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Petrography of roofing slates

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A B S T R A C T

Roofing slate is one of the world's most popular dimension rock products. This special type of slate can be split into regular and thin tiles forming an exceptional covering material. Many historical heritage buildings along Europe use slate covers. Although slate has been quarried worldwide for centuries, in the second half of the past century the production of roofing slate increased hugely, especially in Europe, where the largest outcrops known to date are located.

Despite its importance as a construction material, roofing slate has not been the target of a proportional number of scientific publications, as compared to other materials such as granite, sandstone, marble or limestone. This could be due to the general perception that roofing slate is a rather simple rock with a relatively unvarying mineralogy consisting of quartz, chlorites and mica, and having a monotonous structure dominated by the slaty cleavage and various fracture planes.

This paper deals with the main features of the roofing slate industry, i.e. petrological and mineralogical characterization, and their application on slate production, as well as additional phenomena and significant factors affecting quality which are rarely considered, such as weathering and durability.

Contents

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1. Introduction

The group of stone products referred to as roofing slate is a popular construction material that is widely used worldwide, both in modern architecture and in historical buildings. Most of the rocks used for roofing belong to the low-grade metamorphism of the green schist facies (Arkai et al., 2007) with a well-defined slaty cleavage and high fissility. These characteristics facilitate the slate split into thin and regular tiles used for roofs and façades, as well as for flooring and paving. The technological requirements for construction materials in the European Community (EC) are defined in the European Norm (EN) for roofing slate EN 12326 (Blanchard and Sims, 2007), whereas for the United States they are defined in the standards of the American Society for Testing and Materials (ASTM) C 120–90, C 121–90, C 217–94 and C 406–00 (Hicks, 2008). The ultimate goal of each normalised test is to give a prediction of the service life of a slate tile (Walsh, 2002).

1.1. Brief history of roofing slate mining

Mankind has used slate for construction since the very beginning of architecture. From the point of view of construction, slate is a rock that can be split into continuous tiles and slabs, which are naturally standardised construction materials. Some of the first evidences of slate in constructions (Bendala, 1990) and other uses (Cordero and Martin, 2012) are found during the Neolithic in the Iberian Peninsula. The Romans also used slates as constructing material (McWhirr, 1988; De Clercq, 2011). Slate was used for roofing, walls and flooring, but also as grinding stone or millstone—in short, for almost everything. During the following centuries, slate was mainly used as a building material in areas within just a few kilometres of an outcrop, until the 18th and 19th centuries, when slate mining appeared on a large scale in Western and Central Europe (Fig. 1) and in the United States. However, the golden age of slate mining did not begin until the second half of the 20th century, with the mechanisation of the production processes.

There were two important developments that changed the slate market. The first was that Spain began to produce large amounts of rather cheap high-quality slate, breaking into the market and forcing many quarries across Europe to close (García-Guinea et al., 1997). Nowadays there are still a few quarries in some of these countries which continue to produce slates with an extra value, used for the restoration of historical heritage or in unique new buildings (Hunt, 2006). The second was the introduction of diamond wire technology in the quarrying process. Before this, slate blocks were extracted with explosives, causing extensive fracturing and reducing the volume of usable slate. With the introduction of diamond wire cutting, large blocks could suddenly be extracted cleanly, without damage. This method, together with improvements in borehole technology, brought with it an unexpected advantage: for the first time, the relationships between the main structures in slate (sedimentation S_0 and slaty cleavage S_1) were clearly visible. This was a great help for geologists, who could now better understand the local and regional structure of the outcrops. The slate market subsequently boomed until the global economic crisis of 2008.

At present, many European quarries, most of them in Spain, are facing closure. The world's slate production is being displaced to emerging countries like Brazil, China, India and Vietnam. Other countries, such as the Russian Federation, have an unexplored potential for slate outcrops. Russian exportations of slate went from 15 T in 2008 to 676 T in 2011, still very far from the production level of the leading countries, but a sign that the Russian slate industry is clearly growing.

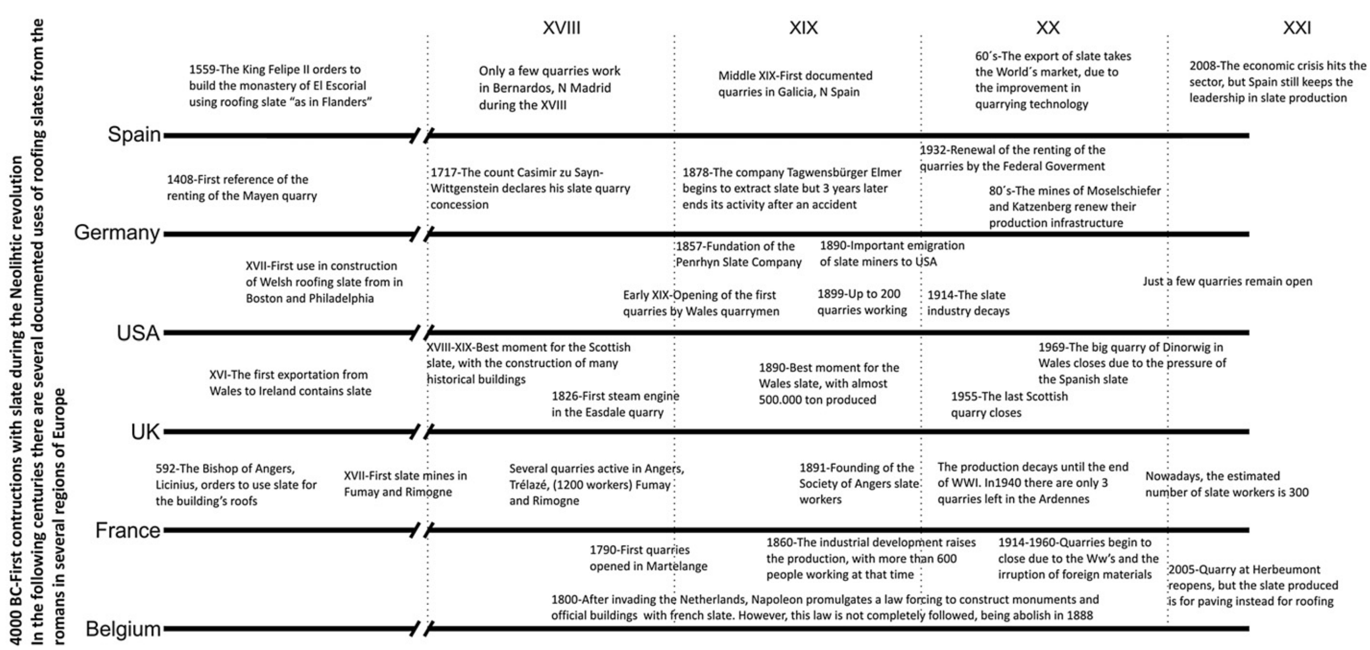


Fig. 1. Timeline of the history of roofing slate mining in the most representative countries.

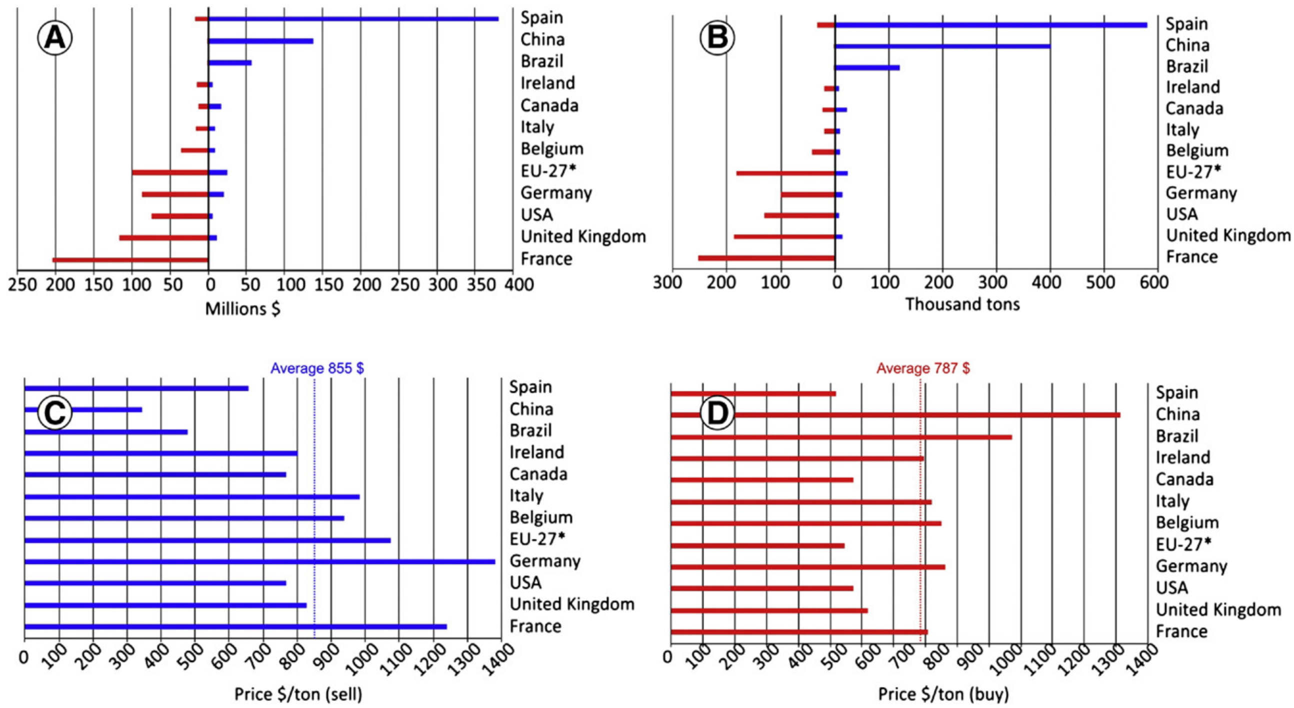


Fig. 2. Economic data on the global roofing slate trade (2011). A and B show sales (blue) and purchasing (red) for the most significant countries, in millions of US$ and thousands of tons, respectively. C and D show the average price of purchasing and sales for the same countries. Source: United Nations Commodity Trade Statistics Database, Statistical Division (http://comtrade.un.org/). *EU-27 in the UN Comtrade database is an economic grouping created for statistical purposes. It does not have a political status. EU-27 is regarded here as a single entity that trades with the rest of the world. Intra-EU trade is therefore not included.

1.2. The global roofing slate market

Spain is the world leader in roofing slate production, with a calculated production for 2012 of more than 580,000 T sold (Fig. 2A) for a value of more than 380 million US$, followed by China and Brazil. Emerging countries like China or Brazil are threatening Spain's leadership in the field, though their average selling price is still far from that of Spain (Fig. 2C and D). This fact could be due to, a lack of high-quality stone, a defective production process, and the lower costs for personnel (Hunt, 1998). China is improving in terms of these factors, and in a few years Spain may lose its lead in slate production. The Brazilian slate industry developed a lot since 1997 and deals with easily extractable stone, together with a well-developed production process and cheap manpower. The world's biggest consumer of slate is France, followed by the UK, USA and Germany (Fig. 2B). Germany, which has a low level of slate production, has the highest selling price. German quarries produce a high-value product, with a high cost of manpower, that is very popular both for restoration and for creating unique buildings. This slate is consumed entirely by the German and Netherlands markets. Other European countries (Portugal, France, Italy, UK) still produce their own slate, but on a very small scale. In Portugal there are still several mines active, whilst the biggest France slate companies near Angers–Trélazé–Noyant are nowadays closed. The last Belgian roofing slate quarry (Warmifontaine) also closed some 15 years ago. Lastly, it is worth noting that in terms of purchasing price, China, which sells its slate at the lowest price (Fig. 2D), is the country that pays the highest price for foreign slate, followed by Brazil. This means that both countries are beginning to consume foreign slate, related to the presence of foreign slate companies within those countries and the construction of many buildings for foreign companies. China and Brazil are both countries with an enormous potential for urban development.

The current economic crisis has caused the sector to slow down. In Spain, many small- and medium-sized quarries are closing, whilst in the rest of Europe only a handful of quarries survive. As pointed out before, slates from China and Brazil are entering the market, threatening Spanish hegemony, though both countries, especially China, still have a long way to go. The coming years will be decisive for the roofing slate market.

2. Bibliographical review

2.1. Roofing slate versus slate

As for most of dimension stones, the commercial and petrological terms do not always mean exactly the same, which can be confusing.

