Present and future challenges of urban systems affected by seawater and its intrusion: the case of Venice, Italy

Eloisa Di Sipio · Fulvio Zezza

Abstract In lagoonal and marine environments, both historic monuments and recent buildings suffer from severe salt damage caused by sea flooding, sea-level rise and frequent storm events. Salt-water contamination of groundwater systems, a widespread phenomenon typical of coastal areas, can lead to a deterioration not only of the quality of fresh groundwater resources, but also of building materials in urban settlements. A general overview is given of the hydrogeological configuration of the subsoil of Venice (Italy), with particular reference to the shallow groundwater circulation. The relationship between the seawater in the subsoil and salt decay processes, due to salt crystallization, is highlighted. These processes affect civil constructions in Venice's historic center. Perched aquifers, influenced by tide variations and characterized by salt-water intrusion, favor the transport of salts within masonry walls through the action of rising damp. In fact, foundations, in direct contact with the aquifers, may become a preferential vehicle for the transportation of salt within buildings. Decay patterns of different building materials can be detected through non-destructive techniques, which can identify sea-salt damage and therefore assist in the preservation of cultural heritage in coastal areas.

Keywords Coastal aquifers · Salinization · Sea salt damage · Non destructive techniques · Italy

Introduction

Seawater intrusion in coastal aquifers is a worldwide phenomenon. Coastal zones are usually densely populated areas where, since the end of World War II, the original features of the environment have been progressively modified under the pressure of urban, industrial, agricultural and tourist development (Bear et al. 1999; Kouzana et al. 2010). Due to the increasing need for fresh water suitable for drinking and for agricultural purposes, an increasing amount of groundwater has been pumped. The overexploitation of coastal aquifers draws salt water from the sea, leading to salt-water encroachment and soil salinization. In coastal plains the extent of salt-water intrusion also depends on the following: the geological characteristics of the subsoil, the hydraulic gradient, the topography and morphology of the territory, the existence of subsidence phenomena and low lying areas, and the land use of the region (Freeze and Cherry 1979; Oude-Essink 2001). Along the northern Italian coast of the Adriatic Sea, from Ravenna to Venice, large areas of the inland are reclaimed land, affected by subsidence and drainage. The existence of paleorivers, lagoon paleochannels, rivers suspended above the surrounding land and the destruction of coastal dunes favor the intrusion of brackish and saline water towards the mainland. Therefore, in these zones the freshwater hosted in unconfined aquifers consists mainly of low salinity water lenses floating above the salt-water wedge (Giambastiani et al. 2007; Antonellini et al. 2008; Di Sipio et al. 2006; Barrocu 2003; Rapaglia et al. 2010).

The study area, the city of Venice, is unique. Surrounded by water, it is located in the middle of the Venetian Lagoon, a large (550 km^2) and shallow (average depth of 0.8 m) sheet of water, on the northern coast of the Adriatic Sea (Fig. 1). Within the lagoon a large number of small islands (118) rise about 1.2–1.3 m above mean sea level (AMSL). Due to Venice's peculiar location and the intense urbanization dating back to 800 AD, the processes that affect this city can be quite different from those observed in other coastal cities. The research efforts presented here have focused on determining the shallow groundwater circulation, highlighting a possible association between seawater in the subsoil and salt decay processes (due to salt crystallization) that affects civil constructions and cultural heritage. Groundwater level, foundations, seawater, cohesive soils and subsidence phenomena together directly influence efforts to preserve the architectonic structures. Moreover, to shed new light on the vulnerability of urban areas located in a coastal

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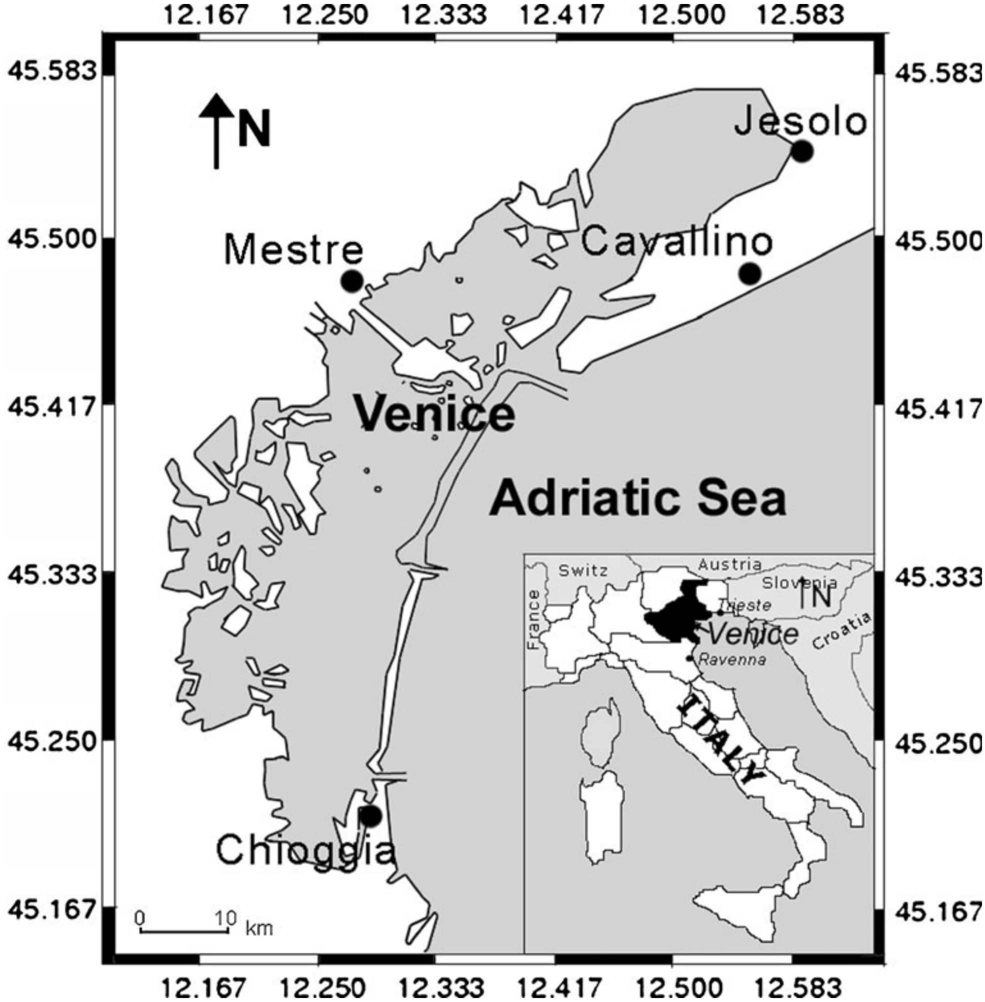

Fig. 1 Location of the city of Venice, in the Veneto district, Italy

environment, the outcomes of several European and national projects that focused on the effects of sea-salt damage on monuments and buildings were taken into consideration (EU Project ASSET - Assessment of Suitable Products for the Conservative Treatments of Sea Salt Decay 2000–2004; EU Project DESALINATION - Assessment of Desalination Mortars and Poultices for Historic Masonry 2006–2009; Protection from high waters and architectural conservation 2001–2003, CO.RI.LA, Consortium for Coordination of Research Activities Concerning the Venice Lagoon System).

Geological background

The region of Venice is in the northeastern sector of the Po River plain, bordered by the Apennines to the south and the Alps to the north. The Po Plain is a foreland sedimentary basin consisting of a sequence of deposits, made up of alternating sands, silts, and clays, which accumulated during the Pliocene and Quaternary in different environments. In the late Pliocene, the area was characterized by the progressive deposition of shallow marine and bathyal sediments. In the Pleistocene a marine regression favored the accumulation of continental sediments belonging to an aggrading alluvial plain, in which fluvial channels, valleys, lacustrine sediments, peat and paleosoils can be recognized (Kent et al. 2002; Massari et al. 2004). In the Holocene, the marine transgression (Flandrian transgression) led to the formation of the lagoon and the estuarine barrier systems, with a typical tidal plain deposition (Fontes and Bortolami 1973; Rizzetto et al. 2003). Afterward, the lagoon was subjected to a complex combination of natural processes and human intervention, such as land subsidence, eustacy, salt-water intrusion, sea-floor erosion, river diversions, and inlet and channel dredging (Zecchin et al. 2009; Gambolati et al. 2006) and so its character evolved. Over the centuries, several hydraulic projects such as the diversion of the fluvial tributaries into the sea, were carried out by the Venetian Republic to preserve the lagoon environment and avoid its conversion into a marshland. In this way, the natural evolution of the lagoon was modified, changing it progressively from a transitional to a marine environment (McClennen et al. 1997; Kent et al. 2002). In the last century, the total altimetric loss of the city was quantified at 23 cm, due to natural subsidence (3 cm), anthropic

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subsidence (9 cm) and sea level rise (11 cm) (Carbognin et al. 2005). The eustatic increase of the mean sea level in the northern Adriatic Sea in the last 100 years, recorded by the tide gauges in Trieste, a coastal city known to be stable, is on average 1.3 mm/year. However, in Venice, the mean sea level registered in the same period is about 2.4 mm/year. This significant difference is due to the anthropogenic land subsidence which occurred mainly from 1930 to 1970 (Carbognin et al. 2004; Ferla et al. 2007). The future scenarios over the next century forecast a sea-level rise for the northern Adriatic Sea ranging from 30 to 50 cm (Ferla et al. 2007; Bondesan et al. 1995). In this environmental condition, an increased number of flooding (*acque alte*) and sea storm events is expected in Venice, combined with an increase in ground displacement and salinization effects that will determine a greater vulnerability of the urban settlement. Therefore, a better knowledge of the weathering phenomena affecting the town is necessary to plan appropriate intervention measures to preserve the city and its historical and cultural value.

