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Wildfires as a Weathering Agent of Carbonate Rocks

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Abstract: While most of the scientific effort regarding wildfires has predominantly focused on fire effects on vegetation and soils, the role of fire as an essential weathering agent has been largely overlooked. This study aims to evaluate rock decay processes during wildfires, in relation to ground temperatures and rock morphologies of limestone, dolomite, and chalk. In 2010, a major forest fire in Israel caused massive destruction of the exposed rocks and accelerated rock weathering over the burned slopes. While a detailed description of the bedrock exfoliation phenomenon was previously reported, here, we conducted an experimental open fire to determine the temperature and gradients responsible for boulder shattering. The results show ground temperatures of 700 °C after 5 min from ignition, while the peak temperature (880 °C) was reached after 9 min. Temperature gradients show a rapid increase during the first 5 min (136 °C/min), moderate increase during the next 4 min (43 °C/min), and slow decrease for the next 9 min (25 °C/min). After 12 min, all boulders of all formations were cracked or completely shattered. The behaviour of carbonate rocks upon heating was studied to identify the erosive effects of fire, namely the formation of new cracks and matrix deterioration.

Keywords: wildfires; mechanical weathering; exfoliation; rock breakdown; thermal shock; carbonate rocks; limestone

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1. Introduction

Fire is a significant driver of rock decay among physical weathering agents that has often been overlooked, specifically in fire-prone environments. However, the physical breakup and removal of rocks through mechanical weathering following a fire is a primary process that denudes and shapes mountainous regions. Accelerated physical weathering following wildfires may also play a significant role in the development of inselbergs and flared slopes in otherwise flat terrains [1].

Early fieldworks described the effects of fire on rock decay [2,3], followed by a series of laboratory simulations on rock burnings [4,5]. Yet, most existing evidence is based on sporadic field observations [6,7] and generally lacks systematic data collection and analyses [8].

The effect of heat on the mechanical properties of rocks poses great significance to weathering, mainly via the following processes: (a) high thermal gradient: under the influence of high temperatures, micro-cracks form in the transition between the hot and cold material, which leads to a gradual weakening of rock strength. Under rapid heating and extreme temperatures (>2000 °C), thin flakes usually form, whilst under lower temperatures and longer heating durations, cracks form deep in the rock material [9]. Consequently, the direct impact of the high temperatures produced by fire is evident in the form of shattering, spalling, and exfoliation [2,3,7,10–12]; (b) expansion of minerals: different minerals have varying coefficients of thermal expansion. Therefore, rocks composed of several minerals experience inner stress resulting from differential responses to heating and cooling cycles [13]; (c) vaporization of pore fluids: rocks may contain trapped water in their pores.

When wet rocks heat up, the trapped air and water expand very quickly and forcefully break the rock apart, sometimes causing it to explode [14]; (d) breakdown of minerals: namely, clay minerals and iron hydroxides that contain water in their crystal structure may contract when the water is released by heating [15,16]. Accordingly, the mineral composition, pore fluids, and conductivity of rocks are important factors controlling the impact of heat [17].

Heat can produce two types of micro-cracks in the rock matrix: cycling and thermal-gradient-induced cracks. The first form is due to varying thermal expansion coefficients of adjacent minerals in a homogeneous temperature field. The latter results from thermal stress caused by the temperature gradients exceeding the local grain strength [18]. Fire-induced cracks appear in nearly all rock types [2]. Early laboratory experiments conducted by [19] indicated that all granitoids exhibit a severe loss of strength when heated to 500 °C and 750 °C. However, the impact of heat was exceedingly varied, subject to the texture, micro-cracks, and porosity of the rocks. Additional study on the mechanical behaviour of granite [20] revealed that the modulus of elasticity decreased with increasing temperatures, and that the reduction rate was most significant when the temperature increased from 500 °C to 600 °C. The modulus of elasticity for the samples heated to 600 °C was 0.37 times that of the samples heated to 105 °C.

Furthermore, the crack network expanded with the rise in temperature, causing increased porosity and permeability, decreased longitudinal wave velocity, uniaxial compressive strength, and modulus of elasticity. At temperatures higher than 500 °C, the rock samples exhibited more significant damage, probably due to the transformation of quartz at 573 °C [21].

