Evolution in the use of natural building stone in Madrid, Spain

Rafael Fort 1
Monica Alvarez de Buergo 1
Elena M. Perez-Monserrat 1
Miguel Gomez-Heras 1
M. Jose Varas-Muriel 1, 2
David M. Freire 1

1 Instituto de Geociencias IGEO (CSIC-UCM) / Geoscience Institute IGEO (CSIC-UCM). Spanish Research Council CSIC – Complutense University of Madrid UCM Madrid, Spain
2 Facultad de Ciencias Geológicas / School of Geology, Complutense University of Madrid, UCM, Madrid, Spain

Abstract

Throughout history, different types of stone have been used in construction in Madrid, depending on the proximity and accessibility of the geological resources, the ease with which they could be quarried and carried to the city, cut and hewn. More recently, quality and durability have also weighed heavily in the selection.

Flint, Madrid's first natural building stone, was used from the ninth to the twelfth centuries. It was subsequently replaced by *Redueña* dolostone (which had been used from earlier dates in areas closer to the quarries), preferred for its colour, workability and availability and because it could be readily quarried. Redueña stone was predominant until the seventeenth century. At the same time, granitic materials from the Central System (Guadarrama Mountain Range) in the northern-most area of the province of Madrid began to be intensively used. This material, traditionally known as *Berroqueña* stone, has been used in Madrid´s built heritage ever since. While quarried in a number of areas, until the seventeenth century the primary point of supply was Zarzalejo (western region of the Guadarrama Mountain Range). Beginning in the eighteenth century, the granite used was mainly quarried in the Alpedrete area (central Guadarrama). Eighteenth century advances in underground quarrying made it possible to extract a limestone (*Colmenar* stone) located in the southeastern part of the province. Together with granite, this white, low porosity, high-strength material became one of Madrid's traditional building stones. Both, highly esteemed for their excellent petrophysical properties, are still used today as building and ornamental stones.

Further to the petrographic and petrophysical properties of the rock used for construction in Madrid, Alpedrete granite is more durable than the Zarzalejo variety, the dolostone from Torrelaguna is better than the Redueña material and the limestones from the Colmenar de Oreja quarries, flint, and Bernardos slate are all characterised by low alterability.

Keywords: traditional building stones, flint, granite, limestone, dolostone, durability

1. Introduction

The use of stone is deeply rooted in Spanish building culture. The Iberian Peninsula has a wide variety of high quality rocks, including granite, limestone, sandstone, marble and slate, well suited to use in construction. In Antiquity, the use of stone to build civil, military and religious structures was determined by the accessibility of the material and stone workability with the technology in place in each age. Consequently, in ancient times the use of stone on the Iberian Peninsula was an eminently local endeavour, in light of the high cost and enormous difficulty involved in transporting huge blocks over long distances. Such difficulties were aggravated by geographic peculiarities, for in addition to being one of the most mountainous regions of Europe, the peninsula has a paucity of navigable rivers. As a result, many of its cities were built with only one type of locally quarried stone, and the lithological variety of their monuments depends on nearby outcrops. The location of urban centres may have even been chosen on the grounds of the proximity and availability of construction materials, as well as of natural resources requisite to survival, such as water.

Stone lends personality to the built heritage and stone type is often associated with a particular place (Gomez-Heras et al. 2010). Traditional building stone may be defined as the rocks continuously and commonly used throughout the history of a given town or region.

Prior to the Industrial Revolution and the rise of "technocratic" criteria for stone selection such as petrophysical properties and durability, the aesthetic features of stone, primarily colour, were more highly valued (Gomez-Heras & Fort Gonzalez 2004; Gomez-Heras et al. 2010). That criterion tended to vary over time with fashion or builders' and architects' tastes. Traditional stone defines cities' colour and texture, shaping their aesthetic portrayal and perception.

The use of stone in cities may, therefore, vary due to changes in aesthetic values, improvements in quarrying techniques and workability (carving) or progress in inland connections and vehicles, as well as to a fuller understanding of material performance and decay, inducing the rejection in later periods of formerly popular but low durability materials (Dreesen & Dusar 2004).

2. Madrid's geological surrounds

The geology in the centre of the Iberian Peninsula is particularly rich in natural stone for use in monumental works, for it comprises a wide variety of rocks whose petrophysical properties are very well suited to construction. The geology of the Community (or region) of Madrid is depicted in Figure 1. Two main groups of materials can be distinguished: the igneous and metamorphic rocks found in the Guadarrama Mountain Range (Central System, Variscan Orogeny) in the north and northwest, which provides the widest variety of ornamental stone lithologies (granite, slate and porphyry), and the Cretaceous and Miocene sedimentary rocks in the north and southeast, respectively, where flint, dolostone and limestone outcrop (Menduiña & Fort 2005). The stratigraphic series in the Madrid Basin is summarised in Figure 2, which shows only the sedimentary units from which stone was extracted to build the city.

2.1. Central System domain

This domain furnishes the widest variety of ornamental lithologies. The stone most commonly used in Madrid is *Berroqueña stone*, consisting of granite whose petrographic and petrophysical properties vary depending on the pluton where it is quarried (Villaseca et al. 1998, 2009). One of the three main plutonic groups (Figure 1) contains cordierite, the second amphibole and the third neither of these two minerals. These comprise several intrusive units which in turn host leucogranites with a fine- to medium-grain phaneritic texture.

