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SPECIAL ISSUE

Micro-environmental change as a trigger for granite decay in offshore Irish lighthouses: implications for the long-term preservation of operational historic buildings

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Abstract Following automation of lighthouses around the coastline of Ireland, reports of accelerated deterioration of interior granite stonework have increased significantly with an associated deterioration in the historic structure and rise in related maintenance costs. Decay of granite stonework primarily occurs through granular disintegration with the effective grusification of granite surfaces. A decay gradient exists within the towers whereby the condition of granite in the lower levels is much worse than elsewhere. The lower tower levels are also regions with highest relative humidity values and greatest salt concentrations. Data indicate that post-automation decay may have been triggered by a change in micro-environmental conditions within the towers associated with increased episodes of condensation on stone surfaces. This in turn appears to have facilitated deposition and accumulation of hygroscopic salts (e.g. NaCl) giving rise to widespread evidence of deliquescence in the lower tower levels. Evidence indicates that the main factors contributing to accelerated deterioration of interior granite stonework are changes in micro-environmental conditions, salt weathering, chemical weathering through the corrosive effect of strongly alkaline conditions on alumino-silicate minerals within the granite and finally, the mica-rich characteristics of the granite itself which increases its structural and chemical susceptibility to subaerial weathering processes by creating points of weakness within the granite. This case study demonstrates how seemingly minor changes in micro-environmental conditions can unintentionally trigger the rapid and extensive deterioration of a previously stable rock type and threaten the long-term future of nationally iconic operational historic structures.

Keywords Micro-environmental · Salt weathering · Deliquescence · Granite · Feedback mechanisms

Introduction

Lighthouses are substantial and iconic structures built to withstand the rigours of exposure to frequently extreme maritime conditions where salt and moisture abound. Lighthouses around the coastline of Ireland are typically stone-built structures that, up until the latter decades of the twentieth century were permanently manned but have since gone through a rolling programme of automation and demanning with the last tower automated in 1997. However, since automation there have been an increasing number of reports detailing rapid deterioration and breakdown of interior granite stonework that typically forms the floors, ceilings and steps within the towers. This deterioration primarily takes the form of widespread granular disintegration with the effective grusification of granite surfaces particularly in the lower levels of the towers.

The deterioration reported is notable for several reasons. First, because of its relatively rapid onset usually first reported some 6–12 months following automation. Second, the deterioration usually follows a prolonged period (usually >150 years) of granite stability from initial construction to automation, stability that is substantiated by detailed maintenance records and routine daily inspection by lighthouse attendants who were resident on the offshore

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islands prior to automation. Third, deterioration is also notable because it affects a lithology specifically selected at the time of construction because of its perceived durability—a perception reinforced by more than 150 years of apparent structural and mineralogical stability. Finally, the lighthouse estate is an important historical asset in terms of both the architectural developments it reflects and its association with Irish and British maritime history. However, despite their operational efficiency these lighthouses, like other functional historic structures elsewhere, require sympathetic, targeted management and recognition of their potential fragility (Reading 2010).

Coastal environments are characterised by high levels of humidity and an abundance of salts occurring as marine aerosols—a combination that would be expected to provide ideal conditions for rock weathering. However, given the inherent complexity of the weathering system, the most obvious explanation for factors controlling rock breakdown may not necessarily be the correct one (Smith and Warke 1997). It is tempting to assume a causal relationship between salt availability and rock weathering, given the undoubted efficacy of salt weathering as demonstrated by numerous laboratory experiments (e.g. Sperling and Cooke 1985; Goudie 1993; Goudie and Viles 1997; Warke et al. 2006) and field-based studies (Johannesseson et al. 1982; Moses and Smith 1994; Zezza and Macrí 1995; Torfs and Van Grieken 1997; Mottershead 1997, 2000; Chabas et al. 2000). However, the apparent lack of obvious deterioration of granite prior to automation of the lighthouses and the coincidence between implementation of automation and the onset and subsequent rapid progression of granite deterioration suggest a more complex explanation in which some other less obvious factor or combination of factors was responsible for triggering the decay sequence in which salt weathering undoubtedly plays a significant role. The explanation is probably related to some change in the granite's conditions of exposure within the towers—a change of sufficient magnitude to initiate the destabilisation of hitherto stable stonework.

It is important to note that salt is an exploitative weathering agent that requires some mechanism to facilitate its deposition and accumulation and the presence of pre-existing weaknesses within the fabric of the stone to allow its ingress. For salt weathering to operate effectively it also requires specific temperature and/or humidity conditions with Price (1996) and Rodriguez-Navarro and Doehne (1999) specifically highlighting the importance of atmospheric humidity fluctuations in determining the efficacy of salt crystallisation and hydration related damage.

This paper reports on the nature and extent of deterioration affecting interior granite stonework in two offshore Irish lighthouses and provides an explanation for the initiation of this deterioration with consideration of the implications for future management actions needed to ensure the long-term integrity of these iconic historic structures.

Site location and description

The two lighthouse towers investigated in this study are located off the coast of counties Galway and Mayo in Ireland (Fig. 1). They are both island-based towers meaning that historically lighthouse attendants did not live in the towers themselves but occupied adjacent cottages and associated outbuildings. Because of their location they are exposed to the full force of prevailing westerly weather systems from across the Atlantic Ocean with an average annual precipitation of more than 2,000 mm a^{-1} coming mostly from the passage of frontal systems (Cabot 1999). In addition to high levels of rainfall, the climate is temperate and characterised by low seasonal and diurnal temperature ranges primarily because of the moderating influence of the sea and the associated effects of the Gulf Stream which maintains sea surface temperatures at a much higher level than would normally be expected at a latitude of around 53°N.

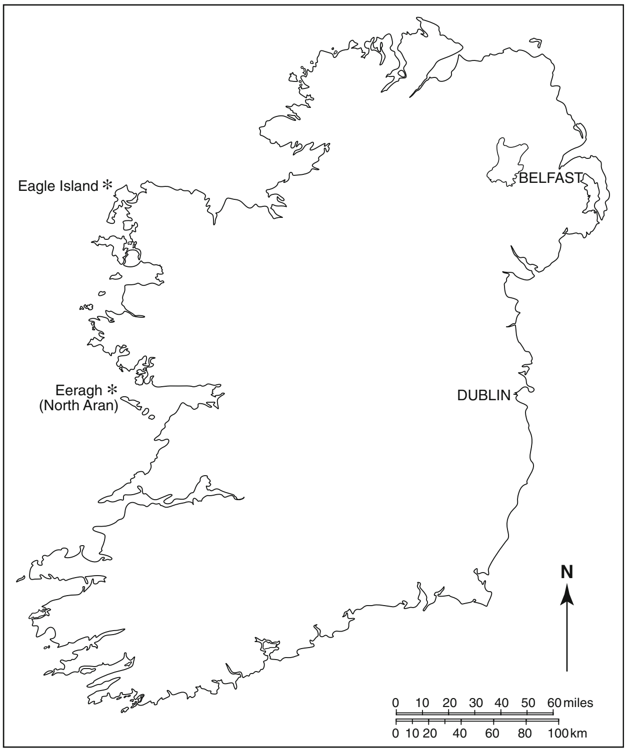


Fig. 1 Map of Ireland showing the location of Eagle Island and Eeragh (North Aran) lighthouses

Eeragh (North Aran, County Galway)

Eeragh was built in 1857 and automated in 1978 (Fig. 2a). This is the tallest tower comprising a total of eight floor levels including the optic (the level that holds the light and lens), which stands some 35 m above mean high water. Local Carboniferous limestone was used in construction of the outer walls of the tower with granite used for the interior floors, ceilings and steps.

Eagle Island (County Mayo)

Eagle Island was erected in 1835 and automated in 1988. This is a comparatively short tower comprising only three floor levels including the optic (Fig. 2b). Because of the island's proximity to the continental shelf, the Eagle Island station complex has had to be heavily defended by a substantial protective wall because of the massive incoming sea swells. Despite this protection, the tower is still frequently overtopped by seawater during storms even though the optic stands some 67 m above the mean high water mark (Fig. 2c).

