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Experimental Observations and Statistical Modeling of Crack Propagation Dynamics in Limestone by Acoustic Emission Analysis During Freezing and Thawing

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Abstract The timing and location of microcracking events, their propagation and coalescence to form macrocracks, and their development by tension, shearing or mixed modes are little known but essential to understanding the fracture of intact rock by freezing and thawing. The aims of the present study are to investigate the mechanisms and transition of microcracking and macrocracking during repeated freeze-thaw, and to develop a statistical model of crack propagation that assesses the distance and angular relationship of neighboring cracking events arranged in their temporal order of occurrence. Eight acoustic emission (AE) sensors mounted on a 300 mm cubic block of chalk captured the three-dimensional locations of microcracking events in their temporal order of occurrence during 16 seasonal freeze-thaw cycles simulating an active layer above permafrost. AE events occurred mostly during thawing periods (45%) and freeze-to-thaw transitions (37%) rather than during freezing periods (9%) and thaw-to-freeze transitions (8%), suggesting that most AE (microcrack) events were driven by the process of ice segregation rather than volumetric expansion. The outcomes of a novel statistical model of crack propagation based on two boundary conditions—inside-out and outside-in modes of cracking—were assessed based on Bayes’ theorem by testing the hypothesis that the inside-out mode of cracking was favored by tensional activity, whereas the outside-in mode was supported by shearing events. In both situations, the hypothesis accounted for 54%–73% confidence level. The microcrack propagation model can distinguish reasonably between cracks formed by volumetric expansion and ice segregation.

Plain Language Summary It is well known that repeated freezing and thawing of water within some porous and fine-grained rocks can form large cracks visible to the unaided eye. But the initiation and growth of precursor tiny cracks too small to see without a microscope remain enigmatic in terms of their timing, location, growth, and coalescence to form eventually large cracks. Thus, prediction of rock fracture by frost is difficult. Here we present results from a laboratory experiment that measured the location and timing of tiny sound (acoustic) waves within a block of limestone subject to 16 cycles of freezing and thawing. The waves indicated the occurrence of tiny cracking events. Measurement of rock temperature suggested that most cracking events resulted from water migrating through the rock toward lenses of ice rather than expansion of water freezing in place within empty spaces in rock. In addition, cracks propagating outward from the block center tended to form as the rock was being pulled apart, whereas those propagating inward tended to form by scissor-like tearing of rock. A new statistical model of rock cracking can distinguish reasonably well between cracks formed by growing ice lenses and those formed by expansion of freezing water.

1. Introduction

Fracture of fine-grained, porous rock by initiation and growth of ice lenses is considered an important mechanism of frost weathering (Ballantyne, 2018; Matsuoka & Murton, 2008). This fracture process—termed ice segregation—refers to migration of premelted water in liquid films through a porous and permeable medium such as soil or rock toward freezing sites, where lenses or layers of ice grow, segregated from adjacent mineral particles and aligned perpendicular to the temperature gradient. Premelting occurs along ice-liquid interfaces, and it enables ice and liquid water to remain in equilibrium at temperatures below 0°C (Dash et al., 2006; Rempel, 2011). Migration of premelted water results from suction induced by temperature gradients within porous media at temperatures below 0°C. Freezing experiments under laboratory conditions...
indicate that macrocracks can initiate and develop in intact rock, and fill with segregated ice (Akagawa & Fukuda, 1991; Maji, 2018; Murton, Coutard, Ozouf, et al., 2001; Murton, Ozouf, & Peterson, 2016; Murton, Peterson, & Ozouf, 2006). Less clear are: (a) When and where do the precursor microcracks occur during different stages of freezing and thawing? (b) Do microcracks develop by tension, shearing or mixed-mode cracking? (c) How do microcracks propagate and coalesce to form individual macrocracks and pervasively fractured (brecciated) horizons? We hypothesize that tension, shearing, and mixed modes of cracking activities of rock vary during different stages of freezing and thawing. We address these questions by monitoring acoustic emissions (AEs) generated by microcracking activity.

AEs are transient elastic waves produced by the rapid release of energy from localized sources within a material (Lockner, 1993). AE testing is a nondestructive method for investigating material behavior based on detection and conversion of high-frequency elastic waves into discrete electrical signals (Goszczyńska, 2014). The transducer element in an AE sensor is a piezoelectric crystal that responds with high sensitivity to motion in the low ultrasonic frequency range (10–2,000 kHz). When the AE wave front reaches the piezoelectric sensors mounted on the surfaces of a test specimen, minute mechanical movements of the fracture surface molecules are sensed by the transducer and converted to detectable electrical signal. The signal is then amplified and split into discrete waveforms with characteristics such as amplitude, absolute energy, duration, and rise time. Multiple piezoelectric sensors arrayed around a structure allow the location of AE activity to be estimated in three-dimensional (3-D) space, based on wave velocity within the material and differences in hit arrival times among the sensors. AE activity has been measured in laboratory freezing experiments with stable thermal boundary conditions (Duca et al., 2014; Hallet et al., 1991). Now it is timely to analyze the changes in AE under dynamic thermal boundary conditions characteristic of natural freeze-thaw cycles.

Here we report observations of AE activity monitored during a laboratory experiment on freeze-thaw of limestone. The rationale for the experiment is that 16 freeze-thaw cycles could be carried out over a substantial period of time (470 days) in order to simulate multiple years of an active layer above permafrost developed within a 300 mm cubic block of tuffeau, a type of chalk (limestone) that readily fractures by ice segregation (Murton, Peterson, & Ozouf, 2006). Our aims are, first, to investigate the mechanisms and transition of microcracking and macrocracking during repeated freeze-thaw, and, second, to develop a statistical model of crack propagation that assesses the distance and angular relationship of neighboring cracking events arranged in their temporal order of occurrence. Our objectives are to (a) determine the 3-D location of individual cracking events within the block using multiple AE sensors, and detect and analyze waveforms emitted during them; (b) identify the spatial and temporal distribution, abundance and mechanical characteristics of cracks during different stages of freezing and thawing; (c) distinguish between cracking modes I (tension) and II (shear) during freeze-thaw cycling by parametric analysis of AE waveforms; (d) construct two boundary conditions that reproduce different modes of crack propagation (inside-outward and outside-inward); and (e) compare the patterns of fracture propagation using Bayes’ theorem for the two boundary conditions with the tension and shear cracks observed using AEs. The experimental set up and observations of macrocracks, temperature, and strain are detailed in a companion paper (Maji & Murton, 2020a) and the freeze-thaw regime is summarized below.

