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Highlights

- Aesthetic change depends on the stone finishing
- Lightness CIE L*a*b* colour coordinate is the most affected
- Water-jet finishing mostly preserves the colour of the tested stones’ range

Chromaticism differentiations: how variegated homogeneous stones used in buildings can gain diversified aesthetic appeal

Abstract

This manuscript presents the results of a research about the change in colour of five different dimension stones, which are worldwide used for cladding and paving, whenever undergoing different surface processings. Substantial changes of the surface features, such as roughness and gloss were measured and correlated with CIE colour parameters. A spectrophotometer has been used in this research to measure the colour coordinates in CIE L*a*b* and CIE L*C*h colour spaces of the stone samples, which have been surface-finished by using traditional methods (i.e. polishing and bush-hammering), advanced technologies (pure water-jet) and diamond-disc sawing. The results show that the variability of L*a*b* coordinates and chroma (C*), is much higher in some stone (Orosei Marble and Rosa Portogallo Venato) than in others (Bianco Carrara D, Verde Guatemala and Sardinian Basalt), as a result of different surface finishing. Hue (h) shows significant variation especially when Verde Guatemala is tested. Bush-hammering brings all the tested rocks to higher lightness (L*) values. When the total colour difference (ΔE*) is recorded, pure water-jetting preserves the original colour of stones similarly to the polishing with the exception of Orosei Marble. A direct correlation between ΔE* and mean average roughness (R_a) has been found. On the contrary, an inverse correlation between specular gloss values and R_a has been acknowledged. How the results can be used in practice is also explained.

Keywords: dimension stone; surface finishings; CIE colour spaces; gloss; roughness; water-jet.

1 Introduction

The colour of the rock has a strategic importance in design, although secondarily to the technical properties of the same rock. No less important is the surface finishing, which is the result of further processing carried out on the slabs to obtain different looks depending on their colour, gloss, and roughness.

Colour is one of the most appreciated characteristics of ornamental stones. Usually, stones of different colours are combined through geometries and designs, often in very complex patterns, giving greater value to the environments in which they are placed.

When building owners and architects have to make a choice of what stone material to use, they focus their vision first on the colour and then on the structural patterns (texture), which are the result of geologically different complex processes [1].

Colour is a very important requirement for stone which is used in cladding and paving. Monochrome rocks are highly prized for these purposes, but they are very rare to find in nature, due to impurities of various kinds that often result in veining; frequently, however, the veining itself contributes to the stone's pleasing appearance. Both colour and texture are decisive characteristics for the use of stone in external cladding/paving, depending on the direction of sawing as “verso” or “contro”: these are Italian words which the Dimension Stone community uses to identify the easiest plane of sawability of the stone and the plane perpendicular to it respectively [2]. The colour of a stone is due to the colour of its main minerals and, in conglomerate stones, to the quantity of components and their size [3].

Another decisive factor in architectural design is the choice of appearance to be given to the surface of the cladding/flooring, an appearance that can be achieved by appropriate processing or by using the split-surface in its raw state [4]

Depending on the degree of finishing obtained on the visible surface of a stone slab, the surface processing can be either “rustic” (i.e. a non-smooth surface that is characterized by more or less accentuated reliefs and roughness) or fine. The different surface finishings modify the characteristics of chromaticity, lightness, roughness and gloss of a same stones.

The colour of stone is enhanced by the fineness of the finishing of its exposed surfaces; it also varies considerably according to the degree of its finish (from saw-plane to rough-hewed, bush-hammered, honed, polished) and with the passage of time (“colour of time”). This is due to the surface oxidation of the minerals that make it up a “patina”, an Italian word, used internationally, which refers to the phenomenon whereby any stone materials, installed for some time, progressively changes its colour due to environmental and meteorological reasons. Dark stones usually tend to lighten and light ones to darken, assuming a monochromatic tone that generally improves the overall appearance of the work.

Rocks that are more resistant to colour change are magmatic, while sedimentary rocks are more subjected to alteration.

The choice of colour is a strategic element in architectural design, albeit subordinate to strength and durability.

In other words, once the designer/architect has decided on a certain colour, the dimension stone expert will be able to show all the available stone materials, which may be suitable depending on their strength and durability, and which have a colour of the type requested [5]. This is to better inform contractors and prevent misjudgements by choosing a material that is not durable and resulting in disappointment and customer dissatisfaction.

1.1 The importance of correct measurement of stone colour

Although a stone colour is the most used aesthetic feature in stone selection, colourimetric characterization is not, and operators must be very skilled at distinguishing colours. Unlike length and weight measurements, there is no physical scale for measuring colour, so it is virtually impossible for a certain colour to be perceived by everyone in the same way. Since this is a characteristic of subjective perception and interpretation, the judgment about colour is typically expressed according to subjective impressions or personal experience [6]. If several observers look at the same stone surface and indicate the same colour with different words [7], this leads to misunderstandings between architects, engineers and builders. Therefore, it is not possible to verbally describe colour and it is necessary to describe it numerically.

The Commission Internationale de l'éclairage", known in English as the International Commission on Illumination (CIE) has introduced in 1976 [8] the L*a*b* colour space (also indicated as CIE L*a*b*). It is currently one of the most common spaces for measuring object colour and it is widely used in all industrial sectors. In this space, L* indicates lightness (white) and a* and b* are the chromaticity coordinates. Fig. 1 shows the a*, b* chromaticity diagram. In this map, the a* and b* indicate colour directions: +a* is the red direction, -a* is the green direction, +b* is the yellow direction, and -b* is the blue direction. The centre is achromatic; as the a* and b* values increase and you move away from the centre, the saturation of the colour increases. The $L^*C^*h_{ab}$ colour space uses the same diagram as the L*a*b* colour space, even though it uses cylindrical coordinates instead of rectangular coordinates. In this colour space, L* still indicates lightness as in L*a*b* colour space described above, C* is chroma, and h_{ab} is the hue angle. The value of chroma C* is 0 at the centre and increases according to the distance from the centre (Fig. 2). Hue angle h_{ab} is defined as starting at the +a* axis and is expressed in degrees: 0° would be +a* (red), 90° would be +b* (yellow), 180° would be -a* (green), and 270° would be -b* (blue).

Fig. 1. Representation of colour solid for L*a*b* colour space (from Konica Minolta)

Fig. 2. L*C*h_{ab} colour space (from Konica Minolta, modified by authors). E.g. the generic point P in the graph represents a colour having C* = $(a^{*2} + b^{*2})^{1/2}$ and h_{ab} coordinates.

Many academic scientists have studied this aspect, with the aim to assess the variation of the stone colour following a change of the surface finishings [9].

Thus, when the appearance of a stone is the strategic selective criterion, it is essential to know how to actually assess the aesthetic quality of the stone which will be used.

Using the CIE L*a*b* methodology, Biscotin et al. [10] evaluated different surface cleaning methods that can be applied to stone. A protocol for evaluating the colour of heterogeneous stones was proposed by Prieto et al. [11]. Sousa and Gonçalves [12] used a colorimeter to measure the colours of a granite in the CIE L*a*b* and CIE L*C*h colour space on both large slabs and small samples.

Sanmartín et al. [13] analysed the effect of traditional surface finishing on the final appearance of different dimension stones (granites) by measuring its roughness, colour, and gloss.

Prieto et al. [14] carried out a study about the Spanish slates. They considered fifty commercial lithotypes in such a way as to define the tolerable colour ranges for the replacement of the slate tiles during the renovation of the buildings. A spectrophotometer working in the CIE L*a*b* colour space has been used in this study.

The colorimetric analysis was also used for the evaluation of the weathering of the soapstone tiles covering the statue of Christ the Redeemer in Rio de Janeiro, Brazil [15].

Other colour measurement methods were applied by Sanmartín et al. [16] by using a calibrated digital camera as a contactless colorimeter in order to assess the colour of some stone artefacts. Akkoyun et al. [17] developed a software based on image processing to assess the colorimetric properties of a polishable limestone used in both cladding and paving. Navarro et al. [18] measured the effect of ultraviolet radiation on aesthetic parameters (as colour and gloss) in ornamental serpentinites.

The CIE L*a*b* methodology is also often used to assess the efficacy of surface cleaning technologies for stone materials [19] and to analyze aesthetic textural features in different commercial varieties of a same stone [20]

The aim of the present study is to show how a different surface processing affects the colour and other aesthetic features (as gloss and roughness) of different ornamental stones, by analysing the whole stone. A second interesting purpose, which is the novelty in this study, is to demonstrate quantitatively to what degree the pure water-jet finishing maintains the original colours of the stone when compared to more traditional technologies.

2. Materials

Five lithotypes, widely commercialized in the world, have been considered in this research. These dimension stones are commercially named as Bianco Carrara D, Orosei Marble "Fiocco di neve", Verde Guatemala, Rosa Portogallo venato and Sardinian Basalt. Thin sections of the natural stone samples were prepared and then were examined under a polarized microscope to determine the textural features of each sample. The petrographic descriptions and microphotographs of the stones of the samples were determined from these thin-sections and given in Table 1.

Table 1. Petrographic descriptions and microphotographs of the lithotypes.

There are three main reasons why these stones have been chosen for this study. Firstly, each of them shows a homogeneous colour. Secondly, all these stones are generally sold easily, in any size and finish (except for flamed), globally, which is why we decided to test also Sardinian Basalt for our research. Sardinian Basalt is less known internationally although it is currently being noticed within the European market [21].

Three 10 cm x 10 cm x 2 cm specimens for each surface processing were used for the measuring tests. The number of samples (3) may seem low, expecially if compared with the number of samples (5) analysed by Prieto et al. [11]; however, this is justified from the fact that we have studied stones whose color is basically homogeneous, while Prieto et al. [11] studied granites whose color varies from mineral to mineral.

The considered surface processing technologies were the following:

- polished surface (POL): polishing is the machining operation used to achieve a bright, mirror finish with the stone surface. It uses abrasives with a very fine grain;
- saw-plane surface by diamond disk (DSP): it is the artificial surface obtained exclusively by means of sawing using diamond-coated disks which give semi-smooth surface, quite flat;
- bush-hammered surface: it is an impact surface finish which produces dotted markings. It performs alternating voids and reliefs with different appearances depending on the type of the tool. Fine (light) bush-hammering (LB) and a coarse (hard) one (HB) were applied in this study;
- pure water-jet surface (PWJ); is a surface abraded by a very high-pressure jet of water. The result is a selective erosion of the rock minerals, forming a rough and rugged surface. The water-jet processing has been carried out by using a Waterline 1620 numerical control water-jet cutting robot. The operational parameters of the equipment, listed in Table 2, were selected based on aesthetic, technical and economical assessments already described in previous research [22]).

Table 2. Pure water-jet operational parameters.

Flaming is not considered in this study. In fact, such surface finishing cannot be used on carbonate stones because the heat and thermal shock it generates ruins the stone (especially those not containing magnesium, which are “destroyed” through calcination) giving it an unattractive appearance [23]. Differently from granites, which show a typical kind of roughness when subjected to flaming [4], Sardinian basalt shows a vitrified surface [21]. The appearance of each specimen is shown in Fig. 3.

Figure 3. The five lithotypes worked by different surface treatment technologies.

3. Methods

The method applied in this study is given in Fig. 4 and it is explained in the next subchapters.

Figure 4. The methodology followed in this study.

3.1 Colour measurements

The colour was measured with a bench-top spectrophotometer CM-3610A provided by Konica-Minolta equipped with Spectra Magic NX PRO software. The measuring parameters set in the device were: illuminant D65, and observer 2° [24] with a d=8° illumination viewing geometry (following [10]). The diameter of the target mask has been set at 25.4 mm diameter in order to allow an average of the stone colour to be measured, simulating viewing from a distance. Fig. 5 shows the target masks with the scale on Orosei Marble sample.

Figure 5. The 25.4 mm diameter target masks used in this study.

As well-known [6], because the surface of the tested stones is not totally reflective or nonglossy, inclusion or exclusion of the specular component is strategic for colour measurements.

SCE (Specular Component Excluded) is the method of colour measurement, which excludes the specular reflectance. On the contrary, when the specular reflectance is included in the colour measurement, we refer to it as SCI (Specular Component Included). In SCE mode only the diffuse reflectance is measured. In this way, it is given a colour evaluation which correlates to the way a real observer sees the colour of an object. Stone surfaces characterized by matte colour and irregularities induce the light scattering in many directions, thus reducing the specular component excluded [19]: for this reason, measurements have been carried out in SCE mode. When using the SCI mode, the specular reflectance is included with the diffuse reflectance during the measurement process. This type of colour evaluation measures the entire appearance regardless of the surface conditions; SCI mode is useful when measuring a polished surface and comparing results with gloss measurements.

For the above reasons, in this study, the measurements were made in both SCI and SCE modes.

Following previous studies [11, 13, 9] 9 random readings were taken of some zones of the surface for each one of the three specimens (100 cm^2) and for each type of surface finishing during the measuring of the whole sample colour. The instrument automatically repeats three times the measurement for each reading, before providing an average result.

As effectively explained by Sanmartín [13], the CIE L*a*b* coordinates are preferred for achromatic colours, whereas the CIE L*C*h* coordinates are recommended for stronger colours. Because the objective of this study was to try to assess the colours of the stones and since the finishing technologies which were used typically change the chromatic or achromatic range of the stone, both sets of coordinates were used.

Moreover, following the suggestions for textured samples reported by Huertas et al. [25], the classical CIEL*a*b* colour equation (1) was applied, rather than the newer improved formulas, as follows:

$$\Delta E = \sqrt[2]{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b)^2} \qquad (1)$$

3.2 Gloss measurements

The gloss measurement has been performed by using a Micro-TRI-Gloss meter provided by BYK Gardner; the gloss values are expressed in GU (gloss units) and ranges from 0 to 100. When measuring surface gloss numerically, a light is directed towards a pre-defined surface angle of the sample. The reflex is then measured with a reflectometer. Measurements were done at 20°, 60° and 85° for each specimen. The measurement unit conforms to the standards ISO 2813 [26], ISO 7668 [27] and ASTM D-523 [28] because there are no standards on gloss measurement in the specific field of stone materials.

Some reference advises that the assessment of gloss values on polished stone surfaces may incur in measurement flaws [29]. In fact, some mineral types have partially transparent surfaces which cause an internal diffusion of a part of the incident light which is not foreseen. This internal diffusion effect, which is a characteristic of many types of polished stone, creates a component of diffused light that alters gloss measurement, which should refer only to the component of specular reflected light. However, this problem is solved easily by re-measuring each sample several times. In this study, eight measurements on each sample have been carried out by placing the glossmeter in eight different positions, as shown in Fig. 6.

Figure 6. Eight different glossmeter positions for gloss measurement used in this study (see also Fig. 4).

3.3 Roughness measurement

The roughness profile of the finished specimen was cautiously analysed using a Feinprüf Perthen S3P mechanical comparator. The measurements were carried out along the whole length of each specimen with each reciprocal distance of 1 cm.

For each specimen the R_a (mean roughness) parameter was determined in accordance with EN ISO 21920-3 [30]. Surface roughness profiles were examined along the x and y directions by 1 cm spacing.

Bearing in mind the results obtained in previous studies [31, 9], it was decided not to consider other parameters returned by the comparator such as: R_z = (average distance between the highest peak and lowest valley in each sampling length), R_{max} (maximum roughness depth) and W_t (waviness depth). This is because the three parameters are not useful in this study.

4 Results and discussion

4.1 L*a*b* colour space

Figs. 7, from a to e, show the CIE L*a* b* values correlated with the different surface finishings.

As confirmed to previous studies [9, 13], for all studied stones the SCI and SCE values are almost identical when considering rough surfaces; on the contrary, they differ considerably when the surface is polished.

Figures 7. Values of the a*, b* and L* chromatic coordinates for the different surface processing; a) Bianco Carrara D, b) Orosei Marble “Fiocco di neve”, c) Verde Guatemala, d) Rosa Portogallo venato, e) Sardinian basalt

Looking at Bianco Carrara D diagram (Fig. 7a), we notice that both a* and b* values are very similar and close to the origin of the axes. Only the PWJ sample shifted upwards. In fact, the water-jet action allows the breakage of the crystals along the cleavage planes giving a greater brilliance of the grains. Moreover, as already demonstrated in the past [32], Carrara marble has a series of distinctive short veins which are irregularly distributed and which are composed by impurities in the form of micro-cryptocrystalline pyrite [33] that reacts plastically to the action of the jet, giving the surface a pleasing appearance.

The L* values are similar in all samples, with a higher value in the bush-hammered ones (LB and HB). As it is known [23], unlike the action of the water-jet, bush-hammering produces non-selective work because the hammers' action is not influenced by the nature of the crystal being hit. This is why bush-hammering gives surfaces with homogeneous colour and lightness.

Fig. 7b, shows how the different finishings have a greater influence on the colour of Orosei Marble “Fiocco di neve”, shifting it in particular towards the direction of yellow (+b*). If compared to polishing, water-jet processing “lights up” the colour more, while bush-hammering “turns it off”. Moreover, unlike the other rocks studied, the SCE and SCI values differ markedly. This may be related to the presence of bioclasts in the stone that react differently to processing than the stone matrix, thus reflecting light more randomly. Finally, this stone exhibits high lightness values for all samples measured.