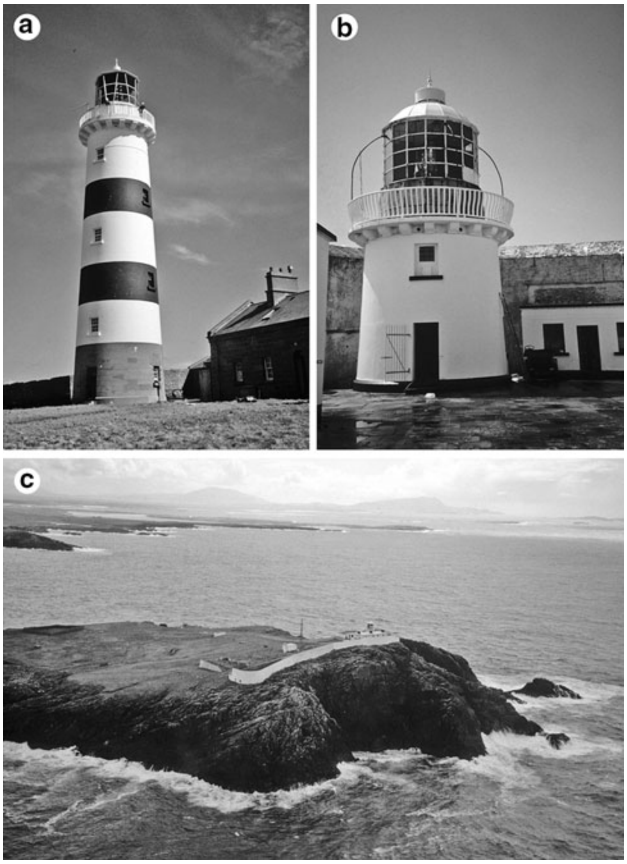


Fig. 2 **a** External view of Eeragh (North Aran) lighthouse; **b** external view of Eagle Island lighthouse; **c** aerial view of Eagle Island lighthouse showing its elevated situation and the protective storm wall that partially surrounds the station buildings

Description of materials

Dry-drilled cores (approximately 20 mm in diameter and 50 mm in length) were removed from interior granite stonework and these allowed analysis and characterisation of weathered and comparatively unweathered material with the former from the outer 15–20 mm of the core while the latter represents the basal 30–50 mm of the core.

Thin-section examination shows that in its comparatively unweathered state, the granite comprises approximately 30% quartz, 53% feldspar (25% plagioclase and 28% alkali feldspar primarily microcline with some sanidine and orthoclase) and 13% mica (6.5% biotite and 6.5% muscovite). Thin-section analysis of substrate samples showed well-developed micro-fracture networks that often cut across grain boundaries—a characteristic that contributes to its porosity of 2–3%, which is a relatively high value for granitic rock.

In addition to the micro-fracture networks, mineral alteration is evident particularly in the feldspars and micas. Many of the micro-fractures possess some iron staining indicating that these are not fresh features associated with core extraction. Both the micro-fracture networks and mineral alteration may be attributed to late-stage hydrothermal activity that may have followed pluton emplacement. Although documentation regarding the original quarry sources for this granite is not available, anecdotal evidence from the Commissioners of Irish Lights indicates that the stone was sourced from quarries in the Wicklow Mountains south of Dublin and because of its ready availability was widely used elsewhere in Ireland as a building stone during the eighteenth and nineteenth centuries (e.g. Trinity College Dublin). Petrographic analysis also indicates that the granite in question closely resembles that of Leinster Granite from the Wicklow Mountains.

Thin-section examination of weathered granite samples from the interiors of the towers showed a similar mineralogical composition to 'fresh' unweathered material. However, in addition to the established micro-fracture network and mineral alteration, weathered samples exhibit significant fragmentation of surface and near-surface grains with the greatest density of fracturing occurring in the outer few millimetres of stone as well as some evidence of dissolution of near-surface feldspar grains.

Nature and spatial distribution of granite deterioration

Anecdotal evidence from former lighthouse attendants who were stationed on the islands indicates that immediately prior to automation the interior granite stonework showed no significant evidence of deterioration. Whilst it is acknowledged that anecdotal evidence is normally no substitute for scientifically robust quantitative data, it is important to recognise that in this instance the records of daily inspection and the rigorous requirements regarding general maintenance and upkeep standards expected by the Commissioners of Irish Lights makes this evidence more reliable than most.

Prior to automation, towers were opened daily and well ventilated with ventilation slats in the optic levels opened (weather permitting) to allow the free-flow of air that established a ‘Venturi’ effect within the towers with air being drawn up through the tower from the lower floor levels and expelled through the ventilation slats in the optic level. Following automation, this daily ventilation practice was replaced by a regime in which towers are effectively sealed and opened for only 1–2 days every 3 weeks unless maintenance requirements necessitate longer or more frequent visits. In some cases the intervals between maintenance visits can be up to 6 weeks.

Since automation and the implementation of this new regime there has been an obvious and significant deterioration in the condition of interior granite with a typically marked acceleration in material loss. Granite weathering and decay primarily takes the form of granular disintegration with some examples of scaling (Fig. 3a, b). In general the granite deterioration follows a decay gradient within the towers. This gradient is best developed at Eeragh where degradation is most severe in the lower 2–3 levels of the tower decreasing in both extent and severity with increasing height until, in the upper floor levels, the granite shows little evidence of deterioration with minimal surface disruption (Fig. 4).

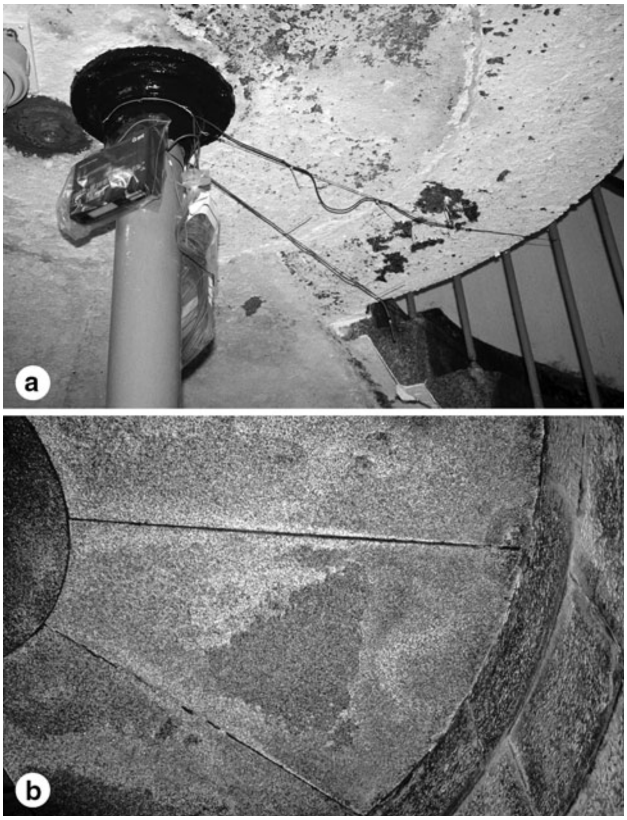


Fig. 3 **a** Ceiling granite in the ground floor level at Eagle Island showing widespread granular disintegration and surface disruption—one of the automatic dataloggers, humidity and temperature probes are also shown in situ; **b** ceiling granite in the ground floor level at Eeragh showing evident surface disruption and loss of material primarily through granular disintegration

Ceiling granite

In both Eagle and Eeragh, deterioration of ceiling granite affects approximately the outer 10 mm of stone producing a friable grusified surface. Release of this material primarily through granular disintegration has produced obvious surface retreat, which is especially noticeable close to the lead infilled gaps between separate ceiling slabs (Fig. 5a) and as loose debris on the floor. Debris release comprises a mixture of silt to sand-sized material reflecting the disintegration of mica and feldspar and the release of individual quartz grains. Some material is also released as small scales cemented together by salt (Fig. 5b). These small scales are typically around 5 mm in depth and between 10 and 30 mm in diameter.