Despite numerous previous investigations on the Venetian Lagoon area, it is a recent study of Venice's historic center subsoil that has identified the singular sedimentary structure underlying the city (Zezza 2010). This structure (50 m in depth) consists of a sequence of multiple stacked sand bodies (*multistorey sandbody*) corresponding to different stream channels that crossed the area during the Pleistocene, completed on the top by the Holocene deposition of sand of fluvial and tidal origin. In contrast, in the surroundings (the interlagoonal area) a more regular succession of sand, silt clay and peat deposits (*cyclothemic organization*) belonging to the alluvial plain of the upper Pleistocene and to the Holocene tidal plain is present. The erosion and deposition processes due to the climatic variations during the Wurmian glaciations and to changes in the fluvial regime are responsible for the formation of this sedimentary structure (Zezza 2010). The lateral variations between channel sand units and alluvial/tidal plain deposits can be clearly seen in the lithostratigraphic section (Fig. 2).

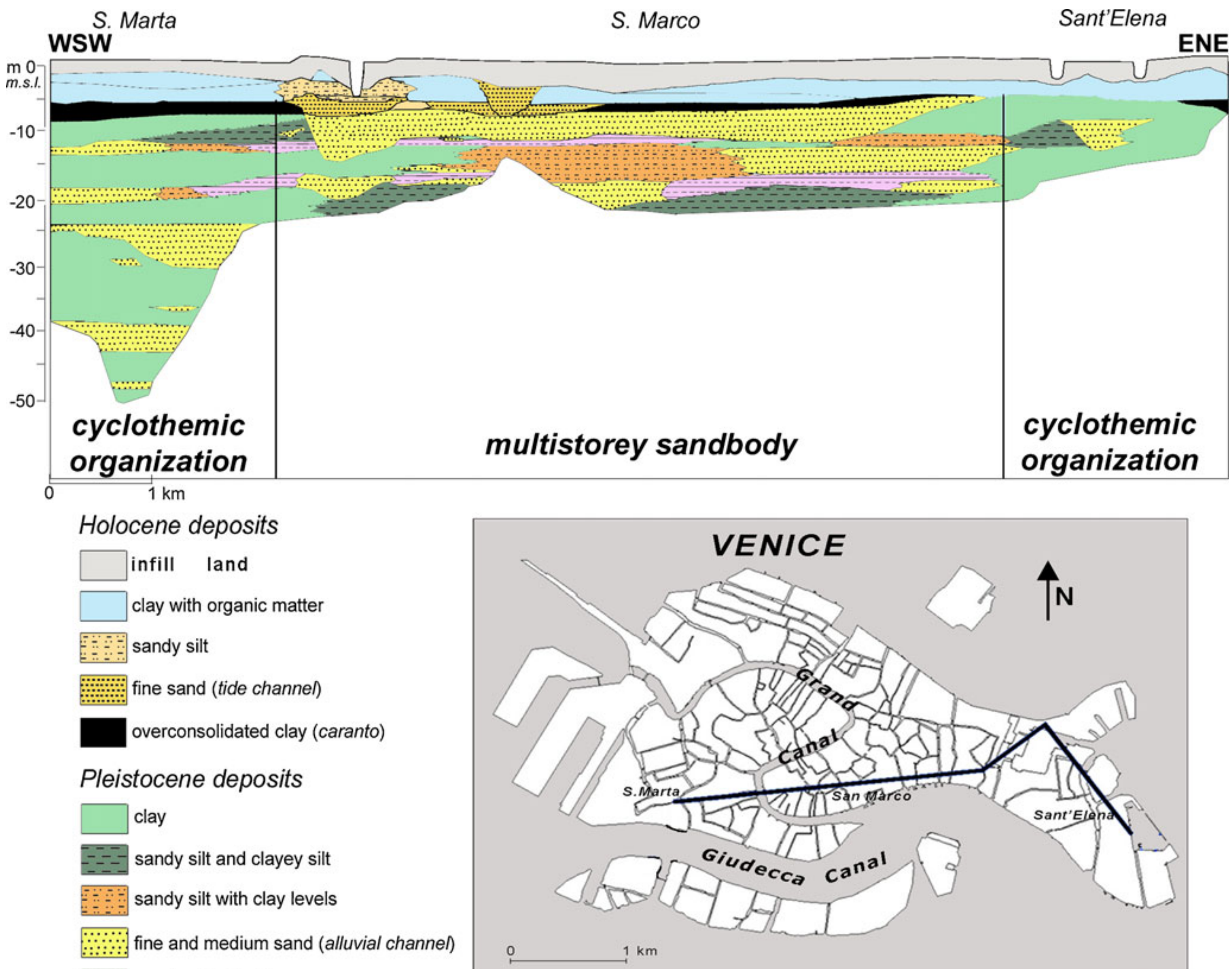

Fig. 2 The sedimentary structure of Venice's subsoil, composed of the multiple overlapping of sand bodies (multistorey sandbody) corresponding to different Pleistocene alluvial channels (by Zezza 2010, modified)

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This new geological model shows that the subsoil of the eastern (Sant'Elena) and western (Santa Marta) sectors of the city, currently subsiding at a rate greater than 1 mm/year (Tosi et al. 2002; Carbognin et al. 2004), is characterized by cohesive deposits belonging to the cyclothemic organization. However, the central area (San Marco), where the ground displacement at present is almost zero, is on top of the granular deposits forming the multistorey sandbody structure (Fig. 2). Therefore, the vertical ground movements cannot be entirely dependent on the local disturbance caused by urban development. The residual component of the secondary consolidation rate of clayey deposits must be taken into account to interpret the deformation evolution and consolidation processes currently acting in the urban settlement (Zezza 2010; Boaga et al. 2010).

From a hydrogeological point of view, the multistorey sandbody structure influences the distribution of the permeable and impermeable levels, respectively represented by sand bodies and silty clayey layers. As a consequence, the shallow groundwater circulation is deeply affected by local conditions. The conceptual model can be summarized as a complex multiaquifer system, formed by a surface perched aquifer followed by four confined aquifers located at different depths (Fig. 3a). The perched aquifer has been recognized both within infill land deposits—widespread today all over the city with an average thickness of 3.5–4 m—and within sandy silt deposits of the tidal Holocene channel. The confined aquifers, instead, are present in late Pleistocene deposits located respectively at depths of 12–14 m, 18.5–21.5 m, 26–30 m and more than 30 m below mean sea level

