Environmental Earth Sciences

URBAN GEOMONUMENTAL ROUTE FOCUSING ON THE PETROLOGICAL AND DECAY FEATURES FOUND IN TRADITIONAL BUILDING STONES USED IN MADRID, SPAIN

--Manuscript Draft--

Manuscript Number:	
Full Title:	URBAN GEOMONUMENTAL ROUTE FOCUSING ON THE PETROLOGICAL AND DECAY FEATURES FOUND IN TRADITIONAL BUILDING STONES USED IN MADRID, SPAIN
Article Type:	SI: Urban Use of Rocks
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Abstract

The stone traditionally used to build cities contributes to their personality and attests to the geological substrate on which they stand. While stone decay in the built heritage can be attributed to a number of causes, anthropic activity has a particularly significant impact. The Geomonumental Routes project is one of the initiatives proposed in recent years for urban routes that convey geological fundamentals by observing the rocks present in heritage structures. Its innovative approach addresses traditional stone properties, original quarrying sites and mechanisms of decay.

Madrid's Royal Palace is a fine example of the use of traditional building stone in the centre of the Iberian Peninsula. In the geomonumental route proposed, the building doubles as an *in situ* laboratory that affords an overview of the main petrological properties of the two traditional stones most commonly used in the city's built heritage, the forms of decay they are subject and the factors underlying such alterations.

This route aims to constitute a tool for showing the main petrological features and decay forms in the traditional building stones found on urban heritage façades, with a special focus on anthropic impact, primarily air pollution and the use of conservation treatments that time has proven to be unsuitable.

Keywords: urban geology, granite, limestone, building stone decay, petrology

1. INTRODUCTION

1.1. Traditional building stone and its decay processes

Stone provides personality to built heritage and leads to common associations between stone type and places (Gomez-Heras et al. 2010). Authors such as Echevarría and García (1996) define traditional stone as a high strength material normally laid as unpolished structural blocks, quarried locally and used regularly over time in a given place or region. Assuming proximity to be the main determinant in its use, traditional stone is associated with the geological substrate in or around the respective cities and towns. Such stone also contributes directly to their image and constitutes one of their most distinct personality traits. In Madrid, the use of building stone has varied over the centuries due primarily to changing architectural aesthetics, supply problems and development of roads and transports. Madrilenian architecture has gone from using traditional stone quarried in the region to importing natural stone from other areas of Spain and even other countries (Gomez-Heras and Fort 2004)

Rock weathering and building stone decay are both essentially induced by the interaction between stone and environmental agents and air pollution, respectively, leading at times to progressive and often intense and accelerated alteration. Both intrinsic and extrinsic factors decay agents can be identified, although considering them separately is no easy task (Gomez-Heras 2006). Intrinsic factors are highly conditioned by the petrological properties of building stone, while extrinsic factors are broader and more varied, ranging from environmental agents to the simple lapsing of time. A lead role in the latter is played by factors directly or indirectly related to human impact, such as air pollution (especially in urban environments), construction methods or interventions that with time have proven to be inappropriate (Pope et al. 2002; Figueiredo et al. 2008; Siegesmund and Snethlage 2011).

1.2. The urban use of the rocks: Geomonumental Routes

With the advent of a wide variety of initiatives over the last few decades designed to draw attention to the geology associated with the rocks in urban buildings, the term *urban geology* has been gradually accepted, and cities have entailed open and outdoor geological museums.

Studies first conducted in the nineteen eighties and nineties began to map urban itineraries to highlight the building stones used in city construction (e.g. Slagle 1982; Doe 1989; Richter and Simmons 1993; Withington 1998). More recently, a number of authors have published papers addressing the geological substrate and risks that condition city growth (e.g. Berti et al. 2004), establishing urban geological routes as a geo-touristic resource (e.g. Rodrigues 2011) or explaining the geological history of different stone types employed at building structures (e.g. Williams 2009). Moreover, many urban geology projects and initiatives focusing on the urban use of rocks have embraced new technologies (e.g. FOP 2010; The Geologic Turn 2012).

Smith and Warke (1996) or Gaffikin (1999) involve prominent studies on the use and decay of traditional stone in the built heritage. Based on these considerations and the research carried out on heritage conservation by the authors of this paper, they have developed the Geomonumental Routes project, an initiative also available on-line (Fort et al. 2005; Alvarez de Buergo et al. 2008; Gomez-Heras and Smith 2009).

The Geomonumental Routes approach constitutes a methodology to raise public awareness of the built heritage, the earth sciences and scientific research applied to its conservation, proposing geology as an added value in this regard (Alvarez de Buergo et al. 2007). The prefix geo- denotes how geology strongly influences the location of urban settlements and establishes the relationship between historical sites and geology, as humans extract the materials needed for their built structures from the earth (Perez-Monserrat et al. 2006). Such routes identify the buildings materials comprising heritage constructions, explain the role of its petrological properties in structures, attend to quarries of provenance or geological formations, list the interventions undertaken and describe the building surroundings development, paying particular attention to the forms of decay and their alteration-inducing factors (Fort et al. 2005).

2. GEOMONUMENTAL URBAN ROUTE: PETROLOGICAL AND DECAY FEATURES IN TRADITIONAL BUILDING STONES USED ON MADRID'S ROYAL PALACE

The urban geomonumental route proposed focuses around Madrid's Royal Palace. In this route the palace is viewed, on the one hand, as an outdoor geological museum in terms of both formation and petrological properties of the traditional stone varieties used to build it (Fort et al. 1996, 2011; Fort and Gomez-Heras 2007). On the other, it is seen as an on-site urban laboratory that allow to understand the interaction between building stones, decay forms and causes of alteration (Fort et al. 2000, 2003; Varas et al. 2007). Careful observation of its façades constitutes a lesson in petrology and conservation science.

Today the Royal Palace is located in the very heart of the city, an area surrounded by emblematic tourist and cultural attractions that draw many visitors (Figure 1). The hill now occupied by the palace, near the River Manzanares and circled by fertile soil, formerly housed a walled Muslim fortress built around 852 as a military outpost to defend the city of Toledo. That structure gave way to a wooden fortress subsequently built by the Habsburg dynasty. When it burned down in 1734 it was replaced by the present palace, built up mainly with granite and limestone (Fort et al. 1996). The palace was constructed between 1738 and 1764 by Filippo Juvarra, after his death the works were continued by Juan Bautista Sachetti, who modified the original design. It was restored between 1944 and 1964, the granite blocks were replaced on the west façade, destroyed during the Spanish Civil War (1936-1939). Cleaning and conservation operations were carried out in 1975. The surrounds underwent substantial remodelling in 1995-1997, Bailén Street was run underground and the immediate area was transformed into pedestrian, reducing the pollution levels (Fort et al. 2004a). Between 2001 and 2003 the façades were thoroughly cleaned, the stone elements were consolidated and some of the limestone replaced.

This geomonumental route covers the north, east and south façades of the Royal Palace, with five stops in accessible areas (Figure 1). The issues addressed, which are inter-related and visible at the various stopping points, focus primarily on building stone geology, construction and decay topics.

2.1. Traditional building stones

The Royal Palace is largely built with two types of stones traditionally used in central Spain, known locally as *berroqueña* stone and *Colmenar limestone*. Both outcrop in the region of Madrid geological substrateand and their optimal properties have determined its ongoing use in construction to date.

The adjective *berroqueña* derives from the noun *berrueco*, a local term local term used to designate the spheroid granitic boulders owed to weathering (Røyne et al. 2008). This stone has been used continually in Madrid from the eleventh century, and most assiduously beginning in the sixteenth. The granite in the city's buildings was quarried from essentially two plutons: Zarzalejo in the sixteenth and seventeenth centuries and Alpedrete afterwards. The granite originally used to build the palace was quarried from the Alpedrete pluton and the replacement stone on the west façade was taken from Zarzalejo.

The construction of the Royal Palace established new stone usage in the city, and limestone became a key architectural material for contemporary court structures. Its use was enhaced by the improvements in both inland roads and quarrying techniques. This limestone was quarried from seven banks, but especially from the so-called *Banco Gordo* (Dapena et al. 1988). The quality, whiteness and purity of the limestone quarried at Colmenar de Oreja fostered that location provided the *Colmenar stone or limestone* generic denomination, even though its geological formation were quarried in other nearby sites. Both the original limestone in the palace as a whole and the replacement material on the west façade were extracted from the *Banco Gordo*, although based on its petrological properties, the replacement limestone might have been quarried from the so-called *Sobrebanco* (Fort et al. 1996).

The colour contrast obtained by combining the city's traditional building stones, grey *berroqueña stone* and white *Colmenar stone*, is characteristic of contemporary Madrilenian architecture.