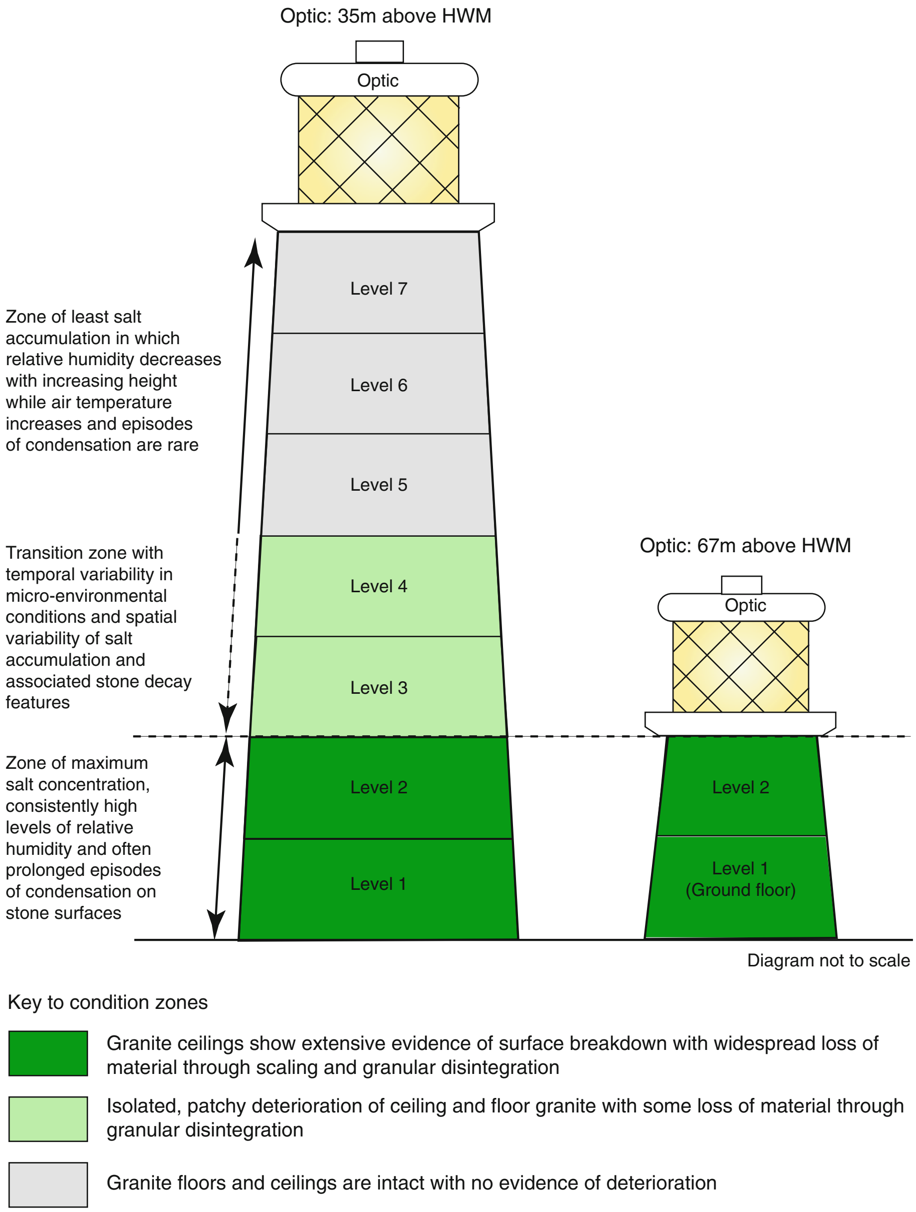
Granite floors

In comparison with ceiling granite, the granite floors show less extensive evidence of deterioration, which primarily takes the form of surface roughening associated with well-developed salt efflorescence and resulting granular release due to salt crystallisation cycles. In some instances, the pattern of salt efflorescence on floors appears to be related to near-surface airflow associated with the operation of free-standing dehumidification units that were installed to reduce condensation within the towers (Fig. 5c). Unlike the deterioration of ceiling granite, the relatively superficial disruption of floor granite can also affect higher floor levels within the towers possibly reflecting the transference of salts carried up from lower levels on footwear.

Steps and understeps

Understep areas also show significant evidence of granular disintegration in the lower tower levels (Fig. 5d, e). The upper surfaces of granite steps, especially the risers, show evidence of surface roughening and granular disintegration through the entire height of the towers again possibly resulting from contamination by salts transferred on the soles of shoes during ascent from lower tower levels

Fig. 4 Comparative diagrammatic representation of the condition of interior granite stonework in Eeragh and Eagle Island lighthouses



(Fig. 5f). All flights of steps show ‘pop-out’ features where corrosion and associated expansion of cast-iron handrail supports embedded in the granite have resulted in the dislodgement of corner sections (Fig. 5g, h). This form of damage tends to be most severe in the lower levels of both towers and is most often repaired with cement.

Investigative methodology

Identification of factors contributing to accelerated deterioration of granite involved three strands of investigation comprising the following:

- Characterisation of micro-environmental conditions within the towers
- Chemical analysis of weathered friable surface material
- Extraction and analysis of dry-drilled cores of granite from the interior and exterior of the towers for comparative structural and mineralogical examination.

Micro-environmental conditions

Air temperature, rock temperature and relative atmospheric humidity data were collected within the towers over a 12-month period using a SQUIRREL automated data logging system (Grant Instruments, UK). Thermistors for recording air temperature were located approximately 300 mm from ceiling surfaces. Rock surface and substrate temperatures were recorded using bead thermistors. Surface thermistors were affixed to the granite using a non-silicone heat transfer

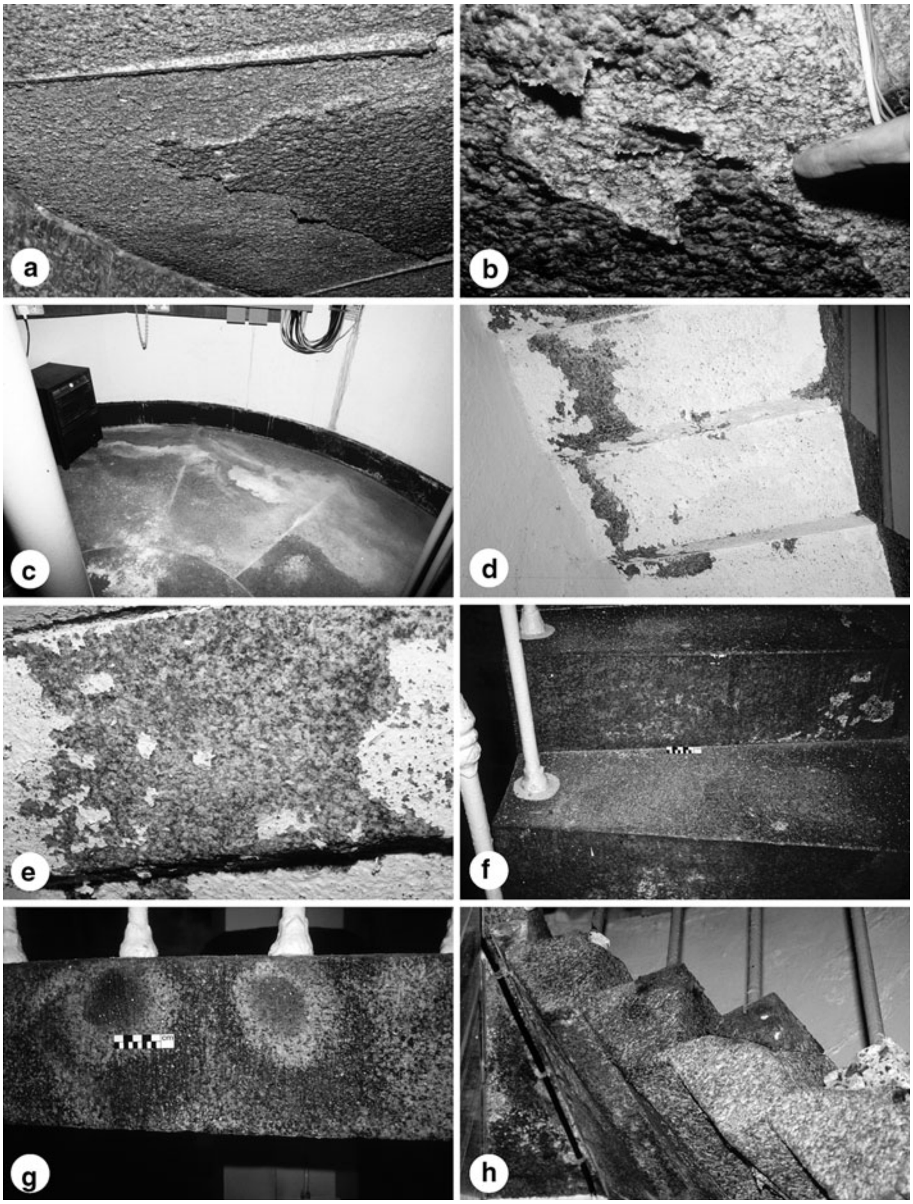


Fig. 5 **a** Details of the ceiling granite on the ground floor level at Eeragh showing the extent of material loss; **b** release of ceiling granite through scaling; **c** development of salt efflorescence on granite floor at Eagle Island associated with the patterns of airflow created by the free-standing dehumidifier; **d** condition of under-step area on the ground floor at Eagle Island showing evidence of surface disaggregation; **e** details of under-step area at Eagle Island; **f** surface of granite steps and risers; **g** circular patterns of iron staining of granite stonework are indicative of corrosion of ironwork embedded within the granite; **h** expansion of corroded ironwork often results in development of 'pop-out' features which in this instance have been repaired using cement

compound while substrate temperatures were logged with thermistors inserted approximately 10 mm into pre-drilled holes backfilled with powdered rock and sealed with a plug of non-silicone heat transfer compound. External air temperatures were also recorded using bead thermistors shielded from the effects of direct insolation. Air and rock temperature data were recorded at 15-min intervals for the full 12-month period and consequently because of the quantity of data collected only selected representative data are presented in the following results section.

At Eeragh, temperature and humidity probes were set up on three different floor levels (1st, 2nd and 6th levels) whilst at Eagle, because of the smallness of the tower, only the 1st floor level was monitored for relative humidity data with air temperature probes also located externally outside the optic.

Relative atmospheric humidity probes were affixed to the ceiling surfaces with the probe head approximately 5 mm from the granite surface. The probes were affixed in this way so that humidity conditions as close as possible to the rock/air interface could be characterised primarily because this is the zone of weathering. Relative humidity data were also recorded at 15-min intervals for 12 months.

Analysis of weathered surface samples

At each of the towers samples of loose weathered surface material were collected from ceilings, floors, steps and understep sites. A combination of ion chromatography (IC), atomic absorption spectroscopy (AAS) and X-ray diffraction (XRD) were used to identify the presence and identity of salt and any clay minerals. IC and AAS analyses were performed on the water-soluble extract from each sample, and XRD was carried out on powder samples comprising the <63 and 2 μm size fractions. IC and AAS provided analyses of element concentrations while XRD supported interpretation of these through mineralogical identification.

