

Review

# The Forerunners on Heritage Stones Investigation: Historical Synthesis and Evolution

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**Abstract:** Human activity has required, since its origins, stones as raw material for carving, construction and rock art. The study, exploration, use and maintenance of building stones is a global phenomenon that has evolved from the first shelters, manufacture of lithic tools, to the construction of houses, infrastructures and monuments. Druids, philosophers, clergymen, quarrymen, master builders, naturalists, travelers, architects, archaeologists, physicists, chemists, curators, restorers, museologists, engineers and geologists, among other professionals, have worked with stones and they have produced the current knowledge in heritage stones. They are stones that have special significance in human culture. In this way, the connotation of heritage in stones has been acquired over the time. That is, the stones at the time of their historical use were simply stones used for a certain purpose. Therefore, the concept of heritage stone is broad, with cultural, historic, artistic, architectural, and scientific implications. A historical synthesis is presented of the main events that marked the use of stones from prehistory, through ancient history, medieval times, and to the modern period. In addition, the main authors who have written about stones are surveyed from Ancient Roman times to the middle of the twentieth century. Subtle properties of stones have been discovered and exploited by artists and artisans long before rigorous science took notice of them and explained them.

**Keywords:** archeology; geology; fortification; durability; conservation; quarries; restoration; architecture



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## 1. Introduction

Stones have been the subject of analysis since humans have sought the best shelters such as escarpments, caves and inverted slopes to protect themselves from inclement weather [1]. Therefore, mankind has explored and exploited building stones throughout history [2–4]. The best-preserved records of human activity are those carved on this material. Much of the current knowledge of the oldest civilizations is due to the study of their heritage stones. The stones that today are considered heritage stones were used by humans mainly as building stones and sometimes they were used for purposes other than those they have today.

The importance of stones is evidenced by the pre-Roman roots Mor (r), Mur (r), Mour present in numerous place names of Iberian Peninsula. For example, La Moraleja, Matamoros, Moralarzal, Moratalla, Montemuro, Moreiras, Morro, Mouçós, Moura, Mourelle, Murgi and Valdemoro, are names of localities linked to stone; material with which *muros* “walls” and *moradas* “dwellings” have been built since prehistoric times. The first stones used as construction material came from the vicinity of the place where they would be used. They were used as prehistoric tools [5,6], amulets [7], support for petroglyphs [8,9], projectiles [10], support for inscriptions of important events or laws [11], walls [12], monuments, dikes, warehouses, paving [13] and all kinds of constructions [14]. Stones have also been used to manufacture mortars [15–17], ceramics [18,19], bricks [20,21] and mosaics [22].

Many ancient cities were built directly on quarries, resulting in harmony in between the landscape and the inhabited environment [23,24]. Exploitation of stones generated large

quarries from which they were extracted for export [25–27]. Some stones were transported long distances and traded for their rarity and durability, [28,29] and some prehistoric quarries have survived to this day.

The study of building stones has evolved from a practical way to make ornaments, tools, houses, temples and infrastructures, among many other constructions to being the subject of scientific research as we know it today. The study of heritage stones cannot be understood without the contribution of druids, clergymen, quarrymen, builders, naturalists, architects, archaeologists, physicists, chemists, curators, restorers, engineers, and geologists, who have all contributed to enriching our current knowledge of heritage stones. Which have been the subject of exposure and study since the first museums started to conserve them, such as the Ennigaldi-Nanna museum in Mesopotamia, dating from 530 BC [30].

Some examples of heritage stones have a special relevance in human culture. For example, the porphyries from Sweden and Russia [31,32], “*Petit granit*” and Lede stones from Belgium [33,34], slates from the Iberian peninsula [35], Bath and Purbeck limestones from England [36], Sydney sandstone [37], granites such as Piedra Berroqueña, of Madrid (Spain) [38–40] and marbles, such as the one from Carrara in Italy [41,42]. These stones have been widely used and with them important buildings have been built that have marked the history of humankind [43].

This work is a historical synopsis of the main events that marked the history of the use of heritage stones. It contains references of the main authors who have studied stones in the ages of human history, focusing on southern European countries, and without missing the important development that research has had in the United States from the end of the 19th century to the 20th century. Scientists from a wide variety of disciplines contributed to the current understanding of heritage stones, and the most important are mentioned in this work.

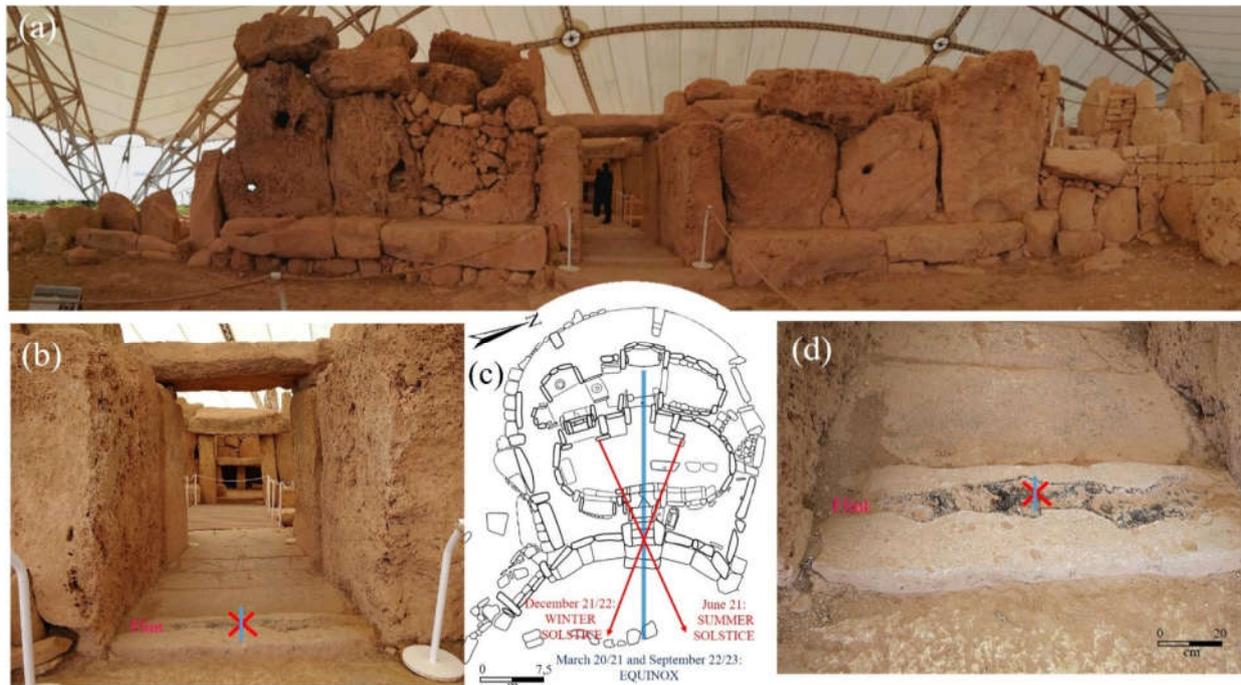
## 2. Stones and Religion

Many myths compare stones to the “bones” of Mother Earth. Stone extraction has been accompanied by complex rituals in different cultures [44]. Stones have also been used in healing therapies and in numerous festivities and pilgrimages. The Holy Black Stone (called al-Hayar-ul-Aswad in Arabic) is a relic that according to Islamic tradition dates to the times of Adam (Adam) and Hawa (Eve). It is a meteorite that the archangel Gabriel (Jibril) gave to Abraham (Ibrahim), who, together with his son Ishmael (Ismail), placed it in the eastern corner of the Kaaba, in the center of the Great Mosque of Mecca, in Saudi Arabia [45–47]. Pedro (Petro-πέτρος) is the masculinization of the Greek word πέτρα (Petra), that is to say “stone”. Paul the Apostle always called Peter by the name “Cephas”, a Hellenized Hebrew word from the Aramaic כִּפְתִּי, meaning “stone” and nowadays many stonemason villages keep their patronal festivals in honor of Saint Peter.

Jade objects and amulets, symbolizing nobility, perfection, constancy, and immortality have been very valued in Chinese culture [48,49]. Jade was also used to make weapons and tools due to its resistance and hardness. Jade was the stone of creation; it meant life, fertility and power for pre-Hispanic cultures of Mesoamerica such as the Olmec, Mayan, Toltec, Quiche, Mixtec, Zapotec, Aztec (Chalchiúhuitl) and Nicoya. It was obtained mainly from the Motagua Valley (Guatemala). This region has been the source of the jade used by Mesoamericans for thousands of years [50].

Quartz has been used as an amulet, acquiring a sacred character in Neolithic, possibly due to its resistance to weathering, frequent transparency and chromatic homogeneity. As well as due to its crystallization in the hexagonal and trigonal system, being able to form hexagonal bipyramids [51]. Quartz has also been a mineral used to create fire. There are cultures in which the word quartz retains a meaning related to the sun. The Irish word for quartz is grian cloch, which means “stone of the sun” An example of the use of flint as a solar baetylus (sacred stone) is found in the southern temple of Mnajdra (Malta) [52–55]. It is one of the oldest free-standing structures in the world (approximately 3000 BC), even predating the pyramids of Egypt and Stonehenge. The entire temple is built with limestone,

except for an ashlar located on the threshold of the main door, where there is a vein of flint (Figure 1). The intersection point of the dawn light beams of the equinox and summer and winter solstices coincides with the center of the vein of flint at the threshold of the main gate of the southern temple of Mnajdra. Using flint as a baetylus of solar character.



**Figure 1.** South temple of Mnajdra (Malta). (a) General view of the main façade. (b) Main door. Note that the threshold has a vein of flint. (c) Plan of the temple with the projection of the light beams corresponding to the equinox (blue) and the summer and winter solstices (red). Note that the intersection point corresponds to the threshold with the flint vein. Modified from J.D. Evans, *The Prehistoric Antiquities of the Maltese Islands: A Survey*, University of London, Athlone Press, 1971. (d) Threshold of the main door with presence of a vein of flint.

Prehistoric tools were made with basalt, diabase, andesite, quartzites, flint, quartz, obsidian and other stones [56]. These tools (Figure 2) were inseparable companions in the daily life of their manufacturers, even after death. Stone axes and arrowheads have been found attached as amulets in necklaces excavated from Egyptian and Etruscan tombs, and from Chaldean temples. Animistic religions associated these objects with spirits or gods, and attributed powers related to atmospheric phenomena and divinities to them. For example, the fall of lightning created stone axes that were called “*astropelekia*” (sky axes) in Greece [57]. Prehistoric axes (Figure 2), polished or not, were called “*cerauni*” by Romans and “lightning stones”, or simply “lightning bolts” in many Western European countries, for example “Arrows of God” in Hungary, “fairy darts” in Ireland, “thunder stone” in Iceland, “stones of Ukko” (god of lightning) in Finland, “arrows of thunder” in Siberia.



**Figure 2.** (a) Hyaline quartz baetylus found in a Neolithic site; (b) flint arrowheads; (c) axes of basalt, quartzite and obsidian; (d) necklace of hyaline quartz beads.

Vikings saw the primitive tools as lightning repellent. Prehistoric “thunderstones” resembled the Norse god Thor’s hammerhead (Mjölnir) and they were purposely placed as good-luck talismans in tombs of Vikings. Additionally, a popular belief exists in some islands in Southeast Asia that prehistoric stone axes (and/or adzes) are natural objects generated by lightning. They are called “teeth of lightning” in Java and “arrows of lightning” in India or Japan. Elongated stones, the work of the first inhabitants of Borneo, were venerated and received the name “*Silum Baling Go*” (nail of the big toe of Baling Go) (god of thunder), because the natives believed that they had fallen from the sky. All of them are names that indicate the importance of stones in different civilizations since prehistory [58].

The Tuaregs of North Africa believed that polished axes were stones dropped from the sky, and that they had beneficial health properties. The importance of meteoric origin stones is evidenced by the presence of laminated metal composites in daggers and other ritual objects such as those found in the Great Pyramid of Giza and Tutankhamun’s iron dagger blade [59,60]. Perhaps the earliest known reference to improved properties in a laminated metal composites can be found in *The Iliad* of Homer (800 BC) which describes Achilles’ shield. In addition, Elagabalium temple (218–222 AC) was dedicated to the Sun god in the northeast corner of the Palatine Hill, in Rome (Italy). This temple had a baetylus at center, that is, Sol Invictus (Unconquered Sun) was represented by a conical black stone, which has been suggested to be a piece of a meteorite (Figure 3).