2.2. Urban Geomonumental Route

2.2.1. First stop: traditional building stones and surface staining (northeast corner)

This stop highlights the magnificence of the palace, the uneven topography of the terrain and the traditional building stones arrangement on its façades. The causes of the surface stains observed are also explained.

The palace is built on a basement (0) designed to accommodate the differences in terrain elevation. The façades comprise three main levels (Figure 2a): socle (1), lower level (2) and upper level, topped with a balustrade (3). The granite blocks in the socle are staggered outward at the corners for greater stability, and the horizontal disposal of the lower level contrasts with the upper level verticality.

The *berroqueña stone*, consisting primarily of different sizes blocks, shapes the smooth walls of the basement, socle and upper level. The elements adorning the window frames of the basement and the voussoir-like stones forming the lintels in the openings of the socle are likewise made of granite. The granite ashlars on the corners of the socle and lower level are cushioned, this effect was attained by rounding off and trimming the side surfaces of the ashlars. *Colmenar stone* conforms the bottom of the socle, imposts, parapets, balustrades and sculptures. The upper level columns and pilasters, as well as the window frames in the lower and upper levels, are also made of this limestone.

The 2002 cleaning operations revealed a series of stains on the granite and limestone surfaces, which became more visible after the stone was cleaned and can still be seen today (Figures 2b, 2c and 2d). Varas et al. (2007), who identified dark stains primarily on the granite and brownish blemishes also on the limestone, found that the highest moisture values in the dark stains on the granite (Figure 2e). The analysis (Figure 2f) showed that these stains were generated essentially by the microcrystalline wax contained in water repellents applied in 1973 and the ethyl silicate components of the consolidants applied in a subsequent intervention. Over time, both treatments formed waterproof films that prevent the water evaporation from the interior towards the surface of the stone elements.

These same authors observed that considerable amounts of gypsum were generated under the wax and that sodium-based compounds had probably been used to attempt to remove it prior to applying the consolidant. These cleaning products, which failed to eliminate all the wax, were not fully neutralised before applying the ethyl silicates. As a result, in addition to gypsum, sodium sulfates and nitrates (primarily thenardite and nitratite) formed underneath the consolidant (Figure 2f). As neither of the treatments was eliminated during the 2002 pressurized water jet operations, the use of other cleaning methods should be considered for future interventions, subject to prior testing.

The brown stains, located mostly on the limestone below cornices and imposts, can be attributed to the filtration of rainwater leaking out of downpipes onto the joints (Figure 2d), which clay fill showed significant loss of cohesion (Varas et al. 2007), and favored by the rusting of some of the metal clamps as well (Fort et al. 2004b).

2.2.1. Second stop: *berroqueña stone* and *Colmenar limestone* petrological features (east façade)

The *berroqueña stone* covers monzogranites, granodiorites and leucogranites with varying petrographic and petrophysical characteristics (Fort et al. 2011) and comprise several plutons (Villaseca et al. 1998, 2000). Their outcrops cross the region of Madrid from north to northeast along the Guadarrama Mountain Range (Central System, Variscan Orogeny). One characteristic feature of the *berroqueña stone* used in the Royal Palace is the presence of what quarrymen call *gabarros*: the dark, elliptical and microgranulated ferro-magnesium enclaves seen on the stone surfaces (Figures 3a and 3b). While these enclaves are not exclusive to *berroqueña stone*, they are particularly abundant in the Alpedrete and Zarzalejo plutons (ITGE 1990).

The Alpedrete and Zarzalejo plutons consist of biotitic monzogranites with a phaneritic and hypidiomorphic texture. Alpedrete monzogranite is equigranular, fine- to medium-grained, with scattered cordierite and a 10% biotite content, while the Zarzalejo monzogranite is somewhat less equigranular, with a medium to coarse grain and a higher biotite content (Fort et al. 2011). Porphyritic varieties may also occur locally in the Alpedrete pluton (ITGE 1990). Occasional phenocrystals can be observed in some of the granite ashlars visible from this stop (Figure 3b).

The majority minerals in the *berroqueña stone* used on the east façade of the Royal Palace, quarried from the Alpedrete pluton, are quartz, potassium feldspar, plagioclase and biotite (Figures 3d and 3e). The alteration minerals observed include sericite (formed from the plagioclases calcium cores), chlorite (neo-formed biotite product) and pinite (micaceous aggregates resulting from cordierite alteration). The accessory minerals identified are apatite, cordierite and certain radioactive minerals, mainly zircon and monacite. The quartz crystals are globular, heterometric and allotriomorphic and exhibit fluid inclusions. The poikilotopic potassium feldspar crystals are allotriomorphic and contain perthitic exsolutions. Plagioclase appears as idiomorphic and subidiomorphic, zonated and macled crystals (Fort et al. 1996, 2011).

The table in Figure 3 gives the values of some of the petrophysical properties of the biotitic monzogranite seen from this stop, both taken from the quarry (Fort et al. 2011) and the façades´s palace (Fort et al. 1996). The high ultrasonic velocity and low percentages of porosity accessible to water and water absorption indicate that it is a building material highly suitable for dimensioning very strong and water-resistant structures. The differences found between the outcrop and the construction recorded values are mostly due to granite blocks decay on façades.

Colmenar stone or limestone is a fluvial-lacustrine carbonate from the Upper Miocene Unit in Madrid's southeastern Tertiary basin (Alonso-Zarza et al. 1993; Calvo et al. 1996; Sanz-Montero et al. 1995). The lithological heterogeneity of the basin margins and their palaeoclimatic evolution were the main determinants in the formation of the complex mosaic of fluvial-lacustrine systems where the Miocene carbonatic series was deposited.

Petrographically, *Colmenar stone* is a biomicrite/biosparite (Folk 1959) with a skeleton consisting primarily of characeae, ostracod and gastropod bioclasts. Its micritic matrix alternates with sparitic cement (Figures 3f and 3g). High ultrasound velocity, compactness, low porosity (table in Figure 3), and a pore size distribution primarily in the 0.1-0.01-µm range (Fort et al. 1996) attest to the excellent quality, strength and durability of this stone. Pore concentration in the smallest sizes (i), where capillary pores are virtually non-existent, affords *Colmenar stone* high resistance to freeze-thaw and salt crystallisation processes.

2.2.3. Third stop: decay forms mainly observed at *berroqueña* stone (east façade, right of main entrance)

Alpedrete monzogranite is highly decay-resistant due essentially to its small crystal size, low biotite content, low capillarity coefficient and scant anisotropy (Fort et al. 2011). Nevertheless, the granite ashlars viewed in this stop exhibit decay in the form of granular disruption and surface spalling. Alteration material seen on the stone elements that shape the parapet and spalling and other weathering forms associated to micro-granular enclaves are also addressed during this stop. Here, the human activity plays an important role in the spalling formation. On the one hand, the façade is placed quite close to a heavy traffic street and, secondly, the high visitors' affluence must be taken into account, as the main entrance to the palace is very near located.

Granular disruption is only observed in the first row of granite ashlars over the limestone socle (Figure 4b). This decay form is majorly related to the kaolinisation of feldspars; a weathering processes that weakens the granite microfabric and enhances building stone decay. This process could probably be accelerated by wet and dry fluctuations (Goudie 1986), that took place in the contact between granite and limestone. Besides, the traffic pollution proximity plays an important role, as in moist and acid urban environments, CO_2 and SO_2 from air pollution hastens feldspar kaolinisation (Schiavon 2007).

It has been suggested that stone spalling is the result of cycles of wetting and drying associated to dissolved salts (e.g. Amoroso and Fassina 1983). This is supported by its confinement to the capillary rising areas of the building and the observation of salt crystals and biological growth beneath the detached areas. However, as discussed by several authors (e.g. Smith et al. 2011), the internal temperature gradients, and specifically multiple temperature reversals with depth, may be of crucial importance to condition the thickness of spalling. In addition to this, stone properties, such as capillary coefficient, will influence their thickness.

The spalling seen from this stop (Figures 4a and 4c) may be related to the presence of sulphates, subject to crystallisation-dissolution and hydration-dehydration due to the natural wet/dry cycles affecting the stone. Gypsum formation from the interaction between monzogranite and atmospheric SO_2 and from the use of gypsum mortars, would supply calcium sulphates (Silva et al. 2010). Although granite reactivity with SO_2 is low in general, granites located in urban areas may be sulfated via the reaction of gaseous SO_2 with the calcium available from plagioclase alteration (e.g. Schiavon 1994). The calcium required to form the gypsum might be provided by the plagioclase sericitisation of the monzogranite (Fort et al. 2003), and from the dissolution of stone elements built with *Colmenar limestone*.

