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ORIGINAL ARTICLE

The Transversal Heritage of Maastricht Stone, a Potential Global Heritage Stone Resource from Belgium and the Netherlands

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Abstract

Maastricht Stone is a soft and porous, pale limestone from the *Krijtland*, a geological region with Late Cretaceous outcrops across the border of Belgium, The Netherlands, and Germany. It has a remarkably high porosity and low strength; however, the stone is very durable in a diverse range of outdoor applications. The stone has been used since Roman times, excavated in some opencast and many underground quarries. Its main use is situated in the period between the fifteenth and first half of the twentieth century. The local community has always been strongly engaged with the production of the stone and the resulting underground landscape, which has served for secondary purposes as shelter, mushroom cultivation, and tourism. Today, the region is appreciated for this particular landscape and the recognisability of the built heritage in Maastricht Stone. The stone is a preferred substrate for scientific research in stone conservation, due to of the homogeneity of the blocks from the last remaining active quarry in combination with its specific petrophysical properties. Therefore, Maastricht Stone is proposed as a 'Global Heritage Stone Resource' to augment its visibility and understanding.

Keywords Maastrichtian · Limestone · Underground quarry · Mosasaurs · Stone conservation

This article is part of the Topical Collection on Global Heritage Stone Resource: The sustainable way forward

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Introduction

Maastricht, the southernmost city of the Netherlands in a region embayed by Belgium and Germany, has become a benchmark on the forging of European unity since the Treaty of Maastricht was signed in 1992. As one of the oldest cities of the region, it is at the core of the *Krijtland*, a relatively small and characteristic hilly landscape extending 40 km from SW to NE, and spanning these three countries, from the Belgian provinces of Limburg and Liège, over Dutch southern Limburg to the Aachen area in Germany (Fig. 1). Maastricht also gave its name to the youngest chronostratigraphical Age of the Cretaceous: Maastrichtian (72.1–66 Ma) (International Commission on Stratigraphy, International Chronostratigraphic Chart, v.2021/07), based on the pioneer work of Dumont (1849).

Within the Maastrichtian Stage, the local Maastricht Formation corresponds to its uppermost part. Building stones extracted from this unit have been widely used in the region, enforcing the links between human culture and the natural environment. The stone is predominant in local, grand, and vernacular architecture, while its extraction is traceable both in the surficial and subterranean landscape. This was

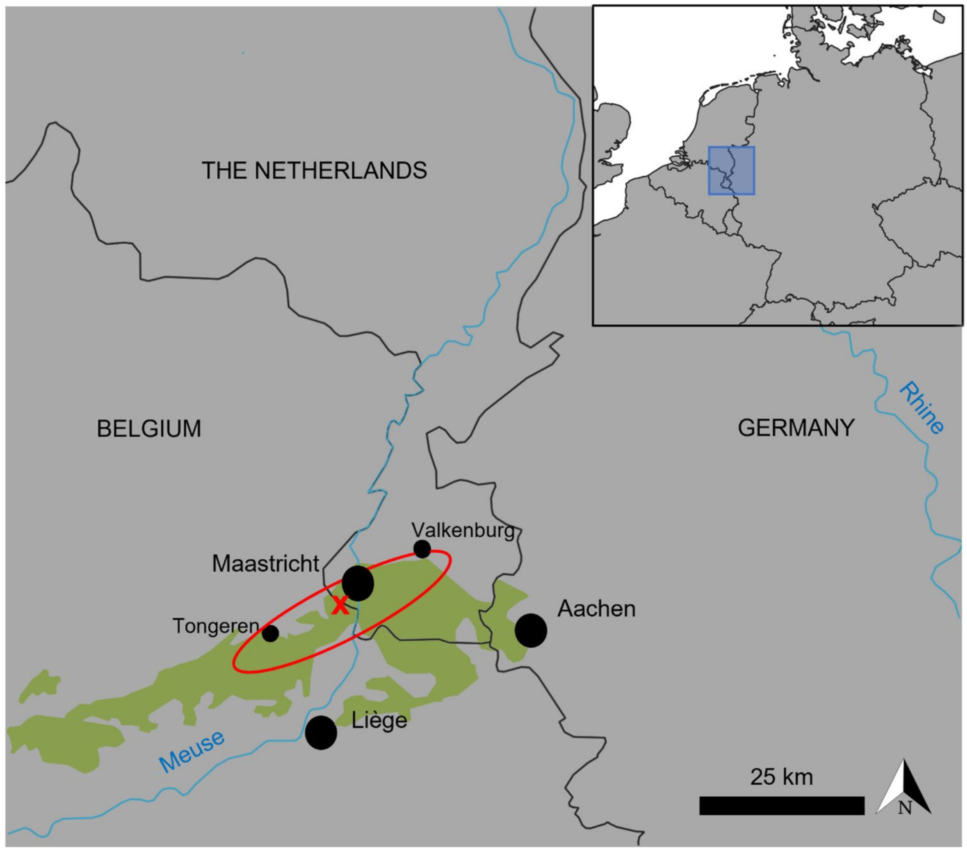

Fig. 1 Location map showing the location of Cretaceous outcrops (green) in the southernmost tip of The Netherlands and eastern Belgium, with Maastricht in the centre. The active Sibbe quarry is located just south of Valkenburg. The red circle indicates location of (underground) quarries of Maastricht Stone. Red cross represents the location of the *Sint-Pietersberg* south of Maastricht, on the Belgian-Dutch border (see Fig. 2)

followed by secondary uses of underground galleries for local practices such as mushroom cultivation. Hence, Maastricht Stone is a key element for valuing the geoheritage of the aspiring Geopark *Krijtland*, in view of both its many underground extraction sites, its architectural applications, and its associated traditional practices. Maastricht Stone is also exceptional because of its unique properties, i.e. it is 'extremely weak, yet time-resistant' (Dubelaar et al. 2006), and it is increasingly being adopted as an ideal substrate for fundamental scientific research in stone conservation. Therefore, Maastricht Stone is proposed as a 'Global Heritage Stone Resource' to the IUGS Subcommission: Heritage Stones (Cooper 2010), and this paper aims to augment its visibility and understanding.

