Geoverse ISSN 1758-3411

# The relationship between crack orientation and solar insolation in Wadi Shehah, Northern United Arab Emirates.

Elisabeth Rewcastle:
Dept of Geography, Oxford Brookes University

## Abstract

In a recent study by McFadden *et. al.* (2005), it was proposed that; the north-south near vertical orientations of many rock surface cracks, relate to thermal stresses that arise daily from non-uniform solar heating, and that this mechanism is viable in other climates. This is based on clast and crack orientation data from eight sites in the deserts of North America. In this study, the presence of north to south cracking, potentially related to thermal stresses is confirmed at the study site in Wadi Shehah, the United Arab Emirates (UAE). However the proposed mechanism did not account for the majority of crack orientations, and a significantly smaller percentage of cracks with north-south orientations were recorded at the site in Wadi Shehah compared to the North American sites. This suggests that the mechanism is 'viable' in the UAE, but both less important, and less dominant as a process of rock breakdown than in the higher latitude North American deserts. Dominance of bi-modal and multi-modal crack orientations emphasize the significance of other processes and mechanisms in the initiation of cracking at this site, as well as solar insolation.

**Key Words**: physical weathering, diurnal variation, thermal stresses, meridional cracking, clast disintegration, Wadi Shehah

## Introduction

Insolation weathering is defined as; the disintegration of rock in response to temperature changes setting up stresses (Thomas *et. al.*, 2000). In this paper, the relationship between crack orientation and solar insolation is discussed, based on both research from Wadi Shehah, located in Ras al-Khaimah (RAK), of the United Arab Emirates (UAE), and the findings from previous studies. A recent study by McFadden *et. al.* (2005) investigated, physical weathering in arid landscapes due to diurnal variation in the direction of solar heating. Data was collected from eight sites on surfaces of different ages in the Mojave, Sonoran, Chihuahuan Deserts and the high (1800m) desert of central New Mexico. The study in Wadi Shehah will help to establish if the theories and models presented in the McFadden *et. al.* paper, in which the hypothesis states; that north-south near vertical orientations of many rock surface cracks, relate to thermal stresses that arise daily from non- uniform solar heating (McFadden *et. al.*, 2005), applies to the UAE in addition to the North American sites.

Rock breakdown caused by thermal stresses has been recorded in studies such as; Bartlett, 1832, Branner, 1896, and Merrill, 1906 (McFadden *et. al.*, 2005). 'Rocks expand and contract as diurnal temperatures rise and fall and the contraction may be sufficient to set up stresses that exceed the tensile strength of the rock', in early desert research this was the most commonly suggested mechanism for the breakdown of rock (Thomas, 2000). The significance of thermal stresses in crack propagation was dismissed by several well cited studies by Blackwelder (1925, 1927, 1933) and Griggs (1936), based on the failure of simulated diurnal cycling to produce cracking without the presence of moisture (McFadden *et. al.*, 2005). The accuracy of the experiments has been questioned by recent papers, Gomez-Heras et al, (2005) and Warke *et al*, (1997), claiming that, clast breakdown is related to micro-environmental conditions at the rock/ air interface which many laboratory tests have not simulated. Furthermore, a number of studies over the last few decades have concluded that thermally induced cracks can form, but probably in association with other processes (McFadden *et. al.*, 2005). There is clearly need for further investigation and collaboration of results spanning all arid geographical regions.

## Study Area

The UAE occupies 83,000km² along the South Eastern tip of the Arabian peninsula, of which RAK is the most northern Emirate (Thomas *et. al.*, 2000). The study area is located in Wadi Shehah, one of two tributaries of Wadi Al-Bih, at N 25º 53.137 dmm, E 056º 06.292 dmm (Figure 1.). Wadi Al-Bih has a drainage basin of approximately 450km², including drainage of both tributaries.


Figure 1. location of the study site,
Wadi Shehah in context with Wadi Al Bih (Google Earth, 2007)

The modern climate of the area is arid with mean annual temperatures >25°C and mean annual rainfall ca. 135 mm, most of which occurs in winter months. The potential evaporation is more than 2000 mm (Al-Farraj *et. al.*, 2004). Terraces A, C and D (Figure 2.) have formed at Wadi Shehah, terrace B has only formed at one local site. The estimated dating for this site suggests it was formed in the last interglacial, probably during marine isotope stage 5e 125,000 to 115,000 years before present (B.P.) (Al-Farraj *et. al.*, 2000). The cliff faces of the mountains are predominantly Musandum limestone, as is the material of the channel, there is variation in colour, and sandstone and iron banding/ veins are present in some clasts. The surrounding mountains were formed as a result of uplifting from the closing of the Tethys Sea. Extensive wadi networks show clearly defined watercourses of the early Quaternary (Glennie, 2001).