Furthermore, Varas et al. (2007) reported the use of gypsum mortars in palace construction, besides cement and lime based mortars. The XRD analysis of altered material displayed on the stone elements that makes up the window parapet in this area (Figure 4a) reveals that majorly consists of dolomite, gypsum and epsomite (Figure 4d). The presence of epsomite could reveal the use of dolomite and/or magnesium lime-based mortar as a source of magnesium supply. The gypsum based mortars also employed and/or the gypsum generated from granite sulfation would provide the sulfur required. Therefore, the presence of calcium and magnesium sulfates could take part in the formation of the observed spalling at this stop on the granite blocks. This information yields data that certainly require further investigation, based on constructive aspects and/or interventions occasionally accomplished in this area.

The micro-granular enclaves show a very different texture and mineralogy than the surrounding host rock. Petrographically (Figure 4e), they show fine-grained porphyritic textures, with phenocrystals commonly of millimetric size, mainly idiomorphic plagioclase and biotite. The groundmass phases consist of plagioclase, biotite and quartz. The enclave's average crystal size is much smaller than in the host rock, plus they are darker in colour and, therefore their albedo is much lower; for example, CIELab parameter L*=58±4 in the enclaves versus L* = 66±4 in the host rock for the same type of granite in other buildings of the city (Gomez-Heras 2006).

In addition to the visual heterogeneity, the different properties of the enclave and the host rock are often reflected in a dissimilar decay pattern between enclaves and host-rock. Quite often, the enclaves display faster decay rates than the host rock and therefore concave shapes in the building blocks (Figure 4f). However, in many occasions this trend is opposed and the enclaves stand proud of the surface forming a positive relief. Although, enclaves appearing more weathered than the surrounding host rock seem to be a more common feature on building façades than the opposite, the reasons for these contradictory features are still not fully understood.

Gomez-Heras et al. (2008) suggested that overheating of enclaves as a result of their lower albedo as well as lower conductivity and heat capacity, might be a factor accelerating the decay of these features in relation to the surrounding rock. As figure 4g shows, the darker surface of a micro-granular enclave heats far more than the surrounding rock under conditions of direct sunlight. The influence of thermal properties on the decay of these features would be supported by the higher occurrence of what Gomez-Heras et al. (2008) called *differential* spalling – i.e. spalling affecting only to the enclave and not to its surrounding – in the aspects of a building showing more short-term thermal cycling. Differential spalling (Figures 4h and 4i) would be identified as a very thin detachment of stone which barely affects to the first plane of crystals and which is confined only to the enclave. In contrast, the rest of spalling in the building would correspond to the definition of spalling as a particular case of contour scaling in a flat surface (such as a façade) in which detachment is generally of millimetric to centimetric scale and *is not following any stone structure* (ICOMOS glossary). This spalling is much thicker than the previously discussed and would be found crossing the enclaves (Figures 4j and 4k).

2.2.4. Fourth stop: blackenig and soling decay forms on building traditional stones (east façade, left of main entrance)

This stop focuses on the decay forms specially affecting *Colmenar stone*, also closely related to human activity. The façade faces a street with both dense vehicle traffic, exposing the stone to air pollution, and a constant flow of pedestrians walking very close to the building stones.

High levels of sulfur dioxide (SO_2) and particulate matter (PM) are among the primary causes of traditional building stone decay in polluted urban areas. Carbonatic stone is particularly sensitive to surface sulfation and the development of black crust due to progressive particulate matter deposition (Winkler 1997; Bonazza et al. 2005). Such physical and chemical decay is very harmful to building stone and detracts substantially from the aesthetic value of heritage buildings (Grossi and Brimblecombe 2008).

SO_2 induces limestone sulfation; in the presence of oxygen it is converted into sulfur trioxide, forming with water sulfuric acid. In the existence of moisture, this acid combines with the calcium carbonate in the stone substrate to form calcium sulphate (Camuffo et al. 1983; Ausset et al. 2000; Lefèvre et al. 2007). Most anthropic combustion processes generate particulate matter (Ghedini et al. 2000) and the type that prevails in polluted areas, metal element-rich carbonaceous particles, is directly involved in façade soiling (Brimblecombe and Grossi 2005).

Nearly a decade after the Royal Palace façades were thoroughly cleaned, their differential blackening and soiling are visible from this stop. These two processes take place jointly on building stones located in urban environments, although the factors involved and the decay forms generated differ. Blackening, caused by surface sulfation and the progressive deposition of particulate matter, induces physical and chemical decay in the stone, especially of carbonate composition, generating black crust. Soiling, defined as a *visual nuisance that can be undone with cleaning* (Haynie 1986), induces aesthetic decay. In the façades palace, blackening majorly affects *Colmenar limestone* (Figure 5a) and soiling both limestone and granite (Figure 5b).

Before the palace surrounds were remodelled in the nineteen nineties, black crusts were seen primarily on its north and east façades, the ones most directly exposed to heavy traffic. A reading station positioned alongside the east façade (where it was Bailén St) measured atmospheric pollutant concentration between 1994 and 1998, before and after remodeling. Fort et al. (2004a) compared the data and found that the concentration of most of the pollutants had declined in that period: 53% for PM, 42% for SO_2 and 25% for NO_x (Figure 5c). The authors likewise analysed the black crusts, developed primarily in areas protected from the rainwater but with high levels of moisture. They report that these crusts were composed primarily of gypsum and different types of particulate matter were deposited on them (Figures 5d, 5e and 5f).

Soling pattern façades is largely conditioned by the surface properties of the building stones and the design of the walls. While stone colour does not affect particulate matter deposition, it does contribute to the greater perception of façade soiling (Grossi and Brimblecombe 2007). Hence, the contrast between cleaned and uncleaned areas is more evident in the elements built with white *Colmenar limestone* than in the grey *berroqueña stone* (Figure 5b). Since stone porosity favours the entrance and remains of particulate matter, limestone in general is more susceptible to these processes than granite. Stone carving also condition soiling; in the cushioned granite blocks, for instance, particles are more likely to accumulate on the horizontal planes (Figure 5g) and, in the wide joints between ashlars they are more difficult removed by rainwater and/or wind. The moulding and embellishments in some of the limestone elements, such as the carved dripstone that protects the vertical surfaces below from the rain (Figure 3c), act as particulate matter container. Soiling is less uniform in the areas affected by runoff, where the stone surface is washed by water flowing over the successive setbacks from the main plane of the façade (Figures 5a and 5b), particularly along the joints (Figure 5h) and/or fracture lines of stone elements (Figure 5i).

Even though SO_2 emissions have declined drastically in recent years, building soiling continues because of the high levels of carbonaceous particles still emitted (Sáiz-Jiménez et al. 2003; Ghedini et al. 2000). Moreover, while practically all the palace surrounds were pedestrianised and Bailén Street's lanes of traffic now run underground, the building stone visible from this stop is very close to a street that is still heavily travelled. Furthermore, the southeasterly direction of the prevailing wind favours the distribution of particulate matter on the east façade (Fort et al. 2004a). Another factor that may contribute to soiling is the application of certain types of protective treatments, as reported by Fort el al. (2002). The *in situ* application to trial areas of the building, particularly on the limestone, has shown that as a rule the use of such products, irrespective of their effectiveness as water repellents, induces greater particle matter accumulation in the treated than in the untreated areas.

2.2.5. Fifth stop: Miscellaneous (south façade)

This stop, which culminates the route, illustrates geological, constructive and decay forms not previously seen in either *berroqueña* or *Colmenar stone*.

Occasional streaks known as *schlieren* can be seen in the *berroqueña stone* (Figure 6a). These dark streaks, consisting majorly of biotites, were formed in the rock when enclaves were elongated by a molten flow (Barrière 1981; Weinberg et al. 2001). The constructive elements include columns consisting of several ashlars (Figure 6a) or a single block (Figure 6b), and ashlars cushioned either on all their visible surfaces or only on the side facing Almudena Cathedral (Figures 6a and 6b). The surface stains on stone due to the rusting of the iron elements (Figure 6b) constitute a type of decay not observed in the previous stops. Fort et al. (2004b) studied the iron elements used to join and anchor the stone and reported that their expansion as a result of water entry induces cracking in the stone support where they are set.

Colmenar limestone is used in the same constructive elements, although the stone pieces that shape the socle of the metallic fence and the entrance to the Arms Courtyard are built with different varieties of limestone than the white one described previously (Figures 6c and 6d). These limestones are also Miocene fluvial-lacustrine carbonates from the Madrid Tertiary basin, but were quarried either at near sites from Colmenar de Oreja or from banks other than the *Banco Gordo*, the source of the highest quality white stone (Dapena et al. 1988). These materials are both less white and more porous than *Colmenar limestone*. One exhibits fenestral porosity (Figure 6c), while the other is stratified and much more porous (Figure 6d).

