EARTH SURFACE PROCESSES AND LANDFORMS, VOL. 17, 605–615 (1992)

THE RELATIONS BETWEEN MODULUS OF ELASTICITY AND TEMPERATURE IN THE CONTEXT OF THE EXPERIMENTAL SIMULATION OF ROCK WEATHERING BY FIRE

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Received 26 July 1991
Revised 27 November 1991

ABSTRACT

Fires occur frequently in many biomes and generate high temperatures on the ground surface. There are many field examples of fire causing rock disintegration. The simulation of fire in the laboratory (using a furnace) and the monitoring of changes in rock modulus of elasticity (with a Grindosonic apparatus), reveal that different rocks respond differently to heating. Significant decreases in elasticity occur at temperatures as low as 200°C and granites display particularly marked reductions. Extended periods of heating are not required for significant reductions to occur. It is postulated that the degree of change in elasticity as a result of simulated fire is such that rock outcrops subjected to real fires are likely to be sufficiently modified as to increase their susceptibility to erosion and weathering processes.

KEY WORDS Fire Rock weathering Simulation Modulus of elasticity

INTRODUCTION

In many environments fire has been recognized as a highly important ecological factor (see, for example, Davis, 1959; Kozlowski and Ahlgren, 1974; Pyne, 1982, 1991; Wein and Maclean, 1983; Booysen and Tainton, 1984; Goldammer, 1990). In appropriate climatic and vegetation situations, fires may occur with a high frequency and create high ground surface temperatures. The purpose of this paper is to investigate the possible geomorphological significance of fire for rock weathering.

BACKGROUND

Observation of rock weathering caused by fire

Numerous authors have described the effects of fire weathering in the field: Blackwelder (1926) described thermal spalling in the forested mountain areas of the semi-arid U.S.A.; Emery (1944) examined the role of brush fires in California; Ollier and Ash (1983) reported block disintegration of granodiorites near Armidale

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0197–9337/92/060605–11$10.50

in New South Wales; Adamson *et al.* (1983) illustrated sandstone weathering in the eucalyptus forests near Sydney; and Bierman and Gillespie (1991) noted granite spalling produced by range fires in California. The present authors have noted Devonian limestone splitting and spalling produced by grass (*Spinifex*) fires in the limestone Napier Range of north west Australia, and by grass fires on Archaean granites in the Highveld of Swaziland.

There have also been various observations that rock disintegration can be caused by other modes of heating, including exhaust gas emissions from diesel generators (Wai and Lo, 1982). Fire was used by prehistoric stone workers to split quartzites, flints and cherts for tool manufacture (Griffiths *et al.*, 1985), and preliminary experiments by the present authors indicates that fresh Cretaceous flints from the chalk of southern England may disintegrate explosively at temperatures as low as 300–315°C.

Fire temperatures, durations and frequencies

The temperatures attained by rock surfaces and soil surfaces in fires vary according to the type and intensity of fire. However, as indicated in Table I, the maximum temperatures that have been recorded can exceed 800°C, and values greater than 1000°C are known. Certainly, values of 500°C are by no means exceptional.

Also important from a geomorphological point of view is the length of time over which extreme temperatures are maintained, and the speed with which they are attained. These properties will serve to control the degree of thermal shock to which rock surfaces are exposed. Some data are presented in Table II. It is evident that high temperatures can be maintained for some minutes.

The frequency of fires in different environments tends to show some systematic variation. Wein and Maclean (1983) suggest that rotation periods may be in excess of a century for tundra, 60 years for boreal pine forest, 100 years for spruce-dominated ecosystems, 5–15 years for savanna, 10–15 years for chaparral, and less than 5 years for semi-arid grasslands. These figures are broadly confirmed by data in various papers (Goldammer, 1990). Thus fire return intervals tend to be between 4 and 45 years for the fynbos of South Africa, and between 1 and 5 years in the savanna of Kakadu National Park in the wet–dry tropics of Australia. Humans can both increase and suppress the frequency of fires (Goudie, 1990, pp. 29–31), but there is no doubt that they do occur naturally (as a result of lightning, rock fall, spontaneous combustion, volcanic activity, etc). Fire is used by hunters, gathers, pastoralists and shifting cultivators, and under such systems, even with low human population densities (as in the Kalahari or the Great Sandy Desert), fire is a frequent and long-continued cause of ecological change.

