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Surface Mechanical Effects of Wildfires on Rocks in Climbing Areas

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Abstract: Wildfires are widely recognized as a cause of mechanical damage to rocks. Nevertheless, previous research has neglected how wildfires might impact sport climbing areas. In Spain, two large wildfires affected two climbing areas between 2020 and 2021. This paper addresses the rock mechanical effects of wildfires that could lead to safety issues, such as rock falls, climbing hold deterioration, and climbing anchor damage. In this study, the Non-Destructive Techniques (NDTs) of Ultrasonic Pulse Velocity (UPV) and Schmidt Hammer (SH) were used, and two types of measurements were carried out: randomized grid measurements and measurements along the climbing routes. Two phenomena were recognized: (a) thermal breakdown and (b) mineralogical changes. The results of using the SH show a relationship between the decrease in the rebound value and the observed mechanical damage. Field observations showed mechanical weathering, such as cracking, spalling, granular disaggregation, and thermochemical weathering with different temperature thresholds. Observed thermochemical reactions included reddening, $CaCO_3$ calcination, rock decomposition, and quartz cracking. The set of changes involves a major rock outcrop transformation and an acceleration of fire-induced weathering processes. Both areas exhibited more effects at the bottom of the wall. Furthermore, in this paper, we explore how iconic climbing routes can be considered a form of cultural heritage and the consequences of their loss.

Keywords: wildfires; rock weathering; hazards; risk perception; rock hardness; ultrasound pulse velocity; sport climbing

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1. Introduction

Wildfires are among the most common causes of catastrophic damage to rock outcrops as well as rock-made structures and assets [1]. The effects of fire are particularly important in the Mediterranean region, where summers are characterized by high temperatures and long droughts [2], and wildfires are expected to increase in frequency in future scenarios of climate emergency. In particular, in Europe, Spain and Portugal are the regions that have, increasingly, more fires and burned surface [3,4]. Structures and assets located in rural and secluded areas, where firefighting is more difficult, are especially prone to fire damage.

Previous studies have shown extensively how fire promotes both short- and long-term mechanical rock damage, particularly in competent lithotypes, in which thermal expansion mismatch enhances cracking because of temperature increase [5–8]. Most of these references come from the cultural heritage studies context and, although recent press reports in specialist journals of the climbing community have echoed the visible damage observed in some iconic climbing areas because of wildfires [9], there are, to the authors' knowledge, no scientific references to evaluations of the mechanical damage caused by fires on climbing areas.

Spain is widely recognized as one of the world's premier sport climbing destinations [10]. Many professional as well as amateur and recreational climbers every year choose some of the world-class climbing areas across Spain as top destinations. One of the preferred areas of this "pilgrimage" of professional climbers is the Spanish side of the Pyrenees, where the highest concentration of hard climbs in the world is located. Climbing difficulty is measured in different scales, with the Yosemite Decimal System (YDS) being the most common scale in the US. The French system is the main system used in European countries and in many international events outside the US. The so-called "French system" grades difficulty from 1 (Easy) to 9c (Hard). The hardest grades (9a and above) are very difficult to find worldwide because only a few climbers can climb these routes and, consequently, they are the ones who find and design these routes. The Southern Pyrenees has more than 80 climbs rated 9a (YDS equivalent 5.14d) or harder. The 9b+ grade route nicknamed "La Dura Dura" (Spanish term for Hard Hard) in Oliana, one of the study sites in this paper, constitutes the most iconic example of this difficulty. This route is considered one of the hardest in the world, and represents the highest difficulty achieved by professional climbers (accomplished in 2013 by Adam Ondra, Figure 1a).

Figure 1. Photographs of selected climbing areas with recent wildfires: (**a**) Oliana site (Catalonia region), with the iconic route La Dura Dura, the first 9b+ in the world achieved by world-class Czech climber Adam Ondra (Image by Bernardo Giménez); (**b**) forested area of Cadalso de los Vidrios (Madrid region) near Madrid city.

There are many other climbing areas that appeal to amateur climbers. For example, southern areas of Spain attract large amounts of amateur climbing tourism due to the warm weather in winter months. All in all, there are more than 85,000 routes throughout the country [11], more than 750 climbing clubs across Spain [12], and around 273,000 federated climbers in addition to the many more who do not belong to a mountain club.

Spain is one of the countries with the most climbing areas in the world, with around 1200 climbing sites across the country [13]. Each climbing site commonly constitutes one or more climbing areas (namely crags). Each of these crags will contain several routes. Bedrock outcrops with climbing routes are usually located in mountain forested areas that are particularly sensitive to wildfires. In addition to the above-mentioned climatic factors, the increase in population density in certain areas and the change in land use have been linked to sudden changes in fire frequency, intensity, and burned area size [14] and to an increase in intentional fires [15].

There is an increasingly large number of burned climbing crags because of the increasing frequency of fires factored by the high density of climbing areas (Figure 2). In addition, in Mediterranean Europe the increase in fires and fire frequency has been noted [15,16]. As mentioned above, the high temperatures attained during fires can cause mechanical rock damage and, therefore, endanger the stability of climbing routes, and the data displayed in Figure 2 estimate that at least 6.5% of climbing areas have been affected by fires in Spain in the last two decades. However, neither the effects of fires on bedrock outcrops nor the effects of potential hazards for climbers have been studied. Despite the large numbers of fires, most of the effects are unknown and there are only a few references to burned crags in climbing magazines when they have occurred in very iconic areas, such as in the case of the Oliana fire. Furthermore, there are only a few mentions of fires affecting outdoor sport and recreational activities in natural environments [17–19].

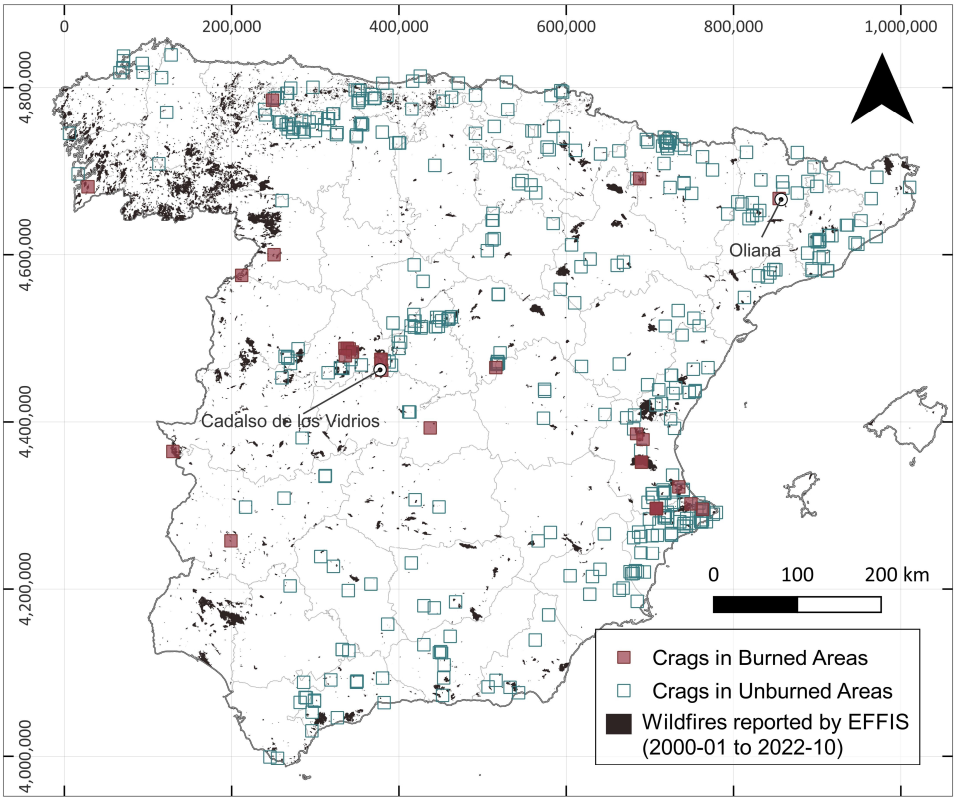

Figure 2. Wildfires reported by the European Forest Fire Information System (EFFIS) during the period 2000–2022 and the climbing areas in Spain. The red circles show the distribution of burned climbing areas in the last two decades.

One of the main recognized short-term effects of fire on competent materials is the loss of strength. Non-Destructive Techniques (NDTs) developed in the field of architecture and civil engineering for assessing the material strength of concrete have been extensively applied to stone buildings (e.g., [20,21]) and rock outcrops (e.g., [22,23]) to assess the mechanical strength of rocks. As well as being non-destructive, which is an advantage when working with materials and structures in need of protection, they allow the characterization of large areas without the need for sampling and they can be used on-site, as most of them are portable.

This paper aims to quantify the loss of mechanical strength and the surface mechanical effects of wildfires on several climbing areas (Figure 1) that could lead to safety issues, such as rockfalls, climbing hold deterioration, and climbing anchor (bolts) damage. To do so, we used the above-mentioned portable NDTs, as subvertical, or overhanging, walls are only accessible with climbing apparel. In addition, in this paper, we explore how iconic climbing routes can be considered a form of cultural heritage and the consequences of their loss.