This second type of limestone may have been the same used to replace the original on the west façade, possibly quarried from the bank known as *Sobrebanco* as has already mentioned (Fort et al. 1996). In some cases, the stratification was not positioned perpendicular to the base of the block (Figure 6d) as it should have been to mitigate decay (Fort et al. 2011). Both limestone ashlars at the gate into the Arms Courtyard are cushioned (Figure 6e).

Another difference between this and the preceding stop is that the south façade is less soiled (Figure 6f), particularly as regards *Colmenar limestone*, for it faces a larger open area and is not directly exposed to the pollutants emitted by the immediate surrounds traffic. Nonetheless, the decorative elements located in the higher parts of the metallic fence or that adorn the courtyard entrance are severely soiled, both because of their location and because their shape allows to retain particulate matter (Figure 6g).

Two further forms of decay that slightly affect building stone can also be seen from this stop: biodeterioration and stone rupture. Biodeterioration includes all the processes of biological origin that affect the built heritage (De los Ríos et al. 2009). Building stones are colonised by lithobiontic communities, a term that covers a wide variety of microorganisms from bacteria, cyanobacteria, algae and free-living fungi, to higher organisms such as lichens, mosses and vascular plants (Ascaso et al. 2002). Vascular plants can be seen to be growing on construction elements (Figure 6h), in the inner zones of stone elements moldings, which are pathways for moisture entrance and/or water accumulation. Lichen growth, sustained by the moisture retained in the pores on horizontal limestone surfaces, is also visible from this stop (Figure 6i). Finally, the loss of material observed in a few stone elements (Figure 6j) may be the result of anthropic activity. The many impacts seen on the west façade of the palace, not included in the route proposed, are remnants of the Spanish Civil War (1936-1939). This decay form weakens the surrounding stone by favouring the entry and action of decay agents.

CONCLUSIONS

This article attempts to illustrate how the built heritage in urban centres can be used to show geology, entailing the Geomonumental Route proposed an urban use of the rocks. Madrid's Royal Palace, a landmark national monument and located in the very heart of the city's historic quarter, is exposed in this study to be an outdoor geological museum. Viewed from the Geomonumental Routes perspective, which combines artistic and historic values with the geological ones, the building exemplifies both geological notions and heritage conservation science principles. This route deals with the traditional building stones used in the palace, their formation, quarries of provenance and behaviour against decay agents. Particular attention is focussed on the causes, processes and mechanisms of decay as well as the alteration forms observed in the façades, largely directly or indirectly related with anthropic activity, especially air pollution and some of the interventions performed on the façades.

The information provided in this route is based on scientific research conducted on the palace for over 15 years by the authors of this article. This proposal, extrapolated to other buildings, cities and countries, shows how built heritage entails veritable urban rock laboratories, as is this case of study. These outdoors laboratories allow displaying the geology sciences applied to heritage conservation trough a didactic mode and with a high scientific support.

ACKNOWLEDGMENTS

The authors wish to express their gratitude to National Trust and Quijano company, responsible of the comprehensive rehabilitation carried out on the Royal Palace façades between 2001-2003, in particular Elsa Soria. Special thanks are given to Geomaterials (P2009/MAT_1629) and CONSOLIDER-TCP (CSD2007-0058) research programmes, and by the Complutense University of Madrid's research group On the Alteration and Conservation of Heritage Stone (921349).

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Figure captions

Fig. 1 Three-dimensional view of Madrid´s Royal Palace and surroundings showing the different stops established in the urban geomonumental route proposed in this paper. Nowdays, Bailén Street is under the pedestrian area that spans from the east façade of the palace

Fig. 2 First stop: traditional building stones and surface stains (northeast corner)

North façade on the Royal Palace: (a) The four vertical levels and granite and limestone placement patterns. (b, c and, on east façade, d) Dark stains on granite. Figures c and d illustrate the granite ashlar cushioning and the outward staggering of these stones in the socle (1). (e) Hygrometry (% of relative humidity measured on the surface) for the granite blocks forming the upper part of level 2; the highest humidity readings were recorded in the areas affected by the dark stains induced by the combination of two treatments applied in the past. (f) The SEM-EDS (SE and BSE mode) analyses conducted revealed the composition of the two products applied and the salts generated beneath them. The wax must have contained methylene (CH_2) potassium components, underneath which gypsum ($SO_4Ca{\cdot}2H_2O$) formed. The Na-base compounds that may have been used for its subsequent removal were neither fully effective nor neutralised before applying the Al- and Si-rich ethyl silicate consolidant, which had a high Si-O and Si-O-Si group content. Consequently, sodium salts, mainly thenardite (SO_4Na), formed underneath this product in addition to gypsum (Varas et al. 2007).

Fig. 3 Second stop: *berroqueña stone* and *Colmenar limestone* petrological features (east façade)

(a) The two-toned façades on the Royal Palace are typical of contemporary constructions. (b) The grey hue in *berroqueña stone* is provided by the feldspar and biotite content in Alpedrete monzogranite, which is also characterised by the presence of *gabarros* or dark enclaves. (c) The limestone quarried at Colmenar de Oreja was used in the city's most emblematic structures due largely to its white colour. (d and f) plane and (e and g) cross polarized light optical microscopy, the main minerals are quartz (Qtz), potassium feldspar (Kfs), plagioclase (Pl) and biotite (Bt). (e) The sericite mineral alteration in the monzogranite is also visible, as well as the (f and g) constituents of the *Colmenar stone* skeleton, primarily consists of characeae. The results given in the table, obtained by determining some petrophysical parameters associated with durability, indicate that both stones are high quality building materials (Fort et al. 1996, 2011). (h) The pores in Alpedrete monzogranite range in size primarily from 0.1 to 1 μm, and (i) in *Colmenar stone* from 0.1 to 0.01 μm (Fort et al. 1996).

Fig. 4 Third stop: decay forms mainly observed at *berroqueña stone* (east façade, right of main entrance)

(a, b and c) The main decay forms in the granite ashlars visible from this stop are granular disruption and spalling. (d) XRD pattern of altered material on the parapet stone elements in this stop, mainly consist of dolomite (Dol), epsomite (Eps) and gypsum (Gy). (e) Fine-grained porphyritic texture of microgranular enclaves observed under optical microscopy with plane polarized light. (f) Concavity in the enclave because of its higher rate of decay than the host rock. (g) The darker surface of a micro-granular enclave reaches much higher temperatures than the surrounding rock. (h) Differential spalling affects the enclave only, not the surrounding material. (i) SEM-SE profile micrograph of differential spalling. (j) Non differential spalling, jointly affecting the enclave and the host rock, (k) and a SEM-SE micrograph of its profile.

Fig. 5 Fourth stop: blackenig and soling decay forms on building traditional stones (east façade, left of main entrance)

(a) In this area, the formation of sulfation crusts on the building stone, the *Colmenar limestone* in particular, is enhanced by the direct exposure of the façade to traffic; these crusts are progressively blackened by the deposition of particulate matter (PM), which is trapped in the areas of the stone protected from the rain and wind. (b) General soiling pattern on façades seen at this stop. (c) Reducction in pollutant levels between 1994 and 1998 and (d, e and f) black crust observed by SEM-SE, note the gypsum crystals underlying different types of PM (Fort et al. 2004a). (g) The horizontal planes of the cushioned granite ashlars favour PM deposition. Rainwater cleans the stone and eliminates these particles (h) from joints and (i) cracked stone elements.

Fig. 6 Fifth stop: Miscellaneous (south façade)

Berroqueña stone: (a) *Gabarros*, *schlieren* and ashlar cushioning only on the side facing Almudena Cathedral; (b) stains caused by the dissolution of iron elements and column consisting of a single, successively cushioned stone block.
Limestone: other types of limestone from the Miocene fluvial-lacustrine carbonates from the Madrid Tertiary basin, whose colour and porosity differ from the white Colmenar de Oreja stone; (c) limestone with an abundance of fenestral pores and (d) highly stratified and likewise porous stone; (e) cushioning on ashlars made from these two limestones at the gate to the Arms Courtyard; (f) façade less soiled than the east façade, with (g) soiling primarily on the decorative elements on the upper part of the fence; (h) growth of vascular plants on the inner areas of the stone moldings; (i) the stone porosity enhance lichens growing; (j) impact possibly resulting from anthropic activity.