The granites found in Madrid are from the plutons closest to the city. The monzogranites containing cordierite, for instance, which are biotitic (nearly 10 % biotite) and have an equigranular texture (1-3-mm crystals), outcrop primarily in Alpedrete, Torrelodones-Galapagar and Colmenar Viejo, towns in the north of the province of Madrid. The Cardin-Hoyo de Manzanares pluton yields the stone with the highest proportion of porphyric facies (Figure 1). The second type of granite traditionally used in Madrid is the variety with no cordierite or amphibole. Likewise a biotitic monzogranite, it has a medium-coarse grain (2-5 mm) phaneritic texture and nearly 15 % biotite arranged in 4-10-mm nodular clusters. As in the cordierite-bearing variety of granite, this stone also has porphyric facies. These biotitic monzogranites, located in the western branch of the Guadarrama Range, from Collado-Villalba to Navas del Rey, were used to build the Royal Monastery at El Escorial in the sixteenth century. These two biotitic granites, with and without cordierite, were the ones most commonly used in the early history of construction in Madrid, due to their proximity to the city.

The third group, or amphibole-containing granites, was not used in construction until much later because of its more distant location, in the southwest region of the Guadarrama Mountains near Cadalso de los Vidrios and in the north around La Cabrera.

In addition to granite, porphyric rock was also used in Madrid's buildings. Quarried from the dikes found in the Colmenar Viejo granites, these are dark rocks with a micro- to cryptocrystalline structure, with a dioritic to granodioritic and quartz dioritic to quartz monzonitic composition (Doblas et al. 1988). These materials were dimensioned for use as cobblestones to pave the city streets.

Slate was used to roof only the most emblematic buildings in Madrid. It was brought in from the Bernardos quarries in the province of Segovia, located in the Schist-Greywacke Complex, which dates from the Precambrian/Lower Cambrian period in the Central Iberian zone of the peninsula (Alonso et al. 2005). The monastery at El Escorial and other Madrilenian buildings were roofed with slate to emulate the central European construction styles and techniques introduced by the Habsburg dynasty. Bernardos slate is black and smooth, with a grain size ranging from 70 to 55 µm. Its components are quartz and plagioclase, along with biotite, muscovite, chlorite and clinochlore. Apatite, tourmaline, zircon and rutile are found as accessory minerals. Other types of slate outcrop in northwestern Madrid, where they were used in local construction. Their much lower quality than the Bernardos stone explains their absence in the capital city.

2.2. Cretaceous limestone

Cretaceous materials outcrop in the north-northeast part of the province, arching from Cerceda to Redueña, and running through San Agustín de Guadalix to Valdemorillo. The base comprises detrital deposits, discordant with and overlying granite or metamorphic Palaeozoic materials; these deposits are in turn overlain by dolostones and limestones, both widely used in regional construction. The initial reddish dolostone in the carbonatic sequence gives way to a whitish-ochre dolomitic unit known as chequered *Caballar* dolostone, which is abundant in the Guadalix de la Sierra-Venturada-Redueña area. Resting on the Caballar material is an erosive discordant limestone and dolostone formation denominated *Castrojimeno*. This formation consists of massive white and grey dolostone with a predominance of rudistid and stromatolite bioconstructions. Very abundant around Torrelaguna, it stretches into the Tamajón area in the province of Guadalajara. It has been dated between the late Coniacian and the Santonian (Upper Cretaceous; Alonso, 1981).

2.3 Madrid Basin

The substrate on which the southeast area of the region of Madrid rests concurs largely with what is known as the Madrid Tertiary Basin, which has three units. The lower unit comprises primarily evaporitic and clayey facies, which transition into more detrital facies along the edge of the basin. The intermediate unit has a wide variety of facies with a prominence of lacustrine carbonatic, mostly dolomitic, rocks with a diagenesis characterised by de-dolomitisation. This unit also hosts silicified limestones and dolostones containing sepiolite and flint (Calvo et al., 1984, 1989; Wright & Alonso, 1990) that were used in Madrid's built heritage. Flint was intensely quarried around Madrid, although only one historic quarry, at Cerro de la Mesa, still exists. The rock that hosts flint is a micritic limestone. Silicification initially gave rise to opal, which diagenetic weathering subsequently transformed into quartz (Bustillo et al., 2012). The highest quality flint has a mosaic-like texture with crypto- to microcrystalline quartz ranging from 20 to 30 μm in size; the absence of opal affords the flint greater stability and strength. The upper unit, pinkish-white lacustrine and fluvial-lacustrine limestones, is be found in different banks with thicknesses of up to 40 m. The materials most representative of Madrilenian construction were extracted from this upper unit in underground quarries at Colmenar de Oreja, in the southeast area of the basin. Of the eight banks in this quarry, the so-called *Banco Gordo* ("thick bank") yields the highest quality stone, which was the material most commonly used in Madrid (Dapena et al. 1989). These limestones, petrographically classified as biomicrite/biosparite, consist of a bioclast skeleton (40 % characeae, ostracods and gastropods) and a paste in which the micritic matrix (20-30 %) alternates with sparitic cement (30-40 %). The same limestones quarried in other areas exhibit similar properties, but are composed primarily of more porous oncolitic materials or more edaphic stone deposited over the oncolites and exhibiting significant bioturbation. In the south and east areas of the basin, they underlie a thin complex of fluvial Pliocene sediments which in some places contain oncolites, stromatolites, tufaceous limestone, lacustrine sediments and calcretes (Ordóñez et al. 1984; Sanz 1996, García del Cura et al. 1994).

3. Traditional stone used in Madrid and its origins

Ground resources were exploited in Madrid from the outset. The earliest stone works in the region of Madrid were the products of the flint industry. These tools have been found in a number of lower Palaeolithic (1 000 000 - 125 000 years ago) digs, located on river banks. Their crafters used the quartzite and flint pebbles outcropping in alluvial deposits or their terraces as prime materials.

The use of stone for construction did not begin in the region of Madrid until the Iron Age, when the Celtiberians erected the first fortified, mainly adobe, acropolis whose plinths were made of stone.