Analysis of dry-drilled cores

In addition to analysis of weathered surface material permission was granted to extract a limited number of small rock cores from the interior and exterior granite stonework of the towers. These cores were 20 mm in width and up to 50 mm in depth and were extracted by dry-drilling to prevent the mobilisation and/or loss of any salts present. Each core was then dry-cut normal to its long axis into approximately 10-mm sections from the core surface to the base. Each 10-mm section was then crushed and the <63 μm size fraction removed. A powder sample from each section was analysed using XRD with water-soluble extracts analysed by IC and AAS. Dry-drilled cores were used to facilitate assessment of the depth of salt penetration into granite substrate but could not be used to assess structural degradation because of the percussion-related damage caused by dry-drilling.

Results

Analysis of weathered surface material

IC and AAS analysis identified high concentrations of sodium (Na^+) and chloride (Cl^-) in surface samples from lower floor levels in both towers with some samples also showing relatively high concentrations of calcium (Ca^+) and sulphate (S^-) (Tables 1, 2). XRD analysis identified

Table 1 Selected IC and AAS data from analysis of weathered surface samples taken from the interior granite stonework at Eeragh (North Aran)

Sample location	Element concentrations (ppm)				
	Chloride	Sulphate	Calcium	Magnesium	Sodium
Ceiling of 1st level	3,634	995	670	72	1,700
Ceiling of 1st level	3,795	189	71	53	1,800
Ceiling of 1st level	3,101	147	43	44	1,700
Ceiling of 1st level	3,026	477	280	64	1,600
Ceiling of 1st level	3,337	347	150	66	1,400
Ceiling of 1st level	2,963	219	124	41	1,400
Ceiling of 1st level	2,744	194	80	42	1,400
Ceiling of 1st level	2,339	161	77	34	1,100
Ceiling of 1st level	2,851	141	48	45	1,400
Ceiling of 1st level	2,809	240	151	47	1,400
Ceiling of 1st level	2,411	157	62	41	1,300
Ceiling of 2nd level	1,498	835	580	7	890
Ceiling of 2nd level	647	370	210	2	360
Ceiling of 2nd level	1,726	103	42	2	1,000
Ceiling of 2nd level	712	374	313	2	440
Ceiling of 3rd level	754	248	166	5	380
Ceiling of 3rd level	433	93	35	2	270
Ceiling of 3rd level	551	93	26	2	320
Ceiling of 3rd level	415	108	45	2	260
Ceiling of 3rd level	607	84	18	2	340
Ceiling of 3rd level	366	163	99	3	170
Ceiling of 4th level	466	287	5	0	580
Ceiling of 4th level	229	44	4	0	230
Ceiling of 4th level	342	170	3	0	340
Ceiling of 4th level	392	194	5	0	410
Ceiling of 4th level	449	396	4	0	650

Table 2 Selected IC and AAS data from analysis of weathered surface samples taken from the interior and exterior granite stonework at Eagle Island

Sample location	Element concentrations (ppm)				
	Chloride	Sulphate	Calcium	Magnesium	Sodium
Exterior of tower	450	18	28	50	150
Ceiling of 1st level	2,601	123	178	69	1,200
Ceiling of 1st level	9,230	858	1,730	540	4,100
Ceiling of 1st level	3,513	2,673	3,610	230	1,800
Floor of 2nd level	92,390	1,781	2,300	1,800	57,000
Floor of 2nd level	4,857	112	249	180	2,700
Floor of 2nd level	351,270	2,397	5,100	2,600	150,000
Floor of 2nd level	3,794	118	260	170	2,400

halite (NaCl), gypsum ($CaSO_4$) and thenardite (Na_2SO_4) with halite present in nearly all samples examined.

Results indicate that in general salt concentrations are typically greatest in the lower levels of the towers with halite being the most common salt and, to a lesser extent, gypsum. This pattern of salt distribution is most clearly developed in Eeragh whereas at Eagle, because it has only three floor levels, the whole tower is effectively a salt accumulation zone equating with the lower salt-rich levels at Eeragh (see Fig. 6a, b).

Analysis of granite cores

IC and AAS analysis of dry-drilled cores extracted from interior and exterior granite stonework demonstrate the relatively limited penetration of salts in substrate material with high concentrations of salts restricted to approximately the outer 10 mm of stone (Fig. 7). Data indicate that while concentrations of calcium and sulphate decrease quite markedly within the upper 10 mm of the cores, concentrations of sodium and chloride can remain comparatively high through the entire depth of the core. This may reflect the greater mobility of these elements in the presence of moisture. XRD analysis supported IC and AAS data with high concentrations of halite, particularly in surface samples where it is often associated with traces of gypsum.

The high concentration of salts identified in interior granite cores is highlighted by comparison with exterior granite cores (Fig. 8a–c). Extraction of these exterior granite cores was particularly difficult because of the intact and ‘robust’ nature of the granite and therefore core depth was restricted to just 20 mm. This, however, was sufficient to demonstrate the low concentrations of sodium, chloride, calcium, sulphate and magnesium—a feature reflected in the absence of any evidence of significant structural deterioration. Regular washing of exterior granite surfaces by rainwater may be responsible for inhibiting salt accumulation and restricting mineralogical and structural degradation.

Micro-environmental conditions

Air temperature

Throughout the 12-month recording period, on a diurnal scale, air temperature data within Eeragh exhibited small-scale fluctuations of between 1 and 3°C. These diurnal fluctuations decrease with increasing height in the tower and may reflect the influence of rising warm air within the tower (Fig. 9a, b). Air temperature data from Eagle show slightly larger diurnal fluctuations with comparatively higher summer and winter temperatures than those recorded at Eeragh (Fig. 9c, d). These warm conditions are attributed to the combined effects of a large storage heater and the comparatively small size of the tower, which is more effective at retaining heat.

As expected, external air temperature was consistently lower than simultaneous conditions within the towers. This difference was particularly noticeable at Eagle where the presence of the storage heater created much warmer conditions within the tower and a greater temperature differential between interior and exterior environmental conditions.

Stone surface and subsurface temperatures

In general, patterns of rock temperature change are closely linked to air temperature fluctuations, increasing when air temperatures rise and vice versa. However, rock temperatures tend to be lower than air temperatures by several degrees Celsius primarily because stone is a poor conductor of heat, warming and cooling more slowly than air. Consequently, in the absence of direct heating, stone cannot respond rapidly enough to reflect either the frequency of changes in air temperature or the same degree of heating

Fig. 6 **a** Summary condition diagram for Eeragh (North Aran) with examples of elemental analyses of weathered surface material. **b** Summary condition diagram for Eagle Island with examples of elemental analyses of weathered surface material