Tree ring and lake sediment studies permit the gauging of the long-term frequency of fires, and indicate that prior to European settlement, coniferous forests in North America suffered from burns with a frequency of once in every 7 to 80 years.

Table I. Maximum temperatures attained in fires

Vegetation type	Source	Temperature (°C)
Minnesota jack pine	Ahlgren (1974)	800
Chaparral scrub	Ahlgren (1974)	538
British heath	Whittaker (1961)	840
Senegal savanna	Daubenmire (1968)	715
Japanese grassland	Daubenmire (1968)	887
Chaparral scrub	Mooney and Parsons (1973)	1100
Nigerian savanna	Hopkins (1965)	>538–640
Sudanese savanna	Hopkins (1965)	850
Heathland	Kruger and Bigalke (1984)	550
Fynbos	Trollope (1984)	770
Grass fires (High Plains)	Wright and Bailey (1982)	388
Chaparral scrub	Wright and Bailey (1982)	685

Table II. Temperature characteristics of fires

A Chaparral fire (from Davis, 1959)

Maximum surface temperature (°C)	Time to reach maximum temperature (min)	Time for which temperature over 66°C (min)
335	9	3
449	4	40
149	5	11
516	8	34

B Minnesota jack pine fire (from Ahlgren, 1974)

Temperature (°C)	Time at that temperature (min)
>800	1
>500	9
>300	17

C Forest fires in Australia (from Humphreys and Craig, 1981)

Maximum surface temperature (°C)	Period soil remained above 80% of maximum temperature (h)
390 (medium slash)	0·2
370 (heavy slash)	5·5
550 (heavy slash)	0·6
830 (windrow or heap of logs)	1·6
750 (windrow or heap of logs)	8·0
670 (windrow of heap of logs)	3·0

The role of rock properties

Quartz expands about four times more than feldspars and twice as much as hornblende (Winkler, 1973), and shows a 3·76 per cent volume expansion from room temperature to 570°C . Amongst the plutonic rocks, granite and granodiorite have the greatest expansion at temperatures up to 500°C (Ollier and Ash, 1983).

Also significant is rock thermal diffusivity, which controls the difference in temperature and hence rate of expansion between the outside and inside of a boulder. A rock with a low value of thermal diffusivity thus has an increased chance of spalling. Observations by Mirkovich (1978) indicate that quartzite and sandstone have high thermal diffusivity values, igneous rocks have intermediate values, and limestones and marbles have the lowest values. Textures may also be significant. Homand-Etienne and Troalen (1984) found that rocks with very heterogeneous textures are less responsive to thermal changes. Wai and Lo (1982) found that the deformation and strength behaviour of limestones was insensitive to temperature change, whereas the strength of granitic gneiss decreased with increasing temperature. Freeman *et al.* (1963) found that quartz content was important and that in most cases rocks containing 20 per cent or more quartz were highly spallable because of the large degree of thermal expansion of quartz at relatively low temperatures. Conversely they found that the presence of large quantities of soft, elastic and fine-grained minerals such as talc, chlorite, mica, sericite or clay minerals tended to prevent rapid spalling. They also found that rocks with granitoid structures were highly spallable. Gaffey *et al.* (1991) have suggested that limestones may be susceptible to fire effects because of the thermal degradation of organics, the expulsion of water in inclusions and the conversion of aragonite to calcite.

Previous simulations

Classic work on the role of fires in causing rocks disintegration was carried out by Tarr (1915) who heated fresh granites at temperatures of 500, 750 and 1000°C. He noted that at 900°C the compressive strength of granite dropped to several per cent of the initial value.

More sophisticated modern work has been undertaken by Homand-Etienne and Troalen (1984). They found, using scanning electron microscopy and wave velocity measurements, that in crystalline limestones, intercrystalline cracks appeared at temperatures as low as 200°C. With granites they found that over a temperature range of 200–700°C intercrystalline boundaries widened out progressively and caused an increase in porosity.