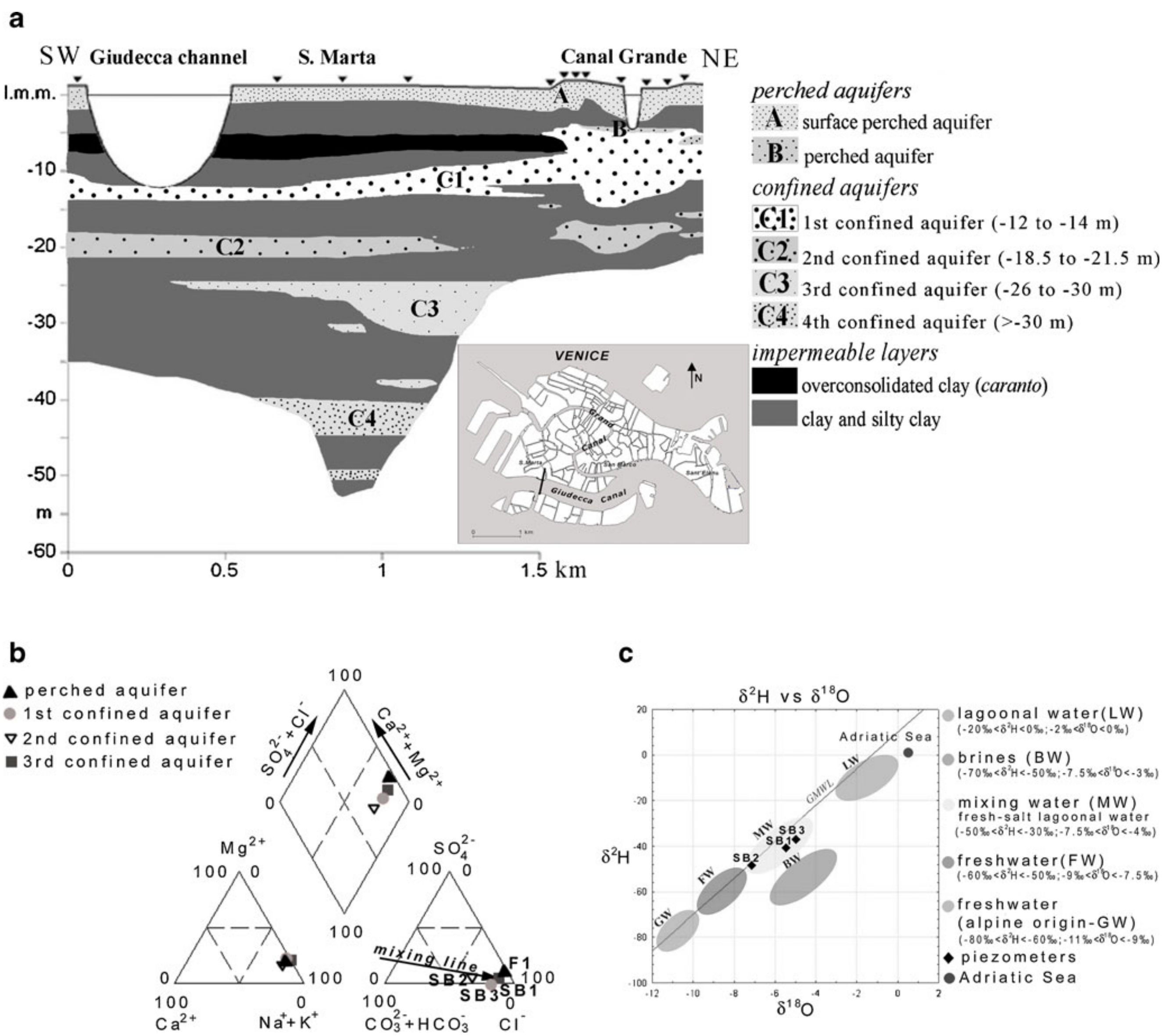

Fig. 3 Groundwater circulation in Venice: **a** hydrogeological section; **b** geochemical classification with Piper diagram (meq/l); **c** isotopic analysis (by Zezza and Di Sipio 2008, modified)

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(BMSL), as determined in the San Basilio sampling area (Zezza 2010; Zezza and Di Sipio 2008). Sixty-one piezometers, disposed at different depths all over the city, allowed for measurement of the groundwater level variations in time (Fig. 4a). More than 50 wells reach a maximum depth of 6–8 m, while the remaining involves the permeable deposits located less than 12 m in depth. Electrical conductivity logs, temperature analyses, pH and water level values have been collected in each well in different periods (Zezza and Di Sipio 2008). The perched aquifers, characterized by high permeability values (k=10^{-3} –10^{-1} cm/s) and limited on the bottom by clay and silty clay of lagoonal origin, are in direct contact with the lagoon and the building foundations (Fig. 5a). The hydrostatic pressure variation driven by tides determines water level variations that gradually decrease away from the channel levees and as the depth increases. Moreover, precipitation is able to affect only the water table of perched aquifers after heavy rains (Ataie-Ashtiani et al. 1999; Critto et al. 2004; Zezza and Di Sipio 2008; Zezza 2010).

In detail, the perched aquifers show homogenous behavior all over the city: during the year the water table fluctuates between +1.0 m and 0.0 m relative to mean sea level. In the test site of Punta della Salute (PS), it was possible to determine the relationship between the observed hydraulic heads and the lagoon level registered in the nearby tide gauge (‘tide PS’, Fig. 4b–c). Tide fluctuation determines water level variations that diminish gradually from 10–15 cm near the channel bank (piezometer PS1) to 2–3 cm at a distance of 8–9 m (piezometer PS6). The delay of the hydrostatic pressure transmission increases in time: from 30 min near the lagoon (PS1) up to 2 h 30 min more inland (PS4) until there is a complete mitigation (PS6) at about 10 m from the channel bank (Fig. 4b). Moreover, the recharge of the perched aquifers seems to be affected by rainfall contribution only when the measurement points are located inside the islands (Fig. 4c).

The high degree of geological variability of the subsoil has determined a complex hydrogeological structure, characterized by inhomogeneity and anisotropy, which can allow the existence of hydrogeological connections between the various sand deposits to be identified. However, while in the mainland these connections have been well described (Regione del Veneto 2009), in the city center these connections are the subject of a research project that has just started, and whose data are not yet available.

In a coastal environment, the decay of buildings is strictly related to the physical–mechanical properties of the soil and to the accumulation and crystallization of salts within masonry walls. In Venice, the soils in which the

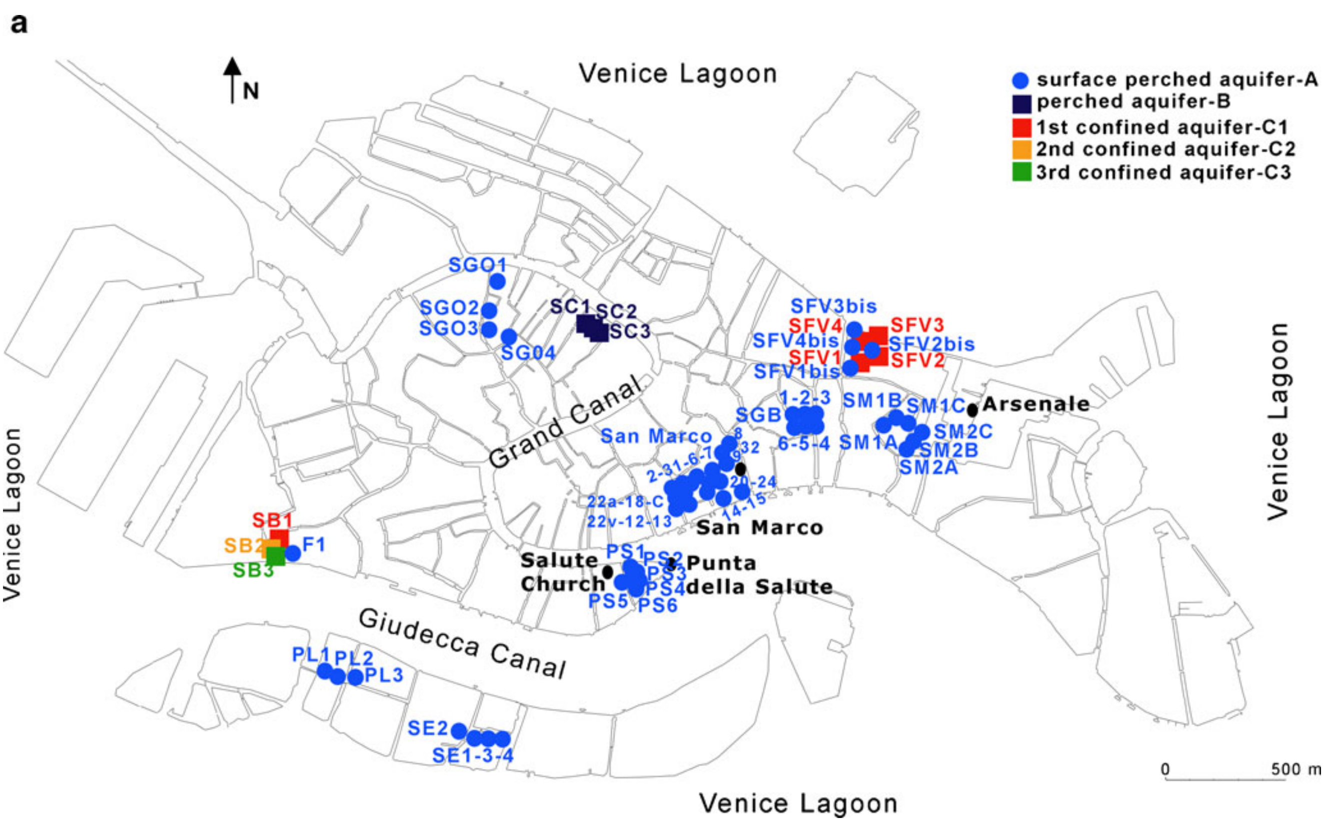

Fig. 4 **a** Location of piezometers. **b** Results of testing at Punta della Salute (*PS*) on 20th July 2001, showing water level in the perched aquifer: with increasing distance from the embankment the influence of the tide decreases. **c** Relationship between water levels, tide fluctuations (collected at the tide gauge of Punta della Salute “tide PS”) and rainfall in the test area at Punta della Salute (PS) in the period 21st June 2001–25th July 2011: the water table near the canal bank (*PS1*) is immediately affected by transmission of hydrostatic pressure, while further inland (*PS6*) the influence of tidal fluctuations is negligible. The contribution of rainfall to aquifer recharge is detectable only at distance greater than 8–9 m (*PS6*) from the canal bank (by Zezza and Di Sipio 2008, modified)

