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TITLE: Non-destructive testing for the assessment of granite decay in heritage structures compared to quarry stone

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Abstract

Several types of granite found in two architectural heritage monuments were assessed with two non-destructive, portable techniques: Schmidt hammer rebound and ultrasound velocity (Vp). Similar assessments were conducted on the rock from which the granite was originally quarried for comparison. The results obtained, which revealed the existence of a direct correlation, constitute a useful indication of decay, particularly if the approximate dates of construction are known. And conversely, if they are not, such stone assessments may provide a rough estimate of when the structure

was built. Both of these convenient, portable and non-destructive techniques may be used as reliable indicators of the degree of stone decay.

Keywords: granite, decay, NDT techniques, quarry, heritage structure, ultrasound velocity, rebound tester, Schmidt hammer

Highlights

- The comparison of the properties of both the building stone placed in a monument, and the provenance quarry rock from which it was extracted for the construction of a structure constitutes a good index to determine the decay degree of the monument building stone.
- The use of two portable and non-destructive techniques, the Schmidt hammer rebound and the ultrasound velocity measurements, is a reliable method that allows the determination of this deterioration index
- The direct correlation between the data obtained from the monument building stone and the quarry rock, allows to provide a rough estimate of when the structure was built, in case it is not known.

Abstract

Several types of granite found in two architectural heritage monuments were assessed with two non-destructive, portable techniques: Schmidt hammer rebound and ultrasound velocity (V_p). Similar assessments were conducted on the rock from which the granite was originally quarried for comparison. The results obtained, which revealed the existence of a direct correlation, constitute a useful indication of decay, particularly if the approximate dates of construction are known. And conversely, if they are not, such stone assessments may provide a rough estimate of when the structure was built. Both of these convenient, portable and non-destructive techniques may be used as reliable indicators of the degree of stone decay.

Building stone weathering, and especially the degree of damage and the rate at which it occurs, have long been a matter of research and discussion. The three main approaches adopted in such research are: experimental, man-made structures and geological materials [1]. The durability of rock used for engineering purposes is determined by: geology (*in situ*), production (quarrying and stockpiling), construction (workmanship) and use (type of structure). Physical, mechanical and simulation tests, along with petrographic evaluation, are commonly used to assess rock durability. When the architectural heritage is involved, however, sampling must be reduced to a minimum. In such cases, the use of non-destructive, portable techniques is essential, for in addition to assessing the surface strength of the stone, they provide substantial information about the monuments themselves.

According to RILEM's (International Union of Laboratories and Experts in Construction Materials, Systems and Structures, www.rilem.net/tcDetails.php?tc=SAM), Technical Committee on Strategies for the Assessment of Historic Masonry Structures with NDT (SAM) -created in 2005-, recent years have brought the development and improvement of a number of methods for on-site monitoring and diagnosis based on non-destructive (NDT) and minimally destructive (MDT) techniques. Two of the most frequently used NDTs were chosen for this study: ultrasound velocity and surface hardness determined with a Schmidt hammer rebound tester. Ultrasound propagation velocity has been widely used to determine the quality and degree of decay in rock and stone materials forming part of the built heritage [2-17]. As early as 1965, De Puy [18] reported that Schmidt hammer rebound testing was suitable for detecting weathered and altered rock, based on the reduction in strength caused by the presence of weak or soft secondary minerals, microcracks, flaws and increases in water absorption capacity. Viles and Coworkers [19] reviewed the use of the Schmidt hammer and the Equotip tester for assessing rock hardness in geomorphology and heritage science.

Some authors have attempted to establish the relationship between Schmidt hammer surface hardness and compressive strength [20-30], as well as between P-wave velocity and uniaxial compressive strength [26,31]. Of the scant references found on the correlation between ultrasonic velocity and surface hardness (Schmidt hammer rebound number R_n) in building materials more dealt with concrete than with rock [32-35]. Nonetheless, a few relevant papers such as [36] have been published on the use of ultrasonic pulse velocity and Schmidt hammer tests to predict granite elasticity and strength.

Moreover, weathering generally lowers rock strength, as reflected in the R values indicative of surface hardness [19,36-37]. The data on monumental stone exposed to degradation over time are even scantier [38].

Some authors have measured surface hardness to establish how long rocks have been decaying or weathering in natural [39-42] or built environments [43].

Material surfaces are usually affected more directly by decay, inasmuch as they are more exposed to agents that reduce rock hardness and compactness, such as thermal fatigue [44], salt crystallisation [45], colour alteration [46] and microorganisms [47].

One of the advantages of combining non-destructive surface hardness and ultrasound velocity measurements is that the results can then be used to replace severely deteriorated architectural elements with materials as similar and compatible as possible with the original stone, by comparison with the findings for different quarry faces [48].

The present study adopted that approach primarily to assess the degree of decay in monumental stone by comparing the results to the values obtained for materials from the sites where the materials were initially quarried. In other words, the aim was to determine the decay undergone by built heritage stone from the time it was laid.

Materials and Methods

GEOLOGICAL SETTING

Granite, in particular the so-called *Berroqueña* variety, has traditionally been used as a building stone in central Spain. The stone is quarried primarily in the south-western part of the Guadarrama Mountains, which constitute the north-eastern branch of the 500 Km long Spanish Central System (NE-SW). This mountain range comprises mainly Variscian granitoids and high- to medium-grade metamorphic rocks. The granitoid Guadarrama Batholith, in turn, is bordered by two Tertiary river basins, the Duero on the northwest and the Tagus on the southeast. The rock in this batholith consists mostly of the peraluminous monzogranite to the leucogranite varieties, with minor proportions of rock with a more basic composition [49].

Monzogranites, the most abundant rocks in the area studied, exhibit differences in texture, ranging from non-porphyritic (homogeneous or equigranular monzogranite) to porphyritic (porphyritic monzogranite), with transitional contacts. Porphyritic monzogranites consist in potassium feldspar phenocrysts (2-3 cm) in a medium to coarse-grain matrix. The non-porphyritic monzogranites outcropping in the areas studied have a hypidiomorphic inequigranular texture, and a medium to coarse grain-size. The main minerals are quartz, potassium feldspar, plagioclase and biotite. Sub-spherical or ellipsoidal micro-grained inclusions are frequent. Monzogranites outcrop along a strip running NE-SW for several kilometres.

Leucogranites are associated with monzogranites. They outcrop as small massifs, stocks and dykes intruding in monzogranites (sharp contacts), and their texture, outcropping shape and dimensions are heterogeneous. They range from biotite leucogranite to biotite-muscovite leucogranite, and from fine to fine-medium grain-size and exhibit a hypidiomorphic texture. The main constituent minerals are quartz, plagioclase and potassium feldspar, followed by biotite and muscovite. In addition to these main varieties of granite, gneisses and dykes of granitic porphyry and aplite are also present in the area.