2. Materials and Methods

2.1. Freezing and Thawing Regime

The block of chalk was saturated by capillary rise before starting the experiment and also between its four phases. The block initially froze downward from the top as a result of chilled air circulating in a cold room. Once the block was frozen through, a cooling plate beneath the block was turned on to maintain subzero temperatures in the lower part of the block (simulated permafrost) for the remainder of the experiment. At intervals during the experiment, the chilled air was turned off and the door of the cold room was opened to allow air at ambient room temperature to circulate the cold room and thaw the upper part of the block from the surface downward (simulated active layer). The temperature of the basal cooling plate was thermostatically controlled, with the thermostat set at three progressively higher temperatures during four phases of the experiment (P1–4) in order to simulate active-layer deepening and permafrost thaw during 16 freeze-thaw cycles. The values were set at −15°C for Phase 1 (P1: cycles 1–4, days 0–68), −10°C for P2 (cycles
5–8, days 69–203), and −5°C for both P3 (cycles 9–12, days 207–312) and P4 (cycles 13–16, days 315–470) (Figure 1a; Maji & Murton, 2020a). In summary, the experiment consisted of 16 temperature cycles that simulated annual freeze-thaw of a deepening active layer above permafrost.

Each freeze-thaw cycle was divided into four parts. (1) **Thaw-to-freeze transitions** represent the time between imposing a subzero air temperature and the onset of more or less isothermal conditions in the frozen chalk block. (2) **Freezing periods** represent the time between the onset of more or less isothermal conditions in the frozen chalk block and the onset of an above-zero air temperature. (3) **Freeze-to-thaw transitions** represent the time between turning off the chilled air supply in the cold room and the development of a stable vertical temperature gradient in the unfrozen simulated active layer. During these transitions the 0°C isotherm descended into the block and stabilized at a certain depth, simulating progressive thaw of the active layer in summer. (4) **Thawing periods** represent the time between the onset of a stable vertical temperature gradient in the unfrozen simulated active layer and the onset of a subzero air temperature at the start of the next thaw-to-freeze transition. The duration of each freeze-thaw cycle and of each stage within it varied between cycles (Table S1). This variation was permitted partly to simulate natural variations between successive seasons and years, and partly because of logistical constraints in the cold room.

### 2.2. Acoustic Emissions

#### 2.2.1. Instrumentation, Data Acquisition, and Processing

Eight AE sensors (R-15 alpha, manufactured by Mistras Group) were mounted on five faces of the chalk block (Figure 2). The sensors were distributed using a 3-D Cartesian coordinate system to locate single cracking events. Two sensors were mounted diagonally on vertical faces A, B, and C, one on vertical face D, and one on the top horizontal surface (to monitor the depth of cracking). A silicon grease epoxy (Pro...
silicone grease 494–124, from RS Components) was used to establish a good contact between the smooth ceramic sensor face and the rough vertical rock surface, and a metal cage secured the sensors in place during the experiment (Figure 2d). Two holes (3 mm diameter, ∼25 mm long) were drilled into the block to mount each cage, and plastic raw plugs inserted into the holes to anchor the cage with screws. A screw on the top of the cage ensured that the sensors were firmly pressed against the rock faces during the experiment. The generation of any AEs by movement between the sensor and cage was minimized by placing a strip of rubber folded into multiple layers between them. After phases 1–3 of the experiment, pencil-lead break tests were performed at the top surface of the block and on vertical face B to test that the sensors were not loosening over time but continued to record AE events and to locate the known position of the pencil breaks.

The signal from each AE sensor was amplified by a 40 dB gain before processing. Each sensor was connected by a cable 1.5 m long to a preamplifier (IL40S with 32–1,100 kHz, Mistras Group) placed inside a box in the cold room. The analog and digital filters used in the preamplifier had ranges of 20–400 and 8–40 kHz, respectively. The preamplifiers were activated by a 28V DC phantom power supply from a PCI Express-8 data card (Mistras Group) installed in a workstation outside the cold room and connected to the preamplifiers by a 10-m-long BNC cable. The layout of the AE data acquisition system is illustrated schematically in Figure 2a.

Data were processed using AEWin software. A threshold of 40 dB was set to separate noise induced in the laboratory from signals of microcracking events. The sampling rate was 1 MHz and the values for peak definition time (PDT), hit definition time (HDT) and hit lockout time (HLT) were 200, 800, and 1,000 µs, respectively. Every hit captured by the sensors included the parameters amplitude, energy, counts, duration, average signal level (ASL), rise time, average frequency, signal strength, and absolute energy.

An AE event was identified if at least four of the eight sensors captured the pulses of energy released (hits). The number of hits and amplitude were considered to eliminate and filter out the noise generated by the freezing system. Data acquisition was continuous throughout the experiment, with a file of AE events produced every 12 h.

2.2.2. Waveform Characteristics

The waveform characteristics obtained from the acoustic waves included the number of hits, duration of the signals, number of counts above a preset threshold (=40 dB), rise time, amplitude, and energy released (Figure 3a). In order to classify the nature of cracking, the RA value and average frequency were calculated from the waveform characteristics as follows:

\[ RA \text{ value} = \frac{\text{rise time}}{\text{maximum amplitude}} \]

\[ \text{Average frequency} = \frac{\text{AE counts}}{\text{duration time}} \]

These two parameters allowed cracks to be classified as mode I (tension) and mode II (shear) cracks (Figure 3b; JCMS-IIIB5706, 2003; Ohno & Ohtsu, 2010). The line separating tension and shear events has a slope of 0.1 kHz ms/V following the convention used in JCMS-IIIB5706 (2003).
Events lying on the separation line are classified as mixed modes of cracking.

### 2.2.3. Three-Dimensional (3-D) Location Detection Principle

The 3-D locations of AE events were determined—with an additional plug-in code in the AEWin 3D-LOC software—from the differences in arrival time of acoustic waveforms at sensors that captured any event. This code took into account the array of sensors around the block with respect to a fixed Cartesian reference frame and the velocity of acoustic waves (longitudinal, shear, and surface waves) propagating through the material. Hits and events were classified based on their arrival times at four or more sensors around the block. The acoustic wave velocity of the entire block was assumed to remain constant throughout the experiment. This assumption is reasonable when the rock was frozen (i.e., during the middle to late stages of freezing periods), but during thawing periods slight differences in acoustic wave velocity probably developed between the simulated permafrost and active layer. The 3-D locations of the events within the block were visualized on a graphical interface in AEWin and the information was stored for further analysis.

### 2.3. Statistical Model

#### 2.3.1. Theory and Mathematical Explanation

We developed a statistical model to assess the distance and angular relationships among the temporal order of AE events. The model assumes that the locations and timings of cracking events during the experiment relate to the crack initiation and propagation history observed in the chalk block. The model measures the mean distance and mean angular relationship of the next specified number \( N \) of consecutive events \((N = 2, 5, 10)\) relative to each event. The input, throughput and output of the model are illustrated schematically in Figure 4. The model is based on two principal cases of fracture propagation and validated with the AE data recorded in the experiment. The model depicts the best result when \( N = 10 \), and so we considered \( N = 10 \) for validation purposes. The model considers the mechanism of crack propagation along the horizontal direction only, because well-developed cracks observed in the block after 8, 12, and 16 freeze-thaw cycles were dominantly horizontal. The model outcomes of the experimental results were correlated with the parametric analysis of the AE waveforms in terms of tension, shear and mixed modes of cracking. Bayesian statistical approaches were incorporated to validate the modeling outcomes on a probability scale.

