Spanish roofing slate deposits

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Synopsis

Spain is the largest producer of roofing slates in the world, accounting for 87% of world production. The expansion in Spanish quarrying of roofing slate is recent and it has been treated in only a few international publications. A review of roofing slate lithotects (with details of three slates of different fissility), quarries and petrological problems is provided. Structural analyses are crucial in slate exploration and quarrying, and this is borne out by examples of exploration methodology applied in central Spain and of computer analysis of the rock mass discontinuities in a quarry at Casaio (Orense) in northwest Spain.

Roofing slate production is an important part of Spain's mining quarrying and industry. The country is the source of 480 000 t of the world production of 550 000 t/year, and this amount was responsible for profits of £148 000 000 in 1995.[22] Slate production has a long tradition in Spain. The monastery palace of El Escorial has roofs of Bernardos (Segovia) slate and eighteenth-century documents describe slate quarrying from Villar del Rey (Badajoz), Carballeda de Vadeorras (Orense), Naharros (Guadalajara) and Santa María del Congosto (León). In 1952 several small, hand-worked quarries opened in Carballeda (Orense), which led to what is now the largest slate-producing area in the world.[11] At the beginning of the 1960s machinery was introduced into some old quarries where until then everything had been done by hand. In 1969 Spain's first large commercial slate company, SAMACA, was founded and in the 1970s the slate industry expanded greatly, exporting ever larger quantities. In the 1980s huge development occurred. Exports increased greatly, but with increased production of waste the quarries became more expensive to run—especially as the majority are cut into steep slopes. Quarrying companies began exploration to locate and assess new slate bodies.

More recently, in the 1990s, the slate industry has acquired new techniques, which include diamond-wire and diamond-saw cutting methods, the development of block sawing and the use of automatic devices to split blocks along the slaty cleavage into roofing slates. These modern methods have increased the yield of usable slate from 2 to about 13% of the total volume of rock in quarry.

Petrological characteristics of roofing slates

Slates are very fine-grained rocks having a penetrative (or slaty) cleavage. They develop mostly from muddy sediments during low-grade metamorphism. A slaty cleavage is due to the strong preferred orientation of phyllosilicates (white micas and chlorites), and this enables the rock to be split into large, thin, flat sheets. The spacing of the planes of potential splitting is controlled by the diameter of detrital, silt-sized grains, mostly of quartz, as stressed by Durney and Kisch,[7] but also by chlorite–mica stacks.[18] A coincidence of geological factors, such as suitable mineral composition, texture and structure, is necessary for a slate formation to be exploitable as roofing slate. This coincidence is rare. A slate lithotect can be defined as a lithological facies the characteristics of which are those of roofing slate deposits. It is required to be at least several metres in thickness.

Mineralogy

Slate is commonly composed of white micas (usually phengitic illite–muscovite ± Na,K-mica ± paragonite), chlorite and quartz together with lesser amounts of one or more of chloritoid, albite, K-feldspar, calcite, iron sulphides, graphitic matter, tourmaline, rutile, zircon and apatite. Roofing slates are 22–25% quartz, 40–60% white micas and 15–20% chlorite. Chloritoid may sometimes reach up to 10%.[19]

Slates that contain large amounts of iron sulphides (pyrite, marcasite and pyrrhotite) and carbonates are not suitable for ornamental use on account of the rapid weathering of these minerals.[29] The biochemical hydroxidation of marcasite and pyrrhotite is very fast and is accompanied by volume changes and acid generation. Pyrite is more resistant, decaying only in acid environments, i.e. in areas of acid rain or peat cover, or in association with pyrrhotite. Carbonates are rapidly leached in acid environments and cause white spots on the slate.

The best roofing slates have been obtained from formations that have experienced low-grade regional metamorphism under low greenschist-facies conditions, i.e. the chlorite zone for metapelites (T = 300–400°C; P = 2–3 kbar). Most have white mica (illite) crystallinity values, or Kubler indices,[15] of 0.15–0.25 $\Delta°2\theta$ and are therefore epizonal rather than anchizonal. The presence of paragonite and/or Na,K-mica, however, leads to speciously high index values and, therefore, to indication of apparently lower grades.[10,28]

Texture

Texture is an important factor in slate fissility. The grain size of roofing slates is very small, being generally less than 75 μm. Slates can be classified as fine-grained (average quartz grain size, <30 μm), intermediate-grained (30–50 μm) or coarse-grained (>50 μm).

