Physical Deterioration of Sedimentary Rocks Subjected to Experimental Freeze Thaw Weathering

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ABSTRACT

Ten types of sedimentary rock were subjected to repeated cycles of freezing and thawing. In addition to monitoring sample weight loss throughout testing, a detailed graphic record was made of deterioration mode and its relationship to pre-existing rock flaws. Results suggest that the presence or absence of rock flaws alone does not control deterioration mode, but rather, that it is the coupled relationship between these flaws, and rock strength and textural properties which exerts greatest influence.

While some pre-existing flaws such as syn-depositional deformation structures do not appear to influence breakdown, others, such as incipient fractures, cavities and minor lithological boundaries frequently coincide with concentrations of deterioration. A characteristic mode of deterioration which is independent of pre-existing flaws tends to develop in sandstones, an indication of the influence, in this case, of rock texture. Particularly strong rocks such as crystalline limestone and metasediment tend to fracture preferentially along distinct linear weaknesses such as mineral veins, stylolites and incipient fractures. Particularly weak rocks, such as low density chalk, break down in a random fashion without regard to pre-existing flaws.

In addition to providing some insight into the role of pre-existing flaws in rock deterioration, this work also has practical implications for (i) the study of landform development due to weathering, and (ii) the selection of representative rock samples in durability testing for building stone.

Keywords: Experimental freeze-thaw, rock flaws, deterioration, sedimentary rocks

INTRODUCTION

A variety of rock properties have been correlated with frost weathering including water absorption capacity (eg Goudie 1974), ultrasonic velocity (eg Remy *et al*. 1994) and fracture toughness (Hall 1986). The intention here is to consider the influence of material flaws and planes of weakness on breakdown due to frost weathering. There is a tendency in experimental rock weathering studies to treat samples as uniform and the potential effects of heterogeneities such as rock flaws have rarely been addressed. Some notable exceptions to this are studies by Douglas (1981); Smith and McGreevy (1983); and Douglas *et al.* (1994). For experimental work, it is attractive to utilise samples which are free from visible defects and flaws, and indeed this may be essential - to test the influence of variations in sample geometry, or to assess the effect of varying temperature and moisture conditions, for example. It can be equally important, however, to represent field conditions as closely as possible in order for results to be more widely applicable. This is not only important for geomorphic studies of landform development, but also for practical purposes, such as rock durability testing in stone selection for construction.

BACKGROUND

The influence of rock flaws on breakdown at the scale of microcracks has long been recognised in classic fracture mechanics theory (Griffith 1920). In principle, brittle rock failure depends upon the concentration of tensile stresses at flaws in the material. These have the effect of reducing material strength and allow crack propagation to take place. McGreevy and Whalley (1985) have also argued that enhanced frost damage may occur at crack locations because of concentrations of moisture compared to the moisture content of the intact material. It is further recognised that crack growth occurs where stresses are less than the critical theoretical intensity required to produce failure. Stress corrosion due to chemical weakening at crack tips is one mechanism by which this 'sub-critical' crack growth occurs (Whalley *et al.* 1982; Atkinson and Meredith 1987). Experimental studies by Matsuoka (1990a) have revealed enhanced frost splitting along pre-existing fractures in shales, and in field observations, Douglas (1981) and Douglas *et al.* (1994) noted the fundamental importance of small scale discontinuities in the large scale weathering of basalt cliffs.

This paper addresses the influence of pre-existing flaws on the durability of ten sedimentary rocks under experimental freeze-thaw weathering. For the purposes of this paper, flaws are regarded in a broad sense as any macroscopic features (ie visible to the unaided naked eye) which introduce mechanical and lithological heterogeneity into the rock material. Thus cracks, are included because of their obvious potential to create planes of weakness in rock, but variations in mineralogy and even colour are also included because they *may* correspond to changes in weathering susceptibility. Micro-flaws (including pores) are not specifically addressed in this work but their potential role in deterioration is recognised. Specimens were selected to reflect the range of pre-existing flaws typically present in the *in situ* rock mass. Throughout testing, weight loss and fracture density were monitored, and a pictorial record of deterioration kept. The main aims of the research were to:

(i)   Assess the general resistance of a range of sedimentary rocks to experimental freezing and thawing;

(ii)   Identify and describe the range of visible pre-existing rock flaws observed and to determine their influence on the *mode* and *severity* of deterioration;

(iii)   Evaluate the coupled relationships between pre-existing flaws and their host lithology (do pre-existing flaws exert their influence in a way which is dependent on the characteristics of the rock?).