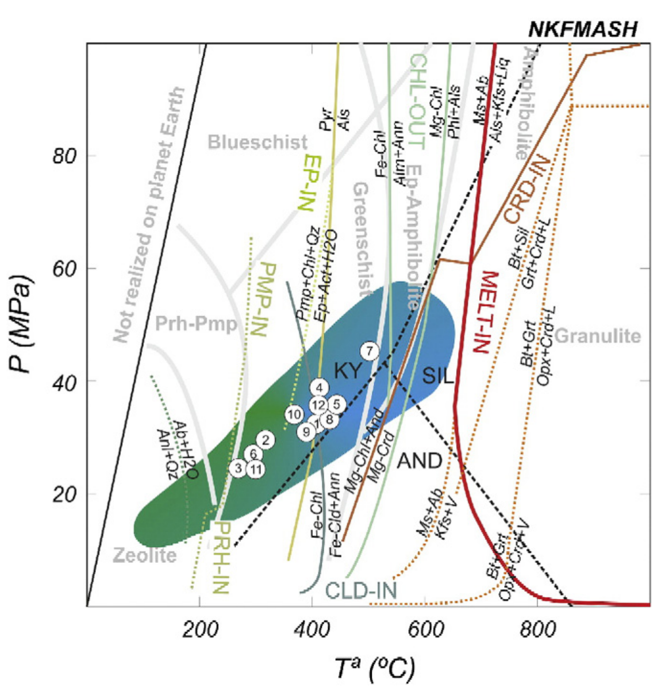


Fig. 3. P–T diagram for roofing slates. The numbers correspond to the samples described in Fig. 8. All the samples belong to the green schist facies, but in a wide range of conditions, from sub-green schists almost to schists s.s. For the carbonated slates (6 and 11), the absence of talc and wollastonite suggests a low metamorphic grade. Modified from Spear, 1993.

According to EN 12326–1:2004, roofing slate is: "[*a*] *rock which is easily split into thin sheets along a plane of cleavage resulting from a schistosity flux caused by very low or low grade metamorphism due to tectonic compression. It is distinguished from a sedimentary slate* [author's note: shale] *which invariably splits along a bedding or sedimentation plane*. *Slate originates from clayey sedimentary rocks and belongs petrographically to a range which begins at the boundary between sedimentary and metamorphic formations and ends at the epizonal-metamorphic phyllite formations*."

This definition makes quite clear, from a petrological point of view, the range of rocks which can be considered as slate (Fig. 3). However, EN 12326–1:2004 goes further in defining roofing slate as "*a rock used for roofing and cladding*, *in which phyllosilicates are the predominant and most important components and exhibiting a prominent slaty cleavage*". Likewise, carbonate roofing slate is defined in the same way as above but with carbonate making up a minimum of 20% of its content.

On the other hand, for the Subcommission on the Systematics of Metamorphic Rocks (SCMR), a slate s.s. is "*an ultrafine- or very fined-grained rock displaying slaty cleavage*" (Arkai et al., 2007). This slaty cleavage is also defined as "*a type of continuous cleavage in which the individual grains are too small to be seen by the unaided eye*".

The distinction between slate s.s. and roofing slate can be summarized as follows: a roofing slate is any type of dimension stone suitable to be used for roofing, whilst from a petrological point of view this commercial term includes several stones (slates s.s., shales, phyllites, cinerites, schists…), mainly composed of quartz and phyllosilicates, with a penetrative foliation or slaty cleavage that makes it possible to produce tiles that can be used as a roofing material. The nature of the foliation can be of various origins, such as sedimentary, metamorphic or even igneous.

Beyond geological classifications, what producers and architects want are flat stone tiles with few to no weatherable minerals. Today's market offers a great variety of roofing slates, with different colours, sizes and uses (Fig. 4).

2.2. Petrography and mineralogy

The petrography of most of the roofing slates is rather simple: The main minerals are quartz, mica and chlorites, with a lepidoblastic texture (Ward and Gómez-Fernandez, 2003; Walsh, 2007). New features of roofing slate have been discovered in recent years thanks to numerous petrographic studies. For example, the relationship between the spatial arrangements of the mica levels has been discovered through the calculation of the Mica Stacking Index (MSI), as in the EN 12326 petrographic study (Ingham, 2005; Ingham, 2010). This index specifically measures the "mica layers" (not the sedimentary planes S_0) formed during metamorphism, evidenced by the accumulations of iron oxides. The MSI indicates the degree of alignment within the spatial orientation, and with this index one can draw conclusions about their influence on the stone's mechanical behaviour (Cárdenes et al., 2010; Gómez-Fernández et al., 2012). Furthermore, this mechanical behaviour shows particular variance during freeze-thaw cycles (Cárdenes et al., 2012b), which directly influences the durability of the slate tile. The relationship between colour on the one hand, and mineralogical and elemental compositions on the other, have been studied (Gutiérrez-Claverol and Encinas, 1990; Prieto et al., 2011; Cárdenes et al., 2012c), revealing a negative correlation between organic matter content and lightness. The more organic matter a slate has, the darker it will be, where the highest acceptable organic matter content is 2% (EN 12326). Colour changes have also been studied in one of the most important varieties of slate from Wales, Penrhyn slate, which is red coloured with occasional green spots. These spots are due to reduction processes of the iron within the slate minerals (Borradaile et al., 1991).

Regarding the weatherability of slate, the two main pathologies that have been defined are iron sulphide oxidation and gypsification (Walsh, 2008; Cárdenes et al., 2012a). The iron sulphide oxidation generates streams of reddish oxide which run across the roof surface, affecting the surface's appearance, but usually without compromising the waterproofing of the roof. As a method to prevent this oxidation, passivation techniques have been proposed (Cárdenes et al., 2009), with promising results. Also, the use of protective products (siloxanes) has been tested in slate tiles (Rivas et al., 2011). The gypsification is the process for which gypsum crystals are formed as a result of the weathering of the carbonate minerals. Since gypsum has a larger volume than carbonate this fact can then lead to a softening and destruction of the slate's fabric, decreasing its general resistance to weathering.

2.3. Architecture and heritage

The preservation of historic roofing slate has also been a target of research. For restoration projects several facts must be taken into account, first of all determining the original material (Walsh, 2006) based on the relationships between mineralogy, fabric, and mayor and trace elements. Then, when it is necessary to substitute tiles in a roof, the second

Fig. 4. Hand specimens of some of the world's roofing slates:

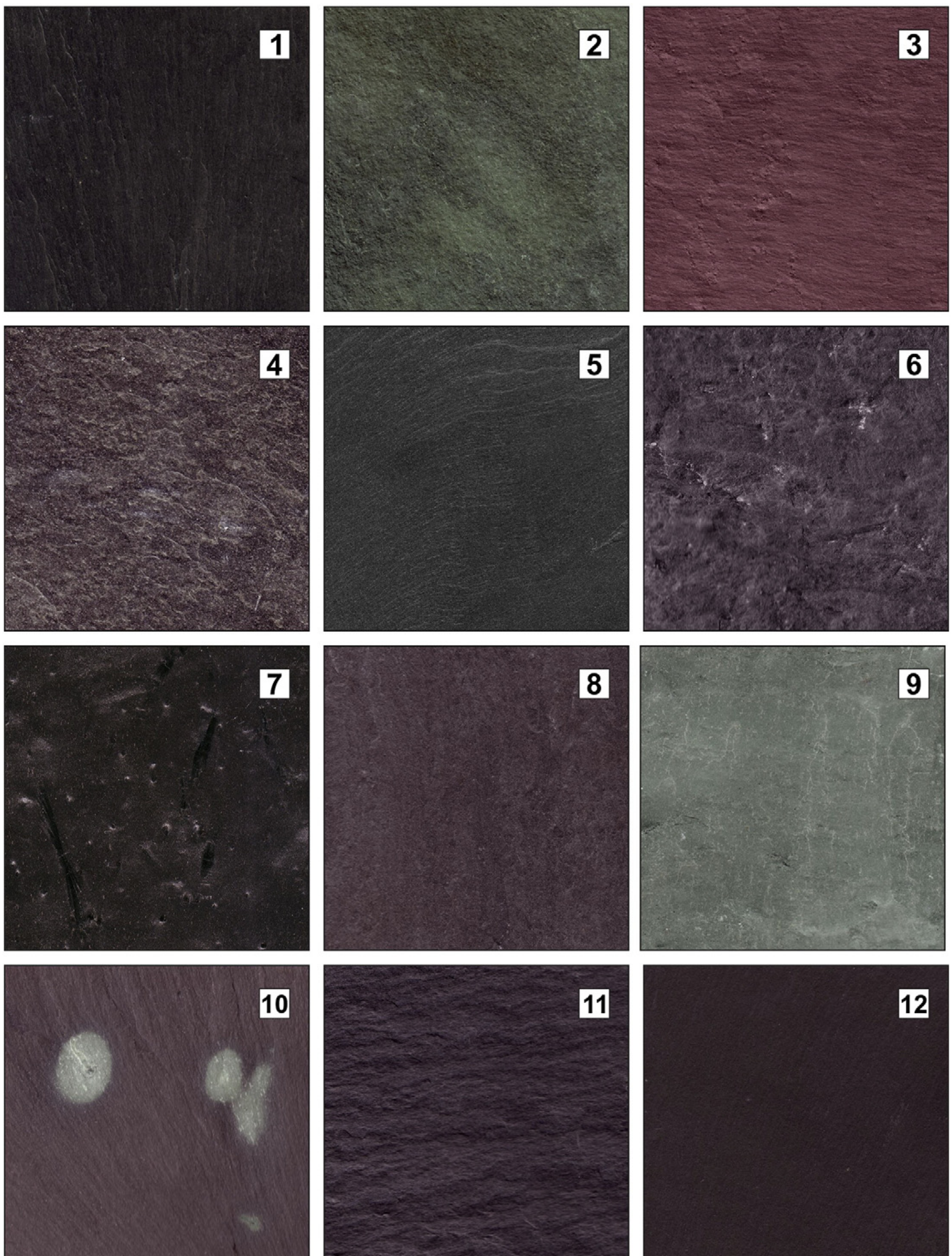
1. Slate from Angers, France. A dark and fine-grained slate with homogeneous texture, which is highly valued in France and has been quarried for centuries. Stratigraphy: Grand-Auverné Formation, Middle Ordovician.
2. Shale from Minas Gerais, Brazil. Green rock, although other colours are also quarried. It has a metamorphic grade slightly lower than that of slate s.s. Stratigraphy: Bambui group, Ediacaran.
3. Red slate from Newfoundland, Canada (Trinity slate). Fine-grained and homogeneous slate with abundant iron oxides, which lend it its characteristic red colour. Stratigraphy: Bonavista Formation, Lower Cambrian.
4. Himalayan slate. This is actually a layered volcanic rock, as can be deduced from the epidote crystals seen in the thin section. The production potential for this area is still unknown. Stratigraphy: Nourpul and Benighat Formations, Neoproterozoic/Lower Cambrian.
5. Slate from Jiangxi, China. Light grey rock, fine grained, with homogeneous texture. Roofing slates from China are very diverse both from petrological and commercial points of view. Thus, there are some exceptionally good materials together with others of lesser quality. Stratigraphy: Shuidonggou Formation, Silurian.
6. Valentia slate, Ireland. This is a coarse-textured grey slate quarried in the region of Valentia, in the south of Ireland. Stratigraphy: Valentia Slate Formation, Middle Devonian.
7. Schist with staurolite from Finnmark, Norway. This type of rock is not usually used for roofing, but rather for flooring and paving. However, in the north of Norway there are several quarries of different varieties of schists that are thin enough to be used for roofing. These rocks have a higher metamorphic grade, and a mineralogy that is clearly different from that of the slates s.s. Stratigraphy: Friarfjord Formation, Lower Cambrian.
8. Slate from Valongo, Portugal. Dark slate, fine-textured. It is quarried in the Valongo area near Porto in Portugal, and is similar to some levels of Galician slate in Spain. Stratigraphy: Luarca Slate Formation, Middle Ordovician.
9. Green phyllite from Lugo, Spain. This type of slate is extracted in the Pol area in the province of Lugo. It is characterised by its intense green colour, the result of a predominance of the magnesic term of the chlorite group, clinochlore. Stratigrapy: Candana Group, Lower Cambrian.
10. Slate from Penrhynn, Wales, where many historical buildings are made with this material. Some levels of this fine-grained lithotect may have characteristic green spots as a result of reduction processes. Stratigraphy: Llanberis Formation, Cambrian.
11. Carbonated slate from Liguria, Italy. This dark and fine-grained slate has high carbonate content. However, when used in accordance with environmental requirements, it offers satisfactory performance. Stratigraphy: Val Lavagna Formation, Middle Cretaceous.
12. Slate from Villar del Rey, Spain. This is the darkest slate variety from Spain, a fine-grained slate with some millimetric cubic pyrites and a smooth surface. Stratigraphy: Gévora Formation, Upper Silurian. Length of each image is 8 cm.

step should be to find the quarry source of the originally used slates. If the original quarry is exhausted, or cannot provide proper quality slates, it is very important to ensure that the new material has the same visual appearance (Prieto et al., 2011) and a similar performance against weathering as the historic one. This can be done by using colorimetric and weathering analysis, as in the EN and ASTM norms, and comparing the results with the available commercial categories of roofing slates (Cárdenes et al., 2014).

In most European countries simple rectangular slate tiles of different sizes are used for roofing and walling (Menéndez-Seigas, 2007), which makes their production fairly simple. In contrast, in Germany and the Czech Republic there are a variety of different styles of slate roofing, requiring single slate slabs of different shapes and sizes (Fig. 5).