Geological Setting

The Late Cretaceous was an overall warm period with rising sea levels, leading to an extensive chalk basin across most of NW Europe when the Atlantic Ocean was still at its incipient stage and Tethyan influences were not yet hindered by the Alpine orogen (Ziegler 1990). During the Maastrichtian Stage, the palaeogeographical configuration began to change and marine environments regressed. However, local inversion tectonics preserved a marine basin surrounding the tectonically active Roer Valley Graben (part of the Lower Rhine graben system), including the Maastricht area, where marine carbonate sedimentation spanned the Cretaceous–Paleogene boundary (Smit and Brinkhuis 1996). On average, about 200 m of Upper Cretaceous and lowermost Paleogene strata were deposited in a marine basin, starting with fluviatile sands and clays discordantly overlying Palaeozoic deposits, terminated again during the Danian Stage by a sea level drop followed by a rise favouring preservation of lacustrine deposits, which announced a major reorganisation of the sedimentary basins with the North Sea Basin as the predominant palaeogeographical unit. Later, the Krijtland was flooded only during the Oligocene, depositing a thin body of marine clayey sand, largely protecting the underlying carbonates from weathering.

Epeirogenic tilting lifted the Maastricht area to about 150 m above present sea level, after which river incision of the Meuse River and its tributaries during the Quaternary glaciations made circa 100 m of Cretaceous sedimentary rocks accessible on the slopes of *Sint-Pietersberg* south of Maastricht (Fig. 2), as well as in the wider *Krijtland* area under a cover of loess deposits. This rich agricultural soil allowed for settlement of the *Krijtland* since Neolithic times, resulting in a rich historical and architectural heritage.

Fig. 2 Maastrichtian strata at the former ENCI quarry (*Sint-Pietersberg*, Maastricht, The Netherlands, see Fig. 1), with stratigraphical subdivisions, covering nearly the entire Maastrichtian chronostratigraphic interval, which runs from the base of the Vijlen Member (not visible here) to the Cretaceous-Paleogene boundary, only a few metres above the truncated top of the Maastricht Formation. Underground galleries for extracting building stone from the Nekum Member of the Maastricht Formation are intersected in the quarry face (white box). The "Maastrichtian system" (today represented by the Maastricht Formation) was defined here by Dumont (1849)

Stratigraphy

The Maastrichtian Stage of the *Krijtland* starts with the upper part of the Gulpen Formation (Vijlen to Lanaye members), whose lower part (Zeven Wegen to Beutenaken members) is of late Campanian age as the termination of a sea level highstand; both stages are separated by a sharp sea level drop. The Maastrichtian Stage terminates within the Maastricht Formation, whose top straddles the Cretaceous–Paleogene boundary (Berg en Terblijt Horizon, exposed only in a limited area and studied in the Curfs and Geulhemmerberg sections) and is capped by the Vroenhoven Horizon at the base of the Houthem Formation, which is of Danian age (Felder 1975; Felder and Bosch 2000; Robaszynski et al. 2002). The Maastricht Formation corresponds *grosso modo* to the 'système maestrichtien' of Dumont (1849).

The carbonate platform of the *Krijtland* hence consists of the upper Campanian to lower/middle Danian Gulpen, Maastricht, and Houthem formations whose succession was controlled by both eustasy and local tectonics. The base of the Gulpen Formation consists of fine chalk deposited during an extensive flooding event covering most of NW Europe. The Gulpen and Maastricht formations were affected by inversion tectonic pulses related to the Pyrenean tectonic phase, reducing the sedimentation area. Nevertheless, a Tethyan open marine connection was maintained; strongly reduced terrigenous influx and warm clear-water conditions favoured the production of biogenic sediments with only subtle changes throughout these units. Towards the inverting Roer Valley Graben, the upper part of the Maastricht Formation is characterised by a hiatus and the remaining part became karstified under influence of meteoric water conditions. This resulted in a diagenetic alternation of compact and loose carbonate layers, which form the Kunrade Formation (in Belgium) or Kunrade facies (in the Netherlands) as a lateral equivalent to the lower part of the Maastricht Formation. The platform carbonates assigned to the Houthem Formation were deposited during a tectonic relaxation phase after the Cretaceous–Paleogene boundary, extending again much further northwards in comparison to the Maastricht Formation.

The Maastricht Formation consists of platform carbonates with some flint nodules and discontinuous layers, especially near its base, reaching an average thickness of 50 m. This has been subdivided by W.M. Felder into six members, separated by hardgrounds and their coarse covering layers (from base to top): the Valkenburg, Gronsveld, Schiepersberg, Emael, Nekum, and Meerssen members (Felder 1975) (Fig. 2). These deposits are related to astronomical cycles, from 20,000 kyr precession cycles for individual beds to 120 kyr obliquity cycles between the hardgrounds up to 400 kyr eccentricity cycles (Zijlstra 1994; Keutgen 2018), subdividing the Maastricht Formation into a lower (Valkenburg to Emael members) and an upper part (Nekum and Meerssen members). The Maastricht Formation thus is characterised by high sedimentation rates, which contributed to the gradual infill of the sedimentary basin and its shallowing upward.

Palaeontology

Notwithstanding early (i.e., Roman, Mediaeval) users of the Maastricht Stone must have come across remains of vertebrate and invertebrate animals, the first illustrated descriptions of a range of macrofossils (Fig. 3A) from underground galleries of the *Sint-Pietersberg* and vicinity first appeared in print only in the late eighteenth century (Faujas de Saint Fond 1798–1803). Subsequently, during the early days of palaeontology as a science, these taxa received formal Latin (or Latinised) names in the literature. In fact, the skeletal remains of marine squamates (reptiles) illustrated by Faujas de Saint-Fond (1798–1803) attracted a lot of attention, as they documented the existence of extinct animals that had no extant counterparts. These were much appreciated objects in the various curiosity cabinets in the city of Maastricht.

The various members of Maastricht Formation have yielded a plethora of vertebrate and invertebrate taxa, as well as marine and terrestrial plants, that document a range of biotopes in a shallow, subtropical sea that generally became shallower and warmer upsection. In recent decades, numerous new taxa have been added and faunal assemblages have been documented in more detail than ever before. Newly collected material includes either species that were already known from correlative strata elsewhere in Europe, or were new to science.

Actively swimming biota included mosasaurs, plesiosaurs, crocodiles, chelonioid turtles, sharks, rays, ratfish, and bony fish, with the first-named group consisting the apex predators in these shallow, subtropical waters. Mosasaur diversity increases markedly in the Lanaye Member (Gulpen Formation), of late Maastrichtian age, with five species being known to date from the overlying Maastricht Formation. *Mosasaurus hoffmanni*, 'le grand animal fossile de Maestricht' of Faujas de Saint-Fond, is best known from the Nekum Member. This species survives until the Cretaceous-Paleogene boundary in the area. Many vertebrate taxa document close links across the Atlantic Ocean (with the Atlantic and Gulf coastal plains in the USA) and North Africa (Morocco, Angola).