Its first use in the city of Madrid can be traced back to a Muslim enclave built as an outpost to defend the city of Toledo. It had a walled fortress built around the year 852 for that purpose. The complex was constructed with flint rubble stone and rough ashlars from the intermediate unit of Madrid's Tertiary Basin (dolostone and flint). When the Christians led by King Alphonse VI conquered this enclave in 1085, they built another outer wall and more buildings with Upper Cretaceous carbonatic rocks and granite from the mountains in the region, in addition to flint. It was not until 1561, however, when Philip II moved his court to the city, that Madrid was to undergo intensive construction, with the erection of new palaces, churches and monasteries. This was the period when *Berroqueña* stone from the granite plutons in the southwest end of the Guadarrama Mountain Range (northwest-west area of the province) was introduced. These were the same plutons that supplied the stone used to build the Royal Monastery at El Escorial (1563-1584). Those works led to a change in taste, favoured by the existence of roadways connecting Madrid and El Escorial, in which brick, flint and even Cretaceous limestone gave way to the granite used in the monastery.

The eighteenth century brought a second revolution in the use of stone in Madrid, led by the Bourbon dynasty. The construction of the Royal Palace, with its combination of *Berroqueña* stone from northern Madrid and Tertiary limestone (*Colmenar* stone), both still in use today, defined new styles and usage. The city was not to see construction on that scale until 1830, after the Napoleonic invasion. That was the year when public works were undertaken to build the region's water utility (Isabel II Canal) with granite and porphyry brought in from the Alpedrete - Colmenar Viejo area. Cretaceous lime- and dolostone were used to build most of the canal.

In the nineteenth century, the use of natural stone in Madrilenian monuments underwent yet another major change, driven in this case by the commissioning of the first railway line (Madrid-Aranjuez, 1851). Its subsequent expansion across the entire peninsula lowered shipping costs in many cases, favouring the arrival of new types of stone whose use in Madrid had formerly been very sporadic or non-existent. Stone thus began to be shipped in from anywhere in the country that was connected by rail to the capital city. Material could even be imported from Portugal and other countries with good connections via sea ports such as at Santander, or railway networks (Figure 3).

4. Intra-regional routes for natural stone in Madrid

As noted earlier, the use of stone depended, among others, on the availability of nearby quarries as well as the existence of good inland connections and the capacity of contemporary vehicles, for those resources determined the capacity, size and amount of blocks that could be transported.

Spain's earliest inland connections were the roads built by the Romans. Two ran very close to Madrid: one connected Emeritaugusta (today's Mérida) and Cesaraugusta (now Zaragoza) and intermediate cities such as Complutum (now Alcalá de Henares) and connected into the road from Toledo to Segovia. Madrid was also fairly near to secondary roads, such as the Mantua Carpetana, which connected Complutum, in the northeastern part of the region, to its southern-most corner (Alonso Otero, 1988) (Figure 4).

Some of these roads were still in use during the Muslim era, such as the one running from the Somosierra mountain pass (northern route into the region) to Talamanca de Jarama (northeast). While this road was heavily travelled, its poor state of repair was an obstacle to its use for carrying stone from the Cretaceous quarries it crossed. As a result, one of Madrid's first building stones was flint, which outcropped on hills located within the city. That would explain its use to erect the Arab walls, which were among the earliest urban structures. Flint met two important requirements: it was sturdy and durable, which was particularly important for defensive structures, and its lens-type deposits made it fairly easy to quarry. Moreover, its proximity to worksites facilitated and expedited construction, reducing transport risks, an issue of prime importance in an area at war. Flint continued to be used until the twelfth century when the city's second wall was built. Later it was applied primarily as rubblestone. Whether newly quarried or taken from earlier structures such as the Arab walls, which were largely demolished in the sixteenth century, flint was also used as a filler and in building foundations.

Madrilenian desistance in the use of this very hard rock was very likely due more to the hewing and carving difficulties involved than to its suitability and availability as a construction stone. Moreover, with the relative peace that came with the consolidation of Christian rule after the twelfth century, roads became safer. More readily hewn and carved materials such as Cretaceous lime- and dolostone could therefore be brought in from the north and northeast part of the region (*Redueña* stone) over the old Roman road (Figure 4). Granite also began to be carried to the city from the mountains. The main material brought to the city in the sixteenth century was *Berroqueña* stone, in particular the medium-coarse-grained monzogranite quarried at El Escorial-Zarzalejo and used as well to build the El Escorial Monastery. The sixteenth-century relocation of the capital city in Madrid concurred with the completion of the monastery. As a result, many of the stonemasons moved to the city, where they used the material they were familiar with, the granite from the aforementioned quarries (which happened to be owned by the king). This stone was carried to Madrid over a road that ran through Valdemorillo, making the quarries in that area equally accessible (Figure 4). Berroqueña stone was used extensively in Madrid in the sixteenth and seventeenth centuries, until it was gradually replaced by the monzogranites from Alpedrete, Galapagar and surrounds, whose quarries were closer to the city. This was the stone used in many of the emblematic buildings erected during Charles III's eighteenth century reign, the Royal Palace in particular, built with granite from Alpedrete, Becerril de la Sierra, Collado Villalba, Moralzarzal and Galapagar.