The colour coordinates measured in Verde Guatemala samples (Fig. 7c) are very similar to each other, slightly shifted toward green (-a*). The DSP surface is the only one whose values lie in the negative axis of b* (towards blue). On the other hand, there are substantial differences in the L* values, especially for bush-hammered surfaces. In fact, in many building applications, this marble is used showing a fine alternation of polished and bush-hammered areas.

As shown in Fig. 7d, finishings tend to dull the colours of Rosa Portogallo, especially when the surface is bush-hammered. On the contrary, the lightness values are almost constant although the bush-hammered samples have a higher L* values.

On Sardinian basalt (Fig. 7e), PWJ finishing maintains the colour and lightness of the stone almost unchanged, as already qualitatively found in previous studies [34]. Bush-hammering and sawing tend to bring the surface colour toward higher b* and L* values.

4.2 L*C*h colour space

The surface finishings on Bianco Carrara D do not seem to affect the chroma values (Fig. 8a); the variation of the hue values is considerably more marked showing higher values on the finely bush-hammered sample (LB).

Opposite results are visible on the Orosei Marble (Fig. 8b). C* values vary strongly according to the finishing: bush-hammering processing tends to decrease the chroma compared to the POL sample, while pure water-jet finishing tends to exalt the colour. Unlike the other stones, the SCI and SCE values differ considerably. In particular, the SCE values have higher values of Chroma and Luminosity than the corresponding SCI values; the reason has already been explained in paragraph 3.1. The h values remain almost constant as the surface finishing changes.

The surface finishings do not have a great influence on the C* values when used on Verde Guatemala (Fig. 8c), but there are clear differences both in the L* values (as already explained) and in the h* values, for which DSP sample tends towards blue and the HB sample tends towards yellow.

In Rosa Portogallo, the C* values depend strongly on the finishing (Fig. 8d): compared to the polished samples, all the finishings tend to decrease the C* values, which reach the minimum with the bush-hammering. The h values vary slightly compared to polished specimens, with higher values on both LB and HB surfaces.

In Sardinian Basalt (Fig. 8e), the water-jet finishing is the closest to polishing in terms of L*C*h* values; on the other hand, an increase in all three values is noted in the other finishings.

Figures 8. Values of the C*, L* and h chromatic coordinates for the different surface processing; a) Bianco Carrara D, b) Orosei Marble "Fiocco di neve", c) Verde Guatemala, d) Rosa Portogallo venato, e) Sardinian basalt.

4.3 Total colour difference (ΔE*)

Fig. 9 summarizes the total colour differences (ΔE*) in each tested lithotype for each surface finishings.

Figure 9. Total colour differences (ΔE*) in a) Bianco Carrara D, b) Orosei Marble "Fiocco di neve", c) Verde Guatemala, d) Rosa Portogallo venato, e) Sardinian basalt for each surface finishings. ΔE* values corresponding to two different JND are also shown.

We note that the action of bush-hammering mostly changes the colours of all the stones, with the exception of Marmo di Orosei, where the ΔE* values are more affected by the water-jet finishing. This is possible because the water-jet excavates more easily in areas where no bioclasts are present, which evidently offers greater resistance to the jet; the result of the different excavation leads to a colorimetric difference.

This is the only case in which water-jet treatment changes the colour of the stone significantly. In the other stones, pure water-jet finishing preserves the original colours more than any other rough process.

The total colour difference is more evident when SCE is considered; this is because the surface finish makes the stone surface rough resulting in increased reflectance, as already explained in subchapter 4.1.

It is interesting to observe the ΔE* values with respect to JND (or "just noticeable difference") [35], which we could translate as the difference that occurs between two intensity levels of a sensory stimulus. This threshold is given by $\Delta E^* \approx 2.3JND$. However, this formula is not optimal: an observer does not notice the color difference when $\Delta E^* < 1$; an unexperienced observer notices the difference when $2 < \Delta E < 3.5$ [36]. Figure 9 shows also the two thresholds ($\Delta E^* = 1$, dashed line and $\Delta E^* = 2.3$, dotted line): the only imperceptible difference in colour seems to be that related to the sawplane surface (DSP) of the Orosei Marble (Fig. 9b).

4.4 Correlations between CIE colour coordinates and roughness measurement.

Taking into account the previous experiences [9, 13, 37] mean roughness R_a has been related to L*a*b* coordinates. Table 3 summarizes the roughness measurements.

Table 3. Mean roughness values R_a, measured in μm, for the different finished surfaces. (BCD = Bianco Carrara D, MOF = Orosei Marble "Fiocco di neve", VG = Verde Guatemala, RPV = Rosa Portogallo venato and SB = Sardinian Basalt).

Considering the total and partial colour differences (ΔE*, ΔL*, Δa* and Δb*) referred to the POL samples with the average roughness difference (ΔR_a also referred to the POL samples), some interesting considerations can be drawn. All values are summarized in Table 4.

Table 4. Total colour difference (ΔE*) between the polished surface and each of the other surface finishes for the five stones tested, in SCI and SCE modes. The mean roughness difference (ΔR_a) is also reported. (BCD = Bianco Carrara D, MOF = Orosei Marble "Fiocco di neve", VG = Verde Guatemala, RPV = Rosa Portogallo venato and SB = Sardinian Basalt).

It is important to explain why the POL samples have been taken as the reference state for comparison: the polishing results in surfaces with the maximum enhancement of the decorative and aesthetic stone qualities [38]; since this process changes the colour back to the natural (original) colour of the stone, POL sample has been chosen as the reference state for comparison in our research.

In Figs. 10, ΔE* values (apart from SCI and SCE values) show some interesting correlations with ΔR_a, expecially when Carrara Marble, Orosei Marble and Rosa Portogallo are considered. However, if PWJ data are not considered (because these samples show very low ΔE* values and higher ΔR_a), correlation exceeds 0.80 (Fig. 10c). This is especially true in the cases of Sardinian Basalt and Verde Guatemala, on which water-jet processing produces greater roughness than other stones. This fact can be easily explained because the PWJ treatment keeps the colours almost unaffected regardless of the roughness as opposed to bush-hammering [9].

It is not easy to make a comparison of the correlations amongst the different stones tested . This would require the previous knowledge of so many parameters, especially those pertaining to: 1) rock properties, 2) operational parameters of each surface processing technology, and 3) desired aesthetic results. Since each of these sets of parameters varies according to the stone, it is extremely difficult to find an overall correlation.

Figures 10. Total colour difference (ΔE*) and mean roughness difference (ΔR_a) in a) Bianco Carrara D, b) Orosei Marble "Fiocco di neve", c) Verde Guatemala, d) Rosa Portogallo venato, e) Sardinian basalt for each surface finishing.

4.5 Correlations between gloss and roughness measurement.

Table 5 presents the three gloss measurements for each surface finishes of the five tested stones.

Table 5. Gloss values, expressed in Gloss Unit [GU], for the different finished surfaces for each tested stone.

The inverse correlation between the R_a and the three gloss values confirms what was found in Careddu, 2020 [9]. Correlations are of exponential type, and they are higher for the gloss 85° (Figs. 11 from a to e) especially for Bianco Carrara D, Verde Guatemala and Rosa Portogallo.

Figures 11. Correlations between specular gloss (measured at 20°, 60° and 85°) and mean roughness difference.

5 Conclusions

In this study, the measurement of the colours of the stones was taken in an extremely precise way by using advanced instruments, as well as the colour variation resulting from a different surface processing.

Bush-hammering is a very versatile process, in fact it offers the possibility to camouflage the colour, hide any defects and give the rock a rough appearance. This was confirmed by the study carried out, as the lowest a* and b* values in both Bianco Carrara D and Rosa Portogallo are related to bush hammering. The a* and b* values of Verde Guatemala, worked by coarse bush-hammering and sawing, are almost identical. The lowest a* and b* values for Sardinian basalt, on the other hand, are related to polishing, even if the difference is tiny, when compared to bush-hammering.

The highest average roughness values, related to the tested stone range, belong to the coarse bush-hammering finishing; on the contrary, both in Sardinian basalt and Orosei marble "Fiocco di neve", the highest R_a is related to the water-jet processing, because of the different operating parameters pertaining to the technology.

Gloss values in polished rocks are obviously high when compared to those processed by other technologies. On the contrary, the chromatic values of polished stones are not always the highest: only by polishing of Rosa Portogallo and Verde Guatemala does the rock obtain the highest chroma values. Carrara Marble and Orosei Marble reach the maximum chroma with water-jet processing, while Sardinian Basalt has maximum chroma values following a fine bush-hammering.

Bush-hammering brings all the tested rocks to higher lightness values. These characteristics can be useful to cover the external walls of buildings, for outdoor paving and for urban furniture, in outdoors areas where you are not expecting colour variations, which are typical of many ornamental rocks, but rather a high lightness.

Polishing produces a surface with a "mirror effect", although it generally has lower L* values than bush-hammering and sawing. These characteristics can be suitable for opposite uses compared to bush-hammering: the polished surface is preferred in interior environments, where the focus is on bringing out the colour of the rocks.

In Sardinian basalt, the surface obtained via water-jet produces a rougher and less bright surface, which causes the almost total absorption of the incident light of both the spectrophotometer and the glossmeter. These characteristics are useful when paving roads of historical centers because of the typical roughness of the surface (hence its anti-slippery feature) and the absence of any reflection, a dangerous occurrence for the circulation of vehicles.

Orosei marble “Fiocco di neve”, when polished, presents the highest value of L*: together with Bianco Carrara D and Rosa Portogallo venato, these stones are particularly suitable for those uses where brightness and high light reflection are both required.

In the following development of the study, the spectral reflectance will be considered. The research will aim to identify which curve can be used to verify that the colour of the investigated stone meets the requirements of the client.

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Figure 1

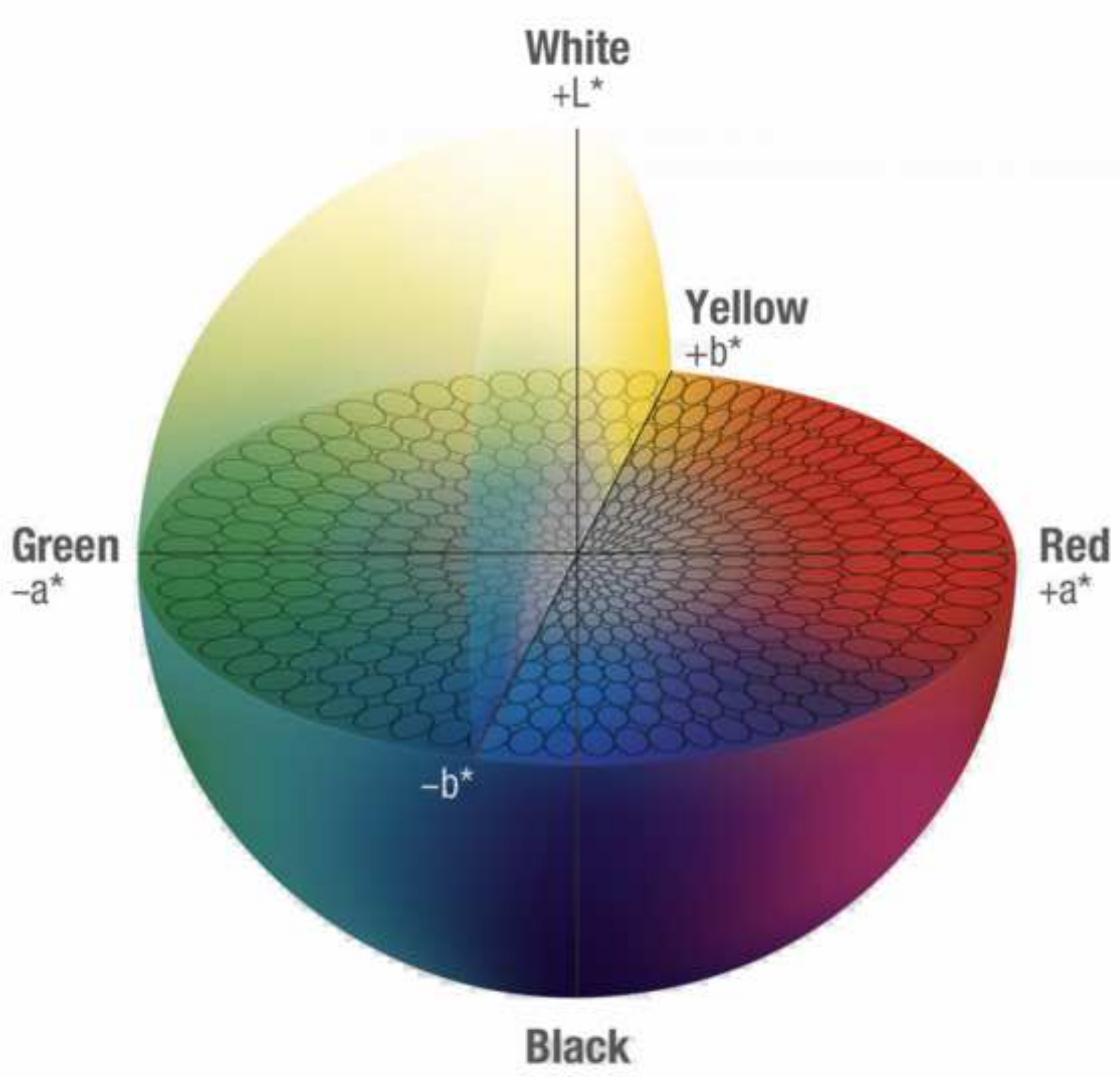


Figure 2

Click here to access/download;Figure (Do not upload picture, .svg format. Upload only PDF, eps or tiff format);Figure 2 - Lch.tiff

