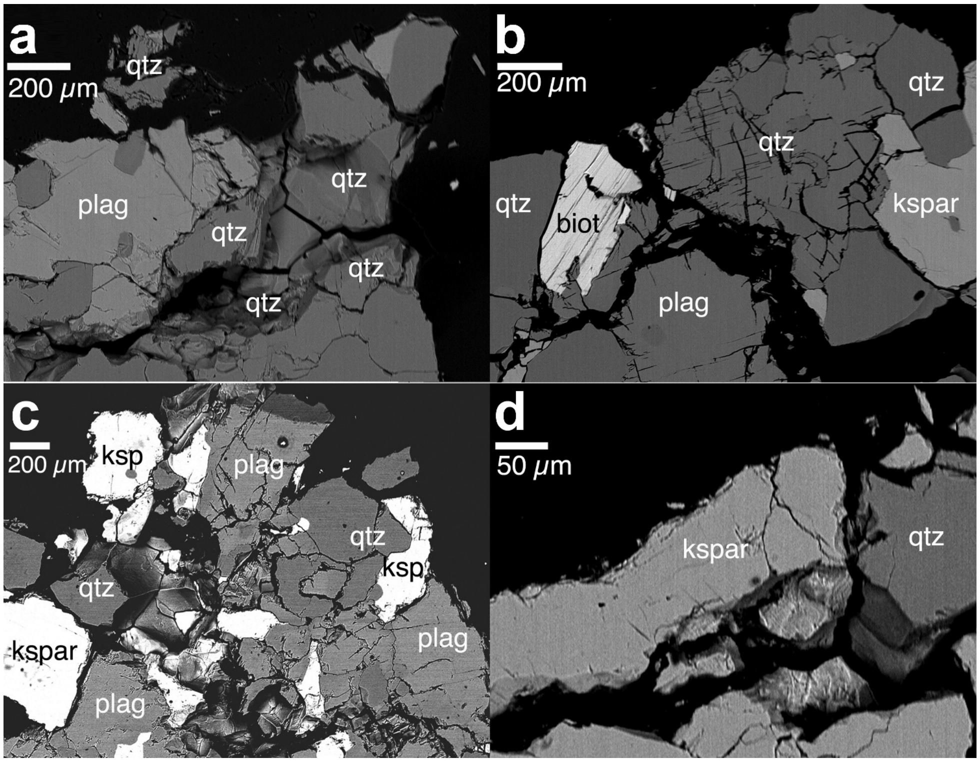

Figure 7. Post-fire surface samples that display cracking within and between different mineral grains. Quartz displays a variety of cracking behaviors: image a cracks have a 3D geometry that leads to the polishing process 'popping out' chunks of the quartz; images b and c show thoroughly fractured quartz adjacent to much less fractured quartz. Orthoclase displays the least amount of cracking, while plagioclase fractures with an intensity between quartz and orthoclase. Mineral abbreviations are qtz (quartz); plg or plag (plagioclase); ksp or kspar (orthoclase); bio or biot (biotite); musc (muscovite); and mag (magnetite).

processes that would have contributed to loss of the petroglyph panel. Using the ergodic assumption, substituting space (in this case moving into the rock's interior) for time, all of these processes are now causing surface erosion. The physical separation of grains from the rock (Figure 7), the clear separation of a flake (Figure 8) or multiple flakes (Figure 9) all show surfaces that are literally 'hanging on by a thread' of rock.

The BSE images of pre-fire samples (Figures 5 and 6) compared with BSE images of post-fire samples (Figures 7–9) suggest that pre-existing 'inherited' rock decay could have contributed to erosion of the panel in response to a fire. The pre-fire samples (Figures 5 and 6) show some separation along grain boundaries and some internal dissolution. Consider the pattern of fractures seen in Figures 8 and 9; some of these fractures sometimes follow grain-to-grain boundaries, and then suddenly break across the interior of a mineral. The thermal stresses associated with heating air in the pore spaces and rock material differentially could have contributed to the patterns observed in the post-fire sample (Figures 7–9).

Further suggestive evidence for the role of rock decay prior to the fire comes from observations at the nanoscale (Figure 10). Before the fire, dissolution generated 100 nm-

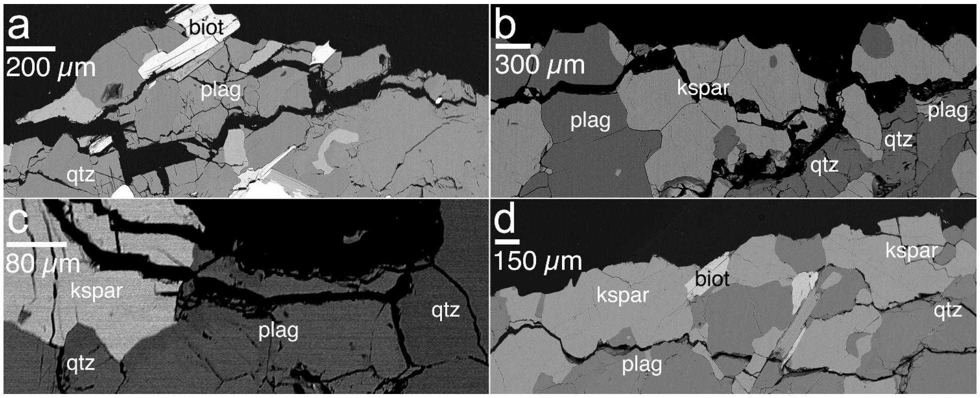

Figure 8. Post-fire surface samples that display the development of fractures that could lead towards future flaking of the surface. Note that the fractures cut across multiple types of minerals. Mineral abbreviations are qtz (quartz); plag (plagioclase); kspar (orthoclase); and biot (biotite).