**Figure 3.** Roman coin of 3rd century AD. The Emesa temple to the sun god Elagabalus with a baetylus at center.

### 3. Prehistory

Humans soon discovered that microcrystalline and vitreous stones fragment conchoidally, producing cutting edges [61] (Figure 3). The Stone Age, or lithic stage, is the first period of prehistory that ranges from the time when human beings began to make tools and vessels with stones, to the discovery and use of pottery and metals [62,63].

The profound change that characterizes the outset of the Neolithic period affected human lives at various levels, e.g., subsistence, technology, environment, social organization, [64] and stones were part of all these levels. They were essential for the development of agriculture, as tools to plow the land and to hunt animals which were represented in painted caves. It is possible that the Neolithic cave painters suffered hypoxia and hallucinations due to lack of oxygen in deep caves [65], which endowed the caves with mystical properties. Pigments extracted from stones were also used for rock-art decoration [66,67].

Building stones specialized as building techniques became more sophisticated. For example, the use of domes or vaults required a suitable type of stone, usually lighter [68].

Khirokitia in Cyprus dates from (ca. 6800–ca. 5200 BC). The circular buildings of this archaeological site supported beehive-shaped corbel domed vaults of unfired mud-bricks and stones, and they also represent some of the earliest evidence of dwellings with an upper floor. Similar beehive-shaped tombs, called tholoi, exist in Crete and Northern Iraq. Cornelian necklaces (a variety of brown chalcedony) have also been found in Khirokitia, indicating exploration, trade, and transportation of this material [69,70].

The first walled settlements of the Old Iron Age were areas surrounded by stone barriers driven into the ground and wide walls of adobe masonry. Vitrified walls were made with masonry and fired adobes [71–73] composed mainly of bones, rubble and earth that served to compact the dry-laid masonry from the late Bronze Age (7th–6th centuries BC) to that of the late Iron Age (2nd century BC).

Stones from several kilometers far-away quarries were used (Figure 4) for the construction of megalithic structures. These early quarries had optimal cleat spacing and exfoliation microcracks for the extraction of blocks with the appropriate dimensions [74].



**Figure 4.** (a) Slab quarries of the Alto do Cotorino dolmen (northern Portugal); (b) Alto do Cotorino dolmen; (c) Dombate dolmen, Borneiro (northern Spain).

Walls of caissons, in a compartmentalized way, were built in modules in the 4th century BC [75,76]. As human activities became more specialized, construction materials had to meet the increasingly specialized needs and thus, for example, the most abrasive stones were used for the construction of mills. Stones that resisted high temperatures together with clays were used in smelting furnaces [77]. Humans also selected the material for firing ceramics [78,79]. This attests to a knowledge of the quality and properties of the stones.

Granite slabs with highly developed exfoliation microcracks.

## 4. Ancient History

### 4.1. Mesopotamia

Even though adobe was the main building material used in Mesopotamia, building stone exploration, cutting, carving and polishing techniques were developed in this area. In fact, the first mentions written about stones as eternal material, are in the *Epic of Gilgamesh* (ca. 2500–2000 BC). Land and river routes and the role of nomads were critical to understanding the use of heritage stones. Obsidian was used for arrowheads, blades, burins, and sickles. It came from Tell Mozan (Urkesh, Syria) and from other sites [80].

Syrian, Anatolian, and Mesopotamian cultures have interacted and mixed through history. The increased use of stone in southern Mesopotamia appears to be directly linked to the increasing significance of the temples. At different times, northern Mesopotamia and Anatolia, the Iranian Plateau, the Persian Gulf (Dilmun and Magan), and the distant Indus Valley (Melubba) were centers from which southern Mesopotamia obtained stone resources.

The first civilizations appeared in Sumeria [81] where adobe was commonly used for construction. The rocks were reserved for temples and palaces and in any case, walls. A lapis lazuli foundation tablet, preserved in the British museum, records that king Lugal-Silasi built the courtyard wall of a temple complex for the gods An and Inanna temple in

Uruk [82]. Colonies of this city could be the agents responsible for the increased shipment of exotic stones into southern Mesopotamia. The temple of the Storm God was discovered beneath Aleppo's Ottoman citadel [83]. It was first constructed by Early Bronze Age peoples with a neat row of carved hard stone ashlar, with gods and mythical creatures. These ashlar have sharply chiseled surfaces show the marks of the sculptors.

An expansive variety of objects as beads, amulets, pendants, vessels, statuary and inlay were produced from amber (and other resins), agate, alabaster, aragonite, azurite, basalt, beryl (aquamarine, emerald), calcite, corundum (emery), quartz (citrine, crystal rock, smoky quartz), cornelian, chalcedony (agates, jasper), heliotrope, flint, onyx, ruby, sapphire, diorite, feldspar, garnet, granite, grindstones (nephrite, jadeite), gypsum, jet, lapis lazuli, limestone, malachite, marble, steatite, chlorite, serpentine, and turquoise among other stones. These objects were placed in temples as votive offerings. From the Late Uruk period to the end of the Early Dynastic period, light colored stones predominated in manufactured statuary, wall plaques, rare royal monuments, maceheads, and even cylinder seals. Toward the end of the Early Dynastic II and throughout the Akkadian and Ur III periods, there was a significant shift to dark stones: diorites, gabbros, and dolerites that were used principally for the manufacture of items for rulers and their high officials. These dark stones, no doubt expressive of the elite status of their owners are believed to have been sourced from the Persian Gulf, although it should be noted that they were also extensively found in the Makhran Range of south eastern Iran. The earlier lighter stones came from the nearby chains of the Zagros Mountains.

Serpentine was the most used stone to produce seals in the Late Uruk and Akkadian periods in southern Mesopotamia. In post-Akkadian and Ur III times, serpentine was replaced by chlorite to produce seals. Additionally, there were several workshops producing decorated vessels in chlorite/steatite coming from different sources. Darre Goodmordane Ashin and Sardare Noe Ashin were the main quarries. The outcrops of Konar Sandal and Tepe Yahya represented a significant stone workshop within the Iranian plateau [84].

Lapis lazuli is one of the first stones used for decorative artefacts and has been found in prehistoric tombs in Asia, Africa, and Europe. Lapis lazuli was imported to Mesopotamia in a semi-processed state from Afghanistan and, in less quantity, from Pakistan [85]. The raw lumps of lapis lazuli recovered from fourth-millennium BC Djebel Aruda in Syria and fourth-millennium BC Mehrgarh in Pakistan indicated both the widespread and early use of this stone. It remained throughout the third millennium a highly prized stone. Throughout the recorded use of lapis lazuli, its principal source has been the Badakshan district of Afghanistan, which has been functioning as a quarry for approximately six thousand years and has been mentioned frequently in historical documents [86].

King Nabonidus (556–539 BC), of the Neo-Babylonian Empire (612–539 BC), discovered and analyzed the foundation deposits of the Akkadian Empire ruler Naram-Sin (ca. 2200 BC) in Ancient Mesopotamia. This king is thus known as the "first archaeologist" [87]. The Mesopotamians developed methods for cutting and polishing stones. Drill bits of diamond were first used in the Sassanian period (224–651 AC) and were procured from India.

#### 4.2. Ancient Egypt

The Egyptians used copper tools with abrasive stones to cut rocks, a technique probably used first for quarrying stone blocks and later in excavating temple rooms inside rock mass. Slaves extracted large blocks of high-quality stones from quarries that were well organized [88,89]. Crushed stones and gypsum were also used to make plaster and mortar [90]. The sculptors chose the type of stone to carve according to the importance or durability they wanted to give to the finished work. In this way, statues of kings were carved mainly in igneous stones, and the bas-reliefs inside temples in softer stones such as sandstones and marl [91,92] (Figure 5). Some of the stone of the pyramids at Giza were quarried from the Giza Plateau. Other parts, such as casing stones, were quarried from the Tura area [93].



**Figure 5.** (a) Colossi of Memnon in front of Luxor city, near Medinet Habu (Egypt) carved in quartzite sandstone which was quarried at el-Gabal el-Ahmar (near modern-day Cairo) and transported 675 km. (b) Flaminio Obelisk, reign of Ramesses II and Merneptá (13th century BC) carved in granite. It moved to Rome by order of the Emperor Augustus and was placed in the spina of the Circus Maximus in 10 BC. It was abandoned and broken into three pieces after the fall of the Roman Empire and discovered in 1587. It was restored and erected in the Piazza del Popolo in 1589. (c) Kom-Ombo temple (Egypt) The construction of the temple with sandstone blocks was initiated by Ptolemy VI Philometor (180–145 BC).

Imhotep or Imutes (ca. 2690–ca. 2610 BC) was the “first known architect and engineer”. He was the author of the funerary complex of Saqqara which has a wall of approximately 1500 m in perimeter, with various buildings and towards the center a stepped pyramid of six tiers with an approximate height of 60 m. It was built with relatively small blocks of limestone, easy to transport and to handle. Previously, adobe bricks were used. The tomb of Djoser (Zoser) and galleries to store funerary vessels and clay figures were excavated under the pyramid [94]. A son of Ramesses II, Khaemweset (ca. 1281–ca. 1225 BC) is called “the first Egyptologist”. He was interested in identifying and restoring the monuments of Egypt’s past, such as Djoser’s pyramid [95].

## 5. Classical Antiquity

Classical Antiquity comprises the Greco-Roman world, that is civilizations of ancient Greece and ancient Rome. These civilizations flourished and wielded great influence throughout Europe, North Africa and the Middle East.

### 5.1. Classic Greece

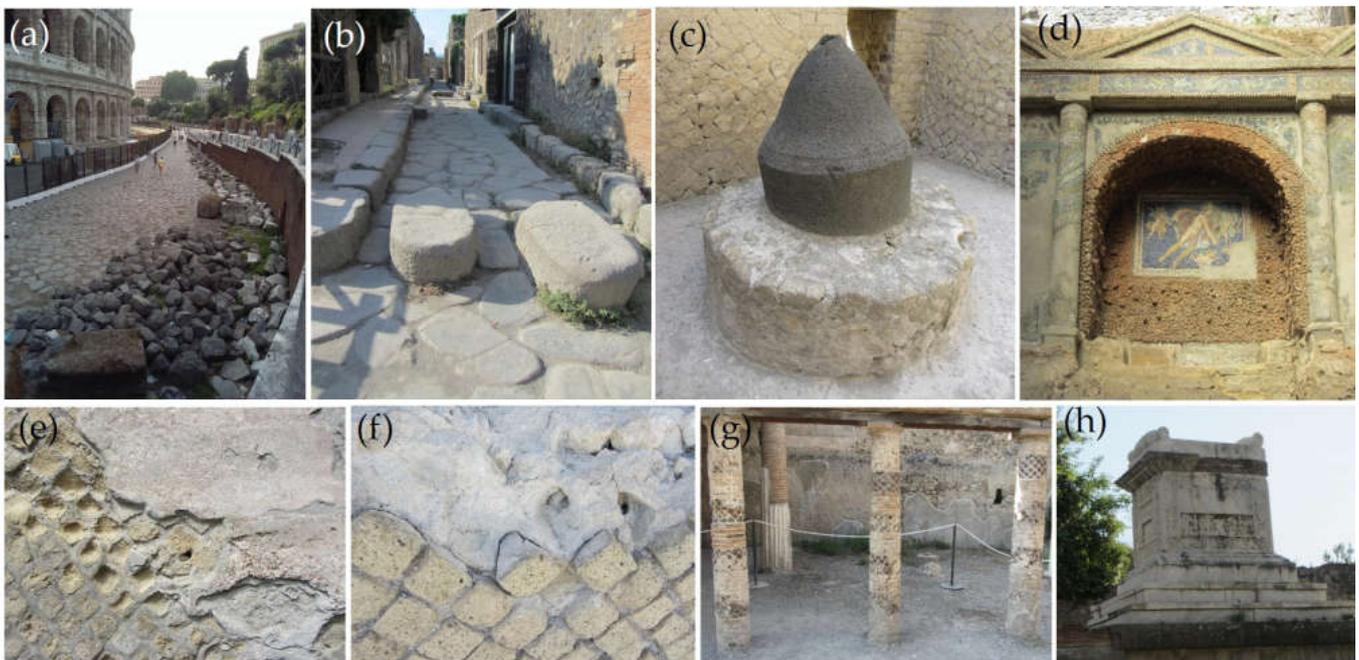
The extensive use of stones as building material by the ancient Greeks began during the 7th century BC. The raw materials were mostly marbles, travertines (“πώρος”), sandstones, conglomerates, gneisses, schists, serpentinites, magmatic rocks, limestones and many others [96]. The ancient quarrymen selectively mined marbles of high quality and purity. The columns were extracted from quarries with few fractures or with joints that would favor extraction. Ancient Greek writers used various names for the quarries. Plato (ca. 427–ca. 347 BC), Strabo (64/63 BC–ca. 19/4 BC) and Plutarch (ca. 46–119 AC) called them “λατομίεζ”, and Thucydides (ca. 460–ca. 400 BC), Herodotus (484–425 BC), Xenophon (ca. 431–354 BC), Theophrastus (ca. 431–354 BC) and Pausanias (480 BC–?) called them “λιθοτομίεζ”. Famous marble quarries existed in Aphrodisias [97], Dokimia, Doliana, Ephesos, Euboea, Hymettus, Naxos, Paros, Pentelikon, Prokonnesus (Marmara sea), Skyros and Thassos.