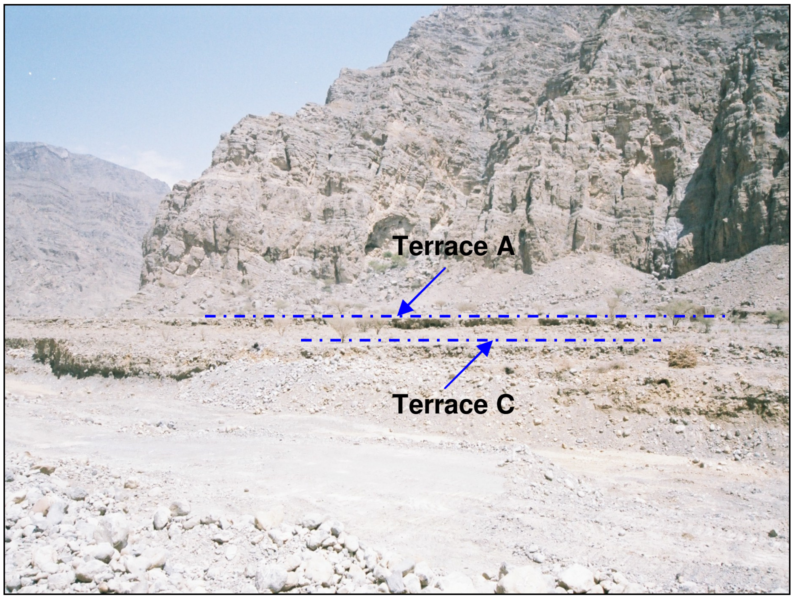

Figure 2. Terrace A and C at Wadi Shehah (source: author)

## Methods and Materials

Data collection methods in Wadi Shehah applied similar methodologies to the 2005 study of the North American sites by McFadden *et. al.* This allows comparison between results to be made, suggesting whether theories and models are compatible with this site in the UAE.

Clast measurements were recorded along 50m transects laid out in north-south orientations on terraces A and C (Figure 3.). Ideally measurements would have been taken on one clast every metre as (Mcfadden *et. al.*, 2005). However this was not possible, as there was not a clast that fully met the criteria at every metre along the transects. It was decided that measurements for 20 clasts along each transect, within 2 metres of the line, would be a large enough sample to provide accurate results.

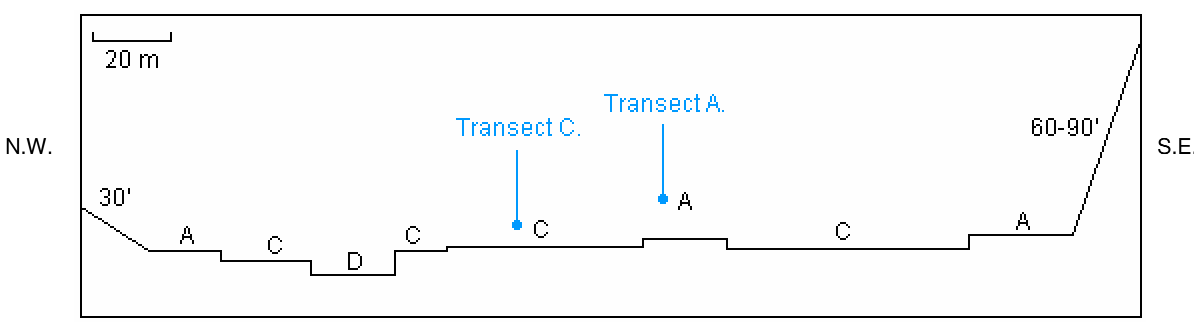

Figure 3. Cross- section across the Wadi Shehah showing
the relative elevations of terraces A and C (source: author)

The assessment of clast suitability was also based upon the McFadden *et. al.* (2005) study. Before measurements were taken it was ensured that; 1. the clast had not been recently disturbed and was from a stable surface, 2. only clasts greater than or equal to 10cm in diameter were included in measurements, 3. that there was greater than or equal to 5cm of the clast protruding above the ground, 4. that due consideration was paid to other possible processes acting on the clast and 5. that the proximity of the subject clast to other clasts was taken into account.