In contrast to polymictic rocks, carbonate rocks are mainly monomineralic. Thus, thermal cracking develops primarily due to internal stress concentrations, resulting from anisotropic thermal expansion of the calcite [22]. In a different study [23], a lower temperature of 200 °C was sufficient to produce intercrystalline cracks in crystalline limestones. Limestones are particularly susceptible to fire-induced weathering due to the thermal degradation of organics, the expulsion of water in inclusions (which can occur at 100–105 °C), and the conversion of aragonite to calcite [24]. Another study [25] determined the density of the cracks by utilising microscopic analysis in limestone and marble heated up to 600 °C. The results indicated a correlation between new fractures, increased open porosity, and crack density for both investigated rocks. Random orientation of the calcites contributes to the high thermal stress in the rock [22]. Given the temperature level, the rate of expansion increases and thermal cracking may occur between neighbouring grains and/or within grains; elevated temperatures lead to expansion along the crystallographic c-direction and contraction along the perpendicular to c-direction [26]. Other parameters affected by high temperature are structural: granularity can amplify differential expansions, porosity, and cracks, leaving free space for expansion at low temperatures [22].

Wildfire is a common, widespread disturbance known to affect Mediterranean ecosystems significantly. However, while most of the scientific effort has predominantly focused on fire effects on vegetation and soils [27,28], the role of fire as an essential weathering agent has been largely overlooked.

This study aims to evaluate the rock decay processes during wildfires in relation to ground temperatures and rock morphologies, namely over partially buried rock surfaces or over totally exposed boulders. Rates of fire-induced erosion are largely controlled by the combined impacts of the fire regime and the prevalent lithology. Rock type, pre-fire petrographic condition, and fire temperatures control the thickness of spalls, whilst the intensity and duration of fires determine the surface area spalled [1]. Fire recurrence intervals are largely controlled by climatic and vegetation regimes. However, as the long-term recurrence interval of wildfires is poorly documented, the rates of fire-induced rock erosion might be erroneous. Thus, research is needed to better understand the process and impact of fire on rock weathering.

2. Materials and Methods

2.1. Study Area

Mt. Carmel is part of the mountainous backbone of Israel, extending over 230 km^2 and rising to an elevation of 546 m a.s.l. It comprises marine carbonate rocks deposited on the Tethys sea platform during the Mesozoic era (Figure 1). These sediments generally consist of limestone, dolomite, chalk, and chert. Facies changes are common and result from the proximity of the area to the platform edge during the Albian to Cenomanian and Turonian stages [29]. The lower part of the sequence is composed of the stratified dolomites of the Yagur formation, which accumulated under shallow platform conditions and was bordered by a narrow belt of barrier reefs on its western side. The dolomite rocks are greyish-brown, primarily fine-grained, exhibiting laminar, platy, or massive structures, and containing sparse faunal remnants [30]. This formation is overlain by the "Main Chalk Complex" (Isfya and Arqan formations). These formations are well developed in northern Mount Carmel and are represented by chalk and limestone, commonly containing nodules of chert, which reflect open, and in some places relatively deep, outer platform environments. Most chalks in Mt. Carmel are covered by "Nari crusts", hardpan/indurated calcrete, 1–2 m thick [31]. The successive Bina formation from the Turonian stage consists of uniform limestone at its southern part, whereas to the north and northeast, it is divided into two members, from bottom to top: (a) the Muhraqa member, which consists of biogenic limestone and dolomitic facies; (b) the Sumaq member, which is characterized by an alternation of limestone and marl beds, and also contains some rudist patch reefs [29].