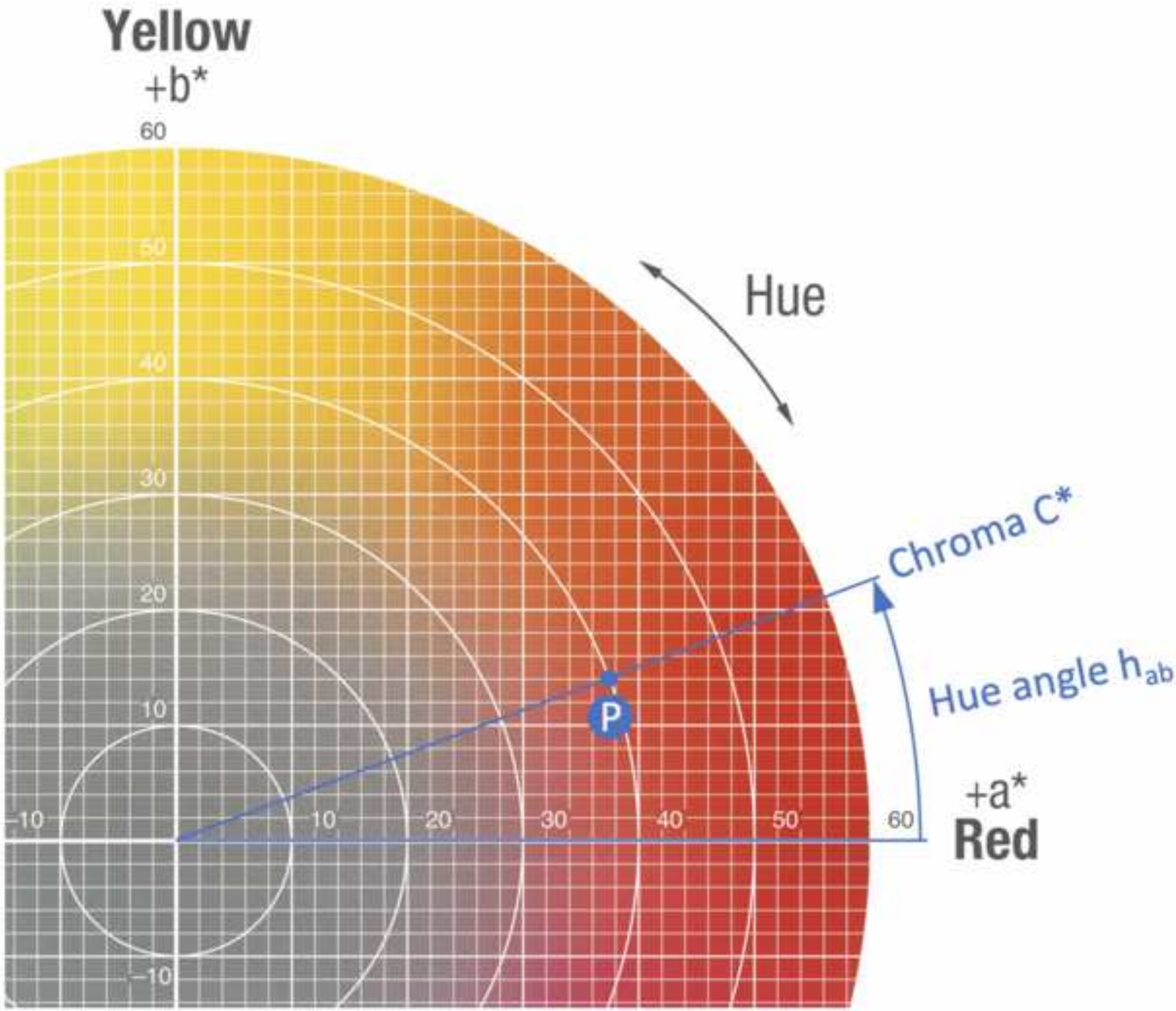
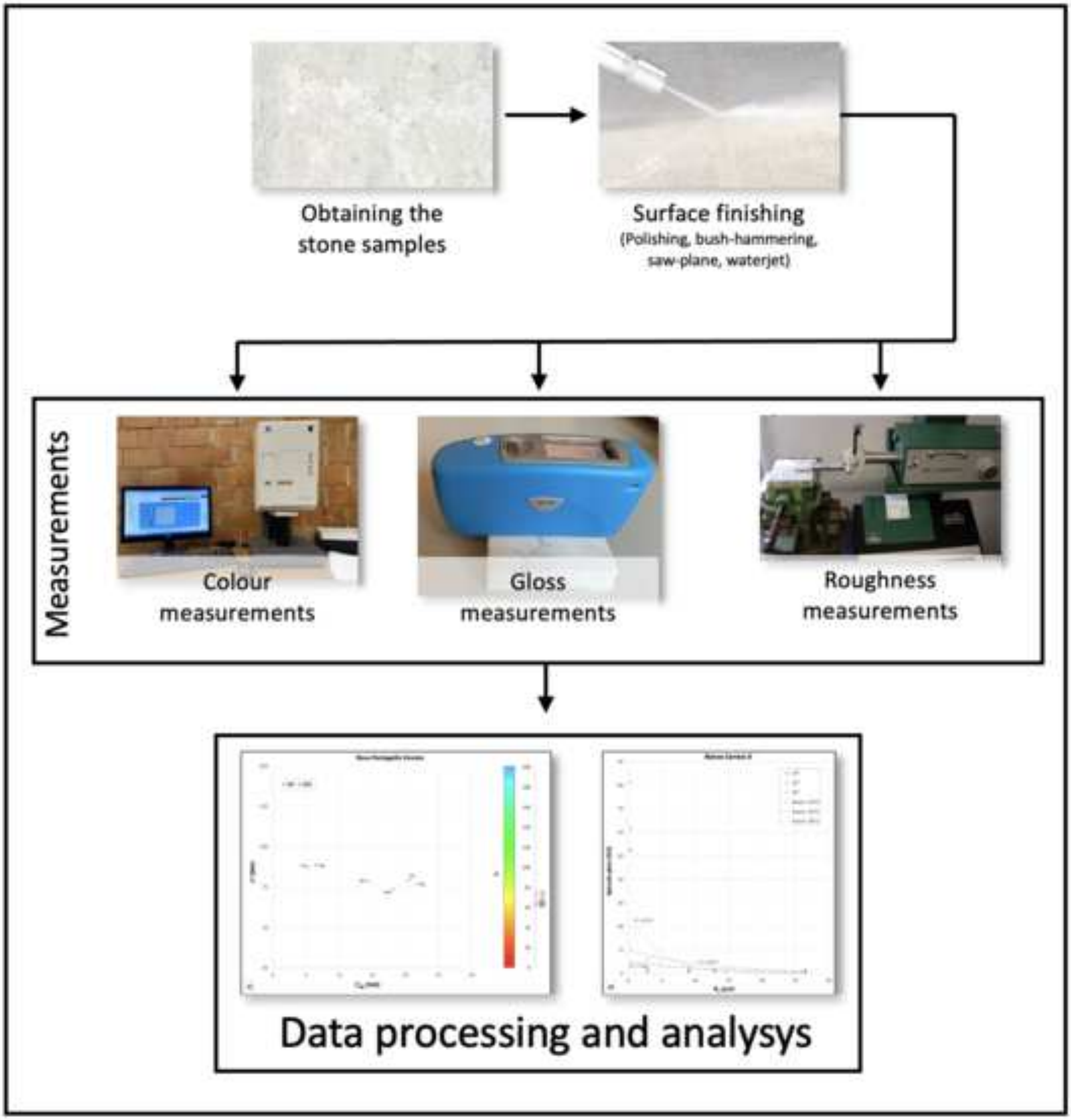


Figure 3


POL
DSP
LB
HB
PWJ
Bianco Carrara D
Orosei marble
«Fiocco di Neve»
Verde Guatemala
Rosa Portogallo
venato
Sardinian basalt

Figure 4



Obtaining the stone samples
Surface finishing
(Polishing, bush-hammering, saw-plane, waterjet)
Measurements
Colour measurements
Gloss measurements
Roughness measurements
Data processing and analysys

Figure 5

Figure 6

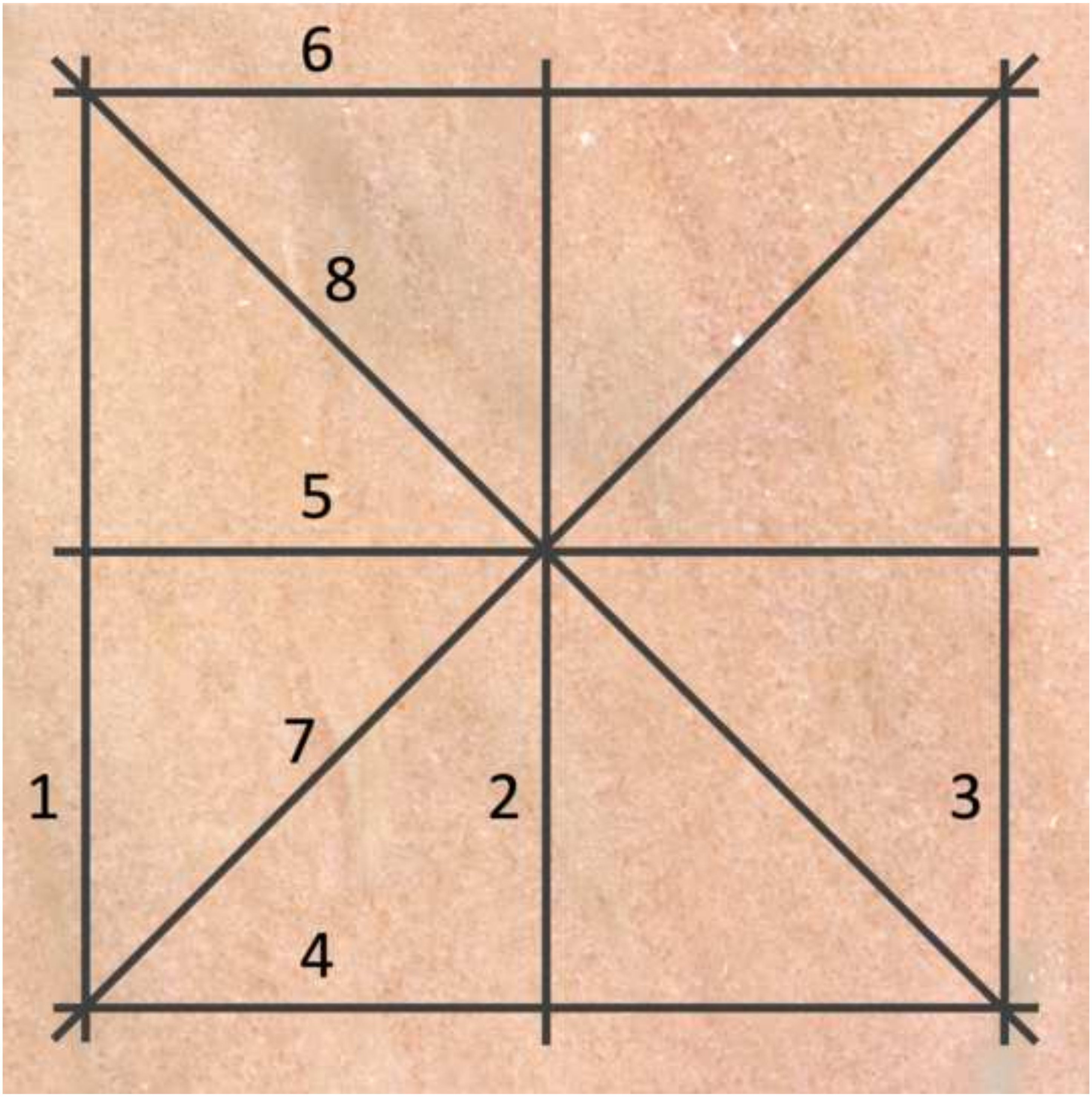


Figure 7a

Click here to access/download;Figure (Do not upload picture, .svg format. Upload only PDF, eps or tiff format);Figure 7a - Lab Bianco Carrara D.tiff

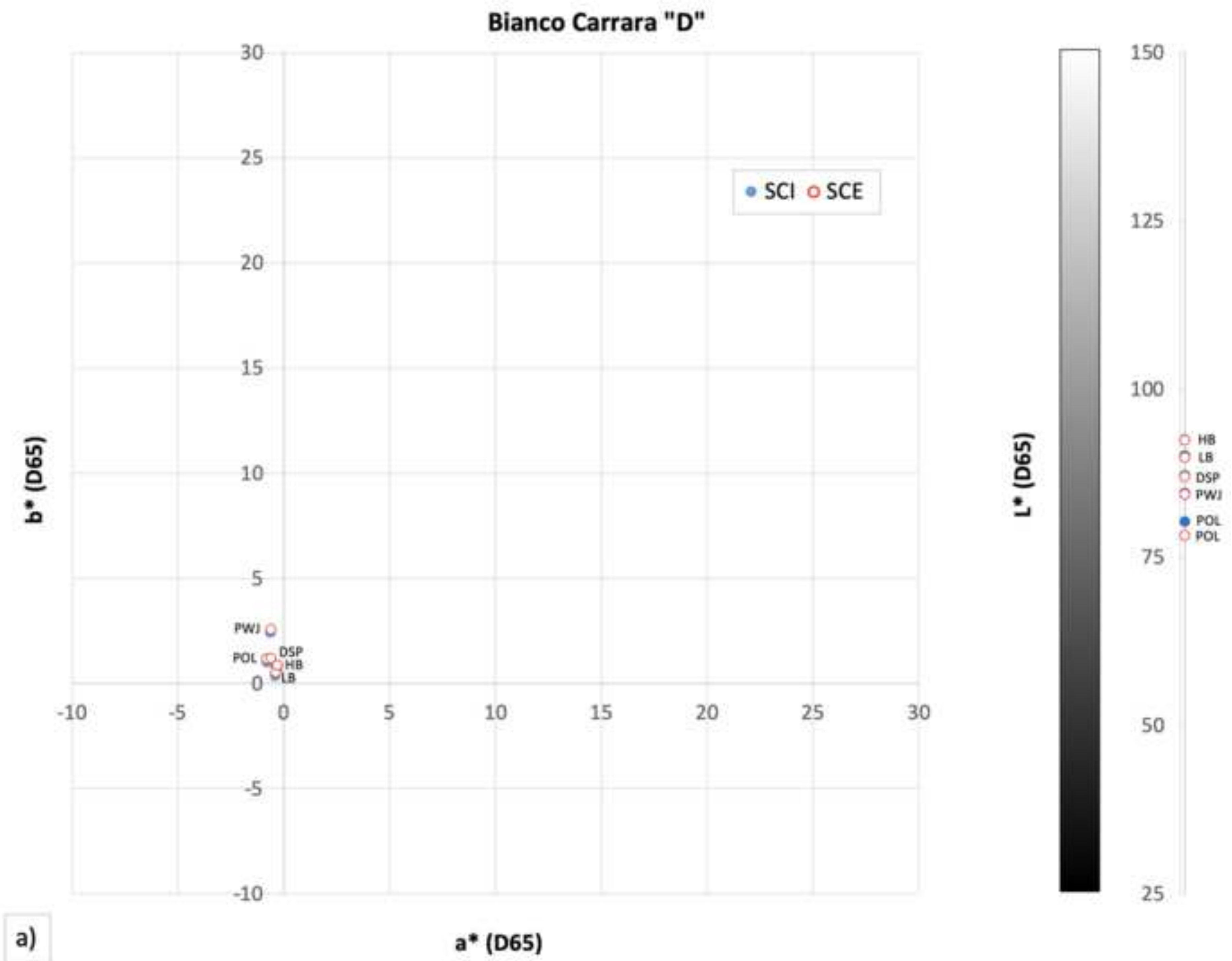


Figure 7b

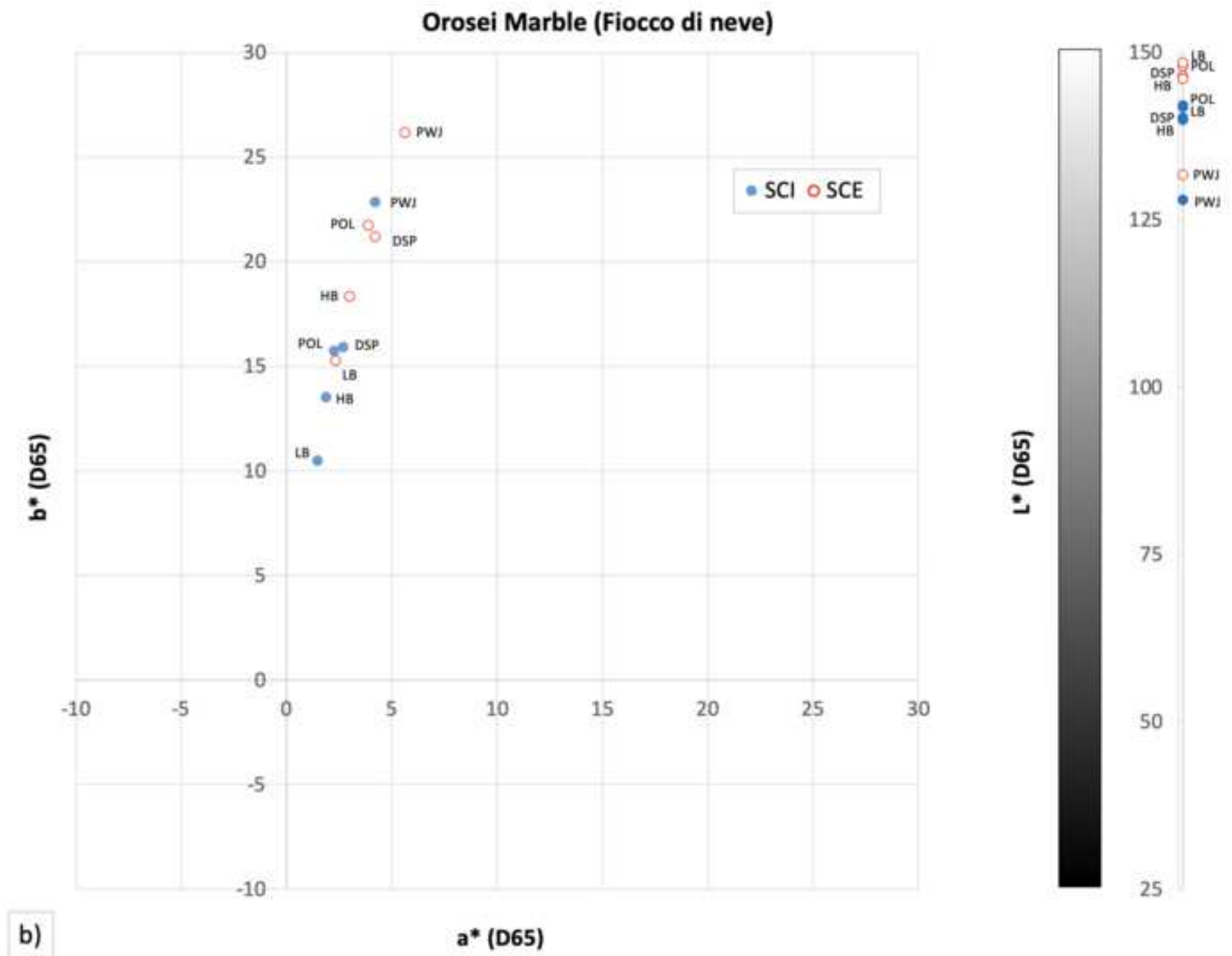

Orosei Marble (Fiocco di neve)
b* (D65)
a* (D65)
L* (D65)
SCI
SCE
PWJ
POL
DSP
HB
LB
30
25
20
15
10
5
0
-5
-10
150
125
100
75
50
b)

Figure 7c

Click here to access/download;Figure (Do not upload picture, .svg format. Upload only PDF, eps or tiff format);Figure 7c - Lab Verde Guatemala.tiff

