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Some effects of weathering on joints in granitic rocks

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Abstract

Standard engineering weathering classifications, most of which are based on weathered granite, typically describe the appearance and condition of the weathered material (e.g. whether or not it is friable), the condition of individual minerals (e.g. degree of pitting and micro-cracking and changes in mineral composition), and the degree of staining on joint surfaces or the distance that staining extends into rock from the joints. These classifications do not address changes in frequency, length, and appearance of joints in the rock mass as weathering progresses. This account of work on vertical or steeply dipping joints in granitic rocks shows that not only are there statistically significant differences in mean joint spacings and mean trace lengths with increased weathering, but that the physical appearances of joints also changes as weathering progresses. Mean joint spacing is wide in fresh rock, becomes closer in moderately weathered rock, and then becomes progressively wider from moderately weathered rock through highly and completely weathered rock. Mean joint lengths follow a similar but inverse pattern. Mean trace lengths become shorter from fresh to slightly weathered rock, lengthen in moderately weathered rock, then progressively become shorter from moderately weathered rock through highly and completely weathered rock. Furthermore, joint appearance changes with increased weathering. Joints in fresh rock are sharp-edged and typically straight. The edges begin to round in moderately weathered rock, and in highly weathered rock, joint traces become sinuous and discontinuous around mineral grains. In completely weathered rock, the only visible joints are filled with minerals or marked with iron staining. It is proposed that this evolution in joint pattern and appearance results from increased cracking along grain boundaries and thermal expansion of individual mineral grains, and within-grain micro-cracking as weathering proceeds. These factors allow individual mineral grains to "move" into the spaces between joint surfaces, thus obscuring individual joints and making them appear shorter. These apparent changes in joint properties could lead to incorrect rock mass classification and thus, to inappropriate engineering design and costly errors during construction. Published by Elsevier Science B.V.

Keywords: Granite; Weathering grade; Joint spacing; Joint length

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1. Introduction

Most standard engineering weathering classifications (e.g. Dearman, 1974; Dearman et al., 1978; Anonymous, 1981, 1995) are based on weathered granite. These classifications tend to be similar, with the exception of the 1995 scheme, which is broader and more flexible than previously published classifications. It is also more easily applied to a greater number of lithologies. Most classifications are based on the engineering properties of weathered materials and typically describe the appearance and condition of the rock material (e.g. whether or not it is friable), the condition of individual minerals (e.g. degree of pitting and microcracking), changes in mineral composition (e.g. the disappearance of existing minerals and appearance of new ones), and the degree of staining on joint surfaces and/or the distance that staining extends into the rock from joints. Rock is separated into various weathering grades based on variations in these properties. Some weathering classifications (e.g. Selby, 1980) also include engineering properties such as changes of rock strength with weathering.

What weathering classifications do not do is address changes in joint properties as weathering progresses, except in terms of staining on joint surfaces. The purpose of this paper is to address this issue — specifically, changes in joint spacing, joint trace length, and joint appearance as weathering progresses — using data collected from two areas of granitic rocks where the full range of weathering grades is present. Analysis of these data has pro-duced results that may have important implications for rock mass classification and engi-neering design.

2. Weathering grade classification

The weathering classification used herein was prepared by Murphy (1985) for the US Army Corps of Engineers (Fig. 1). This classification is simpler than most, and is more easily adapted to field use than many other classifications. Murphy's classification was modified to include the sound and feel of the square end of a 3-lb rock hammer (a Nolan hammer) hitting the rock. This is a personal classification and depends on many factors, including the strength of the individual wielding the rock hammer, as well as the weight of the hammer itself. In addition to the descriptions for each weathering grade shown in Fig. 1, the modified classification includes the following:

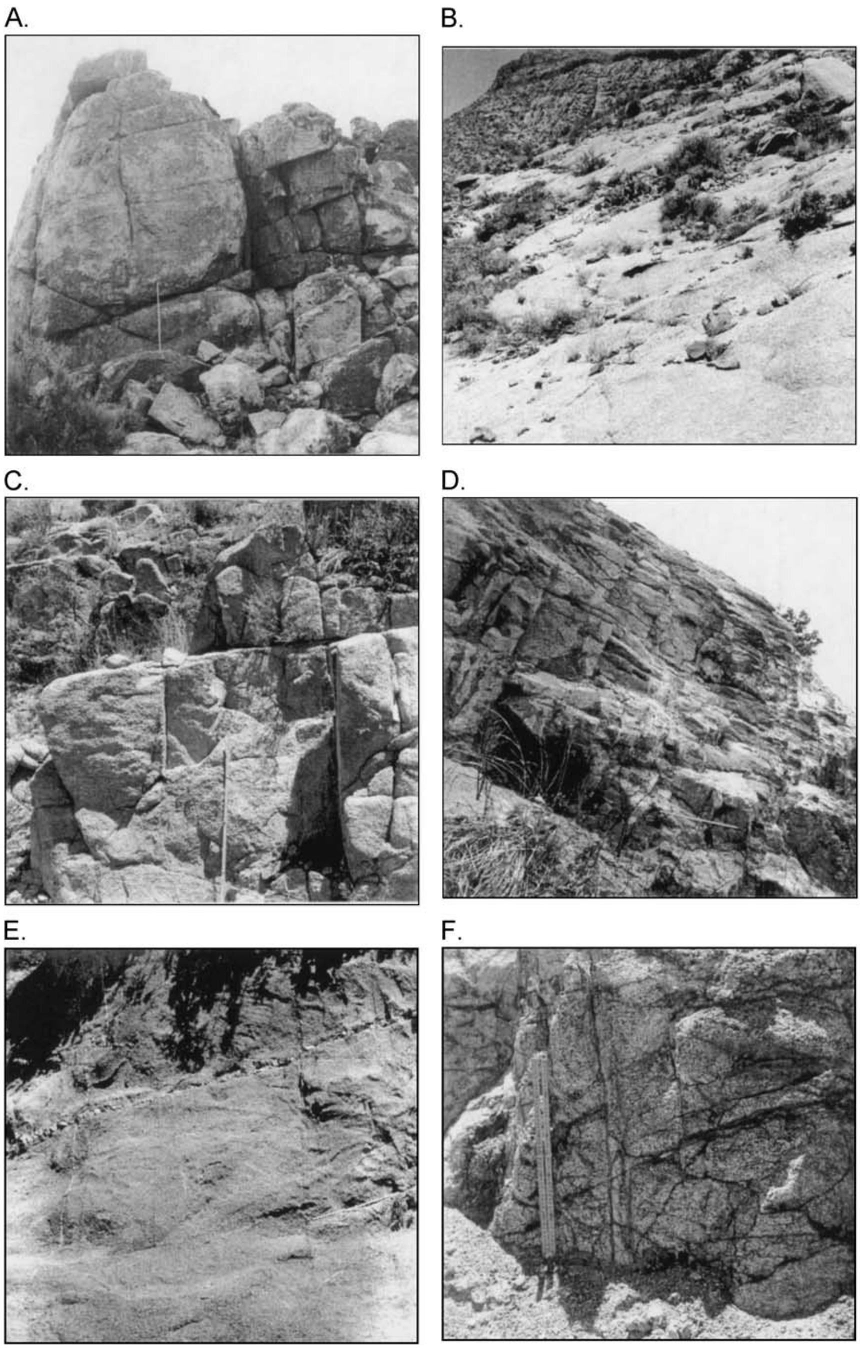
Fresh rock (F). The rock hammer rings and bounces back;
Slightly Weathered Rock (SW). The rock hammer rings and bounces back;
Moderately Weathered Rock (MW). The hammer "thuds";
Highly Weathered Rock (HW). The hammer "thuds" and fragments of rock and individual mineral grains on the surface can easily be broken or rubbed off by hand;
Completely Weathered Rock (CW). The pick end of the hammer easily enters the rock.