2.4. Mining and processing

Generally speaking, the fabrication process is rather simple. Blocks are extracted from the quarry, generally by using diamond wire (Fig. 6A), and then brought to the factory (Fig. 6B and C), where these blocks are sawn (Fig. 6D) into smaller blocks that can be handled by the operator, which splits them into tiles (Fig. 6E). The thickness of each tile is determined individually by the operator. This task requires



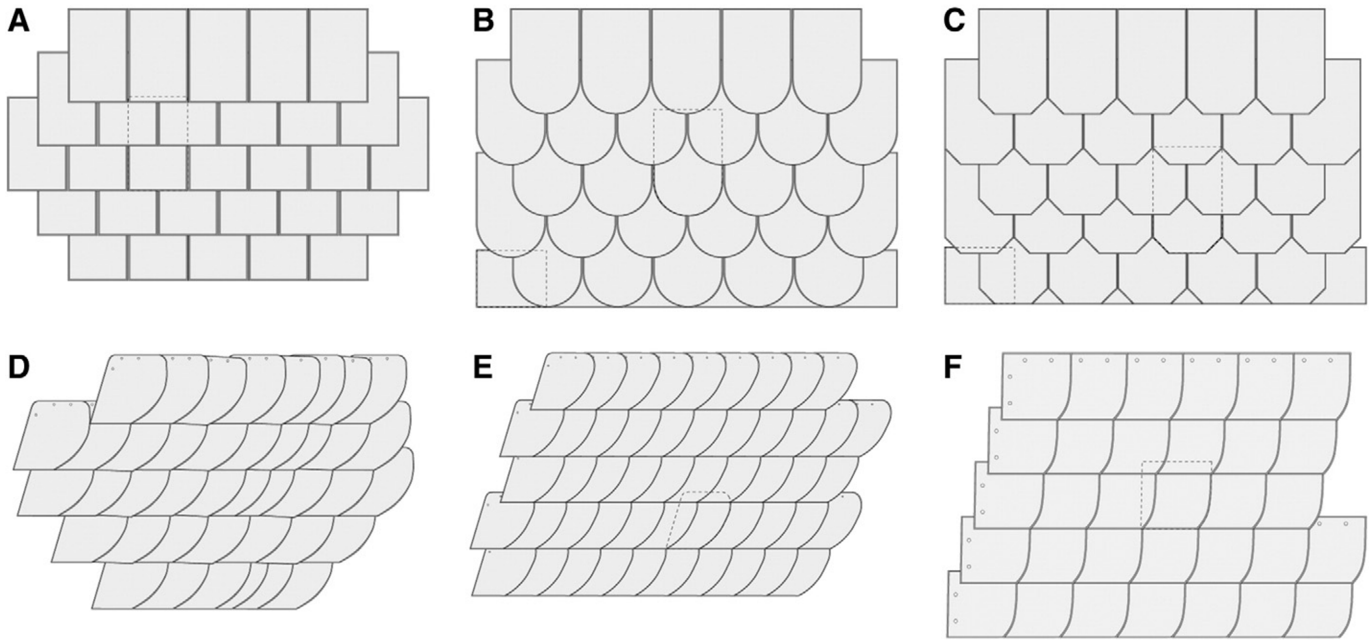


Fig. 5. Some examples of roofing arrangements. The lower row contains typical German format arrangements.

a relatively high level of specialisation. Once the tiles are split, they are formatted following market specifications with automated cutting machines or rock scissors (Fig. 6F). Quality control is performed throughout the process by the corresponding operators and the factory manager. Finally, the slates are stored in a crate (Fig. 6G), ready for shipping (Fig. 6H).

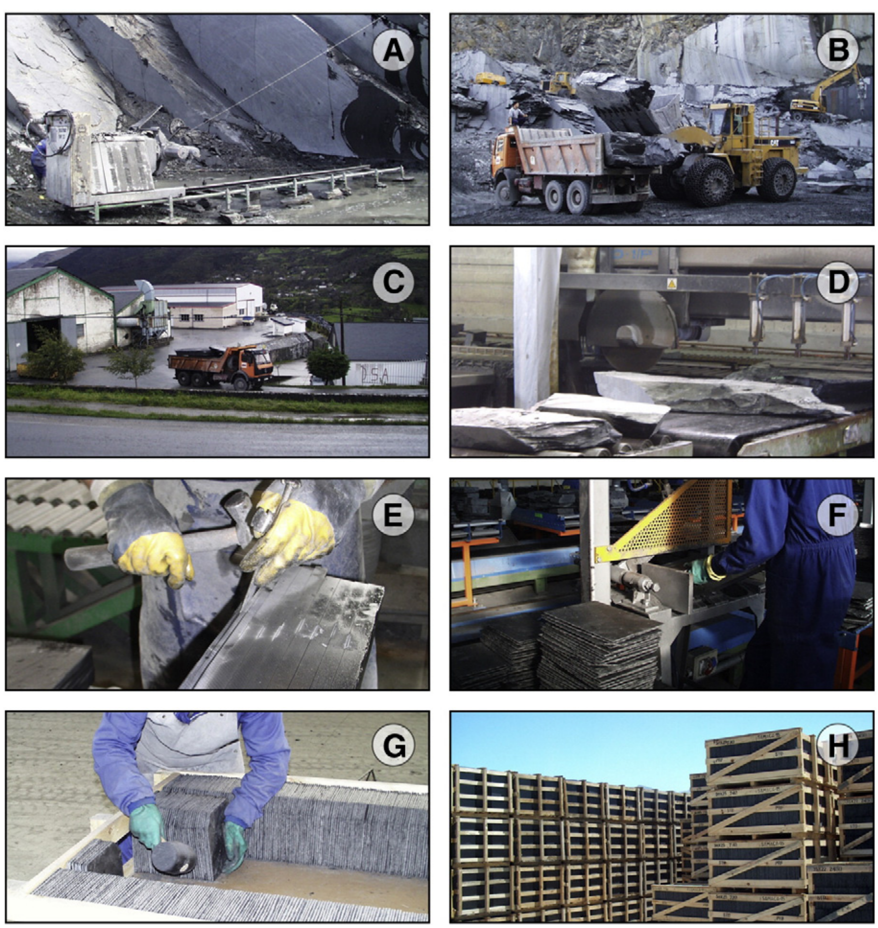


Fig. 6. The slate production process. A Sawing of the blocks at the quarry with diamond wire. B Loading a block onto a lorry for its transport to the factory. C Blocks arriving at the factory. D Sawing large blocks into smaller ones, ready for splitting. E Splitting the slate into tiles. F Formatting slate tiles with pneumatic scissors. G Storing the slate tiles in a crate. H Storing the crates of slate in a warehouse to await shipment. All images are taken in Ourense, Spain.

Table 1
Methods and requirements of EN and ASTM norms.

Norm (part)	Test	Feature	Requirement
EN 12326 (6,7,8,9)	Dimensional control	Standardized dimensions of the slate tile	Customer requirements
EN 12326 (10)	Bending strength	Mechanical resistance of the tiles	None
EN 12326 (11)	Water absorption	Susceptibility to weathering by freeze-thaw	Less than 0.6%, if higher must agree with freeze-thaw test
EN 12326 (12)	Freeze-thaw	Susceptibility to weathering by freeze-thaw	No significant reduction of the bending strength
EN 12326 (13)	Determination of calcium carbonate	Occurrence of weatherable components	None
EN 12326 (13)	Determination of elemental carbon	Occurrence of weatherable components	Less than 2%
EN 12326 (14)	Exposure to SO2	Weathering of harmful minerals	No splitting or cracking of the edges and swelling, softening or surface flaking. Also report any colour changes as information
EN 12326 (15)	Thermal cycle	Weathering and oxidation of iron sulphides	No exfoliation, splitting or other major structural changes and classification of the slates depending on the stain trails on the surface of the tile
EN 12326 (16)	X-ray diffraction	Mineralogical composition	None
EN 12326 (16)	Petrographic examination	Textural and mineralogical composition	None
ASTM C120	Flexure testing	Mechanical behaviour of the tiles	More than 62 Mpa
ASTM C121	Water absorption	Susceptibility to weathering by freeze-thaw	Depending on the absorption, three grades of lifespan are given
ASTM C127	Deep of softening	Weathering resistance	Depending on the resistance, three grades of lifespan are given
ASTM C406	Dimensional control	Standardized dimensions of the slate tile	Customer requirements

Exploration, extraction and production processes have been greatly improved since the beginning of industrial slate mining (Lombardero et al., 2002). Mathematical models used in other fields of mining have been applied specifically to slate (Taboada et al., 1997; Taboada et al., 2005). The use of kriging statistical techniques (Bastante et al., 2005) has proven to be an effective way to evaluate the volume of slate deposits. Based on the information provided by core drills, this method uses specific indicators of slate quality such as sedimentary levels, anisotropies and folding zones. Kriging can be complemented with the estimation of the observed qualities in the outcrop by using Bayesian Networks (Rivas et al., 2007) or the Fuzzy Expert System (Taboada et al., 2006b). Also, the geochemical relationships of the different lithotects in the Iberian Peninsula (Cárdenes et al., 2013c) have proven to be an effective method for distinguishing between these lithotects at the outcrop scale, which is a great help during prospection work. For underground mining, the use of GIS technology has proven to be an effective tool for designing and planning exploitation tasks (Taboada et al., 2006a).

Treatment and use of waste is another field of research which has been the object of research in recent years. Due to the characteristics of the production process, huge amounts of materials are dumped, between 85 and 90% of the slate volume extracted at the quarry (Lombardero et al., 2002). Whilst this waste is not chemically active, and does not represent an environmental risk, the dust emissions

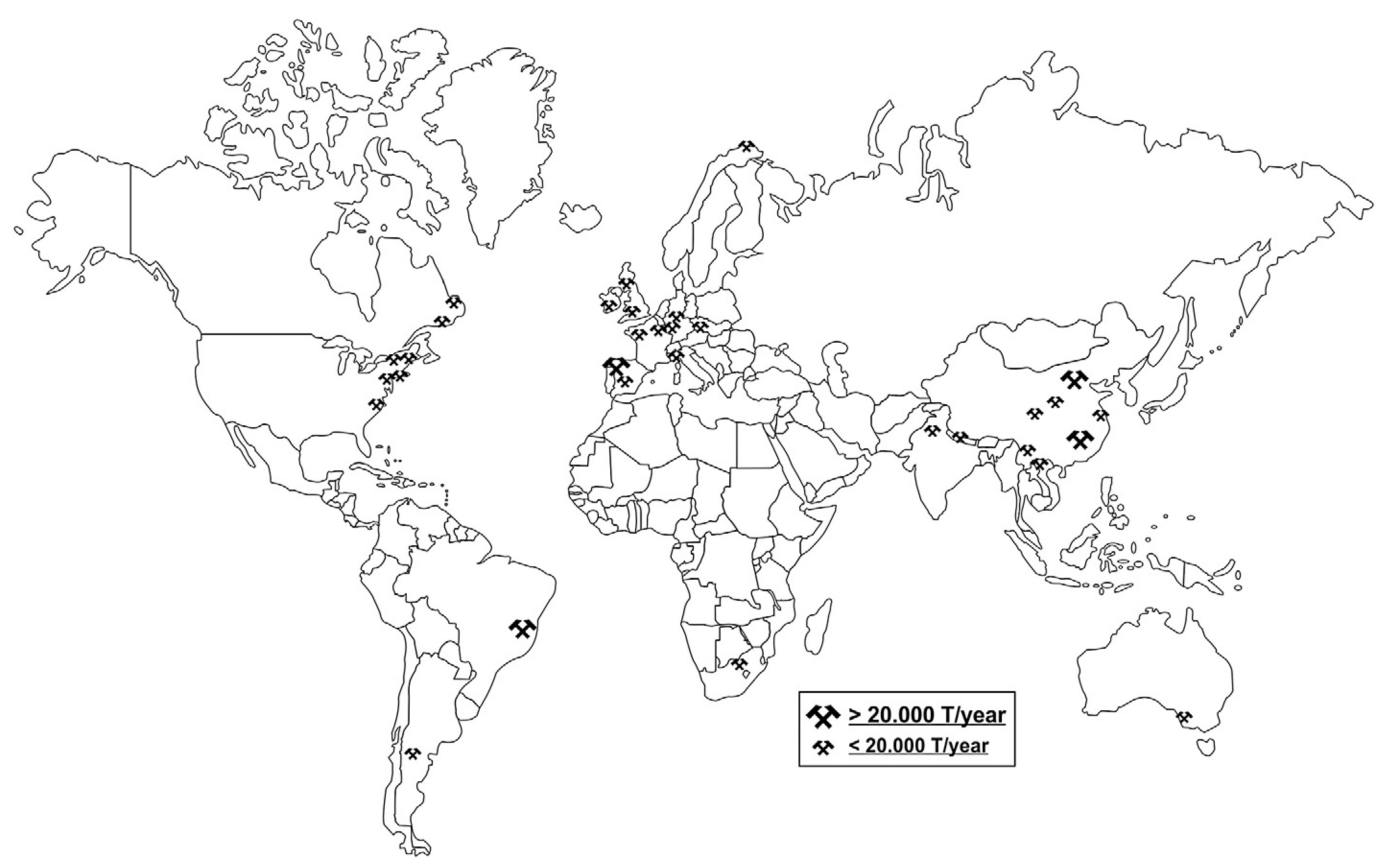


Fig. 7. Location of the world's principal roofing-slate lithotects.