EXPERIMENTS

Simulation of fire in the laboratory

In the experiments described in this paper the following procedures were followed.

(i) A range of seven rock types was selected representing a broad spectrum of lithological types including igneous, metamorphic and sedimentary categories. Their characteristics are listed in Table III.

(ii) The rocks were cut by diamond bladed saw and shaped using a flat-bed grinder into bars with dimensions of *c.* 15 cm × 3 cm × 2 cm.

(iii) The blocks were dried at 50°C and at 20 per cent relative humidity (RH) in an environmental chamber until constant weight was attained. These weights were then recorded and block modulus of elasticity values were determined using a Grindosonic apparatus (see below).

(iv) The blocks were then placed in a furnace. Two types of experiment were conducted. In experiment A, all blocks were subjected to 5 min heating at one of a range of starting temperatures (between 50 and 900°C, see Table IV). This heating period is reasonable in the light of data on fire temperature duration presented in Table II. Temperatures mentioned hereafter refer to starting temperatures. At higher

Table III. Properties of rocks used in the simulation

1. **Gabbro.** A black, ultra-basic gabbro with much orthopyroxene, and displaying herring-bone exolution textures. It is a very mafic rock with small amounts of accessory biotite and interstitial quartz and an interlocking cumulus texture with a relatively small amount of cement.
2. **Slate.** A grey slate from North Wales, displaying very strong foliation and mostly small, angular fragments. The smaller grains are angular quartz surrounding by a strongly foliated matrix of chlorite.
3. **White marble.** A marble with partly dolomitized semi-radiating calcite clusters. It possesses a variable grain size with coarse interlocking lamellar crystals and small grained (tectonized?) crystals in between. The texture is very heterogeneous.
4. **Shap granite.** A coarse-grained pink granite with interlocking texture and some alteration of alkali feldspars. There is *c.* 40 percent quartz and 5 per cent biotite which is marginally altered to chlorite and displays some radiation damage.
5. **White granite.** A coarse-grained very low porosity rock with interlocking texture and healed, fracture grain boundaries. There is a high proportion of mafic minerals. Muscovite and biotite are both present, with the latter dominant.
6. **York stone.** A weakly foliated arkosic sandstone with a high proportion of feldspar and some muscovite. It posseses a strong interlocking texture with medium-grained quartz.
7. **Portland limestone.** A white Jurassic oolitic limestone with a micritic mass. Grain size is constant overall with matrix cement less than 5 per cent.

Table IV. Temperatures in experiment A

Starting temperature (°C)	Min. temperature during 5 min CYCLE (0°C)
50	50
100	100
200	200
300	300
400	375
500	371
600	560
700	634
800	707
900	761

temperatures, the insertion of samples into the furnace caused some cooling to occur, as indicated in Table IV. After heating, the samples were returned to the environmental chamber and allowed to reach equilibrium at 50°C and 20 per cent RH. Weights and modulus of elasticity values were recorded. This procedure was repeated five times at intervals of 24 h in order to assess the changes in rock properties that might occur as a result of a number of fire events.

(v) In experiment B, the same range of rock types with the same dimensions were subjected to various periods of heat exposure to assess the importance of duration of heating. The durations employed were 1,2, 5, 10, 15 and 30 min. A constant temperature was maintained at 500°C. As in experiment A, weights and modulus of elasticity values were recorded at 50°C and 20 per cent RH before and after the treatment.

(vi) As already mentioned, the rock property monitored in this simulation was the modulus of elasticity.

Modulus of elasticity

As the elastic behaviour of rock material changes so does its competence. The rock properties that control intact compressive strength also influence the modulus of elasticity (Johnson and De Graff, 1988) and the relationship between compressive strength and modulus of elasticity is direct and linear (Judd and Huber, 1962; D'Andrea *et al.*, 1965; Deere and Miller, 1966). A reduction in compressive strength is an important consequence of weathering and there is a corresponding decrease in modulus of elasticity with increasing degree of weathering. The changes in strength and elasticity due to weathering are bound to be dependent on the composition of the rock and the resulting susceptibility to alteration. In other words, higher elasticity values will generally indicate less weathered, more competent materials, while lower elasticity values are characteristic of more highly weathered materials (see Dearman *et al.*, 1978 for example). Weathering processes will therefore produce a drop in modulus of elasticity for a given rock (Cooks, 1983).