Redueña stone (Cretaceous lime- and dolostone) had been used in Madrid until that time. Very few Cretaceous limestone structures, or their remains, are to be found in Madrid today, possibly due to the nineteenth century demolition of many of those buildings in the wake of the confiscation of church property or urban expansion plans for the city. Continuous use of this stone came to an end in the eighteenth century when Tertiary limestone called *Colmenar* stone was introduced in Madrid. Consolidation of this latter material was favoured by its higher quality and the growing need for large volumes of stone to build the Royal Palace, the bridge over the River Tagus (Barcas Bridge) and somewhat later the Long Bridge at Aranjuez. Colmenar stone was re-launched with the construction of the first railway in the region of Madrid (1851) to connect the capital city to Aranjuez and subsequently to Alicante on the Mediterranean Sea (Figure 3). This favoured the arrival in the city of Madrid and its entire province of new and more economically competitive materials such as *Novelda* stone (Fort et al. 2002). In 1865, this railway line was extended to Zaragoza in northeastern Spain, by way of Guadalajara. With the expansion of the railroad to

Portugal in 1880, stone from that country could also be economically shipped to Madrid (Gómez Heras and Fort 2004).

5. Stone durability

According to Bell (1993) the durability of a building stone is a measure of its ability to resist weathering and so retain its original size, shape, strength and appearance over an extensive period of time.

Built heritage materials resist decay differently. The specific resistance characteristic of each type of stone is determined by its petrophysical properties. The pursuit of building durability in the past was often the reason for choosing stone as the main construction material. In the first century BCE, Vitruvius noted in his treatises on architecture that good stone buildings must be handsome, functional, sound and long-lasting (Oliver Domingo, 1997), but substantial progress in understanding decay only came in the nineteenth century, when experts observed that not all rocks behaved in the same way when exposed to a given agent (Jiménez González 2008). For that reason, and due to the increase in inter-regional stone trade and shipping, durability began to be the object of laboratory trials (Gómez-Heras and Fort, 2003). Rock performance against the agents of decay and the agents most commonly found at any given site had to be determined to estimate the most suitable type of stone for that site.

Physical alterations such as cracking and loss of strength or material are due to stress generated inside the rock (Calleja & Montoto, 1982; Tsui et al., 2003; Sousa et al., 2005). Such stress may arise in response to the action of water or ice, soluble salts that may crystallise and rehydrate inside the rock, temperature changes (Pérez-Ortiz et al., 1994; Alves & Sequeira Braga, 1996; Vicente, 1996; Moreno et al., 2006; Vázquez-Menéndez et al., 2008, Gómez-Heras et al. 2006) or the pressure exerted by the weight of construction materials themselves.

Petrographic characteristics provide very valuable information on the quality and hence the durability of rocks. Coarsely textured, highly laminated rocks with soft minerals such as clay are more susceptible to decay (Veniale et al. 2001, Delgado 2001, Török & Vásárhelyi 2010, López Arce et al. 2010).

Petrophysical properties also furnish information on material durability. Porosity, hydraulic behaviour and mechanical strength determine the suitability of a rock for construction, for these properties condition its durability against external agents. The number of pores or cracks and pore size distribution are parameters needed to assess rocks (Haynes, 1973; Montoto, 1983; Alonso et al., 1987; Esbert et al., 1997).

Rock porosity favours the ingress of agents such as water, salt solutions and pollutants that induce decay. Moreover, the mobility of these agents inside the stone depends on pore size distribution, morphology and tortuosity (interconnectivity). One of the oldest parameters used is the saturation coefficient (Hirschvald, 1908), although others such as capillary porosity and microporosity (pores with a diameter of under 5 µm, Russell 1927) were introduced later. Microporous rocks or rocks with high capillary porosity are more susceptible to salt crystallisation- and frost-induced decay (Benavente et al., 2004; Ordóñez et al., 1997; Punuru et al., 1990; Richardson, 1991; Rossi-Manaresi & Tucci, 1989). Furthermore, insofar as it constitutes gaps in the solid phase of the rock, creating weak areas, porosity has an obvious impact on mechanical properties.

The degree of anisotropy is another factor that may expedite material decay, for it often favours water ingress through slip planes (structural, textural or mineralogical orientations), generating differential decay (Fort et al., 2011).

Durability of traditional Madrid stone

While the granites traditionally used in Madrilenian construction (*Berroqueña* stone) are mineralogically similar, the variation in their respective quartz, feldspar and mica contents largely condition their durability. Feldspars and micas are significantly altered by the action of fluids and concomitant hydrolysis. Potassium feldspar is replaced with kaolinite, plagioclases are converted to sericite and biotite to chlorite. Hydrolysis may also release iron from biotite, occasioning widespread oxidation of its nodular clusters, especially in the granites that outcrop in the northwestern part of the province (which have a 15 % biotite content). Cordierite alteration, in turn, yields pinite or micaceous clusters that decay more quickly, although cordierite is scantly present in these granites.

Although these processes are often the result of hydrothermal change or surface weathering prior to quarrying, they condition the mineral response once the stone is laid. Texturally speaking, the granites from the provincial northwest, which have a larger crystal size (2-5 mm), are more susceptible to decay than the stone from the northern part of the province, characterised by smaller crystals (1-3 mm). Both types of monzogranites have porphyritic facies that tend to be more readily altered than the so-called uniform facies.

The higher biotite content in the northwestern granites favours salt crystallisation-induced decay, for the salts crystallise between the biotite layers (López-Arce et al. 2010). The occurrence of microgranular enclaves in these granites may also expedite weathering due to differential thermal behaviour associated with non-uniformities, in conjunction with other factors (Gómez-Heras et al., 2008).