Two cases of fracture propagation were considered: (a) propagation of cracks from inside the block outward toward the sides, that is, inside-out (Figure 5) and (b) propagation of cracks from the outer part of the block inward toward the center, that is, outside-in (Figure 6). Each case produced a different set of 3-D points containing the locations of the events arranged according to their time of occurrence. The fracture propagation model was then tested on the 3-D location matrices to discriminate the patterns in both scenarios.

\[ \mathbb{E}_n \] is the set containing information about the location of events arranged in their temporal order during any sequence of cracking. It is defined as

\[ \mathbb{E}_n = \{ \xi_1, \xi_2, \ldots, \xi_n \} \]

where \( \xi_1, \xi_2, \ldots, \xi_n \) are the locations of cracking events and can be expressed as \( \xi_n = [X_n, Y_n, Z_n] \). The fracture propagation mode \( \text{FP}_n \) assesses the mean distance \((r)\) and mean angular \((\theta)\) relationships of a pre-defined number \((N = 2, 5, 10)\) of next consecutive events and is defined as
Values of both $F_P(r)$ and $F_P(\theta)$ of the corresponding events that are far apart indicate events occurred at various locations within the block and can be interpreted as individual cracking events with no definite spatial relationship to each other. Conversely, values of $F_P(r)$ of the corresponding events that are close together suggest spatially localized events and may indicate a sequence of cracking. $F_P(\theta)$ was estimated by converting the location information $\xi_1, \xi_2, \ldots, \xi_n$ into a vector by joining them to the origin, and the angular relationship of events was derived using the dot product of location vectors.

2.3.2. Inside-Out Crack Propagation

The inside-out propagation model assumes that a crack initiated inside the block and propagated outward toward the sides. To evaluate this mechanism against the brecciated layers observed in the experiment (Maji & Murton, 2020a), we considered a definite zone at a depth interval that generated a random set of 3-D numbers representing each AE event. The numbers were generated in order to simulate the inside-out propagation of a crack (Figure 5). As the crack lengthened, the spatial boundary condition of random number generation expanded on the either side, as visualized in Figure 5a. A total of 3,000 random points was considered in ten consecutive segments, each with extended spatial boundary conditions relative to the previous one. The 3-D random numbers simulating AE events were restored in a set ($E_{io}$) according to their directional order of occurrence. The statistical model was then applied through the simulated event
points, and outcomes of both the angular and distance relationships are presented in Figures 5b and 5c. The nearest 2, 5, and 10 next consecutive events were considered while performing the statistical algorithm at the initial model construction stage in order to assess the best possible outcome. When the next number of consecutive events was lowest (N = 2), the fluctuations in angular and distance values were higher, and when the number was highest (N = 10), the curve showed less variation. Both the values of $F_P(\theta)$ and $F_P(r)$ followed a gently increasing trend (Figures 5b and 5c).

### 2.3.3. Outside-In Crack Propagation

The outside-in propagation model simulates a crack originating on two sides of the block within a definite depth interval and propagating inward toward the middle. A similar protocol was applied to create the set $\mathbb{E}_{OI}$ of locations of events that replicate the outside-in propagation of cracking (Figure 6). The distribution of random events that replicate $\mathbb{E}_{OI}$ is illustrated in Figure 6a. Unlike the inside-out model, in the outside-in model, the results of the statistical algorithm for both situations $F_{PO}(r)$ and $F_{PO}(\theta)$ followed a gently decreasing trend (Figures 6b and 6c).

### 2.3.4. Testing the Model

Predicted $F_P(r)$ and $F_P(\theta)$ values of the statistical crack propagation model, developed by considering the two distinct boundary conditions, were compared with the similar distance and angular variations observed at different depth intervals within the specimen during the physical experiment. The observed hypocenters of AE events were spatially grouped into four depth intervals determined from visual analysis of macrocracks and brecciation in the block after 16 freeze-thaw cycles, as described by Maji and Murton (2020a). The AEs in these depth intervals were then filtered and arranged in their order of temporal occurrence follow-
ing the time stamp recorded during acquisition. The step processing structure of the fracture propagation function is schematically illustrated in Figure 4. The process was repeated for each of the four depth intervals.

3. Results

3.1. AE Activity

AE activity during the four parts of a representative freeze-thaw cycle (freezing period, freeze-to-thaw transition, thawing period, and thaw-to-freeze transition) is exemplified from freeze-thaw cycle 5 (Figure 7). The full set of AE activities recorded during all 16 cycles is shown in Figures S1–S20 and summarized below in terms of their constituent parts. The AE rate per day during each stage of successive freeze-thaw cycles is shown in Figure 8, together with mean daily AE rates for all 16 cycles. The preamplifier connected to the sensor positioned at 100 mm depth on vertical face B (Figure 2) was faulty, leaving seven of the eight sensors operational during the experiment.

3.1.1. Freezing Periods

Freezing periods had an average duration and standard deviation of 12.7 ± 6.9 days and encompassed 9.46% of the total number of AE events. AE events were recorded mostly during freezing periods (F) 3–5, with few events during F10 (Table 1; Figures S1 and S2). F3–5 occurred during phases P1 and early P2, when the temperature of the air and basal cooling plate was relatively low (Maji & Murton, 2020a).

AE activity clustered mostly around face A during F3–5, with limited clustering around faces C and D (Figure S1: panels 1–4). High-amplitude events (>64 dB) occurred around face A. F10 experienced relatively few events compared to F3–5. In F10, AEs occurred near face B and in the central part throughout the depth of the block, with moderate-to-high-magnitude events (56–72 dB) around face B. Moderate-to-high-magnitude events were most abundant in the 180–300 mm depth range, although some low-amplitude events (<48 dB) occurred in the upper half of the block (Figure S2: panels 1–4). In F3 and F10, AEs occurred within a short window of time, whereas in F4–5, they continued throughout the freezing period (Figure S1: panels 5–12). In F3–5, the number and magnitude of shearing mode events were higher than those of tension, whereas F10 was dominated by tension mode events (Figure S2: panels 5–12). Overall, comparatively steep freezing gradients during P1 initiated AE activity near the beginning of the experiment, and as the intensity of freezing fell in later cycles, the frequency of AE activity reduced.