MONUMENTS

The two types of monzogranites tested in this study were used to build Our Lady of the Assumption Church at Valdemorillo and Valdemaqueda Bridge at Valdemaqueda, both located in the region of Madrid, Spain.

Valdemorillo lies 30 km west of the capital city (Figure 1), on the western rim of the Guadarrama Mountains. The church (Figure 2a) was built on a hill now in the town centre. Judging from the differences in architectural styles, church construction was an ongoing matter, from the 8th to the 17th centuries. Much of it is built in stone. The Old Tower on the north-western corner, one of the first enlargements, was probably erected for defensive purposes. This originally Romanesque structure was largely rebuilt, particularly in the 12th-14th centuries [50]. In the 14th and 15th centuries, the Cistercian Order of Calatrava made relevant changes in the building. The original chapter house, adjacent to the Old Tower, was enlarged in the 17th century. After the works were completed, the church was consecrated in 1704, with no evidence of further significant works on the monument from that time onward. Valdemaqueda is located 75 km west of Madrid, Spain (Figure 1) and 20 km west of Valdemorillo, in a region of the mountains known as the “ramp” (with isolated hills or *inselbergs*). Valdemaqueda Bridge (Figure 2b) spans the Cofio River in a north-south direction, 3 km south of the town. Locally, it is known as the Roman, Mocha or Five-arch Bridge.

While its dating is unclear, there appears to be more support for a Medieval than a Roman origin. It may have been built as part of the royal system of cattle routes [51]. With its rural location (pine forest), it is presently closed to traffic, for one of the sides of the bridge has been fenced off by the owners of the adjacent property. It may, however, have originally been built by the Romans and enlarged and reconstructed during Medieval times (11th century). The bridge silhouette is slightly arched and while ashlar were used for the voussoirs and vaults, the rest of the masonry consists of rubblework. Only granite was used throughout, however. The ashlar have decayed quite uniformly.

CLIMATIC CONDITIONS

The climate in both areas, Valdemorillo and Valdemaqueda, is Mediterranean, i.e., temperate or mild to cold, and sub-humid, with slight variations between the two. The mean annual temperature is 12 °C at Valdemorillo and 11 °C at Valdemaqueda, with mean rainfall values of 650 mm and 750 mm, respectively, although according to the Papadakis scale, both have humid Mediterranean climates [52]. The air in and around Valdemorillo, a rural area, is scantily polluted. Valdemaqueda Bridge, in turn, is located in a natural site cut off from traffic, with high relative humidity induced by the river that flows under the structure and just a few meters away from the granite quarries.

TECHNIQUES AND SAMPLING

Analyses and measurements were conducted both *in situ* and in the laboratory on stone cores extracted from the monuments. Cores of the most abundant and representative materials in the monuments were extracted for characterization, with the exception of porphyritic monzogranite, for which sufficient material could not be extracted for some of the petrophysical analyses.

Despite the fact that this stone accounted for 11% of all the building materials identified (compared to 70% of homogeneous monzogranite), it was found in ashlar at a height where core extraction would have entailed the use of scaffolding or a crane, which was beyond the limits of this study. Petrographic (ZEISS Axioskop polarizing optical microscope) and mineralogical (X-ray diffraction of the total sample with a PHILIPS PW-1752 instrument) studies were conducted.

The bulk and real densities of the material, as well as its porosity accessible to water, were determined. Ultrasound pulse velocity (C.N.S. Electronics PUNDIT) was also measured, using direct (stone specimens) and indirect (ashlar and quarry surfaces) transmission with 54-kHz transducers.

While indirect measurements are less sensitive and exhibit poorer path length definition than direct measurements, the technique is widely used in the field, where the direct method is not generally feasible. The indirect method does, however, accurately detect the depth of defects (inward distance from the surface) [53-54]. This technique consists in generating a longitudinal vibratory pulse with an electro-acoustic transducer in contact with the surface of the material. The pulse is transmitted through the material, inducing a complex system of stress waves that are detected by a second transducer, the receiver, where they are converted into an electrical signal. What the ultrasound equipment records is the travel time, or time that it takes the ultrasound to travel between the two transducers. Velocity is computed from the path length and travel time. The petrological factors mainly affecting sonic velocity are compactness, porosity, moisture content and micro-cracks [18].

The on site tests included surface hardness, assessed with sclerometric techniques (Original-Schmidt Type N *Proceq* test hammer, applying an impact energy of 2.207 Nm) directly on the facade and indirect ultrasound velocity measurements. The Schmidt hammer furnishes a quick and inexpensive measure of surface hardness that is widely used to estimate the mechanical properties of rock. It measures the rebound of a spring-loaded mass impacting the sample surface, and is based on the principle that the rebound of an elastic mass depends on the hardness of the surface against which the mass impinges [55]. Many authors have proven that the Schmidt hammer value is a relatively reliable measure of the strength of stone, as mentioned above.

A petrological study was conducted of the various types of rocks (outcrops and quarries) in the vicinity of the two monuments, locating and sampling the stone extraction faces for comparison with the materials in the two built structures. The petrographic, mineralogical and petrophysical properties (physical properties of rocks) of the rock in these quarry faces were determined. The methodology was the same as in the monument ashlar, including the use of non-destructive techniques such as sclerometry and ultrasound velocity.

Studies were conducted on 200 of the church ashlars (most from the Old Tower and the initial Mozarabic or Visigothic church) as well as on nearby quarries. In the bridge, 118 representative ashlar and 23 quarry samples were analyzed. The values used for the calculations were the means of five ultrasound and hardness readings taken in the centre of each ashlar, at points positioned radially at 36° angles. The distance between transducers was set at 150 mm.

Results

Quarries

Abandoned quarries dot the area around Valdemorillo (Figure 3a), and are even found in the centre of town. Most are scantily relevant, with stone extracted from the top of the outcrops to make small ashlar. Different historical periods can be delimited on the grounds of the type of quarrying performed: extraction and carving from spherical granite boulders resulting from chemical and physical weathering, small-scale quarrying in which only the upper 20-50-cm horizon was removed from “whaleback” granite domes, and others where the rock was more deeply quarried. The stone used for the 16th century enlargements (monzogranite) was supplied by the St Lucia Hill quarry, 4 km north of the town centre [38].

The quarries that supplied material to build the bridge, in turn, are located no more than one hundred metres from the base of the monument itself and were in fact used solely for that purpose (Figure 3b).