Table 1 gives the main petrophysical properties for traditional Madrilenian stone. According to these data, Alpedrete stone should be the most durable, in light of its lower porosity accessible to water (0.8±0.1 %), high ultrasound velocity (≈4600±200 m/s) and lower anisotropy indices (ΔdM: 5.8 %, Δdm: 1.9 %, where the indices are: dM% = [1-(2Vpmin / (Vpmed + Vmax))]·100 and dm% = (Vpmed + Vmax) / (Vpmed + Vmax)]·100, according to Guydader & Denis (1986). This yields capillary absorption coefficients of 1.5 to 3.9 $g \cdot m^{-2} \cdot s^{-0.5}$ (Fort et al, 2011), compared to the values for Zarzalejo granite, which range from 4.2 to 4.8 $g \cdot m^{-2} \cdot s^{-0.5}$. These findings concur with the pore size distribution values in the two granites, which show that porosity is lower (0.5 %) in the Alpedrete stone, but especially that it has a very clear mode (18 % of the porosity in the 0.1-0.4 µm range). (See Figure 5 for the pore size distributions of the rocks studied.) In the Zarzalejo material, with a pore volume of 1.6 %, the 2-µm mode accounted for 11 % of the distribution, facilitating capillary water absorption. Lastly, salt crystallisation decay is favoured in Zarzalejo granite by its higher percentage of biotite (López-Arce et al. 2010).

The Cretaceous dolostones (*Redueña* stone) exhibit different degrees of de-dolomitisation, with the Redueña stone being more readily altered than the Torrelaguna materials, which have smaller crystals and a greater degree of cementation (lower porosity) (Fort el al. 2008). The Miocene limestone (*Colmenar* stone) has a more uniform mineralogical composition, consisting of automorphic calcite microcrystals (micrite) and characeae, gastropod and ostracod bioclasts (10-20 %) (Wright et al. 1997, Volery et al. 2010). Further to the Folk classification (1959,1962), this is a bioclastic micrite.

The most durable of these carbonatic rocks is Colmenar limestone, given its petrophysical parameter values. Its compactness as defined by ultrasound velocity (Vp), at 5900±100 m/s, is higher than in Redueña stone. Its anisotropy is a very low 4.24 % for ΔdM+Δdm (sum of total and relative anisotropy). Its porosity accessible to water is also low: 4±1 %.

Since most of its pore size distribution lies in the 0.1-0.01 μm range (Figure 5), capillary water absorption does not pose a significant problem.

Of the two dolostones analysed, the Torrelaguna variety is more durable than the Redueña material, according to the petrophysical parameters analysed. Torrelaguna dolostone has higher ultrasound velocity (3800±300 m/s) than the Redueña material (2800±300 m/s) and lower porosity accessible to water (6.2 compared to 10±1 %) and to mercury (7.6 compared to 17.9 %) (Table 1). While the pore size distribution is unimodal in both stones, in the Torrelaguna material 50 % of the pores lie in 1-2 μm range, whereas only 25 % of the pores are found in the 1-6 μm range in the Redueña variety. Fort et al. (2011) report a very high capillary absorption coefficient for Redueña stone (86-89 $g \cdot m^{-2} \cdot s^{-0.5}$), while the values for the Torrelaguna material lie between 8 and 52 $g \cdot m^{-2} \cdot s^{-0.5}$, depending on whether absorption is parallel or perpendicular to the anisotropic direction of the rock. These properties explain why decay due to salt solution-induced salt crystallisation is more intense in Redueña dolostone (Fort et al. 2008).

Bernardos slate is texturally very smooth, although with slight differences in its particle size distribution associated with its mineralogical composition (70-55 μm quartz and phyllosilicates <65 μm). Quartz and some plagioclase (albite) appear in clusters and 0.5-1-mm thick bands adjacent to the phyllosilicates. Phyllosilicates, and more specifically biotite, muscovite, chlorite and clinochlore, constitute the predominant mineralogy. Apatite, turmaline, zircon and rutile are accessory minerals. This stone also exhibits quite acceptable and suitable petrophysical parameters, with a very high ultrasound velocity at 5.694±183 m/s, similar to Colmenar stone and flint), and an especially low porosity accessible to water, 0.4±0.1 %. Even its capillary water absorption parallel to the slip plane is a reasonable 0.17-0.28 $m^{-2}\ s^{-0.5}$, despite its anisotropy index, which is high (ΔdM=33.3 %), as expected. Its pore size distribution is unimodal in the 100-300 μm range, affording the stone high resistance to frost and salt crystallisation.

Conclusions

The choice of traditional stone for construction in Madrid and its variations over time have been conditioned by availability, proximity, ease of quarrying, workability, contemporary taste, inland connections and transport vehicles, along with the properties of the materials themselves that determine their alterability/durability. These materials can be summarised as follows.

Flint was used primarily in early construction for its high strength, which made it apt for building the (ninth century) city walls, and its proximity, as it was quarried from the hills located within the city itself (Madrid´s Tertiary Basin)**.** Its excellent durability is attested to by its performance as a construction material for over 11 centuries. Its hardness and concomitant scant workability led to its replacement with other materials beginning in the twelfth century.

Granite (*Berroqueña* stone) from the Guadarrama Mountain Range (Spanish Central System), still in use today in conjunction with flint and Upper Cretaceous carbonatic rocks, was first quarried in the eleventh century and became especially popular in the sixteenth. Monzogranites were quarried for building from two plutons in the sixteenth and seventeenth centuries, and for reasons of inertia after the El Escorial Monastery was completed, medium-coarse grain (2-5 mm) biotitic (15 %) monzogranite from Zarzalejo was used in the city of Madrid. It was subsequently replaced by cordierite-containing biotitic monzogranite from Alpedrete, located closer to the city. This has proven to be most durable construction granite, thanks primarily to its smaller crystal size and lower biotite content. Low capillary water absorption and scant anisotropy determine even greater resistance to decay.

Cretaceous carbonatic rocks *(Redueña* stone) were also first used in the city beginning in the eleventh century, largely to replace flint due to its ease of quarrying, hewing and sizing, particularly after transport grew safer as the risks associated with war declined. Redueña stone was used through the eighteenth century, when it was replaced by *Colmenar* stone. Of the dolostones studied, Torrelaguna is more durable than Redueña stone, as a result of its smaller crystals and greater degree of cementation. This stone also absorbs less capillary water, due essentially to its greater compactness, lower porosity and especially its pore size distribution. Despite the widespread use of Cretaceous limestone, however, barely any of the buildings made of this material are to be found in Madrid today.