3.1.2. Freeze-to-Thaw Transitions

Freeze-to-thaw (FT) transitions had a mean duration of 1.4 ± 0.3 days and encompassed 36.98% of the total number of AE events. Substantial AE activity occurred during all 16 FT transitions (Figures S3–S8; Table 2). In P1, when the thermal gradient was highest, AE events occurred mostly in the lower half of the block (Figure S3: panels 1–4). In FT1, AEs were mostly in the central part of the block, but in FT2–4, they were mostly near vertical faces A and C (Figure S4: panels 1–4). Some moderate-to-high-amplitude (64–80 dB) activity occurred during FT1–2 (Figures S5 and S6: panels 1–4). The tension mode of cracking dominated over the shearing mode, and the intensity of shearing gradually decreased during the course of P1 (Figures S7 and S8: panels 1–4).

In P2–3, when the basal thermal protocol was moderate (~10°C compared to ~15°C in P1), the modal depth of the frequency distribution of AE events moved upward into the middle of the block (Figure S3: panels 5–12). However, at the onset of restarting the experiment after pauses between P1 and P2, and between P2 and P3, AE activity was concentrated in the lower half of the block, which is also evident in the transition between P3 and P4 (Figure S3: panels 5, 9, and 13). AE events in P2–3 were mostly localized within the block, unlike the clustering of AEs around the faces observed in P1 (Figure S4: panels 5 and 12). Moderate-to-high-magnitude events (56–72 dB) were prevalent, though the high amplitudes clustered mostly around the faces. New clustering of events around faces was marked by high-amplitude activity, as observed in FT 1–2 near face A and in FT 9–10 around face B (Figure S4). High-magnitude activity (>72 dB) was bounded by initiation and follow-up events both in the depth and time domain, as observed in FT1,
Figure 7. AE data for freeze-thaw cycle 5 divided into four constituent parts: freezing period (“freeze”), freeze-to-thaw transition, thawing period (“thaw”) and thaw-to-freeze transition. (a–d) 3-D locations of AE events with their respective amplitude. Vertical faces A–D of the block are labeled in (a); this labeling applies to all subsequent 3-D plots in the article. (e–h) Visualization of AE events in terms of depth, amplitude and time. (i–l) Simplified version of plots e–h with depth versus time, and amplitude ranges marked with different shapes and colors. (m–p) Visualization of AE events in terms of AF values, RA values and time, labeled according to modes of fracture. (q–t) Simplified version of plots m–p with AF versus RA values and fracture modes. (u–x) Frequency distribution of AE events along various depth intervals within the block.
The magnitude of shearing events increased in P2–3, though both tension and shearing modes were abundant (Figures S7 and S8).

In P4, AE events occurred throughout the depth of the block and moderate-to-high-amplitude events were evident (Figures S3–S6; panels 13–16). Both tension and shear modes were abundant.

In summary, intense bidirectional freezing coincided with AE activity concentrated in the lower half during P1, whereas higher temperatures in P2–3 coincided with modal AE activity in the central parts of the block. In addition, AEs were localized within the block rather than clustered around faces, though high-magnitude events were localized around faces during P2–3.

### 3.1.3. Thawing Periods

Thawing periods (T) had an average duration of 13.8 ± 5.0 days and encompassed more AE events (45.37%) than any other parts of the freeze-thaw cycles (Figures S9–S14; Table 3). However, no activity was recorded in T9 and 15.

In P1, AE activity mostly occurred in the lower half of the block (Figure S9: panels 1–4). The events were highly clustered and isolated around the faces A and C (Figure S10: panels 1–4). High-amplitude events (64–72 dB) occurred in the upper half of the block (Figures S11 and S12: panels 1–4). During the entire thawing periods, the tension mode of cracking was of higher magnitude than that of shearing mode. Also, the number of tension events was higher than shearing.

In P2–3, the modal depth of AE activity moved higher within the block, similar to that in FT transitions (Figure S9: panels 5–12). In addition, abundant events occurred within the block, connecting the clusters developed near the faces during P1 (Figure S10: panels 5–12). Faces A and C were mostly connected during P2, whereas faces B and D were bridged in P3. Moderate-to-high-amplitude events (56–72 dB) occurred in the central and lower parts of the block (Figures S11 and S12: panels 5–12).

In P4, AE events occurred in the middle and lower parts of the block (Figure S10: panels 13–16). Clustering of AE occurred around faces, mostly near face D and particularly in the upper half of the block (Figure S10: panels 13–16). Low-to-moderate-magnitude events (56–72 dB) occurred in P4 and were concentrated in the middle to lower half of the block (Figures S11 and S12: panels 13–16).

Overall, high-amplitude events (70–80 dB) were fewer in thawing periods than in freeze-to-thaw transitions. The tension activity was most abundant within the 30–40 (average frequency) kHz window in thaw cycles as compared to freeze-to-thaw transitions, where <30 kHz events were also recorded. In contrast, freeze-to-thaw transitions recorded higher magnitude shear events than thawing periods (Figures S13 and S14).

### 3.1.4. Thaw-to-Freeze Transitions

Thaw-to-freeze (TF) transitions had a mean duration of 1.3 ± 0.7 days and encompassed only ~8.17% of the total number of AE events (Figures S15–S20; Table 4). AE activity was greatest in P1–2. Six transitions (TF 1, 6, 10–12, and 16) lacked any AE events.

During P1–2, AE activity occurred mostly in the lower half of the block, whereas in P3–4 very few events were identified (Figure S15). Events mostly clustered around faces A and C, with limited numbers of AEs occurring in the central part of the block (Figure S16). Medium- to high-amplitude events (56–72 dB) were observed in TF2 at ~100–250 mm depth, whereas the rest of the activities were of low to medium amplitude (40–56 dB) (Figures S17 and S19). Both tensional and shearing modes of cracking occurred, with some shearing mode events of high magnitude (Figures S18 and S20).
3.2. Crack Propagation Models at Different Depth Intervals

The experiment formed visible macrocracks at four different depth intervals in the block. These comprise two brecciated horizons at depths of 70–110 mm and 180–220 mm and two horizons with limited numbers of inclined macrocracks at depths of 0–60 mm and 120–170 mm (Figure 3.2). The brecciated horizons contained mostly horizontal to subhorizontal macrocracks that bifurcated and joined, separating angular and tabular fragments of chalk, and cross-cut by fewer vertical to steeply dipping macrocracks. The lightly cracked horizons above and between the brecciated horizons consisted of single to a few cracks, mostly horizontal to subhorizontal. Further details of the macrocracks are given by Maji and Murton (2020a).

First, we describe the timing of aggregated AE events at different depth intervals during the four thermal phases of the experiment, and then we examine the crack propagation models at these different depths.