Petrological characteristics

Our Lady of the Assumption Church was built primarily with homogeneous monzogranite, the most abundant granite in the surrounding quarries. In the Old Tower, 70% of the 200 ashlar studied were made of this type of monzogranite, 15% of porphyritic granite, 10% of porphyritic monzogranite and the rest of gneiss, aplite and leucogranite.

Homogeneous monzogranite is biotitic, with a medium to coarse grain size and an equigranular structure. Its components are quartz, oligoclase, biotite and potassium feldspar (orthoclase), along with accessory minerals such as apatite, zircon and hornblende. Sericite, saussurite, sphene, chlorite and prehnite are usually present as secondary minerals.

Porphyritic monzogranites are similar to the homogeneous variety, inasmuch as they are biotitic and have a coarse to medium grain size. Phenocrysts are scarce and allotriomorphic, fine grained, usually under 2 centimetres, with a certain amount of intergrowth with other rock components. Mineralogically, they contain quartz, plagioclase, potassium feldspar, biotite and lower proportions of apatite, zircon and sericite.

Granitic porphyries are rocks having a holocrystalline and hypidiomorphic texture, quartz, plagioclase and potassium feldspar idiomorphic phenocrysts, some biotitic, and a variable grain size. These phenocrysts float in a mesocrystalline or cryptocrystalline matrix, in which quartz, potassium feldspar and plagioclase crystals abound. The

accessory minerals include apatite, zircon, epidote, iron oxides, ilmenite and monacite, while the secondary minerals are chlorites and prehnites.

Both mineralogical and textural petrographic differences were observed between the church and quarry monzogranite. As a result of its alteration close to the surface, the potassium feldspar (orthoclase) in the ashlar appeared to be more soiled than in the quarry material, while the conversion of plagioclase to sericite was also slightly more intense in the former. Finally, a much larger proportion of fractured crystals were found in the building than in the uncut stone (Figures 4a, b, c and d).

Most of Valdemaqueda Bridge was built with large grain porphyritic monzogranite, although some rough granitic porphyry and aplite stones were also observed. The monzogranite was found to be biotitic and exhibits an inequigranular hypidiomorphic texture, a medium to coarse grain size and large feldspar crystals (1-3 cm), with a slightly porphyritic texture. Its mineralogical content consisted mainly in quartz, potassium feldspar (orthoclase), plagioclase (with three zones: andesine in the crystal nucleus, oligoclase outside the nucleus and albite along the rim) and biotite. Here the accessory minerals were amphibole, allanite, apatite, zircon and monazite.

As a result of mineralogical alteration processes in the granite, the plagioclase was intensively transformed into sericite, primarily in the crystal nucleus, where the coarsest epidote-clinozoisitic group crystals were observed. The surface biotite shows alteration, with few crystals converted to chlorite. Barely any significant mineralogical or textural differences were detected between the bridge and quarry stones (Figures 4e, f, g and h).

Petrophysical characteristics

The bulk and real densities of the materials in the church at Valdemorillo and Valdemaqueda Bridge, and the respective quarries, are given in Table 1. Table 2 shows the open porosity or porosity accessible to water, as well as the water saturation values for the quarry and used materials. The higher open porosity in the monumental than in the quarry samples was indicative of the more intense alteration in the former.→

The degree of alteration of the materials in the two monuments could be determined by comparing the more highly altered outer areas of the ashlar to the less altered or unaltered inner areas of the extracted cores. The homogeneous monzogranite ashlar had a slightly higher porosity accessible to water value (3.5%) in the outer (from the surface to a depth of 4 cm) than in the inner (depths of five to 10 cm) areas (3.3%). Similarly, water absorption capacity was slightly higher in the outer (1.4%) than in the inner (1.3%) area.

Granitic porphyries were also seen to be more altered on the surface of the cores, with values of 2.2% in the outer areas, which declined slightly to 1.9% in the inner core. The water saturation values (maximum water content in a vacuum chamber) were 0.8% and 0.7% for the outer and inner parts of the porphyry ashlar specimens, respectively.

The ultrasound pulse velocity values, in turn, were found to be lower in the monumental stones than in the quarry rock (Table 3). The rate of decay, defined as the ratio between the velocities for the monumental and quarry stone, was 0.56 for the homogeneous monzogranite and 0.75 for the granitic porphyry in the Valdemorillo stones, and 0.75 for the homogeneous Valdemaqueda monzogranite.

Ultrasound pulse velocity and surface strength

The ultrasound pulse velocity measured on the surface of stone materials is related to the surface hardness measured with the Schmidt hammer rebound test.

The higher the porosity of a stone, the lower is its ultrasound velocity and its Schmidt hammer rebound number (R_n) [26,30].

Porphyritic monzogranite was found to be more severely deteriorated on Valdemaqueda Bridge than on Our Lady of the Assumption Church, as may be deduced from the lower V_p in the former, where the results for each ashlar were, moreover, more widely dispersed. The same pattern was observed in the monzogranite quarries from which the bridge granite was extracted. Such greater decay may be attributed to the bridge's older age (for which the evidence is insufficient), but primarily to the harsher microclimate prevailing around the bridge, where the relative humidity is very high due to the surrounding forest and the existence of the flow of the river water only a few metres from bridge ashlar and quarry faces both.

The lower the degree of deterioration of the materials, the more compact is their structure and the higher their V_p and R_n . On Our Lady of the Assumption Church, for instance, the average ultrasound velocity for the outer homogeneous monzogranites and granitic porphyry ashlars was lower than for the ashlar inside the Old Tower. The higher standard deviation (STD) found for the outer ashlars evinced the non-uniform deterioration of the materials.

The direct ultrasound velocity findings were much lower for the porphyritic monzogranite than for the stone quarried in the Valdemorillo area, despite the similarities in the two materials' petrographic characteristics. A possible explanation is that the Valdemaqueda quarries were probably used to build the bridge only, and have been untouched since.

As a result, the working faces of these quarries are more highly altered than the quarries around Valdemorillo, which are still in use and have a low STD ($60 \text{ m}\cdot\text{s}^{-1}$), denoting scant variability in the data despite the textural heterogeneity of the (porphyric) stone.

According to the deterioration indices calculated for the materials studied ($\text{DI} = \text{monument Vp}/\text{quarry Vp}$) and the ultrasound velocity (surface or indirect method) found for the Valdemorillo area quarries, the granite on the bridge is the most severely decayed stone: a lower Vp was measured on its ashlar (1 225 m/s) than on the Valdemorillo church porphyric granite (1 968 m/s). On Our Lady of the Assumption Church at Valdemorillo, in turn, the homogeneous granites, with an index of 0.59, were the most highly decayed, while the granitic porphyries (0.76) were less intensely damaged (Table 4).