Bottom dwellers included lots of invertebrate taxa, amongst which are predominantly spiny-skinned animals (Echinodermata), such as sea urchins, sea lilies, starfish, brittle stars, and sea cucumbers. Molluscan diversity is also high; several species of oysters forming stable 'benthic islands' on the sea floor that were used for attachment by other biota. Gastropods comprised grazers, detritus feeders, and carnivores. In the levels overlying the underground galleries in the Nekum Member of the Sint-Pietersberg, i.e., Meerssen Member, there are acmes in the distribution and diversity of benthic foraminifera, scleractinian corals (forming mound-like structures, or bioherms), and hippuritoid bivalves or rudists.

In recent years, traces of animal life and behaviour (so-called trace or ichnofossils) have been receiving ample attention. Here too, there is a general trend for faunal diversity to increase upwards through the column of biocalcarenites assigned to the Maastricht Formation. In close proximity of flint nodules and burrows, silicified macrofauna occurs, which is of importance in

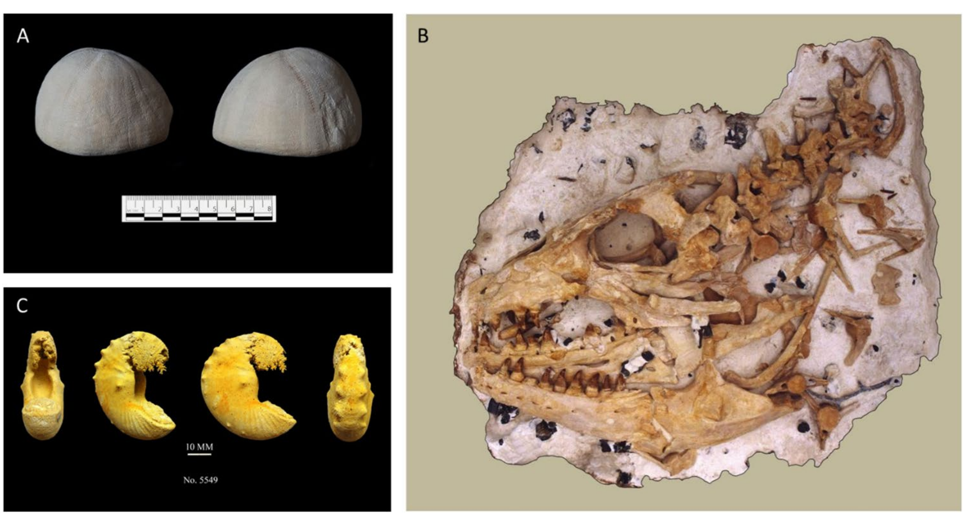

Fig. 3 **A** The first fossil from the Maastrichtersteen to be formally named in 1778: the echinoid *Hemipneustes striatoradiatus* (Leske), a typical warm-water, Tethyan element (photograph and collection: M. Deckers). **B** The type specimen of the mosasauroid reptile *Prognathodon saturator* Dortangs, Schulp, Mulder, Jagt, Peeters, and de Graaf from the Lanaye Member (Gulpen Formation); this species is known to range into the Nekum Member of the overlying Maastricht Formation. **C** The heteromorph ammonite *Hoploscaphites constrictus johnjagti* Machalski (Machalski et al. 2012) from the upper levels of the Maastricht Formation (photograph and collection: G. Cremers)

documenting aragonitic constituents that would have been lost otherwise.

Spectacular recent finds include the first mammal taxon, with a North American link, to be recorded from the Maastrichtian type area (Martin et al. 2005), a new mosasaur species, *Prognathodon saturator* Dortangs, Schulp, Mulder, Jagt, Peeters, and de Graaf (Fig. 3B) (Schulp 1996) and the first 'modern' bird, *Asteriornis maastrichtensis* Filed Benito, Chen, Jagt, and Ksepka (Field et al. 2020).

For age assignment of the Maastricht Stone (and the Maastricht Formation as a whole) and for correlations with occurrences elsewhere in Europe (England, northern Germany, Denmark, Poland, and the Russian Platform), ammonites (Fig. 3C) and belemnites (Jagt and Jagt-Yazykova 2019) are prime tools, in addition to some species of inoceramid bivalves. In addition, bioclast assemblages and chemostratigraphical analyses (Ca, O, and Sr isotopes) provide a sequence-stratigraphical framework that allows detailed correlation with northern and central Europe, and further afield, and places palaeontological finds in a proper context (Felder et al. 2003; Vonhof et al. 2011; Keutgen 2018; Vellekoop et al. 2022).

Petrography

The Maastricht Formation consists of bioclastic grainstones composed of molluscan, echinoderm, bryozoan, and foraminiferal debris (Fig. 4A), which were deposited on a well aerated sea floor in the photic zone, below wave base at the base of the formation (with generally fine-grained sediment), and within the wave zone for the top (with coarse sediment in the Meerssen Member). The sediment accumulated in wavy bedding testifying the deposition under the influence of currents. Astronomically controlled climate change and associated sea level variations impacted biological composition and productivity which resulted in variation in bioclast associations, grain size, bed thickness, formation of flint, or sedimentary standstills evolving into hardgrounds (Zijlstra 1994; Keutgen 2018).

The rapid sedimentation rate resulted in a loose fabric of poorly rounded bioclasts. Moreover, the Maastricht Formation in the type area never has been buried under more than circa 50 m of sedimentary cover on its top (or about 100 m at its base). Consequently, the sediments were not much compacted, and bioclast grains were cemented at point contacts only. Hence, Maastricht limestone retains an extremely high porosity and a relatively low mechanical strength.