The Greeks had a better knowledge than Egyptians did of the mechanical and petrophysical properties of stones, and they built temples and sculptures with harmonious proportions. The first stone ashlar blocks of Greek architecture are those of the mid-7th century temples at Isthmia and Corinth. Their ashlar blocks have grooves that were plausibly used to move the blocks with ropes. Forerunners of the crane appeared in Greece well before the late 6th century BC [98].

It is thought that the Greek philosopher Aristotle (384 BC–322 BC) described seven hundred stones giving their color, greatness, virtue and location [99], but the first preserved written references to the subject of building stones and their decay were made by the Greek philosopher Theophrastus (ca. 372 BC–287 BC), who described numerous stones used in classical Greece in *Peri liton* [100,101]. Theophrastus wrote about the regular use of mortar to cement stones in Cyprus and Phoenicia. Later, the geographer Strabo (ca. 64/63 BC–ca. 19/4 BC) made a description of the world as it was known in ancient times in *Geography*, making references to building stones. Claudius Ptolemy (ca. 100 AC–ca. 170 AC) wrote another work titled *Geography*, with a description of the known world, although with serious errors in distances. Ptolemaeus described, among other cities, Mecca, on the Arabian Peninsula.

### 5.2. Classic Roman Empire

The expansive Roman Empire and its taste for building stones of different colors [102,103] demanded a large supply of good quality stones (Figure 6). Paved roads were developed, and the most suitable stones for their elaboration were volcanic or philonian stones such as basalt, porphyry and diabase [104,105], due to their low abrasion index. These communication routes allowed the transport of heritage stones to cities and villages [106,107] to build walls, bridges, aqueducts, dams, stelae, sarcophagi, mosaics [108], mills [109] and ornamental elements [110]. Quarries were scattered throughout the Roman Empire [111–113] and a trade in ornamental stones was created, mostly from Egypt [114–116].



**Figure 6.** (a) Basalt pavement, Rome (Italy); (b) cobbled street with basalt, Pompeii (Italy); (c) basalt mill, Herculaneum (Italy); (d) nymphaeum with marble, pumice and other stones, Pompeii (Italy); (e) opus reticulatum, Herculaneum (Italy); (f) opus reticulatum, Herculaneum (Italy); (g) opus mixtum, Pompeii (Italy); (h) Pompeii marble tomb (Italy).

The *Collegia Fabrorum* were the groups of stonemasons, master builders and architects who obtained their knowledge about the cutting, carving and working of stones and their properties from Phoenician and Greek architects, who in turn had received it from the architects of Ancient Egypt. A Roman bas-relief of 3rd century AD shows a hydraulic mill to cut stones. It is possibly the first representation of this type of machine used to cut stones [117].

The stones were classified into four types according to their use: *lapis vivus* or *franchus*, hard stones for quality works and sculptures; *lapis villanus*, soft stone for lower quality constructions; *lapis maceralis*, stones for masonry and interior filling of the walls; and *lapis columnarios*, stones of great resistance for pillars [118]. Generally, white marble was used to make column capitals, bases and entablatures. Colored stones were used for column shafts, while both white and colored stones were used as wall veneer and floor paving. Small fragments of colored stones (called tesserae) were used to create mosaics.

The Roman mortars were a mixture of lime and a volcanic ash called pozzolana. Different materials were used as aggregates, primarily broken bricks and tiles and roughly fist-sized pieces of a volcanic stones called *tufa*. Concrete was mainly used to make foundations, walls and vaults. Concrete walls were faced with either brick or stones. Brick-faced concrete was called *opus testaceum*. Concrete faced with irregularly shaped stones was referred to as *opus incertum*. *Opus reticulatum* was made up of stone pieces in the shape of a quadrangular pyramid. The square faces were laid out, forming a diagonal grid (Figure 6). Walls with both brick and reticulate facing were called *opus mixtum*. Walls faced with alternating rows of bricks and small rectangular stone blocks were called *opus vittatum*.

The ancient Roman work that most closely resembles a scientific book was *De rerum natura* (*On the nature of things*) by Titus Lucretius Carus (ca. 99 BC–ca. 55 BC), a poet and philosopher, but this author hardly touches on geology and stones. The architect Marco Vitruvio Pollione (80 BC–15 BC) described quarries and building materials, addressing their durability in *De Architectura Libri Decem* (*The Ten Books of Architecture*) [119]. Later, Gaius Plinius Secundus (Pliny the Elder) (23/24–79 AC) wrote the 37 books that make up *Naturalis Historia* (*Natural History*) based on what he witnessed: local people, animals, plants and stones. Pliny dealt with aspects related to building stones in the last three books. The book XXXV describes the uses of the land, pigments, sulfur and the art of painting. The book XXXVI describes lapidary, sculpture, architecture, obelisks, pyramids, Cretan labyrinths, clay, sand, stone, glass and the use of fire. Finally, the book XXXVII quotes extensively from a variety of literary sources concerning stones from all over the Roman Empire as rock crystal, amber, diamonds, gems and semi-precious stones [120].

Knowledge of building stones and carving techniques spread throughout the Mediterranean basin and Europe in recent prehistoric times and, especially, during the Iron Age. The walls of emplekton, two parallel faces with a core filled with finer material, had a high constructive quality (Figure 7b). For example, the fortified village of Castroeiro (Mondín de Basto, north Portugal) which was occupied from the 4th century BC to the first 1st century BC [121] conserves some very regular ashlar with a trapezoidal plan and pseudo-rectangular front (Figure 7), which certifies skill in carving granite ashlar.



**Figure 7.** (a) Perimeter wall with granite ashlar carved in the shape of a trapezoidal prism; (b) wall of emplekton with granite ashlar in a house; (c) detail of granite ashlar carved in the shape of a trapezoidal prism.

## 6. Post-Classical History

### 6.1. Middle Ages

#### 6.1.1. Early Middle Ages

After the disappearance of the Roman Empire (476 AC), settlement patterns showed hill forts occupations and a new form of peasant site with the abandonment, dismantling or reorganization of Roman villas [122]. The idea of monasteries spread across the Byzantine Empire and then to Western Europe, where they adopted their own distinct practices based on the teachings of the Italian abbot Saint Benedict of Nursia (ca. 480–ca. 543 AC), regarded as the founder of the European monastery model. The reuse of Roman building stones was common and widespread in this period [123]. Many of Byzantine churches were attached to Roman temples and were built with reused Roman elements, such as the Saints Cosmas and Damien basilica, in the Roman Forum (Italy); the Santa Maria in Cosmedin basilica (or Schola Graeca), in Rome (Italy). The basilicas of Saint Apollinare the New and Saint Apollinare in Classe (Italy), the church of San Vital de Ravenna in Ravenna (Italy), Nostra Signora de Mesumundu (Our Lady of Mesumundu) in Sardinia (Italy) and Chiesa di San Giovanni degli Eremiti (church of Saint John of the Hermits) in Palermo (Italy) are some examples of Byzantine churches built with bricks and they have austere façades. The stones, which were more expensive, were destined for more relevant buildings, such as the Mausoleum of Theodoric in Ravenna (Italy) (ca. 520 AC), built with white Istrian limestone (Croatia) [124]. However, in the Iberian Peninsula, especially in the north, and more western countries, building stones continued to be mainly used as a load bearing element [125].

The basilica of Hagia Sophia in Constantinople (Istanbul) 532–537 AC is the most representative building of this time. The marble used for the floor and ceiling was quarried from Anatolia (present-day eastern Turkey) and Syria, while bricks (used in the walls and parts of the floor) are from different construction phases with different clays composition [126]. The interior of Hagia Sophia is lined with enormous stone slabs sourced from multiple places: Green marble of Karystos (Greece), rose-colored marble from Phrygia (Turkey) [127], red Imperial porphyry from Egypt [128], Green porphyry from Sparta (Greece), buff lassikos from Caria (Turkey), white-yellowish marble from Lydia (Turkey), gold-colored marble from Libya, chunky black and white Celticum breccia (so-called marmum celticum) from France, honey-colored onyx from Pamukkale (Turkey), green Verde Antique serpentinite breccia from Thessaly (Greece) [129,130], white marble from Proconnesos (Turkey) [131] and the grey-colored marble from Vosporos (Greece) [132]. Hagia Sophia's columns were brought from the temple of Artemis in Ephesus (Turkey), from Egypt, and from other locations of the Byzantine Empire.

Starting in the 8th century, the Medieval Warm Period influenced the development of large numbers of quarries to build the great monasteries that exploited increasingly extensive land holdings and churches [133,134] where stone was essential for construction. Ancient churches were rebuilt throughout Europe from the 9th century on to build great cathedrals that required the best available building materials.

In 793 AC, the Viking era began with the looting of the Lindisfarne monastery in north-eastern England [135,136]. Beginning with this event and until approximately 1100 AC, the Vikings looted monasteries, abbeys, and cities throughout Europe. Viking balances, weights and touchstones, tools to test the quality of non-ferrous metal, became widespread in the northern part of Europe as a sign of the buried individual's access to precious metals [137,138]. The cities were reinforced in anticipation of new attacks. Hard stones were used to reinforce city walls beginning in the 9th century, as a response to the development of counterbalanced powered war machines and Viking attacks. Thus, for example, coastal defensive towers were built, such in Catoria (Galicia, Spain) (Figure 8) and Santiago de Compostela was walled with stones [139].

*Compositiones ad tingenda musiva*, approximately from the 8th century, is the oldest surviving recipe book for sumptuary arts. It is not specifically dedicated to stones, although there are references to them. Similar in content to this recipe book is the one known as *Mappae Clavicula*, which must have circulated since the 9th century. This book contains the recipe of a glue for stones and for the manufacture of artificial stones.

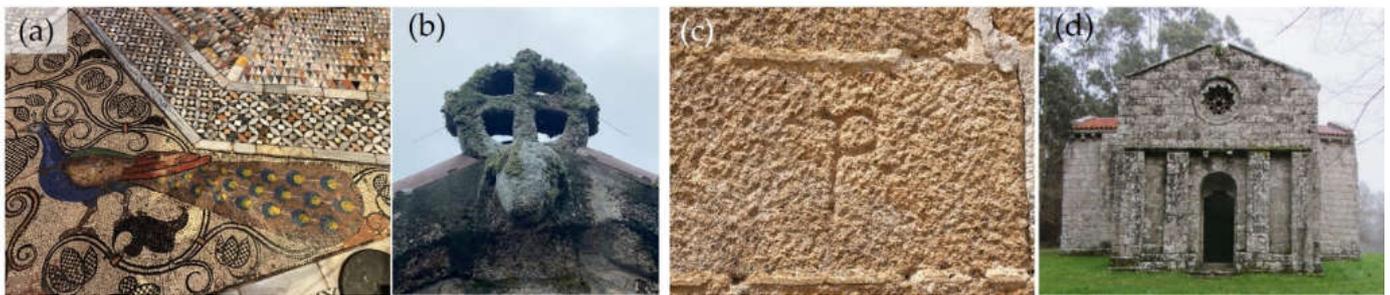


**Figure 8.** (a) Anthropomorphic medieval graves in Pena (Vila Real, north Portugal); (b) coastal defensive towers and Chapel of Santiago (9th and 12th centuries, respectively) in Catoria (Galicia, Spain); (c) example of the 13th century typology of porticoed urban building. *Casa della Dogana* (Padua, Italy).