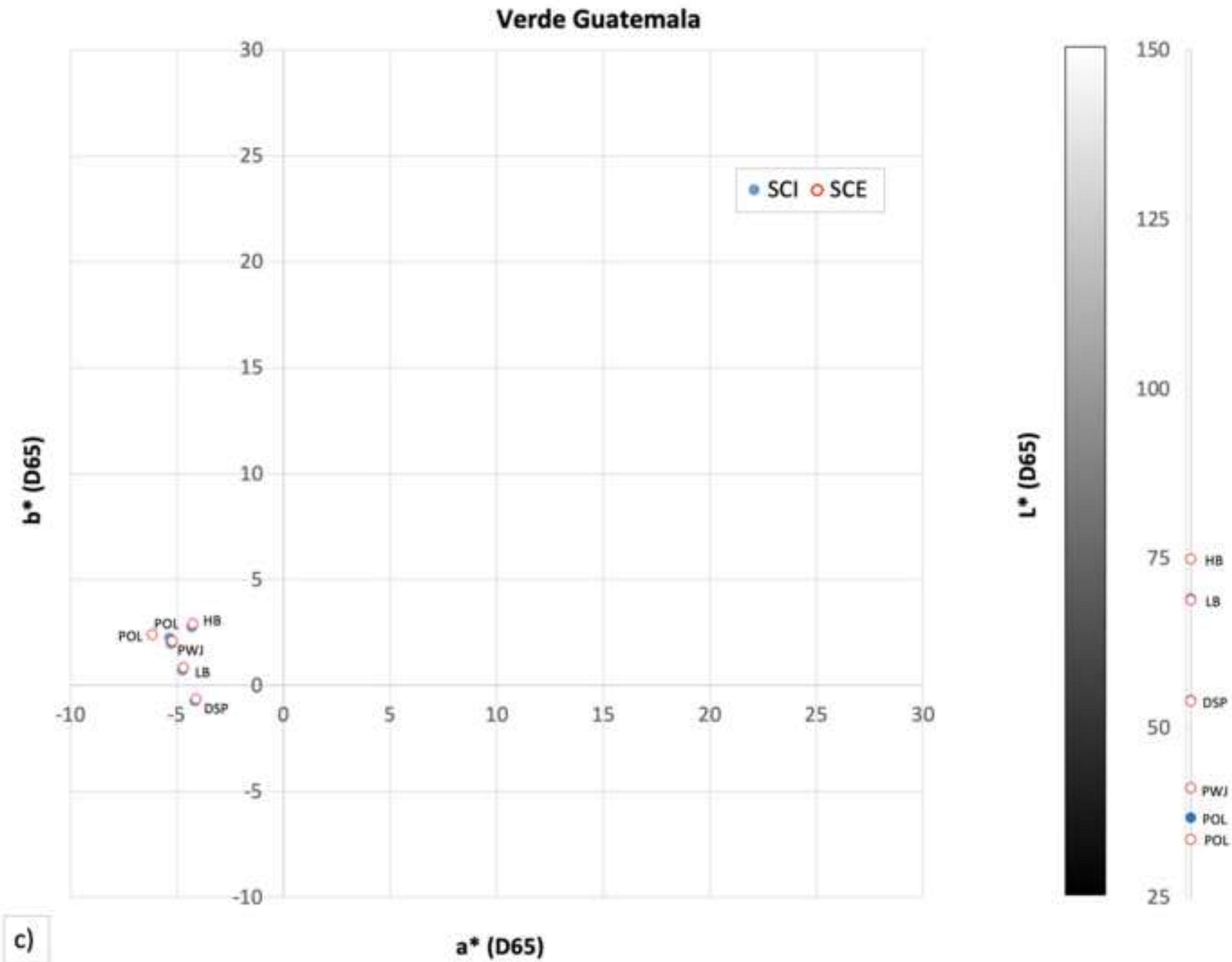


Figure 7d

Click here to access/download;Figure (Do not upload picture, .svg format. Upload only PDF, eps or tiff format);Figure 7d - Lab Rosa Portogallo venato.tiff

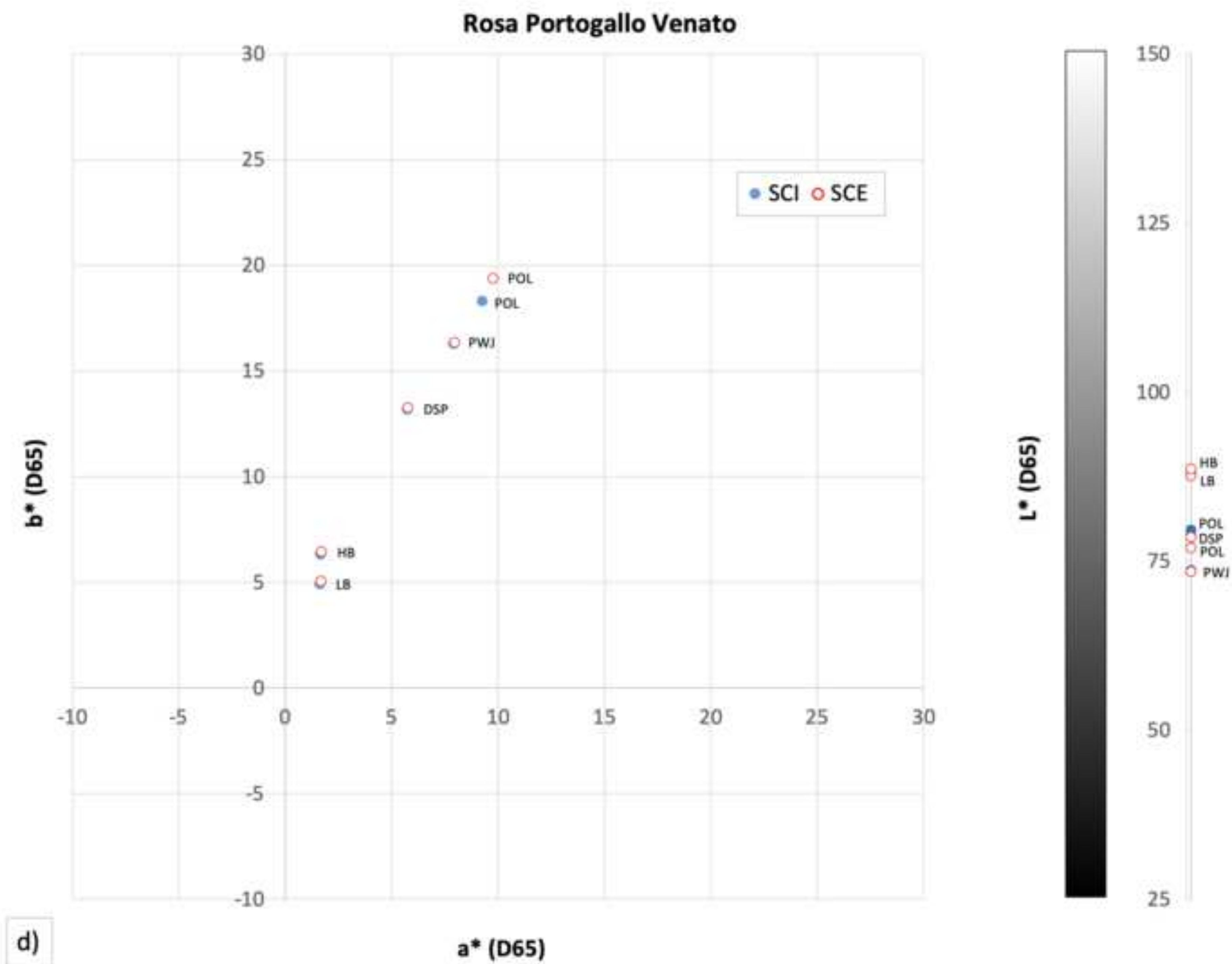


Figure 7e

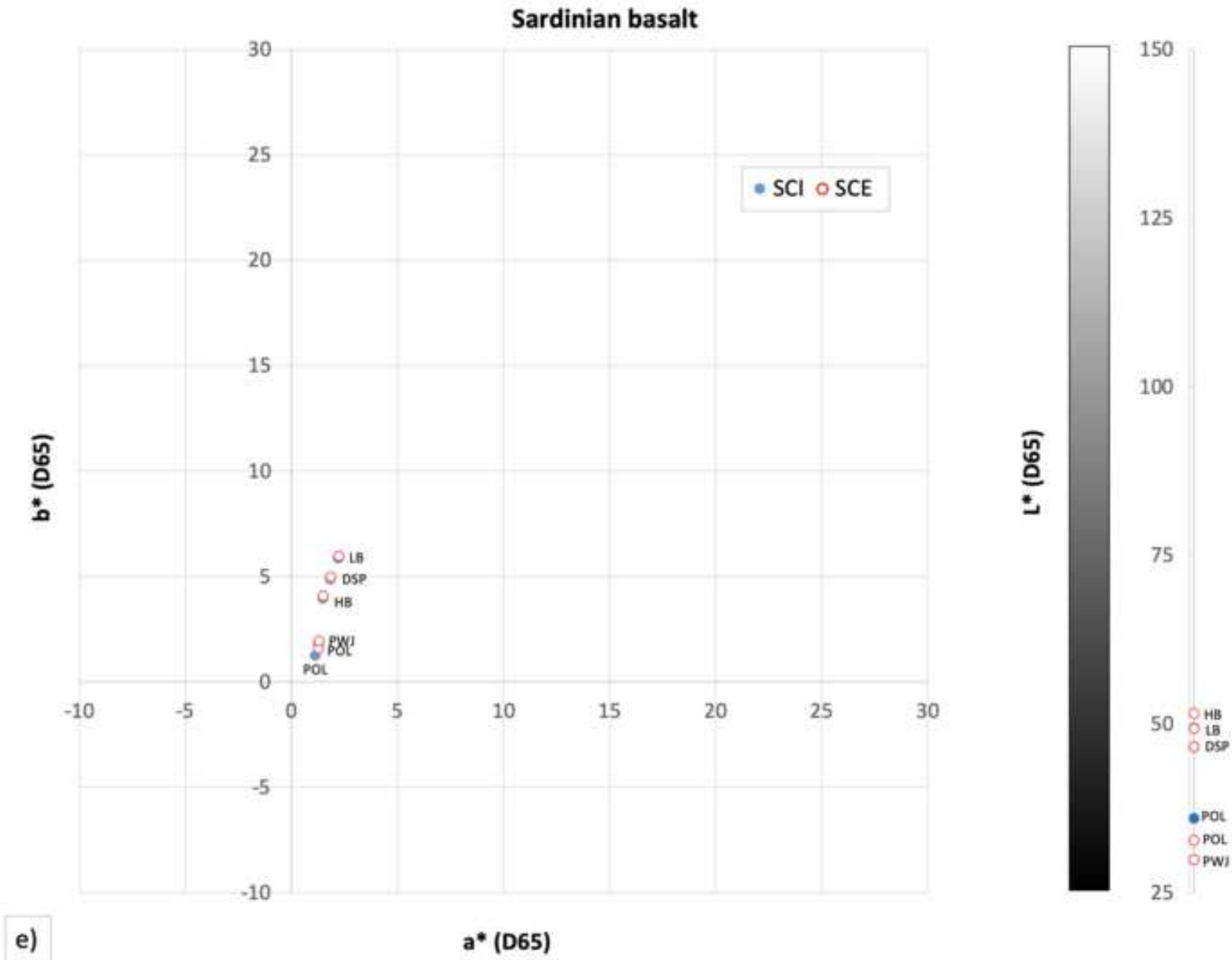

Sardinian basalt
SCI
SCE
b* (D65)
a* (D65)
L* (D65)
30
25
20
15
10
5
0
-5
-10
-10
-5
0
5
10
15
20
25
30
150
125
100
75
50
25
LB
DSP
HB
PWJ
POL
POL
HB
LB
DSP
POL
POL
PWJ
e)

Figure 8a

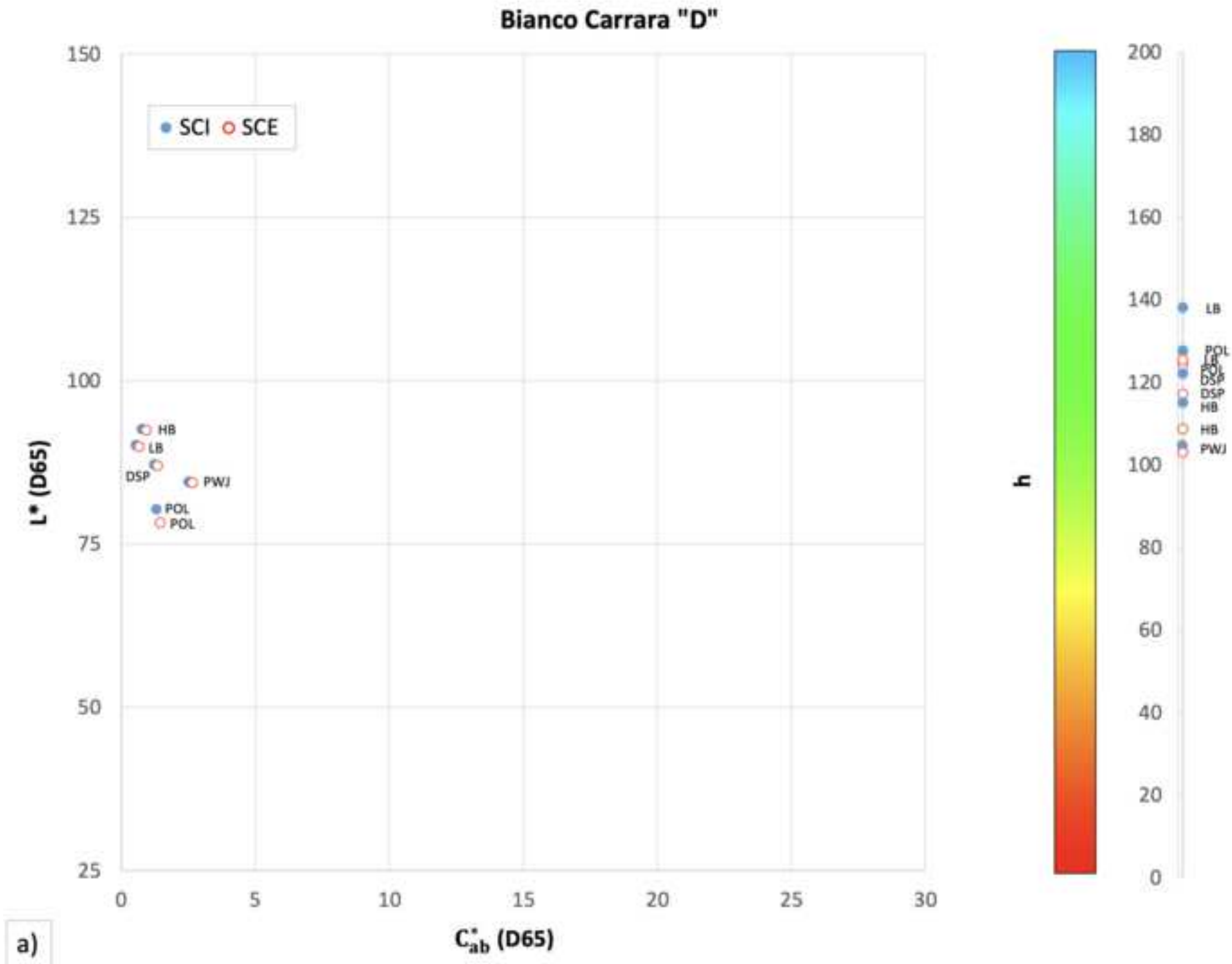

Bianco Carrara "D"
SCI
SCE
150
125
100
75
50
25
0
5
10
15
20
25
30
L* (D65)
C^*_{ab} (D65)
HB
LB
DSP
PWJ
POL
POL
200
180
160
140
120
100
80
60
40
20
0
h
LB
POL
LB
POL
DSP
DSP
HB
HB
PWJ
a)

Figure 8b

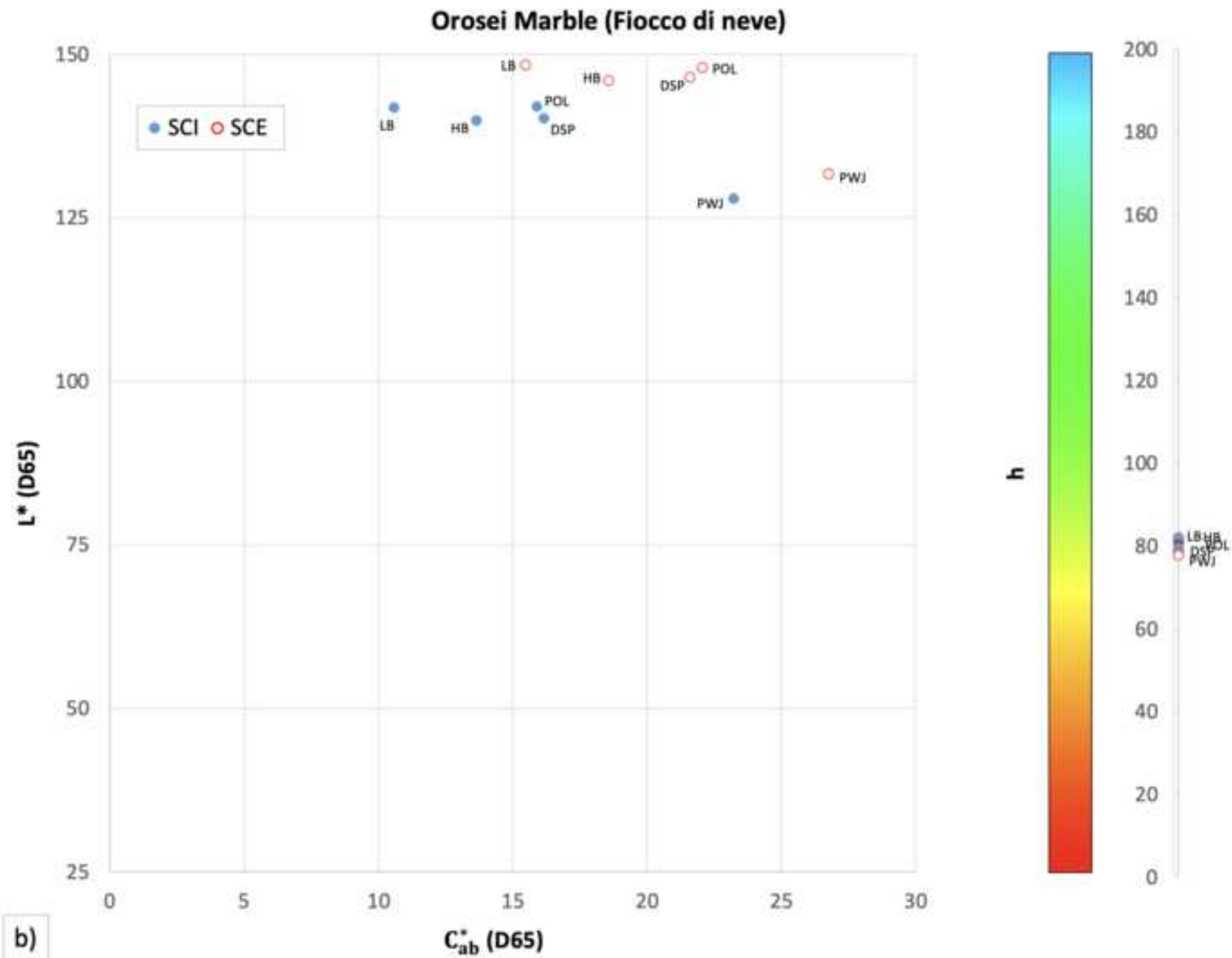

Orosei Marble (Fiocco di neve)
SCI
SCE
L* (D65)
C^*_{ab} (D65)
h
LB
HB
POL
DSP
PWJ
150
125
100
75
50
25
0
5
10
15
20
25
30
200
180
160
140
120
100
80
60
40
20
0
b)

