Geoheritage (2025) 17:45
https://doi.org/10.1007/s12371-025-01099-0

ORIGINAL ARTICLE

Virtutes Materiae: Cagliari, the City of Stone. Innovative Geo-tourist Itineraries Promoting the Use of Stone Resources Throughout Time

Nicola Careddu[1] · Antonio Dessena[1] · Paola Meloni[2,3]

Received: 30 April 2024 / Accepted: 11 March 2025
© The Author(s) 2025

Abstract
The historical urban development of the metropolitan city of Cagliari (Sardinia, Italy) relied heavily on the versatile use of locally sourced stone. The city's extensive exploitation of natural resources is reflected in many settlements, such as the Phoenician-Punic *necropolis of Tuvixeddu* and the complex of ruins from Roman times *Villa di Tigellio*. Among the calcareous lithological formations of the Miocene succession, Pietra Forte stands out for its physical–mechanical characteristics and durability, which has allowed it to be used specifically for the construction of iconic monuments of the city's skyline, such as the Roman Amphitheater, the Pisan Towers, the Bastion of Saint Remy, the Basilica of Bonaria and the Cathedral of *Santa Maria Assunta* and *Santa Cecilia*, to name a few that are considered cultural heritages. Significant evidence of the great, millennial quarrying activity is Buoncammino, the Botanical Gardens, the pit of San Guglielmo, some "latomia", underground quarries and so on. The evidence which has emerged between the subsoil and the built-up area may help develop a diverse and innovative tourism along with the cultural enrichment, which acknowledges the "geological history" of the Upper Miocene period as the result of the use of materials, which can be recognised in the most important city monuments, by its ivory colour range, which gives the city itself an evocative and elegant monumental structuring. A dedicated web application suggests a whole series of different geo-urban itineraries which would be customised to the visitor's needs and developed as part of the project.

Keywords Natural stone · Geotourism · Urban Geological Itineraries · Innovation · Historical monuments and buildings

Introduction

When an experienced observer lays eyes on an ancient or historic building or monument, he immediately recognizes the local rocks amongst the different materials used (Rodolico 1965). If mostly compact limestones are found by an urban settlement, they will likely be extensively exploited; however, if soft limestones are also found in the same area, the attention of many builders will immediately turn to these materials, given the significantly lower cost of working, regardless of their rather inferior quality.

The compact limestone, in these cases, becomes the *living stone*, the strong stone, to be used in place in the most demanding masonry alongside the prevailing soft stone. This duplicity, mainly related to natural conditions and the economic factor (extraction and processing costs), often occurs in countless historic centers of cities and towns around the world.

Where limestone stratifications have different mechanical properties, builders placed stones of particular value (resistance to the most combined stresses, low hygroscopicity, good durability, etc.) in certain parts of the buildings, first and foremost at the base. Conversely, in the upper parts of the buildings, lighter ones were preferred, and therefore they were sought after. Stones with high strength were also essential for reinforcing lintel edges and generally for the contours of the doors and windows, whereas the best available stone,

✉ Nicola Careddu
ncareddu@unica.it

1 Department of Civil, Environmental Engineering and Architecture (DICAAr), Università Degli Studi Di Cagliari, Via Marengo 2, 09123 Cagliari, Italy

2 Department of Mechanical, Chemical and Materials Engineering (DIMCM), Università Degli Studi Di Cagliari, Via Marengo 2, 09123 Cagliari, Italy

3 Research Laboratory for the Conservation of Cultural Heritage 'Colle Di Bonaria (DIMCM), Via Ravenna 09125, Cagliari, Italy

Published online: 20 March 2025

is typically matched with a stone of a lesser quality. Cagliari is no exception.

The stratigraphic and morphostructural characteristics of the land have deeply affected the urban layout (skyline) of the city of Cagliari over the millennia. The various features of the stones, and the way they have transformed into their current state has become subject of study.

The objective of this paper concerns the promotion of cultural routes for tourism purposes, by taking into consideration the morphological-environmental aspect, the geological structuring and the built heritage as a set of closely interconnected elements from which the peculiarity of Cagliari, often referred to as the "ivory city", originates. In this city, the built-up appears to be a ramification generated from the rock (particularly the Pietra Forte at Castello quartier), as a singular interchange expression.

In order to emphasize these features, traditional city routes for tourism purposes can be improved by including a new narrative and a series of visual elements (both natural and anthropic), which are generally not included in the current marketing tools. These elements include signs, traces, textures on the stone—as a millennial constructive excursus that has left some kind of evidence -, traces of quarrying (open-pit and underground quarries), of processing and morphological modifications also of a strong anthropic matrix, now "integrated" in the urban environment (Deplano 2009, 2008). In some sites, the old quarrying traces are strongly embedded in the building environment.

The idea of building geo-urban itineraries is not new: Slagle (1982) mapped urban itineraries to highlight the building stones used in New Orleans, Withington (1998) described the source and appearance of the stones used in Washington D.C, by including also a map and a walking guide to assist the visitor in examining them; Gaffikin (1999) described building stones used in Belfast. Rodrigues et al. (2011) discussed on how urban geoheritage can and must be known and promoted, by setting up geotourism routes for national and foreign visitors. An urban geo-touristic route has been proposed around Madrid's Royal Palace by Perez-Monserrat et al. (2013), where the building palace is viewed as an outdoor geological museum. When promoting a geo-urban itinerary in an Italian medieval town, Carveni et al. (2015) demonstrated how geo-tourism can be strategic in terms of Sustainable Social-Economic Development of the place; Gambino et al. (2017) proposed a few itineraries for the city of Turin (Italy), where visitors could observe many ornamental stones of historical and scientific interest in detail. Freire-Lista and Fort (2019) highlighted the importance of mapping the stones used in historical buildings for heritage studies and in the perspective of suitable conservation solutions.

Geotouristic routes, from quarries to monuments, have been designed by Careddu and Grillo (2019) in Bosa (Italy) and Freire-Lista et al. (2021) in Vila Real (Portugal); however, in both cases the quarries were far from the historic centre of the considered cities.

The novelty of this study lies precisely in the idea of integrating and enhancing information about the provenance of the stone: this would allow visitors to fully understand the reason for the millennial presence of mankind in this extraordinary geo-site, protected by geological ramparts, overlooking rich ponds and lagoons, where the city has taken root with walls, bastions and palaces. Cagliari has maintained textures, colours and matter in harmony and continuity with its geological sub-layer, architectural forms that masterfully fit into the natural morphological system, almost emphasizing its special features. Consider, for example, the possible similarities between the Pisan Towers and tectonic pillars, or between the sheer fault slopes and man-made bastions. The city's urban fabric, archaeological sites, and monuments have adapted to environmental challenges, the result being a showcase of a unique landscape that reflects tradition and identity. This characteristic landscape is important for the local communites and tourism alike (Siegesmund and Snethlage 2011).

Geology, mining, history, archaeology and architecture intersect and pave the way for different approaches, by enriching the narrative with elements of geourban tourism, promoting geoconservation and geoeducation. Such activities, involving aesthetic and emotional experiences, encourage the rediscovery of wonder in geological and human stories (Gordon 2018). In this sense, activities aimed at promoting geodiversity in urban areas could improve the awareness of geoheritage by the lay public (Kubalíková et al. 2021; Meloni et al. 2010, 2013). Moreover, both a proper geoeducation and a high-quality communication to the public through modern and conventional means are strategic for promoting geoheritage topics (Crofts et al. 2021; Simbaña-Tasiguano et al. 2024).

Study area

Cagliari is the regional capital of Sardinia; it is located in the southern part of the island (Fig. 1) and it overlooks the "Gulf of the Angels". The legend that explains such name, is tied with the peculiar limestone morphological profile named "Devil's saddle" (Spano 1861) shown in the Fig. 2.

Cagliari, Rome, and other famous cities share a common feature: they were built on multiple limestone hills (approximately ten in the case of Cagliari, identified as tectonic horsts, studied by Barroccu et al., 1981) which have historically defined distinct city districts in its millenary history.

Archaeological evidence from the 4th to 3rd millennium b.C. confirms that the area where today's town stands was inhabited since the Neolithic period (Lilliu 1988).