#### 6.1.2. High Middle Ages

The construction of the cathedral of Santiago de Compostela (Spain) began in 1098 [140]; new pilgrimage routes were opened, and the mendicant orders of Dominicans and Franciscans were born. For example, just in the city of Segovia (Spain), more than 20 Romanesque churches were built between 1180 and 1250. Thus, specialized workforce was necessary. The master builders controlled the quality of the stones and they oversaw the construction and maintenance of the buildings. Some of the master builders were international experts and their recognition spread throughout Europe, transmitting their knowledge orally to the trade guilds. For example, the French master builder Giral Fruchel introduced the Gothic of the Île-de-France into the Iberian Peninsula, and he worked in the construction of several cathedrals in Spain [141].

Each artisan was member of a trade guild, which protected the artisans' interests and fixed the price of their products. The stonemason marks used to mark the work carried out by stonemasons are very frequent in churches and castles of this time (Figure 9). Members of the guild were classified as: "Apprentices" who were maintained trained by the Master for approximately 6 years; "Officers" who perfected their skills and charged for their work; and "Master builders" who would continue to improve their skills and could open their own workshop. The artisan guilds got the right to maintain a lodge, a place to meet and keep the plans of the building and other documents of the guilds.



**Figure 9.** (a) Mosaic floor with peacocks in the Saint Mark's Basilica of Venice (12–13th century); (b) cross in the Romanesque apse of Sao Tiago church in Folhadela (Vila Real, northern Portugal) built with granite in the 12th century; (c) Stonemason marks in the Romanesque church of Nossa Senhora de Guadalupe of Mouços (Vila Real, north Portugal); (d) San Miguel de Bremao Romanesque church (A Coruña, Spain) built with granite ashlar in the 12th century.

Romanesque architecture was characterized by new models of sculptural representation with great symbolic content (Figure 9b). At the beginning of the 12th century, two architectural innovations, the buttress and the pointed arch, made it possible to prop up walls and make them thinner, allowing them to support a greater weight. This transformation is visible in the Cistercian monasteries, which are in the transition between the Romanesque and Gothic styles. The construction of the first Gothic cathedrals began at the end of the 12th century. The complexity of Gothic buildings [142,143] has been a driving force behind the study of building stones, especially its mechanical resistance. Their columns and nerves had to withstand great pressure.

The Persian scholar Abu Rayhan al-Biruni (973–1048 AC) described the petrophysical properties of 100 known minerals, developing the hydrostatic weighing method to calculate the density of both ornamental as precious stones [144]. The most prominent lapidary is that of the Iranian aristocrat Muhammad Ibn Mansur. It was written in the 12th century and dedicated to Sultan Abbasi of Persia. Weight, hardness, variety and location of stones were described with precision in this treatise. Going back to Europe, the Toledo school of translators of Spain was founded at the beginning of the 12th century and important books written in Arabic were translated into Latin, which contributed to the dissemination of numerous books.

### 6.1.3. Late Middle Ages

The first translation of a lapidary was commissioned by Alfonso X “El Sabio” of Castille (1221–1284). Yehuda ben Moshe ha-Kohen translated it between 1243 and 1250. This lapidary deals with the magical properties of stones in relation to astrology. Albertus Magnus (1193/1206–1280) wrote *De mineralibus* (*Minerals*) consisting of five books on stones. These books describe the astrological influences and hidden powers of stones and the “chemistry” of the alchemists. It attempted to relate the limited and basic knowledge of the time about nature to the properties of stones. The *Tafasi* treatise (13th century) is divided into 24 chapters. It is based on the dictates of Aristotle and Belinas, on the genesis of each stone; and it describes their qualities, prices, varieties and defects. Books written in vernacular language (not in Latin) began to appear also in the 13th century. The best-known work is the travel notebook, dated between 1220 and 1240, of the French master builder Villard de Honnecourt (ca. 1200–ca. 1250), where there is a set of drawings, texts and teachings on building stones. This master builder worked on the construction of the Cistercian abbey of Vaucelles; on several cathedrals in France, such as Notre Dame de Reims, Meaux, Saint-Étienne, Chartres, and Lausanne; and on the cathedral of Košice (Hungary) [145].

A succession of rains and poor harvests led to famines in much of Europe between 1315 and 1318. Territorial struggles and revolts in all of Europe together with the Black Death that reached Europe in 1346 caused the death of approximately 60% of the population in the first half of the 14th century. Due to this crisis, a great deal of knowledge on building stone extraction and construction techniques was lost, with technical limitations in important buildings becoming apparent. Beauvais Cathedral collapsed at the end of the 13th century, and the Gothic cathedrals of Cologne (Germany), Narbonne (France), Siena (Italy) and Oviedo (Spain) were left unfinished due to the lack of funds.

Until the end of the Middle Ages, the use of building stones in the civil construction of cities was not generalized. This material was mostly reserved for religious and military buildings. The population built their houses with combustible materials for economic reasons; as a result, cities often suffered catastrophic fires. To combat this danger, the authorities of some countries enacted, from the end of the 14th century on, laws to impose stone construction.

## 7. Modern History

The economic collapse was a crucial cause for the development of the Renaissance in northern Italy [146]. The construction of the dome of Santa Maria del Fiore cathedral, in Florence (Italy), between 1420 and 1436 by Filippo Brunelleschi (1377–1446) is considered the beginning of the Renaissance. Brunelleschi drew up one of the first contracts in which a master builder specified the most important aspects of the construction and assumed responsibility for it in 1420. The masonry dome over the Florentine cathedral is composed of eight ribs and eight webs: octagonal ribbed pointed dome. The lantern, which is a belvedere, is made of marble [147]. This stone has been widely used during the Italian Renaissance by sculptors and architects [148]. The Italian Leon Battista Alberti (1404–1472) designed the upper part of Santa Maria delle Carceri church in Prato (Italy) with inlaid green marble, also called “*serpentino*”. He also designed the polychrome marble inlay façade of the church of Santa Maria Novella in Florence (Italy) and restored Santo Stefano Rotondo in Rome. Battista Alberti wrote *De Re Aedificatoria (On the Art of Building)* in 1452, a treatise on the theoretical and practical aspects of architecture, based on the work of Vitruvius. The second volume is dedicated to building materials.

### 7.1. Early Modern Period

Towns and cities had grown under the cover of old medieval castles built to withstand an attack with spears and non-powder propelled projectiles. However, the fall of Constantinople to the Turks (1453) and the invasion of Naples by French troops in 1492 marked the widespread use of gunpowder-propelled artillery. From then on, the villages and towns were vulnerable and needed to reinforce their walls [149]. These issues, together with the drop in temperatures [150,151] led to the building of more solid walls and to a greater exploitation of quarries. Intensive construction activity and many publications on building materials, architecture and military urban planning were generated throughout Europe. The construction of forts required knowledge of quarries, of properties of building stones, on how the foundations, walls, pillars, columns and other stone elements should be, of mixtures of mortars, and of tips to save money [152]. Almost a score of treatises was published between 1554 and 1599 just in Italy (Table 1). The main European academies were created in the Renaissance (Table 2) due to the growing interest in the study of architecture.

**Table 1.** Main treatises on fortification and architecture.

Publication	Author	Author's Life	Title of the Book	Country
ca. 1450	Leon Battista Alberti	1404–1472	De Re Ædificatoria	Italy
1465	Antonio di Pietro Averlino	1400–1469	Trattato di Architettura	Italy
1472	Roberto Valturio	1405–1475	De re militari libri XII	Italy
1493	Antonio Cornazzano	1429–1484	Opera bellissima de l'arte militare	Italy
ca. 1478–1481	Francesco di Giorgio Martini	1439–1501	Trattato I (Architettura, ingegneria e arte militare)	Italy
ca. 1490			Trattato II (Architettura civile e militare)	
?	Leonardo da Vinci	1452–1519	Manuscripts (Codex Madrid II)	Italy
1527	Jacopo di Porcia	1462–1538	De Re Militari	Italy
1527	Albrecht Dürer	1471–1528	Etliche Unterricht zu Befestigung der Stett, Schloss und Flecken	Germany
1529	Giovan Battista della Valle	1470–1550	Vallo Libro continente appertinentie à capitanii ... fortificare una città ...	Italy
1536	Daniel Specklin	ca. 1536–1589	Architectura von Vestungen . . . . Bollwerken, Cavalieren, Streichen ...	Germany
1536	Diego de Salazar	?	De Re Militari	Spain
1547	Enrico Rivio	?	L'architettura delle fabriche	Germany
1537–ca. 1575	Sebastiano Serlio	1475–1554	I sette libri dell'architettura—Della castrametatione di Polibio ridotta ...	Italy
1554	Pietro di Giacomo Cataneo	ca. 1510–ca. 1574	I quattro primi libri di architettura	Italy
1567			L'Architettura di Pietro Cataneo Sanese	
1557	Giacomo Lanteri di Paratico		Dil modo di fare le fortificationi di terra ... Città & alle castella per fortificarle	Italy
1558	Jacopo Aconcio	1492–ca. 1566	De Methodo	Italy
1559	Giacomo Lanteri (Lantieri)		Due libri del modo di fare le fortificationi di terra intorno alle città & alle castella ...	Italy
1575–1591	Alonso de Vandelvira y Luna	1544–1626	Tratado de arquitectura sobre el arte de cortar la piedra	Spain
1598	Cristóbal de Rojas	1555–1611	Teórica y práctica de fortificación	Spain

Table 1. Cont.

Publication	Author	Author's Life	Title of the Book	Country
1560	Giovanni Battista Zanchi	1515–1586	Del modo di fortificar le citta	Italy
1564	Girolamo Maggi Giacomo Castriotto (Japoco)	ca. 1523–1572	Della fortificatione delle città	Italy
1564			Opera nuova di fortificare, offendere et difendere	
1571	Girolamo Cataneo	1540–1584	Nuovo ragionamento del fabricare le fortezze; si per pratica	Italy
1567			Dell'Arte militare	
1600			De Arte Bellica	
1567	Domenico Mora	1536–1586	In Dialogo sopra il Fare batterie, fortificare una citta.	Italy
1569			Discorsi delle fortificazioni	
1584	Carlo Theti	1529–1589	Istruzione per i Bombardieri	Italy
1585			Dell'Espugnazione e difesa delle fortezze	
1570	Galaaso Alghisi	1523–1573	Delle Fortificazioni . . . Libri Tre	Italy
1571	Girolamo Cataneo	1540–1584	Nuovo rogionamento del fabricare le fortezze	Italy
1572	Giacomo Fusto Castriotto (Jacopo)	1510–1562	Della fortificatione delle città	Italy
1573	Jan van Schille (Hans Schille)	1510–1586	Form und Weis zu bauwen . . . Vestung, Schlosser, Burgen und Stedt . . .	The Netherlands
1575	Vincenzo Locatelli	ca. 1526–1584	Invito Generale	Italy
1576	António Rodrigues	1525–1590	Tratado de Arquitectura (Manuscrito)	Portugal
1578	Filippo Terzi	1520–1597	Estudos sobre embadometria, estereometria e ordens de arquitectura	Portugal
1579	Marc Aurelio di Passino	?	Discours sur . . . de l'architecture de guerre: concernants . . . l'artillerie	France
1580	Gabriello Busca	1540–1605	Della espugnazione et difesa delle fortezze	Italy
1619			L'Architettura Militare	

Table 1. Cont.