EXPERIMENTAL METHODS

Experimental freeze-thaw weathering method

Ten rock types were tested in all, with between five and nine specimens per rock type. Specimens were a standard cylindrical shape, of size 50mm diameter by 100mm length to reduce the possible effect on results of variations in size and shape (eg Goudie 1974). Specimens were subjected to repeated cycles of freezing and thawing in a modified domestic chest freezer with a built-in heat source. They were saturated at the start of the experiment and placed in distilled water to a depth of 30mm in a metal container within the freeze-thaw chamber. Specimens were placed on a plastic grid to prevent direct contact with the metal base. Each complete cycle of freezing and thawing lasted 24 hours, comprising 18 hours of freezing

to -18±2°C at a mean rate of 2°C/h, and 6 hours of thawing to +18±2°C at a mean rate of 6°C/h. This regime was selected to induce rock deterioration in reasonably realistic circumstances and was not an attempt to specifically model any naturally occurring regime. The transfer from freezing to thawing conditions was achieved automatically using an electronic timer and so specimens were only handled when removed for testing at the intervals indicated in Figure 1.

Indicators of deterioration

Weight Loss (%)

In this research, weight loss is based on the mass of retained fragments exceeding 10% of the initial specimen dry mass. Similar, though not identical criteria, have been adopted by other researchers (eg Goudie 1974; Jerwood *et al.* 1990a, 1990b). To determine weight loss, dry mass was measured after oven-drying samples at 105±2°C to constant weight (reached when consecutive weights were within 0.2% over a 24h interval) to an accuracy of 0.5g. It is recognised that the high drying temperature used had potential to induce breakdown, although there was no visible evidence of any modifications to samples resulting from the 'interrupt' procedure. *Hidden* damage may have occurred but it is considered that since the rock types were subjected to identical test conditions, the results are, nevertheless, broadly comparable.

Fracture Density

Fracture density, described more fully in Nicholson and Lumsden (*in review*), represents the surface area to volume ratio of fractures in a given volume of rock, and is given in units mm^2/mm^3. Fracture density was determined from point counting of fracture intersections with a standard grid superimposed on vertical specimen surfaces (ie all of the specimen surface was included except the ends).

SAMPLE CHARACTERISATION

Five arenaceous and five calcareous sedimentary rocks ranging from Silurian to Cretaceous in age were used in this experiment (see Table 1). Seven of the rock types were cut from loose blocks in disused quarries or in old road cuttings. The remaining three rocks were cut from

loose blocks in an active quarry (LamZ) and on recently engineered road cuttings (MagL, CalS). The rock types display a wide range of effective porosity, ranging from less than 1% to 39%, and uniaxial compressive strength, varying from 7 to 140MPa. Further details of these and other rock properties are given in Table 1.

RESULTS

Weight loss and fracture density

The samples experienced considerable variation in mean weight loss, from negligible to 84% with higher values for most of the calcareous rocks (see Table 2 and Figure 2). One group of rocks (LdCh and OolL) suffered substantial weight loss, particularly in earlier cycles of the experiment, and there was little variation between individual specimens. In a second group (MagL, HdCh, CalS and LamZ), moderate weight loss occurred and there was greater variability between specimens. Most samples deteriorated more rapidly initially, with HdCh and some individual specimens of LamZ being the exceptions. In a third group (SpaL, WeaS, MicS and MetS) weight loss was minimal and little variation between specimens occurred.

The pattern of fracture density was not dissimilar to that of weight loss, and indeed if one anomalous sample (LamZ) is excluded from calculations, the coefficient of correlation between weight loss and fracture density for the test reported here is 0.96. The mean *change* (an increase in every case) in fracture density varied from 7.5×10^{-3} mm^2/mm^3 164×10^{-3} mm^2/mm^3 and, with the exception of MagL and LamZ, was greater in calcareous rocks and lower in arenaceous rocks (see Table 2 and Figure 3). The two weakest rocks (LdCh and OolL) and the highly laminated siltstone (LamZ) suffered substantial fracturing. Those rocks which resisted significant weight loss (SpaL, WeaS, MicS and MetS) were also the most resistant to fracturing. All samples, with the exception of HdCh (see Plate 1), showed more rapid development of fractures early in the test (Figure 3), a pattern similar to that for weight loss (Figure 2).

Pre-existing rock flaws

On the basis of the rocks studied here, a simple classification of pre-existing rock flaws has been developed and this is given in Table 3. Table 4 gives a brief description of the samples, and lists those pre-existing flaws which were present. Figure 4 shows progressive pictorial records of deterioration for three rock types.

For every sample, at least *some* deterioration coincided with one or more types of pre-existing flaw. In some cases deterioration appeared to be induced by flaws, and in others, deterioration was largely independent (ie deterioration would have occurred whether pre-existing flaws were present or not). There is some indication that the degree of penetration and persistence of pre-existing flaws influenced the mode of deterioration. Discoloration (in the form of streaks, patches and bands) and shallow cavities rarely coincided with deterioration, probably because of their non-penetrative nature (no weakening of the rock was involved). Where they did, only localised scaling and minor granular loss occurred. In contrast, persistent incipient fractures (mechanical breaks which retain some tensile strength) and stylolites appeared to cause more intense deterioration by deep scaling, fragmentation and cracking.