These values must be viewed with caution, for in the past, the upper levels of outcrops were the first to be selected and quarried, because the weathering to which they were exposed facilitated extraction, cutting and carving. Similarly, the data for Valdemarqueda Bridge must also be interpreted carefully, not only due to the proximity of the quarries to the river, but also because the faces were carved and cut in the riverbed itself, and therefore more exposed to decay than the surrounding rock, the Vp value observed for the quarry fronts was much lower than the Valdemorillo quarry readings (2 575 m/s).

The ultrasound values, as expected, were always lower for the monumental than the quarry stone.

Decay in ashlar depends on time and/or the aggressiveness of the environment: the longer the time and/or the more aggressive the environment, the greater the decay. In the case studies discussed here, the natural environment surrounding the bridge and its quarries induced material decay more intensely than the rural environment prevailing at Valdemorillo.

From a petrological standpoint substantial differences were found between the granite on the historic structures, especially the church monzogranite, and the rock in the quarries (Figure 4). These differences were mainly related to physical decay, with an increase of cracks both inside the minerals and in between their (inter and intra-crystalline) contacts. Cracking led to much higher porosity, which in turn favoured granite ashlar deterioration. The mineralogical differences between monumental and quarry granite included a slightly greater degree of conversion of plagioclase to sericite in the former, and the potassium feldspar in the monumental granite appeared to be more soiled than the mineral in the quarry rock.

Figure 5 shows the average ultrasound transmission velocity measured on the surface of the monzogranite ashlar in Our Lady of the Assumption Church and its variation according to the period when the stone was laid. The graph shows that the decline in mean V_p values with ashlar age was exponential. Determining the periods of construction was fairly easy in the church, where the different buildings are well defined, but less so in the bridge, for which consensus has yet to be reached about when it was built. In light of the more aggressive environment to which the materials are exposed, however, the V_p readings may contribute to ruling out a Roman origin for the bridge.

V_p and the sclerometric index are directly and linearly related: the higher the V_p , the higher the R_n . Figure 6 shows the V_p/R_n regression lines obtained for the granitic materials in the monuments and their respective quarries. All the building stones measured on the two monuments exhibited behaviour similar to the rocks taken from the original quarries: the slopes were always steeper for the quarry than the monumental materials. This is an indication of more intense alteration of the latter than the former. The minimum V_p value, moreover, was always higher for the quarry rock than the stones in the monuments, providing further evidence of the alteration undergone by the building stone. The lowest values of V_p and consequently the severest deterioration were recorded for the homogeneous monzogranites on the church and the porphyritic monzogranites on the bridge. The regression lines for the monumental stones tended to be sub-horizontal, and always had a positive slope. This denotes significant variations in V_p values and less dispersion in R_n values, a discrepancy that is directly related to the depth of the measurements. The stone in the monuments may exhibit relatively high V_p values (although lower than the quarry granite), which would indicate the degree of decay not only on the ashlar surface, but up to a certain depth, whereas low R_n values show the degree of decay on the surface only, which was consistently more altered in the monuments than in the quarries. The similarity and proximity between these two regression lines for homogeneous monzogranites (Figure 6) may be due to the fact that the different church buildings were built at different historical times (Figure 5).

Conclusions

Ultrasound velocity (V_p) and surface strength (R_n) as measured by the Schmidt hammer are directly related to one another and inversely proportional to the decay of stone materials and consequently to their porosity. In other words, both of these portable, non-destructive techniques are reliable indicators of the degree of decay in stone materials.

The results show that the porphyritic monzogranite on both the bridge and the quarries at Valdemaqueda was less intact than the Valdemorillo granite. The V_p and R_n readings on the outer church masonry (homogeneous monzogranites and granitic porphyries) were lower than the indoor readings, primarily as a result of decay. Standard deviation, in turn, was observed to rise with the degree of stone deterioration. The deterioration index for the materials was determined by comparing monumental V_p to quarry V_p measurements ($DI = \text{monument } V_p / \text{quarry } V_p$). This index was used to define the degrees of decay for each stone.

One of the most relevant findings of this study was the existence of a correlation between the indirect ultrasound measurements on Our Lady of the Assumption Church at Valdemorillo and the construction period, particularly for homogeneous monzogranite. This exponential correlation may be used as a dating criterion for building materials exposed to similar conditions (orientation, climate and so on), as a first approximation of the period when structures were erected. In this regard, the expression obtained for the church monzogranites was as follows:

$$y = 820.43^{0.0005x}$$

where y is ultrasound velocity in $\text{m}\cdot\text{s}^{-1}$ and x is time in years. The correlation coefficient for this expression was 0.96. In other words, the assessment of the condition of the stone in a building may provide a rough estimate of when it was built. Further to this reasoning, the V_p values measured in the monzogranite used to build it would all but rule out a Roman origin for Valdemaqueda Bridge, assuming that the existing stone is the original masonry.

These two convenient, portable and non-invasive techniques furnish substantial information on the condition of building stone. In addition, the comparison of the results for the monumental and quarry granite proved to be an appropriate methodology for this case study.

Lastly, monumental granite decay was greater as a rule than quarry stone decay and the degree of alteration in both was impacted by the conditions in the surrounding environment. The inference is that the use of quarry stone to study the viability of conservation treatments is not necessarily suitable, for the degree of decay and the agents inducing it may differ depending on the immediate environment. In the present study, the bridge quarries would be appropriate for this use, inasmuch as decay in the monumental and quarry stone was similar (similar V_p and R_n values) and the quarries were abandoned shortly after the bridge was built.

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FIGURE CAPTIONS

Fig. 1. Location of the monuments' case study

Fig. 2. a) Church The Assumption of Our Lady, Valdemorillo, Madrid. b) "Roman" bridge, Valdemaqueda, Madrid

Fig. 3. Images of some of the quarries that supplied stone for the monuments construction. a) Valdemorillo, b) Valdemaqueda

Fig. 4. Images of the sampled granites under the polarizing optical microscope. Left images, plane polarized light; right images, crossed polars. a, b, e and f correspond to ashlar; c, d, g and h to quarries. Church granitic ashlar (a and b) show more fissures and alteration of the potassium feldspar than granite quarried (c and d), both homogeneous monzogranite. The bridge granitic ashlar (e and f) and corresponding granite quarried (g and h), both porphyritic monzogranite, display intense plagioclase sericitization. Q: quartz, FK: potassium feldspar, Bt: biotite, Pg: plagioclase.

Fig. 5. Representation of ultrasounds velocity vs time as a matter of decay. Church of Valdemorillo

Fig. 6. Correlation between Schmidt hammer rebound number (R_n) and ultrasound velocity data measured on: a) Homogeneous monzogranite from both the church of Valdemorillo and quarries; b) Porphyritic monzogranite from both the church of Valdemorillo and quarries; c) Granitic porphyry from both the church of Valdemorillo and quarries; d) Porphyritic monzogranite from both the bridge of Valdemaqueda and quarries.