Publication	Author	Author's Life	Title of the Book	Country
1582	Walter Herman Ryff	1500–1548	Baukunst oder Architektur aller fürnemsten . . . Künsten, eygentlicher . . .	Germany
1582			Architettura militare con altri avvertimenti appartenenti alla guerra	
1583	Antonio Lupicini	1530–1592	Discorsi militari dell'eccellentissimo . . . Della Rovere duca d'Urbino . . .	Italy
1583			Diálogos del arte militar	
1587			Discorsi di architettura militare	
1583	Diego García de Palacio	1540–1595	Diálogos militares	Spain
1585	Giacomo Aconcio	1492–1584	Ars muniendorum oppidorum	Italy
1587			Le Timon	
1598	Ambroise Bachot	ca. 1540–ca. 1600	Le gouvernail . . . l'architecture des fortifications . . .	France
1588	Agostino Ramelli	1531–1608	Le diverse et artificiose machine	Italy
1589	Paul Ive	?–1604	The practise of fortification	England
1594	Giulio di Savorgnan	1510–1595	Venticinque regole per la fortificazione	Italy
1594			De Sterktenbouwing	
1649			Van de oirdeningh der steden	
1617	Simon Stevin	1548–1620	Nieuwe Maniere van Stercktebou door Spilsluysen	The Netherlands
1649			Materiae Politicæ, Burgherlicke Stoffen	
1596	Giovanni Scala	1547–1599	Delle fortificationi	Italy
1597	Bonaiuto Lorini	1540–1611	Delle fortificationi libri cinque	Italy
1598	Giovanni Battista Bellucci	1506–1554	Nuova inventione di fabricar fortezze di varie forme	Italy
1599	Francesco de Marchi	1504–1577	Trattato di Architettura Militare	Italy
1599	Diego González de Medina Barba	ca.. 1550–1600	Examen de fortificación	Spain
1599	Charles de Beste	?	De Architectura	The Netherlands

Table 1. Cont.

Publication	Author	Author's Life	Title of the Book	Country
1599	Giovanni Pomodoro	?	Geometria prattica tratta dagl' Elementi d' Euclide et altri autori	Italy
1600	Jean Errard de Bar-le-Duc	1554–1626	La fortification demonstree et reduicte en art	France
1601	Jacques Perret	1540–1619	Des Fortifications et Artifices Architecture et Perspective	France
1602	Mateo Morán	?	Nuevo modo de fortificar	Spain
1604	Giovanni Francesco Fiammelli	1565–1613	Il Principe difeso, nel quale si tratta di Fortificazione ...	Italy
1606			I quesiti militari	
1607			Kriegsbuch: darin die alte und neue Militia eigentlich beschrieben un alle ...	
1640	Johann Wilhelm Dilich	1571–1650	Peribologia (Vestungsgebewen)	Germany
1641			Peribologia seu Muniendorum locorum ratio	
1645			Kurtzer und in Tabulis verfassete underricht ... Bollwercke ... Anzulegen	
1611	Cristóbal Lechuga	1557–1622	Discurso que trata de la artilleria ... con un tratado de fortificación y otros ...	Spain
1611	Claude Flamand	1570–1613	La guide des fortifications et conduite millitaire	Italy
1627	Samuel Marolois	1572–1627	Fortification ou Architecture militaire tant offensive que defensive	The Netherlands
1633			Fortificationis sive artis muniendi	
1614	Mario Savorgnan	1513–1574	Arte Militare Terrestre, e Maritima; Secondo la Ragione ... Itália	Italy
1615	Vincenzo Scamozzi	1548–1618	L'Idea della Architettura Universale	Italy
1618	Alexander von Grotte	1599–1637	Neue Manier mit wenigen Kosten Festungen zu bauen	Germany

Table 1. Cont.

Publication	Author	Author's Life	Title of the Book	Country
1618			Corona imperiale dell'architettura militare	
1627	Pietro Sardi	1560–1642	Discorso, per il quale con vive e certe ragioni si rifiutano tutte le fortezze ...	Italy
1639			Corno dogale della architettura militare	
1642			Discorso sopra la necessità & utilità dell'architettura militare	
1620	Pietro Antonio Barca	1586–1636	Avvertimenti' e regole circa l'architettura civile, scultura ... et architettura ...	Italy
?	Giovanni de Galliano Pieroni	1586–1654	Trattato delle fortificazioni moderne	Italy
1622	Leonardo Torriani (Turriano)	1559–1628	Dos discursos de Leonardo Turriano ...	Portugal
1624	Robert Fludd	1574–1637	De arte militari	England
1624	Francesco Tensini	1581–1638	La fortificatione, guardia, difesa, et espugnatione delle fortezze ...	Italy
1626	Adriaan Adriaansz (Adriaan Metius/Anthoniszoon)	1571–1635	Maet-constigh liniael ofte proportionalen ry ende platten passer	The Netherlands
1627	Matteo Oddi	1576–1626	Precetti di architettura militare	Italy
1630	Pietro Paolo Floriani	1585–1638	Diffesa et offesa delle piazze	Italy
1630	Joseph Furttenbach	1591–1667	Architectura martialis	Germany
1635			Architectura universalis	
1631	Adam Fritach (Freitag, Freytag)	1608–1650	Architectura militaris nova et aucta, oder Neue vermehrte Fortification ...	The Netherlands
1639			L'Architecture militaire ou la fortification nouvelle	
1631	Matheus do Couto, O velho	1616–1676	Tractado de Architectura	Portugal
1633	Johann Faulhaber (Johannes)	1580–1638	Academia fortificatoria	Germany
1637			Ingenieurschul	
1636	Galileo Galilei	1564–1642	Trattato di fortificazione	Italy
1639	Giuseppe Barca	1595–1639	Breue compendio di fortificatione moderna	

Table 1. Cont.

Publication	Author	Author's Life	Title of the Book	Country
1640	Antoine de Ville	1596–1656	Les Fortifications du Chevalier Antoine de Ville	France
1643	Nicolaus Goldmann (Nikolaus, Nicolas)	1611–1665	Elementorum architecturae militaris libri IV	The Netherlands
1643			La nouvelle fortification Polônia Holanda	
1656			Tractatus de usu proportionatorii sive circini proportionalis	
1644	Don Juan de Santans y Tapia	?–1658	Tratado de fortificación militar de estos tiempos	Spain
1645	Blaise François Pagan	1604–1665	Les Fortifications	France
1647	Matthias Dögen	1605–1676	Architectura militaris moderna: variis historiis, tam veteribus . . .	The Netherlands
1650	Cosimo Noferi	1635–1661	La Travagliata Architettura	Italy
1651	Diego Enríquez de Villegas	1600–1671	Academia de fortificación de plazas	Spain
1654	Henrik Ruse	1624–1679	Versterckte vesting, uitgevonden in velerleij voorvallen . . .	The Netherlands
1654	George Fournier	1595–1652	Traité des fortifications, ou Architecture militaire . . .	France
1655	Pierre Bourdin	1595–1653	L'architecture militaire, ou l'art de fortifier les places régulières . . .	France
1657	Gennaro Maria d'Afflitto	1618–1673	Compendio de Modernas Fortificaciones	Italy
1665			Breve trattato delle moderne fortificazioni	
1667			Introduzione alla moderna fortificazione cavata	
1659	Christoph Notnagel	1607–1666	Manuale fortificistorium, oder, Kurtzes handbuchlein . . .	Germany
1659	Luís Serrão Pimentel	1613–1679	Architectonica Militar ou Fortificação Moderna	Portugal
1680			Methodo Lusitanico de Desenhar as fortificações das Praças . . .	
1661	Juan de Torija	1624–1672	Breve tratado de todo genero de bohedas . . .	Spain
1664	Christoph Heydmann	1635–1707	Fortifikations manier—Addimentum Architecturae militaris	Germany

Table 1. Cont.

Publication	Author	Author's Life	Title of the Book	Country
1666	Jean du Breuil	1601–1670	L'art . . . des fortifications françaises, hollandoises, espagnoles, italiennes . . .	France
1666	Johann Matthäus Faulhaber	1604–1683	Fortifikation—Manual zu den Grundregeln der Ingenieurskunst	Germany
1672	Johann Bernhard Scheither	?–1677	Novissima Praxis militaris	Germany
1688			Manuale architecturae militaris	
?	Manuel Fernández de Villarreal		Architettura militar o Fortificacion moderna	Spain
1660	João Nunes Tinoco	1610–1689	Taboadas gerais para . . . obra do officio de pedreiro	Portugal
1664	Vicente Mut Armengol	1614–1685	Arquitectura militar	Spain
1669	Alonso de Zepeda y Adrada	?	Epitome de la fortificación moderna . . .	Spain
1671	Pedro Antonio Ramón Folch de Cardona	1611–1690	Geometria Militar	Spain
1673	Georg Rimpler	1636–1683	Neü-herfürgegebene Kriegsarchitectur	Germany
1673			Ein dreyfacher Tractat von den Festungen	
1674			Befestigte Festung, Artillerie und Infanterie mit drei Treffen . . .	
1676	Annibale Marchese Porrioni	1623–1684	Trattato universale militare moderno	Italy
1675	Francesco Eschinardi (Costanzo Amichevoli)	1623–1703	Architettura militare ridotta a metodo facile e breve	Italy
1677	Johann-Frantz Griendel Von Ach	1631–1687	Nova architectura militaris	Germany
1678	Donato Rossetti	1633–1706	Fortificazioni a rovescio	Italy
1682	Menno van Coehoorn	1641–1704	Versterchinge de Vijfhoeks met alle syne Buytenwerken	The Netherlands
1685			Nieuwe Vestingbouw op een natte of lage horisont	
1683	Jean-François Bernard		Nouvelle manière de fortifier les places	France

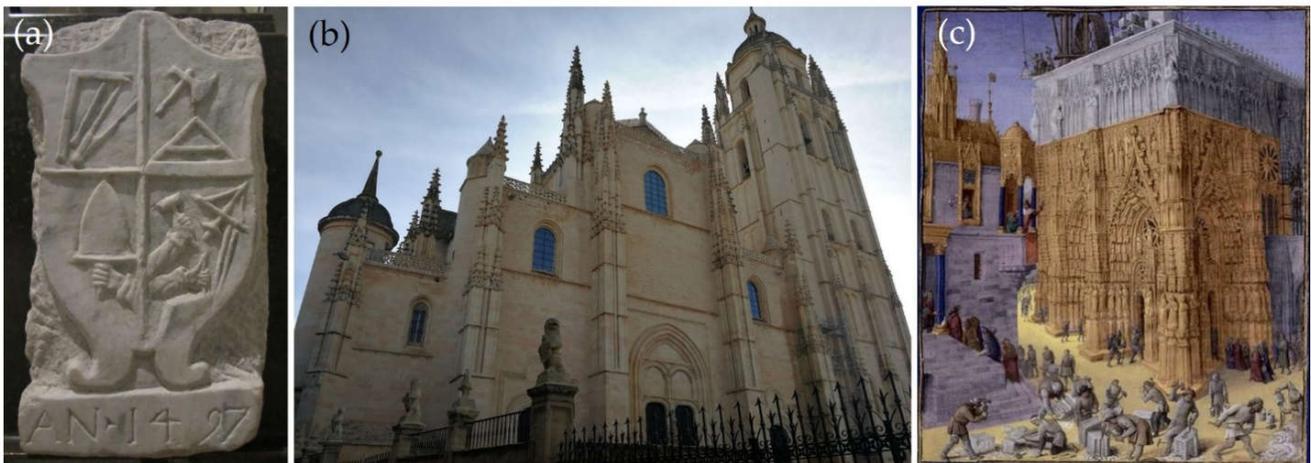
**Table 1.** *Cont.*

Publication	Author	Author's Life	Title of the Book	Country
1685	Sébastien Le Prestre de Vauban	1635–1707	Le Directeur général des fortifications	France
1704			Traité des sièges et de l'attaque des places	
ca.. 1690	Manuel Pinto de Vilalobos	?–1734	Tractado do uzo do pantometra de desenhar as fortificasoins	Portugal
1693	Jose Chafrión	1653–1698	Escuela de Palas ò sea curso mathematico	Spain
1694	Giusto Emilio Alberghetti	1666–1755	Compendio della fortificatione	Italy
1696	Alain Manesson Mallet	1630–1706	Les Travaux de Mars ou l'Art de la Guerre	France
ca.. 1705	Pêro Araújo	?–1715	Tratado de Arquitectura Política e Militar	Portugal

**Table 2.** First main European academies.

Year	City-Country	Name
1583	Madrid-Spain	Royal Mathematica Academy
1593	Rome-Italy	Academy of San Luca
1603	Rome-Italy	Linceana Academy
1648	Paris-France	Royal Academy of Painting and Sculpture
ca. 1657	Florence-Italy	Experiment Academy
1662	Lonson-England	Royal Society of London for Improving Natural Knowledge
1666	Paris-France	Sciences Academy
1666	Rome-Italy	French Academy in Rome
1727	Cortona-Italy	Etrusian Academy
1738	Madrid-Spain	Royal Academy of History
1740	Vatinan	Academy of Profane Antiquities
1752	Madrid-Spain	Royal Academy of Fine Arts of San Fernando
1755	Naples-Italy	Royal Herculane Academy
1768	Lonson-England	Royal Academy of Arts
1779	Lisbon-Portugal	Lisbon Academy of Sciences
1808	Munich-Germany	Royal Academy of Fine Arts
1808	Amsterdam-The Netherlands	Royal Netherlands Academy of Arts and Sciences
1836	Lisbon-Portugal	National Academy of Fine Arts

The dimension stones were not exclusively destined to religious buildings (Figure 10) in this time. The powerful families built great palaces throughout Europe where the building stones acquired a marked decorative character in addition to their structural function. Spanish architect Diego de Sagredo (1490–1528) wrote *Las Medidas del Romano* (*The Roman Measurements*) in 1526, the first book on architecture and building materials printed in Spanish and the first original text published on the subject outside of Italy during the Renaissance. This book was translated into French and published in many countries.