Of all the pre-existing flaws observed (see Table 3), deterioration was most commonly associated with macro fossils, weak or strong incipient fractures, and open fractures. Weak incipient fractures are fragile, and breakable with light hand pressure, while strong incipient fractures require the equivalent of a hammer blow to induce failure. Incipient fractures may be analogous to the 'potential weathering lines' of Whalley *et al.* (1982). Linear weaknesses such as incipient fractures, stylolites and veins did not always break apart, but commonly became extended or widened, and new, parallel cracks often developed. Cracks which developed along laminations only did so in rocks where laminations were particularly closely spaced.

Variations in grain size, porosity and mineralogy often coincided with granular loss or disintegration rather than fracturing, although localised scaling and small fractures also formed along the boundaries of these variations. Very localised grain loss, minor fragmentation, and

non-persistent fracturing commonly occurred in relation to voids and cavities of any origin. The effect of lithic clasts and nodules on deterioration depended upon their strength relative to the host rock. Relatively weak mudstone clasts in stronger rock (WeaS, MicS) were the focus of minor fragmentation, granular loss and cracking. On the other hand, strong calcite nodules resisted deterioration and protruded from the surface at the end of testing due to grain loss from the weaker host material. Shear and deformation structures were strong, and were not usually associated with deterioration.

DISCUSSION

Severity of deterioration

Results indicate that the weakest (lowest compressive strength) rocks are least durable and the strongest rocks are most durable. Such a result is not unexpected since compressive strength relates closely to tensile strength and porosity, properties which have been identified for their role in frost susceptibility (Matsuoka 1990b). In between these extremes however, the relationship is much less clear. For instance, HdCh (see Plate 1) and LamZ (47 and 81MPa respectively) suffer much greater weight loss than MagL and WeaS (8 and 14MPa respectively). The reasons for this probably reflect the complex inter-relationships between pore properties, mechanical, structural and lithological characteristics.

Some general observations can be made on the influence of pre-existing flaws. For most of the samples which were relatively durable (MagL, SpaL, WeaS, CalS, MicS, MetS), the limited deterioration which did occur commonly coincided with the presence of pre-existing flaws. The sample LamZ was also durable in terms of weight loss, but reference to fracture density results reveals that intense cracking occurred (see Plate 2) almost exclusively along laminations. In the two least-durable samples (LdCh, OolL), deterioration was so rapid and severe that association with pre-existing flaws was difficult to determine. It is likely that the role of macro flaws, if any, was incidental (ie the rocks would have deteriorated severely anyway), though this does not preclude the possibility of an association with micro-flaws.

Mode of deterioration

After experimental freeze-thaw, four distinctive modes of deterioration could be identified:

Rapid, severe disintegration (LdCh, OolL)

Two of the weakest rocks (LdCh, OolL) disintegrated rapidly and severely, giving weight losses comparable to those of Goudie (1974) for chalk. Breakage along pre-existing flaws appeared to be incidental. Patches of chalk which were less porous were also more resistant, not surprising given the close association of frost susceptibility with pore-dependent rock properties (McGreevy 1982; Matsuoka 1990b). OolL broke into very irregular lumps, some coinciding with the boundaries of coarse particles, cavities and fossil fragments, although most deterioration was, in fact, independent of these.

Grain loss (WeaS, CalS, MicS)

Grain loss only occurred in rocks with a granular texture, particularly those of coarser grain size. It also occurred in OolL but was of minor significance in relation to the severe disintegration which affected this rock. The close association between sandstone texture and granular disaggregation has been identified by other workers (Smith *et al*. 1994; Robinson and Williams 1996), an indication, in this instance, of the strong textural influence on deterioration mode. The influence of grain size is highlighted in MicS, where increased grain loss coincided with the more fine-grained, mica-rich bands. Some fracturing also occurred in this rock influenced by the presence of mudstone clasts, suggesting that other modes of deterioration could be superimposed on grain loss if suitable pre-existing flaws were present. This suggestion is supported in an experimental salt weathering study of sandstone by Smith and McGreevy (1983) in which the *progressive* nature of deterioration was noted. Initial breakdown by grain loss was succeeded by cracking, which subsequently developed into flaking.

Fracturing and large scale fragmentation (MagL, HdCh, CalS, SpaL, LamZ, MetS)

In the strongest rocks, deterioration almost entirely consisted of fracture and breakage along pre-existing flaws, despite the fact that in SpaL and MetS, deterioration was extremely limited.