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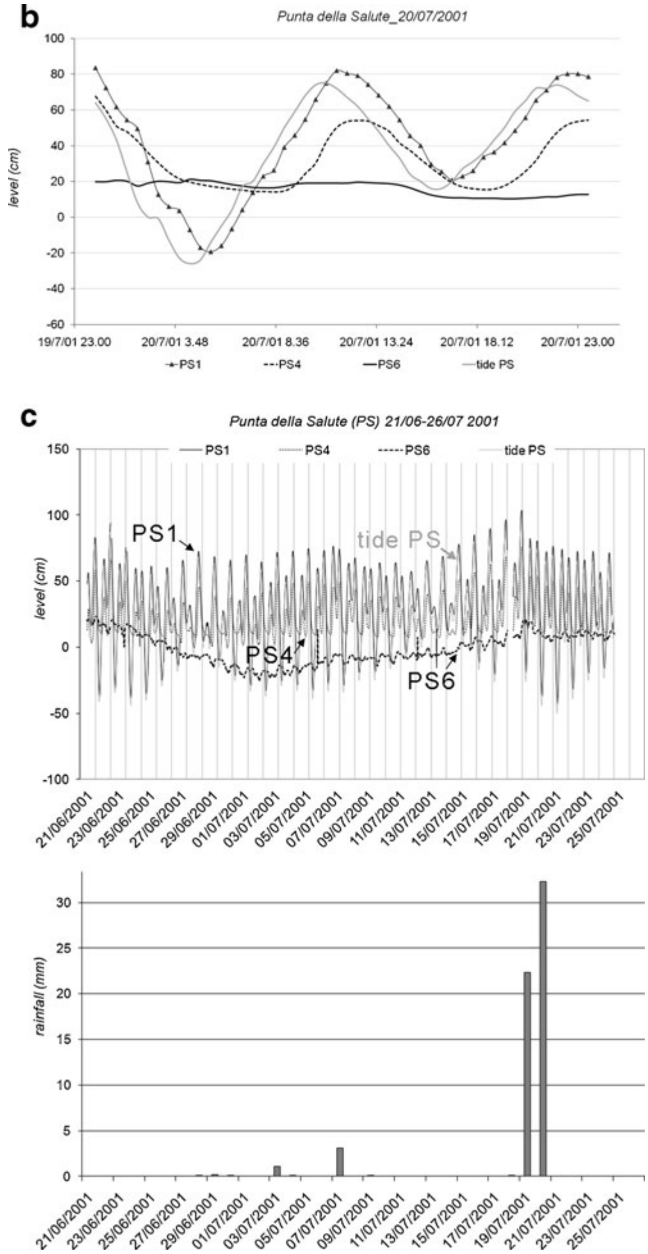

Fig. 4 (continued)

foundations are located, characterized by low-bearing capacity and compression strength, and the physical–mechanical action of water (tide fluctuation, wave motion) affect the stability of buildings. As a consequence of extremely low and extremely high tides, overpressure within sediments and bending stress on walls can be generated, while, after a sea flooding event, overpressure on masonry and loss of sediments near the lagoonal margin can occur (Cecconi 1997). In detail, the direct contact between aquifers carrying salt or brackish water and building foundations can lead to a sea-salt transport within masonry through rising damp, enhancing the risk of salt damage. Therefore, the aim of this report is to verify the following: first, whether salt water penetrates into the aquifers; and second, how this would affect the decay process of building materials in Venice. The most common salts are generally of marine origin (NaCl, $MgSO_4$, Na_2SO_4) and so the contribution of anthropogenic pollution has been neglected. As a matter of fact, sea-salt accumulation and crystallization within masonry walls are causing continuous, slow and cumulative degradation (Calliari et al. 2001; Biscontin 2001; Zendri et al. 2001; Fassina et al. 2002).

Materials and methods

To determine the existence of salt-water intrusion, electrical conductivity logs, and temperature, pH and water-level values have been collected in several piezometers (>50) located all over the city. These piezometers, constructed during different periods of building restoration (from 2001 to 2007), tap mainly the perched aquifers. In spite of periods of non-continuous sampling, it was possible to reconstruct the groundwater-level variation throughout the year, to consider the influence of tidal fluctuations and to depict the salt–freshwater interface in the subsoil (Zezza 2010; Zezza and Di Sipio 2008). Water samples of the unconfined and confined aquifers, collected in the San Basilio (SB) area (Figs. 3 and 4a), were analyzed to determine the hydrogeochemical facies and the isotopic composition of water. The anion content (Cl^-, HCO_3^-, SO_4^{2-}, NO_3^-) was determined by ion chromatography (DionexDX-100, Dionex“Qic”), whilst cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) and trace elements (F^-, Br^-) were quantified by atomic absorption, ion chromatography, and inductively coupled plasma source-atomic emission spectroscopy (ICPS-AES, Perkin Elmer). In addition, a Metrohm Herisau E536 potentiometer with a silver/silver chloride electrode was used to determine the chloride concentration (Haddad and Jackson 1990; Sanz-Medel 1991). Isotopic analyses were carried out for δ^2H and $\delta^{18}O$ for the whole sample set by a Finnigan MAT 250 mass spectrometer at the ISO4 unit in Torino, Italy. The results, expressed as Vienna Standard Mean Ocean Water (V-SMOW), were obtained by water reduction over metallic zinc for δ^2H and by water/CO_2 equilibration at 25 °C for $\delta^{18}O$ (Clark and Fritz 1997; Gonfiantini 1978). The analytical errors were ±1‰ and ±0.1‰, respectively.

In order to detect decay patterns due to the dissolution/crystallization cycles of salts in the most common Venetian building materials (brick, hard stone, mortars), non-destructive techniques (NDT), duly validated by laboratory tests, have been performed following the methods of the above-mentioned European research projects (AA.VV. Asset Project 2004; AA.VV. Desalination Project 2009). In order to determine and quantify the presence, source and distribution of moisture and salt in a wall, powder samples were collected from building materials by means of dry drilling. The drilling was performed at different heights along the same vertical profile (10, 50, 100, 150, 200, 300 cm from ground level), involving the same type of material (brick, stone or

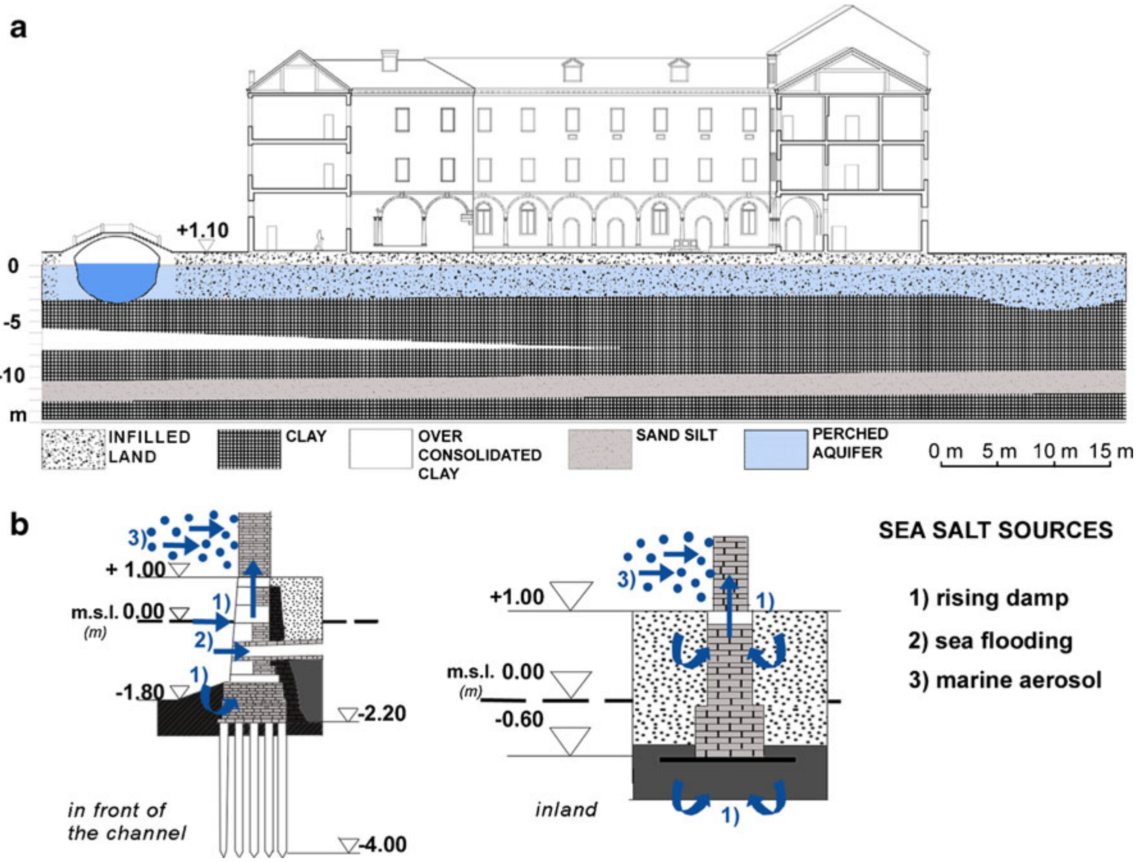

Fig. 5 Relationship between foundation and sea-salt sources in Venice: **a** the perched aquifer hosted in the infill land deposits, representing a direct source of sea salts for buildings; **b** the direct and indirect foundation system adopted (*in front of a channel* and *inland*) and the possible means of moisture/salt transport and accumulation (rising damp, sea flooding and marine aerosol), favored by the presence of porous material and of cohesion loss zones

mortar) since differences in material properties influence moisture and salt content. For each height, samples were usually taken at different depths (0–1; 1–2; 2–5; 5–10; 10–20 cm). In the laboratory, the measurements of total soluble salt content (TSS), moisture content (MC) and hygroscopic moisture content (HMC) were performed to evaluate the actual MC (generally decreasing from the lower to the upper part of the masonry, and from the inner to the outer part of the wall) and the hygroscopic (and soluble) salts accumulation at the upper fringe of the rising damp zone. The HMC method is both a quantitative and qualitative measurement of the salt content in the case of samples contaminated with salts of known or unknown thermodynamic properties (Diaz Gonçalves and Delgado Rodrigues 2006).

To avoid, or at least to limit, invasive sampling, non-invasive technologies have been developed and are today widely applied on cultural heritage sites. A realistic method of characterizing degradation conditions, already used during the study of several monuments in the Mediterranean Basin, is the ICAW technique (Integrated Computerized Analysis of Weathering), a non-destructive methodology created and implemented by F. Zezza (Zezza 1989; 1996). To determine the decay patterns and the thickness of the decayed layer, pictorial images are transformed into digital images, along with the employment of ultrasonic pulses.