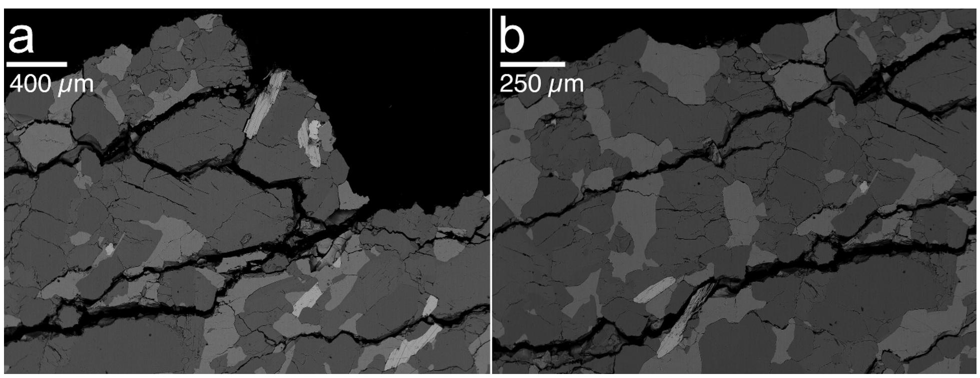

Figure 9. Post-fire surface samples display the development of multiple fractures somewhat parallel to the rock surface. These fractures could lead to future flaking events.

scale holes in quartz aligned along crystal defects (Figure 10(a)). After the fire, those dissolution holes were the places where quartz cracking initiated (Figure 10(b)). The same sort of change can be seen for magnetite where pre-fire dissolution etching (Figure 10(c)) was dramatically altered by the fire (Figure 10(d)). More broadly, it appears that even nanoscale mineral decay can become the nexus of fire-induced damage.

Discussion

Role of Grussification in Fire-Induced Erosion: Engineering Literature

Our findings clearly link even limited pre-existing (inherited) granitic weathering to the ability of a wildfire to destroy the surface of a rock art panel. We acknowledge that greater confidence in linking pre-fire grussification to boulder erosion would require laboratory experiments using the same granite material as the studied petroglyph (with a similar degree of grussification) and subjecting the samples to fires of varying intensity. That

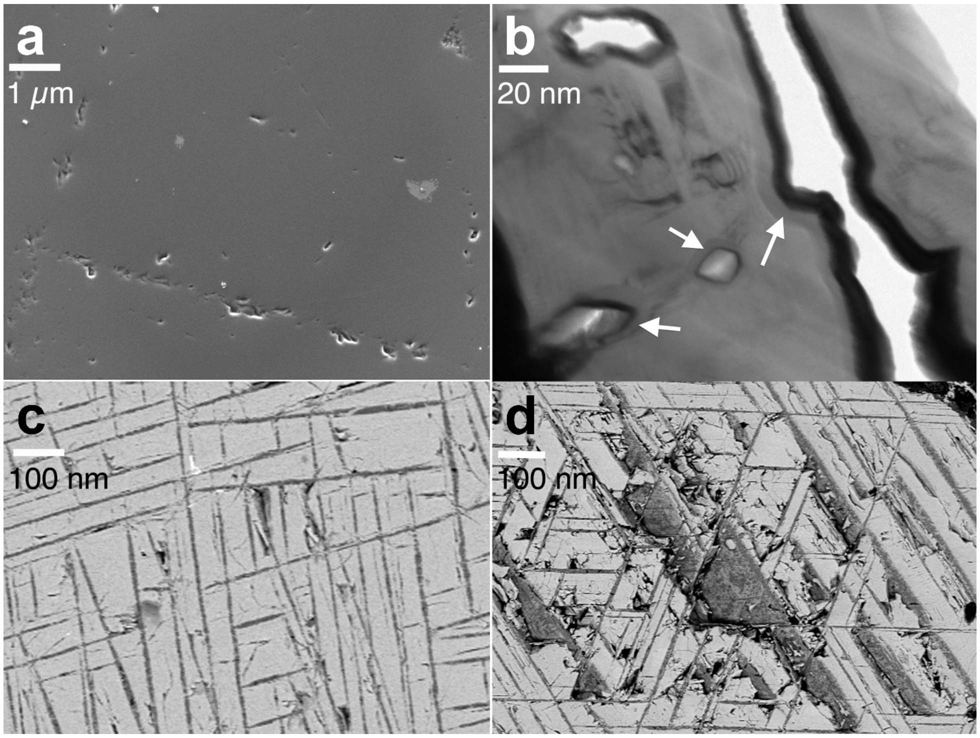

Figure 10. Nanoscale imagery of pre- and post-fire quartz and magnetite. The samples were obtained from the same location within the Pipette petroglyph. Images a and c are pre-fire. Images b and d are post-fire samples collected from the same approximate location, but after the entire surface had been flaked away. (a) Secondary electrons reveal 100 nm-scale dissolution holes aligned along crystal defects in the quartz. (b) HRTEM imagery shows those same type of dissolution hole (white areas), but with the addition of a linear fracture. Note the crisscrossing crystal defects that align with the orientation of the linear fracture and the dissolution holes. (c) High resolution BSE imagery of a pre-fire magnetite grain with dissolution etching. (d) High resolution BSE imagery of a post-fire magnetite grain that shows further alteration of the magnetite; the composition of the darker zones is rich in silicon and aluminum.

systematic strategy is beyond the scope of this research. Instead, we follow the sorts of deduction that other researchers typically employ (Brierley et al. 2021).

Shtober-Zisu et al. (2015), for example, observed that the presence of micro-cracks in rocks prior to a fire can decrease the tensile strength of rock. Shtober-Zisu and Wittenberg (2021a, 2) explain that the impact of this decrease in strength occurs when the

> surface temperature changes faster than that of the underlying rock, producing a steep thermal gradient. Consequently, the outer part of a rock mass expands such that the tensile strength of the rock increases radially causing fractures that are often parallel to the surface.

This is similar to spalling seen in geomorphic research related to granitic rocks in natural settings that had experienced inherited weathering (Buckman, Morris, and Bourman 2021; Dorn 2003; Emery 1944; Ollier 1983). Engineering studies of tunnel fires note this same type of spalling (Wsantha, Guerrieri, and Zu 2021). We, thus, gain confidence in our interpretation because we observe this same process in Figures 8 and 9.

The engineering literature on fire's impact on building stone indicates that fire's thermal shock (Yin, Yang, and Yin 2021) can induce grain microcracking in granitic building materials (Freire-Lista, Fort, and Varas-Muriel 2016; Wang, Fruhwirt, and Konietzky 2020). Pozo-Antonio et al., (2018) observed this same type of intragranular cracking, and they note that granitic 'minerals have different thermal expansion coefficient rates' and this 'varying thermal behaviour favours physical disruption of the rock mass by thermic shock' (Pozo-Antonio et al., 2018, 2445). Pozo-Antonio et al. (2018) specifically note that a granitic petroglyph site impacted by fire experienced the most physical deterioration in the upper few millimetres. Again, this is what we see in Figures 6 through 10 here.