**Figure 10.** (a) Coat of arms of the brotherhood of bricklayers (1497) of the church of Santa María Magdalena, preserved in the Cathedral of Capua, Chapel of the Body of Christ, Diocesan museum (Italy); (b) Cathedral of Segovia (Spain) built in a Gothic style in the mid-16th century; (c) miniature representing the construction of the temple of Jerusalem—Fouquet Jean (1470–75) National Library of Paris (Richelieu).

Andrés de Vandelvira (ca. 1505–1575) was a Spanish architect and stonemason, he read the most famous treatises of his time and has a forerunner of the handkerchief vault and other architectural solutions. His son, Alonso de Vandelvira y Luna (1544–1626), wrote *Tratado de arquitectura sobre el arte de cortar la Piedra* (*Architectural Treatise on the Art of Cutting Stone*) between 1575 and 1591. It synthesized the stonework and constructive knowledge of his family.

The construction of San Lorenzo de El Escorial Royal Monastery (Madrid, Spain) between 1563 and 1584 constituted a milestone in the exploration and evaluation of building stones in Spain [134]. For its ornamentation, Spanish marbles were used and to cut them, a stonecutting workshop was built below the Monastery orchard [153,154]. Felipe II hired Flemish and French experts to locate the slate quarries used on the roof of the monastery. In the same period, “*Opificio delle Pietre Dure*” was an established in Florence (Italy) in 1588. It was a workshop dedicated to the development of the Byzantine technique called “*commesso*”; similar to mosaics, it consists of the inlaying of thin stone plates selected for their colour, opacity, gloss and grain to create elaborate decorative effects like those of the Cappella dei Principi (Chapel of the prince) (1602) in San Lorenzo basilica of Florence.

#### 7.1.1. First “Scientific Investigations”

The French writer and poet François de Belleforest (1530–1583) wrote *Cosmography*, printed in 1575. It describes the figures of Rouffignac Cave (Dordogne, France), being the first reference to rock cave painting. A few years later, the Swiss jurist and art collector Basilius Amerbach (1533–1591) and Andreas Ryff (1550–1603) participated in the archaeological excavations of the Augusta Raurica theater (Switzerland) between 1588 and 1591. The Italian Michele Mercati (1541–1593) wrote *Metalloteca Vaticana*, published in 1719. This book described the stones and fossils of the Vatican museum, indicating that the “lightning stones” or “*cerauni*”, considered to be of celestial origin until that time, could have been manufactured by humans. The Bolognese Ferdinando Cospì (1606–1686) published a full description of the “Cospiano Museum”, a cabinet of curiosities, in five volumes in 1667. The first two described the natural history specimens, and the last three covered the archaeological objects. Although lacking a fully technical and methodological approach, these first studies show a systematic way of proceeding, and therefore, can already be considered “scientific” in analyzing the archaeological sites and heritage stones.

The French Bernard de Jussieu (1699–1777) published *Origin and Uses of the Lightning Stone* in 1723 to defend the human origin of arrowheads, axes and other tools. Seven years later, the also French Nicolas Mahudel (1673–1747), a physician, antiquarian and

numismatist, tried to demonstrate the same to the Academy of Inscriptions and Fine Letters of France, referring to Michele Mercati and comparing tools from one side of the Atlantic Ocean to the other. Nicolas Mahudel also suggested, in 1734, that prehistoric tools changed from being made of stone to being made of bronze and iron.

#### 7.1.2. The “Archaeologist” King

King Carlos VII of Naples (1734–1759), future King Carlos III of Spain (1759–1788) sponsored and closely followed the studies of the Spanish engineer Roque Joaquín de Alcubierre (1702–1780), who began the excavation and exploration of Herculaneum (Italy) in 1738 and of Pompeii (Italy) in 1748. The king created a museum in the Royal Villa of Portici in 1751 and the Regale Accademia Ercolanense in 1755, both in Naples, where specialists in restoration of marbles, bronzes and papyri studied the discovered pieces. The eight volumes of *Le antichità di Ercolano Esposte* (*Herculaneum's Antiquity Exposed*) began to be published in 1753, reproducing engravings of the recovered pieces, as well as plans and designs of the buildings that were coming to light [155]. King Carlos III also sponsored studies on “*verracos*”, zoomorphic sculptures carved in granite around the 5th century BC, phoenician antiquities in Malaga and the Tránsito Synagogue in Toledo (Spain). He commissioned the architect Juan de Villanueva to build the Royal Cabinet of Natural History in Madrid (today Prado museum), founded in 1771 and which would house an important collection of lapidaries from all over the Spanish geography. Carlos III also initiated the first archaeological program carried out in Mexico, the excavation of the city of Palenque [156].

King Carlos III hired Italian experts to continue with the exploration of ornamental stone quarries for the Royal Palace of Madrid (Spain) in 1761. Their reports were scientifically rigorous and included information about stones, such as their color, rarity, prevailing quality, and abundance, as well as the distance of their quarries to Madrid [157]. Carlos III approved the *Instruction for the New Paving and Cleaning of the Streets of Madrid, which Substantially Contains the Don Francisco Sabatini Project*. The Italian architect Francisco Sabatini planned to experimentally pave a central street in Madrid. One half would be paved with flint, a material with which the streets of Madrid had been paved since Arab times, and the other half with granite slabs, in the manner of the basalt slabs used in Naples (Italy). The durability and maintenance cost of both construction materials would be compared with this instruction. This represented the first modern tests of durability and quality of construction materials in Spain.

#### 7.1.3. The “Grand Tour”

The term “*Grand Tour*” appeared written for the first time in 1670, in *Voyage d'Italie* (*Trip to Italy*) by Richard Lassels (ca. 1603–1668). It refers to the scholarly and leisure trip that young aristocrats, mainly British, made through Europe. The scientific advances and growing interest in heritage stones, contributed to including France, Spain and Italy in it. This trip became fashionable among the upper classes of Europe in the second half of the 18th century. The Grand Tour would foster interest in the research on ancient buildings and their stones. The publications of William Bromley, 1702 [158]; Juan Álvarez de Colmenar, 1707 [159]; Francis Carter, 1777 [160]; Richard Twiss, 1775 [161]; Henry Swinburne, 1779 [162]; Maurice Margarot, 1780 [163]; John Talbot Dillon, 1782 [164]; Joseph Townsend, 1791 [165]; Jean-Marie-Jérôme Fleuriot de Langle, 1785 [166]; and George Graydon [167] are some examples of the description of trips made in Spain. Explorers such as the Germans Alexander von Humboldt (1769–1859) and Maximilian Zu Wied-Neuwied (1782–1867) explored America [168]. The reading of historical documents reveals important data on heritage stones and the location of historical quarries. For example, the book *Viaje de España* (*Travel through Spain*) by Antonio Ponz, 1781 [169] facilitated the rediscovery of the historical quarries of the four fountains of the Paseo del Prado of Madrid (Spain) in 2017 [170].

King Gustav III of Sweden (1746–1792) made a trip in 1783–84 to Italy where he purchased classical sculptures that are today in the Gustav III's museum of Antiquities of Sweden. He also visited the stone industry in Florence. Most likely this visit inspired him to support the establishment of porphyry manufacturing operations in Älvdalen (Sweden) with the help of Swedish scientists, such as the naturalist Carolus Linnæus (1707–1778) and the mineralogist Axel Fredrik Cronstedt (1722–1765). A huge grinding house was built in 1796–97, driven by waterpower to facilitate porphyry production [31].

## 7.2. Late Modern Period

The Industrial Revolution marked a milestone in the use of building stones. The invention of the steam engine, in addition to the invention of new scientific instruments [171] at the end of the 18th century, led to a spectacular increase in the construction of factories and generalised the consumption of all kinds of products, services and natural resources. On one hand, this economic boom encouraged the founding of the most important societies and museums (Table 3). On the other hand, improvements in transportation and communication routes made it easier for travellers with cultural concerns and merchandise to travel further and further.

**Table 3.** First main museums.

Year	City-Country	Name Translated into English
1568–1571	Munich-Germany	Antiquarium of Munich Residence
1671	Basel-Switzerland	Amerbach Cabinet
1683	Oxford-England	Ashmolean Museum of Art and Archaeology
1694	Besancon-France	Museum of Fine Arts and Archeology
1727	Saint Petersburg-Russia	The Kunstkammer (Museum of Anthropology and Ethnography)
1734	Rome-Italy	Capitoline Museums
1740	Vatican	Reorganization the Sacred and Profane Museums (Vatican)
1758	Naples-Italy	Herculanense Museum
1759	London-England	British Museum
1763	Madrid-Spain	Antique Cabinet
1764	Saint Petersburg-Russia	State Hermitage Museum
1769	Florence-Italy	Uffizi Gallery
1769–1799	Vatican	Vatican Museums
1773	Charleston-USA	Charleston Museum
1777	Naples-Italy	National Archaeological Museum of Naples
1784	Haarlem-The Netherlands	Teylers Museum
1793	Paris-France	Louvre Museum
1814	Calcutta-India	Calcutta Museum
1819	Madrid-Spain	Prado Museum
1848	Warrington-England	Warrington Museum

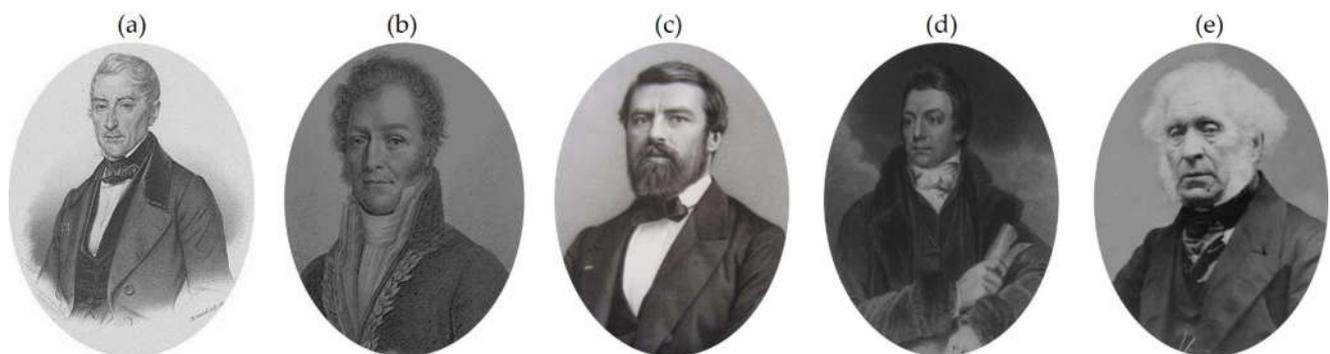
### 7.2.1. Pioneers of Archaeology as a Science

The main precursors of heritage stone research are shown in Figures 11–17. The Englishman Richard Pococke (1704–1765) travelled to Egypt, Palestine, Jerusalem, Baalbek, Syria and Mesopotamia. He wrote and published *A Description of the East and Some other Countries* in 1743 [172]. This author was a forerunner of anthropologists and Egyptologists. Later, the military campaign of Egypt and Syria (1798–1801) carried out by the French general Napoleon Bonaparte (1769–1821) also had scientific purposes and constituted the first systematic exploration of Egypt, discovering the Rosetta Stone in 1799. *Description de l'Égypte (Description of Egypt)* was published between 1809 and 1822, in 24 volumes [173]. The Italians Bernardino Drovetti (1776–1852) and Giovanni Battista Belzoni (1778–1823), together with the English Henry Salt (1780–1827), were the first expedition members to

collect Egyptian antiquities for collectors and museums such as the Louvre museum, the British museum, the Berlin museum, and the Egyptian museum of Turin.



