Zonation within incipient cracks in boulders and indications for slow sub-critical crack propagation over geologic timescales

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1. Introduction

Subcritical rock cracking is a physiochemical process that involves the breaking of chemical bonds in response to stress magnitudes lower than the critical stress of the rock. Whereas experimental studies and modeling efforts have provided invaluable insights into the mechanisms and rates of this process, field-based evidence of subcritical cracking in natural settings over geologic timescales are scarce. To address this knowledge gap, we conducted a systematic study of incipient cracks that developed under subaerial, subcritical conditions within dolomitized micritic limestone boulders on late Quaternary alluvial terraces (~62 and 14 ka) in the hyperarid Negev desert of southern Israel. Crack data from the field, petrographic and scanning electron microscopy (SEM) together with micron-scale laser scanning of inner-crack surfaces were employed.

2. Results

Crack density in boulders (i.e., the number of cracks per surface area) increases as a function of surface age. Incipient cracks on all surfaces display a typical pattern of three distinctive weathering zones (Figure 1) extending inward from the boulder exterior.

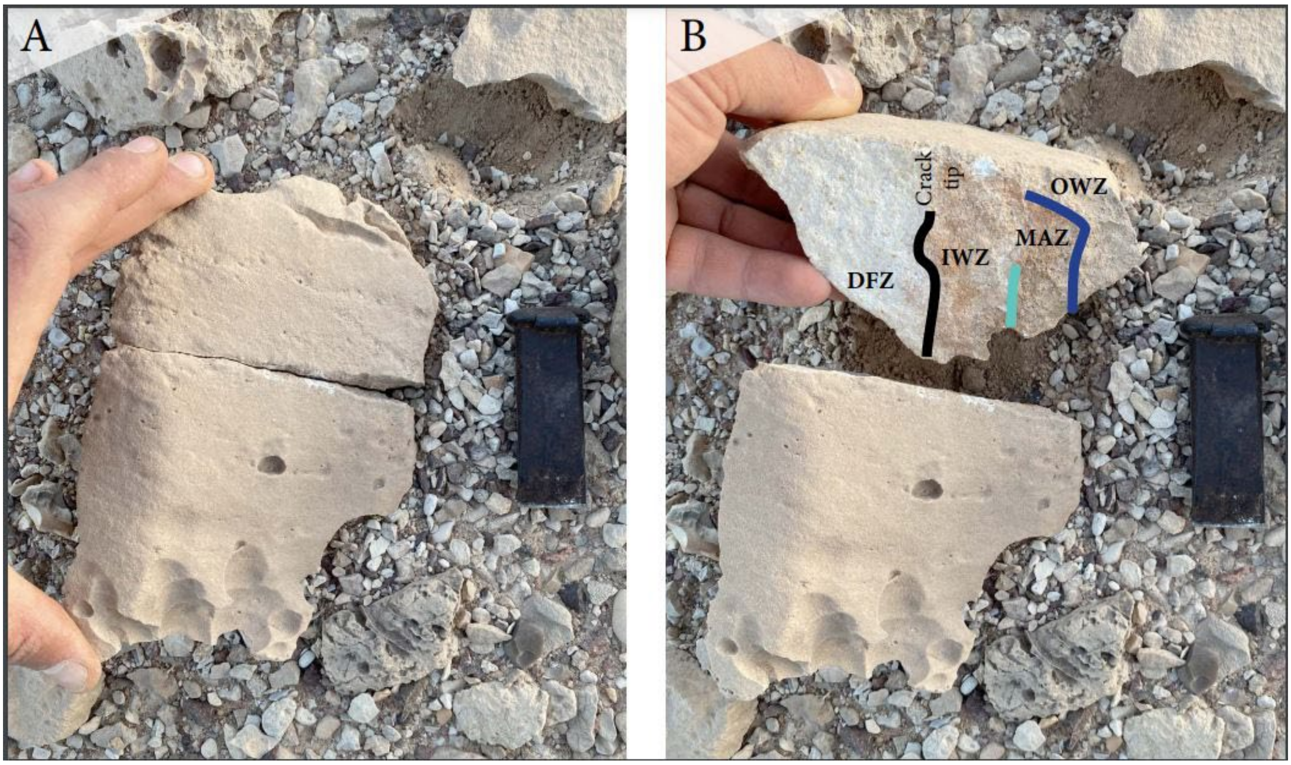

Figure 1. A) In situ micritic limestone boulder in the Negev Desert, Israel. Note that the natural crack ended at the line approximating the "Crack tip" in B. B) Our superimposed crack zonation shows an Outer Weathering Zone (OWZ), Medial Accumulation Zone (MAZ), and Inner Weathering Zone (IWZ) ending at the crack tip. The Dynamic Fracture Zone (DFZ) was previously intact, and results from critically cracking the rock with hammer and chisel.

The 'Outer Weathering Zone' (OWZ) is characterized by a well-developed weathering rind and morphology similar to the boulder exterior. A 'Medial Accumulation Zone' (MAZ) follows, where aeolian particles and weathered rock fragments accumulate. In the 'Inner Weathering Zone' (IWZ), which extends inwards from the Medial Accumulation Zone up until the crack tip, slightly weathered crack surfaces still preserve the initial micro-morphology of the crack, which developed primarily along the boundaries of dolomite grains (Figure 2).

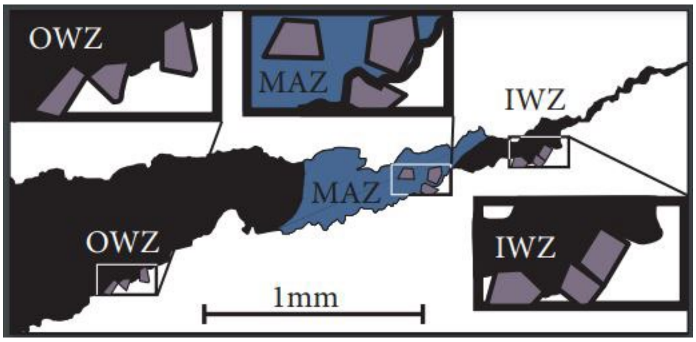

Figure 2. Schematic of micromorphological properties in different natural crack zones, suggesting piecemeal crack propagation. Black areas represent the crack void and blue areas in the Medial Accumulation Zone (MAZ) represent the open crack where allochthonous and autochthonous sediments accumulate. Note preferential cracking along dolomite grains in the Inner Weathering Zone (IWZ) and evidence of eroded matrix between grains in the Outer Weathering Zone (OWZ).

Three-dimensional roughness analysis performed using a laser profilometer revealed an increase in roughness from the OWZ to the IWZ. This reflects the prolonged exposure of the OWZ to external weathering conditions, resulting in the enhanced smoothing of the OWZ. In the inner weathering zone, dolomite rhombs protrude from the crack surface, and pitting indicates recent plucking of dolomite rhombs. Within the 'Dynamic Fracture Zone' (DFZ) where the crack was manually forced open, the surface is characteristically smoother and has lower calculated roughness, likely due to the crack quickly propagating through dolomite grains with minimal preference for grain boundaries.

Penetration of allochthonous chemical elements (e.g., Al, Si, Fe) towards the boulder interior along the entire crack length and micro-morphological evidence for dissolution processes that also occur at the crack tip support the previously proposed role of water in facilitating subcritical crack propagation. Our observations provide uniquely direct indications for slow piecemeal propagation of cracks under subcritical stresses through geologic time and at rates that are likely dictated by aqueous processes at the crack tip.