2. Study Areas

We selected two climbing areas that are destinations for different types of climbers (Figure 3): (1) the Oliana site (Catalonia), which is a prime destination for world-class climbers and, therefore, can be deemed true "climbing cultural heritage", an iconic route that is one of the hardest climbs in the world. The limestone and sandstone Oliana crag was extensively affected by a fire in 2022. Due to the international importance of Oliana, the fire and its effect on the crag had great repercussion in the specialized media (e.g., [24–27]). (2) the Cadalso de los Vidrios site, which is arranged as several granite crags within the highly populated (over 6.5 million inhabitants) Madrid region and is, therefore, often crowded with local climbers. This example of a "mass climbing" site under a lot of pressure was affected in 2019 by one of the most devastating fires in the Madrid area in recent decades.

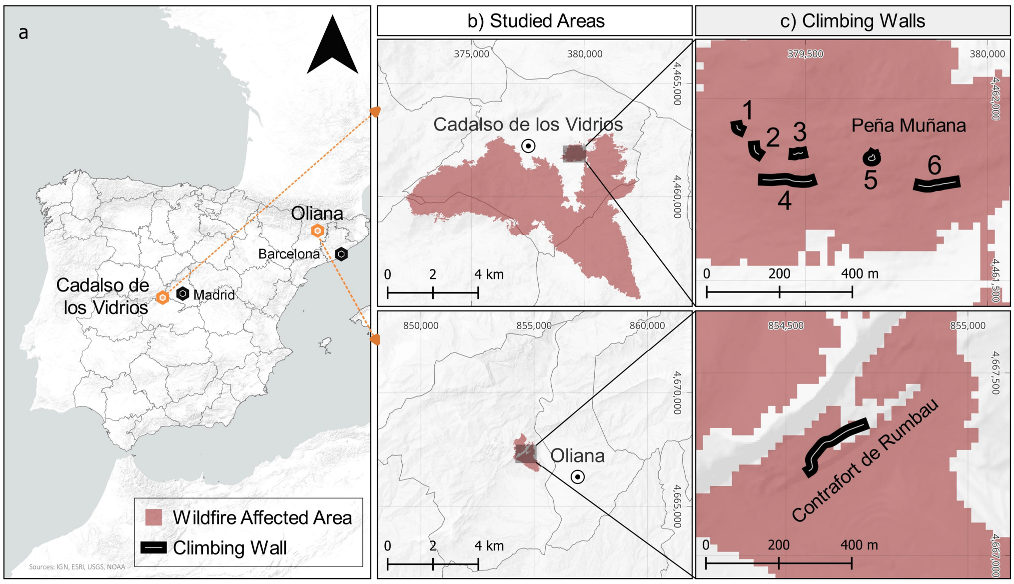

Figure 3. Location of the studied areas: (**a**) general situation map; (**b**) studied areas—Oliana (**top**) and Cadalso de los Vidrios (**bottom**); (**c**) climbing walls (bold black line). The numbers in the Cadalso area indicate six different climbing sectors.

2.1. Oliana Climbing Site

The climbing area of Oliana is popularly known as "Contrafort de Rumbau" and located in the Sierra de Aubenc, 2.5 km north of Oliana village, within the Lerida province (Figure 3). It is part of the Oliana anticline, listed as a Site of Geological Interest in the Spanish National Inventory of Sites of Geological Interest [28]. This wild area contains endemic flora and fauna and a scenic landscape. Consequently, it is listed as a Special Area of Conservation (SAC) and a Special Protection Area (SPA) within the Natura 2000 network [29]. The landscape is Mediterranean calcareous steep relief with NE–SW trending. The climate zone features short-hot summers and dry-cold winters [30]. The annual temperature oscillates between −1 and 29 °C, with an average value of 12.5 °C. The average annual accumulated rainfall is 415 mm.

The climbing area is a rock massif divided into two overlapped walls. The sport climbing routes are placed in the lower wall (located between 700 and 750 m a.s.l.). The upper wall has classical climbing routes with self-protection, and it is located at 950 m a.s.l. There is a hillside from the bottom of the wall to the Segre River (450 m a.s.l.).

The lithology present at the climbing wall is Upper Eocene fine-grained sandstone, conglomerate, and bioturbated ocher silts, located in the north flank of the Oliana anticline (Unit 7, Figure 4a) [31,32]. The conglomerate includes clasts of Mesozoic bioclastic limestone with a sandy matrix. Upwards of Unit 7 appears the conglomerate Unit 8 (Figure 4a), which corresponds to the classic self-protection climbing zone and the peak of Sierra de Aubenc. The stratigraphy of the sandstone and conglomerate (Unit 7) show layers of 50 m thickness, dipping approximately 50 °N. Tectonic thrusting faults appear in the north flank of the Oliana anticline, affecting Oligocene sediments.

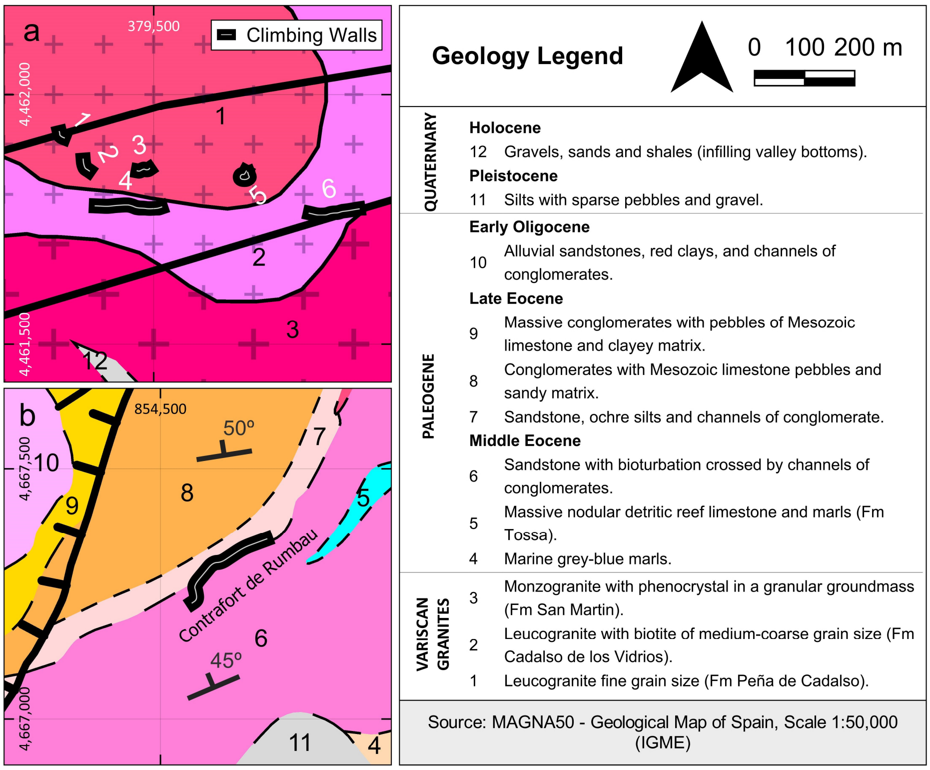

Figure 4. Geological maps of the studied sites: (**a**) Oliana; (**b**) Cadalso de los Vidrios. See text for further explanation.

2.2. Cadalso de los Vidrios Climbing Site

The climbing zone of Cadalso de los Vidrios is located in Peña Muñana Hill (Figure 3), 75 km away from the city of Madrid and westward of the Madrid province. This hill is an inselberg listed as a Site of Geological Interest in the Spanish National Inventory of Sites of Geological Interest [28]. This zone is a Natura 2000 SAC and SPA like the Oliana area [33]. The topographic difference between the foot and the peak of the hill is 244 m (800–1044 m a.s.l.). The climate is warm Mediterranean, with short-dry summers and cold winters. The temperature varies between 0 and 32 °C with a minimum of about −5 °C and a maximum up to 36 °C. The average temperature is 14 °C. The annual accumulated rain is about 600 mm [30].

The landform shows a ramp-like relief with agriculture farms in the lowlands. The landscape of Pinar del Concejo, cataloged as a Public Interest Mountain, is owned and managed by the Cadalso municipality [33].

The climbing area is located between the S and SW sides of the hill, between 800 and 920 m a.s.l., and has more than 100 climbing routes. The geology of the climbing wall shows two different lithologies [34]: (1) leucogranite fine grain (Unit 1, Fm Peña de Cadalso, Figure 4b) and (2) leucogranite with biotite, coarse–medium grain (Unit 2, Figure 4b). Both lithologies comprise a granite stock of 5 km in diameter, eastward of the village of Cadalso de los Vidrios. Unit 1 granite is porphyritic fine-grained granite, is highly resistant to erosion and appears at the top of the pluton. Peña de Cadalso appears as an inselberg. Granite Unit 2 is the most prevalent of granitic pluton, showing "hogback" morphologies. Unit 2 is equigranular, with abundant biotite. Both granites consist of quartz, K-feldspar, plagioclase, and biotite. Both units are densely fractured.

The Cadalso climbing zone is surrounded by monzogranite (Unit 3, Figure 4b, geological map, Fm San Martin). It is composed of gray coarse–medium grain granitoid. Similar to Units 1 and 2, the mineralogy is quartz, K-feldspar, plagioclase, and biotite but it shows phenocrysts of quartz with aggregates of biotite of millimetric size. This unit shows landscapes of low relief with sandy covering, isolated granite boulders, and boulder-strewn inselbergs or nubbins. This unit is affected by the intrusion of the stock (Unit 1 and Unit 2).