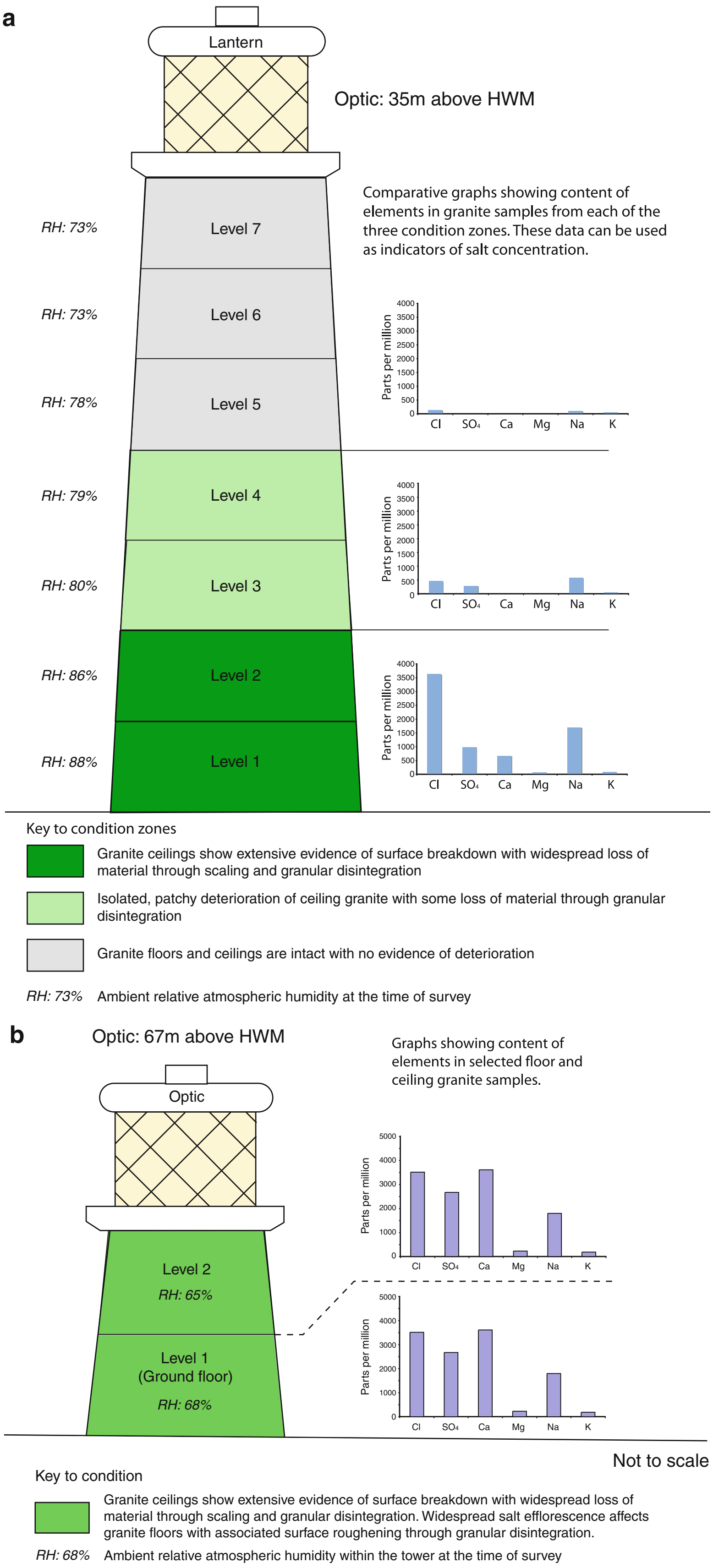
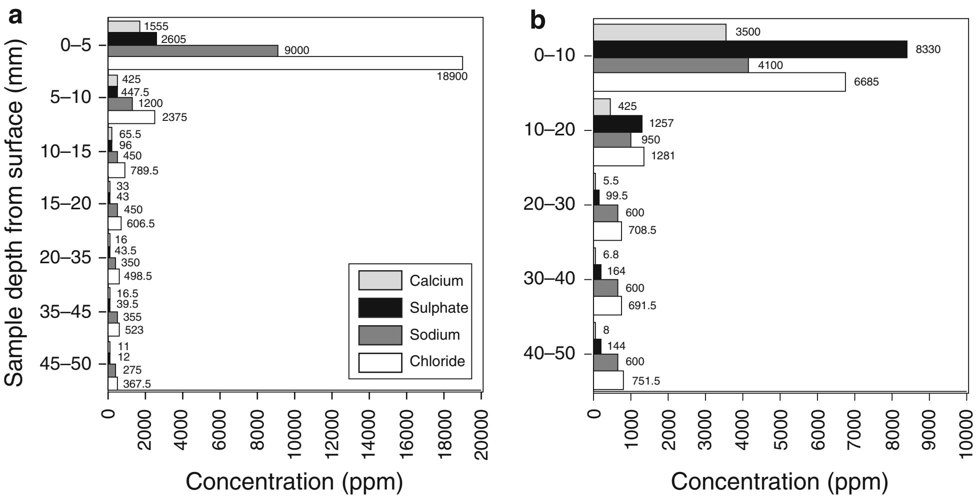


Fig. 7 Elemental analysis from IC and AAS of interior granite cores from Eagle Island and Eeragh lighthouses. **a** Eagle Island interior granite core. **b** Eeragh interior granite core



and cooling. Comparison between granite surface and subsurface temperature data showed little difference generally in the order of <1°C.

Relative atmospheric humidity

At Eeragh the most notable feature of relative atmospheric humidity (RH) data were the high values recorded in the lower two levels of the tower with values exceeding 70% for much of the 12-month recording period. Higher up within the tower, RH tends to be some 10–20% lower reflecting the higher air temperatures recorded here (Fig. 10a, b). RH conditions within both Eeragh and Eagle are characterised by short-term diurnal cycles with superimposed longer-term cycles lasting some 2–3 days and associated with external meteorological events. For example, RH values may exceed 70–80% during the passage of a frontal system and fall below this during more stable anticyclonic conditions although this will be spatially variable within the towers. It is important to note that at Eagle, the effect of the storage heater significantly affected RH data with the amplitude of both short- and long-term fluctuations being much greater and more frequent than those recorded at Eeragh (Fig. 11a, b).

Given their maritime location, it is not surprising that both sites are exposed to consistently high RH values. It is significant that the RH gradient identified within Eeragh corresponds with patterns of salt distribution and granite deterioration in the tower with both being greatest where RH values are consistently highest.

It is important to note that RH data reflect conditions approximately 5 mm above the granite surface at the rock/air interface. These data highlight the abundance of moisture and substantiate regular observations of condensation on the stone surfaces—conditions that have significant implications for weathering activity.

Discussion

Micro-environmental conditions and salt weathering

Although no quantitative data exist regarding conditions within the towers prior to automation and demanning, the former keepers who were stationed on the islands report that towers were well ventilated on an almost daily basis. This was achieved by opening the lower tower doors (weather permitting) and the venting slats in the upper optic levels. This caused a positive throughflow of air enhancing the draw of air up through the towers creating a ‘Venturi effect’ whereby the rate of airflow increases as it is constrained by the walls of the towers. Anecdotal evidence indicates that under such conditions episodes of condensation on interior stonework were rare probably because with almost constant air movement insufficient time was available for atmospheric vapour to condensate out onto cold stone surfaces.

However, since automation ‘still air’ conditions have prevailed within the towers because they are now effectively sealed between maintenance visits with the lower doors shut and the upper venting slats permanently closed. RH data indicate that the lack of ventilation within the towers creates conditions conducive to the development of condensation through the combination of high RH and stone surface temperatures that are consistently lower than air temperature. This is particularly relevant in the lower tower levels where dense and moist cool air tends to collect. High RH levels when combined with conditions of reduced airflow overlying cold stone surfaces for prolonged

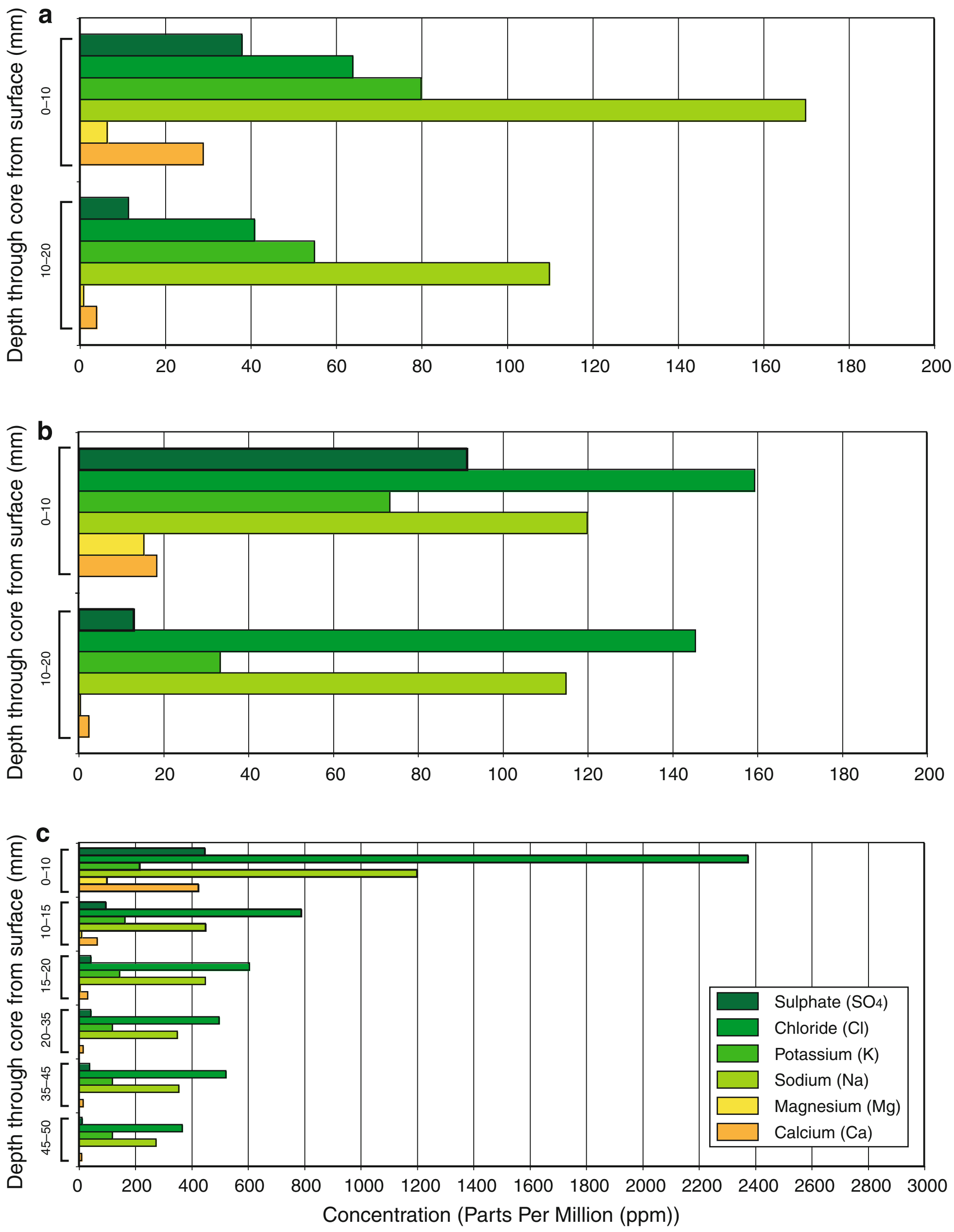


Fig. 8 Comparative elemental analysis of cores taken from the exterior and interior granite stonework of Eagle Island lighthouse. **a** Core from exterior granite stonework of Eagle Island lighthouse. **b** Core from exterior granite stonework of Eagle Island lighthouse. **c** Core from interior granite stonework of Eagle Island lighthouse

periods of time will facilitate the development of condensation. The stone cools the overlying air reducing its ability to hold moisture, which then condenses out onto the surface of the stone. The significance of this, particularly in a salt-rich environment, is that it provides a mechanism for the wet-deposition, surface accumulation and gradual penetration of salts into the fabric of the stone (Price 1993; Zezza and Macrí 1995; Goudie and Viles 1997; Camuffo 1998).