For the most accurate results, every attempt should be made not to strike the hammer on a joint surface; staining and case hardening typically make joint surfaces harder than the surrounding rock material and if such surfaces are struck, a false impression of weathering grade can be obtained.

Weathering Grade	Description
Fresh	No visible signs of weathering. Rock is fresh. Crystals are bright.
Slightly Weathered	Discontinuities are stained or discolored and may contain a thin filling of altered material. Discoloration may extend into the rock from the discontinuity to a distance of 20% of the discontinuity spacing.
Moderately Weathered	Slight discoloration extends from discontinuity planes for a distance of more than 20% of the discontinuity spacing. Discontinuities may contain filling of altered material. Partial opening of grain boundaries observed.
Highly Weathered	Discoloration extends throughout the rock, and the rock material is partly friable. The original texture of the rock has mainly been preserved, but separation of the grains has occurred.
Completely Weathered	The rock is totally discolored and decomposed and in friable condition. The external appearance is that of a soil. Internally, the rock texture is partly preserved, but the grains have been completely separated.
Residual Soil	Not included.

Fig. 1. Weathering grade classification (from Murphy, 1985).

Fig. 2 shows examples of the different weathering grades in granitic rocks. Fig. 2A shows fresh rock, a quartz monzonite tor. Note the sharp-edged joint blocks, particularly in the upper right. Fig. 2B is slightly weathered granite. This exposure is a pavement, which probably represents the weathering front. Iron staining is visible along some of the joints, although not necessarily apparent in this photograph. Most joints have very narrow apertures. Fig. 2C shows a moderately weathered granite outcrop. At this juncture, the joints are mostly open and, in this outcrop, they are not filled with minerals or weathering products. The joint surfaces are stained and the staining extends for significant distances into the joint blocks. On the right side of Fig. 2D, also moderately weathered granite, the dense joint pattern that typically occurs on corners and edges of exposures of moderately weathered granitic rock is apparent. Many of these joints are surficial and are caused by weathering and stress release. Fig. 2E is a road cut in highly weathered granite. The major joints have wide apertures, particularly in the upper portion, and staining occurs throughout most of the rock fabric. The plastic metre stick used for measurements inadvertently removed clumps and individual mineral grains from the rock surface as measurements were made, and small


A.
B.
C.
D.
E.
F.

aggregates could be easily removed by hand. Many visible joints are filled with vein material (e.g. the quartz-filled diagonal joint near the top of the photo), weathering products, or soil. Finally, Fig. 2F shows a granodiorite road cut in completely weathered rock. All visible joints are iron stained or filled with quartz or manganese and most apertures are wide. The pick end of the hammer went into this outcrop about 5 cm. Note the skirt of granular debris at the base of the exposure, which is typical of completely weathered granitic outcrops.

3. Procedures

Joint spacings and trace lengths were measured in two areas of weathered granitic rock, granite in temperate eastern Asia and granodiorite and quartz monzonite in the arid southwestern United States (Table 1). In the temperate area, 13 exposures were measured and 24 in the arid area. The full range of weathering grades is present in both areas. The exposures range from natural outcrops (vertical outcrop and horizontal pavements) to tunnel walls, road cuts, quarry walls, and bulldozed faces (Table 1). Vertical outcrops ranged in size from about 5 to 19 m in length and up to 11 m in height, and flat pavements, from 9.5 to 10 m in length and up to almost 6 m in width. Tunnel wall exposures ranged from 25 up to 74 m in length and either 2.5 or 4 m in height. Road cuts ranged in length from 5 to over 40 m, typically about 2 m in height. The one quarry face measured was 4.6 m long and about 1.5 m high. The bulldozed faces were about 10 m long and up to 8 m high.

Each exposure was classified according to its predominant weathering grade. For example, if the exposure is 15% moderately weathered rock, 30% highly weathered rock, and 55% completely weathered rock, it would be classified as completely weathered. Ehlen (1999) tested the use of this type of classification against a classification using joint spacings in individual weathering grades and found it acceptable.

An areal sampling scheme was used to measure joint properties (Ehlen, 1992). The measurement area typically extended the length of the exposure and ranged between 2 and 3 m in height depending upon actual height and, for taller exposures, accessibility. Measurement area height was calculated by summing spacings between joints in the most gently dipping joint set, so measurement area can be greater than exposure size (compare exposure sizes given above with measurement areas in Table 1). The joint sets to be measured were identified visually in the outcrop and strike and dip were measured on several joints to determine the average orientation for each set. A minimum of three sets was measured for three-dimensional outcrops, typically the most important sets. These joint sets that control outcrop shape are present throughout the outcrop, and commonly contain the largest number of joints. Two vertical or steeply dipping joint sets and one horizontal or gently dipping joint set were typically measured. Three joint sets were usually measured for two-dimensional road cuts, quarry walls, and bulldozed faces as well,

Fig. 2. Examples of the different weathering grades. (A) Fresh rock (scale, 1 m). (B) Slightly weathered rock (shrub in center on right side about 50-cm tall). (C) Moderately weathered rock (scale, about 0.7 m). (D) Increased jointing in moderately weathered rock (scale, 1 m). (E) Highly weathered rock (scale, on right, 1 m). (F) Completely weathered rock (scale, 0.5 m).