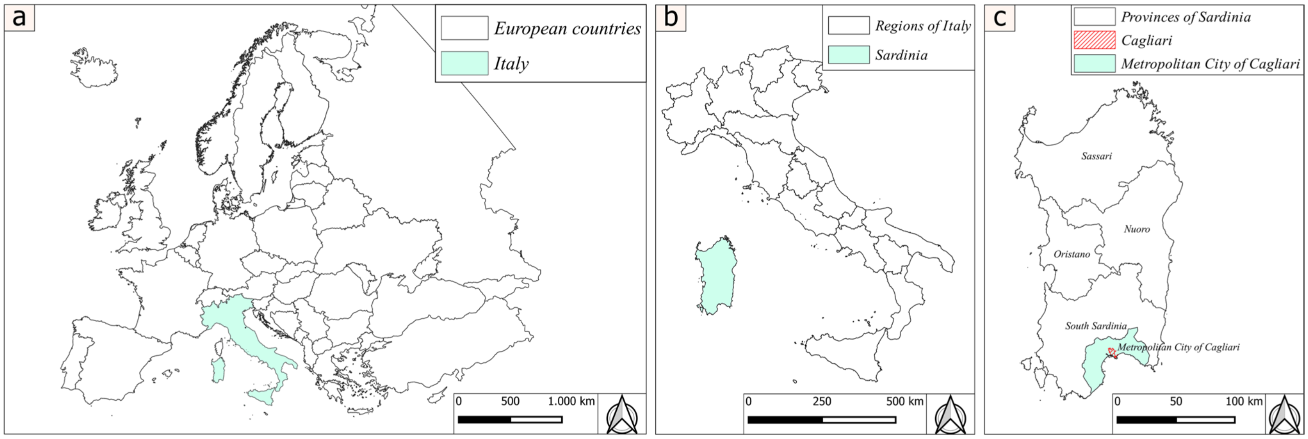

Fig. 1 Geographic location of Cagliari. a) Europe; b) Italy; c) Sardinia

Fig. 2 The limestone morphological profile "Devil's saddle"

Each culture that came into contact with Cagliari had left evidence via their use of local stones. The Phoenicians set the necropolis of the Tuvixeddu hill between the late sixth century BC and the early years of the following century; it was then activated in conjunction with the Carthaginian conquest of Sardinia (Bartoloni 2000). There are countless artefacts and traces pertaining to Roman ruling (since 238 a.C.), the most famous of which are the amphitheater and the villa of Tigellius (Pala 2002; Dadea 2006). Vandals conquered Sardinia from 456 to 534 a.C. (Casula 1998). Byzantines (since sixth century b.C.) built many churches, which can be visited (Coroneo 1993). Bastions and towers protected the city from the Arab raids were built by Pisans (since thirteenth century) (Coroneo 1993). In the Spanish era, since fourteenth century, Cagliari's strongholds were strengthened and modernized; the defensive structure, that was used to contrast the attacks from the Barbarians, was made of coastal towers which were located along the entire Sardinian coast. The structure dates back to the same period (Giannattasio et al. 2016).

The stratigraphic and morphostructural characteristic of the land, which, over the millennia, has deeply affected the urban layout/skyline of the city of Cagliari, is of crucial importance to understand its transformations into its current state (Deplano 2009). In the Miocene limestone succession, three lithotypes can be recognized (Fig. 3).

A marly-arenaceous, porous, pale yellow limestone, locally named as "Pietra Cantone", a term that indicates the specific use of the stone for making small blocks (Columbu et al. 2017).
This formation is topped by the so-called "Tramezzario", a bioclastic, ivory-colored limestone, characterized by slightly superior mechanical performance (Barroccu 2010).

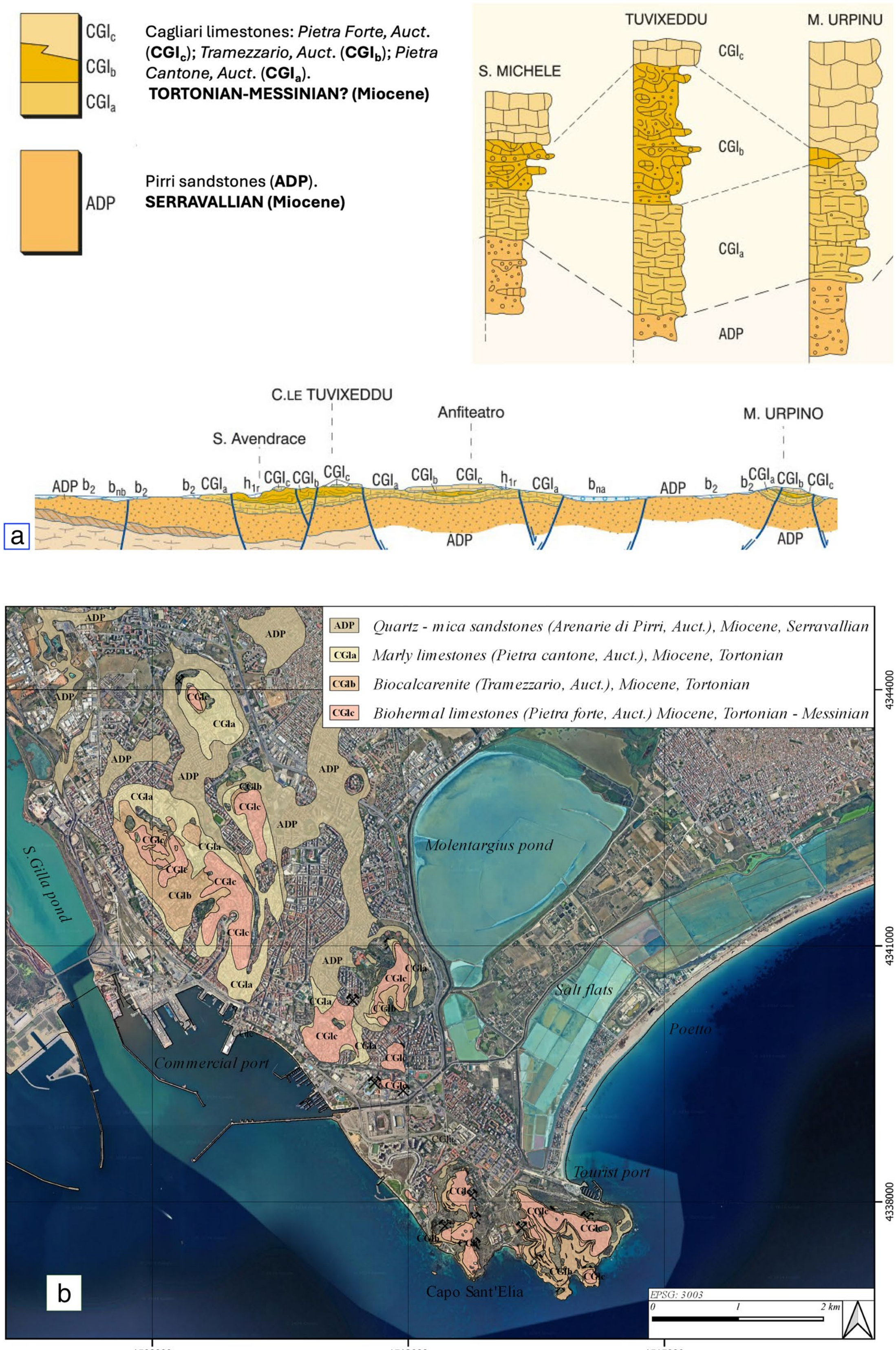

Fig. 3 **a**) Stratigraphy of the Miocene succession (from Barca et al. 2005). **b**) Geological-satellite map of Cagliari

It is followed, at the top of the succession, by the so-called "Pietra Forte", which consists of massive to bioclastic limestone, characterized by good/excellent physical–mechanical performance, with which the buildings of greatest historical interest in the city were made (Cherchi 1971).