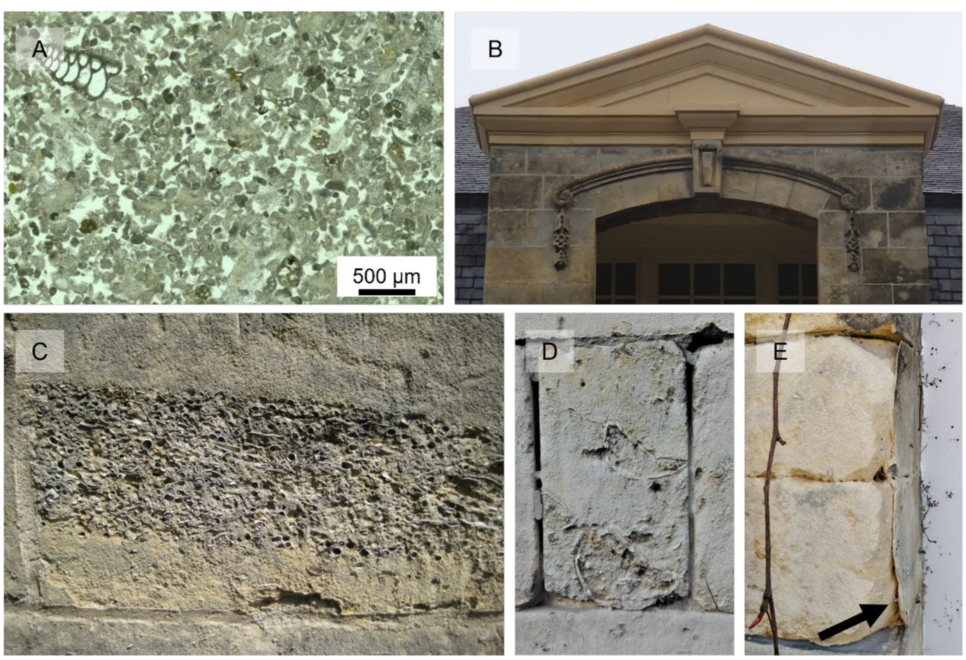

Fig. 4 **A** Thin section of Maastricht Stone from the Sibbe quarry (Emael Member) in transmitted plane polarised light showing the grainstone texture with fossiliferous debris and a high interparticle porosity. **B** New pediment in buff-coloured Maastricht Stone from the contemporary quarry in Sibbe (Emael Member) ©Mergelbouwsteen Kleijnen (www.mergel.nl). **C** Maastricht Stone with granular texture, with serpulid–oyster accumulations, characteristic of the Emael Member at the underground *Sibbe* quarry. **D** Maastricht Stone displaying a whitish patina on calcin, with complete echinoid tests (*Hemipneustes striatoradiatus* (Leske)), which can attain overall lengths of 10 cm and are typical of the upper Nekum Member in the *Kanne–Zichen-Zussen-Bolder* quarry area. **E** Soft and pale Maastricht Stone, likely from the *Kanne-Zichen-Zussen-Bolder* quarry area, with calcin as protective layer (arrow) that is spalling from the substrate

Building Stones from the Maastricht Formation

Building stones have been extracted from any level within the Maastricht Formation. The entire group of building stones can be defined as 'Maastricht Stone', which is proposed here as the standard denomination. In the international scientific literature, the stone is sometimes referred to as 'Maastricht limestone'. In older sources, the term 'Tuffeau de Maastricht' is used. Locally, the stone is better known as 'mergel' or 'mergelsteen', because it was also used as a soil conditioner to facilitate ploughing of the heavy loamy soils. Finally, building stones are sometimes specifically named after their geographical location of origin, independent of their stratigraphical position, using a geographical identifier for the local type of building stone format, e.g. 'Roosburg stone' and 'Sibbe stone'.

Slight differences in grain texture and fossil content allow the recognition of the lithostratigraphical origin of the different building stones. The Valkenburg, Gronsveld, Schiepersberg, and Emael members consist of fine, white-yellowish limestone, with flint horizons and are separated by fossil debris lamina. Limestone has been quarried from each of these members. The Roosburg stone extracted from the lowermost Valkenburg to Gronsveld members is creamy white, very fine grained, and most resistant to weathering (Dusar et al. 2017). The contemporary active quarry in Sibbe targets the upper part of the Emael Member where relatively compact, high-quality limestone is found in a layer of 2–2.5 m thickness. The Sibbe stone is more orange-yellow in colour and granular in texture and is characterised by frequent serpulid-oyster layers (Fig. 4B, C). It has an excellent resistance to weathering.

The Nekum Member in the upper Maastricht Formation is composed of rather poorly indurated limestone, with a low amount of flint near the bottom, but very homogeneous and flint poor near the top. In general, the Nekum Member is relatively rich in macrofossils compared to the underlying units. Its thickness is significant (in average 10–12 m), and although the building stone quality is said to be inferior to stone from the Emael Member, this has never been quantified. The major underground galleries in both Belgium and the Netherlands are situated within the Nekum Member, resulting in stones of different quality, from very solid to friable. The light yellow Kanne stone extracted from this Member is softer and more friable, and can be identified by abundant echinoid debris and even complete tests (Fig. 4D, E).

The Meerssen Member at the top of the Maastricht Formation is the most fossiliferous part of the formation, and consists of alternating fine and coarse-grained beds from which building stones were extracted on a more limited scale, except in the Valkenburg area.

Historical Exploitation

Maastricht Stone has been quarried in an area that extends from the municipality of Heers (Belgium) to the municipality of Valkenburg (the Netherlands), over a distance of approximately 40 km in a region of several kilometres wide (Fig. 1). In total, 412 different underground quarries can be identified, of which 295 are located in the Netherlands, 94 in Belgian Flanders, and 30 in Belgian Wallonia (Dusar and Lagrou 2008; Orbons 2017). Towards the east of the Netherlands and its border with Germany, Kunrade Stone from the lateral equivalent of the Maastricht Formation is excavated, which is not considered in this work.

The use of Maastricht Stone dates back to Roman times in towns such as Maastricht (the Netherlands) and Tongeren (Belgium). Remains of Maastricht Stone used in Roman villas illustrate their application as foundations, basements, and wells (Silvertant 2013). It is uncertain whether Maastricht Stone was excavated in underground galleries or in opencast quarries at that time. Silvertant (2013) suggested that it may have been quarried only occasionally in outcrops as limestone use was rather limited compared to other building material found in archaeological digs (Panhuysen 1996). Archaeological research near the castle of Valkenburg (the Netherlands) has revealed an ancient quarry from the eleventh or twelfth century, based on the dating of overlying layers with pottery remains (Kimenai 2016). Maastricht Stone was quarried here as building material for the adjacent castle.

During the Late Middle Ages, this stone was excavated in underground quarries. From the fourteenth century onwards, the use of Maastricht Stone as a building material emerged and is recorded in ecclesiastical archives (Habets and Jennekens 2020). The Maastricht Stone from the *Sint-Pietersberg* near Maastricht and the village of Zichen-Zussen-Bolder (Belgium) was transported to cities like Liège, Huy and Namur (Belgium) upstream and Roermond, Venlo, Nijmegem, and Utrecht (the Netherlands) downstream the Meuse River. In addition to archaeological research and archives, carbon dating has also yielded a date for underground galleries. Dating of an old soot spot at a height of 10 m in the underground quarry of *Caestert* yielded a date of 1375–1420 AD (Blaauw 2007). The soot sample was located in the centre of the underground quarry. Relative dating of the galleries by studying the directions of excavation demonstrates that the galleries in between the sample location and the entrances where the extraction commenced must have been created prior to this period, which dates the underground quarry of *Caestert* as fourteenth century or older.