Table 1
Outcrop descriptions

Rock type	Weathering grade	Exposure type	Measurement area (m)[a]	No. of joint sets measured	No. of spacings measured	No. of lengths measured
Granite	F	tunnel wall	25.2 × 6.5	4	204	33
Granite	F	tunnel wall	74.0 × 2.8	4	692	131
Granite	MW	natural (3D)	17.3 × 1.8	3	198	67
Granite	CW	road cut	28.2 × **3.0**	2	144	49
Granite	MW	bulldozed face	10.4 × 2.7	3	258	59
Granite	HW	road cut	21.4 × **5.0**	2	177	0
Granite	HW	bulldozed face	10.1 × 3.4	4	197	45
Granite	HW	road cut	35.0 × 2.7	3	143	65
Granite	HW	road cut	11.9 × 5.0	3	152	53
Granite	HW	natural/road cut	22.1 × 10.4	3	207	49
Granite	F	tunnel wall	34.0 × 4.0	5	307	50
Granite	SW	natural (3D)	14.6 × 5.2	3	251	38
Granite	SW	natural	14.3 × 2.9	3	204	41
Granodiorite	MW	natural	18.7 × 5.4	2	190	137
Granodiorite	MW	natural	9.7 × 4.0	3	157	92
Granodiorite	HW	natural	13.0 × 4.8	2	123	51
Granodiorite	HW	natural	15.8 × 2.1	3	133	138
Granodiorite	CW	road cut	40.4 × 11.6	3	216	219
Granodiorite	CW	road cut	13.0 × 6.1	3	85	89
Granodiorite	HW	road cut	16.6 × **4.0**	2	153	114
Granodiorite	HW	natural	5.1 × 3.7	2	75	87
Granodiorite	SW	natural	11.2 × 5.4	3	149	114
Granodiorite	CW	road cut	32.7 × **4.0**	3	266	286
Granodiorite	SW	pavement	9.9 × **4.5**	2	76	64
Granodiorite	MW	natural	9.7 × 4.0	2	63	59
Granodiorite	HW	road cut	10.6 × 2.9	3	144	121
Granodiorite	SW	natural	8.8 × 3.3	4	167	133
Granodiorite	HW	road cut	13.1 × 2.0	3	125	116
Granodiorite	CW	road cut	22.1 × **3.0**	3	212	224
Granodiorite	CW	road cut	23.8 × **2.0**	3	205	204
Granodiorite	CW	road cut	5.0 × 1.8	3	53	66
Granodiorite	CW	quarry wall	4.3 × 2.6	3	212	233
Quartz monzonite	SW	natural	13.7 × 3.2	2	88	95
Quartz monzonite	SW	natural	6.5 × 3.1	3	92	77
Quartz monzonite	F	natural	16.6 × 4.2	3	132	123
Quartz monzonite	SW	pavement	9.5 × 5.4	3	84	97
Quartz monzonite	F	outcrop	15.3 × 8.9	3	184	186

[a] Measurement area dimensions in bold are estimates; no horizontal or gently dipping joints were measured in these exposures.

but occasionally, only two continuous sets, usually vertical or steeply dipping joints, could be identified. Joint spacings were measured between individuals in each joint set in each exposure. Spacings were measured perpendicular to strike regardless of aperture size or trace length. The minimum spacing measured was 0.5 cm.

Joint trace lengths were measured for each set in the same measurement area in which the joint spacings were measured, not over the full exposure face. Only a small sample of joint lengths was measured for each joint set in the Asian granites (Table 1). Analysis of these data suggested that the data set was too small, therefore, a much larger sample was measured for each joint set in the southwestern United States. Trace lengths were measured for all joints present in the measurement area regardless of length or aperture; no thresholds were used.

Joint trace length is impossible to measure correctly — exposure size and accessibility to a great extent control the trace lengths that can be measured (certainly those for the major joints that control outcrop shape), but even worse, one never knows what the true dimensions or shape of a joint are or what part of a particular three-dimensional joint, one is measuring. Trace lengths measured in outcrop are thus likely to be shorter than true length (diameter). Whereas measured joint spacings are absolute, measured joint lengths are relative. Various corrections for this bias are reported in the literature (e.g. Cruden, 1977; La Pointe and Hudson, 1985; Kulatilake et al., 1993), but none were used in the analysis of these data. As noted above, trace lengths were measured in the same area as joint spacings, not over the full height of the exposure. Trace lengths for the major joints that are present in, but extend beyond, the measurement area and through the full exposure were estimated. These long joints comprised about 7% of the data set for the US sample sites, and about 14% for the Asian sample sites. The sparseness of long joints and the limited sizes of the measurement areas tend to bias the joint length measurements toward the shorter joints, but again, no corrections were made for this bias.

Spacing and trace length measurements were made on joints of all orientations, i.e. horizontal ($<30°$), inclined (30–70°), and vertical ($>70°$), but only vertical and steeply dipping joints are addressed herein; these joints provide the bulk of both data sets. In addition, information on joint fillings (i.e. composition, types of joints filled, amount, and continuity), staining, termination percent for each joint set ("T" intersections), and the proportions of each weathering grade and their distribution in each exposure were noted.

The data were compiled and analyzed using Excel and Statgraphics, a visually oriented statistics package. The data sets were compiled from the raw field data in Excel and simple statistics—means, medians, and standard deviations — were calculated. Frequency histograms, comparisons among distributions, and differences among the various properties among weathering grades were determined using Statgraphics. The latter analyses included distribution fitting, analysis of variance, multiple range tests for mean joint spacings and mean trace lengths, and the Kruskal–Wallis test for median joint spacings and median trace lengths.

4. The data

The data for the granodiorites and quartz monzonites from the southwestern United States were combined rather than addressing each rock type separately, because the two lithologies are from one stock and have thus undergone similar, if not identical, weathering. The most widely separated exposures were less than 1.8 km apart in this small stock. The Asian granite exposures were much more widely separated, the maximum distance between exposures being 40 km, but all are mapped as parts of the same large batholith, are of the same composition, and of the same age. Because of these factors, the individual data sets were combined. The individual study sites in Asian granite have also undergone similar, if not identical, weathering.