Pozo-Antonio et al. (2018) observe the most micron-scale cracking in plagioclase in their study, but with less micron-scale cracking in quartz. Here, Figures 7 through 9 show both plagioclase and quartz cracking. In some samples, quartz cracked more than any other mineral (e.g. Figure 7(b)), while plagioclase was sometimes more cracked than quartz (e.g. Figure 7(c)). The pre-fire samples shown in Figure 5(c,d) exhibit much more internal fracturing of plagioclase, and hence it is possible that some observed post-fire plagioclase fracturing observed in this study could be inherited from pre-fire weathering. The broader issue of greatest relevance to rock art conservation rests in the common observation in our study and in prior research – that wildfire fractures the most common granitic minerals and this leads to panel destruction.

The abundant quartz fracturing observed here (e.g. Figures 7 and 8), however, is best explained by the Tiger Fire – where micron-scale impacts cracking (Figure 6(b)) similar to engineering studies of how granite reacts to fire (Biro, Hlavicka, and Lubloy 2019). Figure 10(a) shows a typical pattern of pre-fire dissolution of quartz, where nanoscale dissolution holes align along lineaments. Figure 10(b) presents a HRTEM image of an ultra-thinned quartz where crystal defects show up in a crisscrossing pattern. The holes, inherited from pre-fire dissolution, align with the nanoscale defects. The arrows in Figure 10(b) highlight quartz decrystallization caused by hydration (Dorn et al. 2013; Pope 1995) that rim the dissolution holes. Note this same rim of decrystallization next to a portion of the fire-generated fracture – indicating that the inherited nanoscale dissolution appears to have 'set the nanoscale stage' for the fire-induced quartz fracturing. The key point for conservation is that even a tiny amount of mineral dissolution, seen only at the nanoscale, can be the key weakness that then promotes mineral fracturing. This mineral fracturing then can result in panel erosion.

Yet another example of the importance of pre-fire mineral decay comes from nanoscale observations of magnetite. In micron-scale imagery (e.g. Figures 7–9), magnetite appears relatively unaltered. However, higher resolution BSE images of pre-fire magnetite shows mineral etching (Figure 10(c)). After the fire, these etchings appear greatly altered (Figure 10(d)). The cause that replaces the magnetite with Si-Al-rich (darker) materials in Figure 10(d) is not known, but it is certainly the result of a fire-related process.

An alternative hypothesis to explain the complete erosion of the central Arizona petroglyph (Figure 2) is that fire alone resulted in the loss of the surface – regardless of the presence of inherited grussification of the granite. While this alternative interpretation cannot be falsified, the interpretations presented in this section instead strongly suggest an important role for inherited rock decay.

Implication for Condition Assessment of Rock Art Panels

The importance of our preferred interpretation – that the natural rock decay sets the stage for fire to erode rock art panels – has implications for research on condition assessment of rock art panels. There are a variety of rock art condition assessment methods (Fitzner, Heinrichs, and LaBouchardiere 2004; Giesen, Ung, et al. 2014; Loubser 2001; Sampietro-Vattuone and Peña-Monné 2021), including the Rock Art Stability Index or RASI (Allen et al. 2011; Allen and Groom 2013; Dorn, Dorn, et al. 2012; Dorn et al. 2008; Groom et al. 2019). Many are extraordinarily expensive (Fitzner, Heinrichs, and LaBouchardiere 2004), and some use remote sensing to detect deterioration threats (Sampietro-Vattuone and Peña-Monné 2021).

Regardless of the condition assessment approach, we advocate here adding an additional entry into condition assessments of granitic rock types: to look for evidence of grussification (the granular erosion of granitic minerals from bedrock) in at the base of bedrock in the area around a panel (Anovitz et al. 2021; Dorn, Mahaney, and Krinsley 2017; Hayes et al. 2020; Hoskin and Sundeen 1985; Isherwood and Street 1976; Neely and DiBiase 2020; Wakatsuki et al. 2007). We are asking to simply note the presence of any grus at the base of the panel and surrounding bedrock surfaces. Grus is very different from sand carried by desert washes. Grus mineral grains are angular and look like they just 'popped out' of the bedrock. If the observer simply picks up a dozen grus grains and holds them up to the surface of the bedrock granite – and they look like a size and mineral match – then a wildfire could end up destroying the panel.

Since the pre-fire status of grussification of the eroded petroglyph boulder was not highly decayed, but just starting (e.g. comparison between undefinedFigure 4 and 5), a presence or absence notation in a condition assessment is an important and easy addition. Then, site stewards would have the important job of regularly clearing woody vegetation from the area of these rock art panels. If this had been done for the studied panel, this important cultural resource would still exist. We note that the issue of invasive grasses driving destructive western North American wildfires (Brooks and Pyke 2001) is not a global management issue and that other regions would have other management solutions (Pozo-Antonio et al. 2020).

Sandstone is a granular rock type that can also experience wildfire effects (Tratebas, Cerveny, and Dorn 2004). We speculate that the same processes observed here for granite could operate for sandstone as well, in that inherited weathering set the stage for complete removal of sandstone boulder surfaces (Dorn 2003). To be on the safe side, until further research on the impact of fire on sandstone panels can be conducted, a prudent course of action would be to recommend regular clearing of woody vegetation near even sandstone panels. More broadly, we advocate the position that clearing woody vegetation from the areas of all rock art panels would be a good preventative measure, given the possibility that a wildfire could set the stage for future panel erosion (Shakesby and Doerr 2006; Shtober-Zisu et al. 2018; Shtober-Zisu and Wittenberg 2021b).

Connection Between Rock Art Damage and Anthropogenic Processes

A broader theme in rock art research connects anthropogenic air pollution and climate change to rock art sites. Some have used automobile emissions like lead as a tool to authenticate rock art (Dorn, Gordon, et al. 2012). Others have linked industrial emissions with severe damage to panels (Black, MacLeod, and Smith 2017). Still other researchers focus on the impact of climate change on rock art (Huntley et al. 2021). Our research highlights what is already well known – that anthropogenic activities have increased the potential of wildfire to damage stone surfaces occupied by rock art (Kelly and McCarthy 2001; Knight 2020; Lambert and Welsh 2011; Pozo-Antonio et al. 2018; Sefton 2011; Shtober-Zisu et al. 2018; Shtober-Zisu et al. 2015; Shtober-Zisu and Wittenberg 2021a, 2021b; Tratebas, Cerveny, and Dorn 2004).