This is comparable to the results of an experimental frost weathering study by Brockie (1972), in which several highly resistant schists broke along pre-existing 'fissures or lines of weakness' early in the test procedure. The laminated siltstone tested here, while having a high compressive strength, suffered extensive breakdown by fracturing. It is notable, however, that the mode of deterioration largely depended upon the presence of pre-existing flaws. These results highlight the role of flaws in producing different degrees of deterioration in rocks with similar mechanical properties, subject to identical environmental conditions, and is comparable with the differential weathering of cliff basalts described by Douglas *et al*. (1991). Fracturing and breakage was also common in weaker rocks (though not necessarily the primary mode of deterioration in each case), being associated with incipient fractures, fossil boundaries, stylolites and variations of mineral composition.

Scaling (LdCh, HdCh, CalS)

Scaling, the detachment and peeling off of single surface layers, occurred in three samples in addition to other deterioration modes, but never in isolation. Scaling did not appear to relate to pre-existing flaws and its occurrence is, therefore, likely to relate directly to the frost weathering process. Smith *et al.* (1994) showed that penetration of scales due to salt weathering related to sub-surface crystallisation of salts at the corresponding frequent wetting depth. The cumulative effect of stresses due to crystallisation eventually led to surface detachment. In a similar way, scaling due to freeze-thaw may reflect penetration of the migrating ice front into the sample (Lienhart 1988). In CalS, a progressive cycle of deterioration emerged in which non-penetrative cracks developed and coalesced into shallow scales, the freshly exposed surfaces of which suffered deeper cracking, finally developing into deep scales.

Role of environmental conditions

In addition to the freeze-thaw tests reported in this paper, wetting and drying, salt weathering and slake durability tests were also performed on the same group of rocks. Analysis of these results indicates that most of the rocks deteriorated in a similar fashion regardless of the environmental conditions imposed. This is a strong indication that rock control (Yatsu 1966)

supersedes the influence of environmental conditions. The similarity of deterioration mode across all tests was particularly distinctive for SpaL, LamZ and MetS suggesting that rock strength provides the basic resistance to mechanical weathering of sedimentary rocks, but that this resistance is overridden by the presence of pre-existing flaws (Douglas 1981; Whalley *et al*. 1982). Other rocks displayed a similar style of deterioration and similar relationships to pre-existing flaws, BUT differed in the rate and severity of deterioration across tests indicating a greater environmental influence. The high density chalk deteriorated differently for each type of weathering test conducted, indicating that in this case, *process* had the greatest influence on the mode and severity of deterioration, and that the presence, absence and nature of pre-existing flaws was probably incidental.

CONCLUSIONS

Despite the relatively small sample size involved in this experiment, several models describing the influence of pre-existing flaws on deterioration are proposed. These models are based on the observations made here, but appear to have some theoretical basis.

Model 1: The intrinsic high mechanical strength of strong rocks contrasts with the fundamental weakness provided by any pre-existing flaws present, resulting locally, in regions of low tensile strength. Since the usual corollary to high mechanical strength is low porosity (McGreevy 1982; Winkler 1994), flaws also provide preferential routes for moisture ingress. This moisture is essential in the freeze-thaw process, but may also play a role in deterioration by swelling of clay minerals (McGreevy 1982) and stress corrosion (Whalley *et al*. 1982). Flaws are thus exploited and are the focus of most deterioration taking place, which may, nevertheless, be minimal. Where flaws are present in abundance, deterioration also has the potential to be severe.

Model 2: The intrinsic low mechanical strength of weak rocks usually equates with high porosity (Winkler 1994) and hence greater frost susceptibility (McGreevy 1982). Since the absorption of moisture necessary for freeze-thaw weathering depends upon rock microstructure, it is likely that deterioration in these rocks will be more closely associated with void-dependent properties

and microcracks than with macro-flaws. The role of pre-existing flaws, therefore, is largely incidental to any deterioration which occurs.

Model 3: The influence of pre-existing flaws on deterioration of moderately weak and moderately strong rocks is variable because of their coupled relationship with material strength. Some deterioration is associated with pre-existing flaws, but other deterioration is unrelated and occurs due to material weakness and other factors. These rocks are transitional between those in Models 1 and 2.

Model 4: Textural properties may pre-dispose sandstones to deteriorate predominantly by granular loss (eg Robinson and Williams 1996). This may be because of the relative ease with which microcracks can develop in intergranular cement where this is weaker than the constituent grains. Propagation of grain boundary microcracks may also be frequently halted in coarse-grained rocks so that long cracks rarely develop. The result is that disintegration occurs at the scale of grains rather than through the rock material as a whole.

To determine if this conceptual framework is more broadly applicable, further investigation of other rocks and weathering conditions would be required.