The distributions for joint spacing and joint trace length in any given exposure or any given weathering grade are similar. Fig. 3 shows two examples of distributions for vertical and steeply dipping joint spacings from the two areas. Fig. 3A is for joints in completely weathered granodiorite and quartz monzonite from the southwestern United States and Fig. 3B is for joints in fresh granite from Asia. Fig. 4 shows two trace length distributions for vertical and steeply dipping joints. Fig. 4A is for moderately weathered granodiorite and quartz monzonite and Fig. 4B is for highly weathered granite. These four distributions, as well as the others for these data sets, are representative of joint spacing and joint spacing distributions in other areas formed of granitic rock (Ehlen, 1993; Ehlen et al., 1997). Like most other distributions, they appear to be log normal but are probably power-law or fractal (Barton et al., 1988; Velde et al., 1991; Berkowitz and Hadad, 1997).

It is not known how representative the joint properties in these two areas are with respect to other areas composed of weathered granite. However, it is rare that the full range of weathering grades occurs in any given area where there is consistency in lithology, weathering and tectonic histories, structure, and age. Exposure sizes in each weathering grade are comparable to those found in areas not exhibiting the full range of weathering

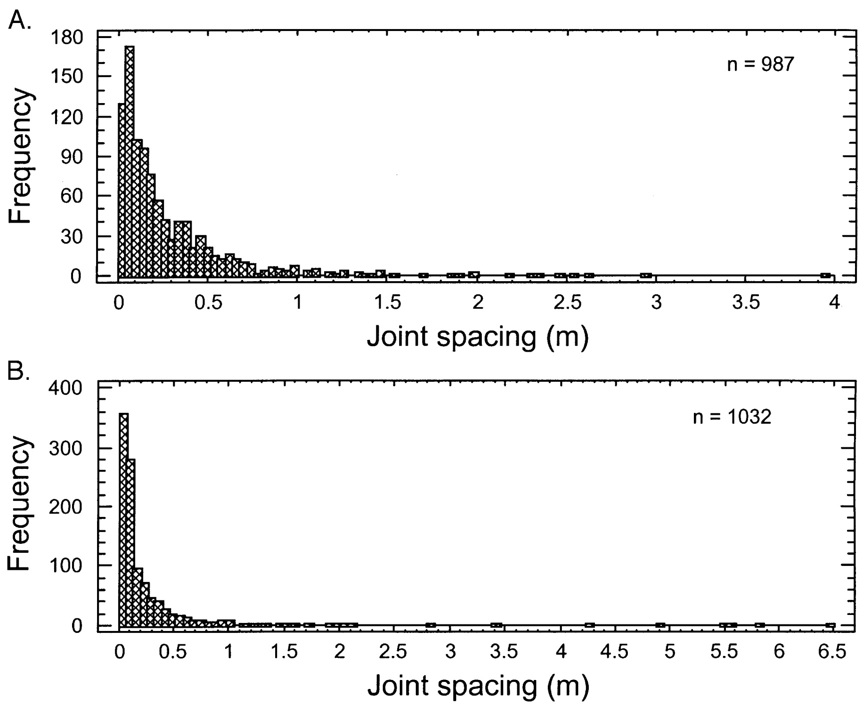


Fig. 3. Typical joint spacing distributions. (A) Completely weathered granodiorite and quartz monzonite. (B) Fresh granite.

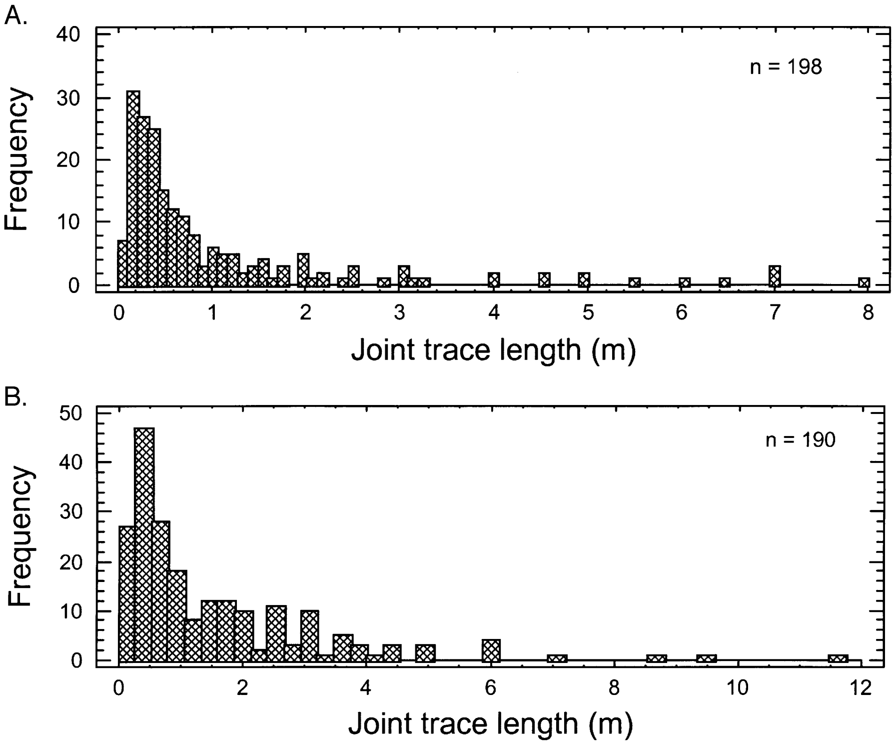


Fig. 4. Typical joint trace length distributions. (A) Moderately weathered granodiorite and quartz monzonite. (B) Highly weathered granite.

grade, except that exposures of completely weathered rock are larger than found elsewhere by the author. In addition, as noted above, both joint spacing and joint trace length exhibit distributions comparable to those found in other areas composed of weathered granitic rocks.

5. Results

5.1. Joint spacing

Fig. 5A shows the mean spacings for the granodiorites and quartz monzonites in the five weathering grades and summary statistics are given in Table 2. Although relationships between medians were analyzed, these data are not shown. Mean spacing increases very slightly from fresh and slightly weathered rock, then decreases to moderately weathered rock. Mean spacings then become increasingly wider from moderately weathered through highly and completely weathered rock. The decrease in mean joint spacing in moderately weathered rock was expected (see Fig. 2D).