The basics lie in the level of restitution of light energy from the exposed surfaces: a color image is transformed into a black and white image (pictorial image 8 bit), considered as a continuous dimensional function in two variable planes x and y, where each image pixel is represented by a value (Lg) indicating the level of luminosity, represented in a gray level histogram. The gray scale histogram represents the distribution of the pixels in the image over the gray level scale. It can be visualized as if each pixel is placed in a bin corresponding to the color intensity of that pixel. All of the pixels in each bin are then added up and displayed on a graph, characterized by a typical range. This graph is the histogram of the image. Every pixel takes values in a range of typical values. Considering that images stored with 8 bits per pixel corresponds to the range 0–255 (256 levels of gray) and that a human observer perceives a continuous scale of gray looking at images stored with 8 bits per pixel, the scale of gray (0–255) has been selected for the purposes of this study. The histogram is a key tool in image processing. It is one of the most useful techniques in gathering information, as contrast, about an image. If the gray-levels are concentrated near a certain

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level the image is low contrast. Likewise if they are well spread out, it defines a high-contrast image. The aim of digital image processing is to obtain the linearization of the histogram through the use of look up tables (LUT), tables linking index numbers (usually ranging from 0 to 255) with output values. One of the most common LUT is the colormap, used to determine the color values and intensity with which a particular image must be displayed (Russ 2007).

Considering the variations of luminosity recorded in a series of rock images characterized by different color, composition, textural and structural properties, as well as different states of preservation and by studying histograms of rocks (from freshly quarried rock to severely damaged stone), it is possible to determine the intervals related to fresh stone and to identify the dispersion of luminosity levels related to weathered stone. In addition, ultrasonic measurements, able to identify buried structures, have been performed to establish the changes in physical conditions of stones and bricks. This non-destructive technique considers the velocity of the ultrasonic pulses (frequency >20 kHz) registered between two transducers (a transmitter and a receiver), located either on the same surface (indirect method) or one opposite the other (direct method). In situ changes in physical properties of brick/stone material can be recorded, taking account of the relationship between the distance between the probes and the time employed to cross the substrate (Zezza 1989; 1996). Ultrasonic velocities acquired on fresh and weathered samples, related to the physical–mechanical parameters of stones, have been observed and summarized by F. Zezza, who has classified in this way the degree of stone decay (Fig. 6, Zezza 1996).

Results and discussion

A recent study concerning the hydrochemical characteristics of groundwater of the Venice historic centre reveals the presence of salt-water intrusion in the aquifers (Zezza 2010; Zezza and Di Sipio 2008). Due to the high hydraulic conductivity, the subsoil is directly connected to the lagoon. Therefore, the perched aquifer is immediately affected by the hydrostatic pressure variation driven by tides. Tidal fluctuations force seawater intrusion inland and create a noticeable effect at the top of the aquifer (mainly at higher tidal levels) near the water table, whose variations are between 0.70 and 0.05 m AMSL.

Chemical and isotopic results

Following the Piper classification, Venice's shallow water can be defined as chloride-sulphate-alkaline water and is generally slightly basic (7.1<pH<8; Fig. 3b). Electrical conductivity (EC) measurements and Cl^- analyses have been performed to determine the presence of salt water within the groundwater, given that EC values ≤1 mS/cm indicate freshwater and Cl^- >300 mg/l indicate brackish water (Di Sipio et al. 2006; Oude-Essink 2001). In the perched aquifers, the values are typical of saline water (2.9<EC<28.9 mS/cm; Cl^- ≥10,000 mg/l) all through the year, while in the confined aquifers they are typical of brackish water (3.8<EC<21.2 mS/cm, 300<Cl^- <10,000 mg/l). In addition, the isotopic analyses focused on the δ^2H–$\delta^{18}O$ relationship and confirmed the existence of a mix between fresh water of meteoric origin and seawater (−50‰<δ^2H<−30‰; −7.5‰<$\delta^{18}O$<−4.5‰, Fig. 3c). The salinization process decreases farther from the lagoonal margins and is conditioned by permeability variations within the subsoil (Zezza and Di Sipio 2008; Zezza 2010). As a matter of fact, direct contact between aquifers carrying salt or brackish water and building foundations can lead to sea-salt transport within masonry walls, aggravating the decay process.

Salt decay process

Salts may enter and be transported within the porous materials only if dissolved in water. Therefore, salt transport can occur directly from soil by rising damp,

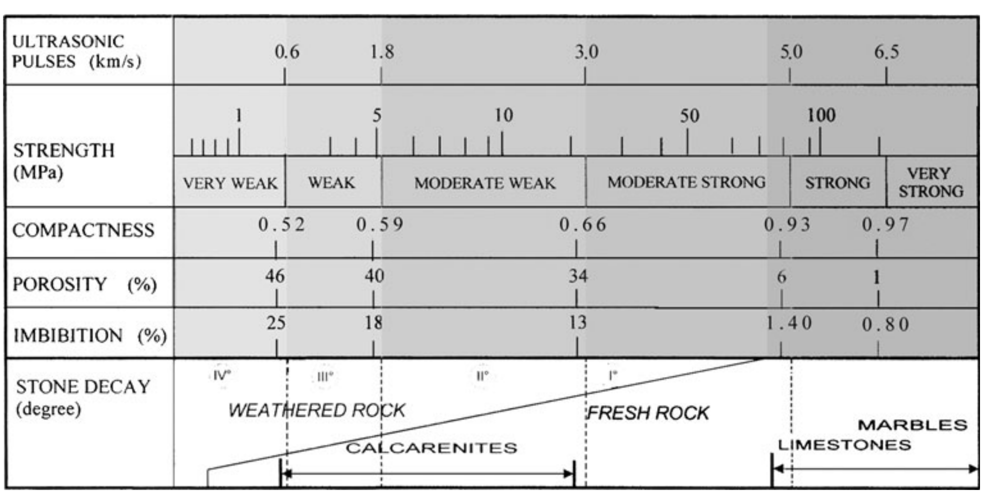

Fig. 6 Ultrasonic velocities and degree of stone decay expressed by the average values of physical–mechanical parameters (by Zezza 1996, modified)

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through marine spray (aerosol) and flooding events, or by constant contact with salt water (Fassina et al. 2002; Antonelli et al. 2002). The origin and spreading of sea salt inside buildings are remarkably influenced by sea-salt sources, masonry morphologies and foundation typologies. Buildings, whether located on the waterfront or inland, are supported by foundations inserted into infill land and, therefore, are directly in contact with the shallow aquifer affected by seawater intrusion. The salts (dissolved in water), due to capillary rise and to the presence of permeable materials both in the subsoil and in the pillars or basements, can accumulate within the masonry, favoring the weathering process of the stones, mortar and bricks (Fig. 5b). As a result, in such aggressive environments, decay phenomena occur due to salt crystallization and frost/defrost actions. According to the European Asset Project findings (AA.VV. Asset Project 2004), the decay patterns related to the coastal environment can be distinguished according to the moisture and sea-salt load accumulated in the walls. It follows that three different zones (*subtidal, intertidal and supratidal*) identified by the direct and indirect methods previously mentioned, can be recognized (Fig. 7). In the *subtidal zone*, below the mean level of the low tide, a permanent presence of water precludes high concentration and accumulation of salts within building materials. As a consequence, damage due to salt crystallization is not possible, because drying processes cannot take place, and the loss of material is mainly due to wave motion. The *intertidal zone*, located within the limits of the mean high and low tide, is characterized by the cyclic presence of seawater causing cyclic processes of dissolution/crystallization of marine salts, responsible for a decrease in the mechanical strength of bricks, mortar and stones. The *supratidal zone*, above the mean high tide level, can be divided in two sub-zones, the rising damp and the marine aerosol zones, according to the prevalent sea-salt sources affecting the buildings. The rising damp zone corresponds to the lower part of the wall, above ground level, and is characterized by high moisture and salt content. In Venice, the TSS determination showed very high and increasing values up to about 1.5 m AMSL, which then decrease according to the characteristic pattern of the rising damp process (Biscontin 2001). Due to the evaporation process, salts accumulate in the outer layer of the material. Crystallization pressure results either in the powdering/sanding of the substrate or, especially in the case of non-homogeneous material, in scaling and spalling effects. In contrast, the highest parts of buildings (>4 m above MSL) are subject to marine aerosol action (Zezza and Macrì 1995). Sea-salt spray, transported by rain, wind or fog (humidity condensation), allows the crystallization of salts within the masonry, which provokes, in turn, powdering, sanding or scaling of the materials (Fassina et al 2002; Lubelli et al. 2004; Lopez-Arce et al. 2009).