Significantly, the areas of most extensive granite weathering and disintegration correspond with zones of highest relative atmospheric humidity (RH) and the zones of greatest salt accumulation. One of the most commonly occurring salts in these towers is halite (NaCl). Halite is a strongly hygroscopic salt, which attracts moisture from the atmosphere—it is therefore said to be deliquescent. Deliquescence forms part of a complex process whereby

> "…condensation nuclei begin to absorb a number of water molecules, and then grow in size becoming first deliquescent, then a very concentrated hygroscopic solution and later a dilute solution…"
> (Camuffo 1998: p. 141–142).

Different hygroscopic salts exhibit particular threshold relative humidity values above which they start to deliquesce. These values are called the equilibrium relative

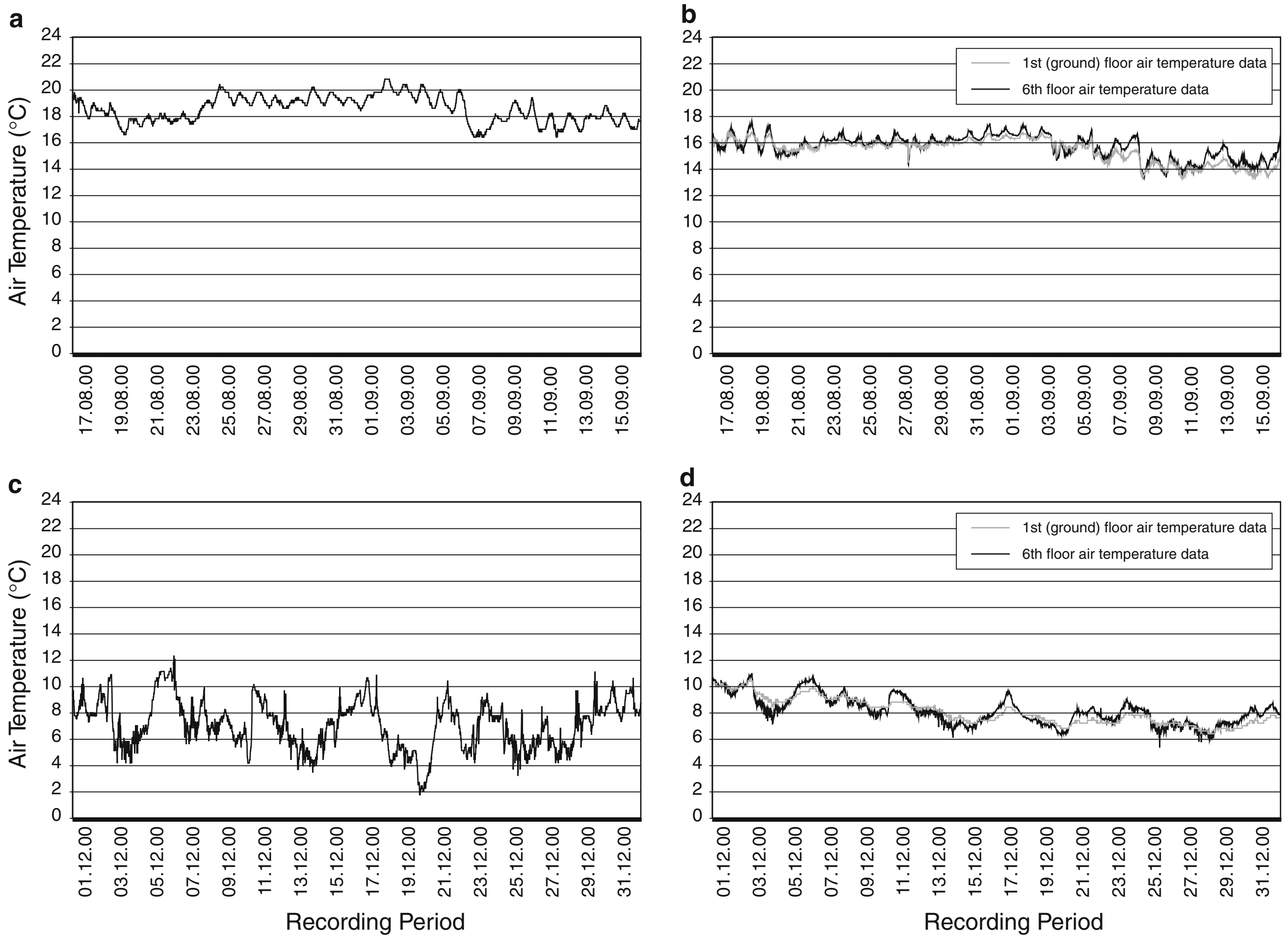


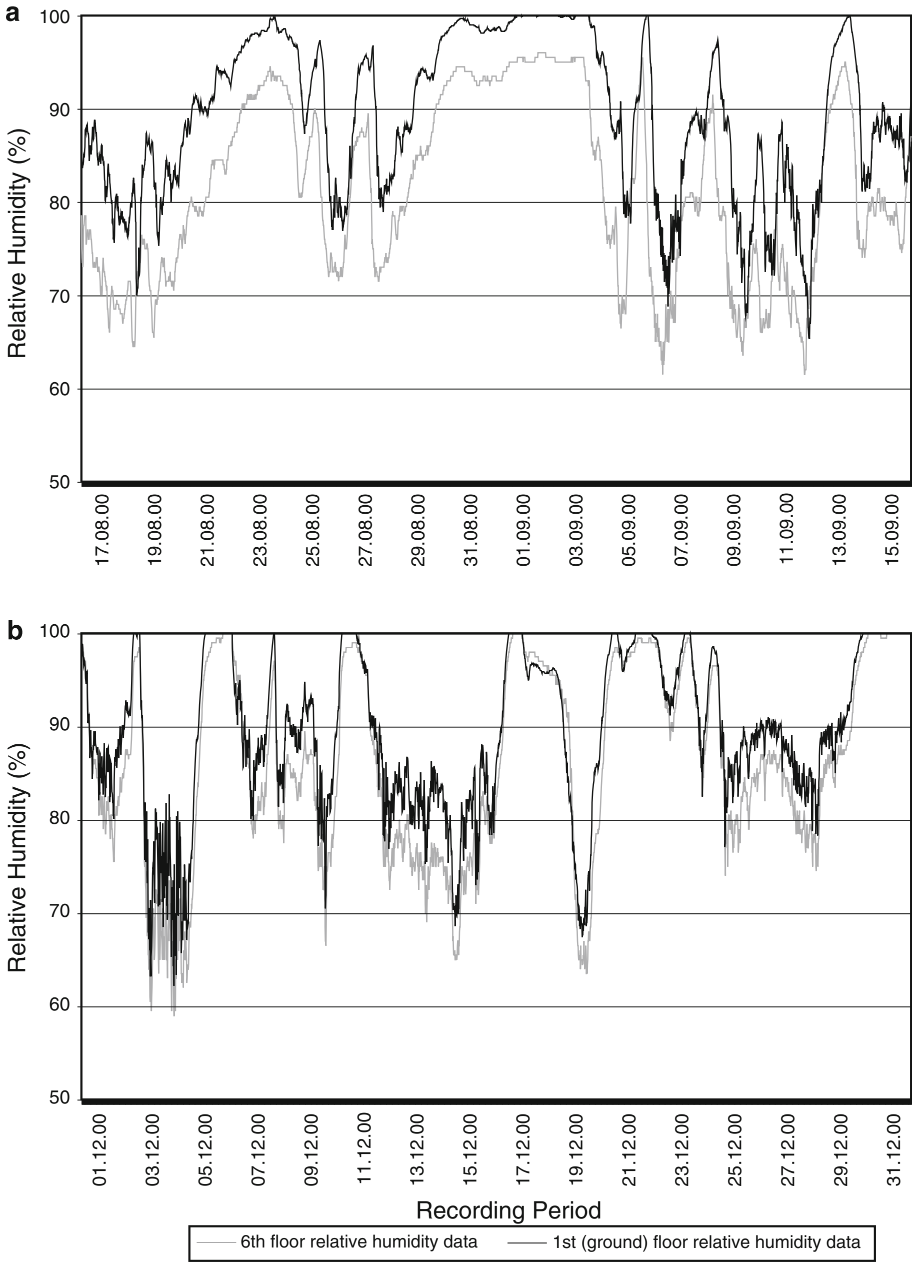
Fig. 9 Summer and winter air temperature data from within the Eagle Island and Eeragh lighthouses. **a** Eagle Island (Summer), **b** Eeargh, North Aran (Summer), **c** Eagle Island (Winter), **d** Eeragh, North Aran (Winter)

humidity threshold values. Laboratory experimentation on pure salt samples has shown the value of this for halite to be between 75.1 and 75.5% over a temperature range of between 0 and 30°C (Arnold and Zehnder 1990; Price 1993). Above the equilibrium RH value, hygroscopic salts will exhibit deliquescence, but if the ambient RH decreases below this the salt solution will become saturated and with a continued RH decline salt crystallisation will begin. Under ‘real world’ conditions where impurities abound, these equilibrium relative humidity threshold values may be quite different but they give an indication of the type of conditions under which deliquescence operates.