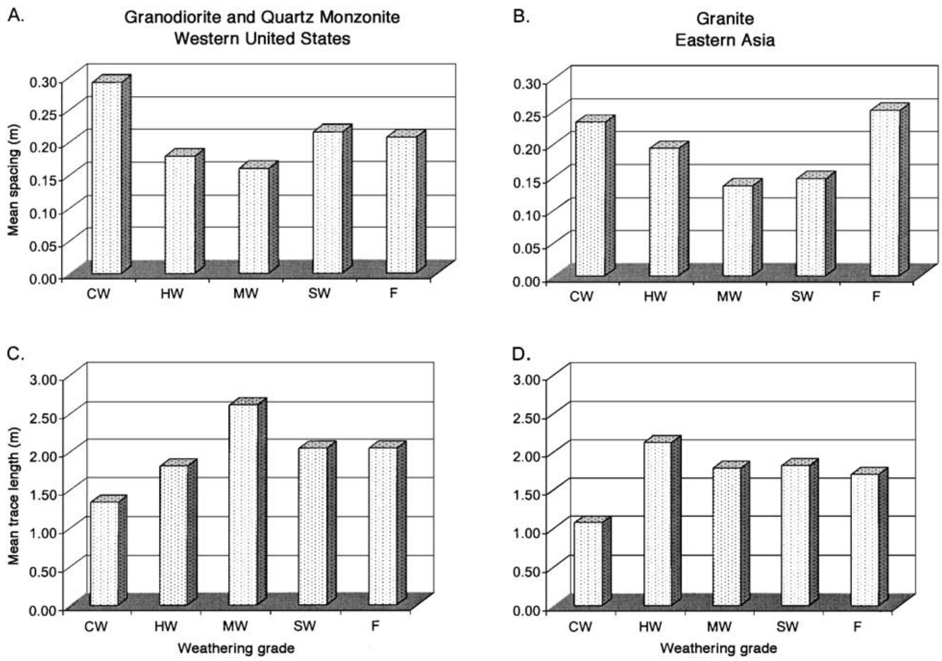


Fig. 5. Variations in mean joint spacings (A and B) and mean trace lengths (C and D) in the five weathering grades in granodiorites and quartz monzonites (A and C) and granites (B and D).

Mean spacings for each weathering grade in the Asian granites are shown in Fig. 5B and the data are given in Table 2. Again, medians are not shown. The widest spacings occur in fresh granites. Mean spacings decrease from fresh to moderately weathered rock, and then become wider in highly and completely weathered granite so that spacings in completely weathered granite are almost as wide as those in fresh granite. Joint spacing relations for these granites were previously reported in Ehlen (1999). The decrease in mean joint spacing between fresh and slightly weathered granite is exhibited by this data set, but not by the data from the southwestern United States, at first appears inexplicable. However, the majority of measurements in fresh rock were made in a very poorly lit tunnel

Table 2
Mean joint spacings and standard deviations

	Granodiorite and quartz monzonite			Granite			Combined data sets		
	N	Mean (m)	Standard deviation	*N*	Mean (m)	Standard deviation	*N*	Mean (m)	Standard deviation
CW	987	0.29	0.29	182	0.23	0.25	1169	0.27	0.34
HW	639	0.18	0.15	789	0.19	0.26	1460	0.19	0.26
MW	319	0.16	0.16	678	0.14	0.17	997	0.14	0.20
SW	471	0.21	0.19	191	0.15	0.16	649	0.18	0.20
F	311	0.21	0.20	1032	0.25	0.51	1357	0.22	0.63

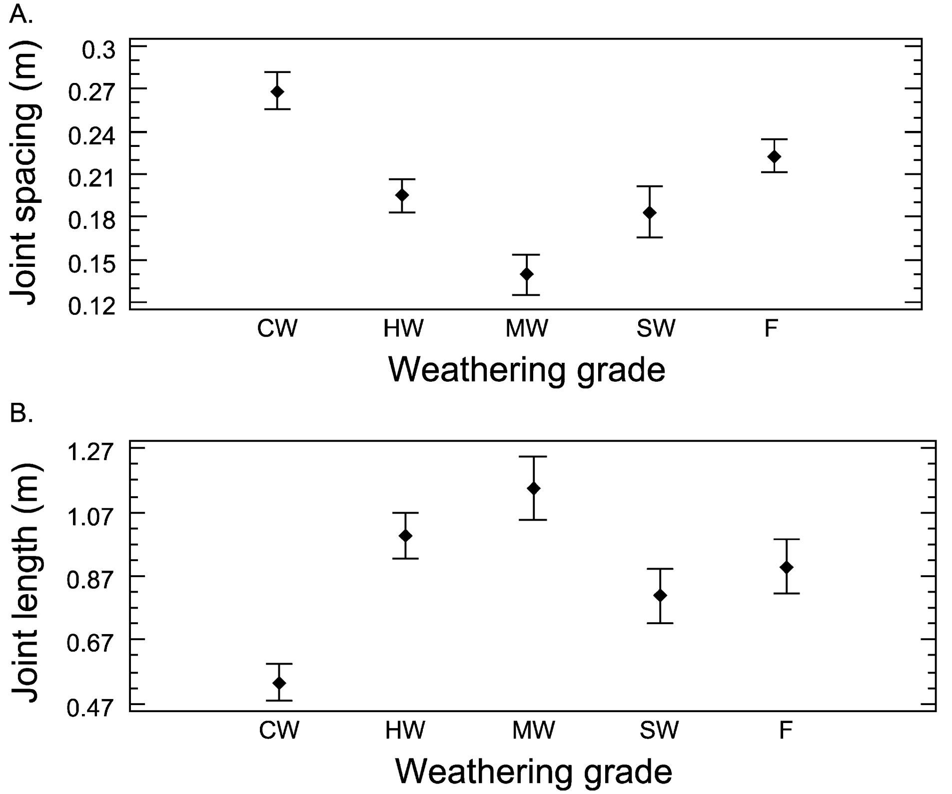


Fig. 6. Variations in mean spacings (A) and mean trace lengths (B) in the combined data set.

(the brightest light was a headlamp). Thus, it is possible that many smaller joints were simply not visible. In addition, this tunnel was formed by blasting and, while every effort was made to avoid fractures formed by blasting, it is possible that there may have been confusion between natural fractures and those formed by blasting.