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Arms courtyard
Royal Theater
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Almudena Cathedral
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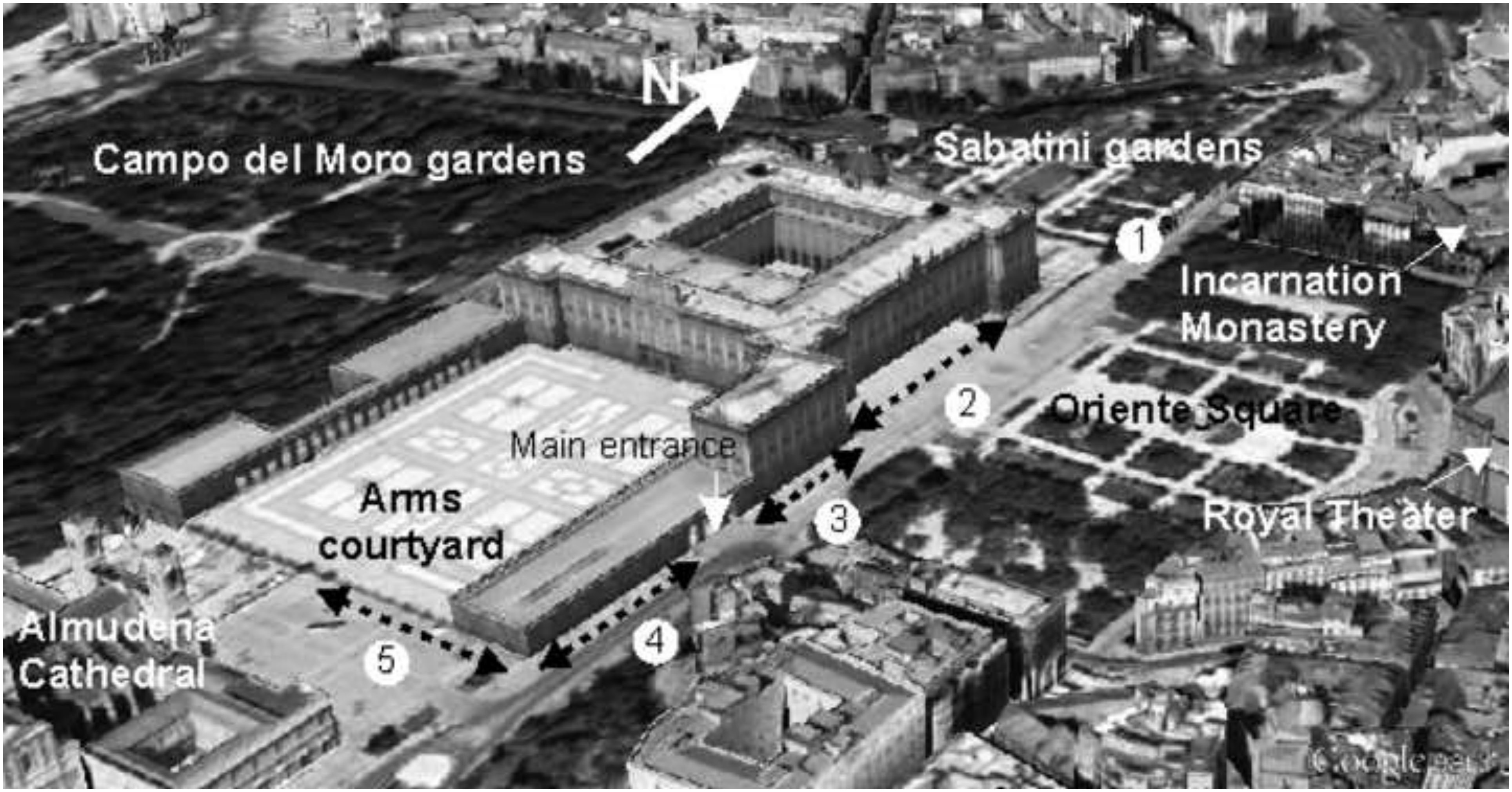