Table 1. Apparent and bulk densities of the stone materials from the quarry and Monument

STONE MATERIAL	QUARRY		MONUMENT	
	Real density (Kg·cm ⁻³)	Bulk density (Kg·cm ⁻³)	Real density (Kg·cm ⁻³)	Bulk density (Kg·cm ⁻³)
Homogeneous Monzogranite ¹	2664 ± 3	2601 ± 7	2653 ± 1	2573 ± 3
Porphyritic Monzogranite ¹	2678	2639		
Granitic Porphyry ¹	2607 ± 4	2547 ± 5	2675 ± 0	2620 ± 1
Valdemaqueda Monzogranite	2650	2540	2660	2560

¹ Valdemorillo**Table 2.** Open porosity or porosity accessible to water (n_0) and percentage of saturation water determined in the granitic stones of the Monuments and quarries.

STONE MATERIAL	QUARRY		MONUMENT	
	Open porosity (%)	Water saturation (%)	Open porosity (%)	Water Saturation (%)
Homogeneous Monzogranite ¹	2.35 ± 1.25	0.91 ± 0.52	2.90 ± 0.23	1.20 ± 0.09
Porphyritic Monzogranite ^{1*}	1.5	0.6		
Granitic Porphyry ¹	3.60 ± 1.61	1.44 ± 0.66	2.03 ± 0.77	0.77 ± 0.29
Homogeneous Monzogranite ²	4.00 ± 0.16	1.62 ± 0.13	3.61 ± 0.15	1.44 ± 0.07

¹ Valdemorillo, ² Valdemaqueda * Only 1 specimen was possible to analyze

Table 3. *Ultrasound pulse velocity of the stones from both monument and quarry*

STONE MATERIAL	QUARRY	MONUMENT	DI
Homogeneous Monzogranite ¹	4103±165	2296±105	0.56
Porphyritic Monzogranite ¹	3558±60	- - -	---
Granitic Porphyry ¹	5008±183	3759±132	0.75
Porphyritic Monzogranite ²	2336±369	1764±156	0.75

¹ Valdemorillo, ² Valdemaqueda

DI: Decay index

Table 4. Surface hardness (Schmidt hammer rebound number, R_n) and ultrasound pulse velocity (V_p) measured on stones from the Monuments and Quarries

STONE MATERIAL	V_p ($m \cdot s^{-1}$)		Rn	
	Ashlars	Quarry	Ashlars	Quarry
Homogeneous Monzogranite ¹	1495±536	2514±637	25±7	37±9
Porphyritic Monzogranite ¹	1968±570	2575±536	34±8	34±10
Granitic Porphyry ¹	2685±883	2474±719	37±10	42±10
Porphyritic Monzogranite ²	1225±360	1459±382	25±6	30±11
Granitic Porphyry ²	3080±371	3280±232	50±5	50±3