Material and Methods

The building history of the city and its monuments is intrinsically related to the selective use of the carbonate stone materials of the Miocene succession of "Cagliari limestones". Among them, Pietra Forte (Fig. 4) stands out for its physical–mechanical characteristics and durability. The Pietra Forte also called "Bonaria Limestone" (CGI_c), is a collection of massive to bioclastic limestones, with biohermal to biostromal depositional characters. The colour of the stone from light ivory, sometimes shows yellow ochre or reddish mottling, as a consequence of microcarious processes. Occasionally brecciated areas appear in outcrop with redeposition of neogenic calcite in venules or clear crystals that carpet small cavities. Fragments of different facies of "*Pietra Forte"* were subjected to instrumental analyses. Petrographic characteristics of the stone were investigated using an optical microscopy in polarized (PL) and reflected (RL) light, respectively, on samples prepared as standard thin sections of 30 µm and on surfaces derived from cuts subjected to flattening and polishing. A Zeiss Axioskop 40 optical microscope with Zeiss camera Axiocam HR, was used. Diffractometric analyses (XRPD) were performed on powdered samples using a Rigaku MiniflexII X-ray diffractometer operating with Cu anticathode, 15 kV, 30 mA, 3°—90° 2ϑ scan, sampling step 0.02° 2ϑ, acquisition rate 0.2° 2ϑ/min. Raw data have been processed using Match Crystal Impact software recognising the mineralogical phases by comparison with the ICDD (International Centre for Diffraction Data) database. Porosimetric measurements were performed with a Micromeritics Autopore IV 9500 Porosimeter, Hg Forced Intrusion (MIP), operating until 2200 bars, with an equilibration time equal to 10 s. Fragments of about 2 cm^3 of Pietra Forte were dried at 60 °C for 24 h, then placed in a Silica gel desiccator until cooling and finally weighed. The Skeletal density and the volume of every sample were measured using a He Picnometer (Micromeritics AccuPycII 1340 V2.00).

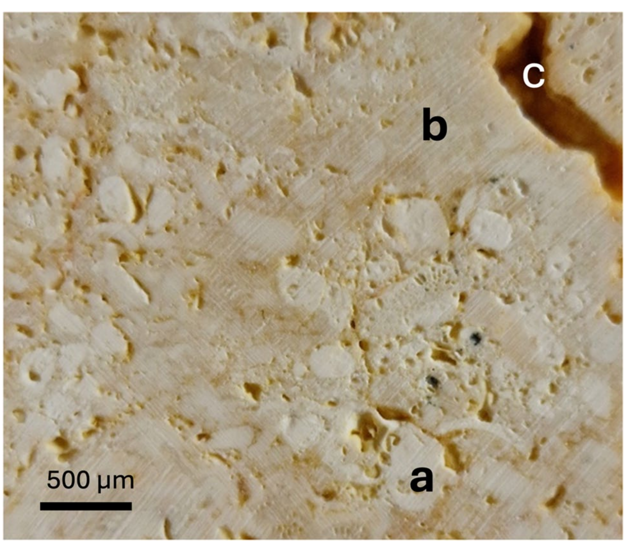

Fig. 4 Microscopic image in light reflection mode (LR) of "Pietra Forte" limestone (diamond disk sawplane surface): **a**) Lithothamnium algae, **b**) massive carbonatic matrix, **c**) microfracture

Results

The calcite is the component mineral of the stone, a virtually exclusive phase, as shown in Fig. 5, which makes the rock a real pure carbonate. On microscopic observation (Light Reflection Mode, Fig. 6 and on thin sections, Fig. 7), it can be observed that the rock is rich in bioclasts and massive carbonatic fragments in sparitic to micritic carbonate cement. The microstructure is affected by the organization in the solid of these components, as well as by a state of fracturing and related calcium carbonate re-precipitation processes.

The MIP porosimetric analysis covered two facies of the Pietra Forte limestone (see listed results in Table 1). Specifically, one porogram (black line in Fig. 8) refers to a massive, homogeneous, very compact facies, named as CPF; the second porogram (red line) refers to a less compact facies (PPF), rich in bioclasts with predominantly lithotamiunm algae. Figure 8 shows a great difference in open porosity. The CPF facies has low porosity (5.2%), with a total intrusion volume of 0.023 mL/g. This reflects a well-cemented structure, typical of a well-established micritic or sparitic matrix with no significant uncemented spaces. The markedly bioclastic facies (PPF) has a much higher porosity (27.1%) with an intrusion volume of 0.128 mL/g confirming a more open structure with large free interstitials, which can be associated with the presence of poorly cemented bioclasts. The average pore radius for the CPF sample is very small (Median Pore Radius—Volume = 0.039 µm), indicating a microstructure characterized by extremely small micropores, typical of a very dense fabric. The PPF facies has a much larger Median Pore Radius (0.174 µm), signaling that the intergranular spaces are larger, consistent with a reduced degree of cementation and the presence of larger interconnected pores related to bioclast morphology.

CPF has a higher bulk density (2.618 g/mL), while PPF, with greater porosity, has a lower density (2.119 g/mL). Bulk