Figure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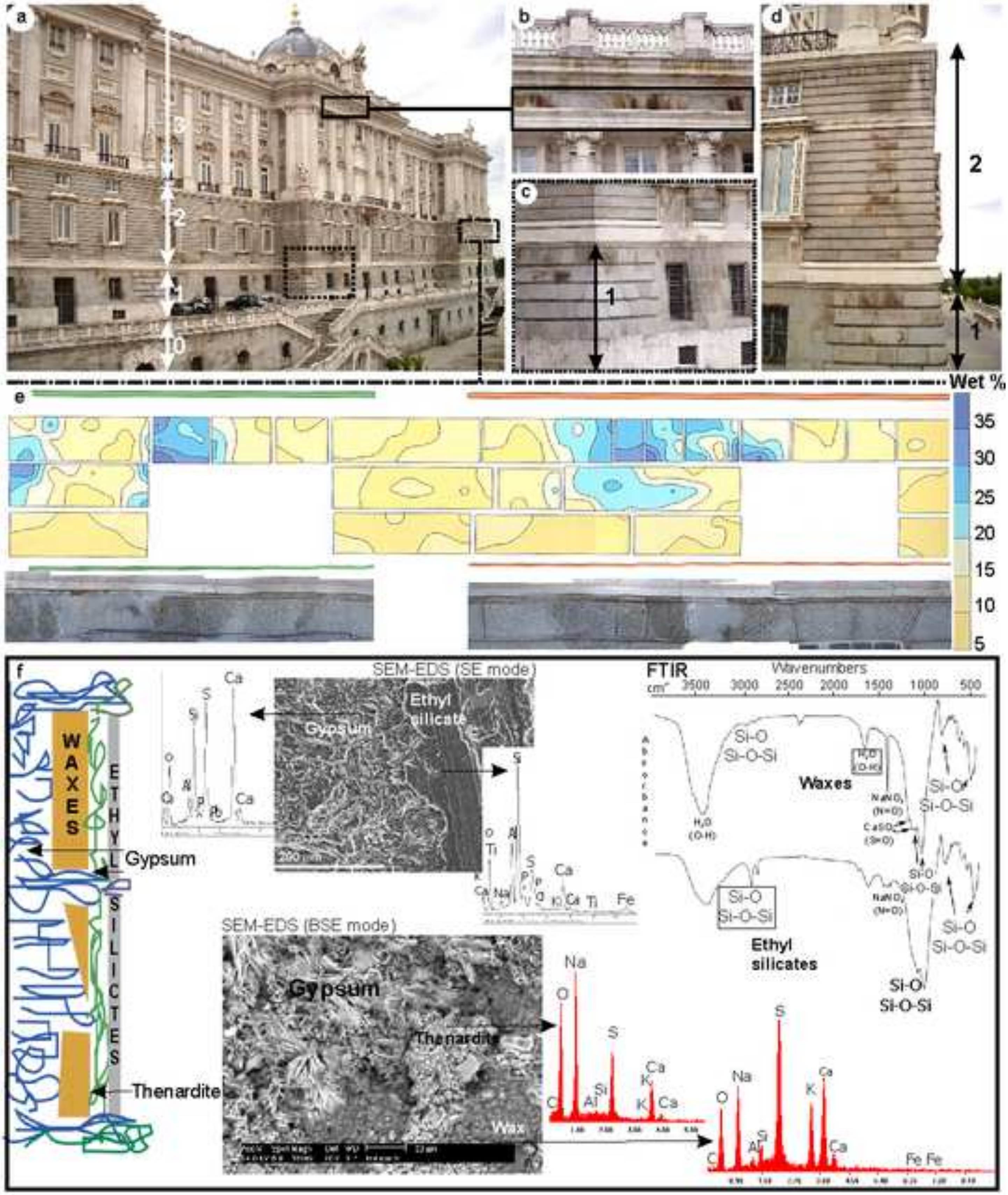
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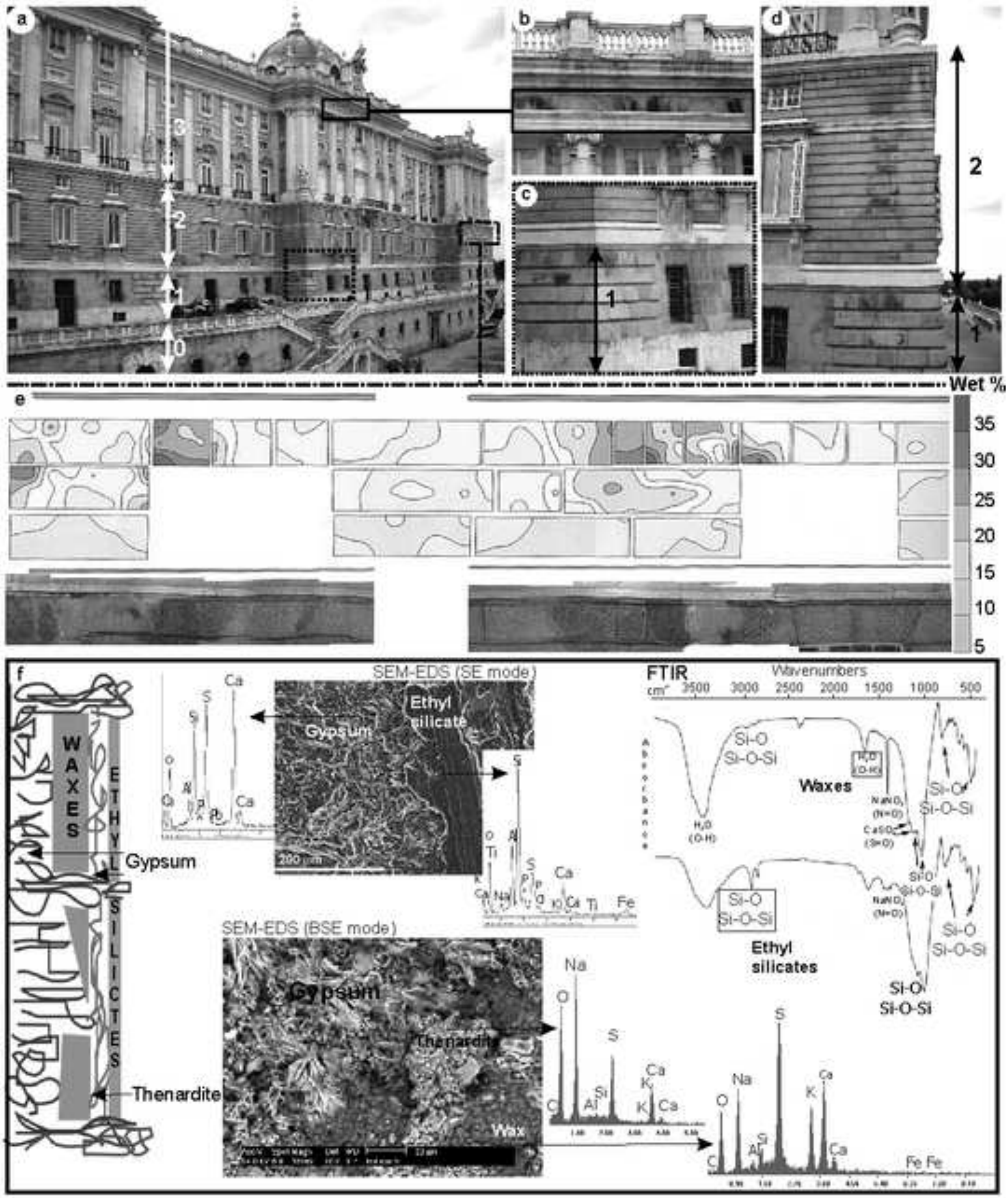
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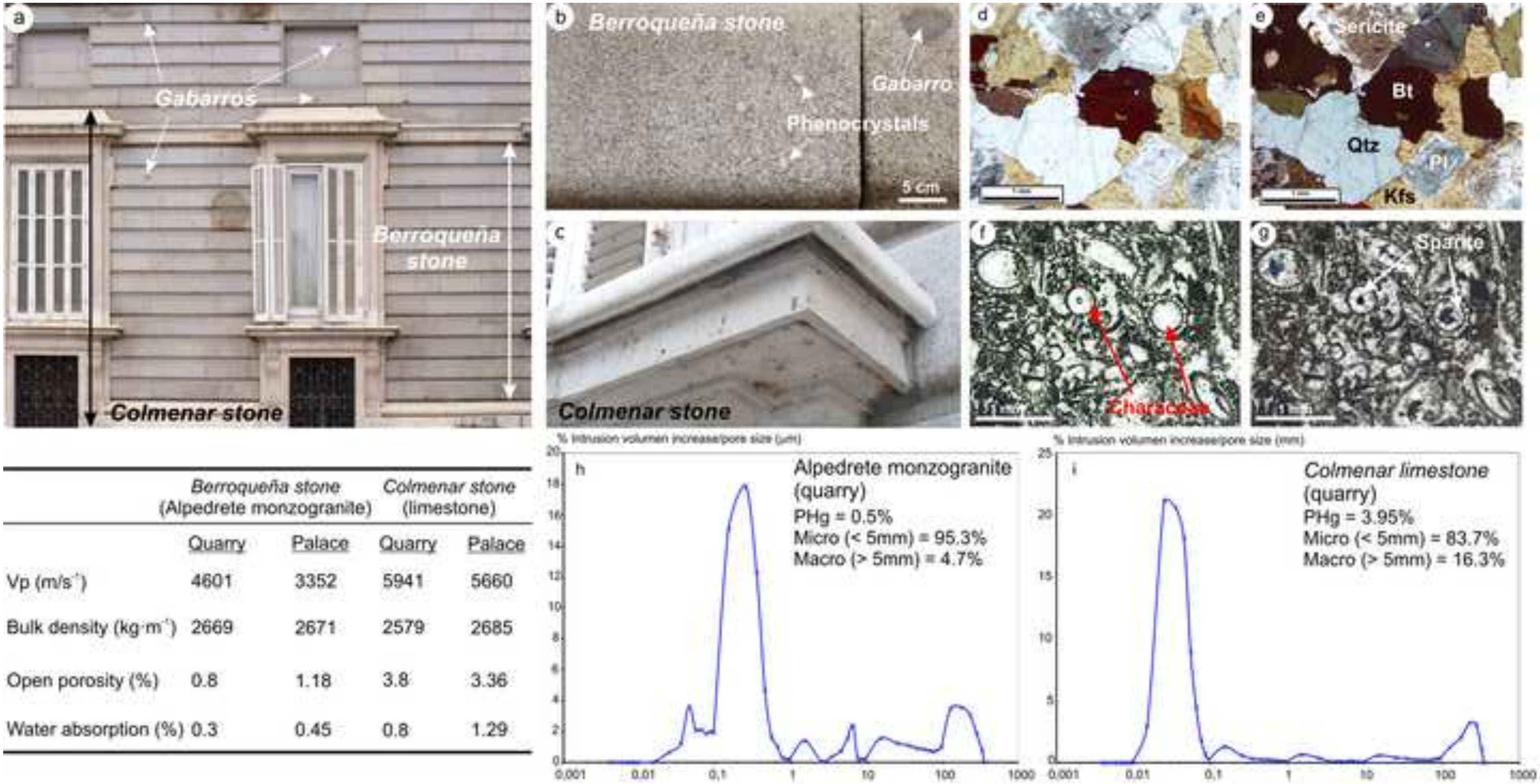
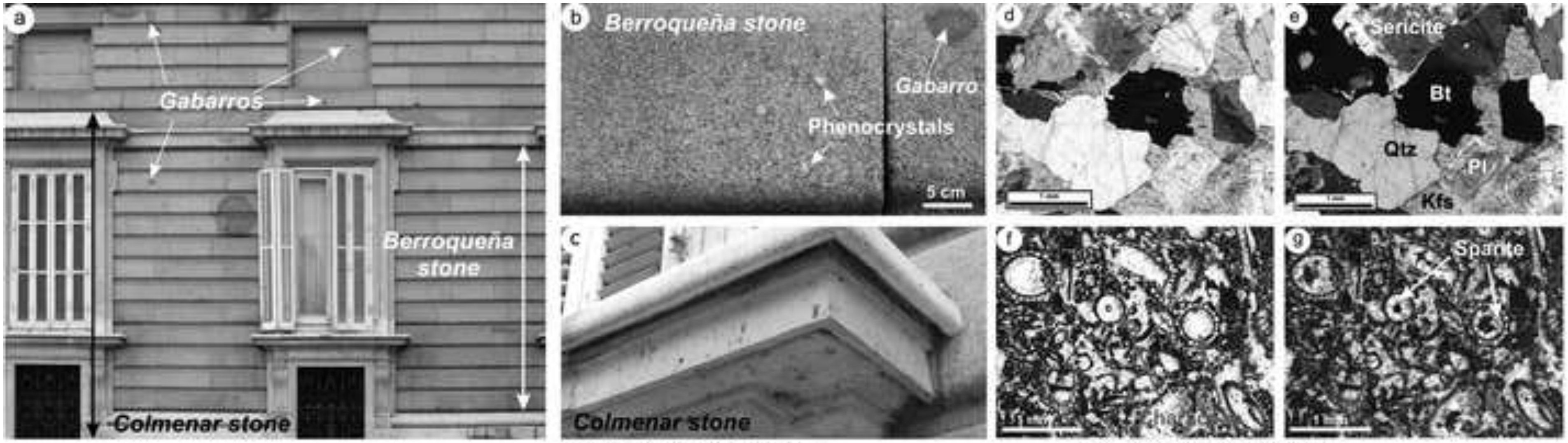