In summary, it would seem that pre-existing flaws are particularly important in the deterioration of stronger rocks, and their direct influence diminishes in weaker rocks as the influence of other rock properties and environmental factors increases. For strong rocks, these findings support the conclusions of Tharp (1987) and Douglas (1981) that environmental conditions are subordinate to discontinuities in terms of their effect on weathering. For weak rocks, the findings indicate that macro-flaws are of less importance to frost susceptibility than other rock properties. For the high density chalk, there are indications that environmental conditions have a much greater role in determining the mode of breakdown. Broad relationships between pre-existing flaws and deterioration mode have also been indicated.

The results are applicable to the selection of samples for rock durability testing, particularly for stronger rocks where, although durability may be high, deterioration which does occur can be expected to relate in large part to the existence of pre-existing flaws. To ensure representative data are obtained, perhaps two parallel sets of durability tests should be conducted, one on more homogeneous material with minimal visible defects and obvious flaws, if available, and the other on material containing flaws typical of field conditions. Increasing the number and size of samples may also ensure closer correlation between laboratory and field sample properties.

ACKNOWLEDGEMENTS

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CAPTIONS FOR PLATES ONE AND TWO and TABLE 3 (provided in a separate file)

Plate 1 *High density chalk* (HdCh) after 39 cycles of freezing and thawing.

Note the typical loss of large fragments of material from the top and base of specimens,

and the deep (3-4mm) scaling around the circumference

Plate 2 *Laminated siltstone* (LamZ) after 25 cycles of freezing and thawing.

Note that, although some material loss has occurred, deterioration is largely confined to intense incipient fracturing.

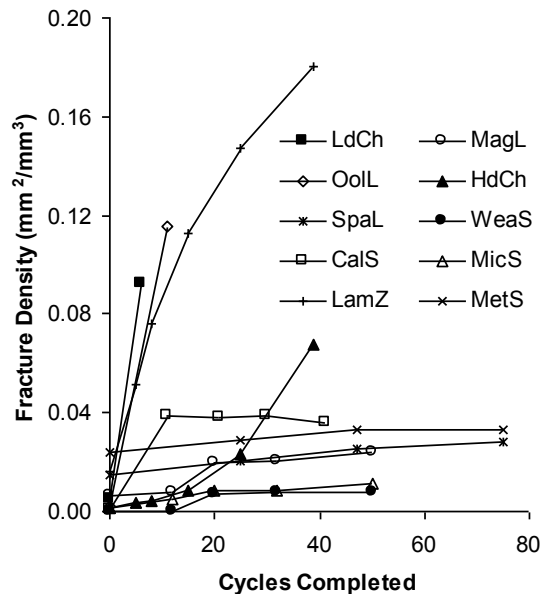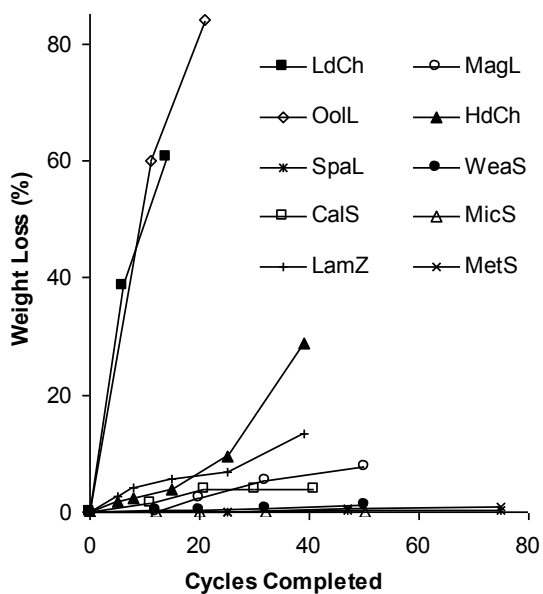**Table 3** Classification of pre-existing rock flaws observed at the material scale
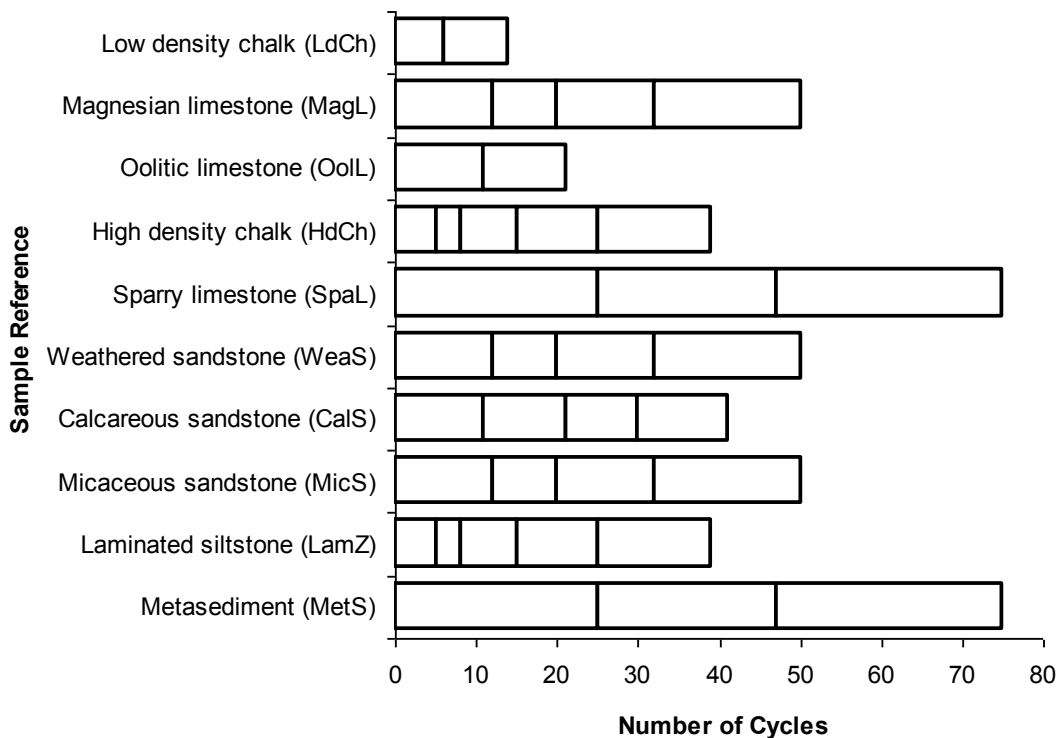
Figure 1 Number of freeze thaw cycles and timing of interrupts for each sample