Table 2
Main world's slate lithotects.

Country	Region	Type of rock	Lithotect	Series/System
Argentina	San Luis	Phyllite	San Luis Fm.	Furongian/Cambrian
Australia	Willunga	Slate	Tapley Hill Fm	Cryogenian
Belgium	Herbeumont	Slate	Mirwart, Villé and La Roche Fms. (High-Ardenne Slate belt)	Lower Devonian
Brazil	Minas Gerais	Shale	Bambui group (Fm Santa Helena)	Ediacaran
Canada	Newfoundland	Slate	Bonavista Fm.	Furongian/Cambrian
	Nova Scotia	Slate	Halifax Fm.	Furongian/Cambrian—Lower Ordovician
China	Anhui	Shale	Ningkuo Fm. (Ningkuo)	Lower Ordovician
	Hebei	Slate	Gantaohe group (JingXing)	Orosirian (ca. 2.09 Ga)
	Hubei	Slate	Jiangxigou Fm. (Zhu Shan)	Ediacaran
		Phyllite	Gaojiawan Fm. (Guizhou)	Lower Ordovician
	Shaanxi	Shale	Baiheshan Fm. (Zhen Ba)	Lower Jurassic
		Slate	Banjiuguan Fm. (Ziyang)	Lower Silurian
		Carbonate slate	Linggou Fm. (AnKang)	Triassic
	Shanxi	Slate	Toutsun group (WuTai)	Cryogenian
	Jiangxi	Phyllite	Shuidonggou Fm. (Jiujiang)	Silurian
	Sichuan	Slate	Aba Fm. (Aba Zang)	Lower Triassic
		Phyllite	Dayanmen Fm. (ChengKou)	Lower Silurian
		Carbonate slate	Wuxingzhen Fm. (Wu Xi)	Cambrian
		Slate	Duiwoliang Fm. (Ping Wu)	Ediacaran
	Zhejiang	Shale	Anji Fm. (An Ji)	Lower Silurian
		Phyllite	Lancang group (XiaoXian)	Cryogenian
	Yunnan	Slate	Fuliangpeng Fm. (Yuxi)	Calymmian—Stenian
Czech republic	Moravia	Slate	Moravice Fm.	Mississipian/Carboniferours
France	Anger	Slate	Grand-Auverné Fm. (Trélazé Mb.)	Middle Ordovician
	Fumay	Slate	Mirwart, Villé and La Roche Fms.	Lower Devonian
	Maël-Carhaix	Slate	Kerroc'h Fm.	Mississipian/Carboniferous
Germany	Rhineland-Palatinate	Slate	Dachschiefer Fm	Lower Devonian
		Shale	Hünsruck Fm.	Lower Devonian
	North Rhine-Westphalia	Slate	Fredeburg Fm	Middle Devonian
	Thuringen	Slate	Lehesten Fm.	Mississipian/Carboniferous
Ireland	Valentia	Slate	Valentia Slate Fm.	Middle Devonian
	Killoran	Carbonate slate	Slieve Bernagh Fm. (Killaloe Slates)	Silurian
India	Kund	Phyllite	Aravalli and Delhi supergroups	Orosirian/Cryogenian
Italy	Liguria	Carbonate slate	Val Lavagna Fm.	Upper Cretaceous
Nepal	Tanahu	Slate/carbonate slate	Nourpul and Benighat Fms.	Ediacaran/Lower Cambrian
Norway	Finnmark	Phyllite/schist	Friarfjord Fm.	Lower Cambrian
Portugal	Porto	Slate	Valongo Fm.	Middle Ordovician
	Arouca	Slate	Valongo Fm.	Middle Ordovician
South africa	Gauteng	Slate	Rietgat Fm (Ventersdorp Spgr)	Neoarchaean/Siderian
Spain	A Coruña	Slate	Agüeira Fm.	Upper Ordovician
	Lugo	Slate	Agüeira Fm.	Upper Ordovician
		Phyllite	CándanaGroup	Lower Cambrian
	León	Slate	Luarca, Casaio, Rozadais and Losadilla Fms.	Middle–Upper Ordovician
	Ourense	Slate	Luarca, Casaio, Rozadais and Losadilla Fms.	Middle–Upper Ordovician
	Zamora	Slate	Luarca Fm.	Middle Ordovician
	Segovia	Phyllite	Schists-Metagraywacke Complex	Ediacaran/Lower Cambrian
	Badajoz	Slate	Gévora Fm (San Mamed Beds)	Upper Devonian
United kingdom	Penrhyn/Bangor	Slate	Llanberis Fm.	Cambrian
	Ballachulish	Slate	Dalradian Supergroup	Ediacaran/Lower Cambrian
	Kirkby	Siltstone	Brathay Fm.	Lower Silurian
	Yorkshire	Shale	Millstone GritGroup	Mississipian/Carboniferous
Uruguay	Lavalleja	Dolomitic slate	Minas Viejas group	Paleoproterozoic
USA	Vermont	Slate	Poultney Fm.	Lower–Middle Ordovician
	New York	Slate	Poultney Fm.	Lower–Middle Ordovician
	Maine	Slate	Carrabasset Fm.	Lower Devonian
	Maryland	Slate	Peach Bottom Slates (Peters Creek/Octoraro schists Fms)	Furongian (Cambrian)/Lower Ordovician
	Pennsylvania	Shale	Martinsburg Fm.	Middle-Upper Ordovician
	Virginia	Slate	Arvonia Fm.	Ordovician
Vietnam	Liu-Chau	Slate	Song Ma Fm.	Neoproterozoic

can in fact be dangerous for the workers if appropriate measures are not taken (Suhr et al., 2003). New methods for recycling the waste into construction materials have been proposed, such as their use in cement mortars (Barluenga and Hernández-Olivares, 2010) or even artificial tiles (Campos et al., 2004). Furthermore, new ways to profit from this waste for environmental restoration purposes (Paradelo et al., 2009) have been proposed as well. Nevertheless, the slate industry has not taken advantage of these recycling methods, since it has so far focused its attention exclusively on the production of tiles themselves.

Regarding the production process, the use of lasers to format the slate tiles has been proposed (Boutinguiza et al., 2002). Unfortunately, this method does not achieve the required performance of the working process, obtaining cutting velocities which are slower than the mechanical scissors currently in use. Another use for laser technology is the classification of slates depending on their thickness. This method has been recently introduced by the Spanish slate company Pizarras del Valle.

Traditionally, the quality of each slate is assessed whilst packing the tiles into the crate. This task could be automated through the use of

Table 3
Quality factors of roofing slate.

		Influence on quality	Optimal requirements
Petrological factors	1. Mineralogy and elemental composition	Very important: weatherability and hardness	Absence of weatherable minerals (carbonates and iron sulphides), adequate proportion of rigid/elastic minerals
	2. Grain size and fissility	Important: thickness, surface aspect and fissility	Well sorted grains
	3. Sedimentation layers S_0	Important: presence of discontinuities	S_0 does not affect the split
	4. Sources of heterogeneities	Important: accumulation of carbonates, iron sulphides and mechanical discontinuities	No occurrence of strange bodies
	5. Pore system	Important: fluid dynamic and weatherability	Close and small pore system
Tectonic factors	1. Microscopic fabric	Very important: mechanical resistance and weatherability	Homogeneous texture ledipoblastic or porphyro-lepidoblastic
	2. Fracture cleavage S_1	Very important: thickness, fissility and smooth surface	Only one cleavage present, continuous and penetrative
	3. Lineation L_0	Important, thickness and resistance	Tiles must be cut with L_0 following their longitude in order to achieve the optimum mechanical performance
	4. Discontinuities	Important, mechanical resistance and smooth surface	Absence of any discontinuity such as fractures fill with quartz, mineral alignments or nodules
Manufacturing factors	1. Formating	Very important, standard size	Tiles must be properly formatted, i.e., plane with standard dimensions, with L_0 parallel to the longitude
Building factors	1. Environment	Important, resistance to weathering	Thickness and mineralogy of the tiles must be according with the environment requirements
	2. Aesthetical aspect and homogeneity	Important, aesthetics of the customer	Depending on the customer own requirements

machine learning techniques (Martínez et al., 2012), which may improve and boost the classification process.

2.5. Regulations

To sell slate in the European Community (EC) it is mandatory to comply with the CE mark, which is obtained by passing the EN 12326. The norm for slate and stone for discontinuous roofing and external cladding has two parts, Part1: Specifications for slate and carbonate slate, and Part 2: Methods of test for slate and carbonate slate. Part 3: Schist and schistose stone types for discontinuous roofing—Requirements and test methods is in preparation. France has its own certification system, the NF (Norme Française) mark, which also uses the tests of EN 12326 but with more restrictive requirements. The NF-mark is regarded highly in the roofing slate world, despite the fact that, from a legal point of view, only the CE-mark is mandatory to sell the slate in the EU. In Germany, there are additional requirements in the Fachregeln des Deutschen Dachdecker handwerks, which have to do with very specific slating styles. Belgium also has its own certification system for roofing slate, the ATG certification. In the Netherlands the use of natural slates for monuments is also certified and controlled by the Rijksdienst voor Archeologie, Cultuurlandschap en Monumenten (2009). In the United

Table 4
Mineralogical analysis results for some authors. ES = Spanish slates, DE = German slates, UK = United Kingdom slates, EU = Europe.

	Quartz	Chlorites	Muscovite	Chloritoid	Opaques	Carbonates	Feldspars	Accessories
García-Guinea et al. (1997)[ES]	22–25	15–20	40–60	0–10				
Wagner et al. (1997)[DE]	24–35	19–26	41–51		1–2	>1		Rt, Ill, Trm
Wichert (personal data)[EU]	20–55	10–20	25–55	2–4		Up to 16	5–20	
Lombardero et al. (2002)[ES]	22–25	15–20	40–60	0–10		0–10		Alb, Rt, Ill, Zr, Trm, Ap
Ward and Gómez-Fernandez (2003)[ES]	17–43	12–34	29–56				1–24	Prg, Ana
Walsh (2007)[UK]	34–47	14–21	26–34		1–3	0–6	4–5	
Cárdenes et al. (2012a, 2012b, 2012c)[ES]	7–27	18–43	31–51	0–17			4–11	

Table 5
Mineralogical analysis (XRD) for some selected slates from the World. Mineral abbreviations after Kretz (1983).

Country	Region	Lithology	Quartz	Chlorites	Muscovite	Chloritoid	Biotite	Carbonates	Feldspars	Hematite	Accessories
Spain	Valdeorras	Lutitic slate	26.2	24.3[Chm]	41.8				7.6[Ab]		Clt, Py, Trm
Spain	Lugo	Phyllite	11.9	23.6[Chl]	43.8			2.0	18.6[Ab]		
Spain	Bernardos	Phyllite	33.8	21.4[Chm]	25.2		13.6		5.9[Ab]		
Spain	Villar del Rey	Lutitic slate	28.2	27.8	36.0	8.0			9.0[Ab]		Py
Portugal	Valongo	Lutitic slate	15.9	21.6	42.6	16.3			3.7[Ab]		
Brazil	Minas Gerais	Shale	28.5	7.8	56.2				7.2[Ab]		
UK	Ballachulish	Lutitic slate	39.4	18.1	36.4			2.8	3.1[Ab]		Clt, Py
UK	Pennryn	Lutitic slate	29.5	16.2[Chl]	49.3					4.3	
Canada	New Foundland	Lutitic slate	29.1	12.9[Chl]	53.4					4.2	
China	Jiangxi	Lutitic slate	25.6	9.8	64.1						Py
China	Sichuan	Phyllite	25.3	12.3[Chl]	43.0				19.2[Ab]		
China	Hubei	Carbonate slate	12.8	6.6	13.2			67.2			
Ireland	Valentia	Lutitic slate	35.7	8.5[Chl]	51.5					4.0	
France	Angers	Lutitic slate	14.1	23.4[Chl]	54.9				7.2[Ab]		Clt
Italy	Liguria	Carbonate slate	10.8	2.9	28.7			57.2			
Norway	Finnmark	Schist quartize	52.2		29.6		5.3		12.7[St]		Grt
USA	Vermont	Lutitic slate	47.0	15.6[Chl]	37.1						
Germany	Mayen	Lutitic slate	29.6	25.6	44.6						Rt

States, the mandatory norms are gathered under the ASTM standards (Hicks, 2008). Both norms (EN and ASTM) share some of the same testing methods (Table 1), but the ASTM norms focus on offering an assessment of the estimated durability of the slate, whilst the EN norm only gives the results of the tests, without an interpretation. It is our opinion that the EN tests are more comprehensive than those of the ASTM and therefore provide more reliable statements about quality. It should be good if the EN results are explained towards the customer, since all types of slates, good and bad ones, are sold with the CE mark.