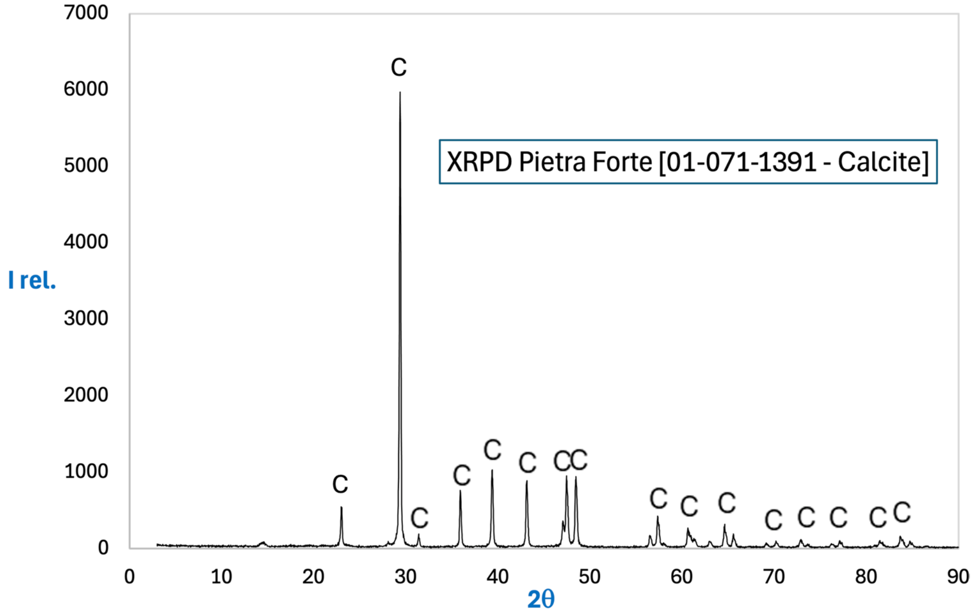

Fig. 5 XRPD Pattern of Pietra Forte limestone

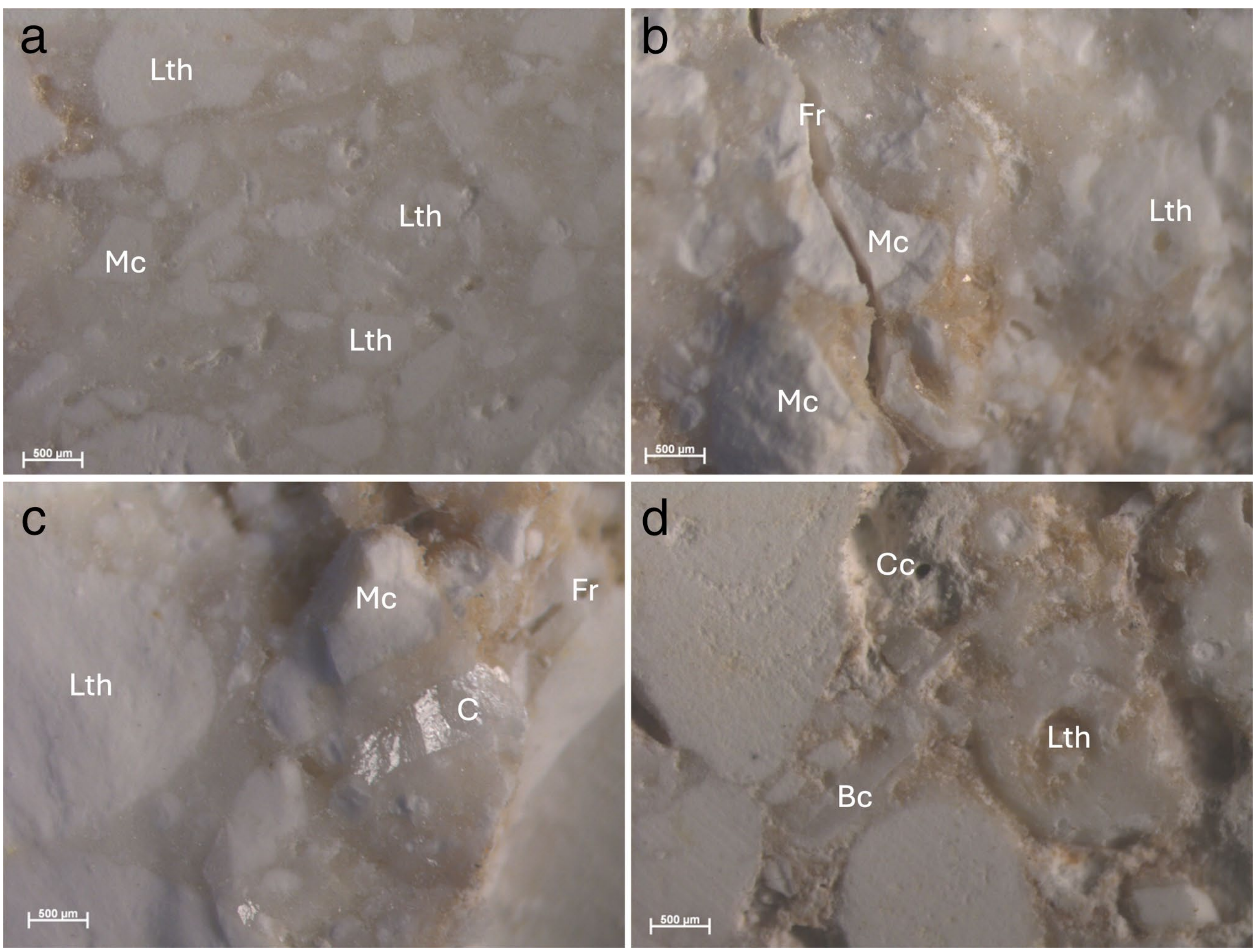

Fig. 6 Microscopic features of Pietra Forte in Reflected Light (RL) photos: (**a**,**b**) Lithothamminum rests, bio-clasts and massive carbonate fragments (**a**,**b**) Microfracture and neogenic calcite deposits (**c**) Spatic calcite venula (**d**)

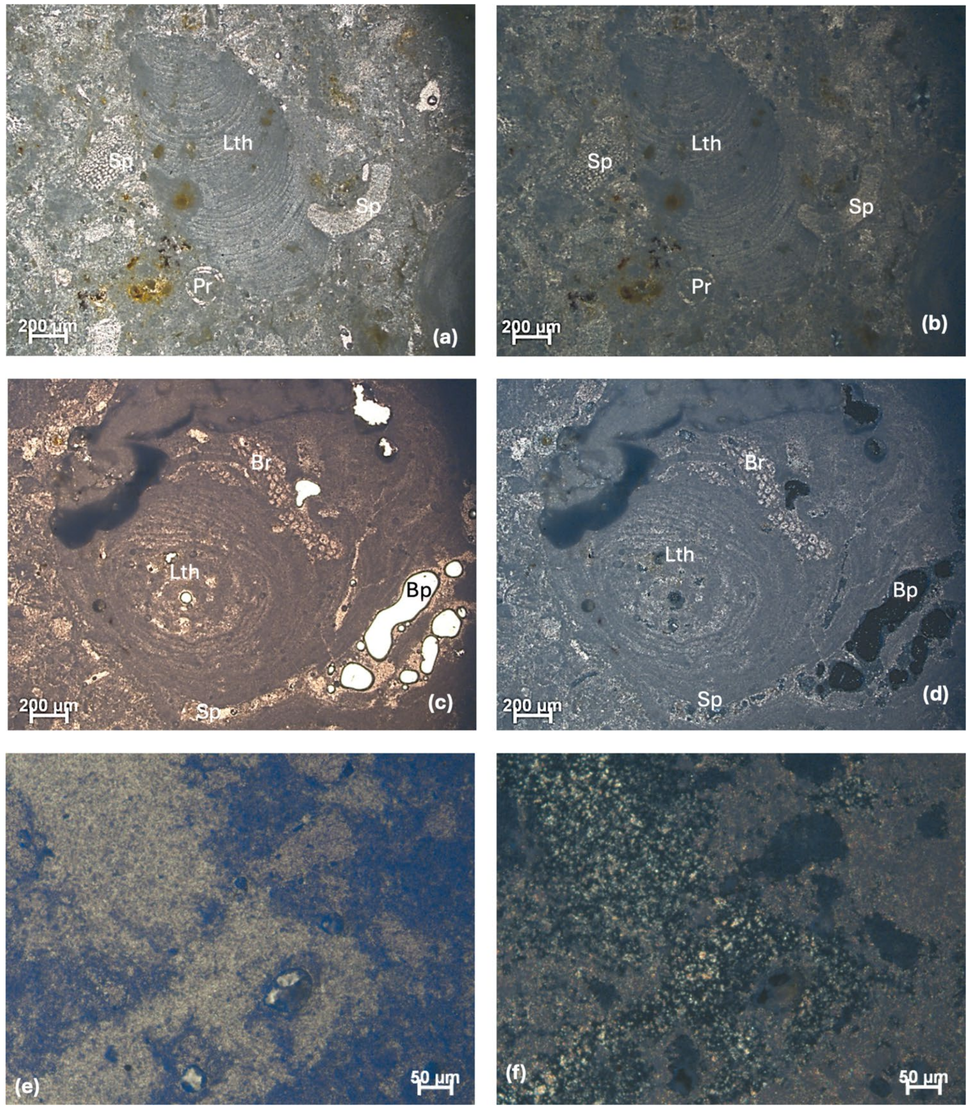

Fig. 7 Optical microscopic microstructure of Pietra Forte. LP-NP mode (**a**) and LP-NX mode and LP-NX mode (**b**): very fine and well cemented matrix (from sparitic to micritic calcite) embedding biogenic fragments especially Lithothamnium algae (Lth), Sponges (Sp), Protozoa (Pr). LP-NP mode (**c**) and LP-NX mode (**d**), very fine and well cemented matrix (from sparitic to micritic calcite) embedding biogenic fragments especially Lithothamnium algae (Lth), and bryozoans (Br); large cavities (Bp) due to partial dissolution of carbonate matrix and small pores (Sp) partially filled of newly formed sparitic calcite. LP-NP mode (**e**) and LP-NX mode (**f**): detail of carbonate matrix (from sparitic to micritic calcite)

Table 1 MIP Porosimetry Data. Pietra Forte, very compact facies (CPF) and less compact bioclastic facies (PPF)

MIP data	Unit	CPF	PPF
Total Intrusion Vol	mL/g	0.128	0.023
Total Pore Area	m^2/g	3.815	1.431
Median Pore Radius (Vol.)	μm	0.174	0.039
Median Pore Radius (Area)	μm	0.023	0.022
Average Pore Radius (2 V/A)	μm	0.067	0.033
Bulk Density	g/mL	2.445	2.678
Skeletal Density	g/mL	2.701	2.702
Porosity	%	27.102	5.213
Tortuosity	-	7.69	12.70

density is also slightly higher in CPF, indicating greater densification and compaction of sub-micrometric constituents of the solid than in the more porous limestone (PPF). The high porosity of PPF (27.1%) is indicative of uncemented open spaces, compatible with limited diagenesis processes. Both samples show low and equal values of the conductivity factor (0.022), but the tortuosity is significantly higher in CPF (12.7) than in PPF (7.69). The higher tortuosity in compact limestone highlights a more complex path for any fluids that must flow through smaller, less interconnected pores. Overall, CPF has a highly cemented microstructure with very small micropores and higher tortuosity, which reduces its overall permeability. In contrast, the porous PPF facies shows more open structure and higher connectivity between pores, with increased permeability and less tortuous structure, reflecting less compact cementation and the presence of bioclasts that are not perfectly embedded in the carbonate matrix.