Most of the climbing routes are located on granite Unit 2 [34]. There are quarries of this lithology in the surrounding area, with the rock called "Blanco Cristal" [35,36].

3. Wildfires at the Study Areas

The Oliana wildfire (Figure 3) started on Sunday 17 June 2022 at 14:32; it was stabilized the following day and was finally brought under control on 21 June. It was started by a combine harvester in a crop field and advanced in the direction of the climbing walls, spreading up the slope. The dryness of the terrain, the wind, and the high summer temperatures favored its spread. It was one of 239 forest and vegetation fires that broke out in just one week in Catalonia. It spread over very rugged terrain, which made it difficult to extinguish with land-based means. It affected a Site of Geological Interest and a Natura 200 Network area. It forced the temporary closure of the main road but did not affect the population and there were no evacuees. It only reached moderate–medium severity levels (Table 1). The burned vegetation in the climbing area was mostly sclerophyllous scrub. The forest is located on the hillside and was severely affected by the wildfire of 20 June 2022 (Figure 5). The vegetation of the forest is sub-Mediterranean conifer (Pinus nigra, Pinus albar), gall oaks (Quercus faginea and Q. pubescens), beech trees (Buxo fagetum), and Erinacea anthyllis.

The Cadalso de los Vidrios wildfire (Figure 3) started on 28 June 2019 at 17:30 due to human negligence and lasted for 11 days until it was extinguished on 9 July. It started in the town of Almorox (Toledo) and spread to the Madrid municipalities of Cadalso de los Vidrios, Cenicientos, and Rozas de Puerto Real (Figure 3). It involved the partial eviction of inhabitants. It burned mainly pastures, but also woodlands and scrublands and even affected some villages. At the time, there were winds in excess of 50 km/h and a heat wave of temperatures as high as 42 °C. It was the biggest wildfire of the century in the region. Two protected areas of the Natura 2000 Network [28] were affected. In the climbing areas, the vegetation affected was mainly conifers (Figure 5b). The vegetal cover is dominated by conifer (*Pinus pinaster*) and oaks (*Quercus ilex*) with broom brush (*Cytisus scoparius*).

The greatest severity of the fire was in the western area of the wildfire, although there were some islands that remained unburned, some of which included climbing areas (Figure 6). Therefore, the incidence was very uneven, covering areas with a burned severity (Normalized Burn Ratio, NBR) from high severity to unburned areas (Table 1).

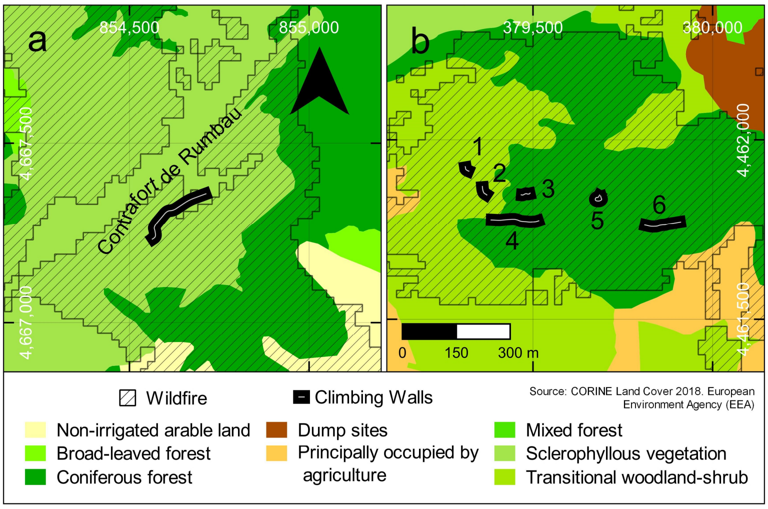

Figure 5. Land cover vegetation in Oliana (**a**) and Cadalso (**b**) partially burned by wildfires. Source: Adapted from [37].

Table 1. Burn severity levels obtained by calculating the differenced Normalized Burn Ratio (dNBR) proposed by the United States Geological Survey (USGS) ([38,39]).

	SEVERITY LEVEL			
	Low Severity	**Moderate–Low Severity**	**Moderate–High Severity**	**High Severity**
dNBR range	0.1–0.269	0.27–0.439	0.44–0.59	>0.66
Oliana	72.77 ha	21.89 ha	-	-
Cadalso	939.84 ha	100.62 ha	649.72 ha	25 ha

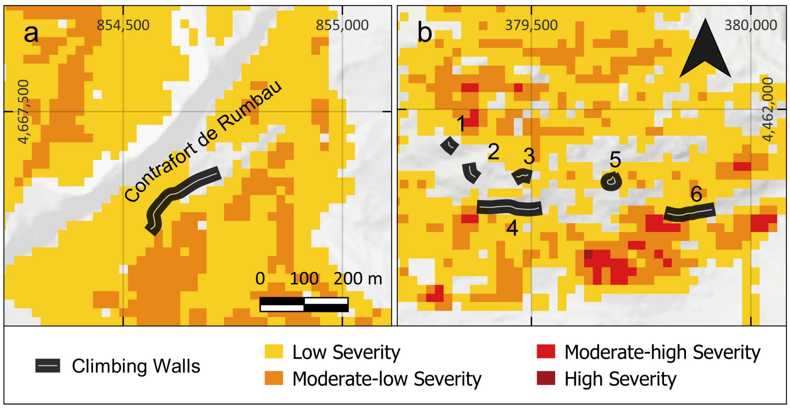

Figure 6. Maps of the dNBR of the (**a**) Oliana and (**b**) Cadalso wildfires.

A comparison of the two fires shows that the Cadalso fire was much larger, much more intense, and lasted much longer, affecting an area almost 20 times larger than the Oliana fire. It affected the climbing areas in a more heterogeneous way, showing a wide variety of damage. This was helped by the fact that there are several independent and separate sectors (Figure 6a). However, in the case of the Oliana fire, the damage was more homogeneous, as it was a continuous rock wall, although there were differences between the extremes (Figure 6b).

4. Materials and Methods

A visual inspection of both sites was made to identify and locate visible features associated with fire damage in the previous literature [40], such as reddening, scaling, spalling, and soot deposits.

Two techniques were used in this study to determine the mechanical strength of rock walls in the climbing areas: (1) the measurement of Ultrasonic Pulse Velocity (UPV) and (2) the use of a Schmidt Hammer (SH) to test how the impact resistance (rebound) of sedimentary rocks varies with the occurrence of fire. Both of these portable NDTs have been extensively used in weathering studies [27,41,42] as they show very good correlation with the Uniaxial Compressive Strength (UCS) of rocks.

Ultrasonic Pulse Velocity (UPV) is the generic name for compressional wave velocity. It is the most widely used ultrasonic parameter, as it can detect a reduction in rock strength even when no deterioration is visible at surface level. UPV is determined from the time spent by a compressional ultrasonic wave traveling a specific distance through a material. Proceq Pundit lab portable ultrasonic test equipment, with 54 kHz P-polarized transducers, was used. A viscoelastic solid couplant (plasticine) was used to ensure good coupling between the transducers and the rock. The distance between the centers of the transducers was kept at a constant distance of 15 cm.

Measurements were made using the indirect mode of transmission (i.e., where transducers are placed on the same surface, as described by [43]), as measuring the climbing walls using the direct mode of transmission (i.e., where transducers are placed on opposed parallel faces of a cut sample) was not applicable.

The Schmidt Hammer (SH) measures the rebound of a spring-loaded mass impacting with a defined energy against a surface, which gives a non-dimensional number that is directly related to UCS. In this case, a Proceq L Schmidt Hammer (0.735 Nm impact energy) was used to perform the tests.

Although both techniques have a direct relationship to UCS, they are sensitive to different rock parameters. For example, UPV gives more information than the SH on widespread rock discontinuities. This is because UPV is influenced by a larger mass of rock than the SH rebound number and, therefore, UPV gives information on larger discontinuities, crossing the path of ultrasound pulses between emitter and receiver [44].

Two types of UPV and SH measurements were made in both studied areas. Firstly, a randomized grid of 10 measurements in 11 stations every 10 m (Oliana) and 1 station in Cadalso in every crag due to the spatial limitations at the bottom of the climbing walls was used to identify whether there was reddening, soot deposits, spalled rock, or apparently fresh rock. In the crags with sufficient width, we measured every 10 m.

Secondly, measurements along the climbing routes were performed. Proper climbing gear (ropes, harnesses, helmets, and ascenders) was needed for data acquisition at the higher points of these vertical walls. This affected which and how many routes could be measured: 3 routes at the Cadalso site and 3 routes at the Oliana site. Routes with noticeable impacts caused by the fire were selected. However, highly damaged routes had to be avoided at Oliana due to the danger posed by rockfalls of flakes and fire-induced spalling. Nevertheless, the “La Dura Dura” route was included because of its international relevance for being one of the hardest climbs in the world.

Four measurements were taken around each of the bolts on the climbing routes (15 m height at Cadalso and 10 m height at Oliana).

For the anchor test, we use the standardized “Hydrajaws Model 2050 Fixing Tester” equipment, performing the test at 5–8 kN (following the standard regulations of the European Union, UNE-EN 959:2021) to avoid material fatigue. The tester works by applying a maximum tensile load of up to 50 kN to the climbing bolts mechanically, and hydraulics are used to register the load through a digital gauge. The bolts are located directly in the tester to validate the correct installation of existing fixings. All analyses were performed on bolt anchors.