Miocene limestone (*Colmenar* stone) started to be used in the capital city in the eighteenth century, primarily to build the Royal Palace, in the wake of improvements in inland connections and quarrying technology. The combination of this limestone and *Berroqueña* stone(together with brick) was to become a characteristic feature of Madrilenian architecture. The high ultrasound velocity of Colmenar stone, an indication of its compactness and low porosity, attests to its high quality and durability. Most of its pores lie in the 0.1-0.01 µm range.

Slate: although some slate outcrops can be found in the province of Madrid, *Bernardos* stone from the nearby province of Segovia was the material of choice for roofing emblematic buildings in the capital city after it had been successfully used in the El Escorial Monastery. It owed its high quality to its uniformity, petrographic and textural characteristics, and very low water absorption, even through its slip planes. Despite its quality and durability, its use was interrupted after the nineteenth century, mainly because of high shipping costs and new architectural tendencies.

With the opening of Spain's first railway in the nineteenth century, new construction stone began to be brought in from other regions of Spain as well as other countries, a practice that has grown steadily ever since. The petrophysical properties that characterise such materials, which are very different from the traditional stone, determine their medium- and long-term durability and resistance to decay, which are often unknown.

Traditional stone must be used cautiously in restoration work, especially where quarried from the original sites, for building stone is a non-renewable resource. An understanding of such stone and how and where it was quarried, transported and traded constitutes a valuable heritage and historical resource that may be used to design more sustainable building strategies for the future.

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Figure Captions

Figure 1. Schematic geology of the Madrid´ region

Figure 2. Schematic stratigraphic column of Madrid basin units, showing only those from which stone was extracted to build the city

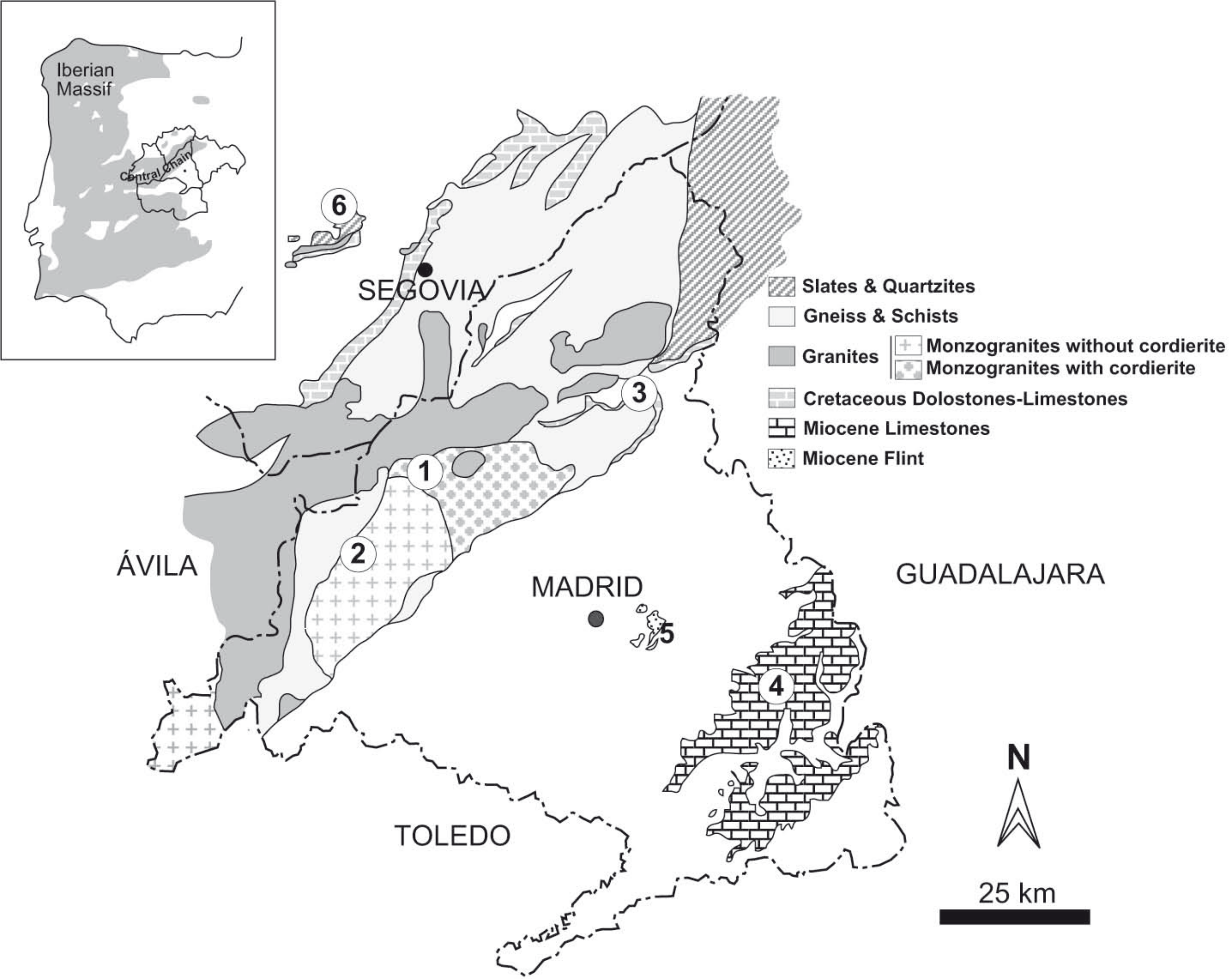
Figure 3. Railway network evolution during the second half of the 19th century