It should be stressed that, while partially characterizing the material, porosity does not significantly affects the

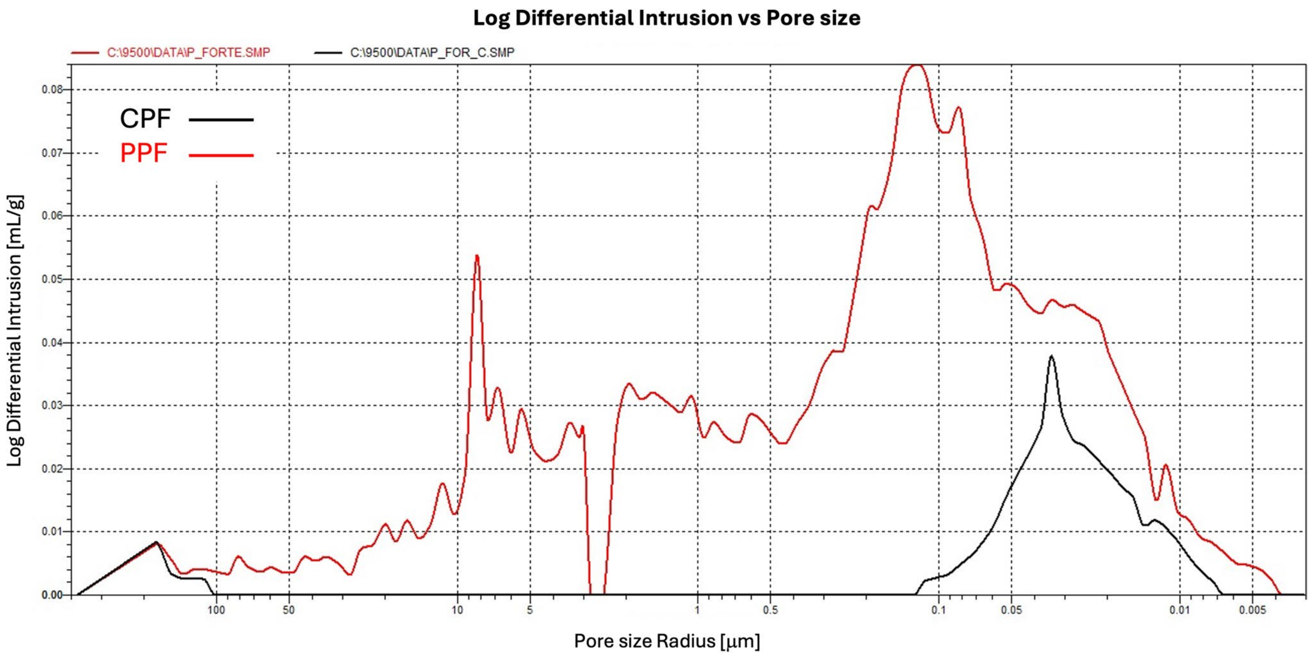

Fig. 8 Pore size distribution as a function of radius. Pietra Forte, very compact facies (CPF) and less compact bioclastic facies (PPF)

Table 2 Physical and mechanical properties of “Pietra Forte” limestone

Properties	Symbol	Unit	Value
Real density	r	[g/cm^3]	2.710 ± 0.06
Apparent density	r	[g/cm^3]	2.589 ± 0.098
H_2O open porosity	P	[%]	14.10 ± 8.70
MIP porosity	P_{mip}	[%]	16.16 ± 10.94
Uniaxial compressive strength	s_{RC}	[MPa]	52.0 ± 8.0
Young modulus	E	[GPa]	53.4 ± 5.2
Ultrasonic pulse speed (direct)	USv	[m/s]	6016 ± 460

physical–mechanical performance of Pietra Forte. The average values of the latter are shown in Table 2.

Discussion

These properties made the stone specifically suitable for the construction of iconic monuments of the Cagliari city's skyline, such as the Roman Amphitheater (I-II century a.C.), the Pisan Towers (built in 1305–1307), the Bastion of Saint Remy (built between 1530 and 1532 during the Aragonese rule), the Basilica of our Lady of Bonaria (whose construction began in 1704 and ended in 1926) (Fig. 9), the Cathedral, to name a few that are considered cultural heritages.

Currently, there are no active quarries in Cagliari: the Superintendency of Cultural Heritage and the Municipality of Cagliari have definitively banned the extraction of Pietra Forte. Unable to use Pietra Forte, in 1989, the “archistar” Renzo Piano designed a bank, which has been built at the foot of the Bonaria hill, using the marble of Orosei (Careddu et al. 2021) a Sardinian stone whose colour is reminiscent of Pietra Forte. This concept was later reiterated by Salameh et al. (2021) when suggestions were made to architects and engineers that they design sustainable buildings by borrowing or reinterpreting passive design concepts from the past.

There are countless sites of interest made with Pietra Forte in Cagliari, some of them are listed in Fig. 10. The Phoenician-Punic necropolis (Fig. 11), which is the largest in the Mediterranean area, is located in the Tuvixeddu hill. Unfortunately, after the second world war, the hill was used as quarry for cement production for the reconstruction of the city after being bombed out by the Allies in 1943. Therefore, a part of the necropolis has been destroyed. The importance of enhancing the necropolis as a cultural geo-heritage site (or geo-archeo site) has been already highlighted by Cugno (2016) as he discussed the potentiality of Cava Cardinale’s prehistoric necropolis (Italy).

Other equally interesting and easy-to-access sites built with Pietra Forte are: Saint Michael’s castle (X century), the Basilica of Saint Saturnino (V-XII century), the cathedral of Saint Cecilia (started in XIII century) and the Pisan bastions (Fig. 12).

When looking at these monuments and buildings, visitors find themselves in a sort of time-travel experience. If the ultimate objective is to create a system of geotouristic-urban roads, the itineraries should start from the old quarries and

Fig. 9 Some representative monuments in Cagliari: **a**) Roman amphitheater, **b**) the elephant tower, **c**) Umberto I terrace (bastion of Saint Remy), **d**) Basilica of our Lady of Bonaria

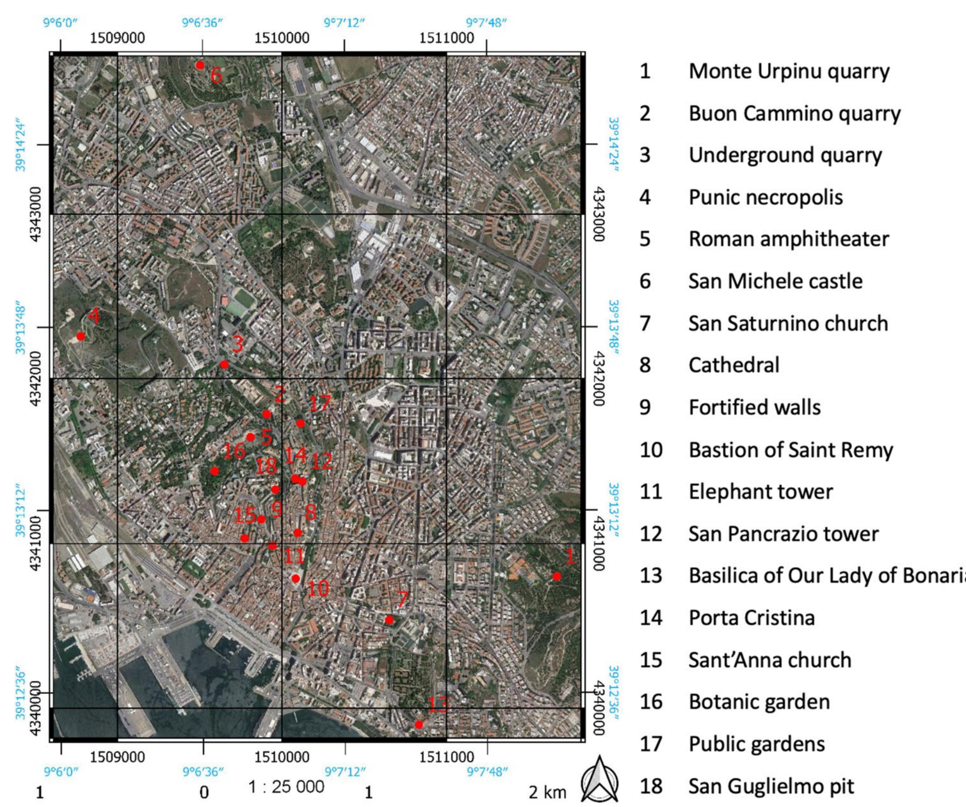

Fig. 10 Location of sites of interest tied with the Pietra Forte uses in Cagliari