Figure 8c

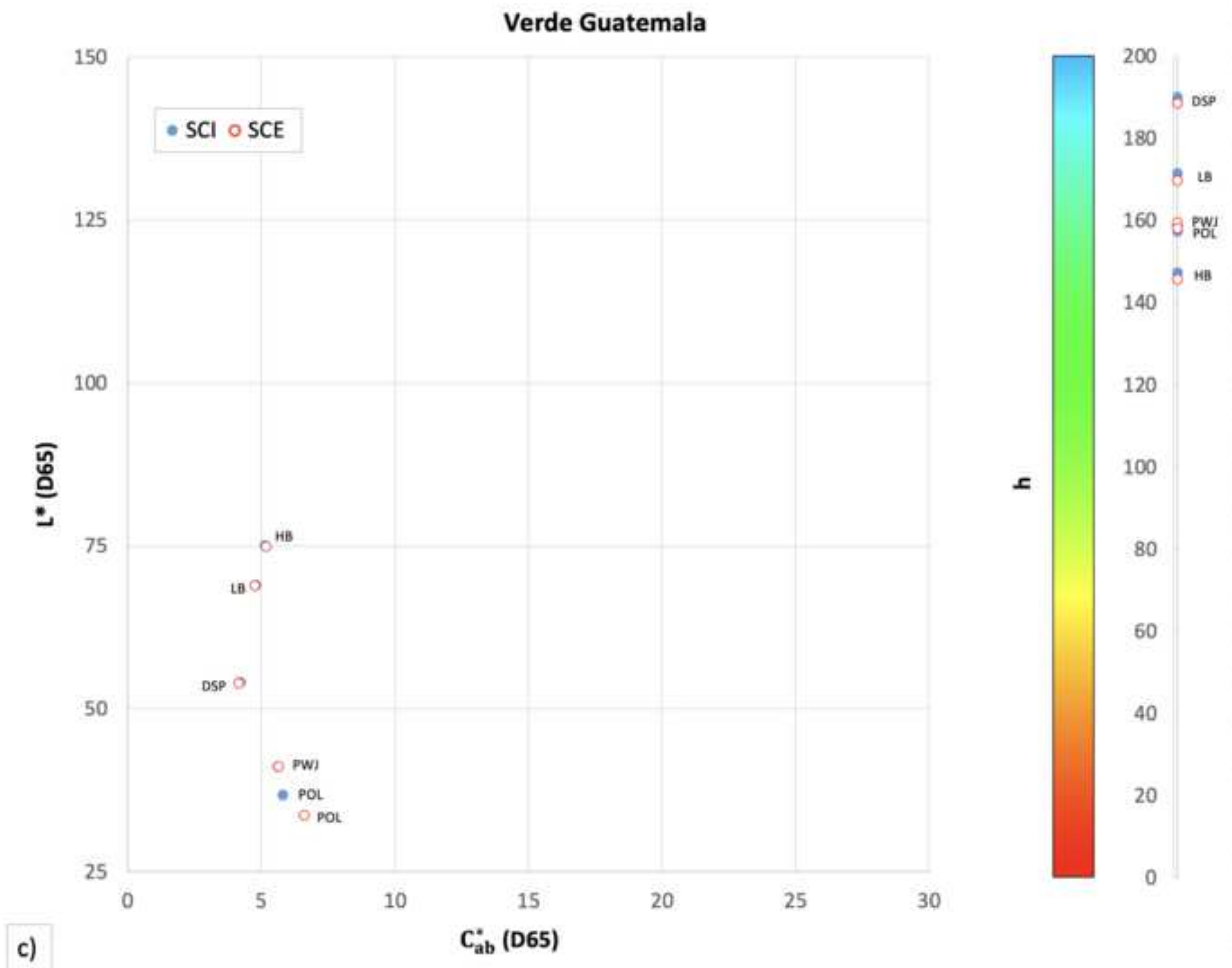

Verde Guatemala
SCI
SCE
150
125
100
75
50
25
L* (D65)
0
5
10
15
20
25
30
C*ab (D65)
HB
LB
DSP
PWJ
POL
POL
h
200
180
160
140
120
100
80
60
40
20
0
DSP
LB
PWJ
POL
HB
c)

Figure 8d

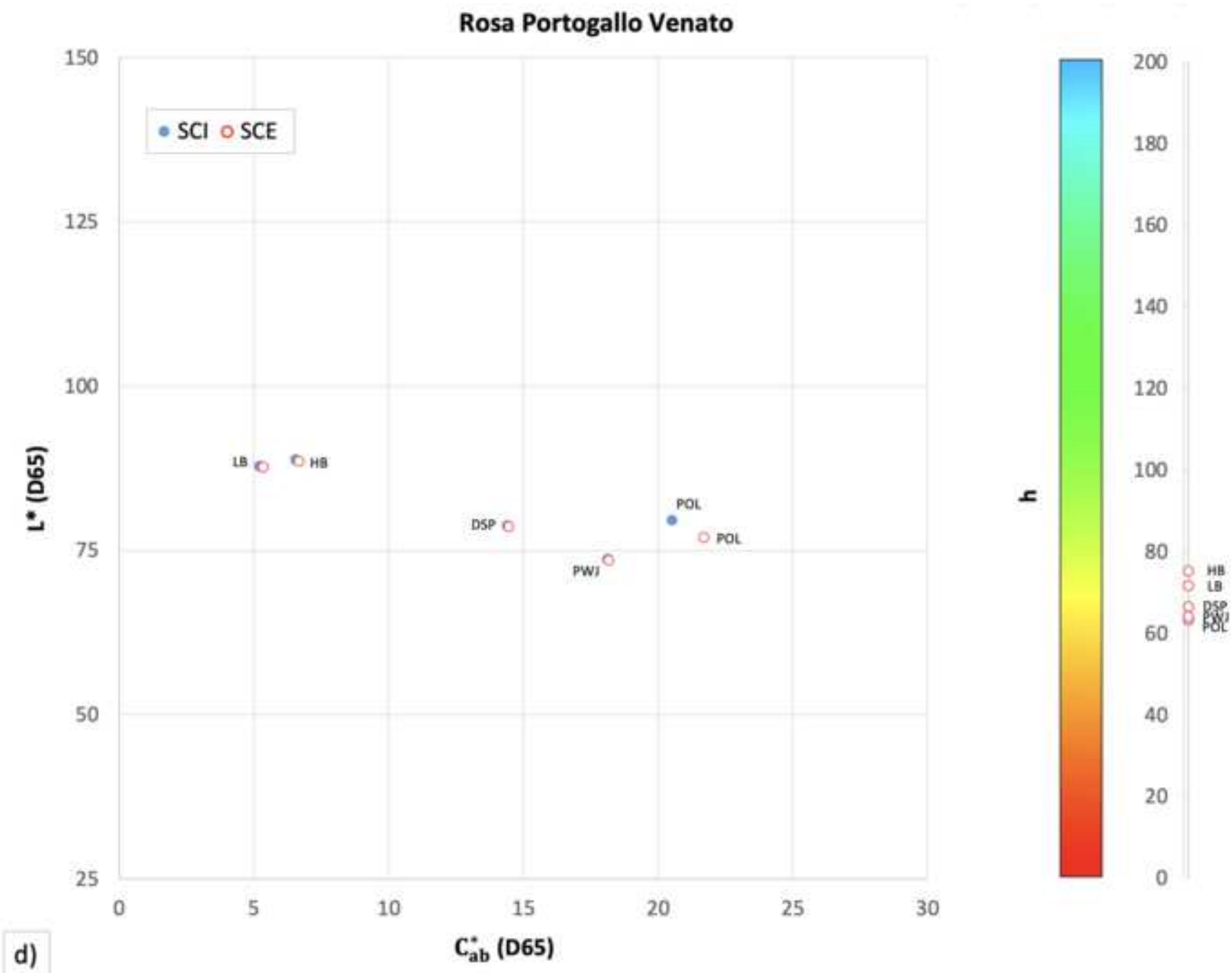

Rosa Portogallo Venato
SCI
SCE
150
125
100
75
50
25
0
5
10
15
20
25
30
L* (D65)
C*ab (D65)
LB
HB
DSP
POL
POL
PWJ
h
200
180
160
140
120
100
80
60
40
20
0
HB
LB
DSP
PWJ
POL
d)

Figure 8e

Click here to access/download;Figure (Do not upload picture, .svg format. Upload only PDF, eps or tiff format);Figure 8e - LCh Sardinian basalt.tiff

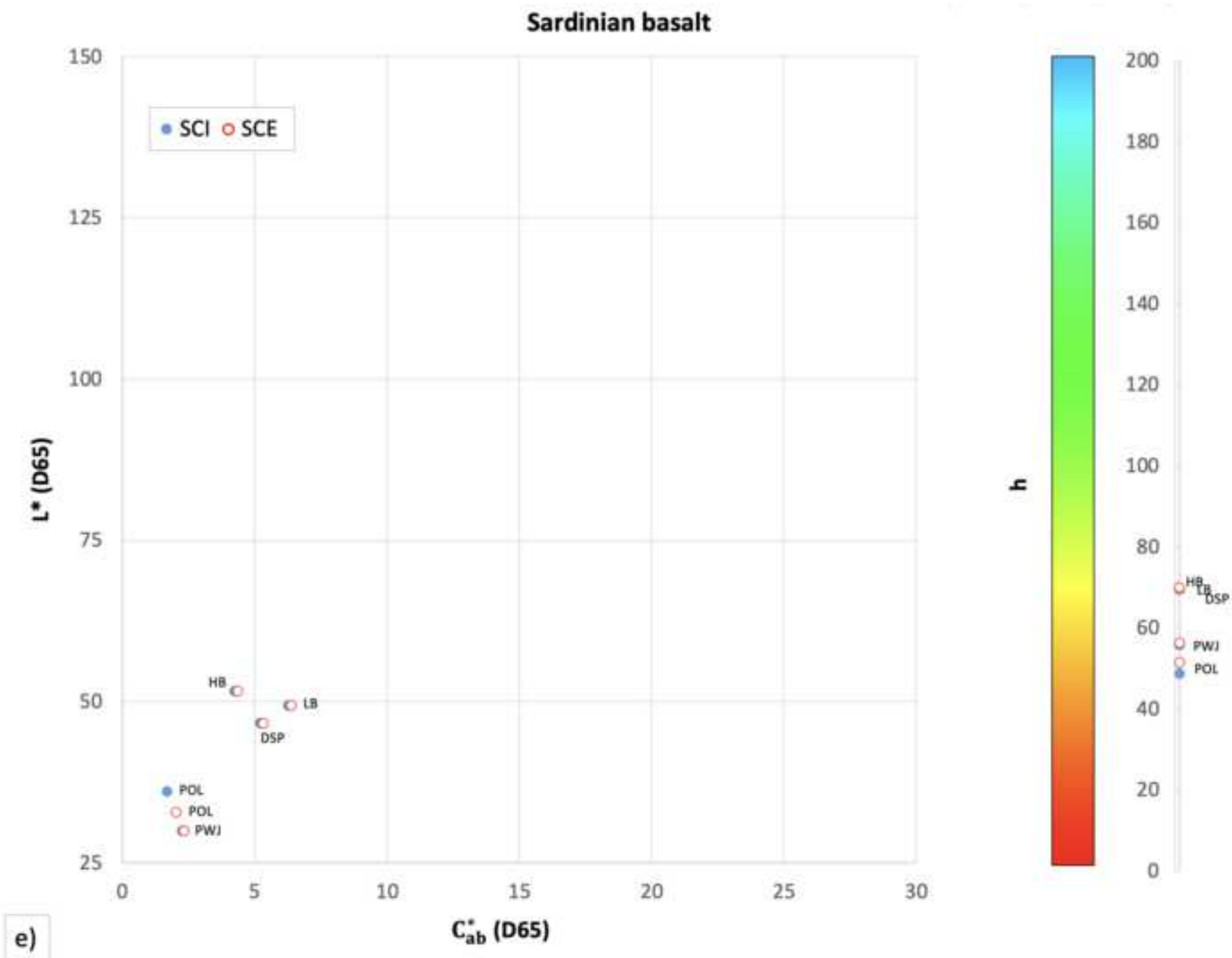


Figure 9

Click here to access/download;Figure (Do not upload picture, .svg format. Upload only PDF, eps or tiff format);Figure 9 - Delta E rev.tiff