2.6. Geology of the world's slate deposits

Slate roofing has a long tradition in Central Europe, which is also the largest market for roofing slate. Historic slate quarries are found in France (Wagner et al., 1994), Germany (Wagner et al., 1997), the Czech Republic (Wagner et al., 1995), the United Kingdom (Born, 1988; Gwyn, 1999; Williams, 2004), Belgium (Cnudde, 1998), Italy (Cimmino et al., 2003), Ireland (Halpin, 2003) and Norway (Kolderup, 1959). Outside Europe, there are slate quarries in China (Xue, 2002; Jinbiao, 2010), Brazil (Chiodi Filho et al., 2003), Canada (Alam et al., 2008), the United States (Evans and Marr, 1988; Jones, 2005), Nepal (Neupane and Paudel, 2007; Neupane and Paudel, 2012), Australia (Cooper, 2011), Uruguay (Morales-Demarco et al., 2013) and other countries (Fig. 7) with some minor and local outcrops.

These outcrops are found in a diverse range of paleogeographic areas, each with their corresponding tectonic regimes. However, in several of the studied areas most of the outcrops have analogous characteristics, since they are located in formations of similar age, mostly Ordovician. A brief summary of the productive lithotects can be found in Table 2.

3. Petrographical characteristics of roofing slate

Traditionally, the slate market has offered a wide variety of different qualities of slate. Because each manufacturer uses its own commercial references depending on the characteristics of its outcrops, the references used on the market are far from standardised, leading to a fair amount of confusion. One company's first-class slate may be very different from the first class of another company. In general, the quality criteria are similar for the entire sector (first choice without alterable minerals, adequate thickness, uniform exfoliation, etc.), although it is the end use of the slate tiles which determines the more specific requirements. For example in the Pyrenees, where the roof has to support the weight of the snow for a significant number of days per year, slate tiles are extra thick (8–12 mm), regardless of the presence of weatherable minerals. On the other hand, slate tiles used in the rest of France, must be much thinner (3–7 mm), without weatherable minerals, and have a smooth, uniform appearance. Broadly speaking, the different commercial varieties can be grouped into first, second and third qualities, although there are plenty of different formats (rustic, first/second/third special quality, first/second economic, second selection, historical monument selection, standard, etc.).

The factors that determine the quality of a slate tile can be divided into four groups: petrological and tectonic factors, both of which refer to the rock itself, and building factors, which refer to their use in construction (Table 3).

3.1. Petrological factors

Petrological factors are related to the mineral and elemental components of the slate and their relationships to one another, which depend on the sedimentary and metamorphic processes. The main techniques used to study these factors are the visual analysis of hand specimens (texture, S_1/S_0 relation), thin section analysis with a petrographic microscope (texture, grain size, mineralogy), polished section analysis with an ore microscope and XRD and XRF analyses (mineralogical and elemental compositions).

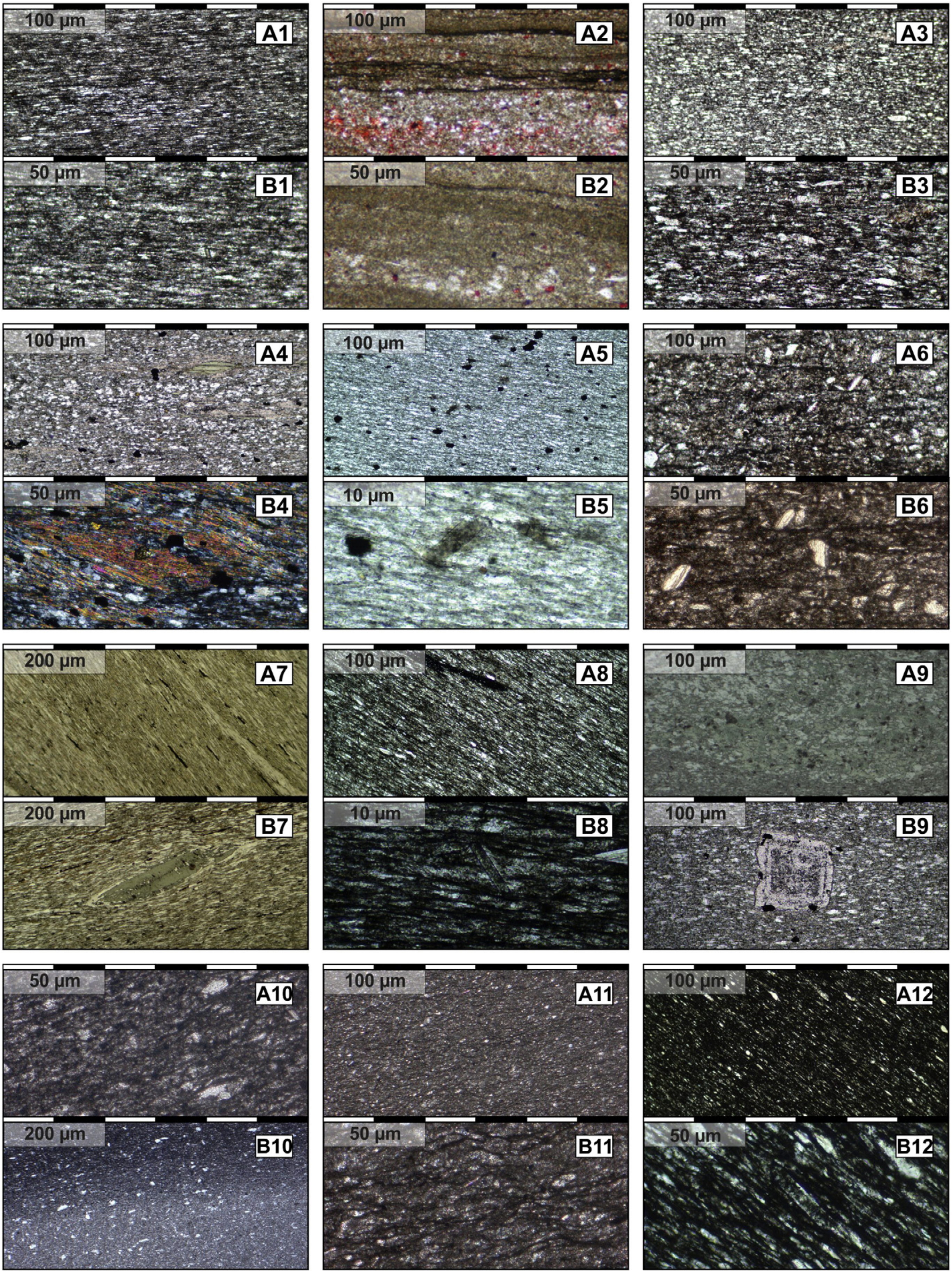
3.1.1. Mineralogy and elemental composition

Several authors have quantified the mineralogical composition of roofing slates from different European deposits using a variety of methods, and with rather similar results across the board (Table 4).

Main minerals are always quartz, mica and chlorites (Table 5). Quartz may be present as relict grains from the sedimentary basin or as recrystallizations filling voids. Mica forms the matrix of the slate, with occasional recrystallizations of acicular crystals, whilst chlorites are always secondary minerals, formed during the processes subsequent to the sedimentation of the original materials. Other minerals can be easily found but in minor quantities, such as feldspar (albite), chloritoid, carbonates, iron sulphides, rutile, tourmaline, zircon and biotite. (Fig. 8). The presence of minerals which are vulnerable to weathering like iron sulphides and carbonates is not desirable in slate (Cárdenes et al., 2012a). Some materials, like Norwegian schist–quartzite, present their own mineral paragenesis, reflecting their characteristic petrology. The predominant textures are lepidoblastic and prophyro-lepidobalstic, even though in some cases other textures can be found (Fig. 8).

Fig. 8. Microphotographs of samples shown in Fig. 4:

1. Lepidoblastic texture in an Ordovician slate. This very fine structure gives the slate a homogeneous and regular external appearance. Main components are chlorites, mica and some quartz (A1), in addition to a scattering of chloritoid crystals (B1). Angers, France.
2. Sedimentary layers are clearly visible in this Brazilian shale. These layers are marked by levels of iron oxide accumulation (A2). Main components are mica, quartz and carbonates, tinted in red with alizarin (A2 and B2). Minas Gerais, Brazil.
3. The red colour of the Trinity slate is caused by the presence of iron oxides. This slate has a rather homogeneous texture (A3), with quartz, mica and chlorites as main minerals (B3). Newfoundland, Canada.
4. Typical structure of a layered volcanic rock, with crystals of chlorite, quartz and opaque minerals (A4), together with epidote (B4, crossed nichols). Himalayas, Nepal.
5. This Chinese slate has abundant opaque elements (A5), corresponding to iron sulphides and organic matter. Main minerals are quartz and mica, with scarce, poorly developed chloritoid crystals (B5). Jiangxi, China.
6. The main mineral components for the Valentia slate are mica and chlorites, with some quartz (A6). In addition, iron oxides and some chloritoid can be found as accessory minerals (B6). Valentia, Ireland.
7. The mineralogy of this schist (A7) is noticeably different from the rest of roofing slates, with minerals that point to its higher metamorphic grade, such as large staurolite (B7) and garnet crystals. Finnmark, Norway.
8. This is a typical Ordovician slate, with mica chlorite and quartz as main minerals (A8) alongside a few accessories, most notably small chloritoid crystals (B8), which are very abundant but not well developed. Other accessories such as iron sulphides and carbonates can be found. Valongo, Portugal.
9. This phyllite's characteristic green colour is caused by the presence of the magnesic term of the chlorite group, clinochlore (A9). Its mineralogy consists of quartz, clinochlore, well-crystallised carbonate crystals (B9) and some opaque minerals. Lugo, Spain.
10. This slate is composed mainly of mica and chlorite, plus some quartz as an accessory (A10). This mineral proportion is optimum for roofing slate. Also, in hand specimens the slate presents green spots due to the reduction of the iron. The edge of one of these green spots can be seen in B10, at the bottom of the image. Penrhyn, Wales.
11. The matrix of this slate is composed mainly of carbonate (A11) and grains of quartz, with well-developed crenulations (B11). However, the fissility is good enough to produce tiles. Liguria, Italy.
12. This slate contains a relatively high level of organic matter (up to 2%), with high mica content along with scattered grains of quartz and chlorite (A12). Chloritoid is also characteristized as a secondary mineral (B12). Villar del Rey, Spain.


100 µm
A1
50 µm
B1
100 µm
A2
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B2
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B11
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A12
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B12

Table 6
Classification of slate hardness.

Group	Relation quartz/ phyllosilicates	Finishing hardness
Very hard slates	>1.3	-High effort during punching and cutting of the slates by means of a hammer -It is partly impossible to process the slate with a hammer due to the extreme brittle behaviour of the slate, leading to breakage or splitting
Hard slates	0.9–1.3	-Higher effort during punching and cutting of the slates by means of a hammer -Possibility of easy splitting
Medium hard slates	0.5–0.9	-Normal effort during punching and cutting of the slates by means of a hammer
Soft slates	<0.5	-Easy punching and cutting -Splitting surface feels slightly soapy

The proportion between rigid and elastic minerals determines a slate's hardness, in particular hardness with respect to wear from abrasion, which is particularly important for rocks used for flooring, scratching and corrosion. The measurable hardness of a slate depends on the hardness, split ability and relative proportions of its component minerals, as well as its fabric. Compared to other rocks like granite, slate is considered a relatively soft rock, and surely for roofing slate hardness is not a very important factor. Regardless, it is still possible to determine production hardness with respect to mining, production and finishing on the roof. Table 6 and Fig. 9 divide the hardness of different slates into groups based on their quartz-phyllosilicate relationship. Production in the quarries is very mechanical and thus small differences in hardness are not readily discernible. By contrast, roofer technicians with their hammer are able to detect even minute differences in hardness.

The aim of such hardness classification is to enable a person to make statements about the "finishing hardness" and the general "finishing behaviour" of a slate, important to the roofing contractors who have to do supplementary cutting to fit some slates on the roof. Further mineralogical investigation of slates from the US and China, for example, could certainly round out, enhance or alter this classification.

As for the mineralogical proportions, elemental composition values found by other authors (Table 7) are reasonably similar, with SiO_2 contents between 51.5 and 69.0%, followed in abundance by Al_2O_3 (14–27%), Fe_2O_3 (4.6–10.6%), MgO (1.4–5.2%) and K_2O (2.1–4.4%). Other major elements are found in small amounts, except for CaO, which may reach very significant amounts (up to 30%) in the case of carbonated slates (Table 8). These proportions are typical of the original sediments' pelitic provenance (Rollinson, 1993).