Figure 2 Weight loss results

Figure 3 Fracture density results

LdCh = low density chalk; MagL = magnesian limestone; OolL = oolitic limestone; HdCh = high density chalk; sparry limestone; WeaS = weathered sandstone; CalS = calcareous sandstone; MicS = micaceous sandstone; LamZ = laminated siltstone; MetS = metasediment.

ROCK TYPE	SAMPLE CODE	COMPRESSIVE STRENGTH[1] (C_o) MPa	DYNAMIC YOUNG'S MODULUS[2] (E_{dyn}) GPa	DENSITY[3] (ρ) g/cm^3	EFFECTIVE POROSITY[3] (n_e) %
Low density chalk	LdCh	6.64	9.44	1.610	38.58
Magnesian limestone	MagL	7.77	5.23	1.819	33.61
Oolitic limestone	OolL	11.56	14.04	2.478	7.62
High density chalk	HdCh	46.95	15.33	2.007	24.23
Sparry limestone	SpaL	79.72	35.03	2.684	0.60
Weathered sandstone	WeaS	13.79	6.30	2.236	14.17
Calcareous sandstone	CalS	31.55	12.17	1.828	26.15
Micaceous sandstone	MicS	41.55	12.49	2.195	12.53
Laminated siltstone	LamZ	81.03	23.08	2.599	5.39
Metasediment	MetS	*140*[4]	28.54	2.695	0.37

Table 1 Pre-test sample properties[5]

[1]   Obtained from uniaxial compressive tests on cylindrical samples (ISRM method, in Brown 1981);
[2]   Calculated from P- and S-wave ultrasonic velocity;
[3]   Derived from mercury porosimetry;
[4]   Mean modulus of rupture (T_{mr}) for this sample is 30.7MPa and point load strength (IS_{50}) is 11.8MPa. C_o here is an *estimate* based on mean ratios of C_o/T_{mr} and C_o/IS_{50} for all samples;
[5]   Mean values for E_{dyn}, ρ and n_e are based on 9 test specimens for HdCh and LamZ, 6 for CalS, and 5 for the remaining rock types.

ROCK TYPE	SAMPLE CODE	MEAN WEIGHT LOSS (%)	RANGE OF WEIGHT LOSS (%) (between specimens)	PRE-TEST FRACTURE DENSITY (mm^2/mm^{3}x10^3)	POST-TEST FRACTURE DENSITY (mm^2/mm^{3}x10^3)
Low density chalk	LdCh	60.7	58.9 - 62.6	4.7	92.5
Magnesian limestone	MagL	7.8	0.0 - 23.9	6.3	24.2
Oolitic limestone	OolL	84.1	80.2 - 86.6	2.4	115.6
High density chalk	HdCh	28.9	8.1 - 45.4	1.1	67.6
Sparry limestone	SpaL	0.2	0.0 - 1.0	14.8	28.0
Weathered sandstone	WeaS	1.1	0.2 - 2.4	0.0	7.5
Calcareous sandstone	CalS	3.9	2.2 - 9.0	0.9	35.8
Micaceous sandstone	MicS	0.2	0.0 - 0.5	1.4	11.2
Laminated siltstone	LamZ	13.5	1.0 - 34.0	16.1	180.4
Metasediment	MetS	0.8	0.0 - 3.3	24.3	32.8