If the spacings for the two data sets are combined, the pattern becomes more distinct as shown in Fig. 6A. Summary statistics for the combined data sets are given in Table 2. Mean

Table 3
Mean joint trace lengths and standard deviations

	Granodiorite and quartz monzonite			Granite			Combined data sets		
	N	Mean (m)	Standard deviation	*N*	Mean (m)	Standard deviation	*N*	Mean (m)	Standard deviation
CW	1005	1.34	0.51	49	1.08	1.19	1057	1.32	1.49
HW	494	1.81	0.81	190	2.12	0.92	702	1.97	1.63
MW	198	2.61	0.89	149	1.79	0.77	359	2.06	2.07
SW	451	2.04	0.68	41	1.82	0.84	492	2.01	1.63
F	268	2.04	0.66	167	1.71	0.47	479	1.84	1.67

joint spacings decrease from fresh to moderately weathered rock, reaching a maximum in moderately weathered rock, then increase from moderately weathered rock to completely weathered rock. Mean spacings are widest in completely weathered rock. An analysis of variance shows a statistically significant difference between the mean spacings for the five weathering grades at the 95% confidence level. The *F*-ratio is 23.00 and the *P*-value for the

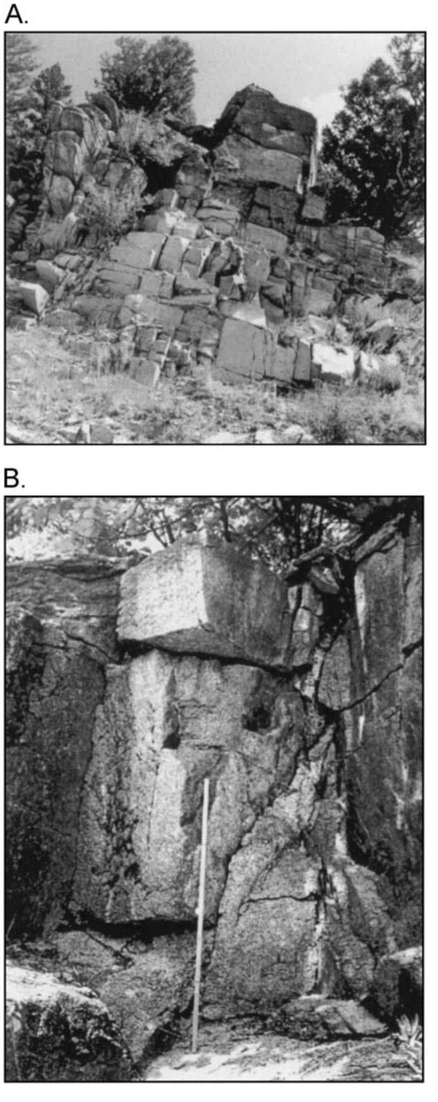


Fig. 7. Changes in joint appearance. (A) Sharp-edged, straight joints in fresh granite (note person for scale). (B) Stained, sharp-edged, and straight joint in slightly weathered granite. (C) Rounded exposure and joint edges in fresh granite. (D) Weathering- and stress-induced joints in moderately weathered granite. (E) Rounded-edged, open joints in highly weathered granodiorite. (F) Iron stained joint locations in completely weathered granite. Scales used: metre stick, 1 m; Nolan hammer, 45.7 cm.

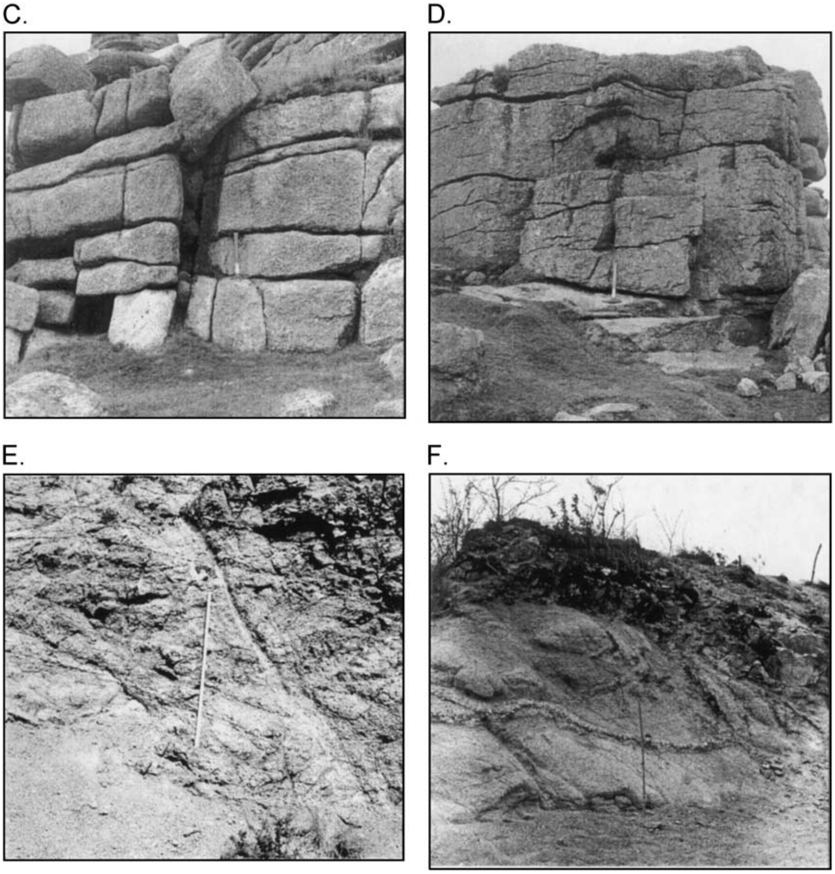


Fig. 7 (*continued*).

F-test is less than 0.05. The Kruskal–Wallis test also shows that there is a statistically significant difference among the medians for joint spacing among the five weathering grades at the 95% confidence level.

5.2. Joint trace length

Joint trace lengths in the two areas also exhibit similar patterns, but the relations are not as clear cut as those for joint spacing. Fig. 5C shows mean joint trace lengths in the granodiorite and quartz monzonite and Table 3 shows the summary statistics. Again, medians are not shown. Mean trace length is virtually the same in fresh and slightly weathered rock, and ignoring moderately weathered rock for the moment, decreases from moderately weathered rock through highly and completely weathered rock. The explanation for the exceptionally long joints in moderately weathered rock lies at least in part with the type of exposure. Two of the three moderately weathered exposures, which contained more than 85% of the joints in moderately weathered rock in this area, were natural exposures. These were very large and much taller than the typical exposures in the other weathering grades, most of which were road cuts along bulldozed dirt tracks. The large, moderately weathered outcrops also contained a proportionately greater number of major joints.