Elemental proportions in roofing slates can also be used as a trace for determining their original lithotect (Walsh, 2007). The relationship FeO_{tot}–MgO and Rb/Sr has proven to be an effective criterion for differentiating between roofing slates from the Iberian Peninsula (Fig. 10). These two elements are mainly contained within the phyllosilicates (mica and chlorite).

3.1.2. Grain size and fissility

The sizes of the grains and relict minerals are related to their nature, and is probably the most important factor for fissility (Lombardero and Toyos, 1995). For slates s.s., grain size is rather small (Blanco et al., 1989), below 75 μm, where one can distinguish between fine-grained slates (<30 μm), medium-grained slates (30–50 μm) and coarse-grained

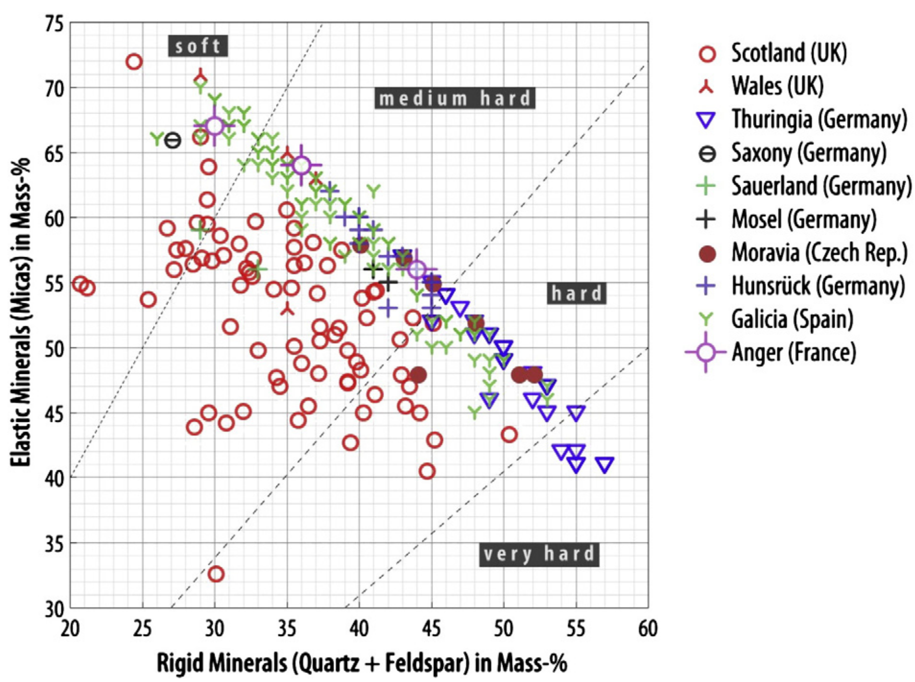

Fig. 9. Portions of the rigid and elastic minerals of different slates. The data are the result of numerous investigations by J. Wichert, of the Freiberg University of Mining and Technology (Germany). Data on Scottish slates from Walsh, 2007.

Table 7
Elemental analysis results for some authors. ES = Spanish slates, DE = German slates, UK = United Kingdom slates.

	SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	LOI
Wagner et al. (1997)[DE]	52.0–59.0	15.0–23.0	4.6–7.3	0.05–0.2	2.6–3.5	0.0–10.4	0.8–1.3	3.1–4.3	0.6–1.3	0.1–0.3	3.6–10.5
Ward and Gómez-Fernandez (2003)[ES]	51.5–65.0	15.3–27.0	5.5–10.6	ND	1.8–3.3	0.1–1.4	0.6–2.5	2.1–4.2	0.7–1.2	ND	2.4–5.3
Walsh (2007)[UK]	57–69	14.5–16.3	5.8–6.4	0.04–0.09	2.2–5.2	0.1–2.1	0.8–1.0	2.5–2.6	0.5–0.9	0.06–0.07	3.2–8.2
Cárdenes et al. (2012a, 2012b, 2012c)[ES]	54.8–64.0	20.0–23.0	5.0–8.4	0.1–0.2	1.4–3.3	0.3–0.4	0.8–1.8	2.5–4.4	0.8–1.3	0.1–0.7	ND

Table 8
Elemental analysis for some selected slates from the world.

Country	Region	SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	LOI
Spain	Valdeorras	62.18	20.75	5.58	0.03	1.60	0.11	0.83	4.76	0.65	0.06	3.45
Spain	Lugo	56.67	20.72	7.88	0.12	3.66	0.27	1.83	4.67	0.94	0.12	3.00
Spain	Bernardos	62.92	18.92	6.21	0.07	2.62	0.44	1.55	4.18	0.87	0.07	2.07
Spain	Villar del Rey	59.43	20.42	8.34	0.24	1.52	0.35	0.85	2.90	1.18	0.17	4.77
Portugal	Valongo	55.54	24.14	8.13	0.08	1.78	0.28	1.13	3.43	1.28	0.08	4.12
Brazil	Minas Gerais	61.88	15.82	6.62	0.11	2.89	1.66	1.85	3.72	0.17	0.78	4.21
UK	Ballachulish	62.61	13.30	7.32	0.12	3.53	1.63	0.92	2.63	0.23	0.12	7.54
UK	Pennryn	57.35	20.33	9.38	0.34	2.36	0.56	1.66	3.03	0.09	1.04	3.84
Canada	New Foundland	58.34	18.97	9.37	0.12	1.90	0.60	1.67	3.99	0.08	1.04	3.83
China	Jiangxi	58.13	20.70	6.89	0.09	1.79	0.31	2.10	4.44	0.19	1.05	3.51
China	Jiangxi	63.34	16.84	7.27	0.10	2.03	0.26	2.12	3.03	0.89	0.14	3.08
China	Hubei	31.69	10.10	4.25	0.06	3.14	23.94	0.63	2.37	0.06	0.44	22.47
Ireland	Valentia	60.48	17.45	7.52	0.14	2.35	1.46	1.23	3.76	1.10	0.16	4.26
France	Angers	50.45	25.38	10.70	0.08	2.07	0.26	1.18	3.01	1.09	0.16	4.97
Italy	Liguria	31.53	7.33	2.59	0.07	1.33	29.20	0.48	1.67	0.34	0.07	25.28
Norway	Finnmark	79.76	8.16	2.87	0.05	0.45	1.45	1.11	3.62	0.61	0.06	1.48
USA	Vermont	58.68	19.74	7.29	0.18	2.37	0.46	1.77	3.57	0.07	1.08	4.00
Germany	Mayen	61.23	18.24	3.40	0.17	3.02	1.01	1.41	3.20	1.11	0.42	6.49

slates (>50 μm). Generally speaking, fine-grained slates can be split into thinner slate plates, though fissility is highly conditioned by the relative sizes of the mineral components (Fig. 11). Coarse-grained slates too may offer good fissility if the sizes of their components are similar to one another (García-Guinea et al., 1998). Thus, homogeneity in grain size is more important than grain size itself. A suitable roofing material should be able to be split into tiles with a thickness of 4 to 10 mm and with minimum dimensions of 30 × 20 cm, although these dimensions depend on market requirements. Materials with higher thickness can still be used for flooring and panelling.

Regarding fissility, there is a well-known problem affecting mainly fine-grained slates. During the manufacturing process, once the slate blocks are sawn, if they freeze or completely dry out, the fissility of the slate greatly diminishes. This effect is circumvented by storing the block submerged in water. Some studies have linked this fact to an Ostwald ripening effect of recrystallisation of the phyllosilicates (García-Guinea et al., 1998; García-Guinea et al., 2000), where the mechanism at work is reasonably clear in the case of the slate drying out, but less so in the case of freezing (Cárdenes et al., 2012b).

3.1.3. Sedimentation S_0

Sedimentation layers are recognised by the occurrence of intercalated or sandy laminations in the slate matrix. These sandy laminations are a negative factor for fissility, as they increase the heterogeneity of the board. Levels or layers are of variable thickness corresponding to sand input stages during the clay sedimentation processes which subsequently formed the slate. Their occurrence can even render a productive level unworkable, depending on the thickness and spacing of the laminations. Also, sediments may form isolated accumulations of sand or shells (lumachella), forming nodules that affects the flatness of the tile (Fig. 12). These nodules are frequently pyritised, which is all the more detrimental to the slate quality. The occurrence of these structures is a useful criterion for polarity in the regional geology of an outcrop.

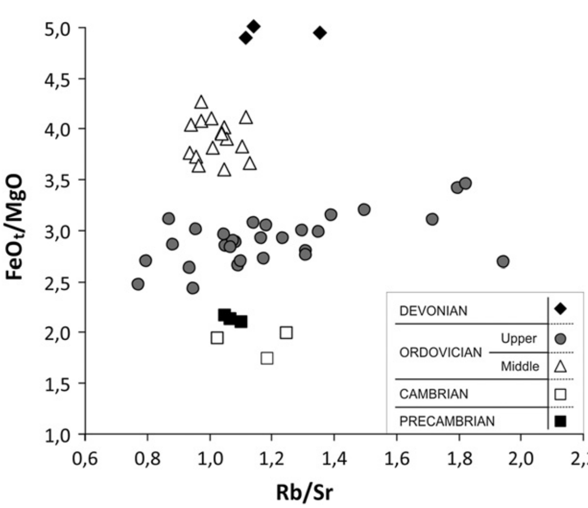

Fig. 10. Geochemical diagram of the relationship FeO_t/MgO vs. Rb/Sr. This relationship has proven to be effective for identifying slates from the Variscan terrains in Spain, although other geochemical relationships can also prove to be helpful (modified from Cárdenes et al., 2013).

3.1.4. Sources of heterogeneity

The presence of strange bodies in the slate matrix causes a mechanical heterogeneity that can greatly affect the fissility of the slate, since they interrupt the continuity of the split layers. The origin of these foreign bodies varies, and can be syndepositional (rock fragments, fossils) or post-depositional (nodules of iron sulphides or carbonates). When they occur in abundance, these foreign bodies may even render an otherwise high-quality outcrop unusable, as in the case of tillites in glacial paleoenvironments.

Also, it is rather frequent in certain types of slate to find fossils, especially slate from the Ordovician period. The presence of fossils in slate is not a quality factor itself; however it is common for the shells of various organisms to become pyrrhotised, which is indeed a quality problem. In some sites the abundance of fossilised fauna may make it more attractive to exploit the quarry for the fossils themselves, rather than for the

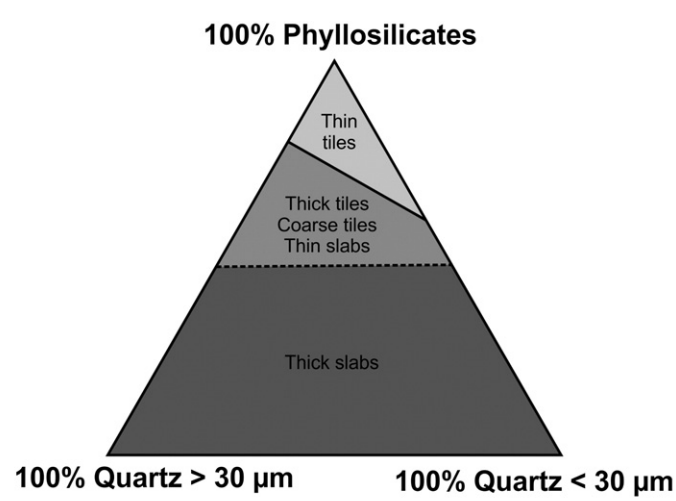

Fig. 11. Average grain size and uses of slate. Modified from Le Corre, 1970 and IGME, 1991.

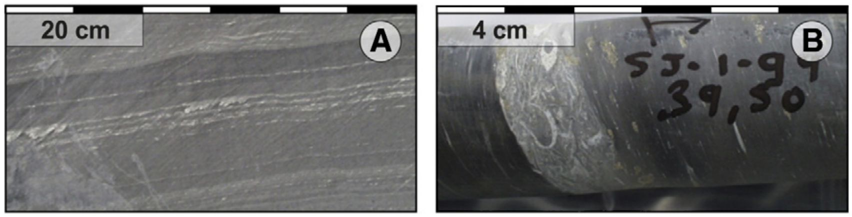

Fig. 12. Occurrence of sedimentation in a slate matrix. Sandy layers in a slate outcrop (A), and a lumachelle level in a core drill (B). Both images are taken in the Ourense outcrops, Spain.

slate. This is the case in the Ordovician quarry in Canelas, Portugal, which has an exceptional record of trilobite species (Gutiérrez-Marco et al., 2009).

3.1.5. Pore system

It is also necessary to highlight the existence of a pore system. A slate s.s. may have up to 1.5% connected porosity (Cárdenes et al., 2012b), which plays an important role over the lifespan of the slate tile (Cárdenes et al., 2013a), since it regulates the fluid transmission of the slate matrix. In norm EN 12326, the pore system is measured indirectly by the water absorption test; with values above 0.6%, the slate must then pass the freeze-thaw test. Our laboratory driven tests show that the water absorption of slate samples diminishes (up to 60%) when heated up to 110 °C for several hours, i.e. EN 12326's drying method. In other words, once the slate sample is heated, its water absorption does not return to initial levels, but rather diminishes, meaning that the test results can be easily manipulated. The pore radius is slightly higher in slates with porphyro-lepidoblastic fabric, and denser in slates with lepidoblastic fabric (Cárdenes et al., 2013b).