Case studies

Sea-salt damages typical of the rising damp zone may be examined by considering three different case studies within Venice: the Dogana da Mar, the Torre Alberaria

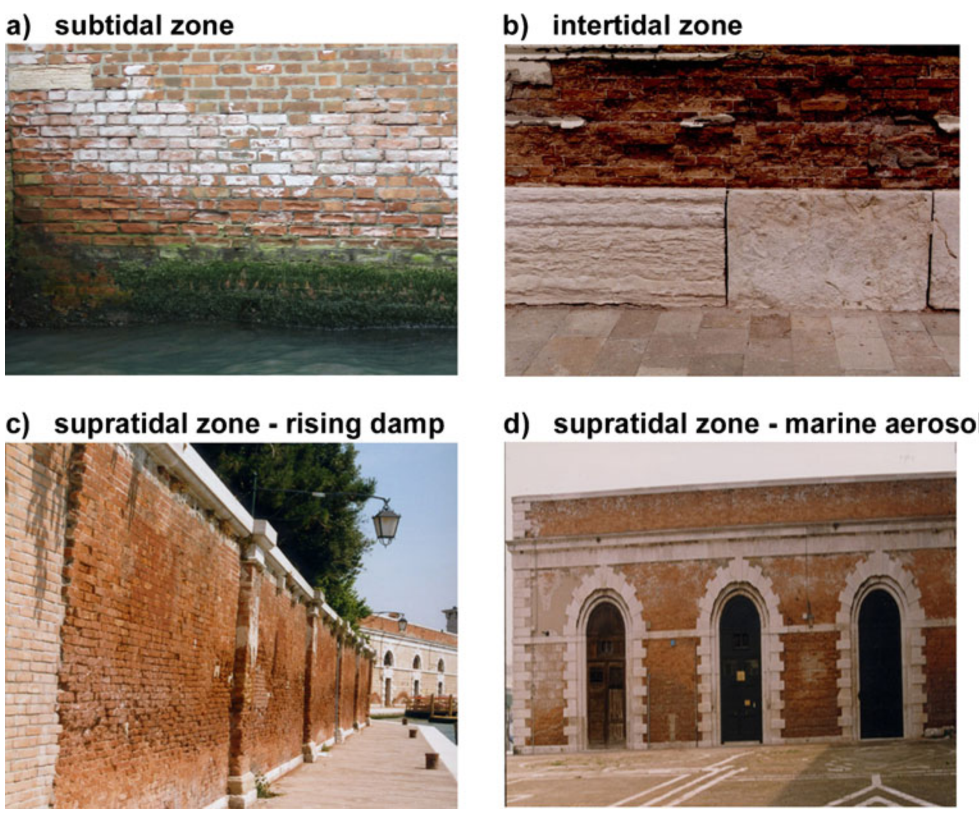

Fig. 7 The recurrent decay pattern zones for building materials in Venice: **a** subtidal zone; **b** intertidal zone; **c**–**d** supratidal zone

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(Arsenale) and the Loggetta del Sansovino. These monuments allow the comparison of decay patterns affecting different building materials located in the supratidal area: brick and Istria stone (hard stone) for the Dogana da Mar; brick masonry for the Torre Alberaria; limestone and marble for the Loggetta del Sansovino. These constructions have been the subject of detailed research, whose results have been extensively described in the final reports of several projects (AA.VV. Asset Project 2004; AA.VV. Desalination Project 2009; AA. VV. Corila Project 2003). Here the attention is focused mainly on the results obtained using the ICAW methodology.

The "Dogana da Mar" is a seventeenth century building located near the Salute Church, between the San Marco Basin, the Grand Canal and the Giudecca Canal. Owing to its central location, it was used as a customs center for goods and shipping trade, and today is a center for contemporary art. Its outside walls, made of brick and Istria stone, lend themselves easily to the assessment of the masonry's preservation state. Destructive analyses, performed in situ and in the laboratory, confirm the existence of moisture and sea-salt accumulation within both bricks and Istria stone. Moreover, the petrographic investigations show that the structural-textural characteristics (i.e. pore-size distribution, preferential orientation planes, composition of the original clay mixture for bricks; lamination, stylolites, fractures, calcitic cements, organic structure for Istria stone) can influence the mechanical damage due to the expansion of crystals. The digital image processing (ICAW methodology), once validated, allows the information to be extended over a wide area, making it possible to recognize the different decay processes acting on the walls. On bricks, the methodology is useful for the following: (1) to reveal where moisture and sea salt are concentrated (shown in red, Fig. 8a); (2) to identify processes of powdering and pulverization (in yellow, Fig. 8b), discoloration and detachment (in purple and blue, Fig. 8b), and cracking (in purple, Fig. 8c–d). In contrast, in Istria stone the ICAW method allows for the detection of layering and differential deterioration phenomena (in white, Fig. 8e), as well as detachment surfaces covered by efflorescence (in blue, Fig. 8f), whose distribution is influenced by the structural-textural characteristics previously recognized.

The "Torre Alberaria" is one of the towers located in the Arsenale, since the twelfth century the heart of the Venetian naval industry. The complex, situated in the northeast part of the city and made mainly of bricks, originally extended over an area of 46 ha and today is where the Navy and several scientific research centers (CNR, Thetys) reside. During the Asset Project, the laboratory tests performed on brick samples collected at different heights (0.20–3.00 m from ground level) showed a high amount of moisture and total salt content between 0.40 and 0.80 m. The highest concentration of NaCl (just below 5%) is found up to 0.50 m in height, in the rising damp area (AA.VV. Asset Project 2004). The digital map obtained using the ICAW assessment confirmed these results. The moisture and sea-salt accumulation (shown in red, Fig. 9) is dominant above the ground level, where detachment, discoloration and efflorescence formation weaken the physical properties of the masonry. The ultrasonic pulse velocity measurements performed along the vertical profile are low in correspondence to the more

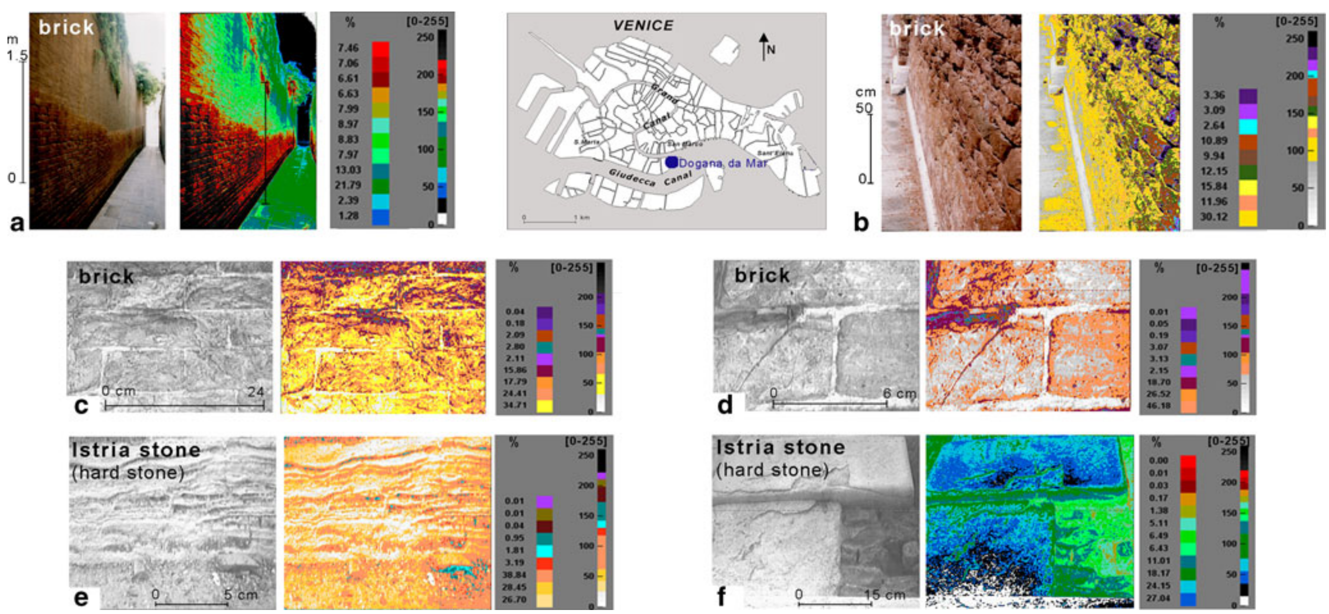

Fig. 8 Dogana da Mar, Venice. Digital image analyses (ICAW methodology) performed on building materials (brick and Istria stone) in the supratidal zone (rising damp process). The decay patterns recognized, due to sea-salt crystallization and the influence of the structural-textural characteristics of the materials, are the following—on bricks : **a** moisture/sea-salt transport and accumulation (shown in *red*); **b** powdering and detachment phenomena (in *yellow* and *purple-blue*, respectively); **c**–**d** cracking (in *purple*); on Istria stone: **e** differential deterioration (in *white*); **f** detachment surfaces covered by efflorescence (in *blue*). For every colormap (LUT) the color legends represent respectively the percentage of the areal distribution of color and the values of the pixel of the image (ranging from 0 to 255) obtained through digital image processing