Figure 4. Historical roads in the region of Madrid

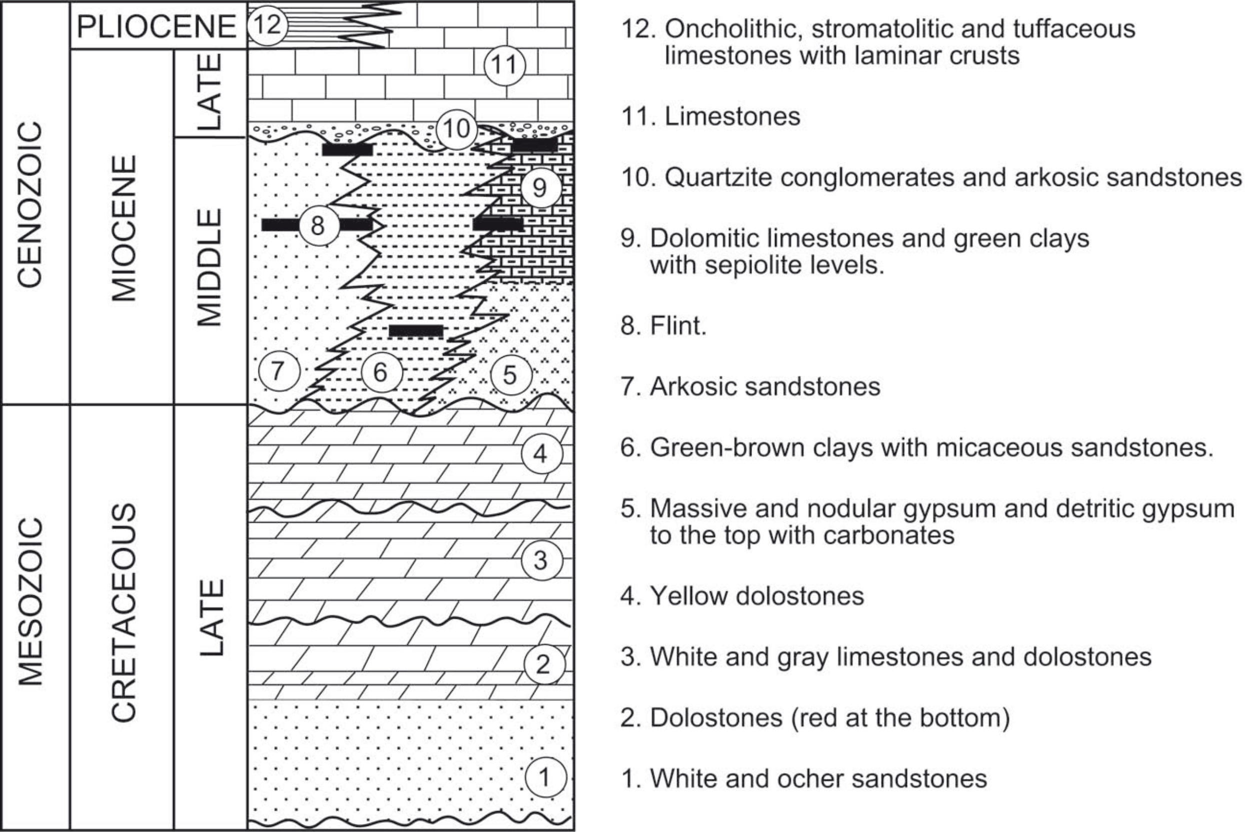
Figure 5. Pore size distribution curves of the different traditional building materials of Madrid

Table 1. Petrophysical properties for traditional Madrilenian stone

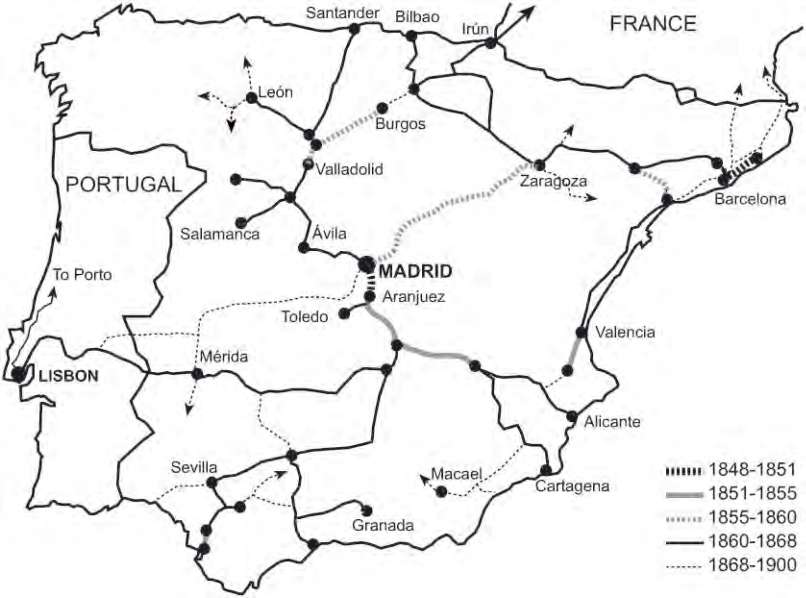
STONE	Alpedrete Granite	Zarzalejo Granite	Redueña Dolostone	Torrelaguna Dolostone	Colmenar Limestone	Bernardos Slate	Black Flint
Density (g/cm^3)	2669±17	2662±21	2349±92	2527±38	2579±30	2751±7	2430±
Water absorption (%)	0.3±0.00	0.6±0.0	5.6±1.4	3.3±0.6	0.8±0.4	0.2±0.0	0.6±0.1
Porosity accessible to water (%)	0.8±0.1	1.6±0.1	16.2±3.4	10.0±1.4	3.8±1.2	0.4±0.1	1.6±0.2
Porosity accesible to Hg (%)	0.5	1.4	17.9	7.5	3.9	0.5	1.3
% Micro porosity	99	99	99	99	84	98	67
% Macro porosity	1	1	1	1	16	2	33
Vp (m/s)	4601±204	3296±198	2753±314	3788±278	5941±111	5694±183	5671±85
Δ dM %	5.8	12.7	5.6	5.6	3.1	33.6	1.1
Δ dm %	1.9	3.1	3.9	3.3	1.2	5.8	1.9



1. Alpedrete monzogranite, 2. Zarzalejo monzogranite, 3. Redueña dolostone,
4. Colmenar limestone, 5. Flint, 6. Bernardos slate.