¹ Valdemorillo, ² Valdemaqueda

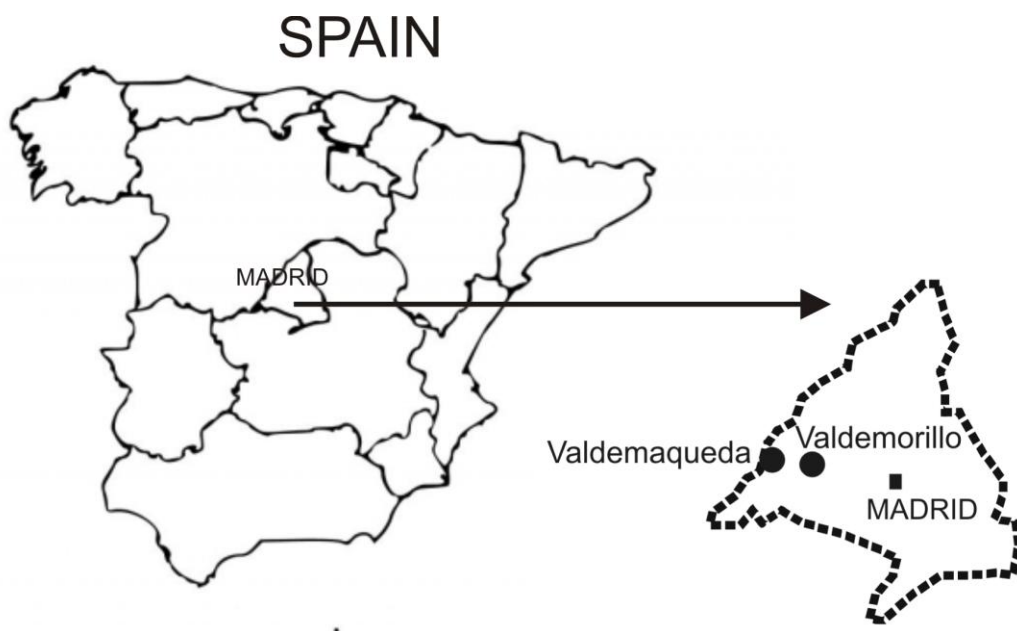


Figure 1

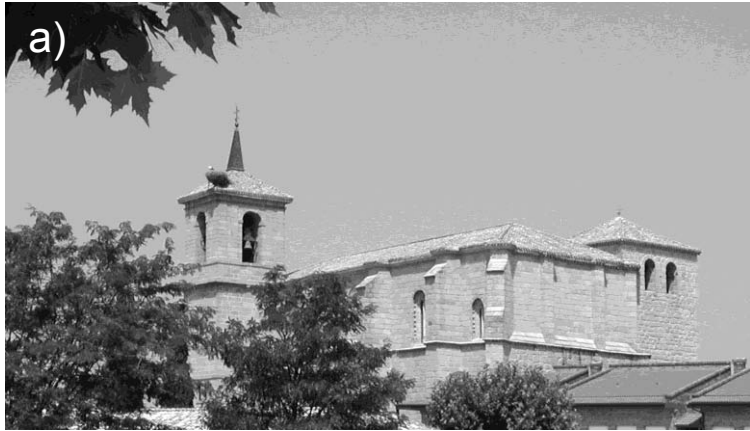


Figure 2



Figure 3

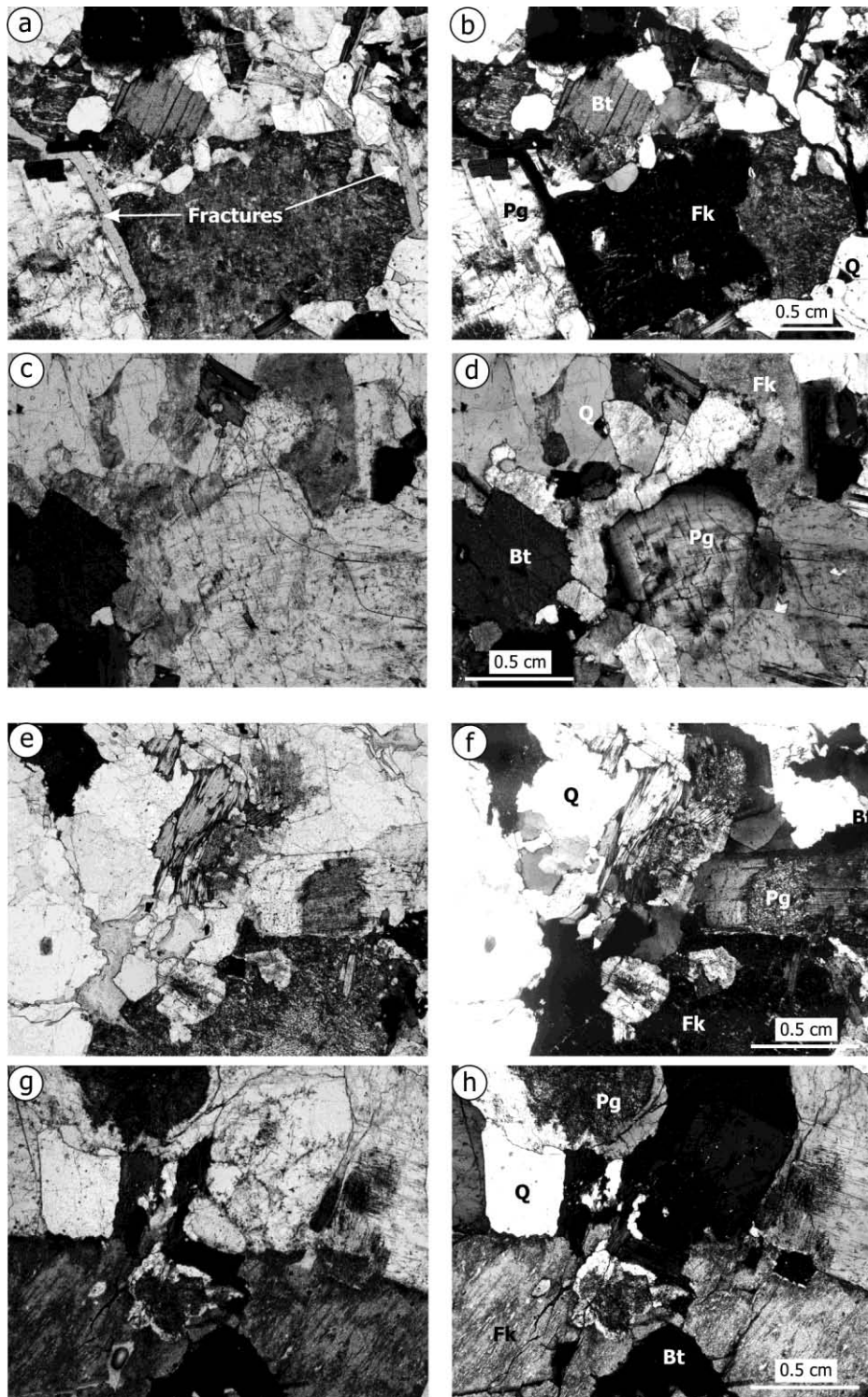


Figure 4

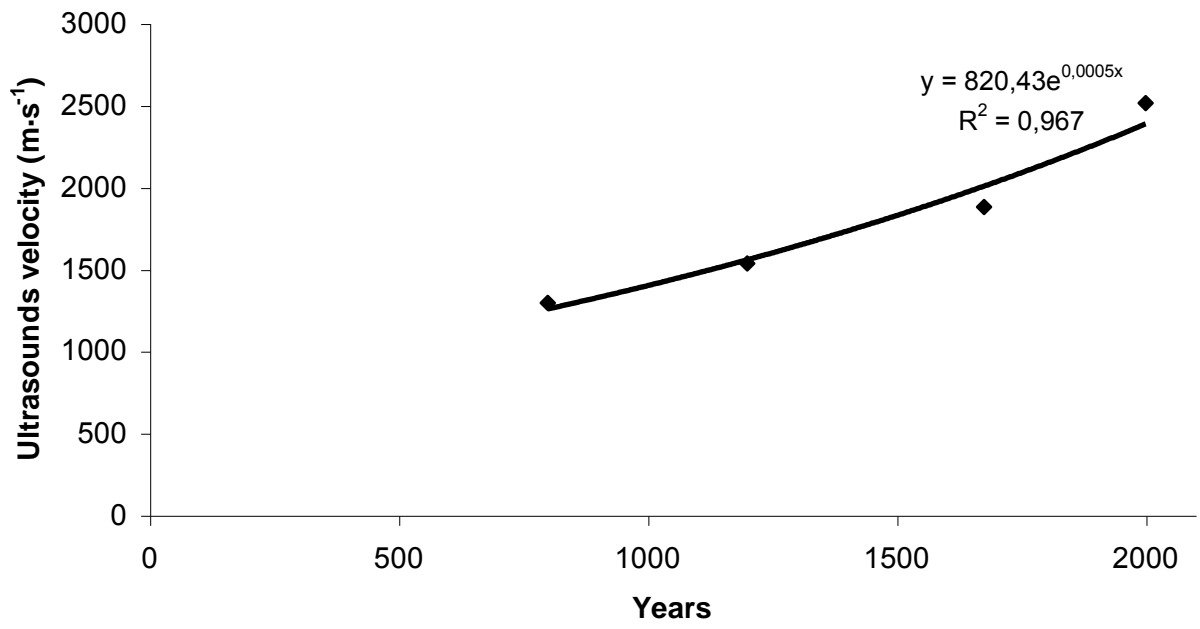