For each clast, the dimensions were measured, along with an overall description of: colour, main crack orientation, presence of spalling or weathering, the main components forming the structure with any weaknesses also recorded. The orientation and width of all cracks on each clast were measured using a geological compass and callipers, avoiding cracks formed by fluvial processes, which are recognizable by the evidence of abrasion along the edges of the crack surface (McFadden *et. al.*, 2005). Four crack-width types were defined by McFadden *et. al.* (2005): incipient, < 0.1 mm; thin, 0.1 - 1 mm; moderately wide, 1-3 mm and large > 3 mm. This study has adopted the same measurement scale. Each clast was numbered and photographed with a compass pointing north for orientation purposes (Figure, 4.).

The number of different coloured clasts measured, varied owing to clast availability on the two transects. The dominant colours of clasts at the site were greys, classed as; dark grey, grey and light grey. There were fewer clasts classified as red and white. Only two clasts have been classified as red, these are attributable to the presence of desert varnish which is composed primarily of iron and manganese oxides causing the red colour (Thomas *et. al.*, 2000).

Figure 4. Measuring the orientation, width and length of cracks of clasts (source: author).

The data collected from the study by McFadden *et. al.* was plotted using GEOrient software (Holcombe, 2006) to create crack orientation rose value- azimuth diagrams. The rose diagrams are a method of statistical evaluation of crack orientation showing, the orientation of all cracks within a data set, alongside the vector mean and dominant orientation. The crack orientation data from Wadi Shehah are grouped depending on their angle, and evaluated using GEOrient to create rose diagrams for crack orientation in relation to; clast colour and clast location (terrace A, C or both).

Four crack types have been defined in the study by McFadden *et. al.*, these are meridional, surface parallel, longitudinal and fabric related. The last three are controlled by clast shape and rock fabric. Meridional cracking is preferentially aligned north-south, and has been connected by McFadden *et. al.* to tensile stresses due to strong radial gradients (McFadden *et. al.*, 2005). Identifying presence and extent of meridional cracking at the site in Wadi Shehah is fundamental in the evaluation of the importance of the mechanism of solar insolation in the initiation of cracking. The McFadden *et. al.* paper classifies cracks with orientations within 33 ° of the north- south meridian as meridional cracks. Therefore the outer meridional limit is defined as +/- 16.5 ° of the meridian. The mean crack frequency is determined by the number of cracks over all clasts of a certain colour divided by the number of clasts of that colour observed. This statistic has been used to analyse whether crack frequency could be linked to clast colour.

## Results

### Mean crack frequency and clast colour

Tables 1. and 2. show frequency of clast colour, crack orientation, and mean crack frequency. On transect A; white and light grey, have a higher mean crack frequency than the darkest clast, dark grey, but a lower frequency than grey and red. On transect C mean crack frequency for white clasts is the highest of all colours, light grey the second highest, with the darkest clasts, (dark grey and red) having the lowest mean crack frequency. Over both transects there appears to be no direct correlation between the colour of clasts and crack frequency.

**Transect A**

| | Dark Grey | Grey | Light Grey | White | Red | TOTAL |
|---|---|---|---|---|---|---|
| **Number of Clasts** | 2 | 10 | 3 | 4 | 1 | **20** |
| **Orientation °** | | | | | | |
| 0-15 | 1 | 7 | 3 | 0 | 0 | **11** |
| 16-30 | 0 | 3 | 0 | 1 | 1 | **5** |
| 31-45 | 2 | 5 | 0 | 0 | 4 | **11** |
| 46-60 | 1 | 10 | 0 | 1 | 2 | **14** |
| 61-75 | 0 | 9 | 0 | 0 | 1 | **10** |
| 76-90 | 1 | 1 | 1 | 2 | 0 | **5** |
| 91-105 | 0 | 4 | 0 | 1 | 0 | **5** |
| 106-120 | 0 | 9 | 1 | 1 | 1 | **12** |
| 121-135 | 0 | 9 | 5 | 3 | 0 | **17** |
| 136-150 | 1 | 13 | 4 | 1 | 0 | **19** |
| 151-165 | 1 | 11 | 3 | 3 | 1 | **19** |
| 166-180 | 0 | 3 | 0 | 4 | 0 | **7** |
| **TOTAL** | **7** | **84** | **17** | **17** | **10** | **135** |
| **Mean Crack Frequency** | **3.5** | **8.4** | **5.67** | **4.25** | **10** | **6.75** |