3.2.1. AE Timing During Phases 1–4

The timing of AE events in the four depth horizons varied with the imposed thermal boundary conditions (basal cooling thermostat values of −15°C for P1, −10°C for P2, and −5°C for both P3 and P4; Figure 1a). AE events were most abundant in the upper brecciated horizon (70–110 mm depth) during P2–4 (n = 273–338) and least abundant in P1 (n = 193), when the temperature was lowest (Figure 11). Conversely, events were most abundant in the lower brecciated horizon (180–220 mm depth) during P1–2 (n = 2,087–2,449), and less common in P3–4 (n = 503–828) (Figure 12). In comparison, AEs were most common in the upper horizon of limited fracture (0–60 mm depth) during P3–4 (n = 158–273), and less common in P1–2 (n = 89–94) (Figure 13). Finally, AEs in the lower horizon of limited fracture (120–170 mm depth) were most common in P2 (n = 1,507) and least common in P1 and P3–4 (n = 437–693) (Figure 14).

3.2.2. Brecciated Horizons

Both brecciated horizons decreased overall in the values of $F_P(r)$ and $F_P(\Theta)$ during the experiment, especially during the first phase (P1). In P1, $F_P(r)$ decreased from ~160 to ~80 mm at 70–110 mm depth (Figure 11b) and from ~180 to ~50 mm at 180–220 mm depth (Figure 12b). Respective drops in $F_P(\Theta)$ in P1 were from ~50 to ~30° (Figure 11b) and from ~50 to ~20° (Figure 12b). The transition between P1 and P2 marked with a sharp increase in both $F_P(r)$ and $F_P(\Theta)$, whereas, the values contin-

### Table 1

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### Table 2

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3.1.5. Summary

Most AE events occurred during thawing periods (~45%) and freeze-to-thaw transitions (~37%), with fewer in freezing periods (~9%) and thaw-to-freeze transitions (~8%). In terms of depth, all AEs (>40 dB), including those of higher magnitude (>60 dB), were concentrated mostly in the lower half of the block in P1, but the modal depth of the events moved upward in P2–3, and events were distributed throughout the block in P4 (Figure 9). In terms of 3-D location, AEs were mostly clustered and isolated around faces A and C in P1. In P2–4, events were observed in the central part of the block connecting the clusters. However, some new clusters developed around faces B and D during P3 and P4. In terms of magnitude, most events were low to moderate amplitude, though moderate-to-high-amplitude events were abundant during P1–3. The modes of cracking were mostly tensional, though abundant shearing activities were recorded. The magnitude of tensional activity was highest in thawing periods. In some instances, however, the magnitude of shearing modes was relatively high in freeze-to-thaw and thaw-to-freeze transitions.
Table 3
Number and Magnitude of AE Events Occurred During Thawing Periods

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<th>Amplitude (dB)</th>
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Table 4
Number and Magnitude of AE Events During Thaw-to-Freeze Transitions

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</table>

ued to decrease during P2 in both the brecciated horizons (Figures 11b and 12b). Both parameters tended to fluctuate, sometimes substantial, during P3–4, where the amount of oscillation surpassed the overall trend. The highest number of AE events was observed at 180–220 mm depth. AE activity was particularly common during thawing periods and FT transitions in P1–2, though substantial activity also occurred during freezing periods in P1, when the thermal boundary condition was at its lowest (Figure 11c). At both depth intervals, the majority of cracking events were of shearing mode in P1 and P2, and of tensional mode in P3 and P4 (Figures 11a and 12a).

3.2.3. Horizons of Limited Fracture

AE activity was least within the shallow horizon of limited fracture (0–60 mm depth, Figure 13), whereas the deeper horizon of limited fracture (120–170 mm depth) showed the second highest AE activity (Figure 14). During P1–2, the values of FP (r) and FP (θ) declined overall at 120–170 mm depth (Figure 14b), whereas no obvious trends occurred in either parameter at 0–60 mm depth (Figure 13b). The maximum fluctuation in FP (r) and FP (θ) at 120–170 mm depth corresponds to 140 mm and 32°, respectively (∼190 to ∼50 mm and 47–15°) and 40 mm and 40° (∼80 to ∼40 mm and 50–10°), and at 0–60 mm depth to 60 mm and 16° (∼150 to 90 mm and 33–17°) and 90 mm and 45° (∼200 to ∼110 mm and 50–5°) during P1–2. During P3–4 the overall changes in both the values of FP (r) and FP (θ) were low at both the depth intervals (Figures 13b and 14b), and both parameters experienced occasional variation, sometimes substantial. The AE events occurred mostly during the freezing periods in P1 and during thawing periods in P2. In contrast, the events were mostly developed during thawing periods followed by FT transitions in the upper horizon during P3–4, whereas the order was reversed (i.e., FT transitions followed by thawing periods) in the lower horizon. The majority of fracturing activity was of shearing mode in P1 and tension mode in P2–4 (Figures 13a and 14a).

4. Discussion

No additional mechanical loading was imposed during the experiment and the fractures developed purely under dynamic thermal boundary conditions. Cracking of rocks under repeated freezing and thawing tends to be slower than that under mechanical loading, and so a long experiment (470 days) with 16 freeze-thaw cycles was required to produce well-developed crack surfaces in a relatively soft limestone. The slow development of cracks—monitored using AEs—elucidates the timing of AEs during freeze-thaw cycles, the depth of AEs and macrocracks, and the modes and mechanisms of cracking. In turn, this permits evaluation of a new statistical model of crack propagation and assessment of the practical significance of distinguishing between cracks formed by volumetric expansion and ice segregation.

4.1. Timing of AE Events During Freeze-Thaw Cycles

The timing of AE events within the four parts of each freeze-thaw cycle suggests that the majority of AEs did not result from microcracks formed by volumetric expansion but instead from ice segregation. The maximum number of AE events (45.37%) occurred during thawing periods, followed by freeze-to-thaw transitions (36.98%), even though the average duration of the transitions was only 1.4 ±0.3 days. The fewest AE
events were observed during freezing periods (9.46%) and thaw-to-freeze transitions (8.17%). Collectively, this timing suggests that the large majority (>82%) of microcracking events was not associated with rock freezing but instead with rock thawing (during the earlier stages of thawing periods and during freeze-to-thaw transitions) or unchanging thermal conditions (during the later stages of thawing periods). Therefore, we discount volumetric expansion—which is predicted to occur in bursts during rock freezing, as liquid water freezes and expands (Walder & Hallet, 1985, 1986)—as the main cause of AEs. We conclude that most AEs resulted from ice segregation. The process of ice segregation is expected when temperature-gra-

Figure 9. AE frequency versus depth during phases 1 to 4 (P1–P4) of the experiment. (a–d) All AEs (>40 dB) and (e–h) AEs of higher magnitude (>60 dB).
ient-induced cryosuction draws liquid water to ice bodies within cracks (Taber, 1930; Walder & Hallet, 1986), which may arise as rock thaws or freezes. However, we cannot discount volumetric expansion as a cause of AEs during freezing periods or thaw-to-freeze transitions. For example, in freezing periods, AE activity was mostly limited to P1, which implies that for the lowest basal temperature regime (i.e., −15°C and lower), AEs were caused by volumetric expansion as the low temperature led to rapid freezing of pore water within the chalk. Freezing of pore water may have been caused by either rapid cooling downward from the rock top and/or upward from the simulated permafrost, which may explain the depth distribution of AEs shown in Figures 9 and S2: F3–F5.