**Figure 11.** (a) Johann Joachim Winckelmann (1717–1768); (b) Jean-Baptiste Rondelet (1743–1829); (c) Bernardino Drovetti (1776–1852); (d) Baron Cuvier (1769–1832); (e) William Smith (1769–1839).



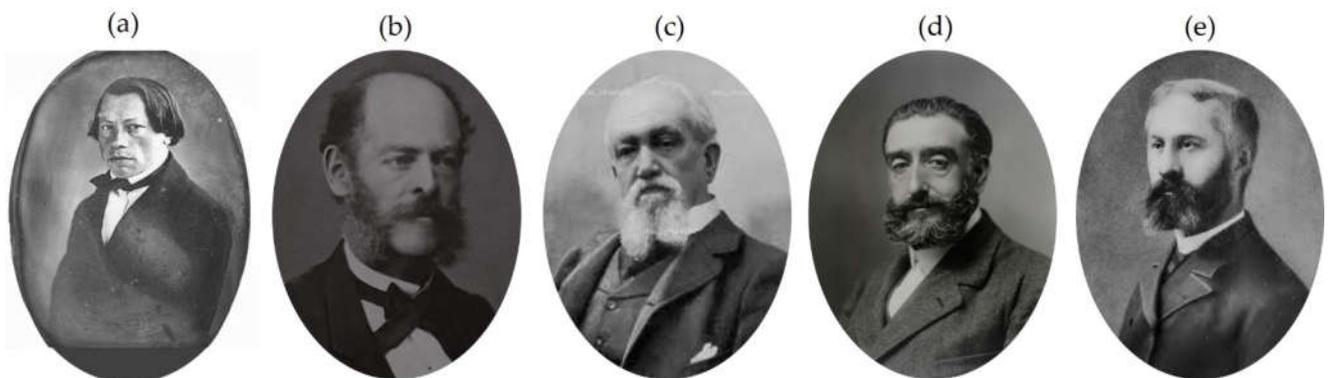
**Figure 12.** (a) Louis-Étienne François Héricart-Ferrand, vicomte de Thury (1776–1854); (b) Louis Jacques Thénard (1777–1857); (c) Giovanni Battista Belzoni (1778–1823); (d) Henry Salt (1780–1827); (e) David Brewster (1781–1868).



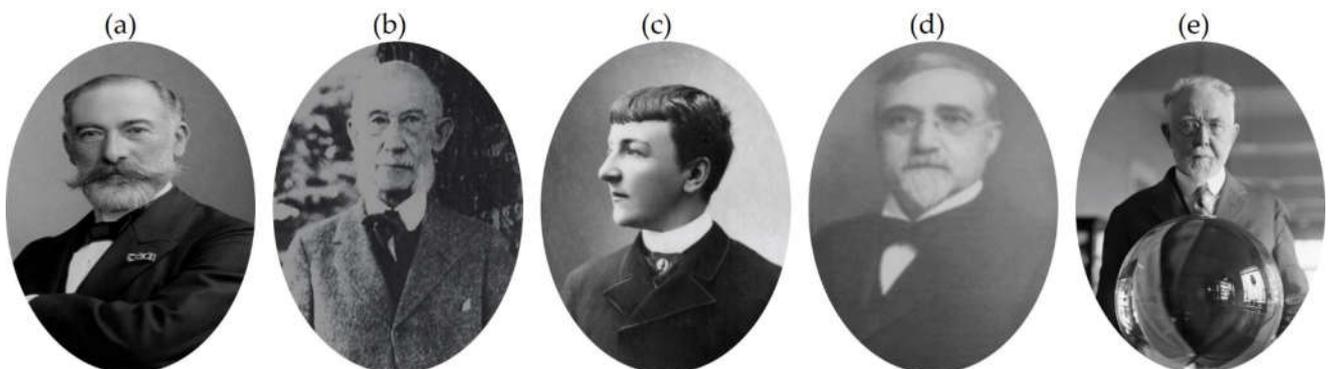
**Figure 13.** (a) Giovanni Battista Amici (1786–1863); (b) Christian Jürgensen Thomsen (1788–1865); (c) Jacques Boucher de Perthes (1788–1868); (d) Johan Gustaf Liljegren (1791–1837); (e) Carl Georg Brunius (1793–1869).



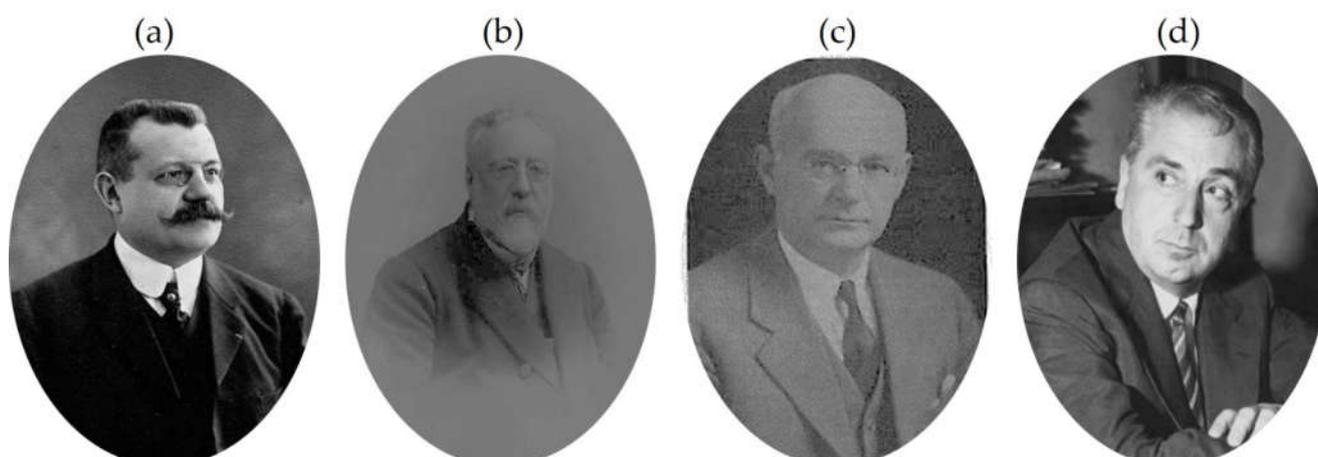
**Figure 14.** (a) John Gardner Wilkinson (1797–1875); (b) Edouard Lartet (1801–1871); (c) Léon Vaudoyer (1803–1872); (d) Henry Christy (1810–1865); (e) David Thomas Ansted (1814–1880).



**Figure 15.** (a) Johannes Menge (1826–1852); (b) Marcelino Sanz de Sautuola (1831–1888); (c) Camilo Boito (1836–1914); (d) José Villa-Amil y Castro (1838–1910); (e) Alexis A. Julien (1840–1919).



**Figure 16.** (a) Julius Hirschwald (1845–1928); (b) T. Nelson Dale (1841–1937); (c) Jane Dieulafoy (1851–1916); (d) Ira Osborn Baker (1853–1925); (e) George Perkins Merrill (1854–1929).



**Figure 17.** (a) Joseph Déchelette (1862–1914); (b) Hernández-Pacheco y Esteban (1872–1965); (c) Gerald Francis Loughlin (1880–1946); (d) Cesare Brandi (1906–1988).

Archaeology was starting to be a science, and the German archaeologist and art historian Johann Joachim Winckelmann (1717–1768), was one of the founders of history of art and archaeology as a modern discipline. He published *Gedanken über die Nachahmung der griechischen Werke in der Malerei und Bildhauerkunst* (*Reflections on the Imitation of Greek Works in Painting and Sculpture*) in 1755 [174]. The Swedish art historian, archaeologist and architect Carl Georg Brunius (1793–1869), together with professor Johan Gustaf Liljegren (1791–1837), wrote the first part of *Nordiska Fornlemningar* (*Nordic Antiquities*) published in 1819 as well as a work on petroglyphs [175]. Brunius later produced the first systematic investigation of medieval art and architecture in current Sweden, writing substantial works on the history of art in Scania and in the island of Gotland.

The Danish archaeologist Christian Jürgensen Thomsen (1788–1865) established the system of the three ages (Stone, Bronze and Iron Age), emphasizing the importance of stones in the development of humanity. His results were published in *Ledetraad til Nordisk Oldkyndighed* (*Guide to Scandinavian Antiquity*) in 1836 [176]. The excavation of a burial mound in 1837 served to corroborate his hypothesis. At the same time, the English Sir John Gardner Wilkinson (1797–1875) published *Manners and Customs of the Ancient Egyptians* in three volumes, an exhaustive study collecting twelve years of works in Egypt and Nubia [177].

The French Louis-Jacques-Mandé Daguerre (1787–1851) patented the daguerreotype (the first photographic machine) in 1839. From then on, photographic cameras were perfected, creating stereoscopic cameras for three-dimensional visualization, widely used to photograph monuments. From this discovery, the evolution of important stone-built monuments has been recorded [178]. The French geologist Jacques Boucher de Perthes (1788–1868) began to write *Antiquités celtiques et antediluviennes* (*Celtic and Antediluvian Antiquities*) in 1847. He was one of the first persons to postulate the existence of the human being during the final stage of the Pleistocene. His work and findings were not ratified until years later by Jean Paul Rigollot in 1855 and Joseph Prestwich in 1859. The Spanish historian José Villa-Amil y Castro (1838–1910) relates geology with archaeological findings in his work entitled *Antigüedades Prehistóricas y Célticas de Galicia* (*Prehistoric and Celtic Antiquities of Galicia*) (1873) [179]. The French archaeologist, novelist, journalist and photographer Jane Dieulafoy (1851–1916), together with her husband, began the first French excavations in Susa (Persia) between 1885 and 1886, and they documented their discoveries with photographs. The French geologist and prehistorian Edouard Lartet (1801–1871) and the English archaeologist Henry Christy (1810–1865) published *Reliquiae Aquitanae. Being Contributions to the Archaeology and Palaeontology of Périgord and the Adjoining Provinces of Southern France* in 1866 [180], a description of the portable art that was known in France at that time. The French archaeologist Joseph Déchelette (1862–1914) was one of the

forerunners of ancient ceramology and published the *Manuel D'archéologie Préhistorique, Celtique et Gallo-Romaine (Handbook of Prehistoric, Celtic and Gallo-Roman Archeology)* in 1908 [181]. The Spanish naturalist and prehistoric Marcelino Sanz de Sautuola (1831–1888) published *Breves apuntes sobre algunos objetos prehistóricos de la provincia de Santander (Brief Notes on Some Prehistoric Objects in the Province of Santander)* (1879), where he described the findings of parietal art in the Altamira cave (Spain) and the Spanish geologist Eduardo Hernández-Pacheco y Esteban (1872–1965) published *The Prehistoric Paintings of Peña Tu (Asturias)* in 1914 [182]. This geologist delved into the study of prehistoric heritage and natural monuments throughout his long career [183–186].

### 7.2.2. Beginnings in Restoration

The restoration of buildings and conservation of heritage stones, as we know today, was also born in the contemporary age. An interest in the restoration of medieval buildings developed in France in the early 1830s. Three main theories of restoration existed. William Morris (1834–1896) argued that restoration damages the buildings. He defined restoration as “stripping from a building”. Anything which looks artistic is worth protecting, so he argued for “Protection” instead of “Restoration”. John Ruskin (1819–1900) argued that it is not possible to restore a building and reach its most beautiful version because the eye of the original workman who built the monument cannot be mimicked. He defended that if the buildings are cared for, they do not need to be restored. He thought that the buildings belong to the person who built them, and restorers do not have the right to intervene. Another important architect was Eugène Viollet-le-Duc (1814–1879). He thought in a different way than the other two and defended restoration. He explains restoration as re-establishing a building in a finished state. Viollet-le-Duc said that the architect can make some additions to the building according to the era that he is restoring. This architect restored the Romanesque abbey of Vézelay, Notre Dame de Paris and various buildings in Mont Saint-Michel, Carcassonne, Roquetaillade and Pierrefonds (France).