Implications for "Microerosion Dating" of Petroglyph

The 'microerosion dating' strategy of attempting to date petroglyphs (Bednarik 1993) relies on the assumption that the petroglyph manufacturing process created what is observed using low power light microscopy in the field. As has been pointed out previously (Pope 2000), this method suffers from the fatal flaw that there is no way of knowing whether new corners formed before the manufacturing process. Pope (2000) explained that any weathering that existed prior to making the petroglyph (secondary alteration) will prevent the use of the microerosion dating method in that this inherited weathering could have caused what someone sees with a low-powered light microscope in the field. It should be obvious from the pre- and post-fire microscope imagery presented here that even a rock that looked 'fresh' in the field was not. All possible use of any microerosion method would require nanoscale analyses (e.g. Figure 10) to ensure that inherited weathering did not influence results.

Conclusion

The July 2021 Tiger Fire resulted from a lightning strike on mats of dried invasive grasses. Aided by long-term drought, the fire spread across a region of the far northern Sonoran Desert in central Arizona. This wildfire completely eroded a Hohokam petroglyph that had been sampled 26 years earlier, providing a unique opportunity to evaluate before-and-after conditions of the host bedrock rock surface. By comparing samples from the petroglyph panel collected in 1995 with those collected in July 2021 immediately after the Tiger Fire, we found that even a small amount of granite rock decay can result in the complete loss of a petroglyph panel that was exposed to a wildfire. This finding is disturbing, because the appearance of the panel in 1995 in the field was that it was 'fresh hard rock' and safe from weathering-generated erosion in some condition assessment approaches (Fitzner, Heinrichs, and LaBouchardiere 2004; Sampietro-Vattuone and Peña-Monné 2021).

The before-fire condition of the foliated granite panel in SEM analysis reported here displayed a little bit granite weathering, with grain-to-grain separation, some development of micron-scale cracking, and development of internal porosity in the minerals. The pre-fire overall state of granite grussification (turning granite into angular sand) was similar to what is found near the centre of core stones in a nearby roadcut exposure of naturally weathered granite.

This pre-fire 'inherited' weathering set the stage for the complete erosion of the rock art panel. The micron-scale cracking decreased the granite's tensile strength; the fire-caused steep thermal gradient generated radial fracturing parallel to the petroglyph panel's surface. Because granitic minerals have different coefficients of thermal expansion, the incipient grain-to-grain separation seen in pre-fire samples provided sufficient weakness for the thermal shock to blow apart mineral grains in the upper few millimetres. Pre-fire internal nanoscale dissolution, combined with crystal defects in individual minerals, led to cracking of the quartz. The micron-scale and nanoscale electron microscope evidence suggests that even a little bit of inherited granite decay can set the stage for the loss of an entire petroglyph panel.

The implication for rock art conservation is a simple management recommendation to first conduct a condition assessment such as the Rock Art Stability Index (RASI) (Dorn et al. 2007; Groom et al. 2019). Then, in the condition assessment for granitic panels, simply note whether or not grus (angular granite sand) is present around the panel base. Even minimal grussification will lead to some granular disintegration of the granite. Since this minimal grussification can set the stage for the loss of an entire panel surface, the management recommendation for this problem is straightforward. Our suggestion is to remove all vegetation from the vicinity of a rock art panel. Every time a site steward visits a site, cut back all woody vegetation to a distance of several metres to prevent an intense wildfire from getting close to the panel surface. If this had been done for the studied panel, there would have been no thermic shock to blow apart the panel surface.

A final concluding thought is to note that some researchers consider rock art to be inert, changing very little due to an inherent stability of stone, needing only protection from vandals. The truth is the rock art is a living, changing part of the landscape (Zerboni et al. 2022)—a perspective often taken by representatives of original owners and affiliated First Nations. Consultations with those who see change as an inherent part of the natural world could shed light on further direct conservation investments.

Acknowledgment

We thank the anonymous reviewers and the editor for improving the paper. We thank BLM archaeologist Connie Smith and three members of the Yavapai tribe for permitting and observing the collection of millimetre-scale samples of the analyzed petroglyph.

Disclosure Statement

No potential conflict of interest was reported by the authors.

Notes on Contributors

Ronald I Dorn is a professor of geographical sciences at Arizona State University, specialising in geomorphology and weathering research.

David S. Whitley is an archaeologist who specialises in rock art studies.

ORCID

Ronald I. Dorn http://orcid.org/0000-0003-1343-4556
David S. Whitley http://orcid.org/0000-0002-1647-1427

References

Allen, C. D., A. K. Cutrell, N. V. Cerveny, and J. Theurer. 2011. "Advances in Rock Art Field Assessment." *La Pintura* 2011 (February Issue): 13.

Allen, C. D., and K. M. Groom. 2013. "Evaluation of Granada's 'Carib Stones' via the Rock Art Stability Index." *Applied Geography* 42: 165–175.

Allison, R. J., and G. E. Bristow. 1999. "The Effects of Fire on Rock Weathering: Some Further Considerations of Laboratory Experimental Simulation." *Earth Surface Processes and Landforms* 24 (8): 707–713. doi:10.1002/(SICI)1096-9837(199908)24:8<707:AID-ESP993>3.0.CO;2-Z.

Allison, R. J., and A. S. Goudie. 1994. "The Effects of Fire on Rock Weathering: An Experimental Study." In *Rock Weathering and Landform Evolution*, edited by D. A. Robinson and R. B. G. Williams, 41–56. Chichester: Wiley.

Anovitz, L. M., M. C. Cheshire, R. P. Hermann, X. Gu, J. M. Sheets, S. L. Brantley, D. R. Cole, et al. 2021. "Oxidation and Associated Pore Structure Modification During Experimental Alteration of Granite." *Geochimica Et Cosmochimica Acta* 292: 532–556.

Aslan, C. E., S. Souther, S. Stortz, M. Sample, M. Sandor, C. Levine, L. Samberg, M. Gray, and B. Dickson. 2021. "Land Management Objectives and Activities in the Face of Projected Fire Regime Change in the Sonoran Desert." *Journal of Environmental Management* 280. doi:10.1016/j.jenvman.2020.111644.