The timing of AE activity under laboratory conditions may be compared with that reported under field conditions. At 3,500 m above sea level in the Swiss Alps, AE activity and rock temperature monitored during the course of four days in a south-facing alpine rockwall formed of granitic gneiss revealed that AE activity increased significantly when rock temperature was <0°C, especially at locations receiving meltwater from snow (Armitrano et al., 2012). Rock at 10 cm depth warmed to 10°C during the day and cooled to −5°C during night, while rock at 60 cm depth remained continuously between about −2 and −7°C. The increased AE activity during periods of subzero temperature, when near-surface rock experienced refreezing, suggested that freezing-induced stresses contributed to rock damage. Subsequently, AE monitoring at this location for a period of one year showed that rates of AE energy detected during freezing conditions were about two orders of magnitude greater than those under thawed conditions, suggesting that freezing-induced processes largely accounted for AE activity (Girard et al., 2013). AE activity during freezing periods ranged over temperatures from just below 0°C—which might indicate in situ freezing and volumetric expansion—down to as low as −15°C—consistent with water migration and ice segregation. A major difference between the field site and our laboratory experiment is rock porosity: the interjoint porosity of the granitic gneiss (1%–2%) is far lower than that of the tuffeau (∼47%; Murton, Coutard, Lautridou, et al., 2000). Thus, it is to be expected that the intact bodies of gneiss between fractures will be much less susceptible to migration of liquid water and resultant ice segregation than the tuffeau. At a rock slope developed in conglomerate in Austria, some AE activity coincided with freeze-thaw temperature cycles, and has been linked to observed detachment of boulders from the slope (Codeglia et al., 2017).

### 4.2. Depth of AE Events and Macrocracks

The depth of AE events during phases 1–4 of the experiment (Figure 9) shows only limited correspondence to the depth of macrocracks observed after phases 2, 3, and 4 (Figure 10). In Phase 1, the majority of AEs—both in terms of total number and high magnitude (>60 dB)—were concentrated below 180 mm depth, peaking between 250 and 300 mm depth (Figures 9a and 9e). In Phase 2, the modal depth decreased to ~190–260 mm (Figures 9b and 9f), whereas in phases 3 and 4 AEs were more uniformly distributed with depth (Figures 9c, 9d, 9g, and 9h). Macrocrack development, by contrast, was observed to form a brecciated horizon initially at 70–110 mm depth by the end of Phase 2 (Figure 10a), followed by a second, deeper brecciated horizon at 180–220 mm depth during phases 3 and 4 (Figures 10b and 10c). The increase in depth of brecciation during the experiment has been attributed to overall deepening of the simulated active layer above permafrost between phases 1 and 4 (Figure 1a; Maji & Murton, 2020a).
The limited correspondence between the depths of AE events and macrocracks is attributed tentatively to one or more of four factors. First, the abundant AEs recorded in the basal part of the block during Phase 1 were mostly of low amplitude (40–50 dB; Figure S1) and may be explained by the low temperature protocol followed at the base. Such AEs did not lead to any observed macrocracks, possibly because many AEs resulted from volumetric expansion within the pores during freezing periods and thaw-to-freeze transitions. Second, some vertical to subvertical macrocracks developed in the chalk, indicating that macrocrack development was not confined to the two brecciated horizons but was more widely distributed in the block. Such cracks may function as conduits for migration of unfrozen water toward the freezing front to facilitate ice segregation (Azmatch et al., 2008; Fukuda, 1983; Maji, 2018; Maji & Murton, 2020a). Third, the number of AEs decreased overall during the course of the experiment (Figure 9), consistent with reduced amounts of AE activity with increasing numbers of freeze-thaw cycles reported in experiments on concrete (Todak et al., 2017) and granite (Wang et al., 2019). This progressive reduction in AE activity probably resulted, at least in part, from increasing heterogeneity in the chalk, as the macrocracks propagated. Increasing heterogeneity as the rock fractured likely caused increasing attenuation of the AE signal (cf. Weber et al., 2018), which may have limited the number of AEs registered by the sensors around the block.

Figure 11. AE events within the 70–120 mm depth interval arranged in their order of occurrence during the four phases (P1–4) of the experiment. (a) AE events classified as tension, shear, and mixed modes of cracking based on the parametric analysis of AE waveforms, using AF versus RA values. (b) $\mathbb{F}$ (r) and $\mathbb{F}$ (θ) values indicated on Y-axes on left and right, respectively, of the corresponding events. (c) Timing of AE events during P1–4 and subdivided into the four constituent parts of the freeze-thaw cycles (freezing period, freeze-to-thaw transition, thawing period, and thaw-to-freeze transition).
Fourth, the velocity of sound waves in the chalk is likely sensitive to the quantity and type of pore-filling phase, with the velocity increasing from air-filled pores through liquid-water-filled pores to ice-filled pores (Hermans, 2019). Additionally, in the case of pores that are partially ice-saturated, the acoustic wave velocity may depend linearly on the volume fraction of the ice. Therefore, there is potentially a large error in localization of the AE-signals.

Boreholes or existing cracks may have influenced the location of new fractures, but are not considered to have been the primary control on the development of the brecciated horizons. If borehole depth was the primary influence on fracture depth, then we would expect that all or most boreholes should have cracks associated with them. However, as shown in Figures 10a–10d of Maji and Murton (2020a), only 10 of 27 boreholes intersected cracks (0 of 5 boreholes on face A, 4 of 8 on face B, 3 of 5 on face C, and 3 of 9 on face D). Furthermore, most cracks do not coincide with boreholes. Overall, these considerations discount borehole location as a dominant control on crack depth, and are consistent with a mechanism of cracking related to the depth of isotherms during freezing or thawing.

Figure 12. AE events within the 180–220 mm depth interval arranged in their order of occurrence during the four phases (P1–4) of the experiment. (a) AE events classified as tension, shear, and mixed modes of cracking based on the parametric analysis of AE waveforms, using AF versus RA values. (b) $F_P(r)$ and $F_P(θ)$ values indicated on Y-axes on left and right, respectively, of the corresponding events. (c) Timing of AE events during P1–4 and subdivided into the four constituent parts of the freeze-thaw cycles (freeze, freeze-to-thaw transition, thaw, and thaw-to-freeze transitions).
Mechanistically, ice segregation alone may have caused microcracking during thawing periods and freeze-to-thaw transitions, but we discount volumetric expansion at such times as a cause because phase change from liquid water to ice requires rock cooling and freezing. However, both ice segregation and/or volumetric expansion may have caused microcracking during freezing periods and thaw-to-freeze transitions.