(Table 1.) Transect A: Clast colour frequency, crack orientation, and mean crack frequency

**Transect C**

| | Dark Grey | Grey | Light Grey | White | Red | TOTAL |
|---|---|---|---|---|---|---|
| **Number of Clasts** | 6 | 5 | 7 | 1 | 1 | **20** |
| **Orientation °** | | | | | | |
| 0-15 | 1 | 1 | 12 | 1 | 1 | **16** |
| 16-30 | 1 | 2 | 3 | 0 | 0 | **6** |
| 31-45 | 3 | 1 | 8 | 0 | 0 | **12** |
| 46-60 | 4 | 5 | 7 | 0 | 0 | **16** |
| 61-75 | 5 | 5 | 2 | 0 | 0 | **12** |
| 76-90 | 3 | 4 | 0 | 0 | 0 | **7** |
| 91-105 | 4 | 0 | 4 | 1 | 1 | **10** |
| 106-120 | 1 | 3 | 5 | 2 | 0 | **11** |
| 121-135 | 7 | 4 | 4 | 1 | 1 | **17** |
| 136-150 | 3 | 3 | 1 | 2 | 0 | **9** |
| 151-165 | 3 | 1 | 5 | 0 | 0 | **9** |
| 166-180 | 0 | 2 | 5 | 1 | 1 | **9** |
| **TOTAL** | **35** | **31** | **56** | **8** | **4** | **134** |
| **Mean Crack Frequency** | **5.83** | **6.2** | **8** | **8** | **4** | **6.7** |

(Table 2.) Transect C: Clast colour frequency, crack orientation, and mean crack frequency.

**Percentage of cracks with meridional orientation**

Table 3. describes the percentage of cracks with a meridional orientation (+/- 16.5 ° of the meridian). The percentage of meridional cracks observed over all the clasts on both transects is 16%. The lighter colours, white and light grey have a generally higher percentage of meridional cracks, and dark grey the lowest. Transect C has 5.4% more meridional cracks than transect A.

| | Transect A | % of Clasts A | Transect C | % of Clasts C | Both Transects | % of Clasts Both Transects |
|---|---|---|---|---|---|---|
| **Dark Gray** | 14.3% | 10 | 2.9% | 30 | 4.8% | 20 |
| **Grey** | 11.9% | 50 | 9.7% | 25 | 11.3% | 37.5 |
| **Light Grey** | 17.6% | 15 | 30.4% | 35 | 27.4% | 25 |
| **White** | 23.5% | 20 | 25% | 5 | 24% | 12.5 |
| **Red** | 0% | 5 | 50% | 5 | 14.3% | 5 |
| **All Colours** | 13.30% | | 18.70% | | 16% | |

Table 3. Percentage of cracks with meridional orientation in relation to colour and percentage of the sample for each colour classification.

**Rose Diagrams for Coloured Datasets**

The rose diagrams in Figure 5a-e, show all crack orientations, and vector mean orientation grouped into colour classifications for clasts across both transects A and C. The dominant orientation can be deduced from the direction of the longest sectors on the rose diagram. The vector mean and dominant crack orientation between different coloured clasts varies greatly, but in most cases, apart from dark grey clasts, the vector mean is reasonably close (within 30°) of the dominant crack orientation. Light grey (c) is the only colour that has a vector mean meridional crack orientation and a dominant north-south orientation. Red clasts are also close, but certainly outside the outer meridional limits. Dark grey clasts (a) have a vector mean near east to west, and bi-modal dominant crack orientations north-west to south-east and north-east to south-west. Grey clasts (b) have a near south-east to north-west vector mean orientation, however the crack orientations are multi- modal with no distinct dominant orientation. White clasts (d) have a vector mean and dominant east to west orientation and red clasts (e) have a vector mean and a dominant orientation that is north-east to south-west.