A number of material properties are important controls on rock behaviour and the response of rock material to weathering processes. Relevant properties are varied and include mineralogy, texture, density, porosity, cementing material, water content and anisotropy. In the context of weathering by fire, such properties will play a role in determining the significance of processes such as spalling and disintegration of the mineral matrix. The above parameters are also important in affecting propagation velocities of waves, such as dynamic Young's modulus, in rocks (Attewell and Farmer, 1976; Augustinus, 1991). It can thus be argued that modulus of elasticity is a measure of the cumulative effect of such material properties. It would be both difficult and time consuming to establish the influence of any one of the above parameters on rock resistance to weathering but in this study it is the overall effect of fire on the rock which is of interest, not the significance of any one particular material property.

The Grindosonic apparatus

The Grindosonic apparatus uses the principle that elasticity theory can be applied to rock masses (Attewell and Farmer, 1976; Scholz, 1990), by directly measuring the fundamental vibration frequency of a rock sample of regular dimensions. The measurement of elastic material properties can be used as an indicator of rock hardness and strength. Grindosonic is an example of ultrasonic pulse velocity testing equipment (Neville, 1981) and analyses the transient vibration pattern of a rock specimen. Samples are struck to set up a mechanical vibration pattern, which is converted into an electronic signal by a piezo-electric detector held in contact with the test piece. A vibrating sample will experience damping relative to its elastic properties and a vibration pattern set up in a hard, rigid test piece, will take longer than the same flexure in a similar sized sample of soft, less durable material (Figure 1).

Grindosonic samples must be prepared to accurate, regular dimensions. Test pieces can be cut into a variety of shapes including bars, cylinders and discs. There are, however, nominal limits to sample dimensions. Bar shaped specimens, as used in this study, must have a length to thickness ratio of more than three and the width of the bar must be less than one third the length. Below these limits, tests cannot be conducted with any guaranteed accuracy. The test pieces were cut using a diamond edge circular saw and finely shaped using a flat-bed grinder to 150 mm by 30 mm by 20 mm.

Tests were conducted with samples resting on a foam mat to damp spurious harmonics. The top face of each bar was struck at its central point using a thin circular glass rod and the piezo-electric detector was held in contact with the sample in the centre of one of the side faces. The Grindosonic apparatus measures the time of eight wave passes. These data, known as the r-value, are used with details of sample length, width, thickness and weight to determine modulus of elasticity. Tests reported previously (Allison, 1988, 1989) have compared modulus of elasticity results obtained using the Grindosonic technique with compressive strength data collected using a standard triaxial Hoek cell, to confirm the accuracy of results obtained using the ultrasonic technique.

RESULTS

Experiment A

The results of experiment A are presented in Table V and Figure 2.

The Portland limestone samples showed a steady decline in modulus of elasticity after a temperature of 200°C was attained. By around 600°C the rock had lost about 50 per cent of its original modulus value.

The York stone showed a more complex response, with a steady increase in modulus of elasticity values to 400°C. This appears to be some sort of case hardening effect that warrants further investigation. It required five cycles at 900°C to cause a reduction in the original modulus of elasticity value to 50 per cent.

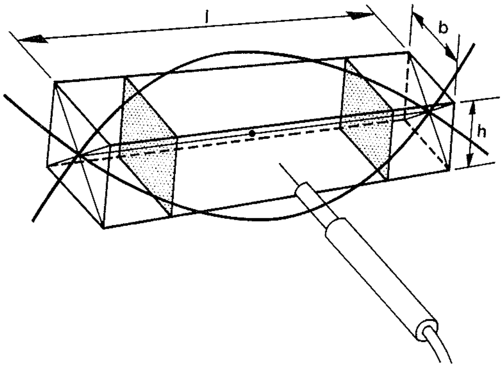

Figure 1. In using the Grindosonic apparatus a piezo-electric probe is held in contact with a rock bar. It measures the time taken for flexural vibrations to pass through the test piece