Regarding the extent of the area affected by the wildfire, Sentinel-2 was used as the remote sensing platform (corrected with Sen2Cor v2.10, European Space Agency, Paris, France), with images from before and after each fire used for the delimitation of the fire’s extent and severity, for calculating the dNBR index, and following the classification used by the United States Geological Survey [45].

5. Results

The results obtained from the field and the lab work are summarized below, in the sections on the mechanical effects in rocks affected by wildfires from NDTs applied on climbing routes and the impacts on climbing and other associated hazards.

5.1. Mechanical Effects of Wildfires on Climbing Areas

5.1.1. Surface Changes in Bedrock Outcrops Affecting Climbing Routes

There are two main phenomena associated with wildfires that can cause damage to rock outcrops: (a) temperature increase causing thermal breakdown, and (b) mineralogical changes. In addition, fumes containing tar, oils, and ash create a surface soot deposit that clogs the pores of the rock. Table 2 summarizes the field observations of a wide variety of fire effects on rock outcrops that generate noticeable changes in the rocks of both studied climbing areas.

Table 2. Summary of effects of wildfires in the two studied climbing areas.

Effects of Wildfires on Rock Surface Properties	Oliana	Cadalso de los Vidrios
Discoloration	low?	moderate
Extinction-related spalling	low?	moderate
Thermal spalling	high	low
Microcracks	?	moderate
Partial calcination of calcite	moderate	n.a. [1]
Soot surface deposits	moderate	moderate–high

[1] n.a.: not applicable.

In Oliana (Figure 7), the lithology affected by the wildfire is sandstone with calcite cement and a conglomerate with limestone clasts. The wildfire affected the occidental and oriental borders (EM1–EM4 and EM10–EM11, respectively), of Contrafort de Rumbau. Both areas were in direct contact with the fire front, due to their proximity to a very dense forest mass. The central part of the climbing wall (EM5–EM9) is separated from the forest, and therefore the fire affected it less. The lithology of the occidental wall is sandstone, whereas the oriental wall is a clast-supported conglomerate with heterometric and polygenic medium-sized clasts.

The wildfire effect observed on the climbing wall is the fall-out of thin slabs, arranged as great patches of metric size in some sectors of the wall. Spall scars show clean and fresh areas, easily observable and different from the dark burned areas without detached slabs. The thickness of the spalling oscillates between 2 and 20 mm, with 5 mm on average (Table 3). The spall size ranges from 5×10^{-3} to more than 0.5 m^2. The lower part of the climbing wall has been affected by the wildfire, where it is impossible to identify the spall sizes. The effect of the wildfire is lower in the upper part of the climbing routes (Table 4).

Table 3. Thermal spall thickness (mm) in areas affected by the wildfire.

Statistics	Oliana (EM1-EM5)	Oliana (EM9-EM11)	Cadalso de los Vidrios
Mean	13.7	9.9	7.8
Standard Deviation	16.3	10.3	3.9
Median	7.8	8.4	7.2
Mode	6.2	4.6	5.2

Table 4. Area (%) affected by spalling in climbing areas.

Climbing Area and Site	Effect of Wildfire (1)	Bottom Part of the Wall	Middle Part of the Wall	Top Part of the Wall
Oliana				
EM1-EM4	R/B/S	70–100	30–70	0–30
EM5-EM9	U	0	0	n.f.
EM10-EM11	B/S	70–100	n.f.	n.f.
Cadalso				
Site 1	U/R	0	0	0
Site 2	U	0	0	0
Site 3	PB	0	0	0
Site 4	PB/R/S	0–30	0	0
Site 5	PB/R	0–30	0	0
Site 6 left	B/S	30–70	0–30	0–30
Site 6 center	R/B	0–30	0	0
Site 6 right	R/B	0–30	0	0

(1): R: reddened, B: blackened, S: spalled, U: unburned, PB: partially burned. N.f.: not found.

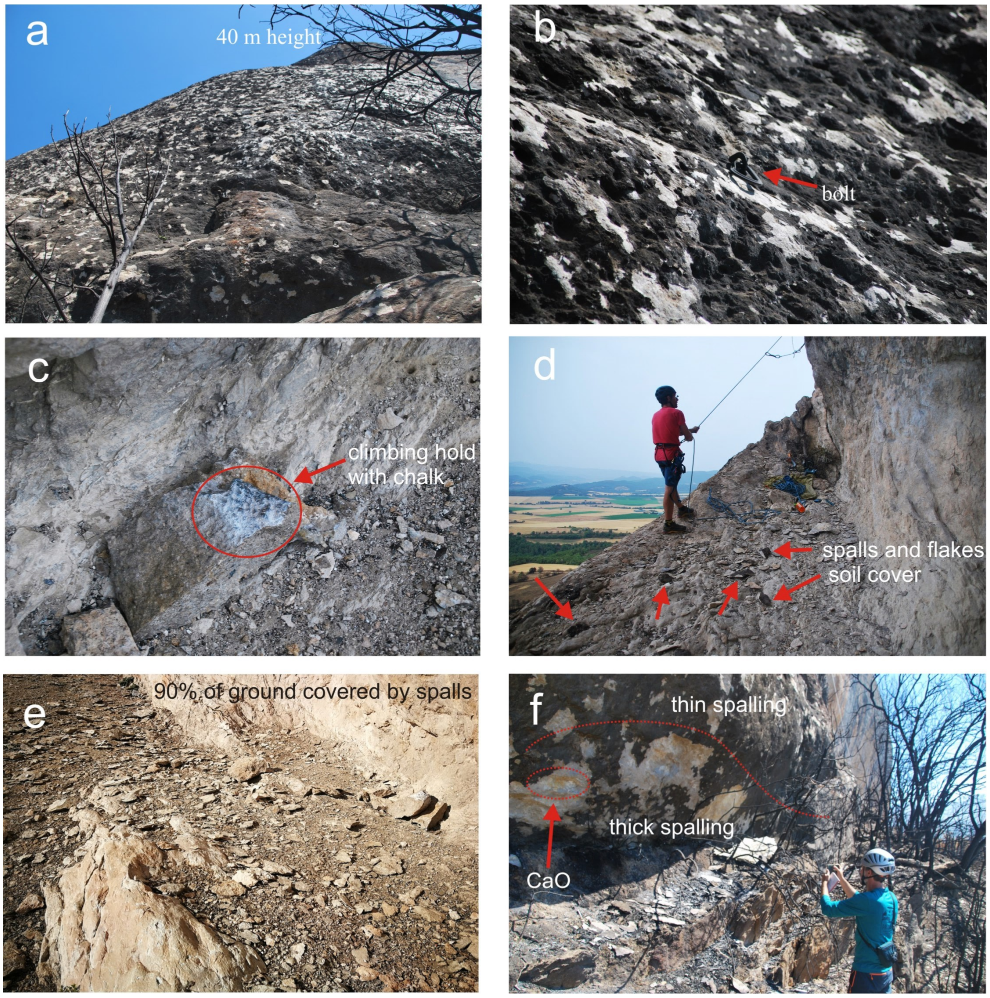

Figure 7. Visible rock surface decay features in Oliana as a result of the fire: (**a**) flaking and spalling on the left side of the climbing crag; (**b**) extensive flaking affecting an anchor; (**c**) large rockfall from a climbing route (notice that the rock still preserves the climbing chalk); (**d**) climbing area covered by spalled flakes; (**e**) ground of climbing area is 90% covered by spalls (photograph: Toni Mas); (**f**) limit of thick and thin spalling due to prolonged heat in the lower part provided by adjacent burned bushes.

Regarding the size of the detached spalls by wildfire in the Oliana climbing wall, we measured blocks of 1.8 m long, 0.15 m thick, and about 2 m^2 in area. These fractured blocks are more abundant close to the ground, although they can be observed up to 3 m high in the wall. Moreover, previous fractures and weakness planes could favor the breaking of these blocks. In the most affected areas, spalls covering 90% of the soil were observed (Figure 7e).

In Cadalso de los Vidrios, the effects of the wildfire affecting the granite rock surface depend on the persistence and temperature of the wildfire. In general, the effects of the wildfire were limited (Table 4), and the bottom 2–3 m of the walls were the most affected parts of the climbing routes. The main effect observed was detached rock spalling, with the spall thickness ranging from a few millimeters to a few centimeters (Table 3). The spalled areas range between 20 cm^2 and 0.5 m^2. The spalled areas are easily visible due to the sharp color change between the discoloration (either reddened or blackened) of the non-spalled rock surface and the lighter fresh-rock color of the spalled areas. Regarding the total affected climbing area in Cadalso, the east part is the most affected area, showing up to 30% of the surface of detached spalling at the bottom part of the climbing wall (Table 4). The top parts of the wall show a much smaller surface of detached spalling.

Another important effect of the wildfire is the formation of cracks in granite blocks (Figure 8), constituting a risk for climbing. These cracks can reach 1.5 m long and 1 m deep from the bottom of the granite rock. Subsets of subparallel fractures appear in areas where the wildfire reached the maximum temperature. Reddening is the result of thermal oxidation from around 300 °C, while spalling and cracking may be due to thermal shock during either the fire or its extinction. Surface temperatures above α to β quartz transition (573 °C) increase the chance of granular disaggregation instead of spalling [1,5,7].