The significance of this for the weathering of interior granite stonework at both Eeragh and Eagle is fourfold:

- Condensation and deliquescence may accelerate surface deposition and accumulation of salts and through the presence of moisture facilitate dissolution of salt and its penetration into pre-existing joints and microfractures on the rock surface (Goudie and Viles 1997). Accumulation occurs because of the absence of any mechanism such as rainwash to remove or ‘control’ salt build-up.
- Due to the hygroscopic properties of salts such as halite, crystallisation damage is not dependent on cycles of wetting and drying such as might be required in the external environment. Consequently, relatively minor fluctuations of ambient RH to either side of the particular salt’s equilibrium RH are all that is necessary for repeated episodes of salt dissolution and crystallisation thus giving rise to a greater frequency of cycles compared with external conditions (Price 1993).
- Chemical weathering processes may be enhanced. This is particularly true for quartz which, although a normally durable mineral, can become more susceptible to chemical corrosion under the alkaline conditions associated with an abundance of salt with disruption of intergranular bonds and crystal lattices and dissolution of silica (Young 1987; Magee et al. 1988; Young 1988). Persistent alkaline conditions may also contribute to the disruption of alumino-silicate minerals (e.g. feldspars

Fig. 10 Summer and winter relative atmospheric humidity date from different levels within Eeragh lighthouse. **a** Eeragh, North Aran (Winter), **b** Eeragh, North Aran (Summer)



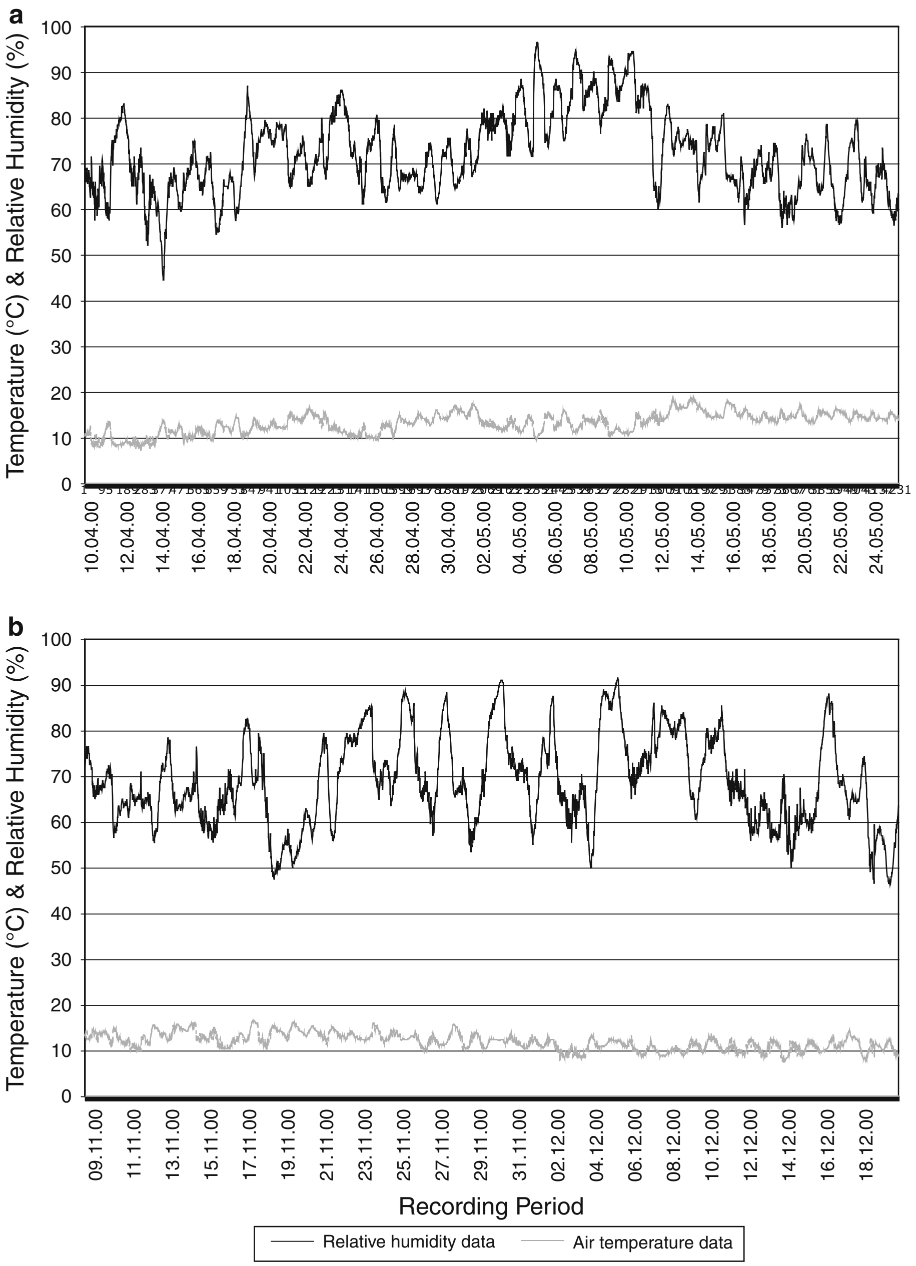
and mica) again associated with the degrading of the silica component of the mineral and disintegration of the crystal lattice.

- Deliquescence may actually inhibit salt crystallisation, especially when a stone surface becomes so loaded with salt that it remains almost continuously damp.

Evidence tends to suggest that at Eeragh and Eagle deterioration of interior granite stonework reflects complex interactions between chemical and physical weathering processes that have given rise to the spatial distribution of the weathering forms observed within the towers.

At Eeragh, granite weathering and breakdown is most severe in the lower three levels of the tower with the overall condition of stonework improving with increasing height above ground level. The highest concentrations of salt (particularly halite) and the highest RH values occur in the first floor level (ground floor) with the granite appearing damp to the touch. Obvious salt efflorescence occurs on the ceiling granite of the second level and to a lesser extent on the third level but is absent from the first level surfaces. The absence of salt efflorescence on the first level may be due to deliquescence where ambient RH levels and the extent of salt loading on stone surfaces are now sufficient to maintain a quasi-continuous state of deliquescence. The slightly lower RH levels and salt concentrations of the second and third levels appear to allow episodes of salt

Fig. 11 Air temperature and relative atmospheric humidity data from Eagle Island lighthouse. **a** Eagle Island Spring/Summer air temperature and relative humidity data **b** Eagle Island Winter air temperature and relative humidity data



crystallisation and development of efflorescence with deliquescence occurring only when RH and air temperature conditions permit.

At Eagle, the whole tower corresponds to the lower three levels of Eeragh and is therefore best characterised as a zone of salt accumulation. At Eagle, however, salt efflorescence occurs in patches throughout the tower and may reflect the effectiveness of the storage heater, which increases heating and hence air temperatures within the tower. When this is activated it creates conditions conducive to the drying of stone surfaces but when not active the high stone surface concentrations of halite in particular deliquesce as air temperature decreases and RH values rise. Granite deterioration at Eagle is much worse than that in the lower three levels of Eeragh. The accentuated temperature cycles caused by the storage heater and the associated similarly intense and frequent relative humidity oscillations appear to be driving the acceleration in granite decay.

Condensation has been cited elsewhere as an important mechanism for salt deposition and accumulation on stone surfaces (Camuffo 1984; Price 1993; Zezza and Macrí 1995; Del Monte and Rossi 1997) and at both Eeragh and Eagle it appears to have played a critical role in initiating the decay sequence. With the accumulation of salt, regular episodes of salt crystallisation followed by periods of deliquescence allow salts in solution to penetrate and exploit naturally occurring weaknesses and/or those initiated and developed by previous crystallisation pressures thereby giving rise to conditions of positive feedback.