Fig. 11 Tuvixeddu punic necropolis (courtesy of Sardegna Film Commission)

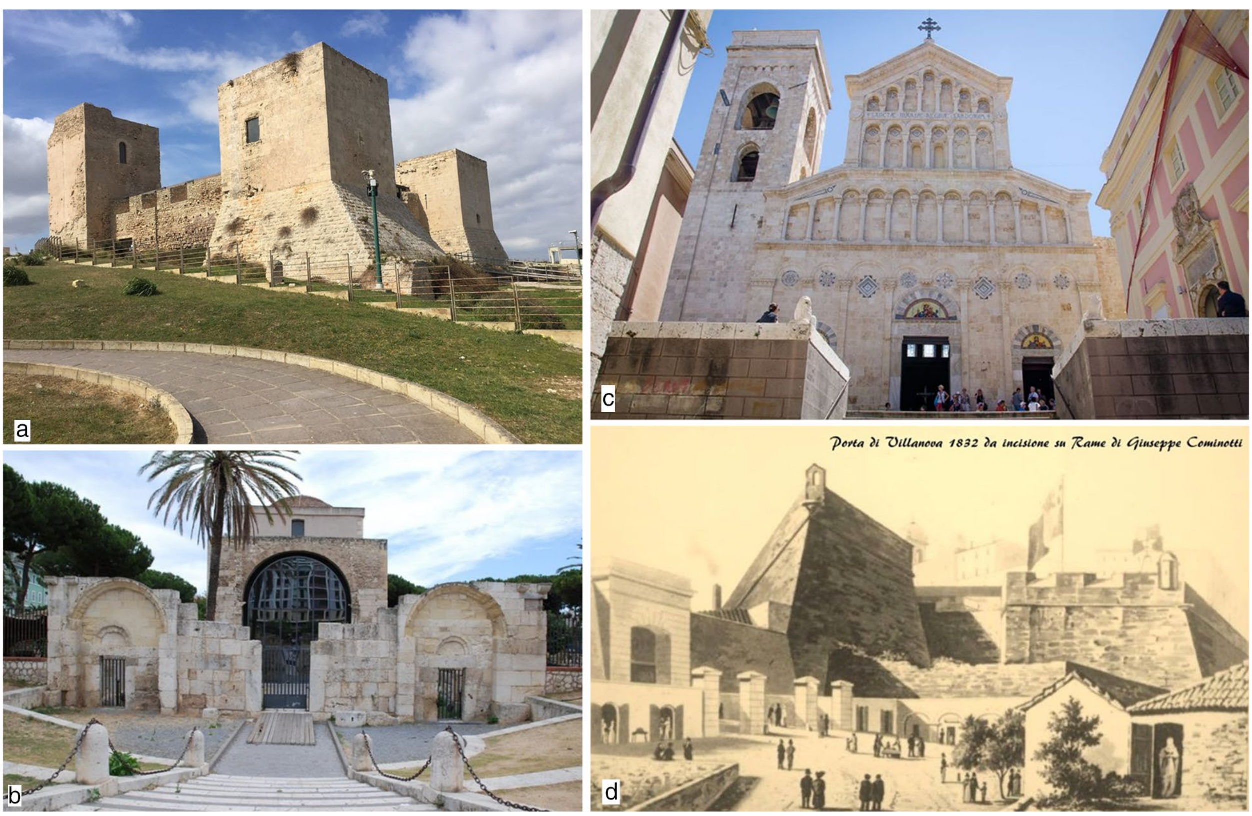

Fig. 12 **a**) Saint Michael's castle, **b**) basilica of Saint Saturnino, **c**) Saint Cecilia cathedral, **d**) old incision (1832) showing one of the gates of the bastions that were built to protect the city from arab raids

excavation traces which are still visible in the city, outdoor and under the ground.

Therefore, the design of tourist routes that are integrating "geo-heritage + environmental-morphological features" altogether, could simply start from the examination of specialized geological/geotechnical cartography followed by a few in situ inspections, and the identification and geo-referencing of "sites of interest" that have peculiar characteristics. An informative database would be necessary with details including the following:

- Identification of the city's structural highs, resulting in a presentation of the Miocene carbonate succession.
- Mapping of quarrying traces (Fig. 13), correlated to the city's building and monumental history.
- Identification of remarkable landscape views, with the presence of residual vegetation (which are still present on the structural highs), that would help the visitors "imagine" and understand the evolution of the different human settlements, starting from the most ancient ones, by simply observing the geo-lithological, geo-structural and environmental characteristics.
- Selection of the most representative buildings and monuments that fit into the proposal of integrated fruition.

Among the "narrative exempla" of these geo-heritage routes, those between the Castello-Buoncammino hills and the Colle di Bonaria should be included. From these vantage points, visitors can observe several ancient quarrying areas (steps, underground quarries, etc.) of the Pietra Forte banks (Fig. 14), cleverly oriented, and how the banks are in relation to the system of geo-structural lineations that characterise and make the city skyline so unique (Meloni 1996). The view of the city from the opposite horst-structures, crowned by the Pietra Forte monuments, would help visitors to identify and locate, for example, the Aragonese and Pisan war posts that, opposed each other during the siege of the main stronghold of Castello for a long time.

A lot of underground, natural and human-built areas, that are visitable, were used as shelters during the II World War in 1943.

The idea of building geo-tourist routes based on stone culture is not new. However, these routes can be organized and promoted in an innovative way in Cagliari by introducing the use of mobile devices—smartphone/tablet—equipped with an audioguide distributed via a web-app (web application).

The routes can be enhanced through cards, figurative elements, diagrams, posters, etc., which can also be retrieved from mobile application by using QR codes. In this way, the web-app is able to highlight specific elements, alongside the monuments and the surrounding area, so as to interconnect multiple cognitive aspects.

With the support of the thorough informative app, tourists will be able to build their preferred itinerary starting from the historic quarries which are still located in the city, to the most important monuments that were built with Pietra Forte. For each single site, the application will provide visitors with all the historical and/or geological referencing.

The web-app, which will be developed as part of the project, will include specific information about the sites that can be visited (quarries and monuments). It comes without saying that each road will present a description of Pietra Forte, of the Miocene succession and all the petrographic characteristics: by then, visitors will have clear in their mind what the main subject of the geourban itinerary would be. Moreover, they will be better aware of the geodiversity and