Figure 5

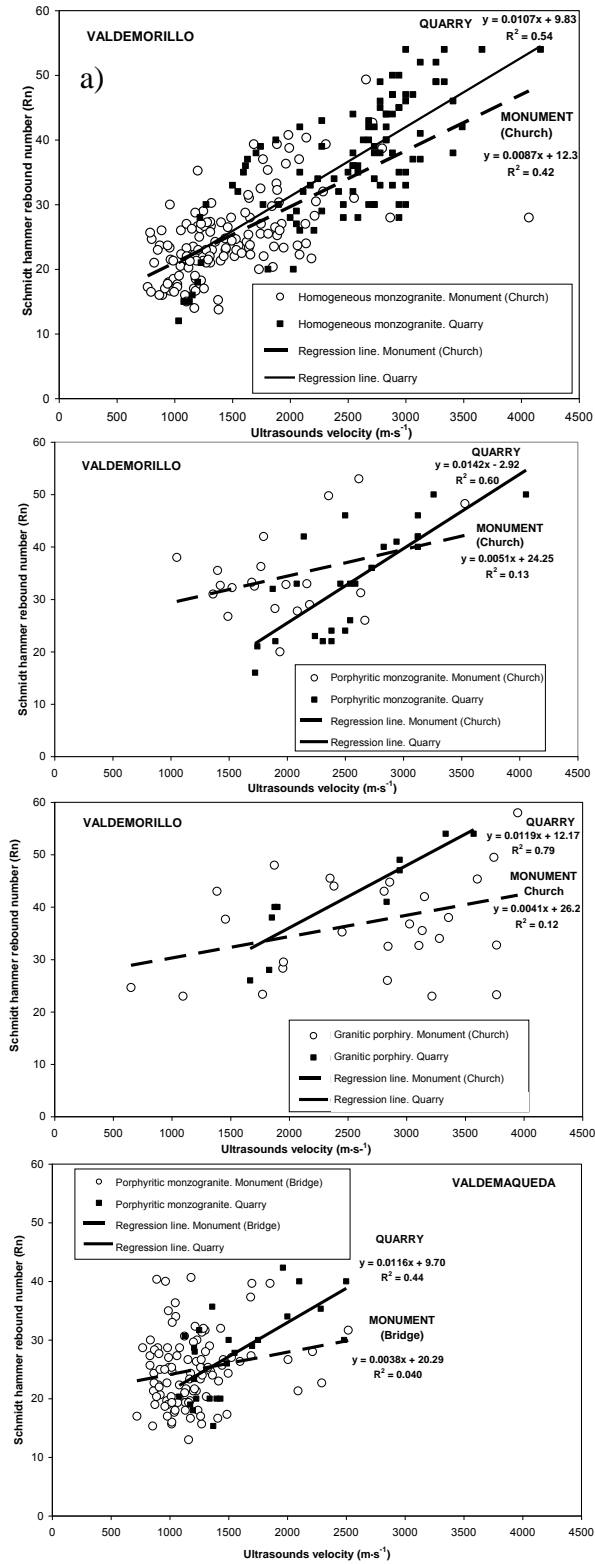


Figure 6

Figure 1
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Figure 3

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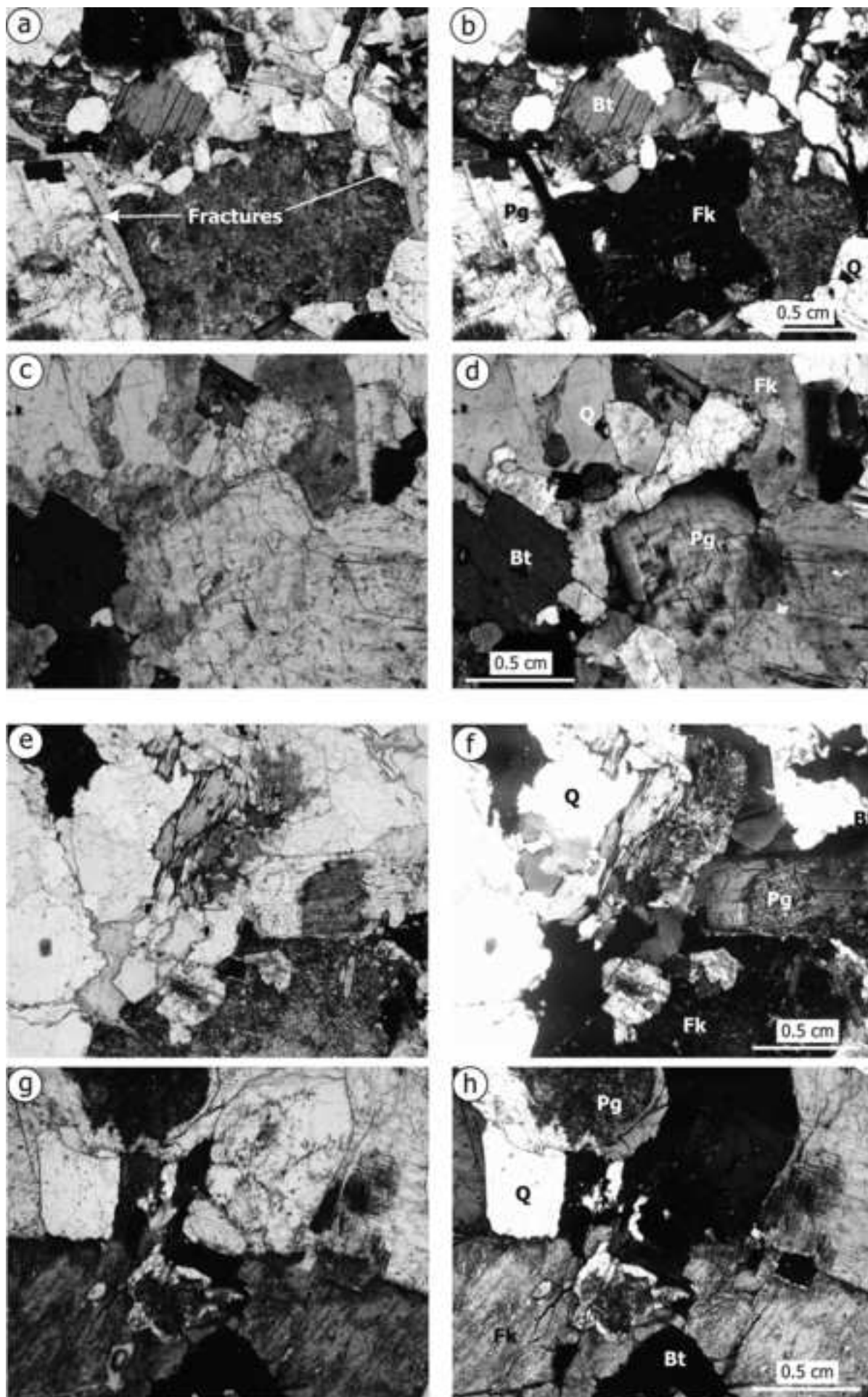