CENOZOIC
MESOZOIC
PLIOCENE
MIOCENE
CRETACEOUS
LATE
MIDDLE
LATE
12. Oncholithic, stromatolitic and tuffaceous limestones with laminar crusts
11. Limestones
10. Quartzite conglomerates and arkosic sandstones
9. Dolomitic limestones and green clays with sepiolite levels.
8. Flint.
7. Arkosic sandstones
6. Green-brown clays with micaceous sandstones.
5. Massive and nodular gypsum and detritic gypsum to the top with carbonates
4. Yellow dolostones
3. White and gray limestones and dolostones
2. Dolostones (red at the bottom)
1. White and ocher sandstones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to Guadalajara
to Salamanca
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Alcalá de
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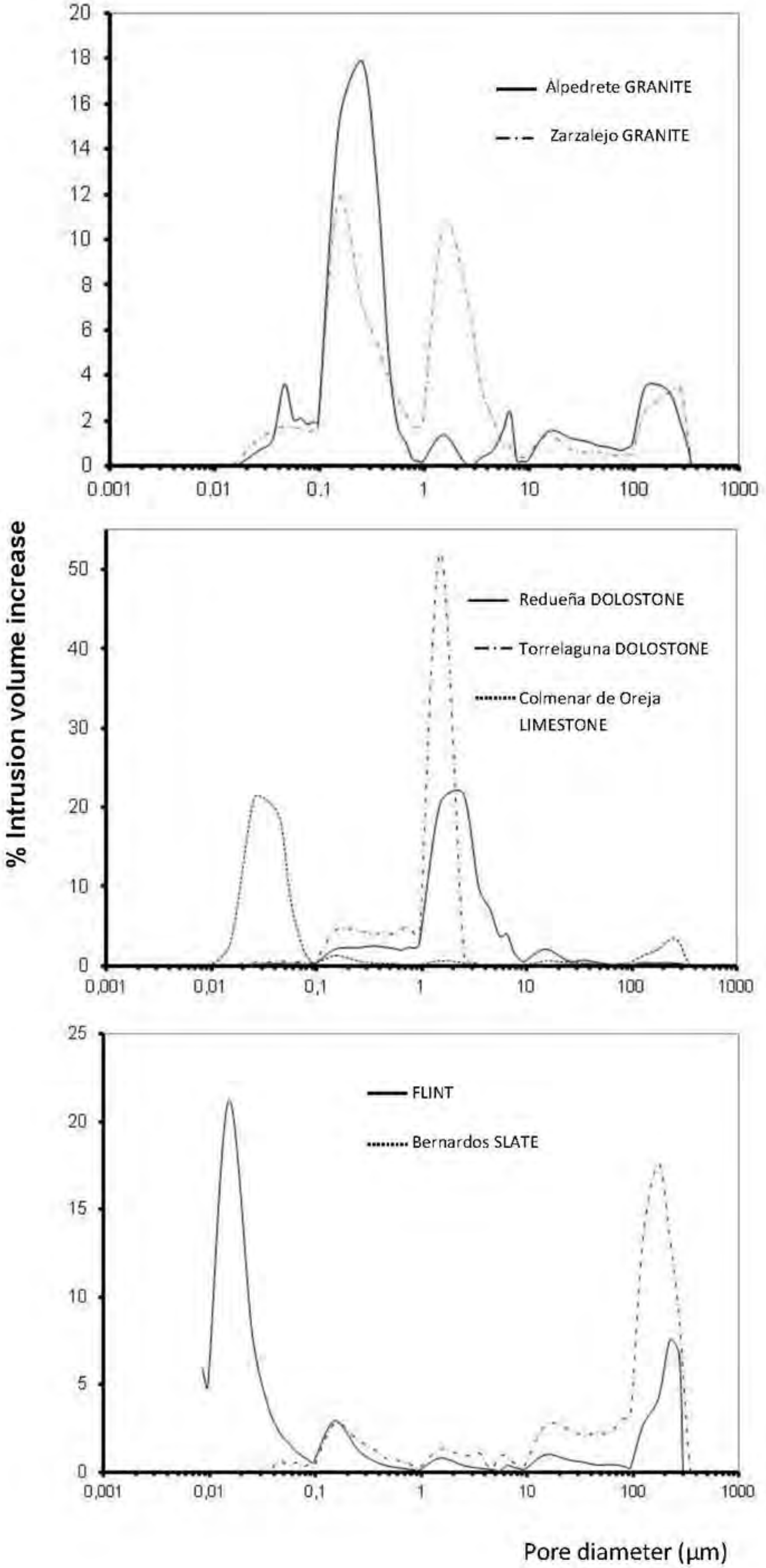

Àlpedrete GRANITE
Zarzalejo GRANITE
Redueña DOLOSTONE
Torrelaguna DOLOSTONE
Colmenar de Oreja LIMESTONE
FLINT
Bernardos SLATE
% Intrusion volume increase
Pore diameter (μm)

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