Table V. Results of experiment A: percentage change (decrease unless otherwise indicated) in modulus of elasticity

Rock type	Number of cycles	Starting temperature (°C) 50	100	200	300	400	500	600	700	800	900
Portland stone	1	+ 1·0	+ 0·9	7·5	17·5	19·8	32·3	49·5	61·2	58·2	63·7
	5	+ 1·9	+ 2·2	7·2	19·2	32·8	42·2	56·0	66·6	72·7	78·3
York stone	1	+ 7·7	+ 8·2	+ 4·4	+ 6·7	+ 4·6	1·6	13·9	12·5	26·9	22·6
	5	+ 29·8	+ 12·3	+ 6·5	+ 8·9	+ 6·8	2·7	16·7	16·2	37·0	48·8
Slate stone	1	1·2	0·5	0·6	0·6	0·6	0·6	0·6	Split		
	5	0	0	0	0	0	0	1·8	Split		
Shap granite stone	1	+ 1·1	+ 0·8	7·9	21·7	27·4	43·3	43·5	63·9	65·4	77·2
	5	+ 0·7	+ 0·3	12·0	24·4	33·2	52·2	59·8	70·4	76·1	93·1
Gabbro stone	1	+ 0·5	0·0	0·0	3·0	9·6	17·7	17·7	43·2	37·1	55·6
	5	+ 1·0	+ 0·5	0·0	3·1	11·0	17·5	29·1	51·1	63·7	79·5
White granite stone	1	+ 2·2	+ 3·0	19·9	22·4	46·5	58·1	66·1	83·3	81·1	91·1
	5	+ 1·8	0·7	26·9	35·0	51·2	61·8	72·0	86·1	87·2	94·6
White marble stone	1	0·4	0	11·4	15·8	15·5	30·5	46·2	70·2	66·6	70·0
	5	0.50		12·1	18·8	17·9	38·0	56·4	74·0	76·9	87·2

The slate samples showed different type of response. There was no significant decline in modulus of elasticity values even after five cycles at 600°C , but at 700°C samples split.

The Shap granite samples showed a response pattern not dissimilar to that of the Portland stone, with a steady decline after 200°C, and with approximately 50 per cent of the original modulus of elasticity value attained after five cycles at 500°C. After five cycles at 900°C there was a 93·1 per cent reduction.

The white granite responded in a broadly similar manner to the Shap granite, except that after five cycles at 200°C the modulus of elasticity value had dropped to 75 per cent of its original value. Approximately 50 per cent of the original modulus of elasticity value had been reached by five cycles at 400°C. After five cycles at 900°C there was a 94·6 per cent reduction. This essentially confirms Tarr's (1915) findings.

The Gabbro showed little response below 300°C but saw a steady decline in modulus of elasticity values thereafter. An approximately 50 per cent reduction was recorded by five cycles at 700°C and 79·5 per cent by five cycles at 900°C.

The white marble showed a significant response by 200°C and a progressive decline from that point onwards. A drop of 50 per cent of the original modulus of elasticity value was attained by one cycle at 600°C and 87·2 per cent by five cycles at 900°C.

The ranking in terms of change of modulus values after five cycles is shown in Table VI. The susceptibility of granites to fire stress is clear.

Experiment B

The results of experiment B are summarized in Table VII and Figure 3. From this experiment it is evident that the heating process does not need to be of very long duration for significant reductions to occur in modulus of elasticity values at 500°C. Four rock types (Portland, the two granites and white marble) showed a reduction of between 14·4 and 37·0 per cent after 1 min exposure to 500°C. In the case of the white granite, the loss after 1 min was half that lost after 30 min of heating.

CONCLUSIONS

1. Literature analysis demonstrates that in many environments fires occur with some frequency (characteristically at once in 1 to 100 years). This is especially true of savanna and shrubland environments. Such fires generate high temperatures (often of the order of 500–800°C) and there are various field observations on a range of rock types that indicate that such fires cause rock spalling.
2. The experiments reported here demonstrate that there is a variable material geotechnical response to simulated firing according to rock type, but that just one cycle of temperature change can lead to a substantial decrease in modulus of elasticity and that for some rock types, significant change occurs at temperatures as low as 200°C (well below the maxima reported for ground surface temperatures in the literature). Additional cycles lead to additional decreases in elasticity values.