Expanding cities meant an increased demand for building material and an increased production of Maastricht Stone by room-and-pillar mining (Fig. 5 A and B). Already in the sixteenth century, this led to various extensive underground quarries throughout the region where the Maastricht Formation outcrops or occurs above groundwater level (Amendt 2008; Amendt et al. 2010).

By studying working directions and tool marks on pillars and roofs, different working methods can be documented in the underground quarries (Amendt 2013). When combined with absolute dating, such as carbon dating, the presence of specific working methods can be used for dating underground quarries. However, diachronism in working methods in and between places renders this dating relatively uncertain. The most primitive working methods that seem to predate the carbon date in the underground quarry of *Caestert* are situated in and around Valkenburg, the *Sint-Pietersberg* near Maastricht, and the village of Zichen-Zussen-Bolder (Amendt et al. 2010). Graffiti's of different type and age make up an important part of the underground heritage. As some of these drawings are dated, they provide a minimum age for some of the gallies (Fig. 5C).

Underground excavation continues up to the present day. Nowadays, there is only a single quarry left where this limestone is extracted, namely the Sibbe quarry near Valkenburg ('*Mergelbouwsteen Kleijnen*' and '*Mergel specialiteiten bedrijf Fer. Rouwet BV*'). Underground quarrying has led to extensive galleries which vary in stability and several gallery collapses have occurred in the past (Fig. 5D). Especially the municipality of Riemst has suffered from many collapse-related sinkholes resulting in large material damage by the destruction of infrastructure and buildings (Van Den Eeckhaut et al., 2007; Willems and Rodet 2018). Several large stability campaigns have been conducted since the second half of the twentieth century by filling unstable galleries with sand and concrete (Bekendam 1998, 2004). As the stability of some underground galleries keeps decreasing, the galleries are continuously monitored and mapped by the use of a mobile 3D laser scanner. Stabilisation projects have become more customised, by targeting only the unstable elements and preserving as much as possible of the stable galleries to conserve the cultural and natural heritage.

The Use as Heritage Stone In and Beyond Limburg

Maastricht Stone is the dominant natural stone in the Dutch and Belgian provinces of Limburg, where it is found in most historical monuments from the thirteenth to the nineteenth century in various indoor and outdoor applications. Further north into the Netherlands, downstream the Meuse River, Maastricht Stone has been used in limited amounts from the fifteenth century onwards. Exceptional examples further to the north can be found in Utrecht (Dubelaar et al., 2007) and even in the province Noord-Holland province (Heiloo, Maria pilgrimage Chapel Onze Lieve Vrouwe ter Nood, built in 1930).

Fig. 5 **A** Entrance of the underground quarry *Grootberg* (Kanne, BE) visible in the surficial landscape of the valley-flanks. **B** Subterranean landscape of the quarry *Grootberg* where the excavation in blocks is comprehensible. This gallery has not been transformed for secondary purposes ©VZW Hulpdienst Groeven. **C** Surficial landscape above an old collapse of an underground gallery of the quarry *Caestert* (Caestert, NL), clearly visible after tree felling. **D** Underground gallery of quarry *Ternaaien Beneden* (Ternaaien, BE), with historical graffiti on the block-shaped wall (black drawings) vandalised by modern graffiti (colored tags) ©VZW Hulpdienst Groeven

During the Late Middle Ages, most churches in Limburg were entirely built in Maastricht Stone, ranging from parish churches to rich collegial or abbey churches. These were built on a foundation of equally local cobbles and blocks from the Meuse River gravel terraces or on flint from the slightly older though still Maastrichtian chalk deposits. From the sixteenth century onwards, Maastricht Stone was increasingly combined with red bricks or grey Lower Carboniferous limestones in alternating layers of which the stone was reserved for openings and edges (Fig. 6A, B). This ‘Lower Meuse’ region was renowned for this colourful combination, which is now described as ‘Meuse renaissance’. The most inspiring parts of churches such as the tower and choir often remained exclusively in Maastricht Stone. However, during the eighteenth century, the more prestigious Carboniferous limestones became predominant with the cheaper Maastricht Stone reserved for wall cladding, rural architecture, or special carvings. During the nineteenth century Gothic Revival, churches and other prominent buildings were again visibly constructed in Maastricht Stone in combination with more solid stones for basements and openings, mainly Carboniferous limestones from the Meuse basin and more rarely with sandstones (Fig. 7A).

Historical connections, ease of transport, and lack of competing stones all combined to establish Maastricht Stone as the main heritage stone of both Limburg provinces (Dreesen et al. 2019). However, tradition weakened with the upcoming nation states and industrial revolution. During the twentieth, century Maastricht Stone became ousted by the geological time-equivalent, though less workable Kunrade Stone in the Dutch province of Limburg and by Devonian sandstones from the Ardennes in the Belgian province of Limburg. These give a more rustic appearance to the buildings in Romanesque Revival style. However, the few examples of more recent use of Maastricht Stone use were significant statements, either preserving the harmony with the past heritage (e.g. cities of Maastricht and Valkenburg) or forging identity rooted in the soil, e.g. the Lutgardis sanctuary in Tongeren (Fig. 7B). More widespread recent use is for restoration purposes, served by the sole remaining quarry at Sibbe near Valkenburg, which makes it fairly easy to distinguish with older building phases when other types of Maastricht Stone came from now abandoned or forgotten quarries (Fig. 7C). Fortunately, local authorities understand that it is essential to keep the remaining quarry open and traditional quarry workers in operation, in order to maintain the link between cultural heritage and geoheritage.

Felder and Bosch (2000) published a list of buildings in South-Limburg (the Netherlands) where blocks of Maastricht Stone have been used in walls and facades. For Belgian Limburg, Dreesen et al. (2019) published a compendium of stone uses in monuments. The stone is present at two Unesco World Heritage sites belonging to the ‘Belfries of Belgium and France’, namely in Tongeren (Fig. 6C) and Sint-Truiden (Belgium), which are located at the southernmost tip of the natural outcrops and approximately 20 km to the west, respectively.