The trace length distribution in the granites is similar to that in the granodiorites and quartz monzonites (Fig. 5D and Table 3). Mean trace length increases slightly, but not significantly, between fresh, slightly weathered, and moderately weathered granite, then, ignoring highly weathered granite for the moment, decreases to the shortest lengths in completely weathered granite. The longest trace lengths occur in highly weathered granite because most of these exposures were bulldozed faces much taller than the rare natural outcrops or numerous road cuts; trace lengths at least for major joints in highly weathered granite were thus longer than in the typical exposures in this area. Furthermore, the trace lengths in fresh and slightly weathered granite are shorter than one would expect, because measurements were made in tunnels, one circular tunnel of approximately 2.5-m diameter and the other, an elliptical tunnel approximately 4-m high.

Regardless of the discrepancies caused by variations in exposure height, the trace length pattern in the two data sets is consistent. Fig. 6B shows the results of combining the two trace length data sets. Table 3 gives the summary statistics. Mean trace length decreases slightly between fresh and slightly weathered rock, then increases to moderately weathered rock. It then decreases from moderately weathered rock to highly weathered and completely weathered rock. The longest trace lengths occur in moderately weathered granitic rock, as noted above. An analysis of variance shows a statistically significant difference between the mean joint length among the five weathering grades at the 95% confidence level. The F-ratio is 20.67 and the P-value for the F-test is less than 0.05. The Kruskal–Wallis test shows that there is also a statistically significant difference for the medians for trace length among the five weathering grades at the 95% confidence level. The overall patterns in the two areas are similar and the reverse of that for joint spacings: mean joint trace length generally decreases from fresh to completely weathered rock.

5.3. Joint appearance

The physical appearance of joints changes as weathering progresses. Joints in fresh granitic rock are angular, sharp edged, and typically straight (Fig. 7A). This is true for joints in slightly weathered rock as well (Fig. 7B), but in addition, the joint surfaces in slightly weathered rock are obviously stained, often with iron. The dark colour on the joint faces on both sides of this photograph are iron staining. The surfaces of fresh and slightly weathered granitic rock are often rounded, however, joint edges may be slightly rounded as well (Fig. 7C). Rounded joint edges are caused by the presence of a thin, more intensely weathered layer on the rock surface.

Joint edges remain fairly sharp in moderately weathered granite, but are beginning to round. The hallmark of moderately weathered granitic rock, however, is the increase in the number of short, closely spaced horizontal joints, caused by weathering and stress release, that occur on corners and edges of an outcrop (Fig. 7D). Note the increased intensity of horizontal joints on the right front corner in this photograph. These joints tend to be slightly wavy rather than straight.

In highly weathered granitic rock, the apertures of major joints are often several centimetres wide (Fig. 7E). Note the diagonal joint above and to the right of the metre stick. It is often difficult to tell the difference between small sheared zones and wide, highly weathered joints. The widely separated joint edges are distinctly rounded and the joints are commonly filled with weathering products. Mineral grains have begun to expand into the smaller, narrower open joints, so the joint traces are no longer distinct and sharp edged. Joint traces can become sinuous and discontinuous around mineral grains and the traces of unfilled and unstained joints begin to disappear. This process may be more advanced in megacrystic granitic rocks than in non-megacrystic rock. Apparent joint length becomes shorter because expanding or crumbling mineral grains and clay is encroaching upon the previously wide apertures of individual joints.

By the time the rock is completely weathered, the unfilled joints have disappeared and only traces of more resistant joint fillings or iron stains appear on the rock surface (Fig. 7F). Few joint openings are visible in the typically rounded exposures of completely weathered rock. In addition, exposures in completely weathered rock are typically short, usually less than 2 m. Three-dimensional natural exposures are virtually nonexistent in highly and completely weathered granitic rock, which are typically found only in man-made exposures. Large measurement areas can only be found in sloping road cuts (e.g. the fifth granodiorite listed in Table 1).

6. Discussion

These relations mean joint spacing becoming wider and mean joint trace length becoming shorter with increased weathering are impossible. Joints simply cannot disappear or become shorter as weathering progresses. Therefore, there needs to be an explanation related to the changing visibility of joint systems as weathering progresses.

6.1. Proposed mechanism for apparent joint disappearance

Weathering begins on the rock surface and in open joints within the rock mass. As weathering occurs in the rock material, small cracks first occur along grain boundaries and then, mineral grains themselves begin to crack, possibly due to thermal expansion. Within-grain micro-cracking occurs at different rates for the different minerals in the rock. Dark-colored minerals, particularly biotite, tend to crack sooner and more than light-colored minerals (Ehlen and Zen, 1986). These new cracks fill with weathered material, perhaps local or perhaps washed in from the ground surface along open joints. These filling materials are primarily clays, which contract themselves and expand under changing thermal and moisture conditions. This in turn causes more within-grain micro-cracking and more expansion in the rock fabric, as well as rounding of joint edges on the rock surface due to erosion of the loosened fragments. Because the minerals in intrusive igneous rocks, such as granite, granodiorite, and quartz monzonite, have an interlocking structure — there is no softer cement that can be compressed or voids into which individual grains can expand or into which alteration products can go — the only space into which mineral grain expansion or crumbling can occur is into the atmosphere or open, weathered joints if the grains are on the rock surface (popping out or upward expansion of the surface), or into existing joint apertures, if they are within the rock mass. When this happens on the rock surface, the original joint can no longer be seen: it thus apparently disappears.

This process is shown in Fig. 8 with reference to trace length. Fig. 8A shows a filled vertical joint in completely weathered granodiorite. This joint cuts a vertical surface in the upper part of the photo above the diagonal joint. It then crosses a flat area, and finally, appears on another vertical surface in the lower part of the photo where the metre stick darkens in tone. The joint is completely filled with manganese on the vertical surfaces, but on the flat surface, the joint filling is discontinuous and very thin where present. Fig. 8B shows the section of the joint on the flat surface 4 cm to the left of the end of the metre stick—it is rather difficult to see because of lighting and the thin filling. Fig. 8C shows the same section of the joint on the flat surface after the rock surface was lightly rubbed: the joint trace is gone. If measured before the rock surface is rubbed, one trace length for one joint would be identified. If measured after the centre section of the joint is rubbed out, two shorter trace lengths would be measured for the two joints. A false impression of trace length thus arises as weathering progresses. This phenomenon also results in apparently fewer joints, such that joint spacing appears to be wider in the more weathered rocks in which enhanced expansion and crumbling occur.

What makes joints visible on the rock surface in these intensely weathered materials is thus, the mineral filling or iron staining, and joints that are not filled with coloured or more resistant material disappear as weathering intensifies. This is of course true only on the surface. Within the rock the joint still exists, perhaps with reduced aperture, but it is on the surface that joint properties are estimated and measurements are made.