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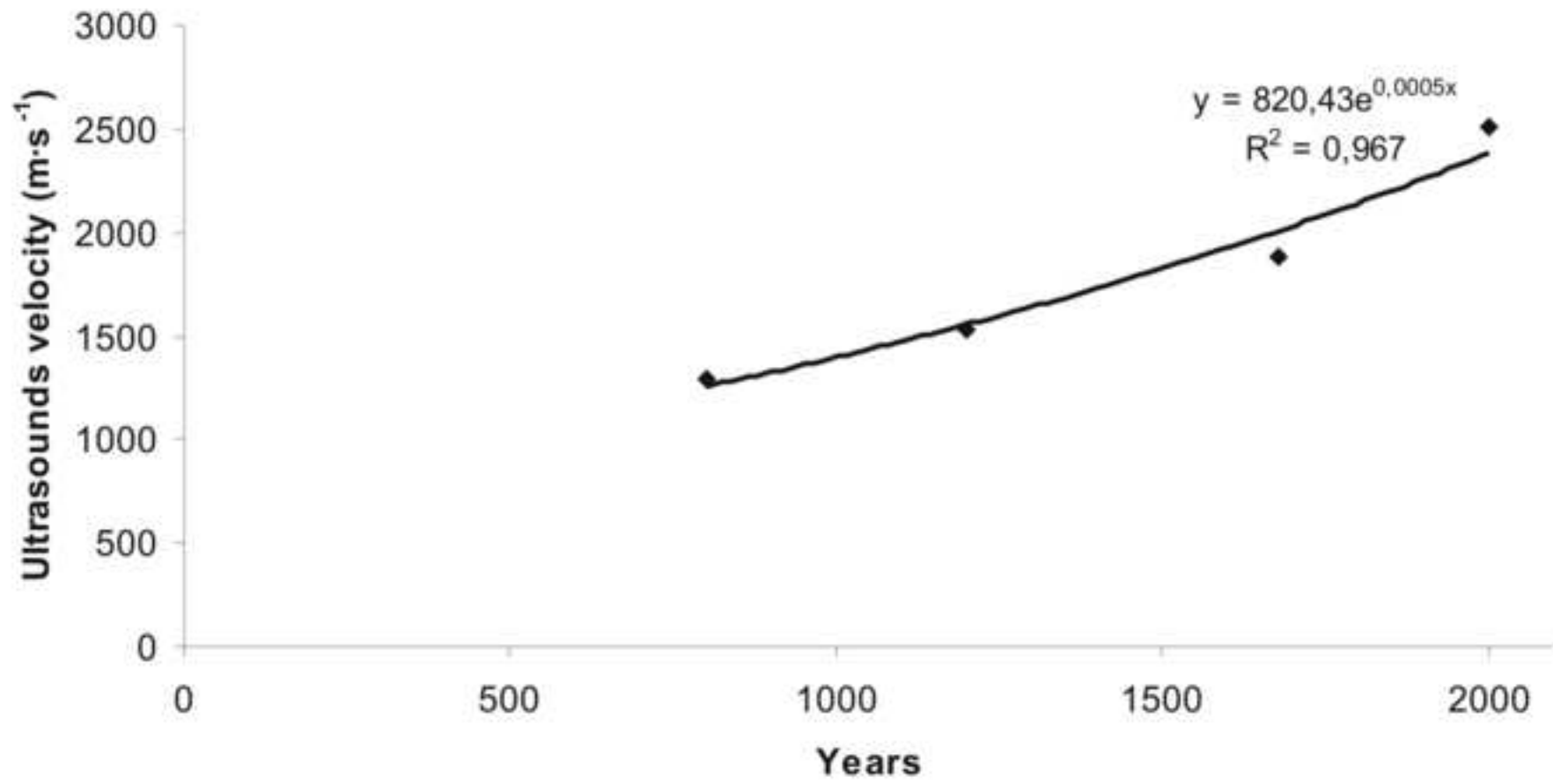


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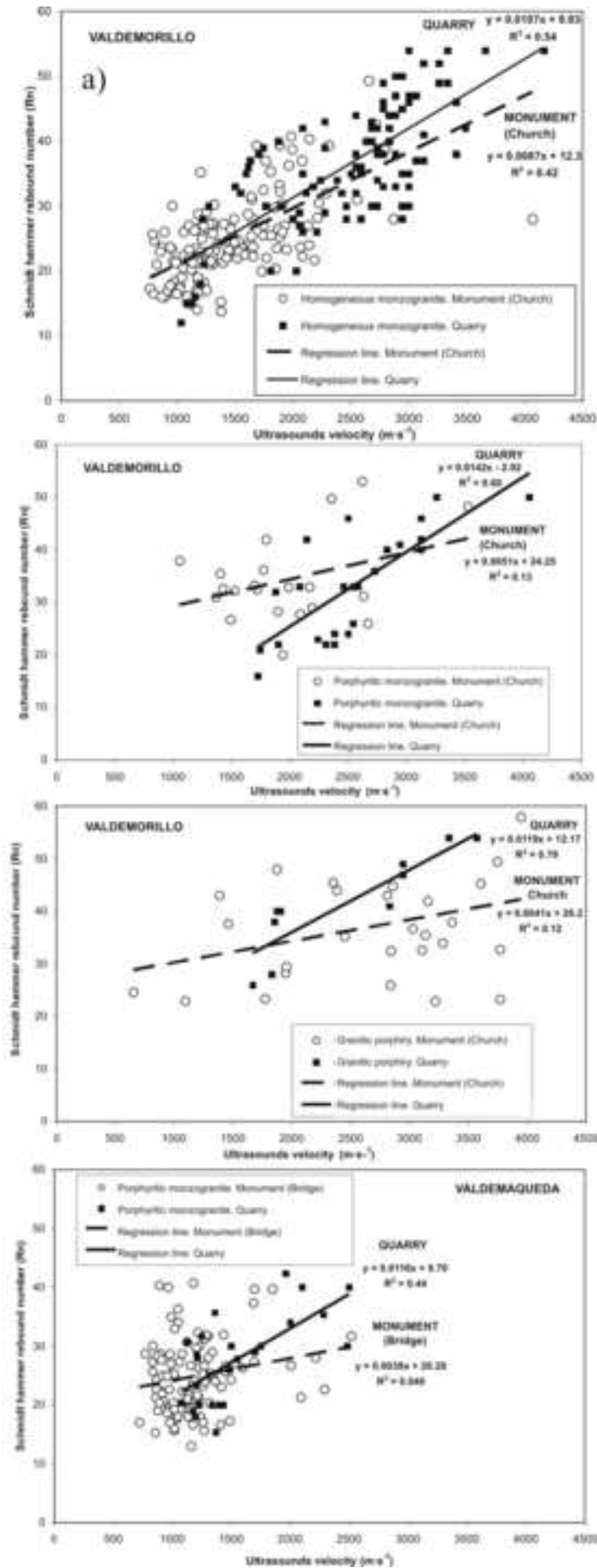


Figure 2_colour

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Figure 3_colour

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