Fig. 6 **A** *Ferme de Caestert* (Ternaaien, BE), located south of Maastricht, with horizontal layers of Maastricht Stone (white) alternating with horizontal layers of brick masonry (red) typical of local renaissance architecture; **B** Infirmerie, Herkenrode Abbey Hasselt, Maastricht Stone in combination with blue stone (Carboniferous limestone) and brick, typical of local renaissance architecture. **C** Gothic Our-Lady Basilica with belfry tower in Tongeren (BE) as part of a World Heritage ensemble (Belfries of Belgium and France), built in Maastricht Stone

Fig. 7 **A** Former Villa Zuyderhorst in Berg en Terblijt (NL), constructed in Maastricht Stone in 1918 in English Gothic Revival style. **B** Saint Lutgardis, patroness saint of Flanders region sanctuary in Tongeren, designed by architect Jos Ritzen and constructed in 1954, clad inside and outside in Maastricht Stone from the two last active underground quarries in Kanne and Zichen (Dusar et al., 2017). **C** Church wall around Brigida church in Noorbeek (NL) with replacements in new blocks of Maastricht Stone. **D** Maastricht Stone as inner wall in a private dwelling in Riemst (BE), visible after removing plaster during renovation works

Properties and Weathering

Despite its extremely high porosity (± 50%) and very low compressive strength (< 5 MPa), it is currently understood that Maastricht Stone is a very durable rock type, which is evidenced by many building elements of several centuries old being in good condition. It was put forward by Camerman (1951) that there is a strong discrepancy between laboratory tests that indicate low freeze–thaw resistance and mechanical strength as opposed to its apparent durability in real-life conditions. Similar discussions had been ongoing in the Netherlands decades before (Quist 2017). Specifically, attention was drawn to the relative resistance against air pollution (sulfation) and freeze–thaw damage, even though black crusts can be formed (Fig. 8A). Therefore, no restrictions were put on its use, except for basements which should endure mechanical shocks or abrasion, to which its resistance is very poor. Nevertheless, a thin veneer of calcite, so-called ‘calcin’ by local geologists, forms at the surface of the stone by internal dissolution and external crystallisation (Figs. 4E and 8C). This calcin acts as a protective layer by increasing its surface hardness and reducing water absorption. The increased hardness specifically protects it against mechanical impacts, as the soft stone is easily carved (Fig. 8B). Therefore, it is advised not to remove this layer during conservation actions like cleaning. Sometimes this calcin is shed in a natural way, leading to partial or complete contour scaling on flat dimension stones in masonry, also referred to as spalling.

Occasionally, specific patterns of stone deterioration can be observed on sculptures in urban environments with (former) high levels of air pollution by sulfur dioxide. Specifically black gypsum crusts can develop on rain-sheltered surfaces (Fig. 8A, D). Generally, these are thin and the stone has a relatively good resistance against sulfation, which was also noticed by Camerman (1951). However, blistering, peeling, contour scaling, flaking, and granular disintegration can occur in association with gypsum crusts (Fig. 8A, D).

The remarkable durability of this rock type can be understood by the nature of its pore size distribution (Fig. 9). Maastricht Stone has a unimodal pore size with a modus of 30 µm, whilst pores smaller than 1 µm are virtually absent. These pores can be considered as relatively large capillary pores. Consequently, the water absorption of this rock is extremely fast as a combination of a high capillary suction velocity in these pores and a large total amount. In tandem, also the drying rate is particularly fast as the ease of capillary transport results in a long period of a constant drying rate controlled conditions at the surface (Scherer 1990). The critical moisture content under laboratory drying, defined by the moisture content that separate the constant drying rate stage from the falling drying rate stage, is approximately one third of the capillary moisture content, which is low. Additionally, as the crystallisation stress induced by growing salt or ice crystals is lower in larger pores (Scherer 1999), critical conditions of supersaturation or undercooling leading to critical stress are unlikely to occur in real-life conditions.

Although slight variations in properties are expected for different lithostratigraphic variants of Maastricht Stone, these have never been extensively studied. Camerman (1951) has tested stones from different locations (Table 1),