Bednarik, R. G. 1993. "Geoarchaeological Dating of Petroglyphs at Lake Onega, Russia." *Geoarchaeology* 8 (6): 443–463. doi:10.1002/gea.3340080602.

Birkeland, P. W. 1984. *Soils and Geomorphology*. Oxford: Oxford University Press.

Biro, A., V. Hlavicka, and E. Lubloy. 2019. "Effect of Fire-Related Temperatures on Natural Stones." *Construction and Building Materials* 212: 92–101.

Black, J. L., I. D. MacLeod, and B. W. Smith. 2017. "Theoretical Effects of Industrial Emissions on Colour Change at Rock Art Sites on Burrup Peninsula, Western Australia." *Journal of Archaeological Science Reports* 12: 457–462.

Blackwelder, E. 1927. "Fire as an Agent in Rock Weathering." *The Journal of Geology* 35 (2): 134–140. doi:10.1086/623392.

Bostwick, T. W. 1998. "Hohokam Rock Art: Ancient Imges Left on Stone." Pueblo Grande Museum Profiles No. 18. Pueblo Grande Museum, City of Phoenix.

Brierley, G., K. Fryirs, H. Reid, and R. Williams. 2021. "The Dark Art of Interpretation in Geomorphology." *Geomorphology* 390. doi:10.1016/j.geomorph.2021.107870.

Brooks, M. L., and D. A. Pyke. 2001. "Invasive Plants and Fire in the Deserts of North America." In *Proceedings of the Invasive Species Workshop: the Role of Fire in the Control and Spread of Invasive Species. Fire Conference 2000: the First National Congress on Fire Ecology, Prevention, and Management*, edited by T. P. Wilson and K. E. M. Galley, 1–14. Tallahassee: Tall Timbers Research Station.

Buckman, S., R. Morris, and R. P. Bourman. 2021. "Fire-Induced Rock Spalling as a Mechanism of Weathering Responsible for Flared Slope and Inselberg Development." *Nature Communications* 12 (1): 2150. doi:10.1038/s41467-021-22451-2.

Carmichael, B. 2016. "Supporting Indigenous Rangers' Management of Climate-Change Impacts on Heritage Sites: Developing an Effective Planning Tool and Assessing Its Value." *The Rangeland Journal* 37 (6): 597–607. doi:10.1071/RJ15048.

Carmichael, B., G. Wilson, I. Namarnyilk, S. Nadji, S. Brockwell, B. Webb, F. Hunter, and D. Bird. 2018. "Local and Indigenous Management of Climate Change Risks to Archaeological Sites." *Mitigation and Adaptation Strategies for Global Change* 23 (2): 231–255. doi:10.1007/s11027-016-9734-8.

Collier, M., and R. H. Webb. 2022. *Floods, Droughts, and Climate Change*. Tucson: University of Arizona Press.

Dai, A., T. Zhao, and J. Chen. 2018. "Climate Change and Drought: A Precipitation and Evaporation Perspective." *Current Climate Change Reports* 4 (3): 301–312. doi:10.1007/s40641-018-0101-6.

D'Antonio, C. M., and P. M. Vitousek. 1992. "Biological Invasions by Exotic Grasses, the Grass/Fire Cycle, and Global Change." *Annual Review of Ecology and Systematics* 23 (1): 63–87. doi:10.1146/annurev.es.23.110192.000431.

Ding, Q. L., P. Wang, and Z. Cheng. 2022. "Permeability Evolution of Fractured Granite After Exposure to Different High-Temperature Treatments." *Journal of Petroleum Science and Engineering* 208: 208. doi:10.1016/j.petrol.2021.109632.

Dionisio, A., E. Martinho, J. S. Pozo-Antonio, M. A. Sequeira-Braga, and M. Mendes. 2021. "Evaluation of Combined Effects of Real-Fire and Natural Environment in a Building Granite." *Construction and Building Materials* 277. doi:10.1016/j.conbuildmat.2021.122327.

Dorn, R. I. 2003. "Boulder Weathering and Erosion Associated with a Wildfire, Sierra Ancha Mountains, Arizona." *Geomorphology* 55 (1–4): 155–171. doi:10.1016/S0169-555X(03)00138-7.

Dorn, R. I. 2014. "Chronology of Rock Falls and Slides in a Desert Mountain Range: Case Study from the Sonoran Desert in South-Central Arizona." *Geomorphology* 223: 81–89. doi:10.1016/j.geomorph.2014.07.005.

Dorn, R. I., N. V. Cerveny, S. J. Gordon, and D. S. Whitley. 2007. "Atlas of Petroglyph Weathering Forms Used in the Rock Art Stability Index (RASI)." Accessed 1 April 2005. http://alliance.la.asu.edu/rockart/stabilityindex/RASIAtlas.html

Dorn, R. I., J. Dorn, E. Harrison, E. Gutbrod, S. Gibson, P. Larson, N. Cerveny, N. Lopat, K. M. Groom, and C. D. Allen. 2012. "Case Hardening Vignettes from the Western USA: Convergence of Form as a Result of Divergent Hardening Processes." *Association of Pacific Coast Geographers Yearbook* 74 (1): 1–12. doi:10.1353/pcg.2012.0003.

Dorn, R. I., S. J. Gordon, D. Krinsley, and K. Langworthy. 2013. "Nanoscale: Mineral Weathering Boundary." In *Treatise on Geomorphology*. 4 vols, edited by G. A. Pope, 44–69. San Diego: Academic Press.

Dorn, R. I., M. Gordon, E. O. Pagán, T. W. Bostwick, M. King, and P. Ostapuk. 2012. "Assessing Early Spanish Explorer Routes Through Authentication of Rock Inscriptions." *Professional Geographer* 64 (3): 415–429. doi:10.1080/00330124.2011.603659.

Dorn, R. I., W. C. Mahaney, and D. H. Krinsley. 2017. "Case Hardening: Turning Weathering Rinds into Protective Shells." *Elements* 13 (3): 155–158. doi:10.2113/gselements.13.3.165.