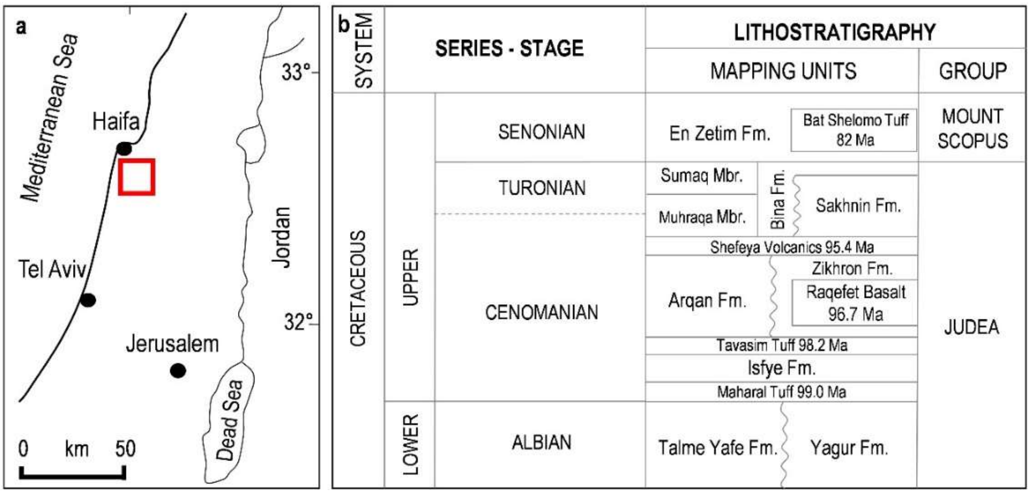

Figure 1. Study site. (**a**)—location map, red square marks Mt. Carmel; (**b**)—lithostratigraphy of Mt. Carmel and mapping units mentioned in the text (modified after [29]). Mbr: Member, Fm: Formation.

Field observations presented in the current study were conducted after the major forest fire that hit Mt. Carmel (35° E, 32° N) in 2010, consuming approximately 2500 hectares of Mediterranean forests and chaparral. Boulders used in the open fire experiment were collected in Mt. Carmel from the in situ outcrops of the geological formations presented above, in areas unburned for at least 70 years.

2.2. Methods

- Field observations were carried out on the carbonate slopes of Mt. Carmel during several campaigns over the last decade, from areas hit by high temperatures, where fire severity was considered "high" or "very high" [32]. The photos presented in Figures 2 and 3 were taken two days after the fire was extinguished, on 9 December 2010.

- Micromorphology using thin sections: small rock chips were mounted in epoxy, where the rock surface was normal to the cross-sectional surface. The surface of the fragment was marked, and the chip was polished to ~30 μm.
- An open fire experiment was conceptualized for this research, to determine the temperatures at which carbonate rocks shatter or spall. The experiment was set in an open fire environment. Fifteen boulders weighing between 1.5–3 kg, representing the carbonate formations burned in the Carmel (limestone of Muhraqa Fm., chalk of Sumaq Fm., and dolomite of Yagur Fm.), were placed on organic fuel beds, and the fire was ignited using a flamethrower. The combustible material consisted mainly of pine (*Pinus halepensis*) trunks, branches, and needles, resembling the natural vegetation typical to the Mt. Carmel environment. Surface temperatures were measured during the first 18 min until we observed that the burned boulders cracked or shattered. After the fire was completely extinguished, we manually removed the rock fragments and examined the consistency without applying external force. To measure and record the searing temperatures, we used a portable infrared thermometer (Minolta LAND; CYCLOPS 300bAF). This instrument is a general-purpose, high-precision tool designed for accurate measurements of temperatures from −50 to 1000 °C. Accurate sighting is ensured by the clear, wide angle (8°) field of view and small, clearly defined (1/3°) measurement. The precision reflex optical system thus permits the clearly defined measurement of high temperature targets as small as 4.8 mm at 1 m distance. We used the "average" mode for 5 s measurements.

Figure 2. Severe exfoliation of the partially buried rock surfaces: a series of expansion cracks and joints develop roughly parallel to the rock surface, evolving into a series of onion-skin-like sheets or slabs of rock separated by crudely curved, subparallel cracks.

Figure 3. Boulder response to high temperatures: (**a** + **b**) moderate size boulders (D < 0.5 m) completely disintegrate and shatter; (**c** + **d**) large boulders (D > 0.5) usually exfoliate and partially shatter.