	Berroqueña stone (Alpedrete monzogranite)		*Colmenar stone* (limestone)	
	Quarry	Palace	Quarry	Palace
Vp (m/s^{-1})	4601	3352	5941	5660
Bulk density (kg·m^{-3})	2669	2671	2579	2685
Open porosity (%)	0.8	1.18	3.8	3.36
Water absorption (%)	0.3	0.45	0.8	1.29



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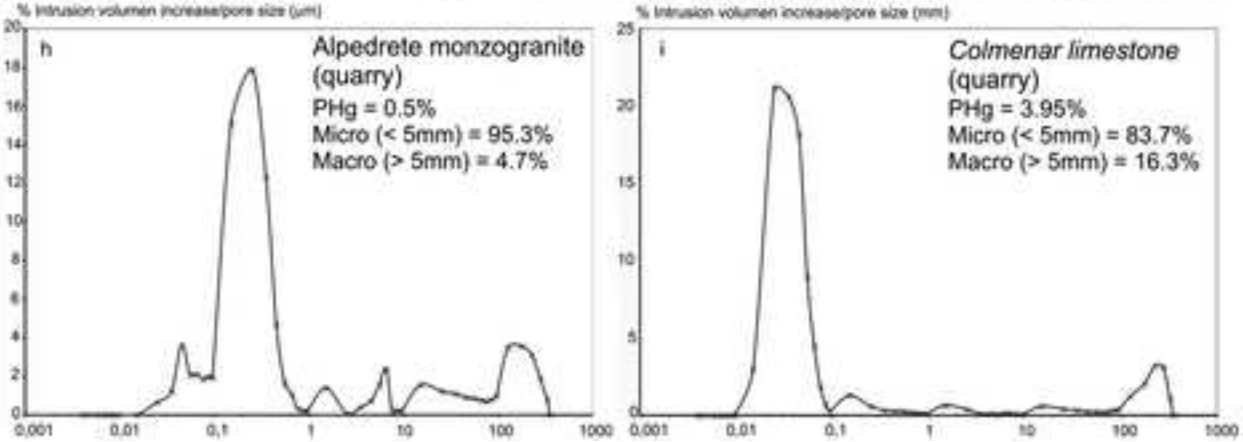