5.1.2. Non-Destructive Testing

UPV and the SH test have a direct correlation with compressive strength, although they both offer different information. The SH test resembles a point-load test, and it gives information from a much smaller volume of rock than UPV. UPV is affected by cracks, pores, and other rock discontinuities through a larger mass of rock determined by the distance between transducers (15 cm in this case).

The Schmidt Hammer (SH) rebound numbers from the random grid at the bottom of both climbing areas show a clear relationship between the decrease in the rebound value and the observed mechanical damage features. The results from Oliana reinforce the idea of the increase in mechanical damage in the burned areas (Figure 9a) and also an increase in variability. The latter could be related to higher SH values measured in spalled areas in contrast with lower values in damaged areas not spalled during the fieldwork measurements.

Partially burned areas show a pattern with more variability and their characteristics and visual damage to the rock are sometimes similar to burned areas. Higher rock resistance values are found in unburned areas (green color).

There are two types of granite in Cadalso de los Vidrios, as seen in Figure 4b, each of them with different mechanical properties. Therefore, the results of these two granites cannot be compared with each other. Figure 9b shows the SH results for each of these granites. In the crags located in Granite 1 (corresponding to Unit 1 in Figure 4b), the highest SH values correspond to areas that do not show any feature resulting from fire (displayed with a green color), while the partially burned crags (yellow color) decrease the range of values. The two main crags located in Granite 2 (see Figure 4b, Unit 2) have been burned (red color), and the figure shows a wide range in the SH results, with more variability.

Figure 10 shows the UPV values for the random grid measurements obtained at the bottom of both climbing sites. Figure 10a shows the results displayed as a boxplot for the different climbing routes in the Oliana area. They are similar along the main wall, with the higher average values on the left side, which corresponds to the area with more visible effects caused by the fire, particularly blackened, soot-covered surfaces.

Figure 8. Visible rock surface decay features in the Cadalso de los Vidrios site as a result of the fire: (**a**) flaking of blackened surface and thick spalling at the bottom part of a boulder, possibly generated by thermal shock during aerial firefighting; (**b**) spall showing the surface black soot layer penetrating and clogging the fire-induced surface cracks, an intermediate thermally reddened portion, and seemingly unaffected rock; (**c**) completely shattered boulder as a consequence of intense thermal shock; (**d**) boulder showing a 1 m thick shattered portion at the bottom and spalling at the top, possibly due to prolonged heating caused by the burning of an adjacent log that appears to be completely burned; (**e**) reddened spall due to thermal oxidation of iron-rich micas; (**f**) boulder with extensive detached scaling and spalling, where a new "fresh" surface appears in the detached areas; (**g**) the clearer "fresh" surface formed after spalling is more abundant in areas that were totally covered by fire. Blackened surfaces of soot deposits appear in the area only partially affected by fire.

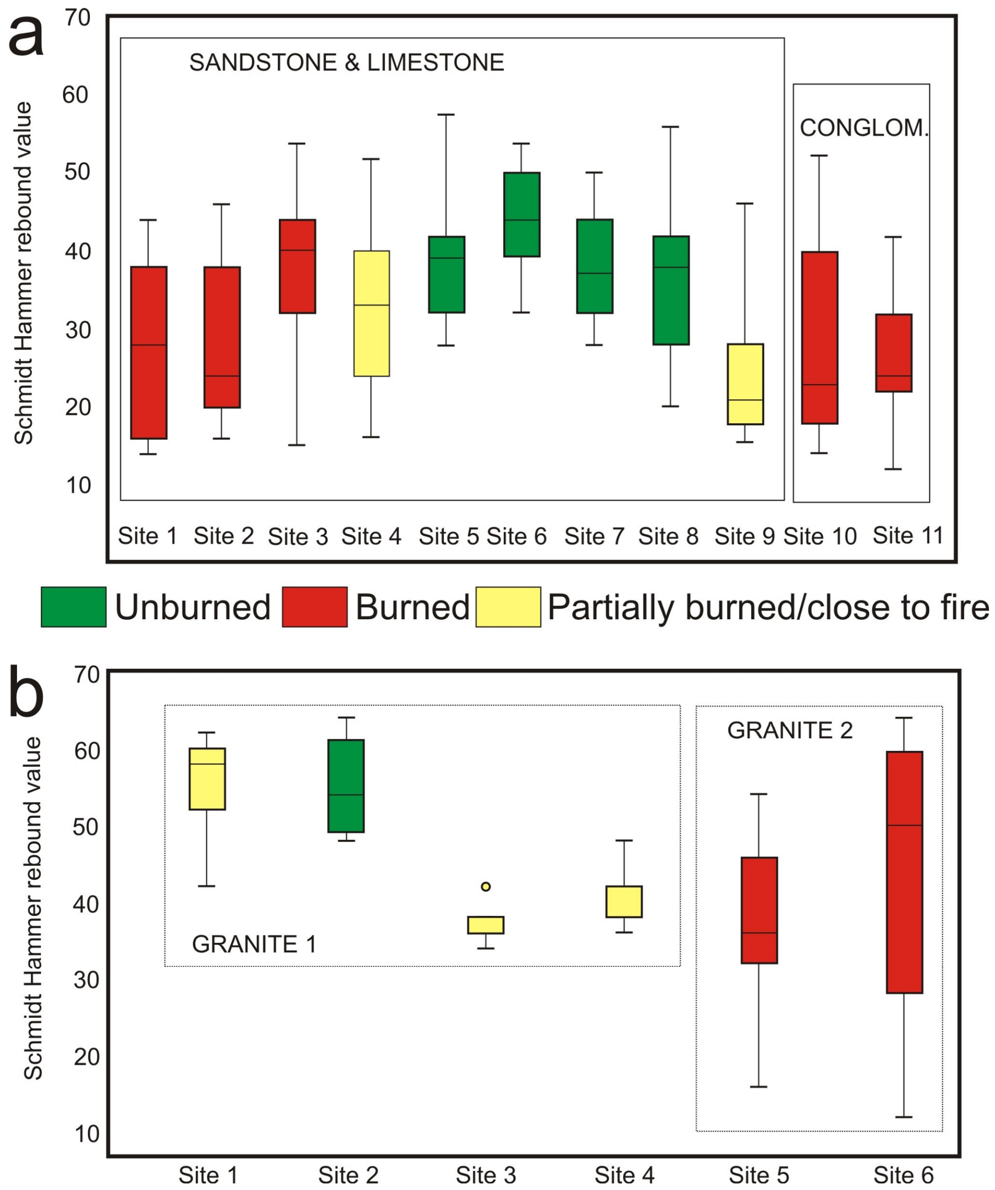

Figure 9. Schmidt Hammer (SH) values of the two studied areas: (**a**) Oliana with a clear variation of rebound values between sites visibly affected and non-affected by fire; (**b**) Cadalso de los Vidrios with two different granites along the various crags.

Figure 10b shows the results in the Cadalso de los Vidrios area. As mentioned for the SH values, the climbing walls occur in two types of granite; thus, the values are only comparable within each type of granite. These results do not show a clear relationship between those obtained in areas that were not affected and those that were either partially or totally affected by the fire. The comparison between the boxplots lacks statistical relevance (22.5% probability in Granite 1 and 5.6% in Granite 2 of relevant differences between data sets for a t-Student two-tailed test).

The large data dispersion and the lack of significant differences between the routes is not surprising, as fire dynamics, temperature, and fumes distribution are extremely complex and their effects may vary in different routes. Therefore, to assess the differences between areas with visible damage generated by fires, we chose a site in Cadalso de los Vidrios where a noticeable limit between different areas was identified (Figure 11). The bottom part of the wall up to 1.5 m high displays blackening due to soot cover and detached spalling (Zone a). Above this, a reddened area appears up to 5-6m height (Zone b). Close by, on the right-hand side, is an area where preserved lichens and moss show clearly that it was not affected by the wildfire (Zone c).