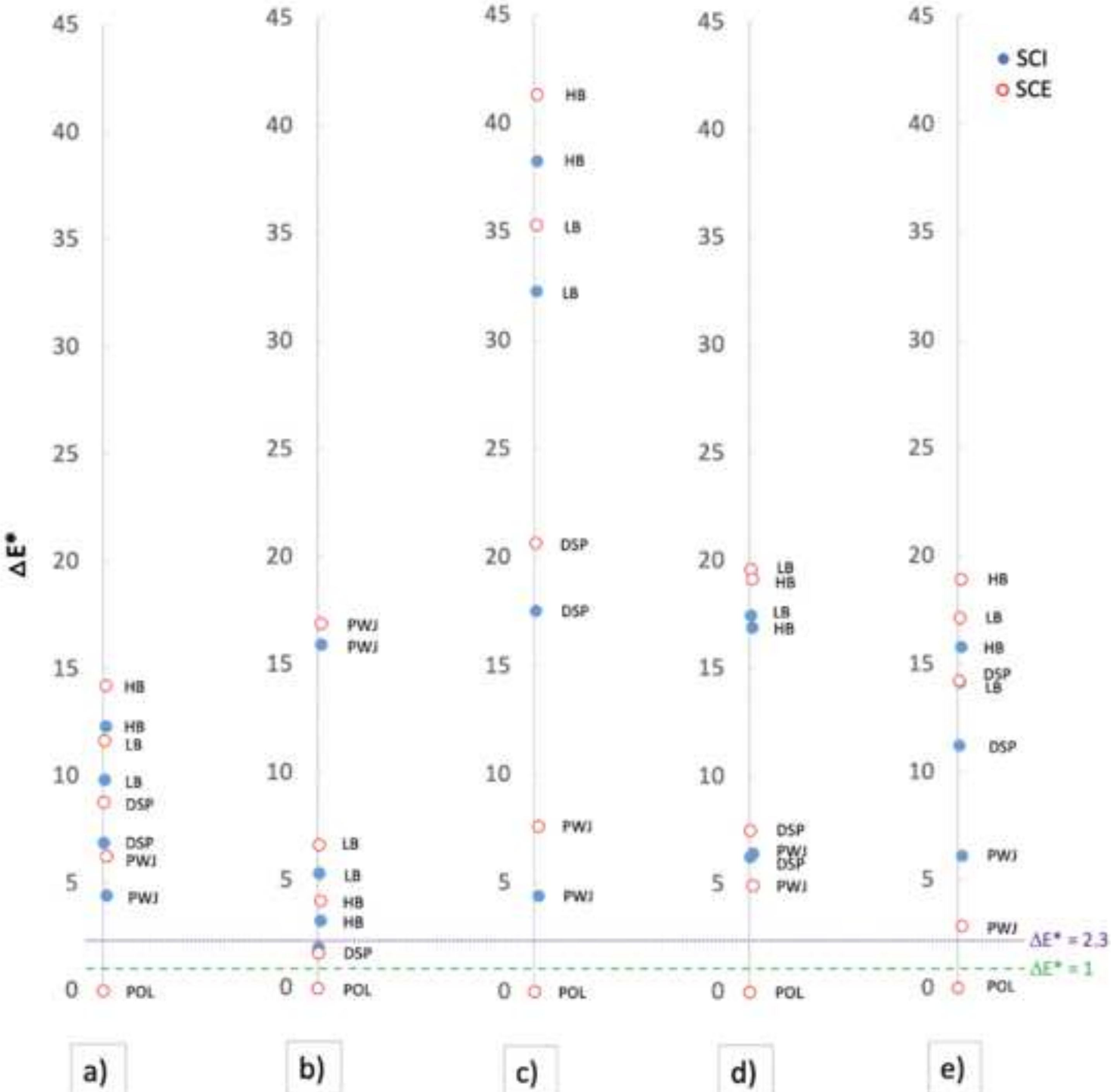


Figure 10a

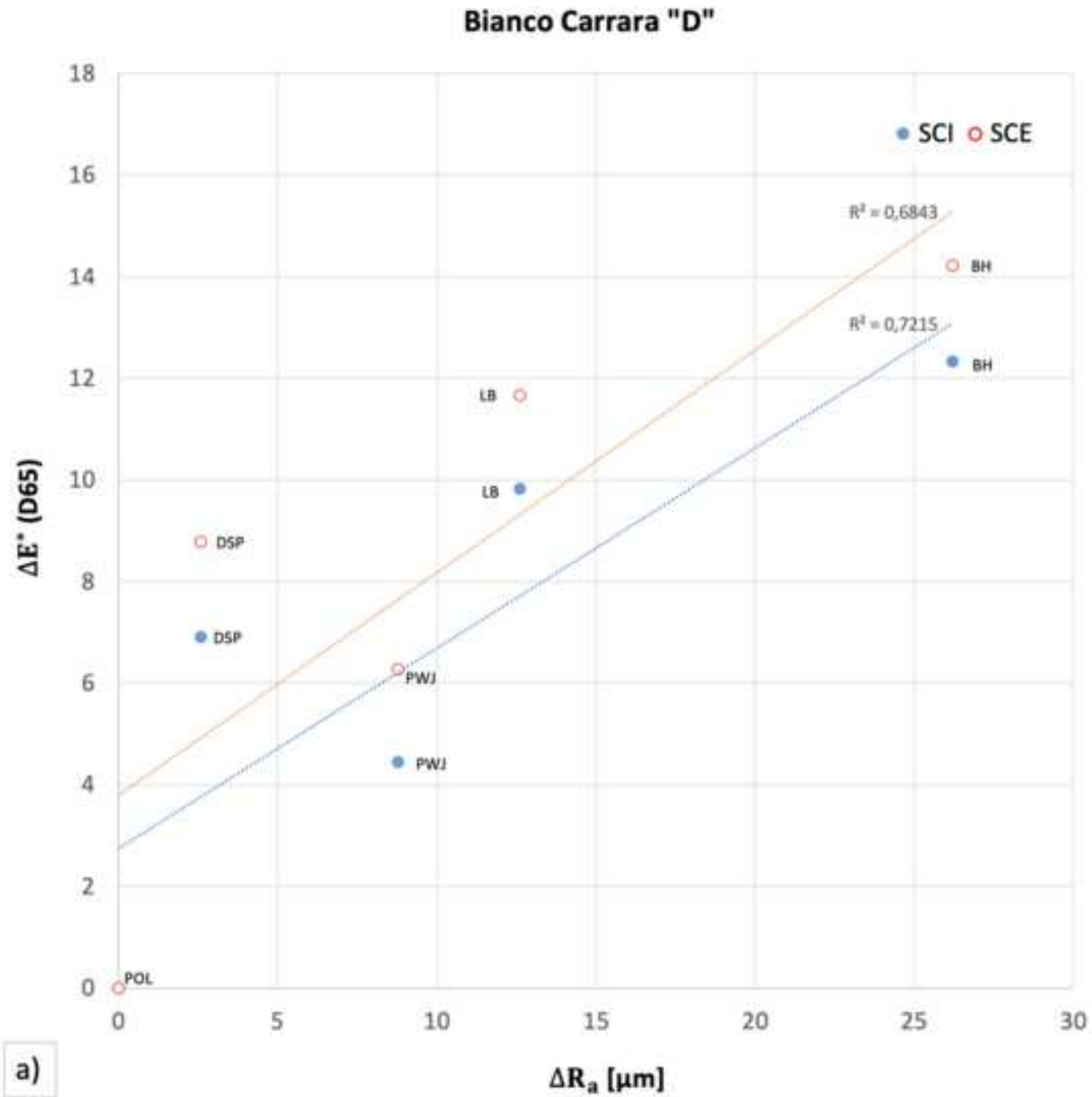
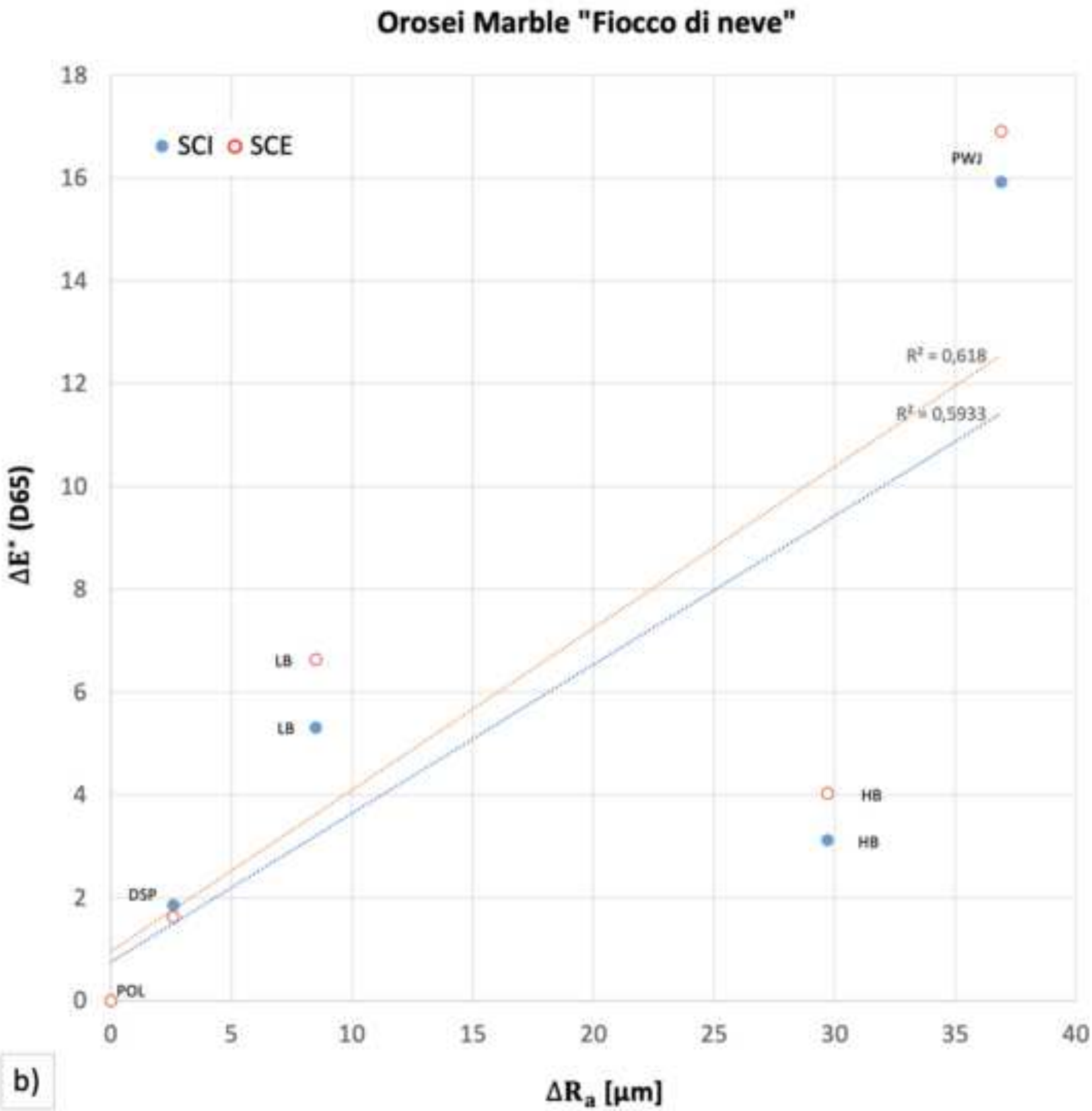
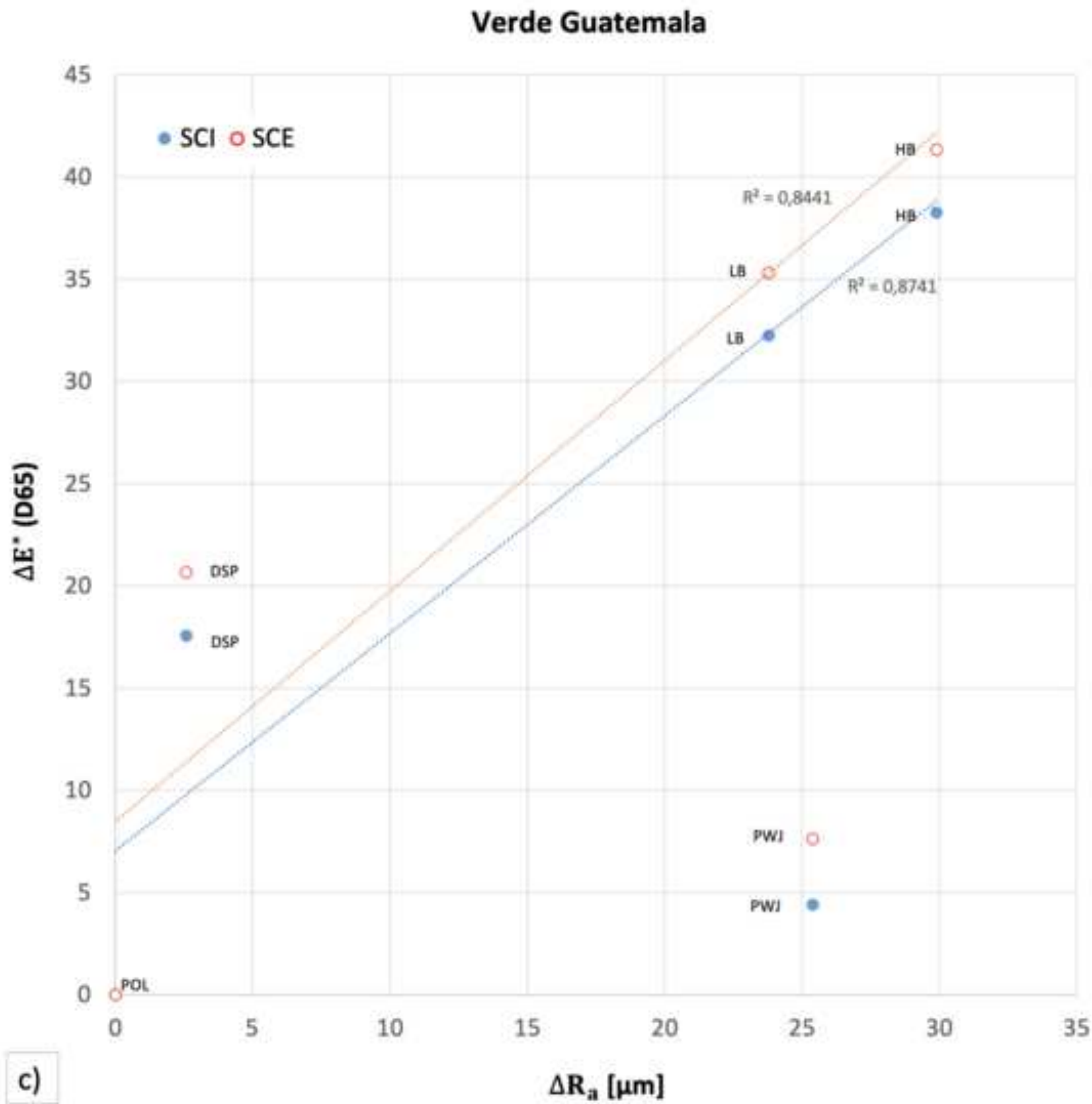

Bianco Carrara "D"
SCI
SCE
R² = 0,6843
R² = 0,7215
BH
BH
LB
LB
DSP
DSP
PWJ
PWJ
POL
ΔE* (D65)
ΔRa [µm]
0
2
4
6
8
10
12
14
16
18
0
5
10
15
20
25
30
a)

Figure 10b


Orosei Marble "Fiocco di neve"
SCI
SCE
PWJ
LB
LB
HB
HB
DSP
POL
R² = 0,618
R² = 0,5933
ΔE* (D65)
ΔRa [µm]
0
2
4
6
8
10
12
14
16
18
0
5
10
15
20
25
30
35
40

b)

Figure 10c



Verde Guatemala
SCI
SCE
HB
HB
LB
LB
DSP
DSP
PWJ
PWJ
POL
R² = 0,8441
R² = 0,8741
ΔE* (D65)
ΔRa [µm]
0
5
10
15
20
25
30
35
40
45
0
5
10
15
20
25
30
35
c)

Figure 10d

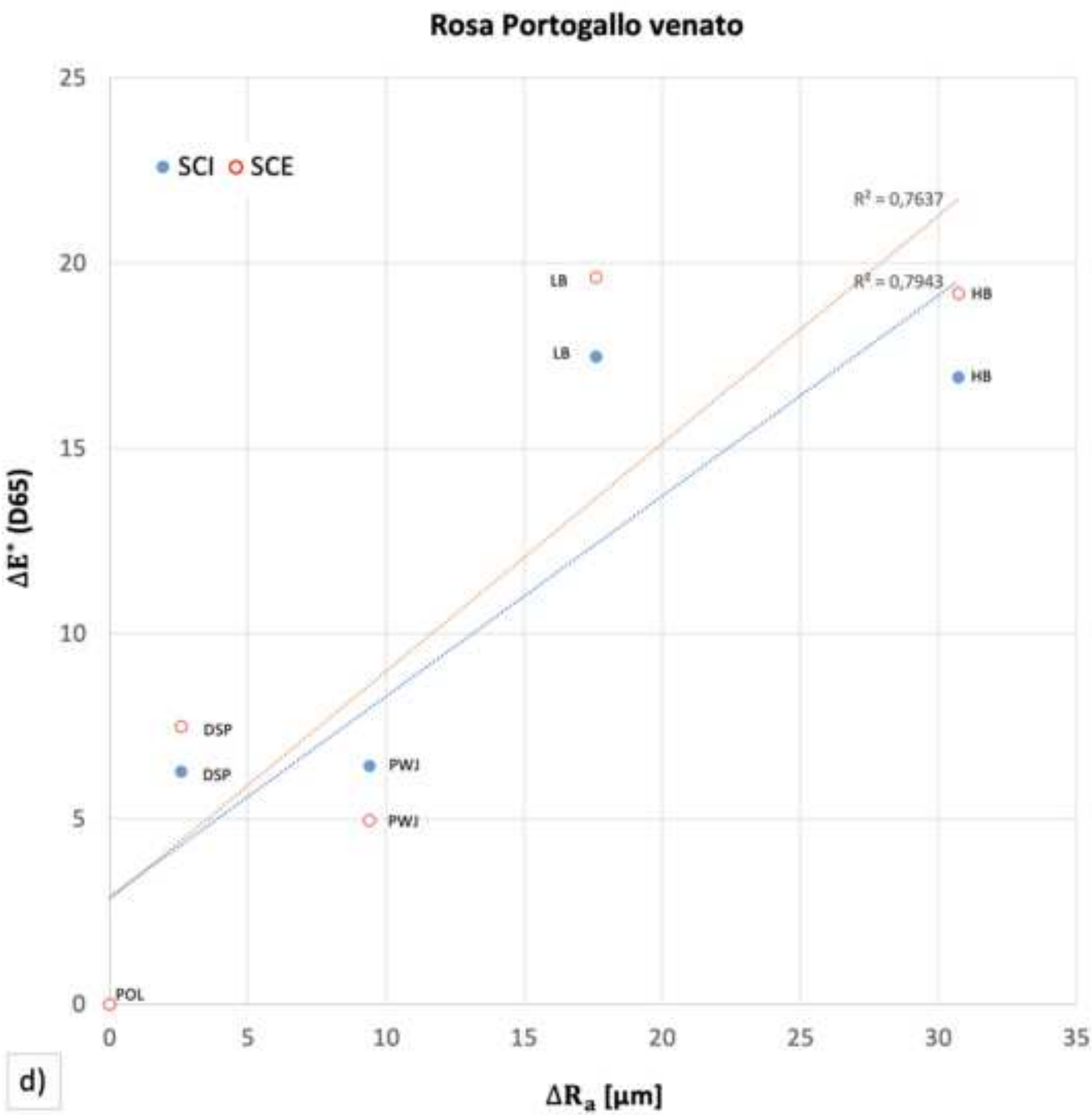

Rosa Portogallo venato
SCI
SCE
R^2 = 0,7637
R^2 = 0,7943
LB
LB
HB
HB
DSP
DSP
PWJ
PWJ
POL
ΔE* (D65)
ΔR$_a$ [µm]
0
5
10
15
20
25
30
35
d)