Moderate-to-high-amplitude (64–80 dB) AE activity during freeze-to-thaw transitions was observed as clusters near faces A and C early in the experiment, suggesting that development of new clusters was facilitated at the face boundaries, followed by high-magnitude events (>70 dB). In Phase 1 (i.e., lowest thermal boundary conditions; Figure 1a), the dominant low-magnitude tension mode of cracking suggests that the microcracks were caused by volumetric expansion mostly during freezing periods and thaw-to-freeze transitions as the chances of well-developed lenses of segregated ice were minimal in the early phases of the experiment. By contrast, AE events during thawing periods in P1 were mostly isolated near the face boundaries (Figure S10: panels 1–4), whereas in freeze-to-thaw transitions, some events occurred within the block (Figure S4: panels 1–4), which suggests that melting of ice initiated events within the well-developed clusters near the face boundaries. Also, high-amplitude events in the upper half of the block during thawing periods in P1 correlate with the well-developed brecciated layer at ∼70–110 mm depth.

In P2–3, moderate-to-high-amplitude events (56–72 dB) occurred within the block, implying that warmer thermal boundary conditions were suitable for developing segregated ice lenses. However, the clustering of high-magnitude activity near the faces suggests that surface boundaries are weaker zones for initiation of

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**Figure 13.** AE events within the 0–60 mm depth interval arranged in their order of occurrence during the four phases (P1–4) of the experiment. (a) AE events classified as tension, shear and mixed modes of cracking based on the parametric analysis of AE waveforms, using AF versus RA values. (b) Φₚ (r) and Φₚ (θ) values indicated on Y-axes on left and right, respectively, of the corresponding events. (c) Timing of AE events during P1–4 and subdivided into the four constituent parts of the freeze-thaw cycles (freeze, freeze-to-thaw transition, thaw, and thaw-to-freeze transitions).

**4.3. Mechanisms and Modes of Cracking**

Mechanistically, ice segregation alone may have caused microcracking during thawing periods and freeze-to-thaw transitions, but we discount volumetric expansion at such times as a cause because phase change from liquid water to ice requires rock cooling and freezing. However, both ice segregation and/or volumetric expansion may have caused microcracking during freezing periods and thaw-to-freeze transitions.

Moderate-to-high-amplitude (64–80 dB) AE activity during freeze-to-thaw transitions was observed as clusters near faces A and C early in the experiment, suggesting that development of new clusters was facilitated at the face boundaries, followed by high-magnitude events (>70 dB). In Phase 1 (i.e., lowest thermal boundary conditions; Figure 1a), the dominant low-magnitude tension mode of cracking suggests that the microcracks were caused by volumetric expansion mostly during freezing periods and thaw-to-freeze transitions as the chances of well-developed lenses of segregated ice were minimal in the early phases of the experiment. By contrast, AE events during thawing periods in P1 were mostly isolated near the face boundaries (Figure S10: panels 1–4), whereas in freeze-to-thaw transitions, some events occurred within the block (Figure S4: panels 1–4), which suggests that melting of ice initiated events within the well-developed clusters near the face boundaries. Also, high-amplitude events in the upper half of the block during thawing periods in P1 correlate with the well-developed brecciated layer at ∼70–110 mm depth.

In P2–3, moderate-to-high-amplitude events (56–72 dB) occurred within the block, implying that warmer thermal boundary conditions were suitable for developing segregated ice lenses. However, the clustering of high-magnitude activity near the faces suggests that surface boundaries are weaker zones for initiation of
ice lenses than within the block due to the differences in confining pressure, as high pressure favors melting of ice even if the temperature gradient remains identical. In addition, the magnitude of shearing events increased in P2–3, which is interpreted to indicate the coalescence of microcracks into developing macrocracks. Specifically, ice segregation was facilitated as the basal temperature conditions increased and the time duration was enhanced in P2–3 relative to P1 and corresponds with crack coalescence by connecting isolated clusters developed in P1, as evident by the well-developed brecciated layers at depths from ∼100 to ∼200 mm.

In thawing periods, the tension activity was most abundant within the 30–40 kHz window (Figure S13 and S14) compared to freeze-to-thaw transitions, where <30 kHz events were also recorded (Figures S7 and S8). During thawing periods, the temperature gradient allows for the development of segregated ice within the preexisting cracks and voids that open up the cracks in tension mode. Depending on the size of the segregated ice lenses, the magnitude of tension events varied and in the case of thawing comparatively higher magnitude activity was recorded. In contrast, freeze-to-thaw transitions recorded higher magnitude shear events than thawing periods (Figures S8 and S14). We hypothesize that in freeze-to-thaw transitions, partial melting of ice crystals formed during freezing periods begins and the premelting layer of water acts as a slip surface for fractures to slide one after another, causing relatively high-magnitude shearing activity observed in freeze-to-thaw transitions.

Figure 14. AE events within the 120–170 mm depth interval arranged in their order of occurrence during the four phases (P1–4) of the experiment. (a) AE events classified as tension, shear, and mixed modes of cracking based on the parametric analysis of AE waveforms, using AF versus RA values. (b) $F \theta (r)$ and $F \Phi (\theta)$ values indicated on Y-axes on left and right, respectively, of the corresponding events. (c) Timing of AE events during P1–4 and subdivided into the four constituent parts of the freeze-thaw cycles (freezing period, freeze-to-thaw transition, thawing period, and thaw-to-freeze transitions).
4.4. Statistical Modeling of Crack Propagation

Maji and Murton (2020b) classified different zones of microcracking based on microcomputed tomography (μ-CT) analysis of 20 freeze-thaw cycles of a cylindrical core of the same chalk lithology (30 mm long, 20 mm diameter). However, the mechanisms of crack propagation were not identified. For the statistical model of crack propagation proposed in the present study, the results of the hypothetical simulation were compared with the experimental results. The relationships between the proposed mechanisms of crack propagation (inside-out and outside-in) and the modes of cracking (tension, shear, and mixed) are summarized in a Venn diagram (Figure 15). It is evident that each mode of propagation consists of cracks of tension, shear, and mixed modes of origin.