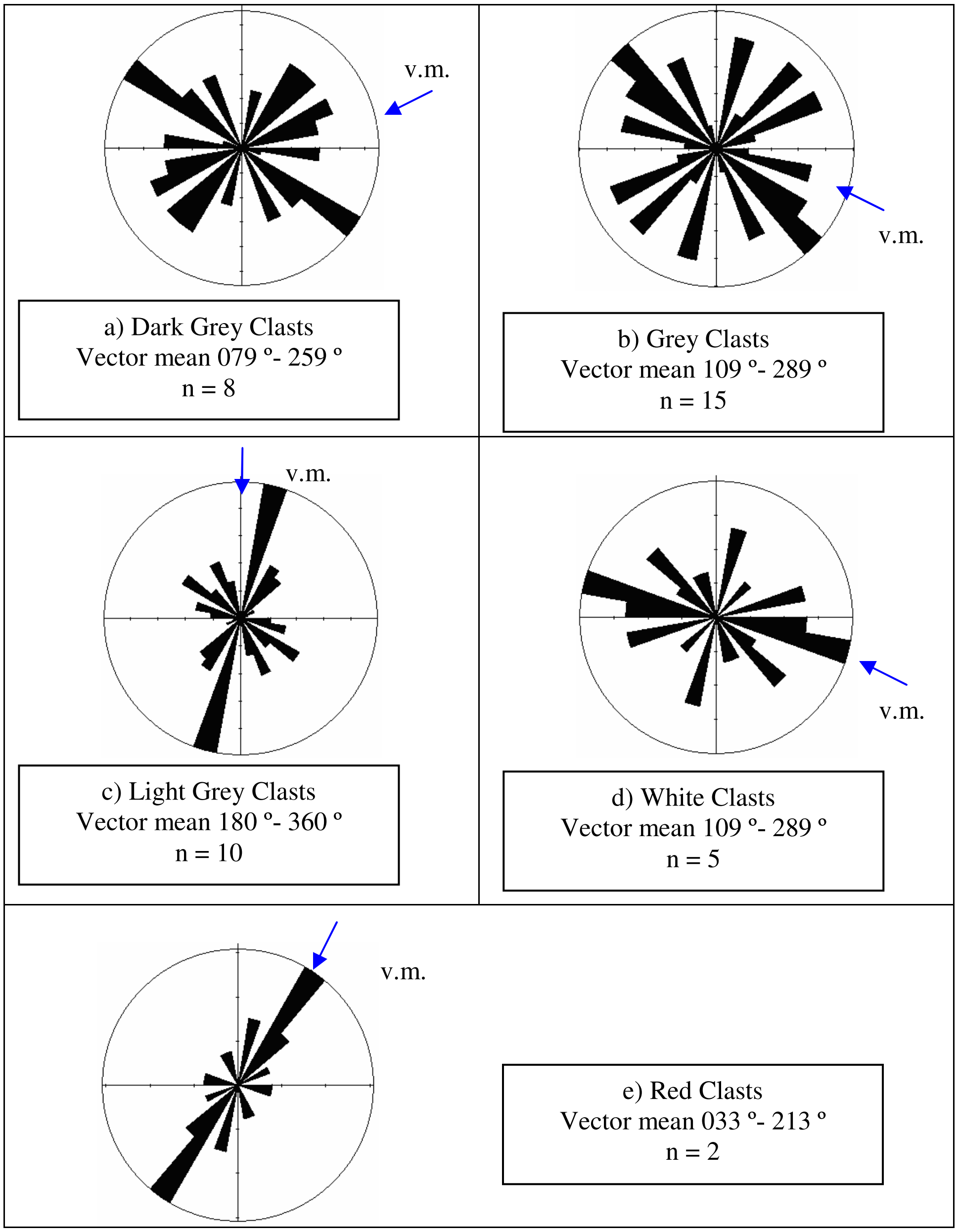


Figure 5a-e. Rose Diagrams showing crack orientation data dependant on the colour of clasts across both transects A and C. The arrow indicates the vector mean of the data set, and n = the number of clasts for the colour classification.

The rose diagrams in Figure 6a-c., show the vector mean and dominant crack orientation data separately on transects A and C, and for all clasts across both transects. All clasts on transect A (a) have a north-west to south-east vector mean crack orientation, with no obvious dominant orientation. The vector mean of all clasts on transect C (b) has an opposite orientation to transect A of north-east to south-west, but a significant near north-south dominant crack orientation. All clasts on both transects (c) are a combination of transect A and C, with a mean vector orientation of east- west, crack orientation is reasonably spread, however there is a dominant north to south orientation.