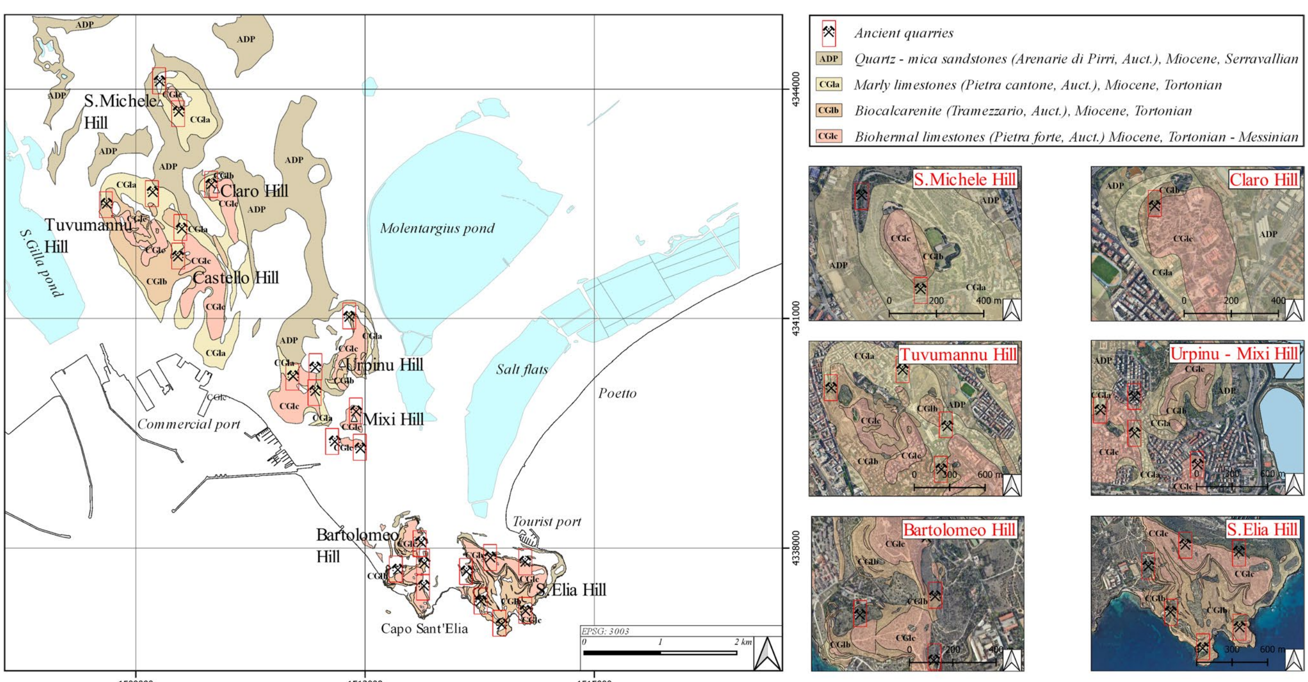

Fig. 13 Quarrying sites, identified by the red rectangles, in Cagliari and geology of the area; satellite view of the most important ancient quarries of Pietra Forte

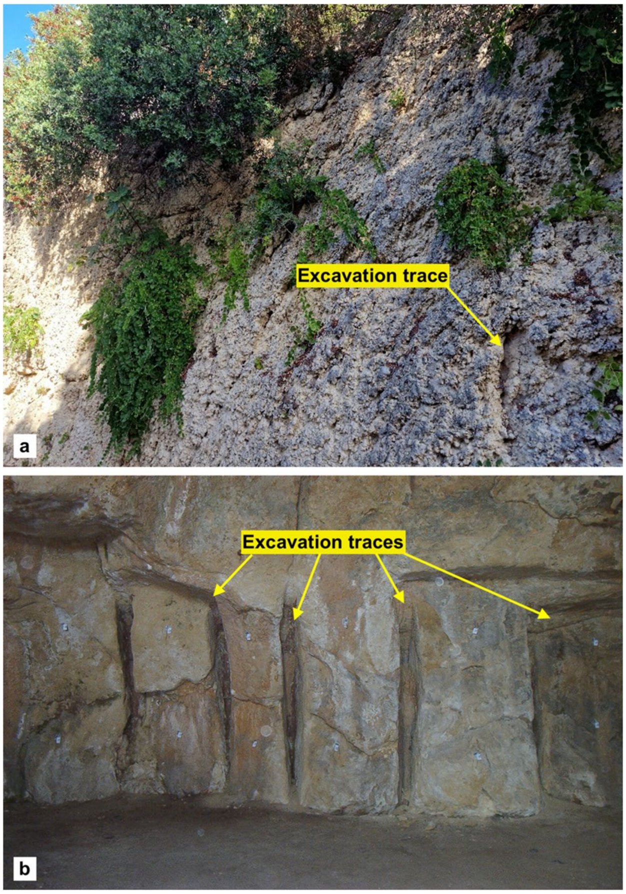

Fig. 14 **a**) Ancient quarrying face of the Pietra Forte in Bonaria Hill, **b**) ancient underground quarry (artificial caves of the Public Gardens in Cagliari). The traces of the excavations are evident

geoheritage features of the area. With regard to a diversified range of itineraries, a range of diversified options will be offered:

the app will be able to suggest different itineraries according to length, duration and difficulty. Cagliari is a seaside city that is also visited by tourists on Mediterranean cruises. They often have only a few hours to devote to the city, so an itinerary focussed on the duration of their travel can be a successful solution;

other options may be itineraries by different themes. For example, visitors can choose to visit only Roman monuments; other people might be more interested in visiting just the Pisan towers and bastions. Those interested in religious monuments can focus on churches and cathedrals. Those more intrigued by geology can start their visit at the surface quarries and continue by visiting the underground areas of Cagliari.

in addition to their own interests and/or time available, visitors will be able to construct their itinerary according to their own mobility. People with motor impairments will be able to identify the monuments that are suitably equipped.

Conclusion

The above considerations support the introduction in Cagliari of a more up-to-date narrative that embraces tourism and culture in an innovative way. That puts together interdisciplinary themes, which would integrate and disseminate the professional experience of geologists, mining engineers, architects and botanists. The census of sites of interest related to the Pietra Forte is still a work in progress. Once it is completed, it would be easier to identify the types of geo-urban routes that can be developed.

With regards to the scientific aspects of the project, the following actions can make the routes more impactful and highly innovative:

1.Elaboration of a series of maps and 3D-models that provide a better knowledge about the historical structuring of the city.
2.The creation of geo-touristic routes, including the city's monuments, that support the appreciation of a diverse range of features.
3.The creation of a more inclusive narrative that suggests a greater and better integrated offer of pathways dedicated to children. These resources, e.g. activities with simplified explanations and hints about what the young visitors are going to observe presented as "detective files", would be made available at each station, and advertised on the app. The young visitors, for example, will be prompted to look for specific details to be spotted on the monument, during their "explorative walk" as “detectives” solving a mystery. Other paths will be dedicated to tourists, students or professionals who are more interested in geology, quarrying, architecture and historical buildings.

Side by side, a new web-app will be created and tested by a start-up supported by the University of Cagliari.

All these actions will lead to a better quality of tourist enjoyment, while also improving visitor awareness of both geology, mining and heritage issues.

The next step will involve exploring other notable stones found in the city, including not only local ones, but also those quarried elsewhere on the island, with the aim to improving the visitor's geo-heritage knowledge.

Acknowledgements We extend our gratitude to the Municipality of Cagliari, the Regional Secretariat for Cultural Heritage of Sardinia, and the Superintendency of Archaeology, Fine Arts, and Landscape for the Metropolitan City of Cagliari and the Provinces of Oristano and South Sardinia, who are kindly acknowledged for their support of the Cultural Heritage Conservation Laboratory 'Colle di Bonaria' in its research and teaching activities."

Authors' contributions Dr. Nicola Careddu proposed the main concept and was involved in the write-up, editing, and reviewing of the manuscript. Dr. Antonio Dessena was involved in cartography elaboration. Dr. Paola Meloni was involved in both writing, instrumental data acquisition and interpretation and editing the manuscript.

Funding Open access funding provided by Università degli Studi di Cagliari within the CRUI-CARE Agreement. This work has been developed within the framework of the project e.INS- Ecosystem of Innovation for Next Generation Sardinia (cod. ECS 00000038) funded by the Italian Ministry for Research and Education (MUR) under the National Recovery and Resilience Plan (NRRP)—MISSION 4 COMPONENT 2, "From research to business" INVESTMENT 1.5, "Creation and strengthening of Ecosystems of innovation" and construction of "Territorial R&D Leaders".

Data Availability The datasets used and/or analyzed during the current study are available in the article/ from the corresponding author on request.

Declarations

Ethical Standard The authors declare that this research article complies with the ethical standards of this journal.

Informed Consent This article does not contain any information that requires informed consent.

Conflict of Interest The authors declare that they have no conflict of interest.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

Barca, S., Melis, E., Annino, E., Cincotti, F., Ulzega, A., Orrù, P., Pintus, C., 2005. APAT, Dipartimento Difesa del Suolo, Servizio Geologico d'Italia. Note Illustrative della Carta Geologica d'Italia alla scala 1:50.00. Foglia Cagliari n. 557. Ente Realizzatore RAS. Edizioni SELCA, Firenze, 2005 (in Italian).