Figure 10e

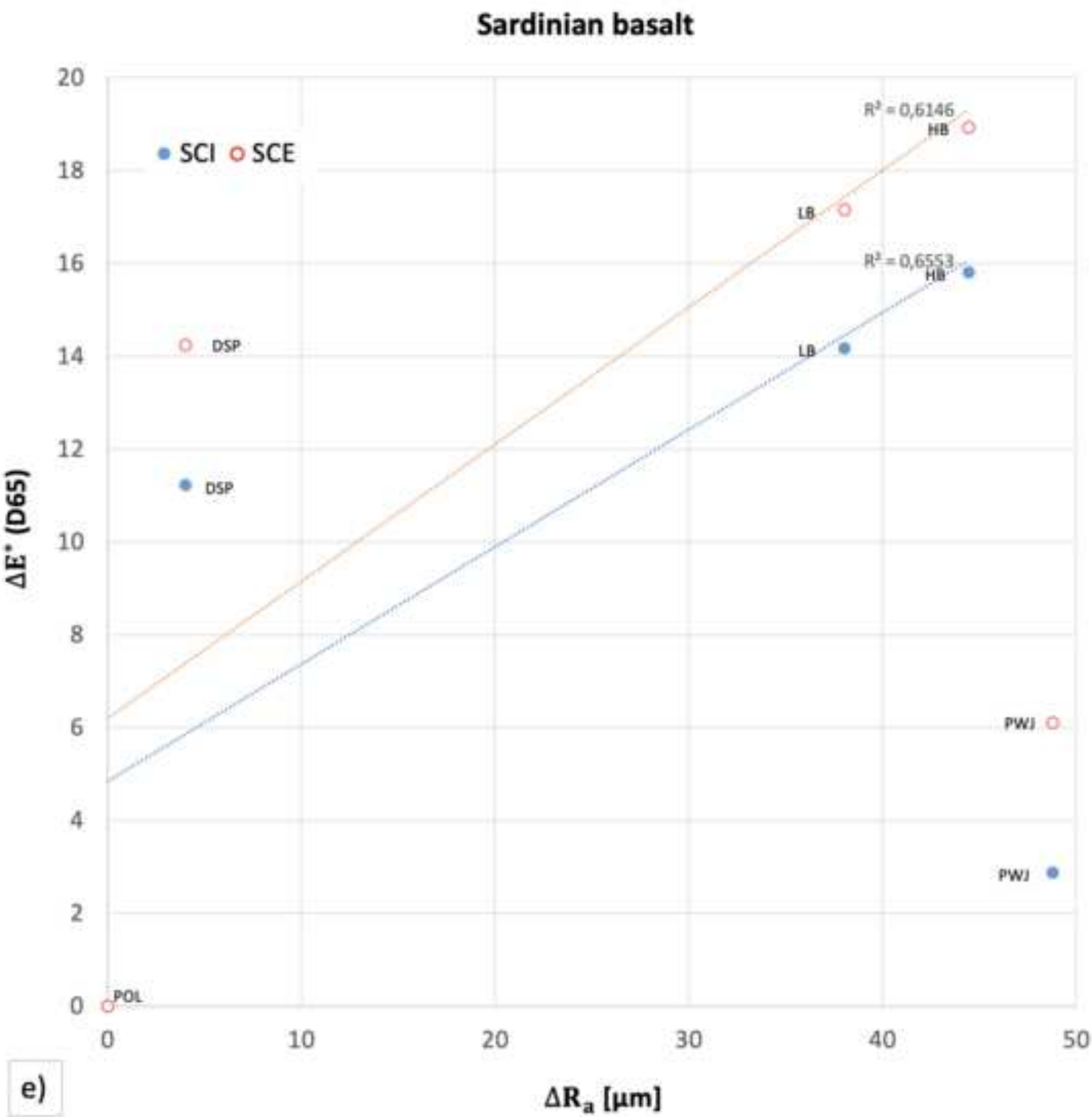

Sardinian basalt
SCI
SCE
R² = 0,6146
HB
LB
R² = 0,6553
HB
LB
DSP
DSP
PWJ
PWJ
POL
ΔE* (D65)
ΔRa [µm]
0
2
4
6
8
10
12
14
16
18
20
0
10
20
30
40
50
e)

Figure 11a

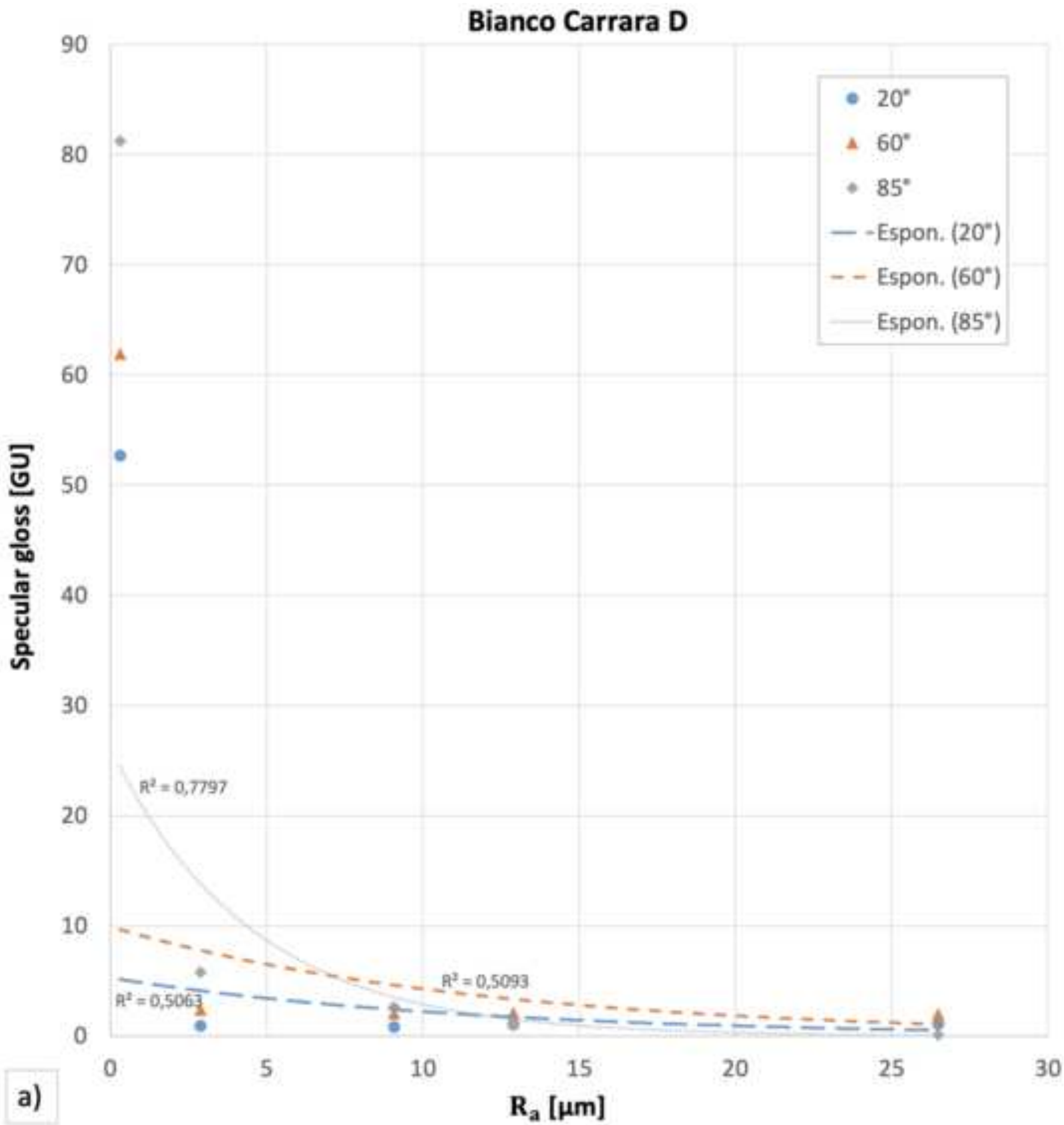
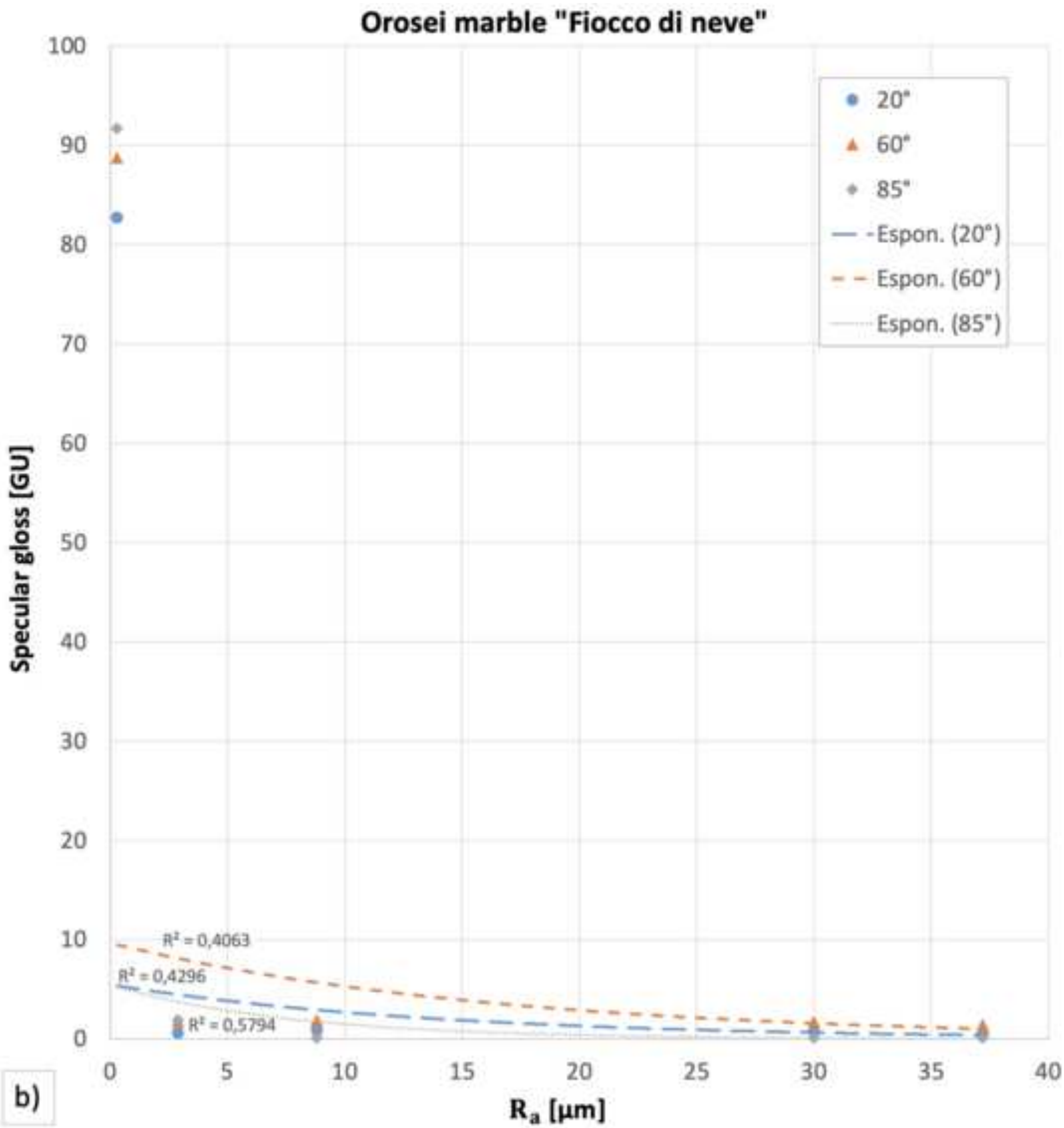
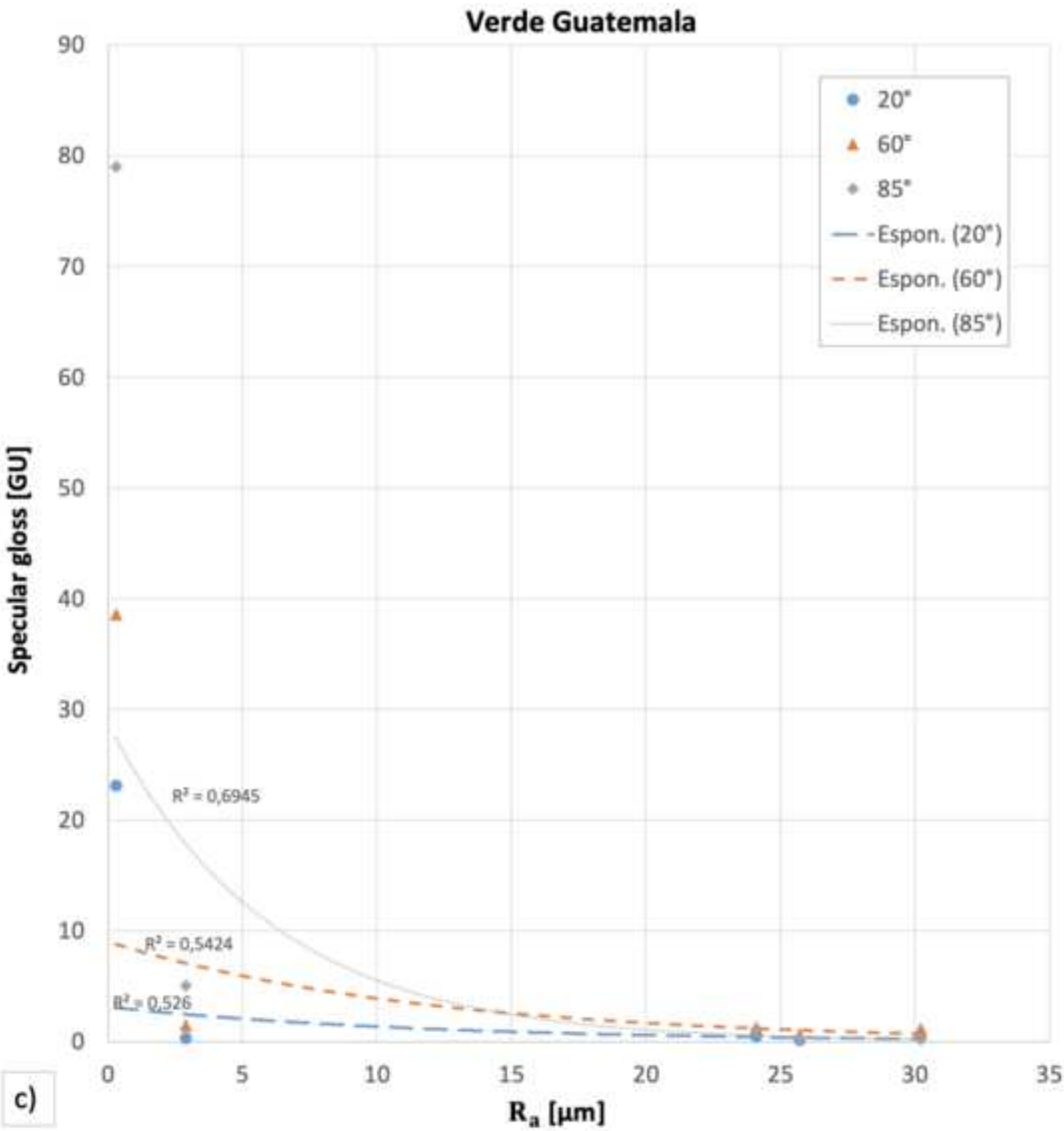

Bianco Carrara D
Specular gloss [GU]
0
10
20
30
40
50
60
70
80
90
0
5
10
15
20
25
30
Ra [µm]
20°
60°
85°
Espon. (20°)
Espon. (60°)
Espon. (85°)
R² = 0,7797
R² = 0,5093
R² = 0,5063
a)

Figure 11b



Orosei marble "Fiocco di neve"
Specular gloss [GU]
100
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35
40
Ra [µm]
20°
60°
85°
Espon. (20°)
Espon. (60°)
Espon. (85°)
R² = 0,4063
R² = 0,4296
R² = 0,5794
b)

Figure 11c


Verde Guatemala
Specular gloss [GU]
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35
Ra [µm]
20°
60°
85°
Espon. (20°)
Espon. (60°)
Espon. (85°)
R² = 0,6945
R² = 0,5424
R² = 0,526

c)