Dorn, R. I., D. S. Whitley, N. C. Cerveny, S. J. Gordon, C. Allen, and E. Gutbrod. 2008. "The Rock Art Stability Index: A New Strategy for Maximizing the Sustainability of Rock Art as a Heritage Resource." *Heritage Management* 1 (1): 35–70. doi:10.1179/hma.2008.1.1.37.

Dragovich, D. 1993. "Fire-Accelerated Boulder Weathering in the Pilbara, Western Australia." *Zeitschrift Für Geomorphologie NF* 37 (3): 295–307. doi:10.1127/zfg/37/1993/295.

Emery, K. O. 1944. "Brush Fires and Rock Exfoliation." *American Journal of Science* 242 (9): 506–508. doi:10.2475/ajs.242.9.506.

Esposito, G., E. Esposito, F. Matano, F. Molisso, S. Porfido, and M. Sacchi. 2013. "Effects of a Wildfire on Rocks and Soils in the Sarno Mountains, Campania, Southern Apennines." *Rendiconti Online della Società Geologica Italiana* 24: 119–121.

Figueiredo, R., E. Paupério, and X. Romão. 2021. "Understanding the Impacts of the October 2017 Portugal Wildfires on Cultural Heritage." *Heritage at Risk* 4 (4): 2580–2598. doi:10.3390/heritage4040146.

Fillatre, V. L., E. Robert, S. Petrognani, E. Lesvignes, C. Cretin, and X. Muth. 2021. "Mapping the Walls: High-Resolution Cartography Applied to the Analysis of Prehistoric Cave Art in the Grotte du Mammouth (Domme, Dordogne, France)." *Journal of Archaeological Science* 127: 105332. doi:10.1016/j.jas.2021.105332.

Fitzner, B., K. Heinrichs, and D. LaBouchardiere. 2004. "The Bangudae Petroglyph in Ulsan, Korea: Studies on Weathering Damage and Risk Prognosis." *Environmental Geology* 46 (3–4): 504–526. doi:10.1007/s00254-004-1052-x.

Franklin, N. 2014. "Monitoring Change at Indigenous Rock Art Sites in Australia." *Australian Archaeology* 79 (1): 65–76. doi:10.1080/03122417.2014.11682020.

Freire-Lista, D. M., R. Fort, and M. J. Varas-Muriel. 2016. "Thermal Stress-Induced Microcracking in Building Granite." *Engineering Geology* 206: 83–93. doi:10.1016/j.enggeo.2016.03.005.

Giesen, M. J., A. D. Mazel, D. W. Graham, and P. A. Warke. 2014. "The Preservation and Care of Rock-Art in Changing Environments." In *Open-Air Rock-Art Conservation and Management: State of the Art and Future Perspectives*, edited by T. Darvill and A. P. Batarda-Fernandes, 38–52. New York: Routledge.

Giesen, M. J., A. Ung, P. A. Warke, B. Christgen, A. D. Mazel, and D. W. Graham. 2014. "Condition Assessment and Preservation of Open-Air Rock Art Panels During Environmental Change." *Journal of Cultural Heritage* 15 (1): 49–56. doi:10.1016/j.culher.2013.01.013.

Giorgi, M., and P. S. Tacon. 2019. "Carnarvon Gorge: Safekeeping a Place and Indigenous Agency Within Rock Art Research and Management." *Australian Archaeology* 85 (2): 184–195. doi:10.1080/03122417.2019.1647508.

Goss, M., D. L. Swain, J. T. Abatzoglou, A. Sarhadi, C. A. Kolden, A. P. Williams, and N. S. Diffenbaugh. 2020. "Climate Change is Increasing the Likelihood of Extreme Autumn Wildfire Conditions Across California." *Environmental Research Letters* 15 (9): 094016. doi:10.1088/1748-9326/ab83a7.

Goudie, A. S., R. J. Allison, and S. J. McClaren. 1992. "The Relations Between Modulus of Elasticity and Temperature in the Context of the Experimental Simulation of Rock Weathering by Fire." *Earth Surface Processes and Landforms* 17 (6): 605–615. doi:10.1002/esp.3290170606.

Groom, K. M., N. Cerveny, C. D. Allen, R. I. Dorn, and J. Theuer. 2019. "Protecting Stone Heritage in the Painted Desert: Employing the Rock Art Stability Index in the Petrified Forest National Park." *Arizona: Heritage* 2 (3): 2111–2123.

Hall, K. 2009. "Rock Art Vs. Cultural Stone: Some Geomorphological Perspectives on Weathering and Conservation Under a Changing Climate." *South African Geographical Journal* 91 (2): 58–62.

Hayes, N. R., H. L. Buss, O. W. Moore, P. Krám, and R. D. Pancost. 2020. "Controls on Granitic Weathering Fronts in Contrasting Climates." *Chemical Geology* 535. doi:10.1016/j.chemgeo.2019.119450.

Hoskin, C. M., and D. A. Sundeen. 1985. "Grain Size of Granite and Derived Grus, Enchanted Rock Pluton, Texas." *Sedimentary Geology* 42 (1–2): 25–40. doi:10.1016/0037-0738(85)90071-5.

Hosono, T., E. Uchida, C. Suda, A. Ueno, and T. Nakagawa. 2006. "Salt Weathering of Sandstone at the Angkor Monuments, Cambodia: Identification of the Origins of Salts Using Sulfur and Strontium Isotopes." *Journal of Archaeological Science* 33 (11): 1541–1551. doi:10.1016/j.jas.2006.01.018.

Humphrey, R. R. 1963. "The Role of Fire in the Desert and Desert Grassland of Arizona." *Proceedings of the Tall Timbers Fire Ecology Conference*, Tall Timbers Research Station, Tallahassee, Florida. 2: 45–61.

Huntley, J., M. Aubert, A. A. Oktaviana, R. Lebe, B. Hakim, B. Burhan, L. M. Aksa, et al. 2021. "The Effects of Climate Change on the Pleistocene Rock Art of Sulawesi." *Scientific Reports* 11 (1): 11. doi:10.1038/s41598-021-87923-3.

Isherwood, D., and A. Street. 1976. "Biotite-Induced Grussification of the Boulder Creek Granodiorite, Boulder County, Colorado." *Geological Society of America Bulletin* 87 (3): 366–370. doi:10.1130/0016-7606(1976)87<366:BGOTBC>2.0.CO;2.