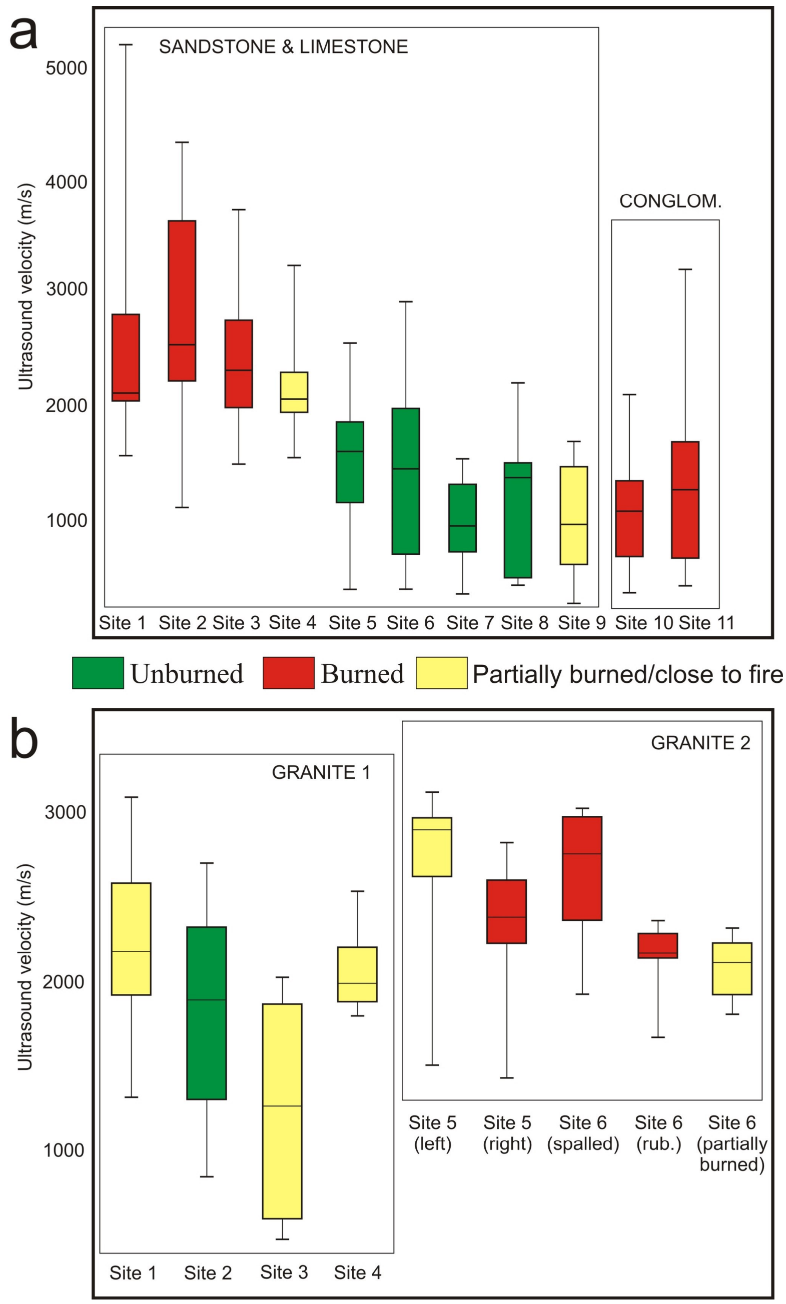

Figure 10. Ultrasound pulse velocity of the two studied areas: (**a**) Oliana across the entire climbing wall; (**b**) Cadalso de los Vidrios with two different granites along the various crags.

The boxplot display of UPV in Figure 11 does not show highly relevant differences between "fresh" (Zone a) and reddened (Zone b) areas with 61.8 % probability of significant differences between data sets for a t-Student two-tailed test. UPV shows a significant increase in Zone c because of the combination of two effects generated by fire: detachment of spalling, which reveals new surfaces that were not affected by cracking during the fire event, and pore clogging due to the penetration of soot and fumes within the surface cracks.

Distribution maps using Inverse Distance Weighting (IDW) interpolation of the SH test and UPV along climbing routes in both studied areas are shown in Figures 12 and 13.

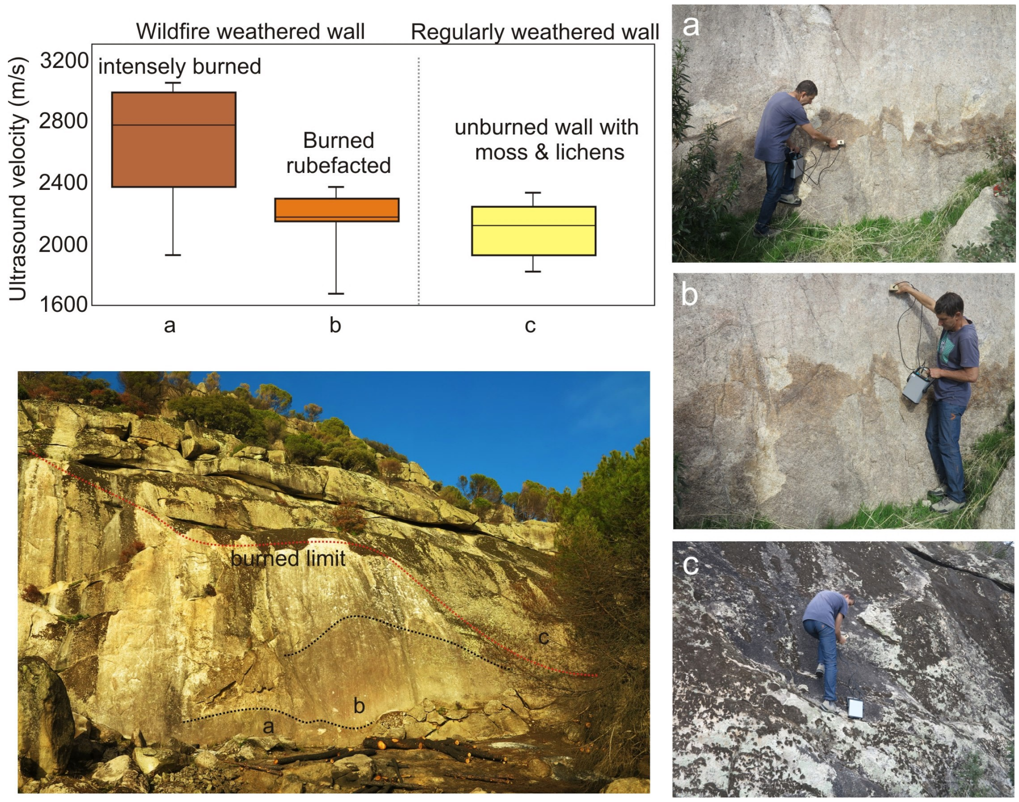

Figure 11. Detailed UPV values in the Cadalso de los Vidrios climbing wall along two areas with different degrees of fire damage: (**a**,**b**) wildfire weathering. (**a**) Intensely burned area with a soot deposit and detached spalling at the bottom part of the wall; (**b**) reddened area, which occurs above one meter in height; (**c**) area on the right side of the wall with preserved lichens and moss, indicating that it was not affected by the fire.

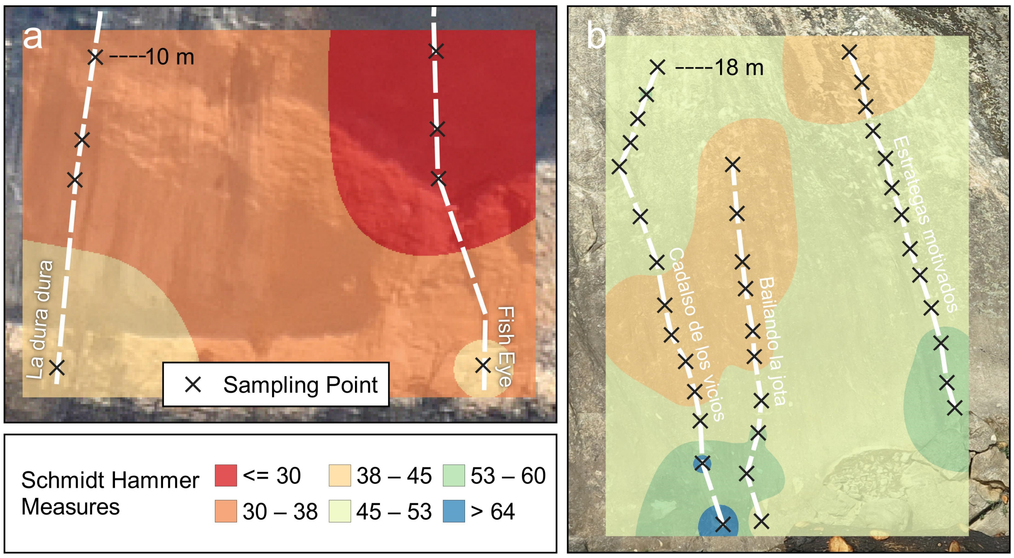

Figure 12. Spatial distribution of the SH measurements in: (**a**) "La Dura Dura" (Oliana) and (**b**) three routes in Site 6 of Cadalso de los Vidrios.

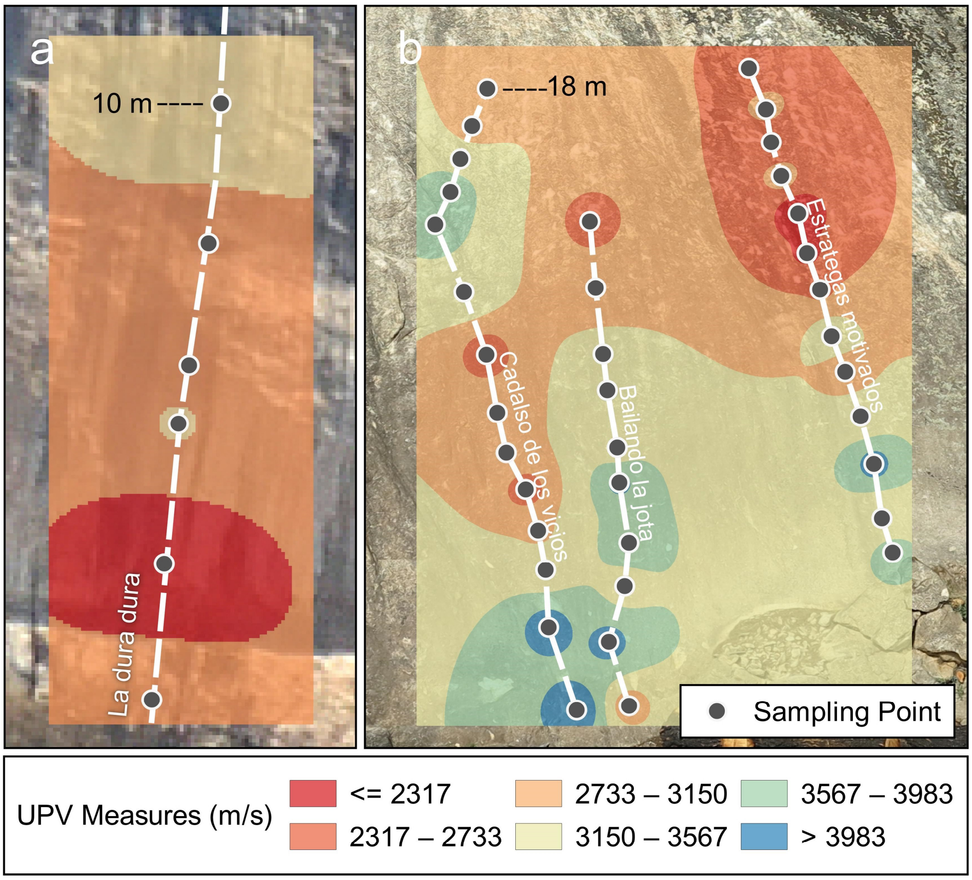

Figure 13. Spatial distribution of UPV measurements in: (**a**) "La Dura Dura" (Oliana) and (**b**) three routes in Site 6 of Cadalso de los Vidrios.