Figure 11d

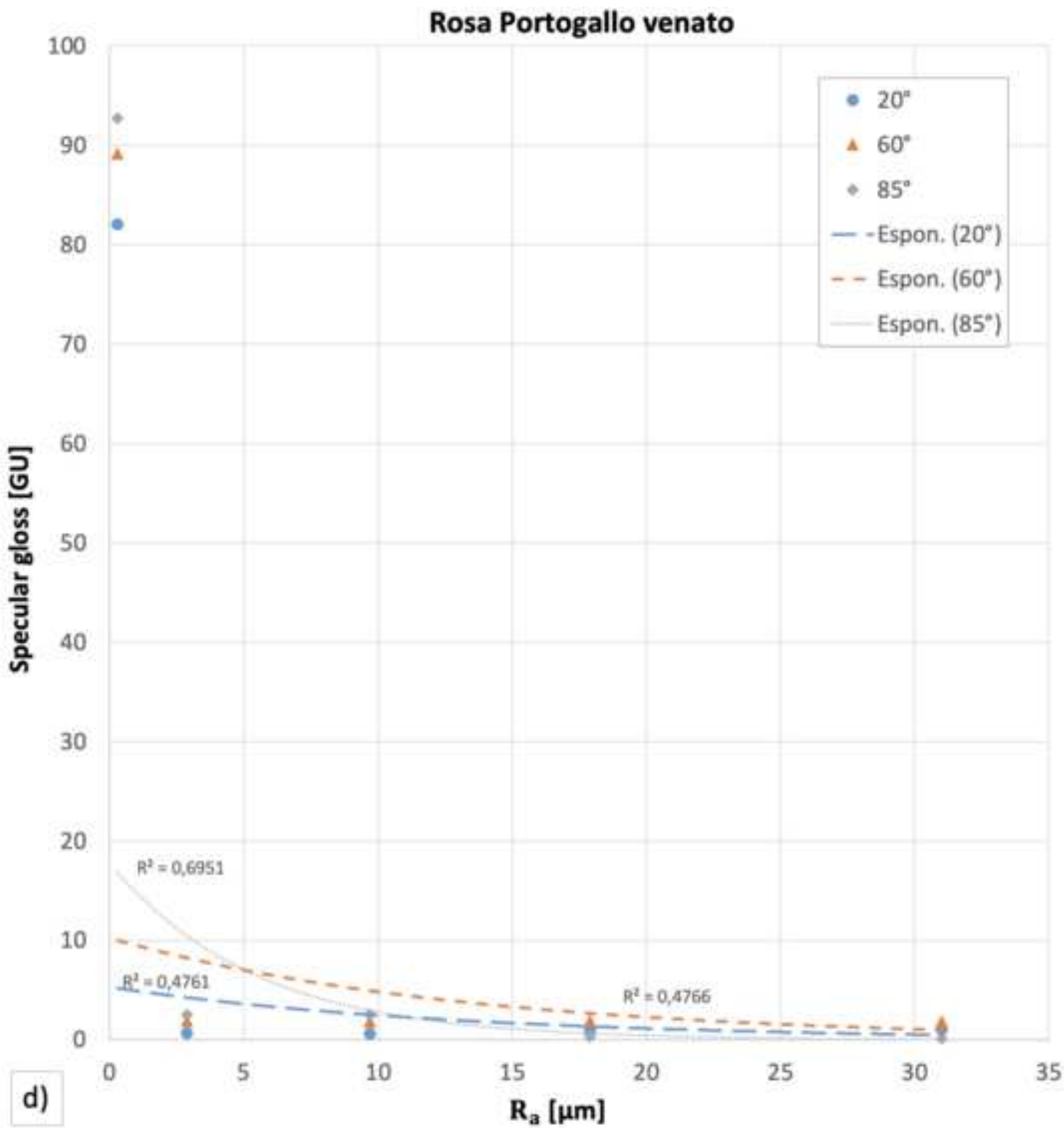

Rosa Portogallo venato
Specular gloss [GU]
100
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35
R_a [µm]
20°
60°
85°
Espon. (20°)
Espon. (60°)
Espon. (85°)
R² = 0,6951
R² = 0,4761
R² = 0,4766
d)

Figure 11e

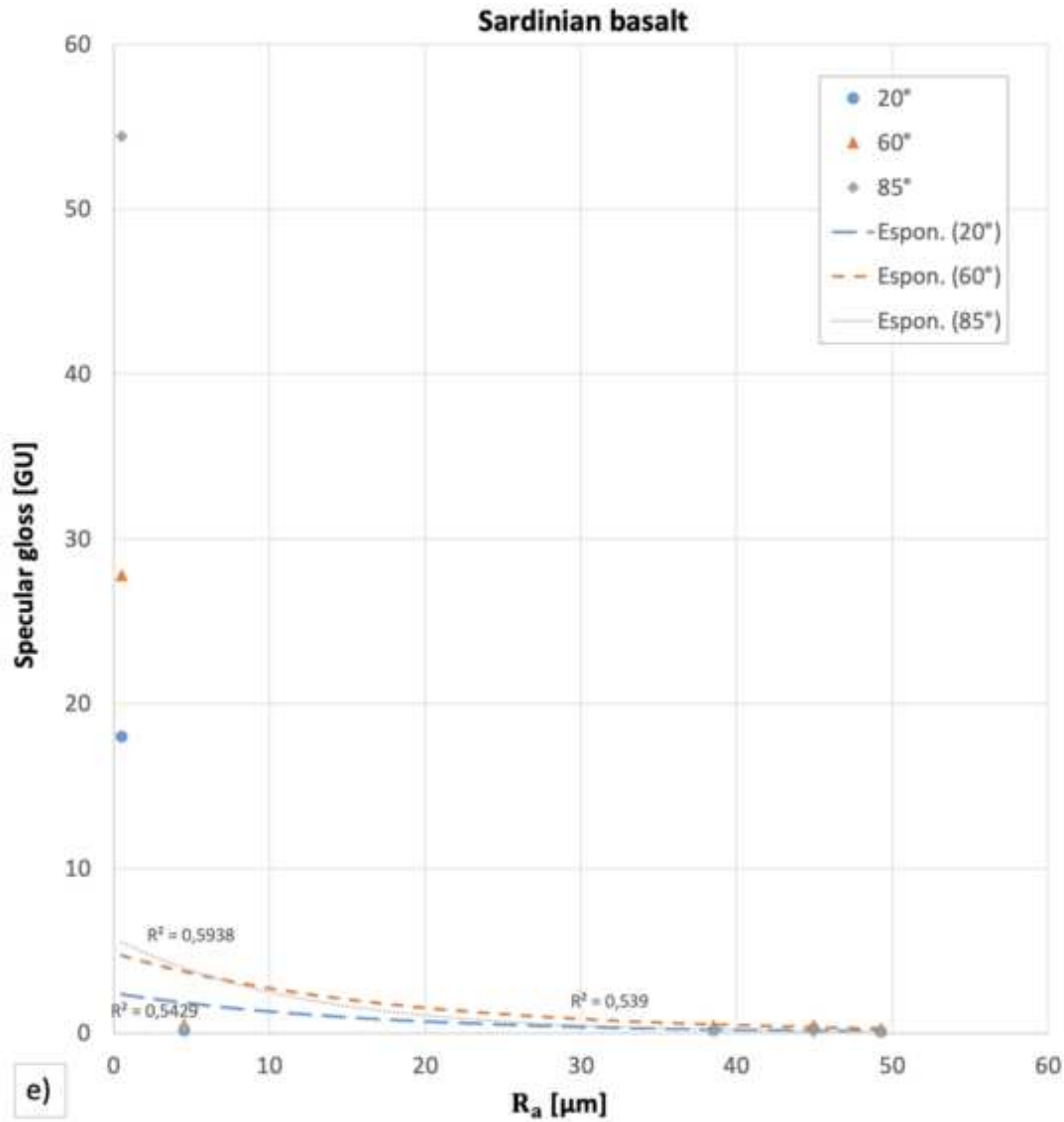
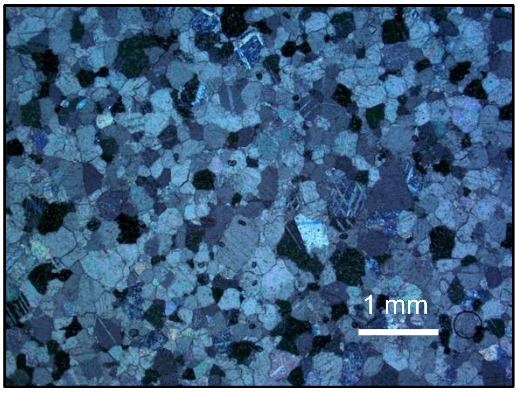
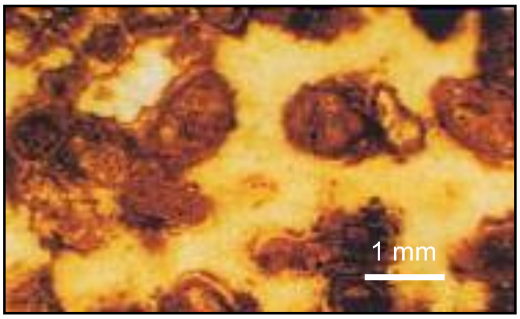
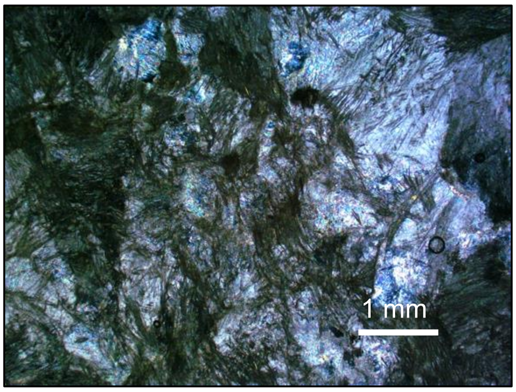
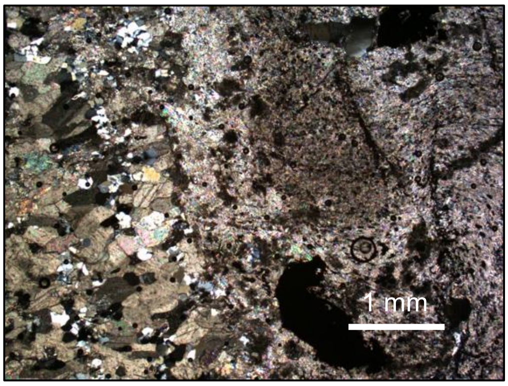

Sardinian basalt
Specular gloss [GU]
60
50
40
30
20
10
0
0
10
20
30
40
50
60
R_a [µm]
20°
60°
85°
Espon. (20°)
Espon. (60°)
Espon. (85°)
R² = 0,5938
R² = 0,5429
R² = 0,539
e)

Table 1. Petrographic descriptions and microphotographs of the lithotypes.

Lithotypes	Petrographic descriptions	Microphotographs of the stones (Crossed Nicols)
Bianco Carrara D	White marble; granular (saccharoid" texture, fine and compact; homeoblastic/granoblastic structure with exclusive presence of calcite granoblasts in a polygonal shape or, subordinately, non-oriented allotrimorphs in small sizes (0.2 - 0.6 mm).	
Orosei Marble "Fiocco di neve"	The limestone consists of micrite (crypto-crystalline calcite) with interclasts (indigenous fragments, derived from wave-driven demolition of limestones formed in the same basin) and micritic bioclasts (peloids) with veins of micro-crystalline calcite, which sutured up tectonic lesions in final cement, improving the mechanical properties of the stone.	
Verde Guatemala	Serpentine marble; granular texture with a non-oriented granoblastic/fibroblastic structure, with the presence of medium-sized (0.8 - 2.5 mm) calcite granoblasts with irregular and/or lobed edges and scattered aggregates and little veins of fibrous serpentine (under 1 mm to 1 mm), with chlorite, white mica and opaque minerals. Pervasive serpentization tends to obliterate the original structure.	
Rosa Portogallo venato	Pink marble; hetero-granular texture, slightly oriented due to deformation, granoblastic structure with larger calcite granoblasts (0.2 - 0.8 mm) and thin micro-granular beds mainly of calcite (crystalline elements < 0.1 mm), quartz and white mica, that follow deformation planes; the marble is crossed by metasomatic greenish veins: a diffused alternation of the preceding facies, with granoblastic-structured relicts of calcite embedded in a fine sericite and talc-chlorite groundmass with quartz in tiny veins or aggregates, beds of probably dark oxides and opaque minerals (hematite, magnetite).	

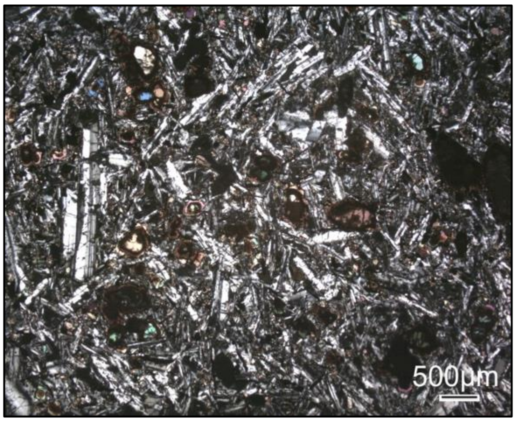
Sardinian basalt	Porphyritic basalt with phenocrysts of twin plagioclase (grey, white), olivine (pink, blue) showing alteration rim of brown iddingsite (black) set in a finely groundmass with intersertal structure of plagioclase and olivine. In the left is the presence of small-voids.	

Table 2. Pure water-jet operational parameters.

Operational parameters	**Bianco Carrara D**	**Orosei Marble “Fiocco di neve”**	**Verde Guatemala**	**Rosa Portogallo venato**	**Sardinian basalt**
Nozzle diameter [mm]	0.30	0.30	0.30	0.30	0.30
Focusing tube diameter [mm]	1.00	1.00	1.00	1.00	1.00
Water pressure [MPa]	200	300	300	200	200
Jet inclination* [°]	30	30	30	30	30
Pass spacing [mm]**	1.0	1.0	1.0	1.5	2.0
Stand-off distance [mm]	100	100	50	100	100
Water-jet travel speed [m/min]	25	15	20	25	20

* respect to the horizontal plane

** distance between water-jet parallel passes

Table 3. Mean roughness values R_a, measured in μm, for the different finished surfaces. (BCD = Bianco Carrara D, MOF = Orosei Marble "Fiocco di neve", VG = Verde Guatemala, RPV = Rosa Portogallo venato and SB = Sardinian Basalt).

	Natural stones R_a				
Type of surface (ID)	**BCD**	**MOF**	**VG**	**RPV**	**SB**
POL	0.3	0.3	0.3	0.3	0.5
DSP	2.9	2.9	2.9	2.9	4.5
LB	12.9	8.8	24.1	17.9	38.5
HB	26.5	30.0	30.2	31.0	45.0
PWJ	9.1	37.2	25.7	9.7	49.3

Table 4. Total colour difference (ΔE*) between the polished surface and each of the other surface finishes for the five stones tested, in SCI and SCE modes. The mean roughness difference (ΔR_a) is also reported. (BCD = Bianco Carrara D, MOF = Orosei Marble "Fiocco di neve", VG = Verde Guatemala, RPV = Rosa Portogallo venato and SB = Sardinian Basalt).

Type of surface (ID)	Natural stones ΔR_a					Natural stones ΔE* SCI					Natural stones ΔE* SCE				
	BCD	**MOF**	**VG**	**RPV**	**SB**	**BCD**	**MOF**	**VG**	**RPV**	**SB**	**BCD**	**MOF**	**VG**	**RPV**	**SB**
POL	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DSP	2.6	2.6	2.6	2.6	4.0	6.90	1.86	17.55	6.27	11.23	8.78	1.62	20.65	7.50	14.23
LB	12.6	8.5	23.8	17.6	38.0	9.83	5.32	32.25	17.48	14.17	11.67	6.64	35.32	19.62	17.15
HB	26.2	29.7	29.9	30.7	44.5	12.33	3.12	38.27	16.92	15.81	14.22	4.03	41.34	19.18	18.93
PWJ	8.8	36.9	25.4	9.4	48.8	4.45	15.92	4.40	6.44	6.11	6.27	16.91	7.62	4.96	2.87

Table 5. Gloss values, expressed in Gloss Unit [GU], for the different finished surfaces for each tested stone.

Natural stones	Type of surface (ID)	GU		
		20°	**60°**	**85°**
Bianco Carrara D	**POL**	52.68	61.91	81.21
	DSP	0.91	2.39	5.78
	LB	1.04	2.09	0.99
	HB	1.13	1.99	0.11
	PWJ	0.84	2.04	2.65
Orosei marble "Fiocco di neve"	**POL**	82.70	88.70	91.70
	DSP	0.60	1.80	1.90
	LB	0.90	1.90	0.10
	HB	0.80	1.70	0.10
	PWJ	0.50	1.40	0.10
Verde Guatemala	**POL**	23.10	38.59	79.03
	DSP	0.30	1.49	5.08
	LB	0.50	1.29	1.14
	HB	0.55	1.14	0.18
	PWJ	0.15	0.66	0.28
Rosa Portogallo venato	**POL**	82.01	89.15	92.70
	DSP	0.70	1.88	2.51
	LB	1.00	1.90	0.33
	HB	1.05	1.86	0.10
	PWJ	0.61	1.84	2.54
Sardinian basalt	**POL**	17.99	27.80	54.41
	DSP	0.20	0.55	0.38
	LB	0.20	0.46	0.15
	HB	0.26	0.48	0.10
	PWJ	0.10	0.30	0.21

Conflict of Interest (Please upload in Word format)

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Credit author statement

Nicola Careddu: Conceptualization, Methodology, Writing - Original Draft, Investigation, Writing - Review & Editing, Supervision, Project administration, Funding acquisition. **Walter Aru**: Formal analysis, Visualization.