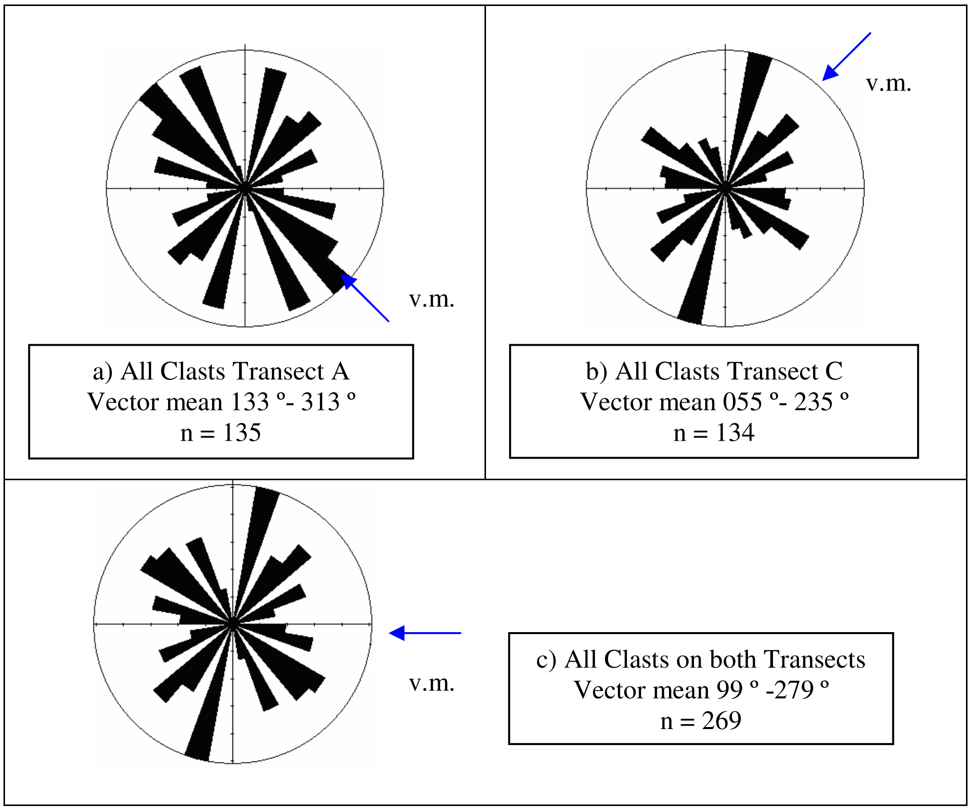


Figure 6a-c. Rose Diagrams showing clast orientation data for all clasts separately on Transects A and C, and for all clasts across both transects. The arrow indicates the vector mean of the data set and n = the number of clasts for the colour classification.

**Difference between the Vector Mean and the Outer Meridional Limits**

Tables 4. and 5. show the degree that the vector mean of the different clast classifications varies from the outer meridional limits. Table 4. Shows that dark grey clasts vary from the outer meridional limits most significantly, jointly followed by grey and white clasts. Closest to the outer meridional limit, but still outside, are red clasts. The only clast that is within the meridional limit is the light grey clast. Table 5.shows that the vector mean of all clasts on transect A vary to a similar extent, but in an opposite direction, from the outer meridional limit as the vector mean of all clasts on transect C. However the vector mean of all clasts over both transects varies from the outer meridional limit almost twice as much as transect A and C separately.

| Colour | Vector Mean | Meridional | Difference between Vector Mean And Outer Meridional Limits |
|---|---|---|---|
| Dark Grey | 79- 259 º | No | 62.5 º |
| Grey | 109- 289 º | No | 54.5 º |
| Light Grey | 180- 360 º | Yes | Within meridional limits |
| White | 109- 289 º | No | 54.5 º |
| Red | 33- 213 º | No | 16.5 º |

Table 4. Data for colours over both transects; the degree that the vector mean of varies from the outer meridional limits

| Colour | Transect | Vector Mean | Meridional | Difference between Vector Mean And Outer Meridional Limits |
|---|---|---|---|---|
| All Rocks | Transect A | 133- 313 º | No | 30.5 º |
| All Rocks | Transect C | 55- 235 º | No | 38.5 º |
| All Rocks | Both Transects | 99- 279 º | No | 64.5 º |

Table 5. Data for all clasts separately on transects A and C and combined on both transects; the degree that the vector mean of varies from the outer meridional limits.