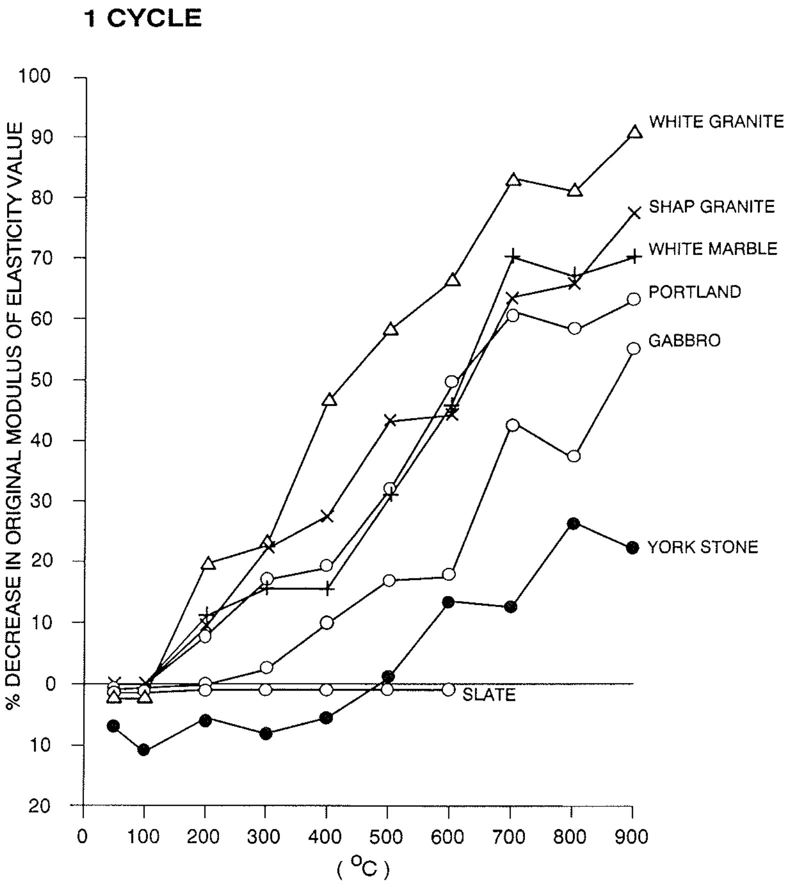

Figure 2. Results of experiment A showing change in modulus of elasticity after 5 min heating at various starting temperatures: one cycle and five cycles of heating