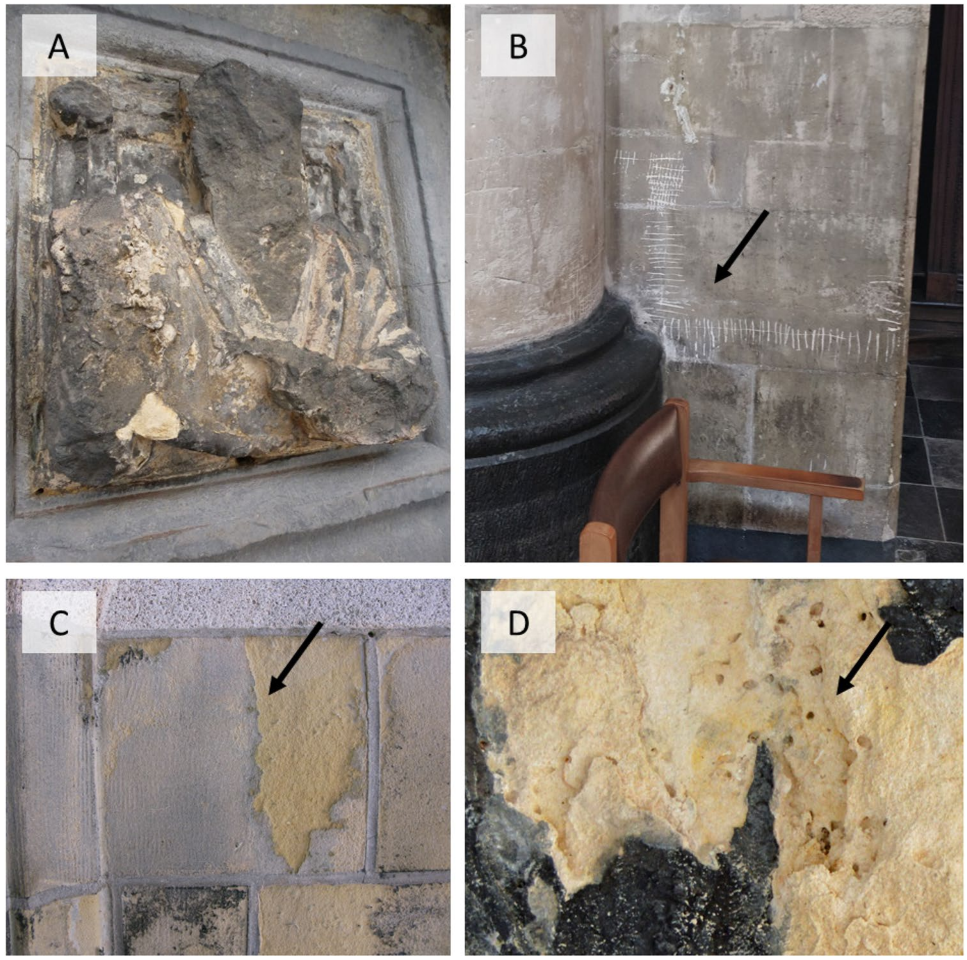

Fig. 8 **A** A smashed bust in high relief with black gypsum crusts that are primarily prominent on old fractured surfaces. The deeper areas in this relief are characterised by less or even no gypsum crusts, and it can be assumed that in these areas the binder from historic (polychrome) finishing layers have limited the development of gypsum crusts (Renaissance portal of St James' church, Liège, BE) ©KIK-IRPA. **B** Mechanical degradation in the form of cuts that represent countings (arrow) shows how easily the soft Maastricht Stone walls are scratched (Our-Lady Basilica in Tongeren, BE). **C** Spalling of thin, grey calcin (arrow) on the flat surface of dimension stone and fresh, yellow Maastricht Stone visible underneath (St Martin's church, Sint-Truiden, BE), ©KIK-IRPA. **D** Detail of black gypsum crust and perforations (arrow) showing crust-related flaking and granular disintegration on Maastricht Stone, together with biological perforation formed by insects (Renaissance portal of St James' church, Liège, BE) ©KIK-IRPA

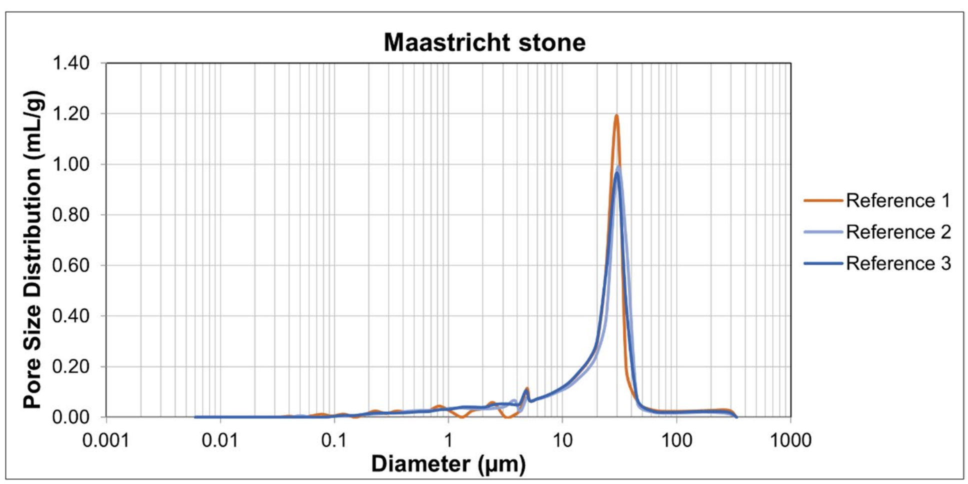

Fig. 9 Pore throat size distribution (Diameter) of Maastricht Stone (Sibbe stone) from the quarry in Sibbe, measured by mercury intrusion porosimetry on three reference samples in 2021. The three samples indicate a unimodal size distribution with a modus around 30 μm. ©KIK-IRPA

showing very little spread in properties. The most detailed analysis of petrophysical properties mainly apply to the recently quarried Sibbe stone of the Emael Member the in the middle Maastricht Formation (Cnudde 2005) (Table 1).

Geoheritage and Geotourism

Both rural and urban areas in the *Krijtland* are characterised by the local use of Maastricht Stone in all types

Table 1 Petrophysical properties of Maastricht Stone (Sibbe stone) from the quarry in Sibbe, measured in between 2000 and 2004 (adapted from Cnudde 2005). Additionally, historical measurements from the first half of the twentieth century on samples from Kanne and Sint-Pietersberg are given as comparison (adopted from Camerman 1951). Apparent density and compressive strength of the historical measurements were originally represented in g cm−3 and kg cm−2 respectively and have been conversed

Material properties	Cnudde (2005)	Camerman (1951)		
Origin	*Sibbe stone*	*Kanne*	*Kanne*	*Sint-Pietersberg*
Porosity (vol.%)	51.7 ± 0.8 (46.4–53.2)	53.00	55.20	50.70
Apparent density (kg m^{-3})	1322 ± 18 (1217–1417)	1270	1310	1333
Capillary Absorption Coefficient (g m^{-2} $s^{-1/2}$)	2394.5 ± 225.4 (1985.0–2845.6)	-	-	-
Capillary Moisture Content (wt%)	31.6 ± 1.0 (28.6–33.5)	-	-	-
Water absorption after 24 h immersion at atmospheric pressure (wt%)	-	32.09	30.2	29.7
Constant Drying Rate (g m^{-2} h)	81.47 ± 21.63 (54.01–124.22)	-	-	-
Critical Moisture Content (drying) (wt%)	10.76 ± 7.55 (3.31–3.65)	-	-	-
Compressive strength (N mm^{-2})	3.2 ± 0.7 (2.1–4.6)	2.9–4.5 MPa		
Water vapour permeability (kg m^{-1} s^{-1} Pa^{-1})	$5.7.10^{-4} \pm 0.7.10^{-5}$ ($4.1.10^{-4}$–$7.1.10^{-4}$)	-	-	-

of applications. This local signature reflects the historical intimacy of human culture and natural environments, and is generally appreciated as significant for the geology and geoheritage of a particular region (De Wever et al. 2017; Brocx and Semeniuk 2019).

Equally, the surficial and subterranean landscape related to stone extraction is characteristic for the area and widely embedded in local folklore and nature. The underground galleries have been used for food storage, shelter and touristic purposes. As stone extraction from the underground quarries gradually became inactive, their galleries were adapted for mushroom cultivation. The touristic exploitation of the underground quarries is nothing new. Sixteenth and seventeenth century inscriptions in several galleries reveal the presence of visitors who were attracted to this underground scene. To date, several galleries in Belgium and the Netherlands can be visited during guided tours, while others can be booked as banquet hall for weddings, etc. The development of the city of Valkenburg as a touristic hub in the nineteenth century also led to an increase in tourist tours in the underground quarries like the *Gemeentegrot*. Since then, more underground quarries have been exploited for touristic purposes, thus becoming part of the local folklore. The use of the galleries for mushroom cultivation has been strongly restricted after the 1958 Christmas eve disaster at the *Roosburg* quarry, whereby a significant section of the quarry collapsed and 18 workers died during activities related to mushroom cultivation. As activity diminished, most galleries were abandoned, resulting in a high unemployment in the local municipalities. Since their closure, many underground galleries have been used for all kinds of harmful purposes ranging from waste dumps, organising rave parties, burning fires, and applying graffiti on the historical walls. This has led to a serious degradation of the underground subterranean landscape and (partial) damaging of the historical inscriptions and drawings (Fig. 7D). Also, the hibernating bat population suffered from all these disturbances.