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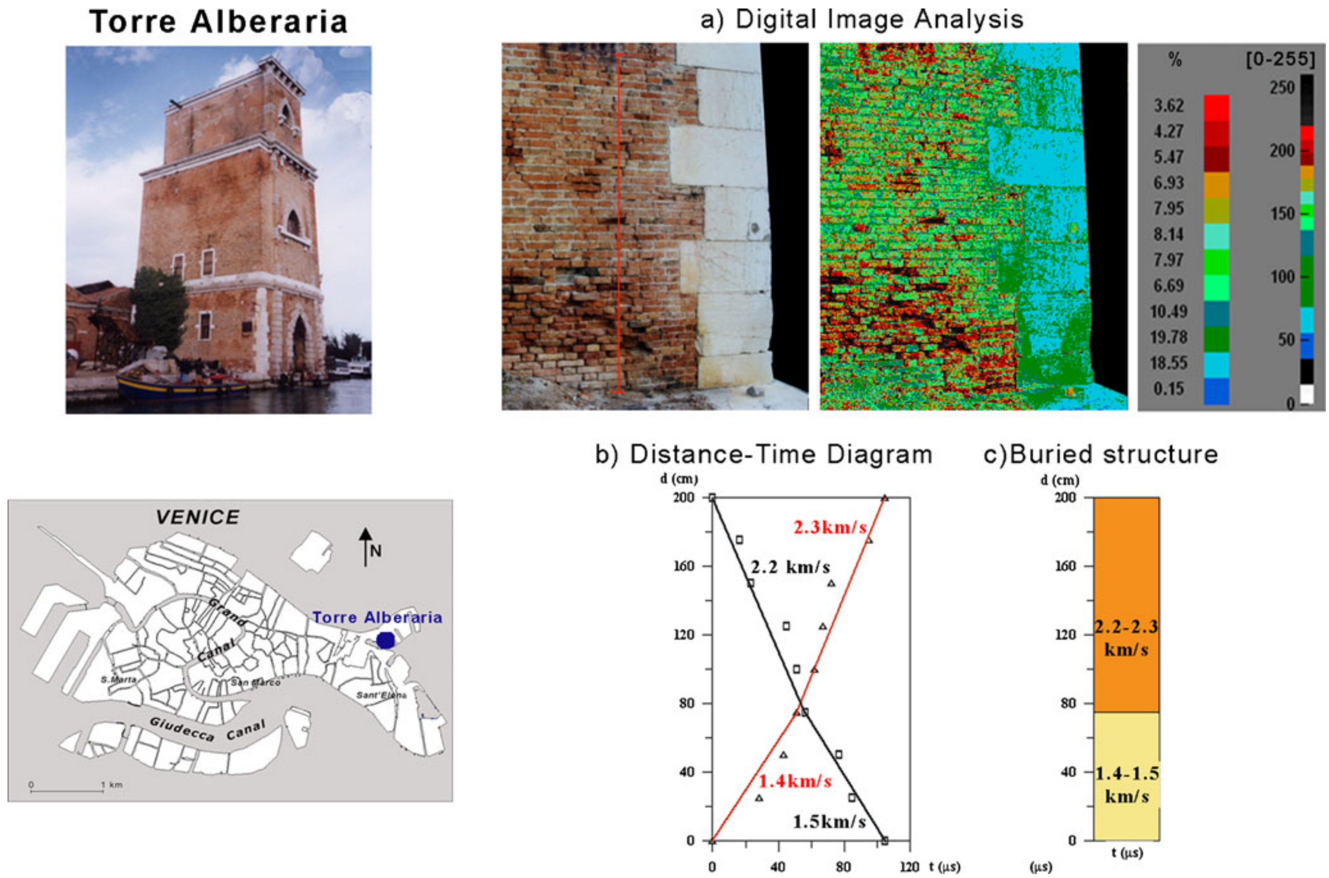

Fig. 9 Torre Alberaria (Arsenale), Venice. Digital image analyses detected in situ show in *red* the moisture/sea-salt transport and accumulation and in *yellow* the powdering affecting the bricks masonry; the color legends of the colormap represent respectively the percentage of the areal distribution of color and the values of the pixel of the image (ranging from 0 to 255). **b** The distance-time diagram shows the values of ultrasonic velocities calculated for the masonry considering the time between the transmitted and the received ultrasonic pulse (x-axis) and the increasing distance between the two probes, used in the indirect method (transmitter and receiver on the same surface). The *red line* and the *black line* refer to measurements made along the same vertical profile on the outward and return mode (i.e. changing the position of the two probes). **c** The thickness of the weathered masonry underneath the outer surface, determined from the velocity of propagation of ultrasonic pulses in the material and the time employed to cross the substrate

weathered bricks (1.4–1.5 km/s below 0.80 m) and start to increase (2.2–2.3 km/s above 0.80 m, Fig. 9) above the rising damp zone, where the action of salt crystallization and the weathering processes are reduced.

The "Loggetta del Sansovino" is a small building, conceived as a triumphal arch at the base of the San Marco bell tower. It was built between 1537 and 1549 to a design by Jacopo Sansovino. The façade is characterized by three arches separated by columns. Destroyed by the collapse of the tower in 1902, it was rebuilt in 1912 using the original material, consisting of marble and limestone, wherever possible. Within the Corila Project, together with laboratory and in situ tests, non-destructive analyses (mainly direct method ultrasonic measurements) were carried out to improve the knowledge of aspects which enhance the deterioration processes such as (1) the relationship between discontinuity planes, sources of moisture and salt transportation; (2) the structural-textural properties of stone; (3) the orientation of the architectural elements. The research efforts focused on the column bases of the main façade. The red limestone (Rosso Ammonitico of Verona) bases are 45 × 45-cm^2 parallelepipeds, and are 16 cm high. They have been in place since the sixteenth century and are characterized by a sub-vertical or sub-horizontal sedimentation plane. For every pair of the base's sides, three measuring sections were set: one central and two outer (located at 2, 22.5 and 43 cm from the margin), parallel to the two basic directions (EW-Doge's Palace/Procuratie Vecchie; NS-Clock Tower/Lagoon). A total of six ultrasonic measurements were made for every base, three in the NS direction (named *a-b-c*) and three in the EW direction (named *e-f-g*). Moreover, ultrasonic measurements were made at intervals of 2 cm along each section (Fig. 10).

Column base 4 and base 5 (Fig. 10), characterized respectively by sub-vertical (base 4) and sub-horizontal (base 5) bedding planes, were carefully investigated by means of ultrasonic measurements, to highlight the existence of changes in the physical characteristics of the limestone. According to the scheme determined by Zezza (1996; Fig. 6), the ultrasonic velocity measurements collected on stone can be related to the degree of stone decay and to the average values of the physical–mechanical parameters. Low velocities (vel ≤3 km/s) identify weathered stone (II<decay

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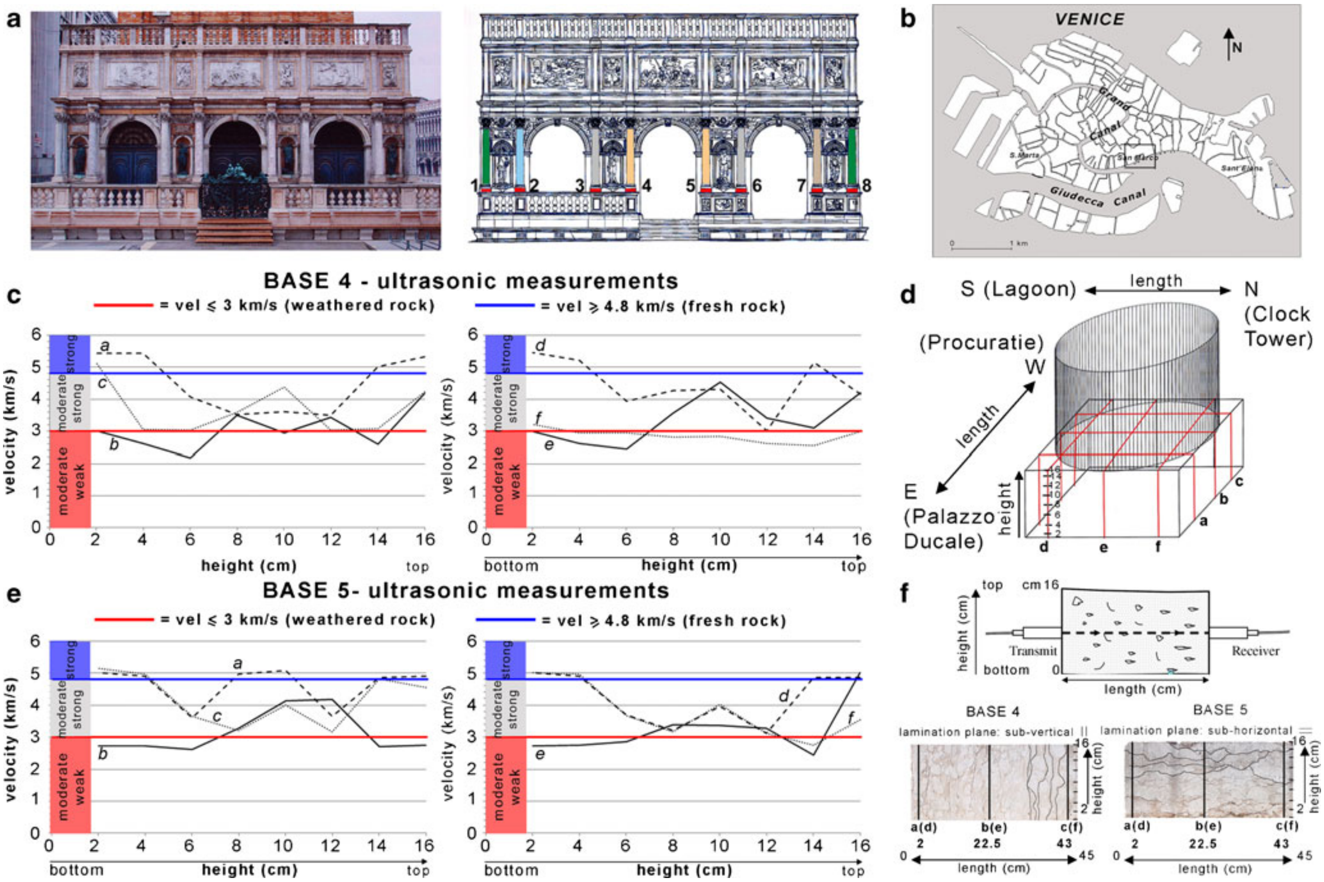

Fig. 10 Loggetta del Sansovino, San Marco Square, Venice: **a** prospect and architectural elements; **b** location; **c** sonic velocities determined on base 4; **d** planning and section of the ultrasonic measurements ; **e** sonic velocities determined on base 5; **f** ultrasonic measurements (direct method) section and orientation with a picture of base 4 (sub-vertical sedimentation plane) and base 5 (sub-horizontal sedimentation plane)

degree<IV), ranging from moderately weak to very weak in terms of strength ; intermediate velocities (3<vel <4.8 km/s) correspond to stone classified as slightly weathered (decay degree=I) and moderately strong; high values (vel ≥4.8 km/s) are typical of fresh and strong/very strong stone.