Table 2 Weight loss and fracture density results

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PRIMARY FLAWS **Primary Depositional <u>S</u>tructures (S)** • laminations (**l**), truncated surface (**t**), cross laminae (**x**), and fold hinges (**h**); • shear and deformation structures (**s**); • syn-depositional cavities (**c**) and voided zones (**v**).	
<u>L</u>ithological Variations (L) • grain size variations or boundaries (**g**); • other variations in porosity or surface texture (**t**); • variations in mineralogical composition (**m**); • lithic clasts (**c**) or nodules (**n**) (may be secondary)	
<u>O</u>ther Primary Flaws (O) • macro fossils (**m**) and shell fragments (**f**)	
SECONDARY FLAWS **<u>D</u>iagenetic and Metamorphic Effects (D)** • mineral veins and healed fractures (**v**); • stylolites and other pressure solution features (**s**); • cleavage (**c**), foliation (**f**) or banding (**b**).	
<u>W</u>eathering Effects (W) • discoloured: spots (**d**), patches (**p**) banding (**b**) or streaking (**s**); • solutional or physical removal of material leaving cavities (**c**) or voided zones (**v**) - also in **S** above.	
<u>F</u>ractures (F) • part open fractures (**o**) eg with rock bridges; • weak incipient fractures (**w**); • strong incipient fractures (**s**).	

Table 3 Classification of pre-existing rock flaws observed at the material scale

SAMPLE CODE	ROCK TYPE	LITHOLOGICAL DESCRIPTION	PRE-EXISTING FLAWS[1]	MODE OF DETERIORATION	SOURCE
LdCh	Low density chalk	Heterogeneous soft chalk containing a wide range of pre-existing flaws (fossils, deformation structures, stylolites, incipient fractures, iron oxide weathering stains and higher porosity zones).	**Ss**, **Lt**, **Om**, Of, **Ds**, Wd, Wp, Ws, Wv, Fw	Rapid and severe disintegration; shallow scaling; intense fracturing	Upper Cretaceous Chalk of Lewes Nodular Chalk Beds, from Lewes, Sussex
MagL	Magnesian limestone	Very fine, weathered crystalline limestone with many small cavities and voids, stylolites, discoloration and incipient fractures.	**Ds**, Wd, Wb, Wc, Wv, **Fo**, **Fw**, **Fs**	Fracturing; minor fragmentation; minor scaling	Permian dolomitic limestone from west Yorkshire
OolL	Oolitic limestone	Medium to coarse grained oolite with many fossils, shell fragments and large cavities, and some discoloration.	**Sc**, **Sv**, **Om**, **Of**, Wd, Fs	Rapid and severe disintegration; intense fracturing; deep scaling	Jurassic limestone from Hovingham, north Yorkshire
HdCh	High density chalk	Uniform hard chalk containing large fossil fragments and stylolites. Rarely, calcite veins, discoloration and isolated voids.	**Om**, Of, Dv, **Ds**, Wp, Wc, **Fs**	Fracturing; deep scaling	Upper Cretaceous Chalk of Flamborough formation from north Yorkshire
SpaL	Sparry limestone	Strong, dense, highly fossiliferous limestone with many calcite veins. Some stylolites and deformation structures.	Ss, **Om**, Of, Dv, Ds, Wd, Ws, **Fs**	Minimal fracturing	Carboniferous Scar Limestone from Faulds Brow, north Cumbria
WeaS	Weathered sandstone	Coarse grained muddy sandstone with many discoloration bands and small mudstone clasts.	**Lc**, Wd, Wb, Ws	Granular loss	Carboniferous Millstone Grit from west Yorkshire
CalS	Calcareous sandstone	Fine to medium grained sandstone with alternating patches of calcareous and quartz rich matrix.	Sl, Lt, **Lm**, Ws	Fracturing; scaling	Jurassic sandstone from Sutton Bank, north Yorkshire
MicS	Micaceous sandstone	Alternating mica-rich (fine grained) and quartz rich (medium grained) sandstone with laminations, calcite nodules and rare mudstone clasts.	Sl, St, Sh, **Lg**, **Lm**, **Lc**, Ln, **Fs**	Granular loss; minor fracturing	Triassic St Bees formation from Birkhams Quarry, west Cumbria
LamZ	Laminated siltstone	Very closely spaced deformed laminations of alternating siltstone and very fine sandstone with tight fold hinges. Many incipient fractures, is highly fissile, and anisotropic.	**Sl**, St, Sx, Sh, Ss, Lg, **Fo**, **Fw**, **Fs**	Severe fracturing	Carboniferous Coal Measures siltstone from Wigan, Lancashire
MetS	Metasediment	Slightly metamorphosed very fine grained sandstone turbidite with feint laminations and many incipient fractures.	**Sl**, Dm, Ws, **Fs**	Minimal fracturing	Silurian turbidite of Bannisdale Slates from east of Cumbria