The Italian architect Camilo Boito (1836–1914), wrote the first restoration letter at the Third Congress of Italian Engineers and Architects in 1883, and around this time the “*Opificio delle Pietre Dure*” of Florence stopped the production of works of art and began the study of stone restoration. The Italian architect Gustavo Giovannoni (1873–1947) proposed the “Restoration Theory” in 1912. Giovannoni promoted the consolidation and maintenance works using modern techniques. He rejected reconstruction and admitted so-called renovation restorations.

The First World War (1914–1918) caused damage to the towns closest to the battlefields; the use of long-range cannons ruined much of the minor architecture, church towers and supply areas of the armed forces. After the First World War the value of minor architecture was recognized and with it a heritage was identified in cities and villages. Post-war reconstruction practices led to specific interventions, in which the restoration had to be carried out in identical conditions to the original through procedures such as anastylosis. That is, the re-composition of existing but dismembered parts. This principle was very favourable because it restored the image of buildings and towns to the one they had before the war. A new current of thought, exemplified by Gustavo Giovannoni, began to propose that urban settlements contained, like architecture, use and museum values, which led to the inclusion of the concepts of urban heritage and protection of historic city centers during their reconstruction. Gustavo Giovannoni headed the Italian delegation in 1931 at the First International Congress of Architects and Technicians of Historic Monuments in Athens, spreading the doctrines of Camilo Boito, and was met with great reception. The Athens Charter for the Restoration of Historic Monuments was accepted internationally in 1931, and from this time on, a debate was created about how to conduct restorations and what materials to use. The Charter of Athens, as the first international document related to the protection of ancient structures and monuments highlighted the necessity of the production of inventories and cataloguing of goods that enriched the history of Europe. The Italian Restoration Charter was drawn up in 1932 by the Consiglio Superiore per le

Antichità e Belle Arti (Superior Council of Antiquities and Fine Arts), and set limits on reconstructions, recommending conservation work over restoration work.

The Second World War (1939–1945) paralyzed research on building materials, and scientific research was mainly focused on the War [187]. It seriously damaged the European Built Heritage, aerial bombardments destroyed entire cities. The reconstructions were done mainly with natural stone and Portland cement. To obtain natural stone, historical quarries were exploited, and new ones were opened. After the War, UNESCO (United Nations Educational, Scientific and Cultural Organization) was founded in 1945.

The Italian Institute Centrale del Restauro (ICR) was created in 1939. Its first director, the art historian Cesare Brandi (1906–1988), initiated a work methodology like that of the Fogg Art museum Restoration Laboratory in United States of America, beginning to study heritage from a more scientific point of view.

The First Congress of Architects and Specialists of Historic Buildings (Paris, 1957) recommended that the countries lacking a central organisation for the protection of historic buildings provide for the establishment of such an authority. In addition, that all member join the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM), based in Rome.

The Second Congress of Architects and Specialists of Historic Buildings (Venice, 1964) adopted several resolutions, the first one being the International Restoration Charter, better known as the Venice Charter, and the second one, put forward by UNESCO, provided for the creation of the International Council on Monuments and Sites (ICOMOS-ISCS).

Concepts such as “systematic maintenance” were introduced as a fundamental operation for the conservation and “in situ conservation” of excavated remains. It also excluded “a priori, any reconstruction work”, accepted only anastylosis, and urged that the material used for the intervention should be fully recognisable.

The Italian Charter for the Restoration of Historic Monuments or “Carta del Restauro”, signed in 1972 [188] defined the concepts of conservation, restoration, safeguarding and reversibility, as well as giving precise instructions for the custody of heritage. That same year, the UNESCO convention for the protection of world heritage was signed, which defined the kind of natural or cultural sites which can be considered for inscription on the World Heritage List.

The European Charter of Architectural Historical Heritage (Amsterdam Charter) was signed in 1975, which states: “The European architectural heritage consists not only of our most important monuments: it also includes the groups of lesser buildings in our old towns and characteristic villages in their natural or manmade settings” [189].

### 7.2.3. Pioneers in Scientific Research on Building Stones

Regarding the investigation on properties of building materials, the French architects Jean-Baptiste Rondelet (1743–1829) and Léon Vaudoyer (1803–1873) calculated the mechanical resistance and water absorption respectively of the most used building stones in the late 18th and early 19th centuries. David Brewster (1781–1868) was a British scientist and inventor who worked in physical optics, studied the polarisation of light, and discovered Brewster’s angle. Contemporarily, Scottish physicist and geologist William Nicol (1768–1851) developed a method for preparing thin sections for microscopical study in 1815. Nicol also invented the prism that bears his name in 1828. The first fully polarising microscope was built in 1830 by the Italian astronomer and optician Giovanni Battista Amici (1786–1863). These scientific-technological advances were fundamental for the scientific study of construction materials as it is understood nowadays.

The French naturalist Baron Cuvier (1769–1832) published between 1816 and 1845, 61 volumes of the *Dictionnaire des Sciences Naturelles* (*Dictionary of Natural Sciences*) with important contributions to the subject of building materials, such as the description of the making of bricks (Volume II), in addition to other books on geology. The Italian archivist and politician Luigi Bossi Visconti (1758–1835) published *Dizionario Portatile di Geologia, Litologia e Mineralogia* (*Portable Dictionary of Geology, Lithology and Mineralogy*) [190] in

1819, and James Mitchell published *A Dictionary of Chemistry, Mineralogy, and Geology: in Accordance with the Present State of those Sciences* in 1823 [191].

The French mining engineer Louis-Étienne Héricart de Thury (1776–1854) developed frost durability tests in 1828 [192–194], and the French chemist Louis Jacques Thénard (1777–1857) conducted tests of durability on plaster bas-reliefs to study their dissolution.

The English geologist William Smith (1769–1839) was part of a commission to select replacement ashlar in the restoration of the Palace of Westminster in London in 1838 [195] where the durability of the material played a fundamental role in the choice of the stones. Around this time, the English were also exploring their South Pacific colonies. The planners of colonial South Australia appreciated the important potential of building stone resources, as evidenced by the appointment of the German Johannes Menge (1788–1852) as Geologist for the South Australian Company [196].

Portland cement was invented by the English builder Joseph Aspdin (1778–1855) in 1824. This invention, together with the development of the internal combustion engine, electric power and railway lines would revolutionise the trade and export of natural stone in the second half of 19th century [197]. Tests were frequently conducted prior to the opening of new quarries to evaluate the quality of construction stones [198]. The English professor of geology David Thomas Ansted (1814–1880) published *On the Decay and Preservation of Building Materials* in 1860 [199], where he pointed out that all stones are altered or weathered on the topmost part of quarries or near the ground surface and studied the alteration of potassium feldspars.

The German geologist Julius Hirschwald (1845–1928) participated in the commission for the determination of a method for the study of the resistance of rocks against atmospheric phenomena in 1893 and defined a coefficient based on the saturation kinetics of stones for the evaluation of their resistance to frost in 1908 [200]. He also published a guide to laboratory tests of building materials for engineers, architects and stonemasons in 1912. The English geologist John Allen Howe (1876–1959) published *The Geology of Building Stones* in 1910 [201] and *Stones and Quarries* in 1920 [202].

The International Union of Laboratories and Experts in Building Materials, Systems and Structures (RILEM, from its name in French) was created with the aim of promoting scientific cooperation in building materials and structures in 1947.

#### 7.2.4. First Research in the United States of America

The Brownstone industry for the construction of buildings, monuments and stone walls in the United States developed in the 18th and 19th centuries. Brownstone is a brown Triassic-Jurassic sandstone used as building stone. There are five main types: Apostle Island brownstone from Basswood Island (Wisconsin); Hummelstown brownstone from Hummelstown, Pennsylvania. It was very popular along the East Coast of the United States. Delaware, New York, Maryland, Pennsylvania and West Virginia government buildings were faced entirely with this stone; Portland brownstone, from Portland, Connecticut, and nearby localities were used in a number of landmark buildings in Baltimore, Boston, Chicago, New York City, New Haven, Hartford, Philadelphia and Washington D.C.; New Jersey brownstone from the Passaic Formation in northern New Jersey supplied mainly New York City and the state of New Jersey; and South Wales brownstone was commonly used in Southern Wales [203].

The development in building stone research by North American scientists from the late nineteenth to the mid-twentieth century is noteworthy. The selection of the stone for the Lincoln Memorial was entrusted to the American geologist George Perkins Merrill (1854–1929), who published *On the Collection of Maine Building Stones in the United States National Museum* in 1883 [204]. The same author published the book entitled *The Collection of Building and Ornamental Stones in the United States National Museum* in 1889 [205]. He also published *Stones for Building and Decoration* in 1891 [206] and *Principles of Rock Weathering*, an important article on the principles of decay in 1896. In 1897 he published *A treatise on rocks, rock-weathering and soils* [207]. The also American geologist Alexis A.

Julien (1840–1919) wrote *The Durability of Building Stones in New York City and Vicinity* in 1884 [208].

The University of Illinois professor of civil engineering Ira Osborn Baker (1853–1925) published *A Treatise on Masonry Construction* in 1890 [209], where the durability of construction materials figures prominently. The geologist George Wesson Hawes (1848–1882) started a collection of building stones for the National museum in Washington D.C. (now the Smithsonian Institution’s National museum of Natural History), where petrophysical and petrological studies were carried out. Additionally, in the United States of America, the “National Bureau of Standards” (NBS) was founded in 1901, which began the study of building stones in 1912, with the publishing of many scientific articles in “Technological Papers”. The American geologist Gerald Francis Loughlin (1880–1946) wrote his thesis on Boston building stones in 1903 and a year later, together with his colleague William Otis Crosby (1850–1925), they published an article on the subject [210]. That same year, the American geologist, T. Nelson Dale (1841–1937) published an important work on the construction granite of Massachusetts, New Hampshire, and Rhode Island [211] and on New England building granite with studies of quarrying and durability in 1923 [212]. The American geologist Edwin Clarence Eckel (1875–1941) published *Building Stones and Clays* in 1912 [213].

The American Daniel W. Kessler, of the National Bureau of Standards (Figure 18), published a treatise on physical and chemical tests on building materials in 1919 [214]. In 1927, he also published a book on the physical properties of the main commercial limestones used for the construction of buildings in the United States of America [215]. Some of this work culminated in the publication of several American Society for Testing and Materials (ASTM) standards on dimension stones which are still in use today. Mr. Kessler was honored by ASTM in 1950 with the ASTM Award of Merit. His compatriot, the American geologist Stephen Taber published works on the mechanisms of ice crystallization in stones in 1929 and 1930 [216,217], and the American Robert John Schaffer published *Weathering of Natural Building Stones* in 1932 [218].



Figure 18. Daniel W. Kessler, 1925. National Bureau of Standards (USA).

## 8. Recent Works

Erhard M. Winkler (1921–2005), professor of University of Notre Dame (Indiana, USA) wrote in 1973 *Stone. Properties, Durability in Man’s Environment*, and *Stone in Architecture Properties, Durability* in 1997, among other publications [219–222]. In addition, Joseth T. Hannibal published many books on the subject about building stones from the 1980s onwards [223,224] and Doehne and Price [225] published a magnificent compilation of articles on stone conservation in 2010. The past few decades has seen an unprecedented level of research activity in this area, the results of which are summarized in the latest edition of *Stone in Architecture Properties, Durability* by Siegfried Siegesmund and Rolf

Sneathlage [226]. It is a currently reference book in this field and it is a revision of the first editions by Erhard M. Winkler.

In this time, there is a growing interest in the investigation of deterioration and conservation of building stones [227–234]. The development of analytical techniques allows scientists to quickly obtain increasingly reliable results and non-destructive and portable diagnostic techniques have improved considerably and play an important role in the conservation of built heritage [235–237]. However, we scientists must not forget that each heritage stone is a remains of the past, unique and unrepeatable. The traditional techniques and the conditions in which the heritage stones have been extracted from the historical quarry, carved and placed in the monument are key to understanding its deterioration and conservation. The challenges of heritage stone research in the 21st century are: climate change mitigation, monitoring, remote sensing [238–241], adaptation [242], restoring after conflicts, disasters, or pandemics, the achievement of sustainable development goals [243–249], and most importantly, the preservation of a legacy for the future.

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