3. Results

3.1. Effects of Natural Fires on Weathering on Carbonate Rocks

Following the severe wildfire that hit Mt. Carmel in December 2010, an extensive field campaign included field survey, mapping, and sampling. Field observations revealed massive destruction of the carbonate rocks, especially in areas hit by high temperatures, where fire severity was "high" or "very high". As the soil depths of Mt. Carmel's slopes are shallow and rock outcrop accounts for a large proportion of the slopes, rock masses underwent direct heating and thermal shock during the fire. Consequently, the bedrock surfaces were extensively covered with flakes and spalls, encompassing as much as 80–100% of the exposed rocks (Figure 2). The chalk formations exhibited the severest response with extreme exfoliation, occasionally forming an "onion skin" structure of flakes with one layer above the other, up to a depth of 20 cm. In addition, a series of expansion cracks and joints developed roughly parallel to the rock surface, emerging into a series of slabs of rock separated by crudely curved, subparallel cracks. In contrast, large boulders scattered over the slopes were both fractured and exfoliated, while smaller boulders (D < 0.5 m) were shattered and disintegrated (Figure 3).

3.2. Experimental Open Fire to Simulate Weathering of Carbonate Rocks

While a detailed description of the exfoliation phenomenon over the bedrock outcrops during the 2010 fire was previously reported, here, we conducted an experimental open fire to determine the temperature and gradients responsible for boulder shattering. Figure 4 presents the course of the temperatures and the calculated gradients per minute. Our results show a rapid increase in fire energy within the first 2 min after ignition that caused ground temperatures of 400 °C; after 5 min from the ignition, the recorded temperature reached ~700 °C; the peak temperature (880 °C) was reached after 9 min, which persisted for a short duration (1–2 min). Thus, the graph in Figure 4 is likened to the course of a natural wildfire, where the temperature gradient climbs rapidly at first due to the available fuel, peaks, and slowly descends. Similarly, we measured a rapid temperature increase in the first 5 min (136 °C/min.), followed by a moderate increase for the next 4 min (43 °C/min) which eventually slowly descended for the next 8 min (25 °C/min). The fire was entirely extinguished, after several hours.

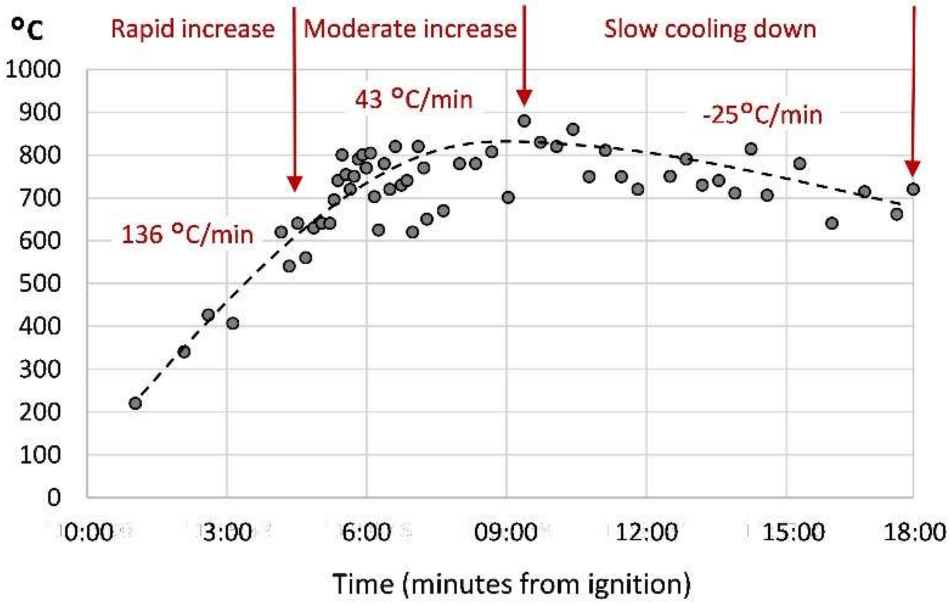

Figure 4. Ground temperatures during the burning experiment. At 2 min from the ignition, the temperature was 400 °C; 5 min from the ignition, the recorded temperature reached ~700 °C; peak temperature (880 °C) was reached after 9 min, following which temperatures started to reduce. Temperature gradients calculated per minute (°C/min) in red.

As the flames ceased (ca. 12 min from ignition), we observed the boulders of all formations were already shattered (Figure 5): The boulders of the Yagur formation cracked and completely disintegrated (Figure 5b). In contrast, the boulders of Muhraqa limestone only partially disintegrated (Figure 5d). The two chalk boulders of the Sumaq formation did not disintegrate but cracked and turned greyish. While applying moderate pressure by hand, one of the chalk boulders disintegrated and pulverized (Figure 5f).