Jolly, W. M., M. A. Cochrane, P. H. Freeborn, Z. A. Holden, T. J. Brown, G. J. Williamson, and D. M. Bowman. 2015. "Climate-Induced Variations in Global Wildfire Danger from 1979 to 2013." *Nature Communications* 6 (1): 1–11. doi:10.1038/ncomms8537.

Kelly, R., and D. F. McCarthy. 2001. "Effects of Fire on Rock Art." *American Indian Rock Art* 27: 169–176.

Knight, A. 2020. "Native American Rock Art in the Sant Monica Mountains: A Post-Woolsey Fire Condition Report." *Southern California Archaeology Proceedings* 34: 197–212.

Krinsley, D. H., R. I. Dorn, and N. K. Tovey. 1995. "Nanometer-Scale Layering in Rock Varnish: Implications for Genesis and Paleoenvironmental Interpretation." *The Journal of Geology* 103 (1): 106–113. doi:10.1086/629726.

Krinsley, D. H., K. Pye, S. Boggs, and K. K. Tovey. 2005. *Backscattered Electron Microscopy and Image Analysis of Sediments and Sedimentary Rocks*. Cambridge: Cambridge University Press.

Lacanette, D., D. Large, C. Ferrier, N. Aujoulat, F. Bastian, A. Denis, V. Jurado, et al. 2013. "A Laboratory Cave for the Study of Wall Degradation in Rock Art Caves: An Implementation in the Vézère Area." *Journal of Archaeological Science* 40 (2): 894–903. doi:10.1016/j.jas.2012.10.012.

Lambert, D., and B. Welsh. 2011. "Fire and Rock Art." *Rock Art Research: The Journal of the Australian Rock Art Research Association (AURA)* 28: 45–48.

Liu, T. 2003. "Blind Testing of Rock Varnish Microstratigraphy as a Chronometric Indicator: Results on Late Quaternary Lava Flows in the Mojave Desert, California." *Geomorphology* 53 (3–4): 209–234. doi:10.1016/S0169-555X(02)00331-8.

Liu, T. 2022. "VML Dating Lab." Accessed 3 January 2022. http://www.vmldating.com

Liu, T., and W. S. Broecker. 2007. "Holocene Rock Varnish Microstratigraphy and Its Chronometric Application in Drylands of Western USA." *Geomorphology* 84 (1–2): 1–21. doi:10.1016/j.geomorph.2006.06.008.

Liu, T., and W. S. Broecker. 2008a. "Rock Varnish Evidence for Latest Pleistocene Millennial-Scale Wet Events in the Drylands of Western United States." *Geology* 36 (5): 403–406. doi:10.1130/G24573A.1.

Liu, T., and W. S. Broecker. 2008b. "Rock Varnish Microlamination Dating of Late Quaternary Geomorphic Features in the Drylands of Western USA." *Geomorphology* 93 (3–4): 501–523. doi:10.1016/j.geomorph.2007.03.015.

Liu, T., and W. S. Broecker. 2013. "Millennial-Scale Varnish Microlamination Dating of Late Pleistocene Geomorphic Features in the Drylands of Western USA." *Geomorphology* 187: 38–60. doi:10.1016/j.geomorph.2012.12.034.

Loubser, J. 2001. "Management Planning for Conservation." In *Handbook for Rock Art Research*, edited by D. S. Whitley, 80–115. Walnut Creek: Altamira Press.

Marston, R. A. 2003. "Editorial Note." *Geomorphology* 53 (3–4): 197. doi:10.1016/S0169-555X(02)00329-X.

May, S. K., P. S. C. Taçon, D. Wright, and M. Marshall. 2015. "The Rock Art of Kakadu: Past, Present and Future Research, Conservation and Management." *Kakadu National Park Symposia Series: Symposium* 6: 36–44.

McDonald, C. J., and G. R. McPherson. 2013. "Creating Hotter Fires in the Sonoran Desert: Buffelgrass Prouces Copious Fuels and High Fire Temperatures." *Fire Ecology* 9 (2): 26–39. doi:10.4996/reecology.0902026.

Meiklejohn, K. I., K. Hall, and J. K. Davis. 2009. "Weathering of Rock Art at Two Sites in the Kwazulu-Natal Drakensberg, Southern Africa." *Journal of Archaeological Science* 36: 973–979. doi:10.1016/j.jas.2008.11.020.

Mol, L., and M. Grenfell. 2022. "Influence of Landscape Moisture Sources and Topography on Rock Weathering Patterns Associated with Wildfire." *Earth Surface Processes and Landforms* 47 (7): 1761–1777. doi:10.1002/esp.5345.

Narog, M., A. L. Koonce, and C. Cocoran. 1995. "Burning in Arizona's Giant Cactus Community." *USDA Forest Service General Technical Report* PSW-GTR-158: 175-176.

Neely, A. B., and R. A. DiBiase. 2020. "Drainage Area, Bedrock Fracture Spacing, and Weathering Controls on Landscape-scale Patterns in Surface Sediment Grain Size." *Journal of Geophysical Research: Earth Surface* 125 (10): e2020JF005560. doi:10.1029/2020JF005560.

Nhamo, A. 2018. "Burning Images: A Critical Review of Rock Art Conservation in Zimbabwe." *Conservation and Management of Archaeological Sites* 20 (2): 58–75. doi:10.1080/13505033.2018.1453725.

Ollier, C. D. 1983. "Fire and Rock Breakdown." *Zeitschrift Für Geomorphologie* 27 (3): 363–374.

Pillans, B., and L. K. Fifield. 2013. "Erosion Rates and Weathering History of Rock Surfaces Associated with Aboriginal Rock Art Engravings (Petroglyphs) on Burrup Peninsula, Western Australia, from Cosmogenic Nuclide Measurements." *Quaternary Science Reviews* 69 (1): 98–106. doi:10.1016/j.quascirev.2013.03.001.

Pope, G. A. 1995. "Newly Discovered Submicron-Scale Weathering in Quartz: Geographical Implications." *Professional Geographer* 47 (4): 375–387.

Pope, G. A. 2000. "Weathering of Petroglyphs: Direct Assessment and Implications for Dating Methods." *Antiquity* 74 (286): 833–843. doi:10.1017/S0003598X00060488.

Post, A. K., and A. K. Knapp. 2020. "The Importance of Extreme Rainfall Events and Their Timing in a Semi-arid Grassland." *The Journal of Ecology* 108 (6): 2431–2443. doi:10.1111/1365-2745.13478.