The measurements collected on base 4 were all performed on sections parallel to the sub-vertical lamination (Fig. 10a–d–f). Given the values of those oriented NS (section a-b-c), section b shows an average ultrasonic velocity of 3 km/s, characteristic of weathered rock (moderately weak stone, decay degree=II). Sections a and c, with an average velocity of 4.49 and 3.69 km/s respectively, fall in the field of moderately strong rock, at the boundary between fresh and slightly weathered material (decay degree=I). Among the sections oriented EW (section d-e-f), it is section f, with an average velocity of 2.86 km/s, that is characterized as weathered (decay degree=II) and moderately weak stone. Sections d and e, with average velocities of 4.43 and 3.35 km/s respectively, suffer a slight weathering process (decay degree=I) and are characterized by a moderately strong value of strength (Fig. 10c).

The measurements collected from sections on base 5 were all made perpendicular to the sub-horizontal lamination (Fig. 10f). The sections (a-b-c) oriented NS show average ultrasonic velocity values of 4.63, 3.14, and 4.19 km/s respectively, belonging to the field of moderately strong stone, in the transition zone between fresh rock and slightly weathered rock (decay degree= I). Among the section (d-e-f) oriented EW, the values of average ultrasonic velocity progressively increase moving from the inner (section e vel=3.23 km/s) to the outer (section f vel=3.79 km/s and section d vel= 4.21 km/s) parts. In this case the rock can also be classified as moderately strong and slightly weathered (decay degree=I). However, each trend shows local variations that must be considered (Fig. 10e). To summarize, the height/velocity diagrams show different behavior: when the alignment of the probes is parallel (base 4) or across (base 5) the bedding plane of the limestone, a variation of the sonic parameters can be observed. In general, the values of average ultrasonic velocity collected for base 5 are greater than those of base 4 along every sounding. The observed differences are not very significant and the classification of the physical condition of stone does not vary. Both base 4 and base 5 are moderate strong limestone presenting a decay degree=I. The discrepancies recorded can be attributed to different orientations of the lamination

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plans and to different distributions of decay patterns in the two architectural elements.

If the bedding planes have a subvertical orientation (base 4), this is in agreement with the rising damp diffusion process (Fig. 10f), so the moisture/sea-salt transport and the decay process are enhanced. In contrast, if the discontinuities have a subhorizontal orientation (base 5), this is perpendicular to the vertical capillary rise (Fig. 10f), so the weathering is slightly reduced and the structural-textural properties favor the preservation of the material. Finally, the ultrasonic velocities contour maps show, in a qualitative way, the velocity trend within each base (Fig. 11). The limestone is more damaged (lowest ultrasonic velocities) in the core (plan 1) and in the outer northern side (plan 2) for base 4, and only in the core for base 5. Usually, the highest values would be expected in the inner zone, assuming a greater deterioration on top and bottom, but the outcomes reveal that in this case study this is not true. Apart from the structural-textural properties of stone, other factors such as the orientation of architectural elements or environmental conditions (rainfall, wind, etc.) could contribute to the damage process. Therefore, further investigation is needed in order to better understand how these factors can influence building materials.

Conclusion

Urban settlements located in coastal areas and affected by seawater intrusion are characterized by building damage. The city of Venice is representative of this condition. The geological configuration of the city subsoil reveals a direct contact between building foundations and shallow aquifers affected by seawater intrusion. The perched aquifer underlying the whole city can be considered as a continuous source of sea salt for the anthropogenic structures, through the rising damp phenomenon. Together with floods and marine aerosols, capillary rise within building materials (depending on structural-textural properties of stone and brick) is responsible for moisture and sea-salt transport inside masonry walls and so for the damage provoked by sea-salt crystallization. The ICAW methodology employed is a useful tool to determine the decay patterns' areal distribution, to monitor the natural decay condition (daily, monthly, seasonal) and to obtain, in case of recovery treatments, a micro-morphological evaluation of the untreated and treated surfaces before and after treatment application.

If in the future, climate changes become responsible for sea-level rise, Venice and all coastal centers will suffer

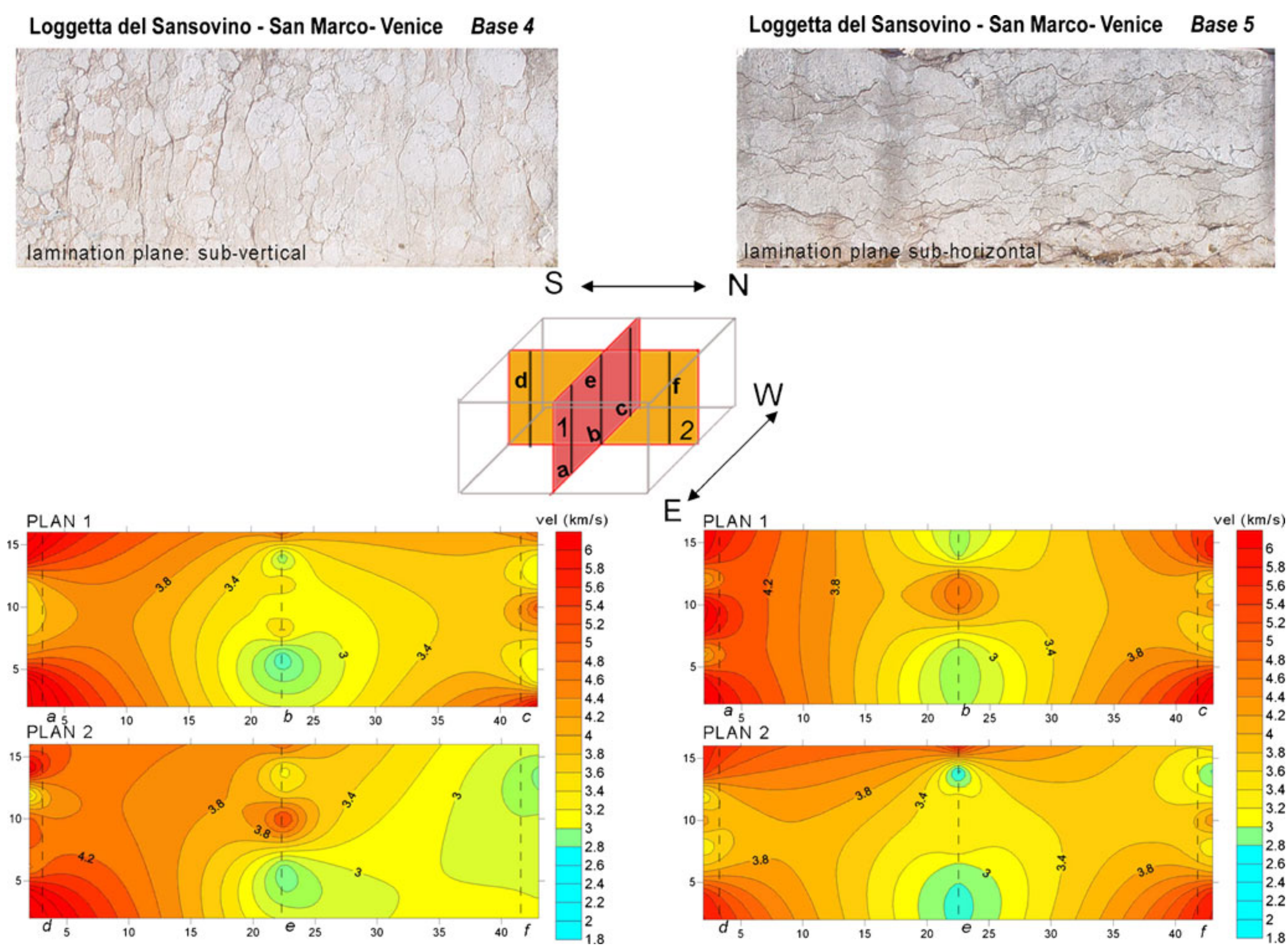

Fig. 11 Loggetta del Sansovino, San Marco Square, Venice. Ultrasonic velocity maps for base 4 (sub-vertical sedimentation plane) and base 5 (sub-horizontal sedimentation plane)

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further deterioration effects. Therefore, future projects concerning the preservation of cultural heritage and architecture must take into consideration the knowledge of sea-salt sources and related decay processes, and also the possibilities for improving desalination systems.

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