Detailed examination of photomicrographs of the burned rocks (Figure 6a,b), reveal the impact of organic material covering the rock surface. Charred microbiotic crusts covered the surface or passed through micro-fissures, populating pores, voids, and fissures that developed parallel to the surface at a depth of 0.5–1 mm or more. These fissures and micro-cracks accelerated the weathering process.

In many other cases, laminated fissures were observed parallel and subparallel to the surface, occasionally filled with recrystallized sparitic calcite (Figure 6c,d). These cracks and fissures are especially characteristic of chalk and calcretized surfaces, but less abundant in limestone and dolomite. Their presence promoted the flaking process during the fire, as the flakes were detached from the bedrock along the calcrete laminae that served as planes of weakness in the rock.

Along with the presence of initial porosity, fissures, and burned organic materials, weathering is primarily affected by the petrographic characteristics of the rocks. In detritic or biochemical rocks where grains, calcareous plankton fossils, and other remains accumulate along with crystal growth (as in the case of chalk), the presence of matrix may cause a dampening effect of particle dilatations, especially mineral crystal (Figure 7a). However, in massive rocks, such as dolomite or crystalline limestone, high density of the crystals increases the efforts between them as they dilate, forming both intercrystalline and intracrystalline cracks (Figure 7b). In fissured, massive rocks, this process is enhanced by thermal shock and fissure dilatation (Figure 7c).

Figure 5. The boulder conditions "before and after" the open fire (where the temperature reached up to 880 °C); the dolomite boulders completely shattered, while limestone and chalk boulders cracked but only partially broke down.

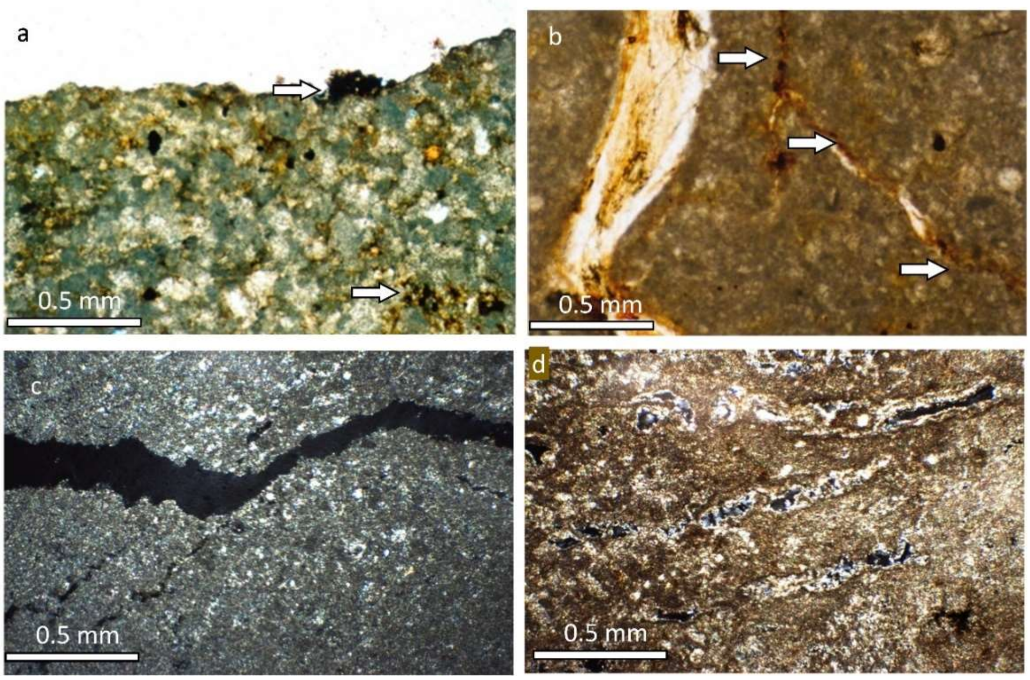

Figure 6. Thin sections of severely burned spalls. (**a**) Weathered chalk surface with charcoal particles attached to the surface, and colonies of endolithic green algae at a depth of 0.5 mm (white arrow); (**b**) weathered chalk with charcoal particles penetrating micro-cracks and roots (white arrows); (**c**,**d**) fissures in chalk, enlarged by the heat, parallel, and subparallel to the rock surface.