Ironically, it is the abundance of moisture that helps to retard deterioration of external granite stonework. Regular washing by rainwater followed by thorough drying by wind enhanced evaporation and insolation prevents surface accumulation of salt. Halite in particular, is a highly soluble salt and it has been shown that under natural coastal conditions exposed rock surfaces often exhibit evidence of salt-related weathering but, may not contain high concentrations of the more soluble salts (Gumuzzio et al. 1982; Mustoe 1983; McGreevy 1985), particularly if conditions prior to sampling were wet. Comparison of IC and AAS data from external granite cores with those from the interior of the towers clearly exemplifies the impact of exposure conditions on salt accumulation and contamination of substrate material.

Granite decay sequence

Granite is widely perceived to be a durable lithology. It tends to have a relatively low porosity with constituent minerals that are comparatively stable under temperate conditions (Jones et al. 1996). The weathering behaviour of exterior granites on Eeragh and Eagle tends to support this perception of stability with only minimal evidence of structural and/or mineralogical deterioration identified. Such stability, however, will vary in response to factors such as the prevailing weathering environment (Gerrard 1994), the length of time exposed to subaerial conditions (Power and Smith 1994) and the efficiency of weathering product removal (Gerrard 1994; Goudie and Viles 1999).

Anecdotal evidence suggests that prior to automation interior granite stonework exhibited the same apparent immutability as external granite. Since then, however, interior granite has switched from a condition of comparative stability to one of accelerated deterioration. The trigger for this change in response appears to have been the change in micro-environmental conditions within the towers, especially with regard to airflow characteristics. It is important to note, however, that there is a spatial variation within the towers regarding the severity of granite deterioration. Granite in the lower levels is well established in the decay sequence while granite decay on the upper floor levels may either be at a less advanced stage or has not yet started (Fig. 12). This sequence is best established in Eeragh where the height of the tower has contributed to the creation of a clearly defined gradient in micro-environmental conditions.

Obvious surface deterioration of interior granite stonework forms only one part of the deterioration process. Friable surface material may be merely a tangible expression of more complex and unseen changes taking place within the substrate material—changes closely associated with the migration of a ‘weathering front’ into the stonework (Warke and Smith 2000). As surface material is loosened and lost through the combined effects of salt weathering and chemical destabilisation of minerals, deliquescent salts will migrate in solution further into the substrate by exploiting micro-fracture networks. The transition from salt-rich altered stone to mineralogically and structurally intact substrate material marks the ‘weathering front’. This ‘weathering front’ will continue to migrate into the stonework as long as friable surface material continues to be removed or lost from the system, thereby exposing a ‘new’ surface to the continued sequence of salt accumulation, crystallisation and chemical weathering, structural weakening, failure and progressive surface retreat.

Management

Central to any discussion of management options is recognition of the fact that first and foremost these historic structures fulfil an operational role as navigation aids for the mariner and that conservation of their historic fabric is more of a secondary concern. Consequently, in their management a balance exists between achieving the ‘ideal’ in terms of conservation intervention and what can actually be achieved within budgetary constraints and the technological demands of the service.

The primary management action in the case of both Eagle Island and Eeragh lighthouses was to improve airflow within the towers by trialling vents in external doors and windows on the ground level and by reopening ventilation slats in the optic level to encourage the throughflow of air. This work is ongoing. Unfortunately, it is not possible to return the interior granite stonework to its pre-automation condition because of the structural and mineralogical changes that have already occurred and which have resulted in considerable salt loading of surface and subsurface granite, especially in the lower levels of the towers. The aim of management intervention is twofold:

- To avoid any future intervention that may inadvertently contribute to granite decay
- To slow or control current rates of deterioration.

Conclusions

Stone decay is a complex subject involving the interaction of several controlling factors. Laboratory analysis of granite samples and assessment of micro-environmental data have identified the major factors responsible for

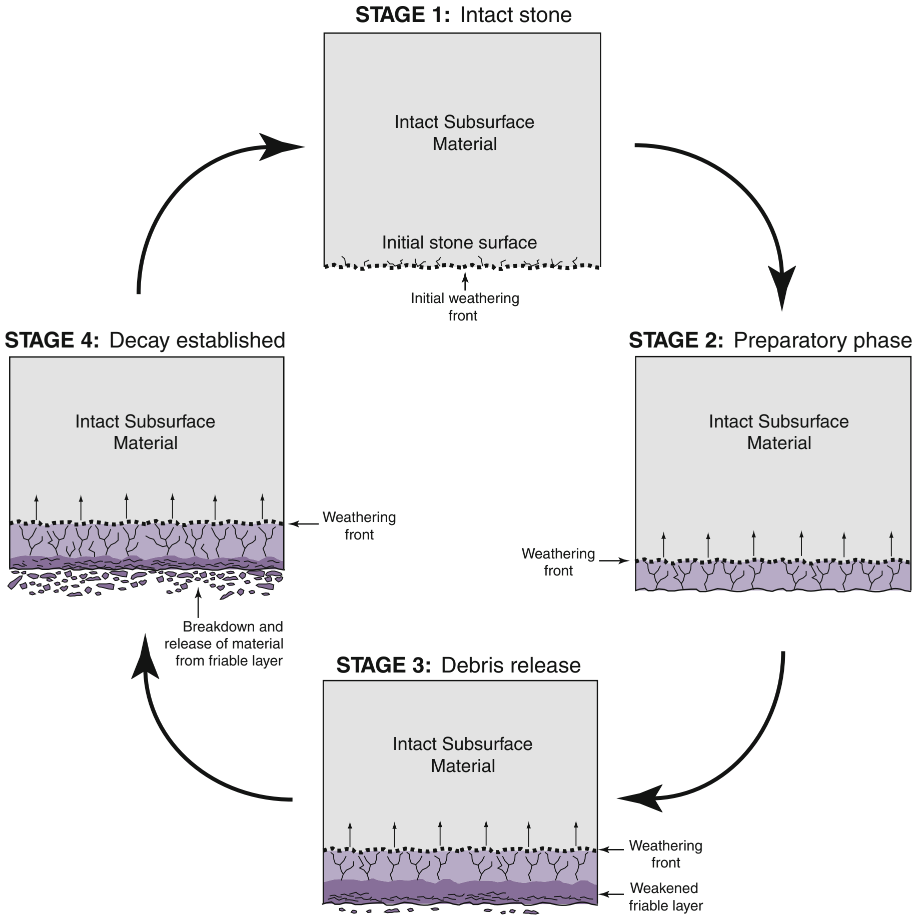


Fig. 12 Conceptual model showing the different stages of the granite decay sequence at Eeragh and Eagle Island lighthouses. *Stage 1* surface flaws and discontinuities facilitate some salt penetration under conditions of limited condensation but with reduced ventilation and more frequent episodes of surface condensation, salts start to accumulate. *Stage 2* micro-fracture networks initially developed at the stone surface begin to extend into subsurface material as a result of salt weathering and chemical alteration which break or weaken intergranular bonds and degrade the lattice structure of individual mineral grains. *Stage 3* positive feedback conditions prevail whereby release of weathered surface material facilitates further salt/moisture penetration which in turn maintains development and extension of microfracture networks with a gradual migration of the weathering front into intact subsurface material. *Stage 4* loss of weathered material aided by the effect of gravity results in progressive surface retreat of granite blocks and facilitates inward movement of the weathering front—once established, the decay sequence is difficult to stop especially in the context of a salt and moisture-rich environment where reduced ventilation and condensation persist

accelerated decay of interior granite stonework at Eeragh and Eagle observed since automation.

- The structural and mineralogical characteristics of the granite used in construction of the towers make it naturally more susceptible to decay when exposed to exploitative weathering processes. The granular nature of the rock and, in particular, the abundance of mica and feldspar minerals and an in-built microfracture network, provides many potential access points for salts in solution on rock surfaces.
- The availability of salt and moisture is an important factor controlling deterioration. Salts in solution enter the stone through pre-existing microfractures and mineralogical flaws. When temperatures fluctuate, these salts can crystallise out of solution exerting considerable pressures on confining material with repeated episodes of crystallisation leading to a gradual weakening of intergranular bonds through fatigue effects and, eventually to the release of surface material primarily through granular disintegration. An abundance of salts also gives rise to conditions of increased alkalinity, which has implications for the stability of normally durable elements such as silica.
- Reduced airflow in combination with the availability of atmospheric moisture contributes to the development of condensation on stone surfaces when air saturated with moisture overlies colder stone. If the parcel of air is relatively static, it is cooled by the stone, which reduces its moisture holding capacity to the point where condensation occurs. In addition to providing a source

of salts, the significance of condensation on stone surfaces is that it provides the mechanism for getting salts into solution and thus facilitating their ingress into the fabric of the stone.

The data presented here clearly highlight the inherent complexity of this particular weathering system and demonstrate the ease with which a previously stable system can be destabilised through the introduction of well-intentioned changes to micro-environmental conditions within the towers. These data also demonstrate the potential fragility of these iconic historic structures and the potential threat to their long-term existence. However, first and foremost these are operational historic buildings and as such, compromises have to be made between maintaining an acceptable level of conservation of the historic fabric and the operational requirements of the service. Achieving this balance will undoubtedly become increasingly challenging in the future as these structures continue to age and the financial support available comes under increasing pressure.

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