As referenced in the methodology, the iconic route of "La Dura Dura" in Oliana was selected for a detailed SH and UPV survey (Figures 12a and 13a). As this route was only partially affected by the fire, the results do not show the same large gradation as Cadalso. Figures 12b and 13b show SH and UPV maps from the three studied routes in Cadalso de los Vidrios and show a gradation of values: lower SH and UPV at the bottom, and lower SH and UPV to the top right. This gradation is coherent with the results obtained from the random grid measurements (Figure 11), in which the areas with detached spalling show higher SH and UPV values than those areas showing reddening. This is because reddened areas with non-detached spalling have more microcracks than those in which the surface affected by fire has detached and, therefore, a "new" surface not affected by the fire is exposed. The SH values differ slightly more than those of UPV and show less significant trends. This is because UPV values are influenced by a larger volume of rock than the SH rebound number, and are, therefore, less sensitive to minor and localized mineralogical heterogeneities of the rock.

5.2. Impacts on Climbing and Other Associated Hazards

As a consequence of rapid heating during the wildfires, several weathering processes of the bedrock surfaces have been reported, such as shattering, spalling, and exfoliation. However, a surficial examination of the climbing walls suggests differences in sudden "thermal shock". The set of transformations has generated important changes in the climbing walls (Table 5), which will affect the practice of the sport as it risks safe practice.

Table 5. Summary of effects of wildfires on the two studied climbing areas.

Impacts of Wildfires on Climbing Areas and Other Impacts	Oliana	Cadalso de los Vidrios
Route destruction	high	low
Boulder damage	n.a. [1]	high
Changes in route grading	moderate	low
Changes in rocky texture	moderate	moderate
Reduction in the climbing period [2]	high	moderate
Spalling affecting anchors	moderate	low
Anchor damage	none	none
Geoheritage damage	low [3]	n.a. [1]
Increase in geologic hazards [4]	high	moderate
Soil erosion in trails	low–moderate	moderate

[1] n.a.: not applicable; [2] Decrease in shade by burned/disappeared trees; [3] Neolithic paintings and iconic climbing routes undamaged; [4] Rockfalls and landslides.

Sport climbing has only been slightly affected in Cadalso de los Vidrios, because the fire only affected the first meter of the routes. Most of the spalling was located up to 1.5 m and no damage was reported on the anchors, despite several flakes being found near or in the anchors (Figure 14e). The anchor test suggests no damage after the fire. As a consequence of the few changes, most of the routes maintain their pre-fire condition, without affecting their grading (difficulty). Nevertheless, climbing in the area needs strict cold temperature conditions for practice to take place. As most of the trees disappeared after the wildfire, optimal conditions have been restricted.

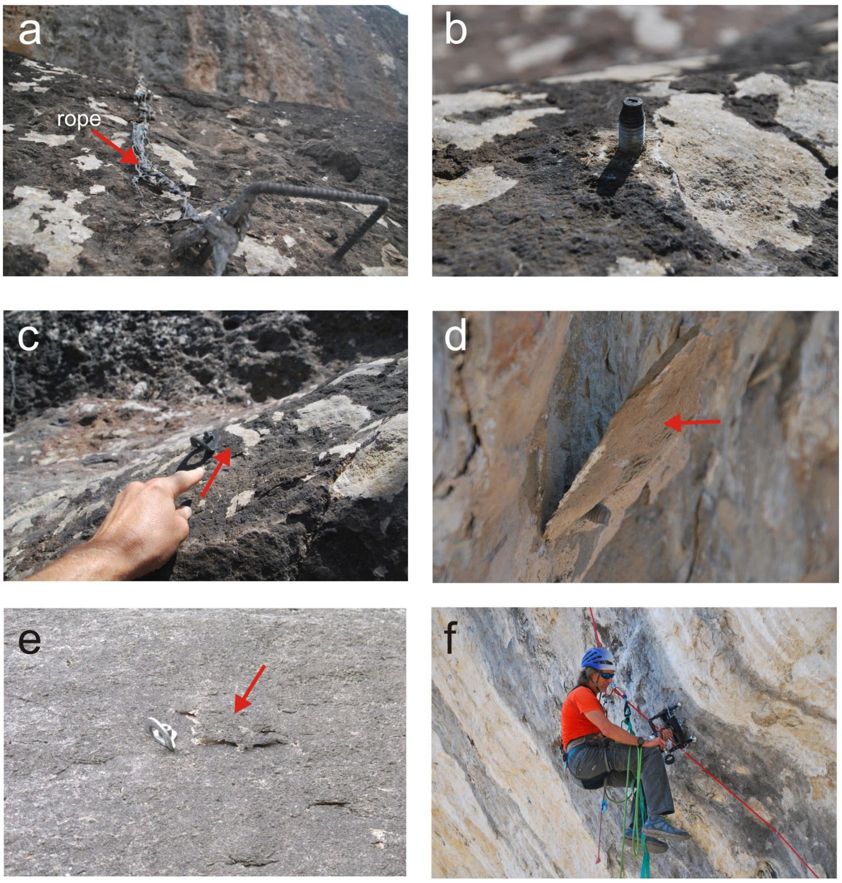

Figure 14. Impacts on climbing anchors: (**a**) remains of climbing ropes and iron stairs in Oliana; (**b**–**d**) spalling on anchors in Oliana; (**e**) exfoliation in Cadalso de los Vidrios near a bolt anchor; (**f**) anchor test in the "La Dura Dura" route.

The most significant impact has been seen in both the Oriente crag (high severity values of the dNBR index) and adjacent boulders, covered entirely by the fire, which show the greatest shattering effects (Figure 8c,d). Hopefully, bouldering (climbing without a rope in small rocks) in this area is not relevant. Little routes were damaged by spalling in the Oriente crag.

The iconic climbing area of Oliana was affected in a different way. The left side of the wall has experienced dramatic changes by spalling, rockfalls, and shattering (Figure 7). All routes on the left side have been destroyed by fire, even up to the highest part (~40 m). The vertical hot currents caused a sudden thermal shock. Conversely, the central part of the wall—the place where the most iconic routes are located—was protected from the fire. The right side of the wall was also damaged (Figure 14a). Spalling not only affects the wall, but also several anchors lost a few centimeters of rock cover (Figure 14b–d). Surprisingly, the anchor test (Figure 14f) showed a good condition of all protections.

In addition, other relevant elements have occurred since the fires, such as the increase in geologic hazards, soil erosion in trails, and potential damage to the geoheritage in Oliana.

6. Discussion

The effects of fire in Cadalso de los Vidrios on the rock wall show a marked spatial distribution: the very bottom areas of the wall display a brighter color, higher UPV, and lower SH because of detached spalling. Above this, a blackened rim appears because of a soot deposit on the original rock surface. Above, a large, reddened surface appears. Both blackened and reddened surfaces have sparse areas with detached and undetached spalling, with overall lower UPV and higher SH values.

The effects of fire in Oliana are similar, although the soot cover and undetached flaking and spalling is more frequent. This observation was made only a few days after the fire event; early enough for the soot cover to have not washed away and the flakes and spall to have not detached. However, a similar sequence of spalled brighter rock at the bottom and reddened surfaces right above was observed.

We believe that fire timing is one of the causes of the main differences in mechanical response found in both areas. The Cadalso de los Vidrios fire was much larger and intense and lasted much longer in time, almost 11 days. It affected the rocky outcrops in the climbing areas in a more heterogeneous way due to the sparse character of pine forest patches, showing a wide variety of damage. The Oliana fire lasted for less time, almost two days, and the damage was more homogeneous, as it was a continuous rock wall, although there were differences between the extremes.

The comparison between the Cadalso and Oliana areas affected by wildfires shows similarities and differences, in accordance with the lithology of the climbing wall, the intensity and persistence of the fire, and the morphology and topography of the areas. In addition, the geometry of the climbing wall is a relevant parameter to be considered. The similarities are the formation of spall, in granite, sandstone, and conglomerate, showing different spall surfaces and thickness. In addition, both climbing areas exhibit more effects at the bottom of the wall, the zone closest to the front of the fire, although the upper parts are also affected depending on the geometry of the wall (vertical and overhang). The preliminary results (Table 2) show lower spall thicknesses in granite, followed by conglomerate (EM1-EM5), and sandstone (EM9-EM11).