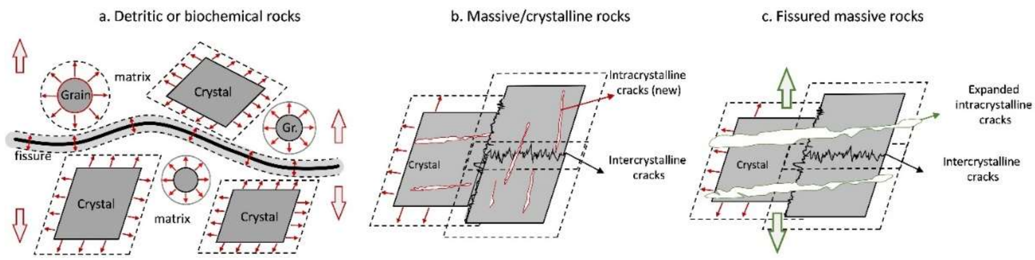

Figure 7. Thermal expansion effects in detritic and massive rocks, enhanced by micro-fissures (modified after [33]). Arrows indicate the direction of particles movement.

4. Discussion and Conclusions

4.1. The Influence of Fires on Rock Weathering

Despite the global increase in fire activity, the well-established knowledge on fire effects mainly targets vegetation dynamics and soil-related processes. In contrast, there has been relatively little research on the role that fire plays in rock weathering. Numerous studies have examined the impact of temperature on rocks by using laboratory heating and cooling cycles, mainly to assess the basic properties of materials suitable for construction and infrastructures [34–37]. Additional information on the fire-related behaviour of carbonate rock is available from archaeological sites [38,39]. However, most previous studies have almost exclusively focused on "insolation weathering", a process caused by thermal stress fatigue and repeated thermal expansion and contraction under natural conditions, due to diurnal temperature changes.

To better understand the effects of a short-lived rise in temperatures on carbonate rocks, the methodological approach taken in this study was a mixed methodology based on post-fire surveys and open fire experiments. We considered two rock morphologies: boulders of varying sizes deposited loosely on the hillslope, and bare exposures of carbonate outcrops (Figure 8). The rock outcrops are typically partially buried beneath the soil and only the superficial layer is exposed. In contrast, the boulders are intact and exposed to the ambient temperature in most of their surface area. All rock samples considered in this experiment were taken from areas of similar lithology, that is, limestone, dolomite and chalk.

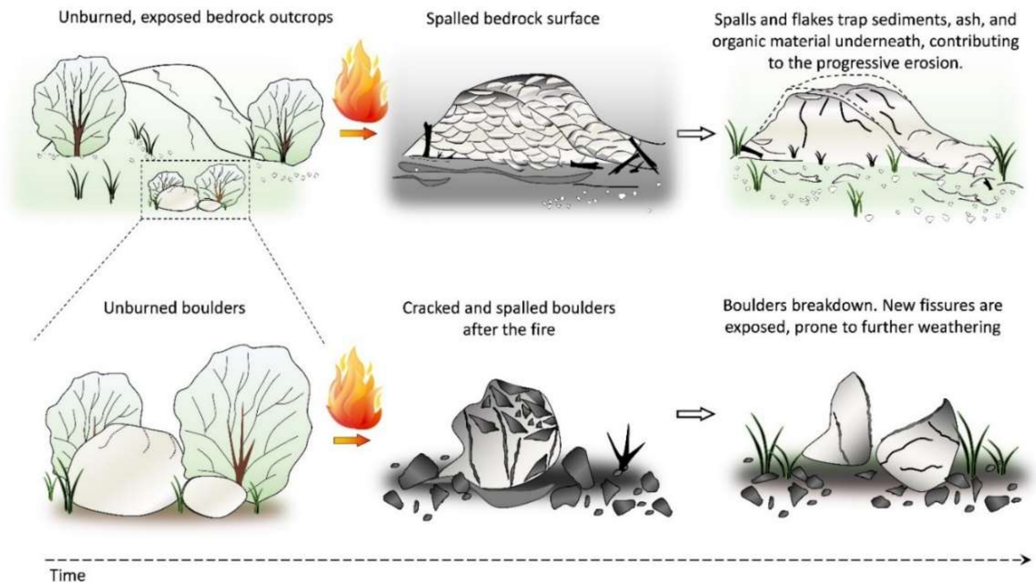

Figure 8. Schematic model of carbonate rock disintegration following forest fires over exposed bedrock outcrops and over detached boulders.