3.2. Tectonic factors

Tectonic factors are related to the deformation processes that occurred in the slate matrix during the metamorphic stage. The internal structure of the slate is defined during this stage, resulting from the development of the slaty cleavage S_1, which forms the planes from which the tiles will eventually be split. However, some roofing slates do not exhibit the S_1 planes, e.g. shale, which splits following its S_0 planes. From a production point of view, the rock massif or lithotect should be homogeneous, with none or just slight deformation.

3.2.1. Microscopic fabric

The microscopic texture of a slate s.s. always displays a strong preferred orientation of its minerals, or in other words, has a lepidoblastic fabric (Fig. 13A), which may occasionally take the form of porphyro-lepidoblastic fabric (Fig. 13B) in slates with high quartz content (Ingham, 2005). Other types of roofing materials may have porphyroblastic, granoblastic (Fig. 13C) or even nematoblastic fabrics (Fig. 13D) (Passchier and Trouw, 2005), though these textures are uncommon.

There is a strong relationship between slate fabric and mechanical behaviour. Slates with a fine-grained and homogeneous fabric usually have higher values in the bending strength test (Cárdenes et al., 2012b). As pointed before, norm EN 12326 has a specific section on petrographic study in which the abundance, thickness and density of the mica levels composing the slate fabric are measured, calculating the MSI (Fig. 14).

3.2.2. Fracture cleavage S_1

The fracture cleavage is a planar and continuous feature that penetrates into a body of slate (Williams, 1990; Passchier and Trouw, 2005). It is the basic feature that characterises any roofing material, since it forms the planes from which the rock exfoliates into tiles. It can be of sedimentary (primary foliation, S_0) or metamorphic (secondary foliation, S_1) origin. The metamorphic foliation or fracture cleavage is planer and more regular than the sedimentary foliation, thus being more favourable for the splitting of large and sufficiently plane tiles. However, EN 12326 further specifies that this foliation must be of metamorphic origin to ensure sufficient elasticity and bending strength.

As a result of the effort sustained during the creation of S_1, microscopic structures such as strain fringes and boudins can develop (Fig. 15). The occurrence of further deformation phases may give rise to additional cleavages, which have a negative impact on the fissility and integrity of the slate tile due to the interference of these phases.

3.2.3. Lineation L_0

Lineation L_0 is the intersection between the secondary foliation and the sedimentary beds, which, as such, is only present in metamorphic slates (Fig. 16). The miners sometimes use the term lineation for the grain or longrain, a visible alignment of mica minerals, and also to be taken into account when splitting the tiles. The length of the tiles must be parallel to the weakest direction lineation or grain, otherwise

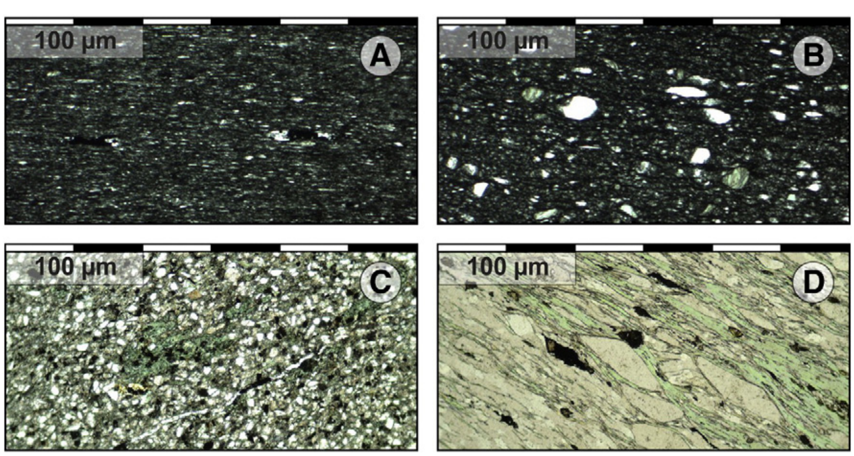

Fig. 13. Most typical textures in roofing slates. A Lepidoblastic texture, Valongo, Portugal. B Porphyiro-lepidoblastic texture, León, Spain. C Granoblastic texture, Ballachulish, UK. D Nematoblastic texture, Finnmark, Norway.

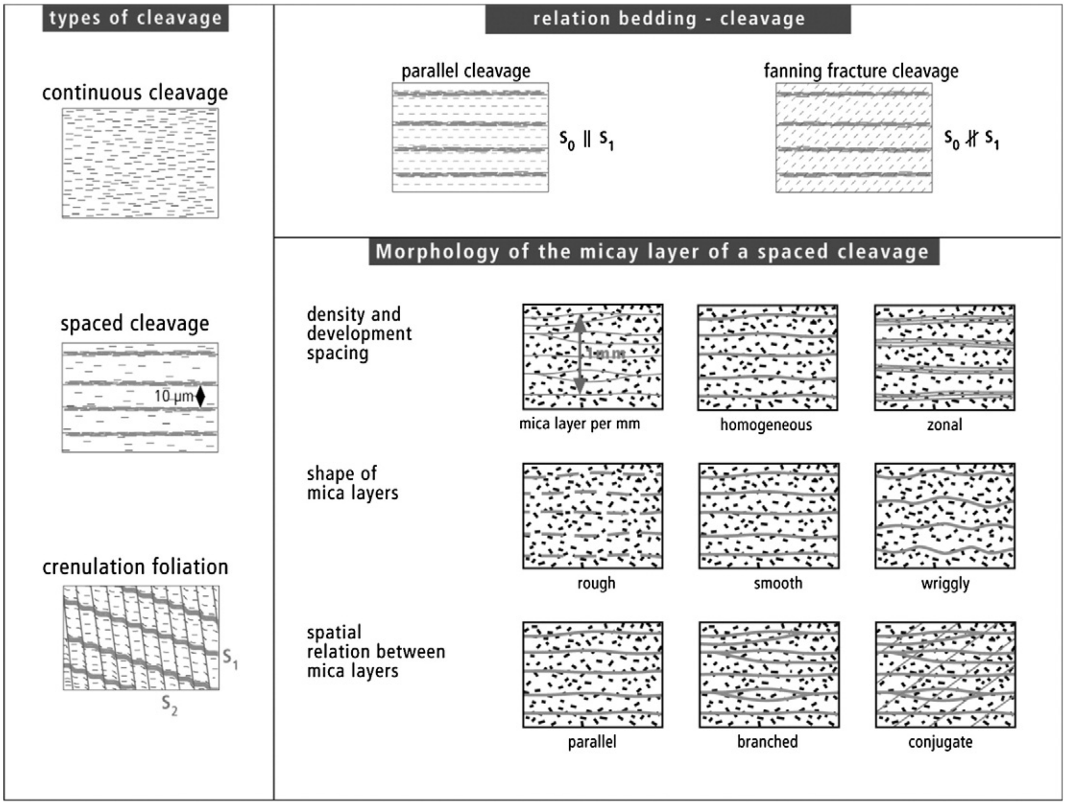

Fig. 14. An applicable classification of the morphology of the mica layers in order to make general statements about properties in terms of elasticity, smoothness of the surface and vulnerability to breakage. Modified from EN 12326.

the tiles will not achieve their optimal bending strength (Wagner, 2007; Cárdenes et al., 2012b). Thus, both EN and ASTM tests emphasize the fact that specimens must be prepared with the L_0 direction in mind. Despite the importance of this feature, it is relatively common to find tiles on the market that are cut with the lineation oblique to their length, due to a poor manufacturing process.

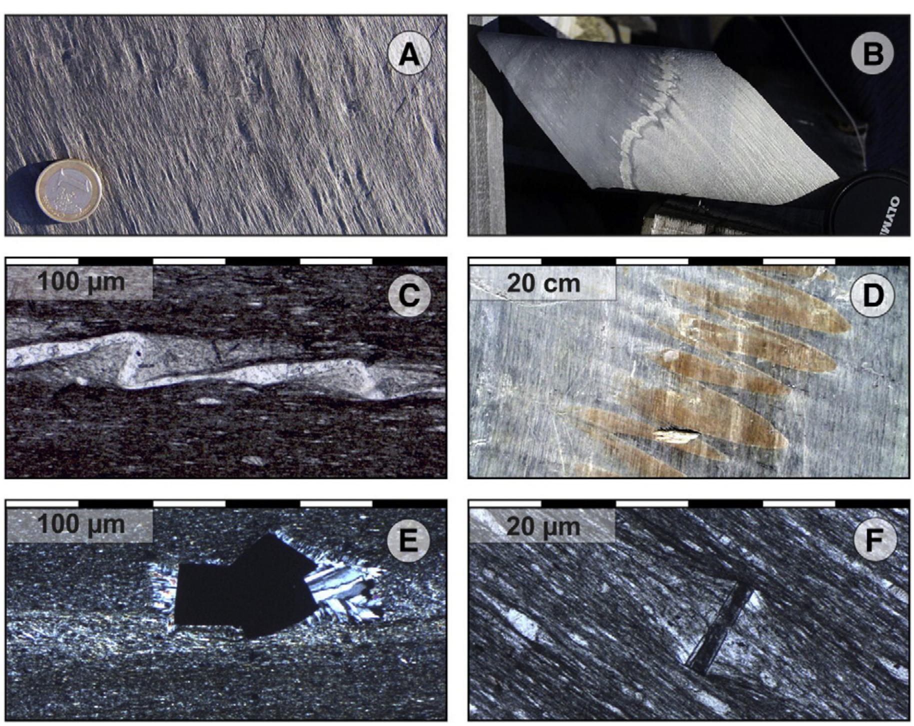

Fig. 15. Traces of deformation. A Undulations due to the occurrence of crenulations over a slate surface, Ourense, Spain. B Refraction of the S_0 layers due to the action of the S_1 slaty cleavage, Ourense, Spain. C Undulate deformation on a quartz vein, Zamora, Spain. D Syntagmatic fold on a slate quarry front, Ourense, Spain. E Quartz fibres in a strain fringe associated with pyrite cubes, crossed nichols, Lugo, Spain. F Pressure shadows filled with quartz associated with a chloriotid crystal perpendicular to S_1, Lugo, Spain.

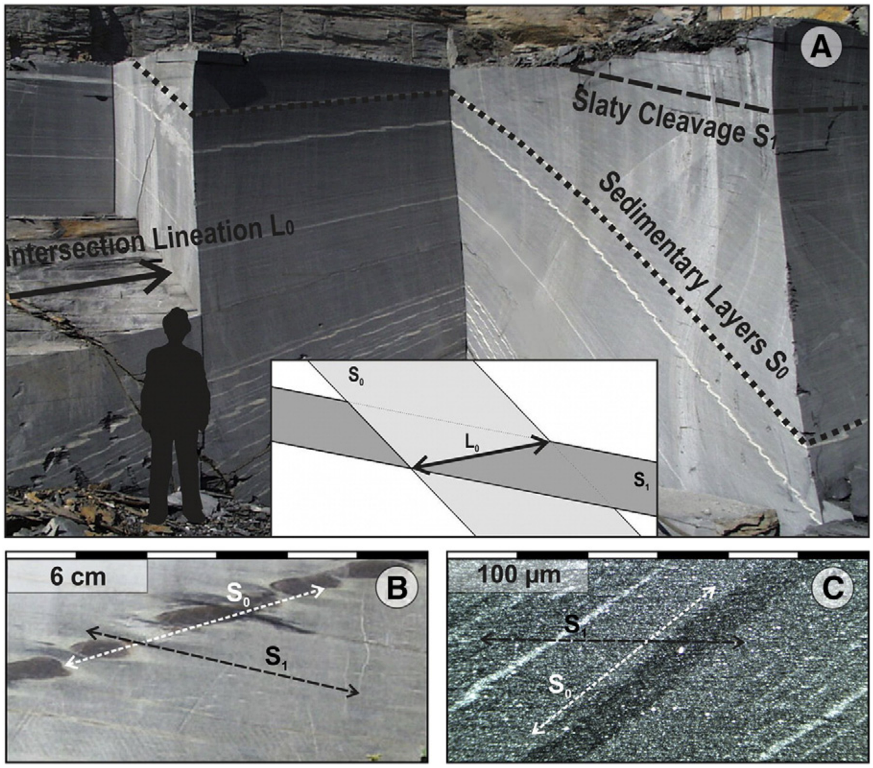

Fig. 16. Several examples of $S_1/S_0/L_0$ associations. A Relationships in a quarry front between these main structures: slaty cleavage S_1, sedimentation beds S_0 and lineation L_0, Ourense, Spain. Modified from Cárdenes et al., 2012b. B S_1 vs. S_0 in a sawn slate block, Ourense, Spain. 15C S_1 vs. S_0 in a thin section, Ourense, Spain.