Barroccu, G., 2010. Urban geology and hydrogeology of the Metropolitan Area of Cagliari. In: Abis E (ed) Il caso di studio dell'Area metropolitana di Cagliari: Pianificazione sostenibile: paesaggio, ambiente, energia. Future Mac 09, pp. 116–121, Gangemi editore S.p.A, p 64

Barrocu, G., Crespellani, T. Loi, A., 1981. Caratteristiche geologico-tecniche del sottosuolo dell'area urbana di Cagliari. Riv. It.di Geotec, 15, 98–144

Bartoloni, P., 2000. La necropoli di Tuvixeddu tipologia e cronologia della ceramica. RStFen, 28 (1), 2000, pp. 79–122.

Careddu N, Cuccuru S, Grillo SM (2021) Sardinian granitoids: 4000 years of geoheritage and dimension stones. Resour Policy 74(2021):102339

Careddu, N., Grillo, S.M., 2019. "Trachytes" from Sardinia: Geoheritage and Current Use. Sustainability (2019), 11(13), 3706, Special Issue "Natural Stone and Architectural Heritage"; https://doi.org/10.3390/su11133706.

Carveni, P., Sibi, P., Torre, A., Torre, F., Valletta, M., 2015. A geological itinerary in the Sclafani Bagni village. Ideal way for the discovery, defense and divulgation of geological heritage and promotion of geotourism. In Proc. Congr. Naz. "Geositi, Geomorfositi e Geoarcheositi patrimonio geologico-ambientale del Mediterraneo", Portopalo di Capo Passero (SR), Italy, 4–5 september 2015. Geologia dell'Ambiente, suppl. 3/2016. ISSN 1591–5352.

Casula, F.C., 1998. La Storia di Sardegna, Sassari, C. Delfino ed., Sassari (Italy), 1998. ISBN 88–7741–760–9.

Cherchi A (1971) Appunti biostratigrafici sul Miocene della Sardegna (Italia). Mem BRGM 78:433–445. (in Italian)

Columbu, S., Lisci, C., Sitzia, F., Buccellato, G., 2017. Physical–mechanical consolidation and protection of Miocenic limestone used on Mediterranean historical monuments: the case study of Pietra Cantone (southern Sardinia, Italy). Environ Earth Sci 76, 148 (2017).

Coroneo, R., 1993. Architettura romanica dalla metà del mille al primo '300, Ilisso Ed., Cagliari, Italy, 1993. ISBN 88–85098–24-X.

Crofts R, Tormey D, Gordon JE (2021) Introducing new guidelines on geoheritage conservation in protected and conserved areas. Geoheritage 13:33

Cugno S.A., 2016. Cava Cardinale's prehistoric rock-cut necropolis: proposals of valorization of a geoarcheosite in the hinterland of Syracuse. In Proc. Congr. Naz. "Geositi, Geomorfositi e Geoarcheositi patrimonio geologico-ambientale del Mediterraneo", Portopalo di Capo Passero (SR), Italy, 4–5 september 2015. Geologia dell'Ambiente, suppl. 3/2016. ISSN 1591–5352.

Dadea, M., 2006. Guida all'anfiteatro romano di Cagliari. C. Delfino ed., Sassari (Italy), 2006. ISBN: 9788871384047.

Deplano, C., 2008. Laboratorio del paesaggio urbano: analisi morfologica del quartiere Castello in Cagliari. Edicom Ed., Monfalcone, Gorizia (Italy), 200. ISBN 978–88–86729–92–5.

Deplano, G., 2009. Analisi del paesaggio urbano: Cagliari ed il suo centro storico. Edicom Ed., Monfalcone , Gorizia (Italy), 2009, ISBN 978–88–86729–99–4.

Freire-Lista DM, Fort R (2019) Historical city centers and traditional building stones as heritage: the Barrio de las Letras, Madrid (Spain). Geoheritage 11:71

Freire-Lista, D.M., Sousa, L., Lourenço, M., Becerra Becerra J.E., 2021. Granite of Pena, Vila Real: a heritage stone of northern Portugal. In Proc. II International Workshop on Heritage Stones, Torino (Italy) 5–7 October 2021.

Gaffikin, P., 1999. Set in stone: a geological guide to the building stones of Belfast. Environment and Heritage Service, Belfast.

Gambino F, Borghi A, d'Atri A, Gallo LM, Ghiraldi L, Giardino M, Martire L, Palomba M, Perotti L (2017) TourInStones: application for mobile on ornamental stones of the city of Torino. Rend Online Soc Geol It 42(2017):81–84

Giannattasio C, Grillo SM, Murru S (2016) The Sardinian coastal towers in the Mediterranean (16th–17th century): An archaeometrical approach for the study of masonry. J Cult Herit 22:1072–1078

Gordon, J.E., 2018. Geoheritage, Geotourism and the Cultural Landscape: Enhancing the Visitor Experience and Promoting Geoconservation. Geosciences, 2018, 8, 136; 10.3390.

Kubalíková L, Bajer A, Balková M (2021) Brief notes on geodiversity and geoheritage perception by the lay public. Geosciences 11:54

Lilliu, G., 1988. La civiltà dei Sardi dal Paleolitico all'età dei nuraghi, Nuova Eri (pub.) 1988 (in Italian)

Meloni P (1996) Dati sismici e geostrutturali sulle formazioni carbonatiche costituenti i colli storici dellacittà di Cagliari. Plinius Supplemento All'european J Mineral 16:144–145. (in Italian)

Meloni, P., Vacca, G., Massidda, L., Carcangiu, G., Mameli, P., Cocco, O., Toreno, G., 2010. Vulnerabilità dei beni culturali: Sistemi informatici finalizzati alla conservazione programmata e preventiva di monumenti in marmo. In: Pensare la Prevenzione: Manufatti, Usi, Ambienti; Ricerche, A., Ed.; Parco Scientifico Tecnologico di Venezia: Marghera-Venezia, Italy, 2010; pp. 385–392 (in Italian).

Meloni, P., Toreno, G., Carcangiu, G., Cocco, O., Deiana, M., Murru, A., 2013. Sinergie per la conservazione degli spazi della memoria: L'esperienza didattica dei cantieri pilota del cimitero monumentale di Bonaria in Cagliari. In: Atti 2° Congresso Specialistico Internazionale sui Cimiteri Monumentali: Conoscenza, Conservazione e Restyling; Cicop Italia - Centro Internazionale per la Conservazione del Patrimonio Architettonico: Firenze, Italy, 2013; pp. 166–171 (in Italian).

Pala P., 2002. L'anfiteatro Romano di Cagliari, Quaderni di archeologia n.1, Editore Insula , Nuoro (Italy), ISBN 978–88–86111–15–7.

Perez-Monserrat EM, de Buergo MA, Gomez-Heras M, Maria Jose Varas-Muriel MJ, Fort Gonzalez R (2013) An urban geomonumental route focusing on the petrological and decay features of traditional building stones used in Madrid, Spain. Environ Earth Sci 69:1071–1084

Rodolico, F., 1965. Le pietre delle città d'Italia. 2° ed. F. Le Monnier, Firenze, 1965, 501 pp. (in Italian).

Rodrigues ML, Russo Machado C, Trabazo FE (2011) Geotourism routes in urban areas: a preliminary approach to the Lisbon geoheritage survey. Geojournal of Tourism and Geosites 8:281–294

Salameh MM, Touqan BA, Awad J, Salameh MM (2021) Heritage conservation as a bridge to sustainability assessing thermal performance and the preservation of identity through heritage conservation in the Mediterranean city of Nablus. Ain Shams Eng J 13(2022):101553

Siegesmund, S., Snethlage, R., 2011. Stone in Architecture - Properties, Durability. Fourth Edition, Springer-Verlag Berlin Heidelberg 2011. ISBN 978–3–642–14474–5.

Simbaña-Tasiguano M, Cabascango-Chiliquinga E, Sánchez-Cortez JL, García-Frank A, Grefa-Shiguango H (2024) Geoeducation strategies in the Amazon. Napo Sumaco Aspiring UNESCO Global Geopark, International Journal of Geoheritage and Parks 12(3):465–484

Slagle ES (1982) A Tour Guide to Building Stones of New Orleans. Society, New Orleans Geol, p 68

Spano, G., 1861. Guida della città e dintorni di Cagliari. Italia, Timon A. Ed.

Withington, C., 1998. Building stones of our Nation's Capital: Washington, D.C., US Geological Survey, US. Govt. Printing Office, p 36.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.