Industrial limestone extraction competes with the safeguarding of this underground landscape in the well-known underground quarries of the *Sint-Pietersberg*, situated in Belgium and the Netherlands just south of Maastricht. The discovery of mosasaur remains in these galleries in 1766 and 1778 drew attention to the geological history of the Maastricht Stone and, even more importantly, laid the foundation for discussions on evolution and natural extinction, as a reaction to the biblical notion of God's creation of Earth and all of its inhabitants. Seen in this light, it comes as no surprise that the French revolutionary government, by decree, ordered one of those mosasaur skulls to be transported to Paris where it would be put on exhibit as a great trophy of the 'new thinking'. Much has already been published on the seizure (in 1795) of this skull, the later type specimen of *Mosasaurus hoffmanni* Mantell, 1829, and more may be expected to follow (Bardet and Jagt 1996; Pieters et al. 2012; 2019; Hovens 2020). Later, geologists established the Maastrichtian Stage based on the outcropping limestone along to the valley of the Meuse River. Since the first half of the twentieth century this unique landscape has been threatened by the expanding limestone industry which raised awareness by environmentalists and citizens to protect and maintain this old cultural landscape. Unfortunately, a large area of the oldest underground quarries have already been quarried away, leading to physical destruction of cultural and natural heritage.

Meanwhile, concerns over the preservation of these unique historical sites grew among local inhabitants and professionals alike. Nowadays, a large group of people put effort in protecting, conserving, safeguarding, and documenting the underground history of the extraction of the Maastricht Stone. Organisations like the *Studiegroep Onderaardse Kalksteengroeven* (SOK) have been studying underground galleries and publishing the results for the general public since the 1970s. The foundation *Stichting ir. D.C. van Schaïk* manages 13 underground quarries, allowing researchers to conduct studies and '*berglopers*', local experienced explorers, access to enjoy their hobby while guarding the natural and cultural features. In the summer of 2021, three underground quarries on the *Sint-Pietersberg* in Belgium have been completely cleaned from litter, left behind from rave parties and visitors, by *berglopers* in collaboration with local authorities. The formation of nature reserves in the underground quarries and later on NATURA2000 law regulations has led to the closure of most entrances and a rise in bat populations and species diversity. Since 2016 the Flanders Heritage Agency has initiated a new instrument: the creation of a management plan (so-called *onroerenderfgoedrichtplan*) for the underground quarries of the municipality of Riemst. This comprises an integrated vision of how to cope with the severe quarry-collapse related sinkholes and the stabilisations of unstable galleries and as well preserving as much cultural, natural, and geoheritage as possible (de Haan and Lahaye 2018).

Currently, different governmental and non-governmental institutions are investigating whether the international *Krijtland* can be awarded Unesco status. As the geological heritage is well represented, a Unesco Geopark is most suitable. Organisations such as the tourist office of Dutch southern Limburg create touristic routes in which the geological heritage is the central keyword. Stops include opencast quarries and entrances to underground quarries where tourists may receive additional information on the geoheritage.

Scientific Research in Stone Conservation

Recently, Maastricht Stone has been increasingly used by the international scientific community as a test substrate for different types of stone conservation research. Several factors can support this choice: (i) it is a relatively pure limestone ($CaCO_3$ of ± 98 wt%); (ii) it has a unimodal pore size distribution; (iii) the stone is very homogeneous with constant properties, which increases reproducibility of and during testing; (iv) its high porosity and low mechanical strength increase the detection of changes; (v) its fast water absorption favours the fast uptake of fluids and particles; and (vi) the material is available and easily handled.

Therefore, the stone has been used in different types of research, mostly with respect to stone consolidation. This includes the study of ethyl silicate consolidation (Cnudde 2005; Cnudde et al 2007; Vitry et al. 2011; Berto et al. 2017; Le Dizès et al. 2021), the use and improvement of nano-lime applications (Borsoi et al. 2016a, b, 2017; Niedoba et al. 2017; Ševčík et al., 2019, 2020; Badreddine et al. 2020), and even consolidation through biodeposition (Erşan et al. 2020). Research in stone consolidation has additionally led to research on artificial stone weathering to improve test substrates (Lubelli et al. 2015), or the application of new techniques in the assessment of fluid absorption (Masschaele et al. 2004; Koudelka et al. 2014). Also, on-site testing methods and other test methods have been tested and validated by using Maastricht Stone substrates (Rescic et al. 2010; Ngan-Tillard et al. 2011).

Additionally, Maastricht Stone has been adopted in a series of salt weathering tests to define a new standard test protocol for salt weathering resistance of stone materials (Lubelli et al. 2018; Lubelli and RILEM TC 271-ASC members 2021). Therefore, a profound characterisation of the general petrophysical properties as well as very specific water transport properties for experimental testing and numerical modelling has been undertaken (Nunes et al. 2021a; D'Altri et al. 2021). Several others have focused on the assessment of salt crystallisation in Maastricht Stone, and thereby provided data on its texture and strength (Nunes et al. 2021b; Kyriakou et al. 2021; Gulotta et al. 2021; Salvi and Menendez 2021).

Conclusion

Maastricht Stone is an important heritage stone in the *Krijtland* at the Belgian-Dutch border. It is omnipresent in local architecture from the Late Middle Ages to the twentieth century, while older use has been evidenced by archaeological remains. It is particularly remarkable that porosities exceeding 50 vol.% are common, notwithstanding numerous examples of historical monuments prove that the stone is very durable. It is extracted from multiple levels in the Maastricht Formation, which gave its name to the Upper-Cretaceous Maastrichtian Stage. Magnificent examples of vertebrate and invertebrate animals have been found in these deposits. Its extensive use is a part of the local culture and has led to the formation of an incredible subterranean landscape, which has been additionally used for other purposes, such as tourism. Finally, over the past decade, Maastricht Stone has been increasingly used by the scientific community as a model substrate for stone conservation research. Therefore, Maastricht Stone is a transversal heritage stone that is proposed as a potential Global Heritage Stone Resource.

Declarations

Conflict of Interest The authors declare no competing interests.

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