## Discussion

### Albedo

Desert surfaces have an albedo of between 25- 30 % (Thomas *et. al.* 2000). It is generally accepted that rocks with low albedos will warm both faster and to higher temperatures than rocks with high albedos (Hall *et. al.* 2005). In relation to the proposed mechanism of thermal cracking, this would suggest that dark coloured clasts, with a lower albedo, will absorb more heat in the illuminated portion, causing greater temperature differences within or across the clast, potentially initiating a greater number of cracks. Light coloured clasts, with a higher albedo, should have a lower difference in temperature across the clast and therefore initiating fewer cracks. However the results from Wadi Shehah do not show this pattern, suggesting there is not a progression of mean crack frequency from light to dark clasts. This implies that thermal cracking is not initiated in relation to clast colour, which supports the theory that, colour is not of primary importance in the generation of cracks (McFadden *et. al.* 2005). The thermal properties and albedo for each mineral of a clast are more important to consider than the general colour. (Gomez- Heras *et al*, 2005).

### Crack Orientation

Light grey clasts show the most defined north-south cracking at Wadi Shehah. Over both transects light grey clasts display; an obvious north-south dominant orientation, and an exact north-south vector mean (Figure 5c.). It is the only colour classification with a vector mean within the outer meridional limits (Table 4.), and has the highest percentage of meridional cracks of any colour classification (Table 3.). Of the colours observed, there are no obvious reasons why light grey clasts have the most defined north-south cracking, however in the context of this site, these results are important as light grey clasts consist of 25% of all clasts examined. Further research is required to determine whether clast colour is of significant importance in the effect of thermal stresses from non- uniform solar heating.

Light grey is the only clast colour classification to display such significant north-south cracking tendencies. Clasts classified as red have one extremely dominant crack orientation (Figure 5e.) which is close to, but still outside the outer meridional limits. This observation must also be kept in context with the number of red clasts examined, which was one from each transect. No meridional cracks were recorded on the red clast in transect A, but a large number were recorded on transect C.

Dark grey clasts have; the lowest percentage of north-south cracking (Table 3.), a near east-west vector mean, and vary the most from the outer meridional limits (Figure 5a.), making this colour classification the least compatible with the McFadden *et al* theory of solar insolation being a dominant factor in crack initiation. Crack frequency of grey clasts is significantly high (Tables 1 and 2), but with a relatively low percentage of meridional cracks (Table 3.). The crack orientations are multi-modal with no distinct dominant orientation (Figure 5b.), suggesting that other mechanisms are responsible for the majority of crack orientation.

White clasts displayed a high number of meridional cracks relative to this study (Table 3.), however, also displayed a strong east to west vector mean and dominant orientation, well outside of the outer meridional limits. This suggests north-south cracking is occurring possibly due to thermal stresses, but also that cracks of an east-west orientation are being produced by other processes.

The obvious dominance of a north-south crack orientation displayed in all clasts on transect C (Figure 6b.), and to a slightly lesser extent on all clasts over both transects (Figure 6c.), further implies that north south cracks are of significance on this site. However neither of the vector means for these datasets concurs. The vector means for terrace A and terrace C are in opposite directions, and so there is a possibility that this trend relates to terrace age, however further study is necessary. The east-west vector mean for all clasts at the site, has the greatest variance from the outer meridional limits, reiterating the finding that multiple mechanisms are responsible for crack initiation at this site.

Whilst some of the rose diagrams produced for the data sets from Wadi Shehah show a dominant north to south orientation, the corresponding vector mean often does not. Rose diagrams produced in the McFadden *et. al.* paper show a much greater dominance of north-south crack orientations along with concurring vector mean calculations.

**Meridional Cracks**

In the McFadden *et. al.* (2005) paper, 462 of the 688 cracks could not be assigned to longitudinal, fabric related or surface parallel classifications. By implementing the meridional limit (+/- 16.5 º of the meridian) 57% of the 462 unidentified cracks could be classified as meridional. This resulted in 263 (38%) of the total 688 cracks observed by McFadden *et. al.* to be meridional. Applying the same meridional limit to the data set from Wadi Shehah revealed that 43 (16%) of the 269 cracks observed could be defined as meridional. There is a significant difference between the percentage of meridional cracks in sites studied by McFadden *et. al.* and the site at Wadi Shehah, suggesting that the mechanism of thermal cracking is viable at this site, but of greater importance in the American sites . This could be due to the difference in latitude, discussed below.