Probabilistic assessment of the experimental results based on Bayes’ theorem is summarized in Table 5 for the four parts of each freeze-thaw cycle (freezing period, freeze-to-thaw transition, thawing period, and thaw-to-freeze transition). For each part, the probability of occurrences of any particular type of event was assessed based on prior knowledge related to the prevalence of that event. Column two represents the probability of occurrences of tension events provided that the inside-out mode of propagation had occurred as a related background condition. The reverse scenario is represented in column three, where the probability of the inside-out mode of propagation is evaluated following the prior correlated condition assuming that the tension mode of cracking had taken place. Column four illustrates the probability of occurrences of shearing events following the condition that the outside-in mode of propagation has occurred. Column five documents the opposite situation, evaluating the probability of outside-in events when shearing modes of cracking existed. Overall, we tested the hypothesis that the inside-out mode of crack propagation (i.e., increasing $\mathbb{P}$) is facilitated by tensional cracks, whereas the outside-in mode is assisted by shearing cracks (i.e., decreasing $\mathbb{P}$). The hypothesis is supported by 54% (minimum) to 73% (maximum) confidence level, with an average of 64.88% for various parts of freeze-thaw cycles.

Acceptance of the hypothesis suggests that the inside-out and outside-in approach of quantifying the fracture propagation method—based on statistical modeling of the crack propagation dynamics—was influenced to some extent by the modes of cracking (tension, shearing, and mixed). By implication, the growth of any crack that develops under such dynamic thermal boundary conditions can be broadly predicted.

4.5. Application of Crack Propagation Model for Isolating Volumetric Expansion and Ice Segregation Mechanisms

The negative trends for both $\mathbb{P}(r)$ and $\mathbb{P}(\theta)$ were relatively steep in P1 compared to other phases, and contained short episodes of increase (Figures 11–14). Some episodes of tensional activity attributed to volumetric expansion formed at various locations throughout the depth window, and started to interact with each other, as indicated by the sharp decreases in $\mathbb{P}(r)$ and $\mathbb{P}(\theta)$. In P2, when the thermal protocol was higher than P1, the slope of the negative trend reduced, and the episodic spikes in positive trend increased. The increases were of steep slope, suggesting potential tensional events attributed to ice segregation that may have allowed growth of thicker ice lenses as compared to volumetric expansion when an extreme thermal protocol was established. Similar mechanisms were inferred during P3 as well, except during some high-magnitude spikes. Repeated spikes occurred in P4, when the temperature at the bottom of the block was highest. Such spikes were correlated with the hypothesized thicker ice lenses as thermal protocols and duration of freezing and thawing cycles were highest, favoring ice segregation.
also correlated with the brecciated horizon at ∼70–110 mm depth that was partially formed after 8 FT cycles but well developed after 16 cycles.

4.6. Limitations and Recommendations for Future Research

The present study investigated the applicability of using AEs as a nondestructive method during rock freezing and thawing for an order of magnitude longer duration than previous experiments (Duca et al., 2014; Hallet et al., 1991) and, for the first time, during dynamic thermal conditions. However, several limitations of our experiment are apparent.

First, the dynamic thermal boundary conditions around the chalk block imposed a vertical thermal gradient, causing the lower part to remain frozen during most of the experiment, while the upper part experienced repeated freeze-thaw. We assumed a uniform AE wave velocity throughout for detecting the 3-D locations of the micro- and macrocracking events, although the variation in temperature changes the consistent attenuation of the AE wave velocities.

Second, deformation-induced heterogeneity was excluded in the present study. However, it was observed that the degree of deformation controls the waveform attenuation to a certain extent. The intact specimen at the beginning of the experiment showed a steady value of attenuation and the wave velocity may have varied through time as the material developed brecciated horizons and other macrocracks.

Third, because only a single block of rock was used in the present experiments, we cannot discount the possibility that randomness of rock samples impacts the experimental results. But our experiment reproduced macrocrack patterns similar in size, shape and depth to those generated in previous experiments (Murton, Ozouf, & Peterson, 2016; Murton, Peterson, & Ozouf, 2006) on multiple blocks of the same rock type. Nonetheless, future experiments could monitor microcracking in additional blocks of tuffeau as well as attempting longer experiments with more freeze-thaw cycles in harder rocks.

Fourth, the statistical model considers crack propagation primarily in the horizontal direction, consistent with the imposition of horizontal isotherms and development of brecciated horizons dominated by horizontal to subhorizontal cracks. Future modeling, however, should also investigate the propagation of vertical to steeply inclined cracks, which may require additional sensing methods to measure local pore water pressure, water saturation and identification of potential flow paths for transporting liquid water toward ice lenses.

Fifth, the mechanism of crack propagation is analyzed mainly on the basis of AE data and the distribution of crack morphology. The cracks developed under varying thermal boundary conditions and there was no suitable proxy to transpose the kinematics into an appropriate loading situation. This restricted integration of our experimental observations with conventional fracture mechanics theory. Future experiments that apply conditions of known loading to specimens might combine our approaches with that of fracture mechanics to analyze the mechanism of cracking and crack propagation.

In view of these limitations, we therefore recommend that future experiments consider the temperature-induced and deformation-induced changes in AE wave velocities for precisely locating the cracking events in 3D as these two factors influence the attenuation of AE waveforms.

5. Conclusions

The following conclusions are drawn from the present study:

1. AE events occurred mostly during thawing periods (45%) and freeze-to-thaw transitions (37%) rather than during freezing periods (9%) and thaw-to-freeze transitions (8%). This observation supports the hypothesis that the majority of AE activity was associated with rock fracture caused by ice segregation rather than volumetric expansion.

2. The modal depths of AE events were poorly correlated with the depths of macrocracks that comprised two brecciated horizons. Possibly, the low-magnitude AE events have limited influence on developing the brecciated horizons.
3. Early phases of the experiment revealed significant AE activity around the vertical faces of the block, whereas later phases had high-magnitude events within it. This suggests that face boundaries are weaker regions where microcracking initiated, compared to interior regions. We hypothesize that lower confining pressure around the faces facilitates stable growth of ice crystals.

4. Phase one of the experiment—with the lowest basal temperature protocol (−15°C)—was dominated by tension mode microcracking, which suggests that the lowest temperatures initiated volumetric expansion. Higher basal temperature protocols in phases 2 (−10°C) and 3 (−5°C) were associated with shearing events, allowing stable growth of ice lenses developed mainly by ice segregation. The magnitude of tension mode cracking was higher during thawing periods, facilitating development of ice lenses. By contrast, the occurrence of high-magnitude shearing events mostly during freeze-to-thaw transitions is hypothesized to indicate that partial melting of ice provided slip surfaces (of low friction) for fractures to slide over the thin film of premelted water.

5. Microcrack propagation from inside the block toward the outside (inside-out mode) favored tensile cracking, whereas propagation from the outer part of the block toward the interior (outside-in mode) favored shearing events.

6. The proposed microcrack propagation model can distinguish reasonably between cracks formed by volumetric expansion and ice segregation, based on the slope of the probabilistic values connecting the distance and angular relationships of corresponding events.

Data Availability Statement
The data set for this research is available from the University of Sussex Research Data Repository https://doi.org/10.1029/2021JF006127.

References