The results indicate two distinctive fire-related weathering patterns given the level of rock exposure: spalling and exfoliation over the exposed bedrock, which is typically partly covered and protected by soil, and disintegration and breakdown, as in the case of scattered boulders. Notwithstanding, for all studied cases, a single peak of maximum temperature of 880 °C, which lasted for no more than 2 min, was sufficient to trigger prominent rock disintegration.

4.2. The Mechanisms Responsible for Fire-Induced Mechanical Weathering

The cracking and detachment of small rock pieces from exposed surfaces are essential erosional processes operating across various rock types and climatic settings, having far-reaching consequences on soil-related processes. Thus, understanding the precise mechanisms responsible for fire-induced mechanical weathering helps to assess long-term erosion rates and landscape evolution. When exposed to high temperatures (>400 °C), various minerals, such as illite, kaolinite, magnesium illite, and calcium montmorillonite, start to decompose and break down [40]. At higher temperatures (>600 °C), some metallic bonds, such as Ca-O, break, and parts of the minerals melt or decompose, leading to enhanced wearying of the rock material (e.g., calcium carbonate and calcium montmorillonite) [41]. Excessive heat may also provoke volume changes; for example, at 573 °C, the quartz rearranges the silicon/oxygen atoms and transforms from α phase to β phase with a volume increase of 2.7%. Such change can trigger considerable thermal stress between the minerals [42].

4.3. Influence of Fire on Rock Weathering within the Soil Profile

During a fire, soil temperatures vary temporally and across the soil profile. However, given the typically low soil thermal conductivity, the high temperature at the soil surface sharply declines with depth [43]. Thus, the effect of fire is most profound at the upper layer. Soil surface temperatures during fire typically range between 200 and 700 °C [44], although extreme surface temperatures of 1150 °C have been reported [45]. Additionally, a maximum temperature of 850 °C at the soil–litter interface has been suggested [46]. A similar peak temperature was empirically obtained during an experimental fire in Portugal [47]. While the mean observed flame temperature reached 735 °C, the average soil temperatures were much lower: 104 °C at the soil surface, 27 °C at 1 cm, and 13 °C at 3 cm depth. During prescribed fires of sand pine scrub in Florida, surface and profile soil temperature were measured. The results showed that soil surface temperatures increased to extremely high (>628 °C) and brief maxima (<2 min), producing various combinations of temperatures and temperature durations [48]. In contrast, maximum temperatures at the 2 cm depth were less than 300 °C and persisted for a longer duration. Soil temperatures responded very slowly to the heat of the flames, especially at greater depths. In a fire experiment following the traditional practice of slash-and-burn, surface soil fire temperature measurements ranged from 355 to 660 °C [49]. Temperatures fell abruptly at 2 cm and were slightly above 56 °C. As noted previously [50]), the highest surface temperatures persisted for a few seconds.

Fire temperature at the soil surface is often moderate, even under intensive fires. However, it might briefly reach extreme temperatures (>800 °C), exceeding the breakdown thresholds of diagnostic assemblages in the carbonate rocks. Given the different alignments, the surface of the outcrop tends to develop thin flakes and spalls due to the thermal gradient between the hot rock surface and the inner (cooler) buried material. On the other hand, the boulders are exposed to sudden and abrupt thermal shock, which produces cracks due to rapid component temperature change. The experimental results, coupled with field-based evidence, indicate that a single and short peak temperature during severe fire might lead to substantial cracking and disintegration of the exposed rocks. In addition to the immediate short-term effects, lower temperatures may generate micro-fractures, initiating progressive weakening of the rock mass due to the accumulation of dust and ash [51]. The detachment of thin flakes from exposed rock surfaces is an essential erosional process operating across a range of rock types and climatic settings (Figure 8). The results show that fire-induced thermal shock can have a rock-type-specific effect on physical weathering rates and longevity.

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