**Other Factors affecting crack Initiation:**

***Lithology***

Clasts examined over the eight sites in North America by McFadden *et. al.* were diverse in material and characteristics. Whereas clasts examined at Wadi Shehah were predominantly formed of Musandum limestone with some variations. Other materials, namely quartzite and iron banding, were present within the dominant clast material. Crystal size of quartzite is suggested to be the main factor controlling temp differences between minerals (Gomez- Heras *et. al.*, 2005). Some clasts exhibited signs of; spalling, detachment of surface material due to variation of temperature (Hettema *et. al.*, 1998) and encasement of desert varnish, composed of iron and manganese oxides, darkening clast colour (Thomas *et. al.*, 2000). Differential heating causes different mineral types to expand unequally along 'crystallographic axes' (Hockmann *et. al.*, 1950) undergoing magnified stresses (Gomez- Heras *et. al.*, 2005) and potentially causing fabric related cracking which are associated predominantly with sedimentary clasts (McFadden *et. al.*, 2005). Considering these factors, susceptibility to fabric related cracking at the site in Wadi Shehah will be high, and this may be a significant mechanism for crack initiation.

***Clast Size***

The size of a clast is a significant factor in the probability of crack initiation by solar insolation. Temperature differences within or across small clasts may not become large enough to cause significant stresses that exceed tensile strength and initiate cracking. Thermal stresses are expected to rise as clast size increases (McFadden *et. al.*, 2005). Clast size was controlled in both the study by McFadden *et. al.* and data collection in Wadi Shehah; only clasts greater than or equal to 10cm were included in measurements. However the size of clasts above 10cm was significantly different ranging from 16 x 15 cm to 98 x 77 cm, causing a variation in the likelihood of solar insolation to be the main cause of crack initiation. Clasts close to the cliffs, or smaller clasts close to large clasts, are also more likely to be over-shadowed compromising their use in the evaluation of the effect of solar insolation.

***Differences in latitude and altitude***

Temperature regimes in arid areas differ considerably affected by; latitude, altitude and continentality (Thomas, 2000). In McFadden *et. al.* (2005), exact latitudes of the eight sites in North America are not supplied, however by obtaining general latitude for the deserts of the study sites, it is possible to estimate an average latitude of approximately, N 34º 48.115 dmm, a relatively high latitude arid area. The site at Wadi Shehah has latitude of N 25º 53.137 dmm, considerably lower, therefore experiencing different temperature regimes. Variations in temperature will affect the seasonal availability of moisture due to varying rates of evapotranspirtation. Altitude is another differing factor; the desert of central New Mexico, a site in the study by McFadden *et. al.*, is at 1800m, considerably higher than the site at Wadi Shehah. Site variation is likely to be a substantial factor of difference in dominance of meridional cracking attributed to thermal stresses between the North American sites studied by McFadden *et. al.*, and the site at Wadi Shehah in the UAE.

## **Conclusion**

Evaluation of crack orientation at the site in Wadi Shehah confirms the presence of north to south cracking, potentially related to thermal stresses from non uniform solar heating, as proposed by McFadden *et. al.* However this mechanism does not account for the majority of crack orientations, rejecting it as a singular dominant process at this site. Considerably less north-south cracking is recorded at Wadi Shehah compared to the North American sites. It is therefore proposed that variation in site conditions and latitude is a major factor in the difference of relative importance of thermal insolation as a mechanism of rock breakdown.

Future research in the relative importance of thermal insolation in the initiation of cracks should involve; 1) Further data collection from the Wadi Shehah/ Al-Bih region, to confirm findings from this site, 2) Data collection on a site in the Wadi Al-Bih region that includes terrace B, this may reveal if terrace age is a contributing factor. 3) Measurements from diverse locations, over different latitudes, 4) Testing to find the minimum clast dimensions that the mechanism can be applied to, 5) Development of laboratory simulations, that evaluate the micro- environmental conditions at the rock/ air interface that may cause cracking.

## Acknowledgements

Data was collected by the research group, Ben Couzens, Louise Martin, Lucy McNicol and George Wilson. Azma Al- Farraj, suggested the site location and discussed site characteristics. Adrian Parker and Jon Wells provided advice and guidance, and Chris Coleman introduced us to GEOrient.

## Author Profile

I am currently in the final year of a joint Physical Geography and GIS degree at Oxford Brookes University. The research for this paper was undertaken as part of my degree during a week's field trip to Ras al-Khaimah northern United Arab Emirates.

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