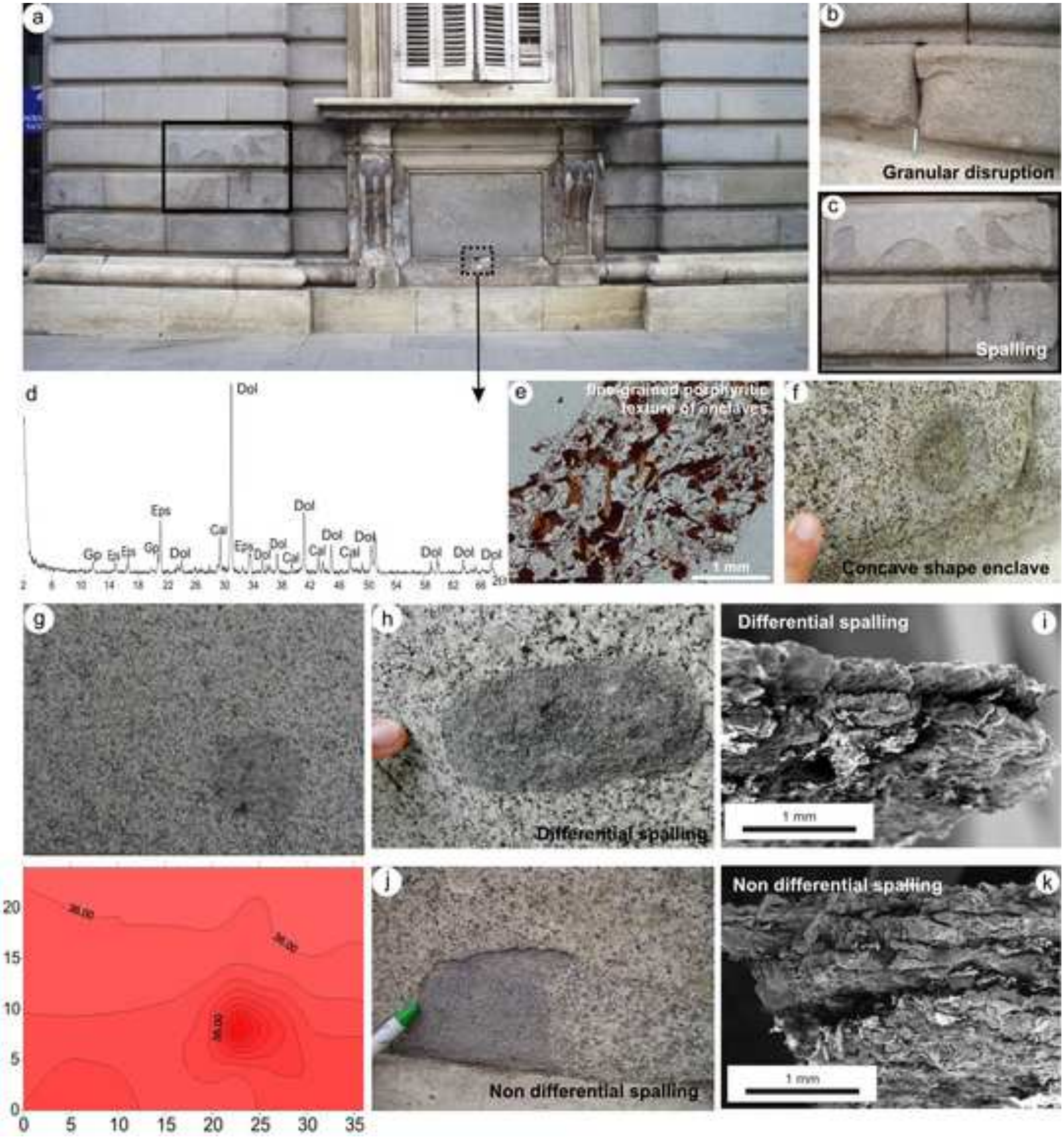
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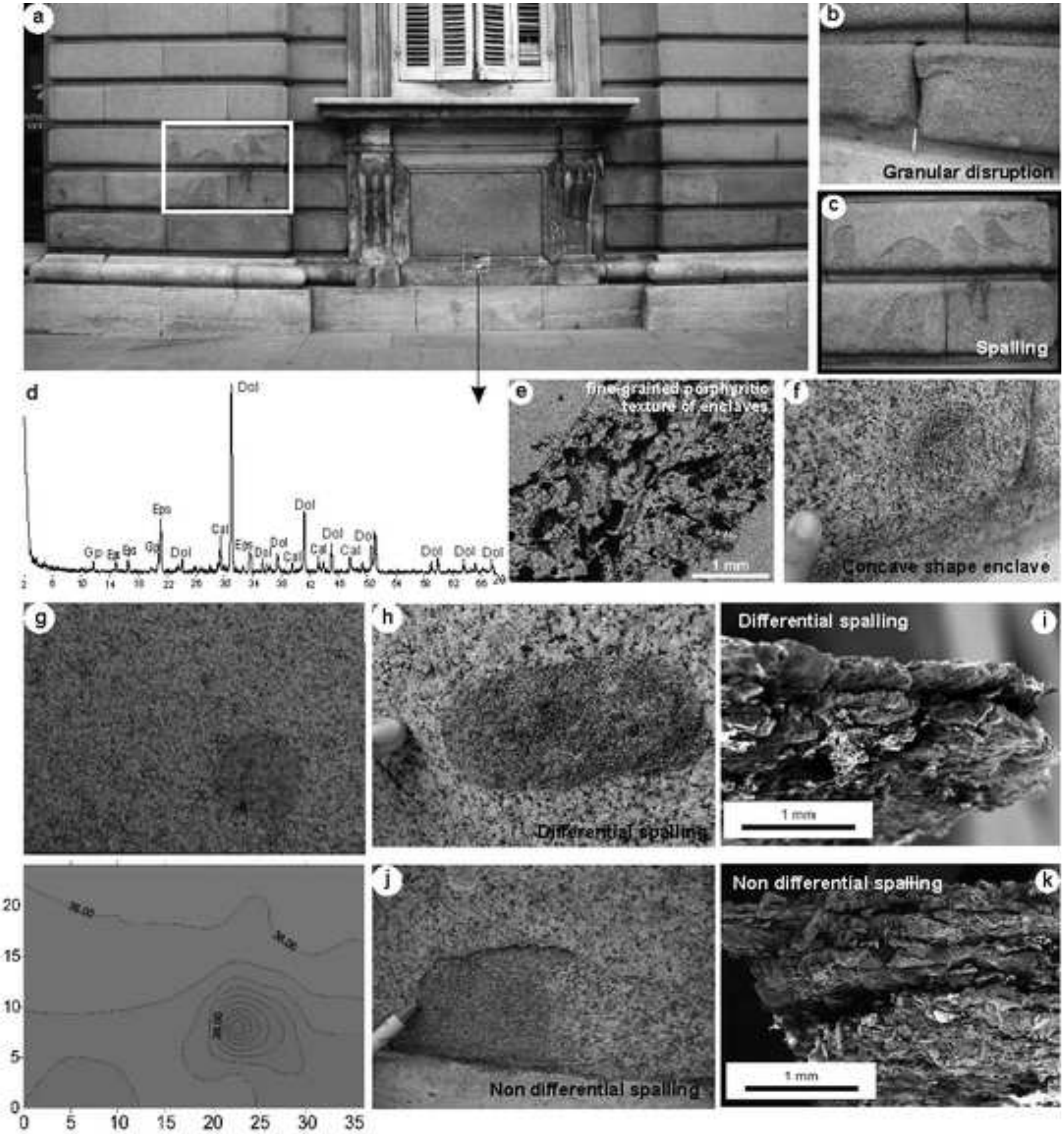
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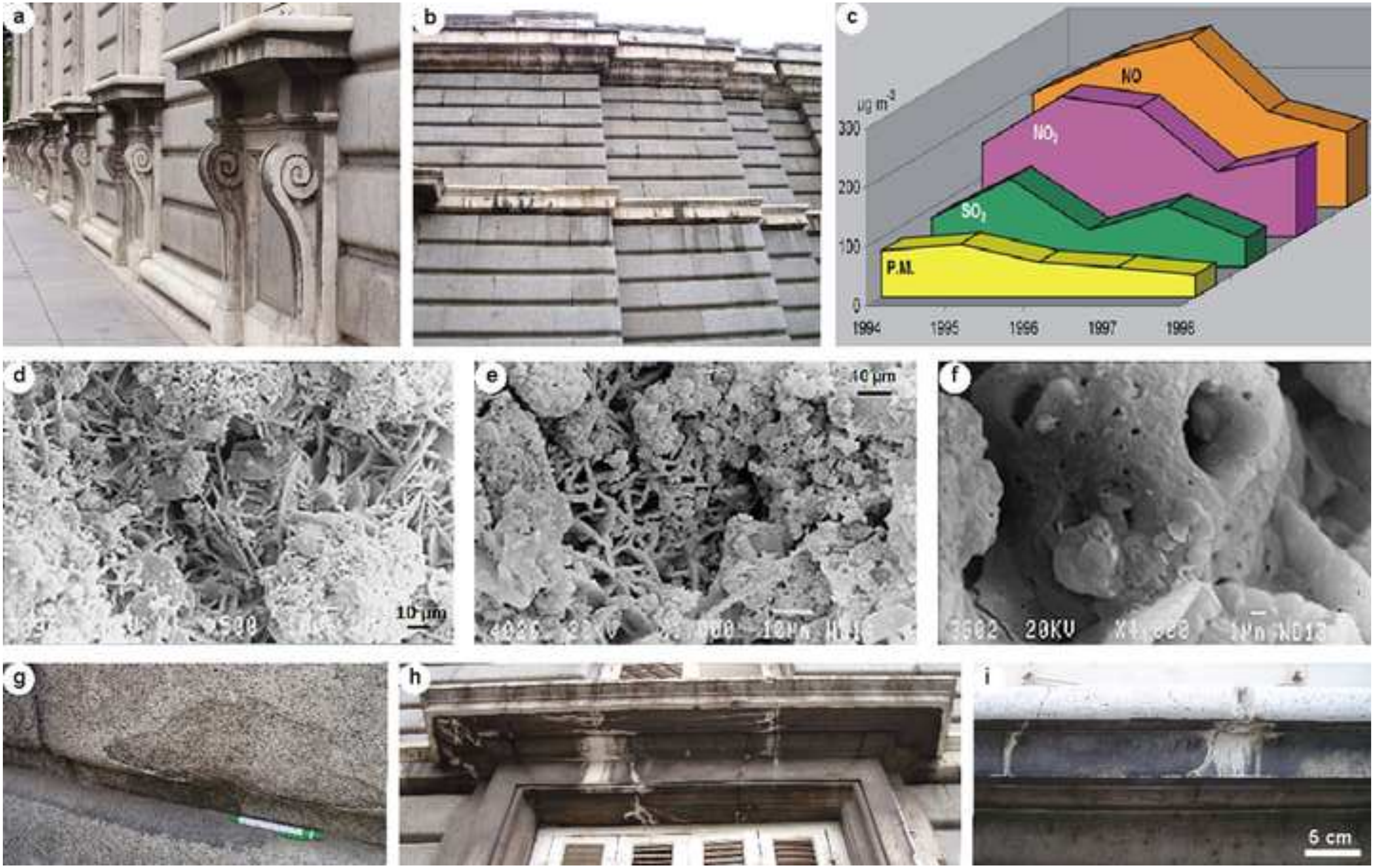
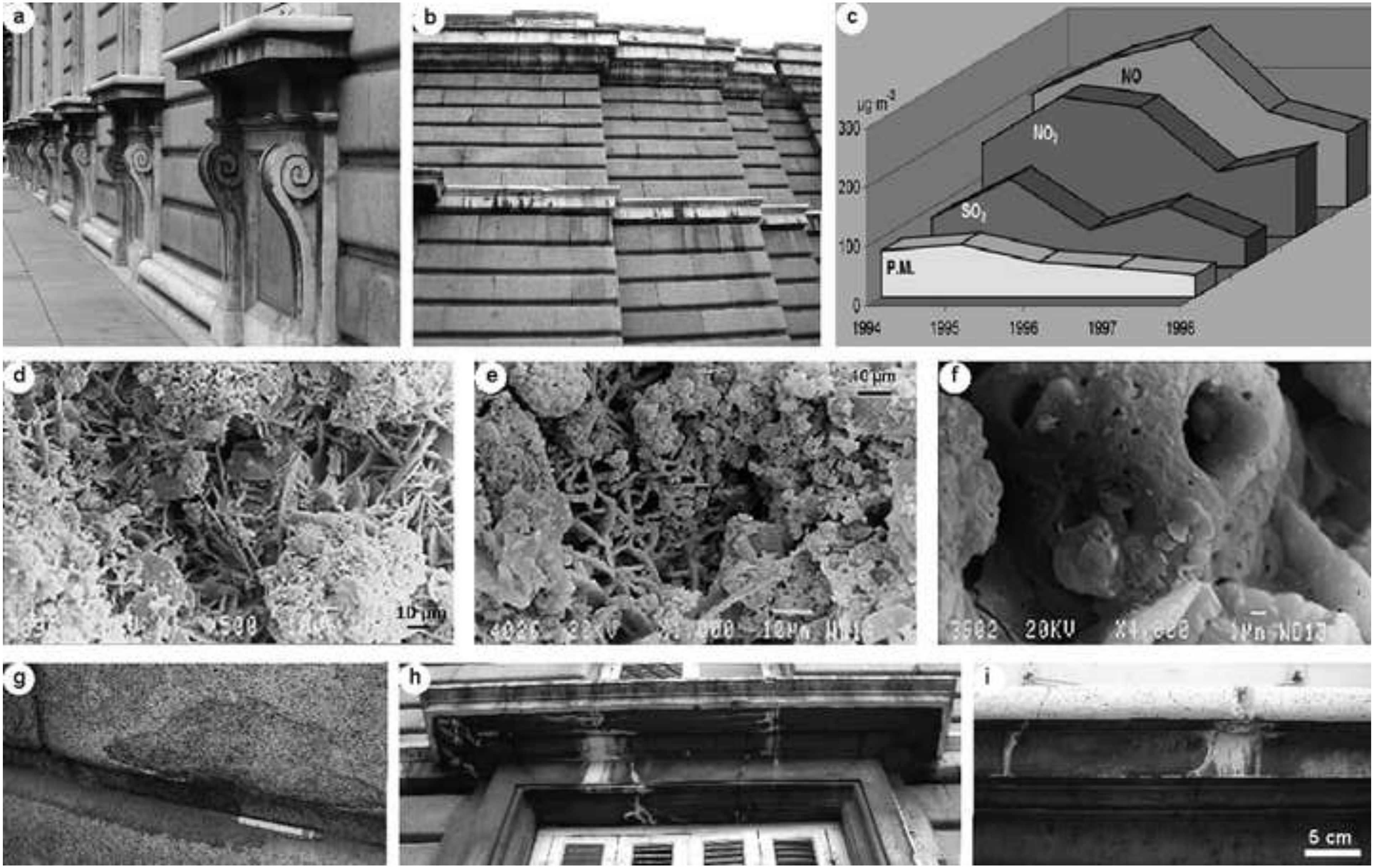
25
30
35


a
b
c
µg m-3
300
200
100
0
NO
NO2
SO2
P.M.
1994
1995
1996
1997
1998
d
10 µm
e
10 µm
f
20KV
g
h
i
6 cm


a
b
c
µg m-3
300
200
100
0
NO
NO2
SO2
P.M.
1994
1995
1996
1997
1998
d
10 µm
e
10 µm
f
20KV
g
h
i
5 cm

Figure

Figure