The distribution of the observed and measured deterioration patterns is coherent with the usual temperature distribution within a flame, with lower temperatures in the nucleus of the flame, higher temperatures in the middle part of the flame, and soot moving upward in the flame.

In Cadalso, the most intense damage, expressed as severe reddening and spalling, appears in boulders on the ground surrounded by vegetation, especially logs, in line with the findings of [46] and a densely burned forest mass (Figure 8). These boulders have been subject to prolonged high-temperature wood combustion [47]. The distribution and thickness of the detached spalling is consistent with data presented by previous research in other areas [46]. Analogously, the most intense damage in the climbing walls also appears in the first few meters, close to the ground. In this area, the rock has completely lost its original surface due to the spalling detachment, displaying, therefore, a new "fresh" surface. This explains the apparent contradiction of having higher values of UPV and SH (which would mean a less mechanically damaged rock) in the area affected by the highest temperature.

The topography and morphology of the climbing wall in Oliana controls a different distribution of fire damage. The climbing walls are located on the top of a steep slope with upward winds. This generated a "chimney" effect during the fire, which projected a hot stream toward the upper parts of the wall, so the effects of thermal spalling appear higher in the wall, up to 30–40 m high. On the left side (EM1–EM4), the detached spalling affects a larger surface and appears higher in the climbing route than on the right side of the wall (EM10–EM11) (Table 4). This "chimney" effect is only observed in the vertical wall of "sector oriente" of Cadalso, with spalling up to 20 m high (Table 4).

Our field observations show a great variability in the surface effects on rocks in a relatively small space, such as in both climbing areas. This includes mechanical weathering, such as cracking, spalling, and granular disaggregation, and thermochemical weathering with different temperature thresholds. Observed thermochemical reactions include reddening (from 300 °C [1,5–7]), $CaCO_3$ calcination (partial from 400 °C and total from 600 °C [48–50]) resulting in rock decomposition, and intense quartz cracking (from 573 °C [5–7,48]). The variety of observed thermochemical reactions coupled with measured SH and UPV allow an approximation of the maximum temperatures attained during the fire [5,51] in a temperature range of 400 to 700 °C, coherent with observed temperature distributions in comparable fires [52]. The local temperature variations reflect very local variations of fire severity and are conditioned by an uneven distribution of vegetation. All these changes will be reflected in the effects on the rocks on which climbing is practiced. This poses an added risk to the activity of climbing, as damage can be found on a small scale, with heavily damaged areas next to other areas with no apparent change.

In fact, from the two types of climbing practiced in Cadalso de los Vidrios, bouldering is the most affected, as the boulders were completely covered by the fire, causing major damage: thick spalls or shattering.

If we compare the results of wildfire in both lithologies, the Oliana area, despite the lesser severity, exhibits major mechanical changes in outcrops. This is also noted by [53], because limestone may be more impacted by fire due to the conversion of aragonite to calcite, the thermal degradation of organics, and the expulsion of water. Granitic areas are more resistant to wildfire impact due to their more homogeneous configuration and higher strength, despite the dNBR index showing moderate to high values.

However, all granitoids exhibit a severe loss of strength between 500 and 750 °C [54], and we reported intense changes (reddening and rock peeling) in areas of a higher dNBR index. The SH values reflect these changes effectively, as Figure 9 shows. Thus, the intensity and duration of fire appear to be the most significant determining factors in the surface transformation of rocks after a wildfire, as suggested by [47,54].

Wildfire weathering (Figure 15) has been noted as an important erosive agent, with changes in soil stoniness of up to 90% in the most damaged areas of Oliana. In Mediterranean areas, this effect has been demonstrated [46] by means of intense spalling. Both in Oliana and Cadalso, we noted the degree of spalling as a result of an increase in fire intensity and resulting sudden thermal shock. This effect is one of the most critical for sport climbing.

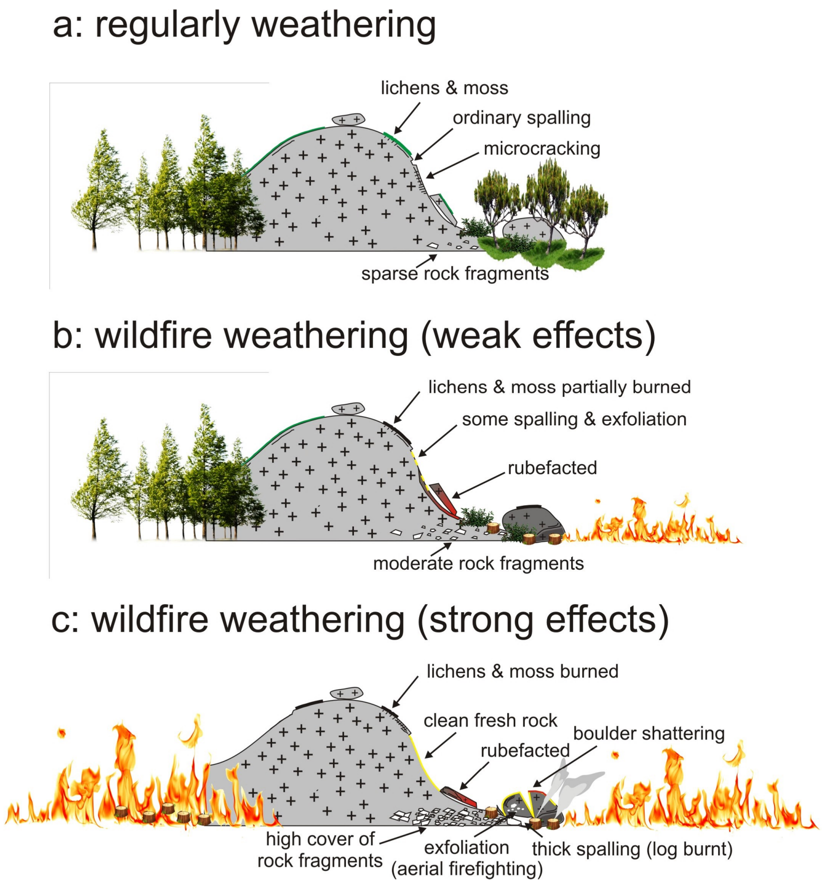

Figure 15. Surface mechanical effects of wildfires on rocks in the climbing areas: (**a**) ordinary situation with current weathering; (**b**) changes in bedrock by weak wildfire partially affecting an area; (**c**) strong effects of a wildfire on a bedrock wall.

The results obtained come from field measurements taken immediately after the occurrence of the fire. In the case of Oliana, this was two weeks after the event, and in the case of Cadalso de los Vidrios the first reconnaissance fieldwork was carried out two weeks after, but most of the measurements related to mechanical changes were made, firstly, four weeks after the wildfire and, secondly, two years later. No changes in the values were observed, except at the base of the rocky outcrops, where, due to spalling, the rock has been cleaned and refreshed.

The work carried out has allowed the identification of some geological risks, mainly due to rockfalls of flakes and blocks from the walls most affected by the fire. Prior to this publication, we suggested to local climbing communities, social networks, and official mountain federations some general safety recommendations for climbers visiting walls affected by fires similar to those discussed in this paper: (1) the first visitors to affected areas should alert the climbing community to the possible risks of transit and climbing; (2) wear a helmet at all times when approaching the walls and avoid walking close to the base of the walls; (3) clean the entire wall, starting from the top, removing all loose rock fragments that have not yet fallen; (4) test the anchors of the routes affected by the fires; and (5) allow several rain events to pass that favor natural rockfall.

7. Conclusions

Wildfires cause damage and physical and chemical alterations to rocks, which can significantly affect the mechanical properties of rocks. The alterations suffered by the rocks cover a wide range of conditions, both at the surface and the subsurface, which require specific instrumentation for assessment. These conditions can be assessed with several Non-Destructive Techniques (NDTs), which are particularly useful as they do not require the extraction of samples. Alterations to the rocks can condition the practice of climbing, which is based on overcoming vertical cliffs using the hands and feet. Small modifications to the rocks and their grip can lead to major changes in the difficulty and characteristics of climbing routes. This is especially significant in routes of high difficulty, where the holds are so small that slight modifications can significantly affect their difficulty. In some places, where climbing routes are iconic because of their difficulty and because they have been important milestones in the evolution of climbing as a sport, fires can have dramatic consequences by modifying these routes forever. It is necessary to assess both the mechanical modifications to the rocks caused by fire and the fire's influence on the aspects that affect climbing.

The incidence of fires in climbing sectors is high, especially in semi-desert regions such as part of the Mediterranean area, and it is expected to become higher in the coming decades due to the climatic emergency. The variety of lithologies, types of escarpments, types of vegetation, and the severity of fires in climbing areas make studies of their effects complex as a multitude of variables must be considered. However, due to the high number of climbers in some climbing sectors and the possible effects on the safety of climbers due to the modification of the rock and anchors (bolts), the study of fires in climbing areas is of interest.

The differences in fire intensity and severity (much more intense in Cadalso), the effects of the fire (homogeneous in Oliana, heterogeneous in Cadalso), the different lithologies (siliciclastic and calcareous in Oliana, granitic in Cadalso), and the different types of crags (linear and continuous in Oliana, dispersed in Cadalso) highlight a variety of interesting situations for the evaluation of the effect of fires in climbing areas.

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