Table 4 Sample source and pre-test descriptions [1] Codes in bold and underlined indicate flaws which made a significant contribution to deterioration
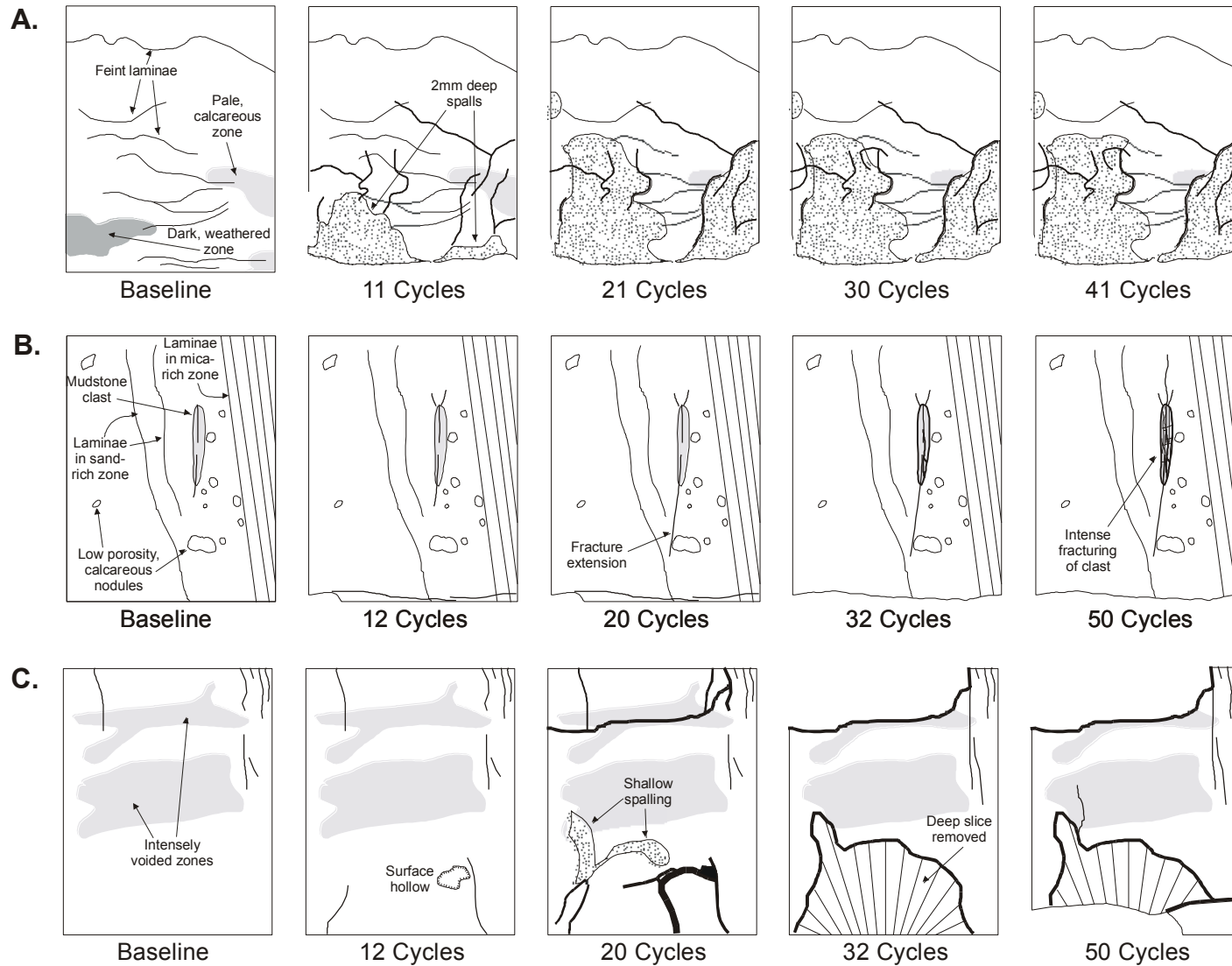
Figure 4 Selected graphic records of deterioration. A: Calcareous sandstone (CalS);

B: Micaceous sandstone (MicS); C: Magnesian limestone (MagL).