6.2. Ramifications

Potential effects of these results on engineering design and construction can be shown using the rock mass rating (RMR) classification of Bieniawski (1989). In this classification, the wider the joint or discontinuity spacing, the higher the rating, and thus, the better the quality of the rock. The wide spacings in fresh rock and those in completely weathered rock would both result in higher ratings, indicating better quality rock. This conclusion would obviously be erroneous. The very close spacings in moderately weathered rock would result in a low rating, indicating lower quality rock. However, moderately weathered rock is of much better quality than either highly or completely weathered rock. Highly and moderately weathered rocks are in fact rippable, whereas moderately weathered rock is not. Admittedly, there are other factors included in the total rating in the RMR classification, but discontinuity spacing comprises 20% of the rating and the effect of apparent joint spacing could be significant.

With respect to joint or discontinuity length, short joints receive higher ratings and thus, occur in higher quality rock. On first look, this does not sound logical, but if the joints are short, they are less likely to connect with each other, and it is joint connectivity that is important to rock mass stability. The results reported in this paper indicate that the shortest joints occur in the most weathered rock, and that longer joints occur in the best quality rock. So again, an incorrect rating could be determined for weathered materials. The rating would be just the opposite of what it should be: too low for good quality rock and too high

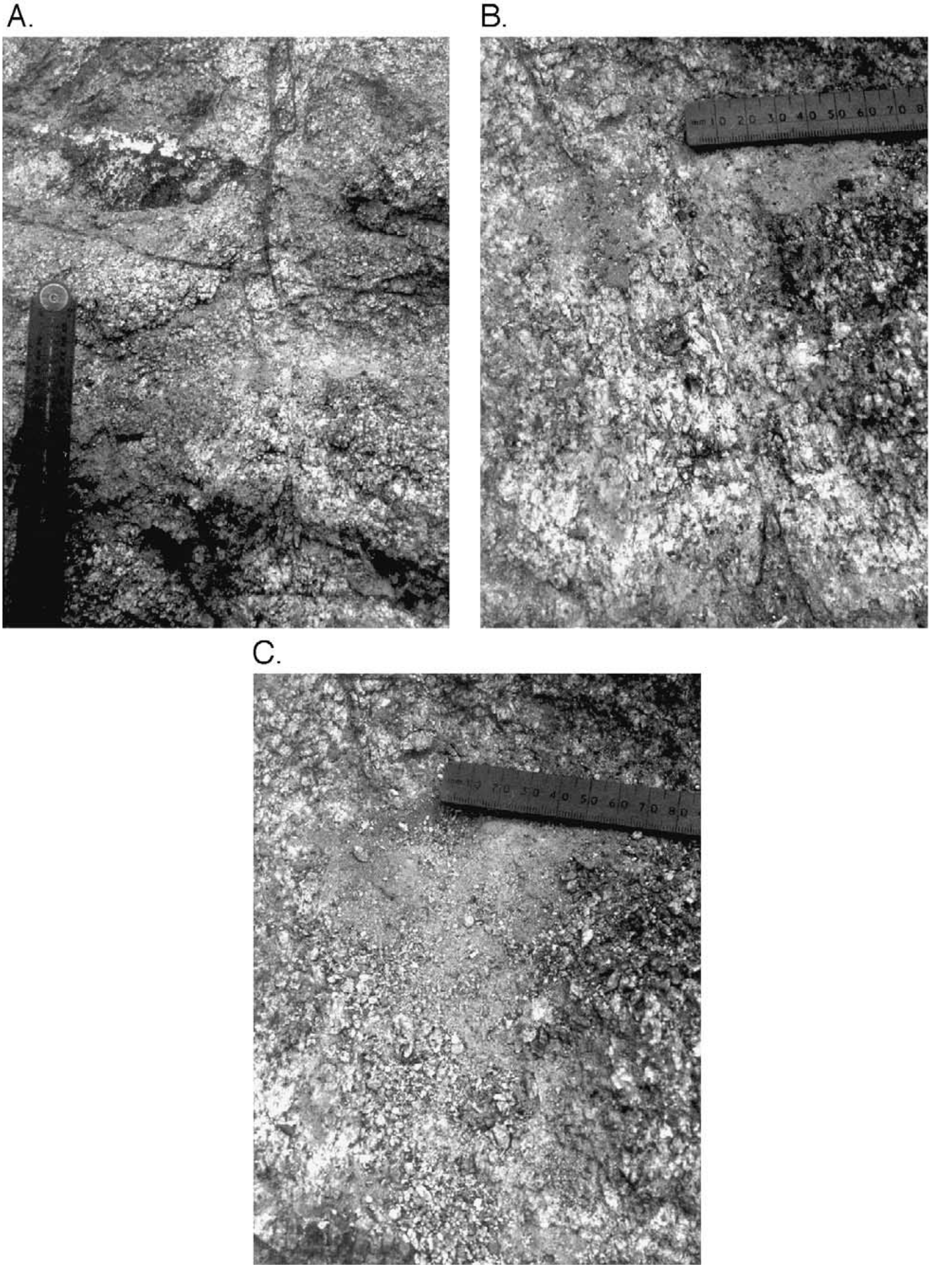


Fig. 8. The disappearance of a joint. (A) Full joint trace. (B) Center section of joint. (C) Joint after being lightly rubbed.

for poor quality rock. Joint or discontinuity length carries much less weight in the total rock mass rating than does joint spacing, but the combined result could be significant, resulting in an incorrect RMR classification with significant effects on engineering design and construction.

7. Conclusions

Mean joint spacing appears to decrease from fresh, through slightly and moderately weathered granitic rock, then increases from moderately weathered rock, through highly and completely weathered granitic rock. The widest joint spacings occur in either fresh or completely weathered rock, and the closest, in moderately weathered rock. Mean joint trace lengths decrease from fresh rock to slightly weathered rock, increase in moderately weathered rock, then appear to shorten from moderately weathered rock through highly and completely weathered granitic rock. The shortest mean trace lengths occur in completely weathered granitic rock, and the longest, in moderately or highly weathered rock. It is likely that these "impossible" relationships result from cracking along grain boundaries; thermal expansion of individual mineral grains, and increased within-grain micro-cracking as weathering intensifies. These factors allow individual mineral grains to "move" into open, weathering-, and erosion-widened joint apertures, thus obscuring individual joints. The implications of these relationships may be significant and could result in inaccurate rock mass classification, which could in turn effect engineering design and cost estimates.

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