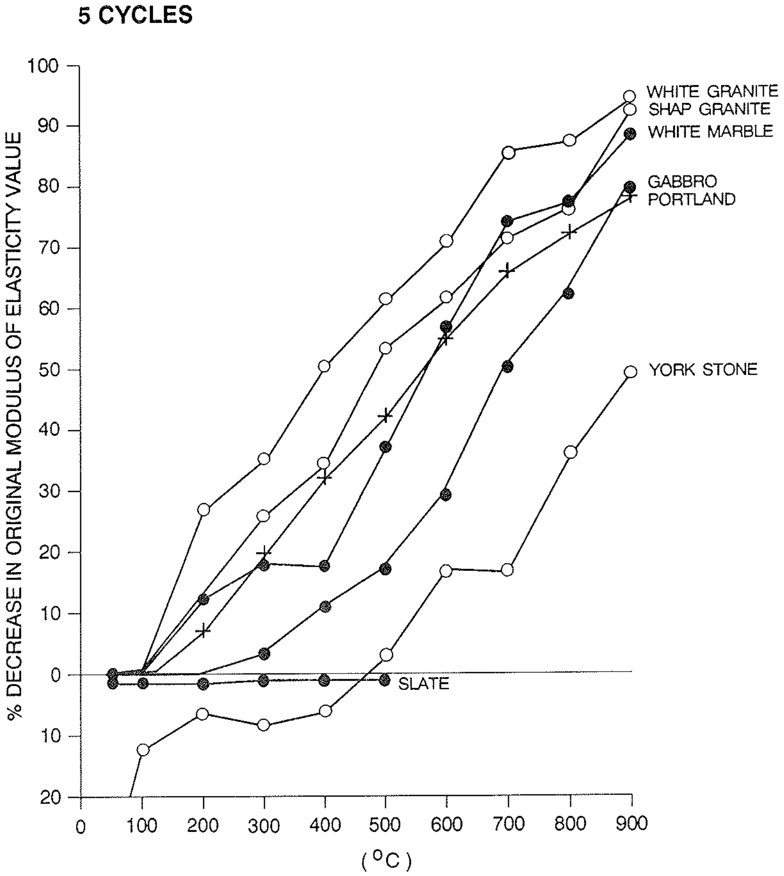

Table VI. Ranking of rocks based on change of modulus values after five cycles

	500°C	900°C
Greatest change	White granite Shap granite Portland stone White marble Gabbro York stone	White granite Shap granite Gabbro White marble Portland stone York stone
Least change	Slate	Slate (split)

3. The length of time required to cause a marked decrease in elasticity at 500°C is not great (in some cases no more than 1 min). This is significant in terms of the duration of high temperatures in natural fires in the field.
4 The degree of change in rock elasticity as a result of simulated fire is such that rock outcrops subjected to natural fires are likely to be sufficiently modified as to cause either disintegration or to increase their susceptibility to erosion and other weathering processes.

Table VII. Results of experiment B: percentage change in modulus of elasticity after heating at 500°C for six different periods

Rock type	Time at 500°C (min)					
	1	2	5	10	15	30
Portland stone	14·4	17·5	13·3	38·5	43·2	52·5
York stone	3·9	3·0	1·6	4·3	12·1	18·6
Slate	0	0·6	0·6	0	0·6	0
Shap granite	17·8	13·9	46·7	46·7	57·7	69·0
Gabbro	2·0	0·5	14·2	18·0	0	36·3
White granite	37·0	37·0	58·1	65·6	71·2	74·0
White marble	16·0	10·7	30·5	40·7	53·2	65·4

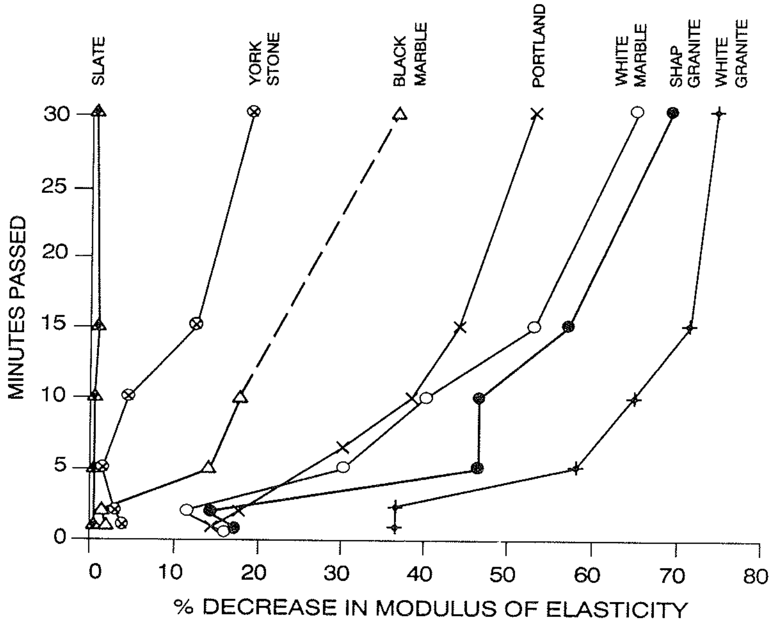

Figure 3. Results of experiment B showing the change in modulus of elasticity resulting from heating of rock bars at 500°C for varying lengths of time

ACKNOWLEDGEMENTS

The simulation work was undertaken in the School of Geography, University of Oxford. Rocks were prepared in the Department of Geological Sciences, University College London. The assistance of Dr Adrian Jones and Mr S. Moulding is gratefully acknowledged.

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