Pozo-Antonio, J. S., T. Rivas, F. Carrera, and L. García. 2018. "Deterioration Processes Affecting Prehistoric Rock Art Engravings in Granite in NW Spain." *Earth Surface Processes and Landforms* 43 (11): 2435–2448. doi:10.1002/esp.4406.

Pozo-Antonio, J. S., P. Sanmartín, M. Serrano, J. M. De la Rosa, A. Z. Miller, and J. Sanjurjo-Sánchez. 2020. "Impact of Wildfire on Granite Outcrops in Archaeological Sites Surrounded by Different Types of Vegetation." *The Science of the Total Environment* 747: 141143. doi:10.1016/j.scitotenv.2020.141143.

Rahmntara, T., and C. Krawczyk. 2022. "Combined Seismic and Borehole Investigation of the Deep Granite Weathering Structure - Santa Gracia Reserve Case in Chile." *Earth Surface Processes and Landforms*. doi:10.1002/ESP.5457.

Reed, S. J. B. 1993. *Electron Microprobe Analysis*. 2nd. Cambridge: Cambridge University Press.

Reynold, S. J., F. M. Conway, J. Johnson, M. F. Doe, and N. J. Niemuth. 2017. "The Phillip Anderson Arizona Proterozoic Archive." *Arizona Geological Survey Contributed Report CR-17-D: 1-5*.

Ryan, K. C., A. T. Jones, C. L. Koerner, and K. M. Lee. 2012. "Wildland Fire in Ecosystems: Effects of Fire on Cultural Resources and Archaeology." In *General Technical Report RMRS-GTR-42-Vol. 3*. Fort Collins: U.S. Department of Agricutlure, Rock Mountain Research Station.

Sampietro-Vattuone, M. M., and J. L. Peña-Monné. 2021. "Application of 2D/3D Models and Alteration Mapping for Detecting Deterioration Processes in Rock Art Heritage (Cerro Colorado, Argentina): A Methodological Proposal." *Journal of Cultural Heritage* 51: 157–165. doi:10.1016/j.culher.2021.08.006.

Sefton, C. 2011. "The Effects of Fire on the Rock Art of the Woronora Plateau." *Rock Art Research: The Journal of the Australian Rock Art Research Association (AURA)* 28: 49–52.

Shakesby, R. A., and S. H. Doerr. 2006. "Wildfire as a Hydrological and Geomorphological Agent." *Earth-Science Reviews* 74 (3–4): 269–307. doi:10.1016/j.earscirev.2005.10.006.

Shtober-Zisu, N., A. Brook, D. Kopel, D. Roberts, C. Ichoku, and L. Wittenberg. 2018. "Fire Induced Rock Spalls as Long-Term Traps for Ash." *Catena* 162: 88–99. doi:10.1016/j.catena.2017.11.021.

Shtober-Zisu, N., N. Tessler, A. Tsatskin, and N. Greenbaum. 2015. "Accelerated Weathering of Carbonate Rocks Following the 2010 Wildfire on Mount Carmel, Israel." *International Journal of Wildland Fire* 24 (8): 1154–1167. doi:10.1071/WF14221.

Shtober-Zisu, N., and L. Wittenberg. 2021a. "Long-Term Effects of Wildfire on Rock Weathering and Soil Stoniness in the Mediterranean Landscapes." *The Science of the Total Environment* 762. doi:10.1016/j.scitotenv.2020.143125.

Shtober-Zisu, N., and L. Wittenberg. 2021b. "Wildfires as a Weathering Agent of Carbonate Rocks." *Minerals* 11 (10): 1091. doi:10.3390/min11101091.

Shyrock, D. F., T. Esque, and F. C. Chen. 2015. "A 30-Year Chronosequence of Burned Areas in Arizona: Effects of Wildfires and Vegetation in Sonoran Desert Tortoise (Gopherus Morafkai) Habitats." *US Geological Survey Open File Report* 2015-1060: 1–61.

Stone, C. L. 2015. *People of the Desert, Canyons and Pines: Prehistory of the Patayan Country in West Central Arizona*. Grand Junction: Bureau of Land Management.

Swanson, F. J. 1981. "Fire and Geomorphic Processes." In *Fire Regimes and Ecosystem Properties*, edited by H. A. Mooney, T. M. Bonnicksen, N. L. Christensen, J. E. Lotan, W. A. Reiners, H. A. Mooney, T. M. Bonnicksen, N. L. Christensen, J. E. Lotan, and W. A. Reiners 401–420. Washington D.C: U.S. Department of Agriculture General Technical Report WO-26.

Todhunter, P. E., C. C. Jackson, and T. H. Mahmood. 2020. "Streamflow Partitioning Using the Budyko Framework in a Northern Glaciated Watershed Under Drought to Deluge Conditions." *Journal of Hydrology* 591: 125569. doi:10.1016/j.jhydrol.2020.125569.

Tratebas, A. M., N. Cerveny, and R. I. Dorn. 2004. "The Effects of Fire on Rock Art: Microscopic Evidence Reveals the Importance of Weathering Rinds." *Physical Geography* 25 (4): 313–333. doi:10.2747/0272-3646.25.4.313.

United Nations Environment Program. 2022. *Spreading Like Wildfire: The Rising Threat of Extraordinary Landscape Fires*. Nairobi: United Nations Environment Program.

Wakatsuki, T., Y. Sasaki, Y. Tanaka, and Y. Matsukura. 2007. "Predictive Equation of Unit Weights, Shear Strength Parameters and Permeability of Grus Using a Simplified Dynamic Cone Penetrometer Hardness and Grain Size." *Journal of the Japan Society of Erosion Control Engineering* 59: 38–46.

Walderhaug, O. 1998. "Chemical Weathering at Rock Art Sites in Western Norway: Which Mechanisms are Active and How Can They Be Retarded?" *Journal of Archaeological Science* 25 (8): 789–800. doi:10.1006/jasc.1997.0224.

Wang, F., T. Fruhwirt, and H. Konietzky. 2020. "Influence of Repeated Heating on Physical-Mechanical Properties and Damage Evolution of Granite." *International Journal of Rock Mechanics & Mining Sciences* 136. doi:10.1016/j.ijrmms.2020.104514.