3.2.4. Discontinuities

Later tectonic efforts may deform the foliation planes and generate other families of planes or fractures which will reduce mechanical performance or even hinder the splitting of the tiles. These structures can be identified as kink-bands, joints and veins (Fig. 17).

Kink-bands are a special type of folding, resulting from compressive efforts on a foliated rock matrix, forming the characteristic stair-type morphology. The presence of these kink-bands is undesirable for the quality of the slate, since they hinder the splitting process reducing the mechanical resistance. However, kink-bands are acceptable in roofing tiles as long as the vertical displacement caused by the kink-band is lesser than a third of the thickness of the tile. Sometimes, families of joints just a few millimetres thick may be filled and recrystallised. Although seemingly harmless since they do not hinder splitting, these joints create a potential line of rupture in the tile. The presence of successive deformation phases may create deformation structures such as fringes and pressure shadows, often made up of recrystallised quartz.

3.3. Manufacturing factor

3.3.1. Formatting

This factor refers to how the slate is split and formatted at the factory, and plays a fundamental role in the slate's quality. Sometimes a defective manufacturing process can ruin even high-quality slate, leading to a considerable loss of money and effort. Slate tiles must be formatted following the specifications of the producer, with a range of dimensional tolerances defined in EN 12326 for slates sold in Europe. The norm defines different measures, i.e. thickness, dimension and curvature. Other measures not defined in the norm are chamfers and perforations.

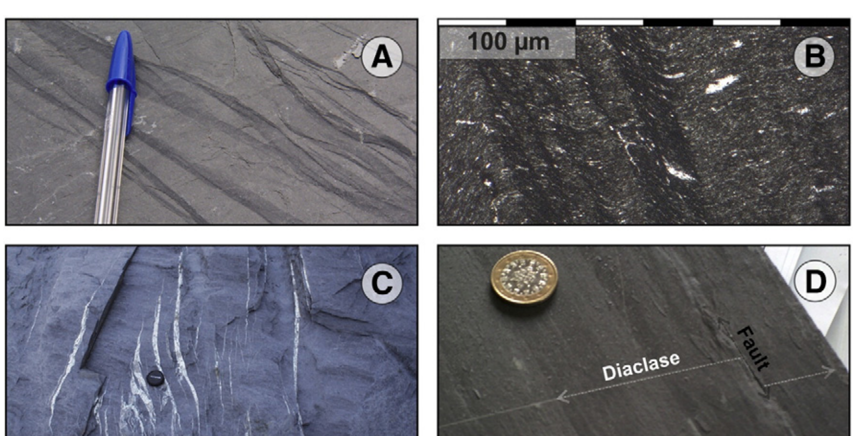

Fig. 17. Discontinuities. A Kink-band folds on a slate block, Ourense, Spain. B Kink-bands seen under a petrographic microscope, Ourense, Spain. C Set of joints filled with quartz in a slate block, Ourense, Spain. D Diaclase filled with quartz (left-right) crossed by a small fault (upper bottom), Ourense, Spain.

These types of defects occur with relative frequency if the cutting devices and tools are not revised and calibrated often. This task should be carried out at least once a day by the person in charge of the factory.

3.4. Building factors

The group of building factors make reference to the aesthetic and constructive properties of roofing slates, and are decisive for architects and builders.

3.4.1. Environment

Climatic conditions are a decisive factor when choosing a particular variety of slate. In environments with high potential weathering conditions, such as coastal zones (saline environment) and urban zones (acidic environment), carbonates and oxides will be easily weathered, so the slate used should have at most a very small proportion of these minerals. However, in a dry and clean environment, these minerals should not cause problems, since their rate of weathering will be very low and thus colour change will be slow and homogeneous for the whole cover, keeping the visual impact to a minimum.

Another fact to take into account is the daily thermal oscillation. Since most slates are rather dark rocks, they are particularly affected by direct sunlight. The thermal diffusivity, measured with pulsed Nd:YAG laser on a disc of roofing slate from Valdeorras, is $k_l = 5.20 \pm 0.80$ W/m K (Boutinguiza et al., 2012), which is slightly higher than for most dimension stones (Amaral et al., 2013). Slate's freezing point occurs when the air temperature is below −5 °C (Cárdenes et al., 2012b), due to the thermal inertia of the slate (Fig. 18). This temperature marks the point at which freeze-thaw weathering may begin to affect the slate.

3.4.2. Aesthetical aspect and homogeneity

Colour depends on the mineralogy of the slate components, whilst gloss depends on the amount, orientation and size of the phyllosilicates. Although aesthetics are very subjective and depend on each customer's preferences, a minimum degree of homogeneity in appearance is necessary, even for heterogeneous materials. Thus, it is mandatory that slates in a single batch are from the same quarry. Furthermore, if there are different slate units at the quarry (i.e. oxidised units vs. non-oxidised units), the slate from each unit should be selected and stored in separate crates. Although there are exceptions for some particular materials, the customer must have all the information about the material which he/she is buying.

The range of colours in roofing slates varies from green and light slates, typical of the Cambrian, to intense red slates rich in iron oxides (Fig. 19).

4. Conclusions

Despite their importance as a construction material, there is still room for improvement on a number of issues surrounding roofing slate. Although the production system seems to be rather simple, it depends very much on human work and experience. As such, there is a great need to develop new specific machinery for roofing slate. Regarding slate petrology, new research in this field will lead to better methods for understanding and investigating outcrops, and better ways to advise builders about the material's potential uses. The main points which need further development are summarized as follows:

– Scientific characterisation of roofing materials, as opposed to empirical characterisation. The slate market uses an inherited terminology which is very confusing. The term “roofing slate” comprises a wide variety of different rocks (shales, slates, schists, etc.) with different performances, with the only common property of being able to be split into light and thin tiles, such that each country has its own particular varieties of roofing slates. The definition from a petrographic point of view each slate variety will help to understand their performance and hence to find the best place and geographical area in which to use them. Then, uniform criteria are needed for naming these types of stones, a good starting point can be the petrological definitions given in reports of the Fettes et al. (2007).
– Changes in the mechanical properties of slate during weathering. The evolution of the mechanics of roofing slates during their service life is not a clear process, a fact which has contributed to the large number of lawsuits related to bad performance of slate. This is particularly important when it comes to cultural heritage, since replacement slate tiles could break and ruin the restoration work. The evolution of the slate fabric during weathering merits an in-depth analysis, using techniques that allow for the monitoring of the slate texture and fabric's internal evolution, such as X-ray Micro tomography.

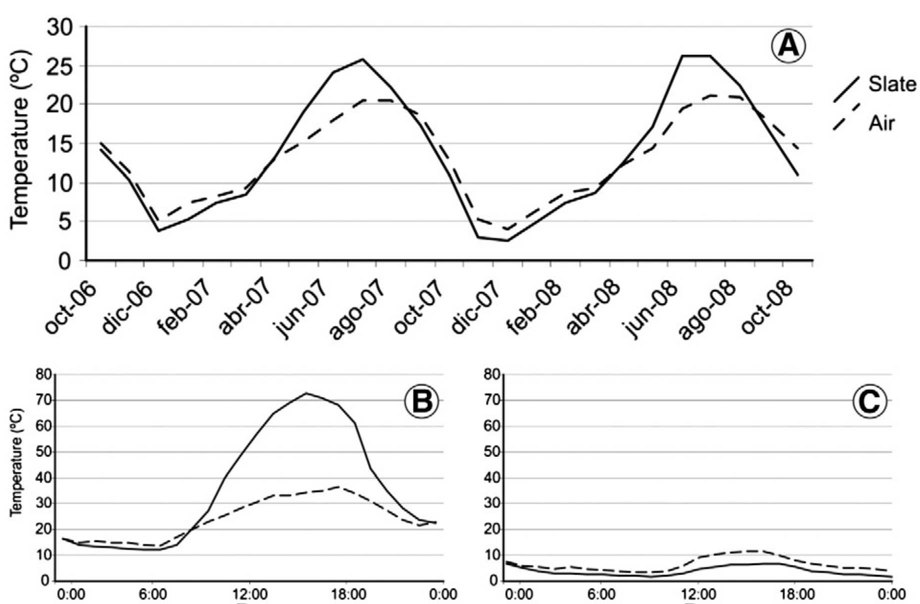

Fig. 18. Monitoring over 24 months of the temperature reached by a slate tile and surrounding air in direct sunlight. A Monthly average temperatures. B Temperature on a single summer day. C Temperature on a single winter day. Modified from Cárdenes et al., 2012b.

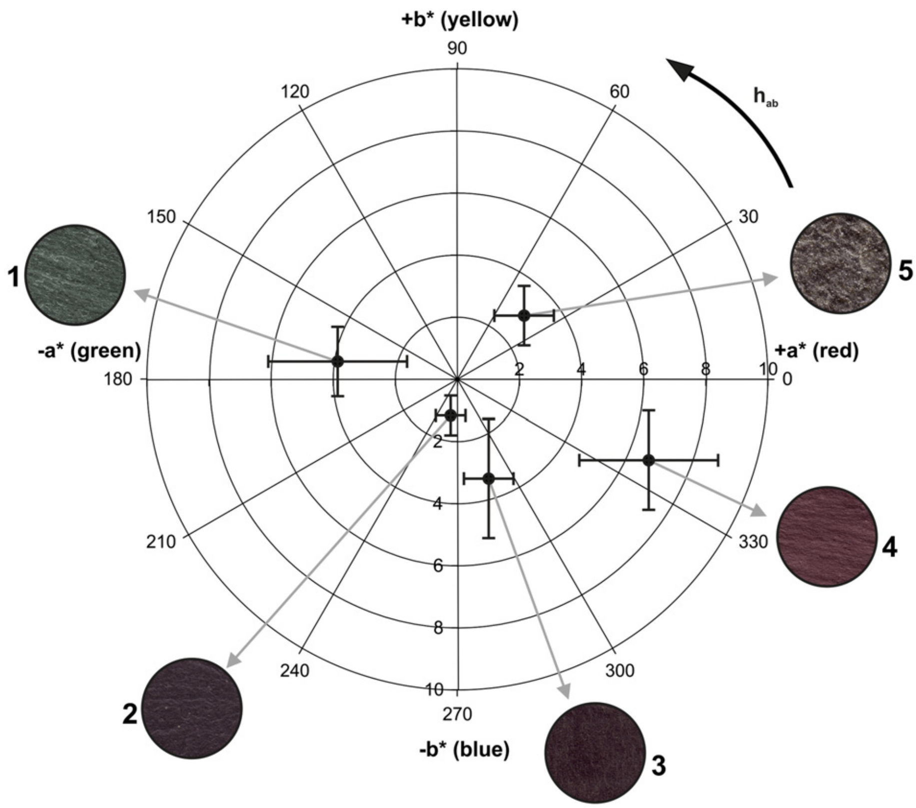

Fig. 19. CIELAB colour space representation of the area in which the chromatic parameters a*, b* and h_{ab} of the roofing slates under study are included. Lightness can be deduced from the proximity to the diagram's centre; the farther from it a point is, the greater its lightness. Depending on colour, five main groups can be distinguished (in parentheses are some characteristic lithotects): 1. Green slates (Trinity slate from Canada, Verde Pol slate from Spain, Jiangxi slate from China); 2. Dark grey slates, which comprise most of the Ordovician lithotects; 3. Blue-grey slates (Penrhyn slate from the UK, Jiangxi slate from China); 4. Red slates (Trinity slate from Canada, Penrhyn slate from the UK); and 5. Light-grey slates (Bernardos slate from Spain, Finnmark slate from Norway).

– Evolution of the porous system and dehydroxylation induced by heating under direct sunlight. This fact is closely related to the previous point, but has some unique characteristics. The evolution of the pore system affects other aspects aside from mechanical performance, such as the formation of new potentially harmful mineral phases, and their subsequent weathering. Previous studies have shown that sunlight plays an important role in this phenomenon. Again, monitoring the pore system is only possible with an accurate technique that is able to model the slate's structure.
– The influence of the microscopic fabric on the technical properties of slate. The main property of any roofing slate is its ability to be split into tiles. There are several geological processes that cause this property (sedimentation, folding, cleavage, etc.). The trace of these processes is found in the microscopic fabric of the slate. Depending on this fabric, slates are more suitable for one use or another (roofing, flooring, paving, etc.). Accurately identifying this microscopic fabric will make it possible to recommend the best use for a particular variety of slate.
– Development of a methodology for identifying the provenance of historic slates. Frequently it is necessary to determine the provenance of a slate, e.g. when restoring a historical building, or in a legal case. The best method is to find the geochemical trace and compare it with the trace of known slate outcrops. However, this is not always possible, due to a lack of available geochemical background data. There is a real need for alternative techniques with a maximum degree of accuracy.
– Development of a protocol for replacing the slates in a historical building, in cases where the original quarries are not available, and slates from other quarries or even from other countries must be used. This process must be exhaustively documented and justified, and this can only be done after a proper study of the original slate. Standard techniques, such as optical microscopy and normative tests, provide accurate information, but in these cases the slate characterisation must be precise. The development and use of new techniques can remedy this situation.

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