Grain-size homogeneity is a critical factor. Fine- or medium-grained slates normally have especially good fissility, but homogeneous coarse-grained slates that do not contain microclasts or micro-porphyroblasts may also have good fissility. The texture of a roofing slate must be lepidoblastic with a continuous slaty cleavage.[3,26,33] The slaty cleavage forms in the X–Y plane of the strain ellipsoid[30] and usually has an approximately axial-planar relationship to associated tectonic folds. Continuity of the cleavage is dependent on the degree of preferred orientation, grain size and homogeneity.

Some slates develop a penetrative lineation, parallel to the X direction of the strain ellipsoid, which is seen on the cleavage surfaces. This is termed 'grain' by British quarrymen and 'downdip lineation' by Hobbs and co-workers.[13] Le Corre[16]

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described it from slates in western France and developed an optical method to determine its direction. It strongly influences the preferred direction of saw cut in producing blocks in that it causes less wear on the diamond heads of the cutting tools. It is distinct from the non-penetrative lineation produced by bedding–cleavage intersections, though this lineation also usually influences the direction of saw cut in block production. Potential for confusion exists because U.S. quarrymen refer to this non-penetrative lineation as ‘grain’.[8]

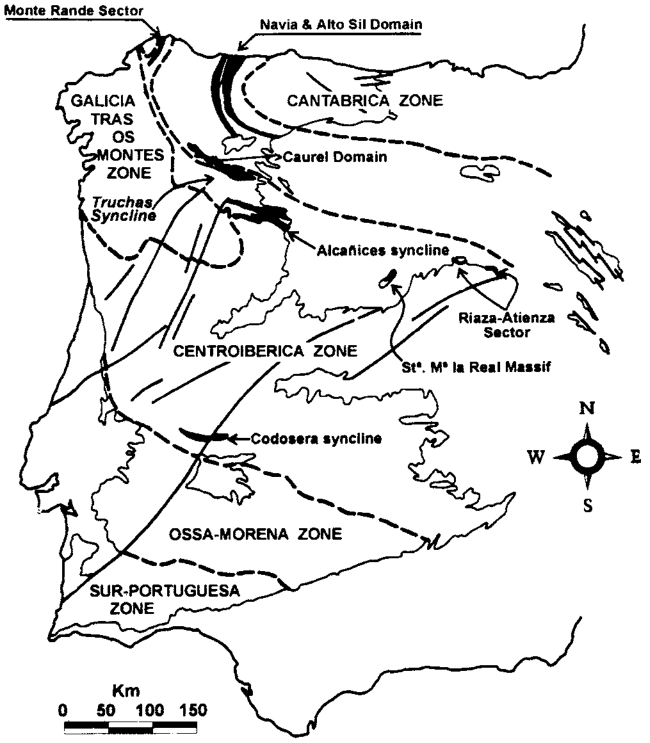

Fig. 1 Simplified tectonic map of Iberian Peninsula, after Julivert *et al.*,[14] showing elements discussed in text. (*Black areas*, lithotects; *broken lines*, zone borders; *continuous lines*, major faults)

Structure

Bedding and lamination traces (S_0), due to changes in grain size and composition, usually result in cleavage refraction or even in breaks in the continuity of the cleavage and make exploiting the slate difficult. This may become more of a problem where the bedding and cleavage angles of intersection are greater than 10°.

The slaty cleavage is often the primary foliation (S_1), which is also the anisotropy that defines the planes of potential splitting. The presence of younger foliations that deform S_1, such as crenulation cleavage (S_2), causes, at best, irregular surfaces of potential splitting that do not allow flat sheets to be produced or, at worst, provides discrete terminations to S_1. The presence of kink-bands and mineral veins, especially quartz veins and quartz–chlorite veins, introduces similar problems. Low angles between S_1 and S_2 may lead to low-angled wedges of slate instead of parallel-faced sheets. Such wedges develop a characteristic surface known as *pizarra quemada* (burnt slate).

All slate bodies are affected by joints that occur in all rocks as sets of geometrically related planar fractures across which there has been no detectable shear displacement. They have a variety of origins and may develop sequentially at a number of stages in the geological history of a slate body.

Folds present in slate formations are usually of similar type. The geometry results in thickening in the hinge zones and attenuation in the limbs such that in tight, similar folds an orthogonal thickness of 90 m in a hinge zone may be reduced to 15 m in the limbs.

Spanish slates—geological setting

All Spanish roofing slate quarries are located in the Iberian Massif, the Iberian section of the Hercynian range of Western Europe (Fig. 1). Most authors recognize three main phases of Hercynian deformation in the northwestern area of the Iberian Massif.[12,23,24,25] The polyphase deformation was accompanied by polyphase metamorphism. The first deformation phase, D_1, led to the development of the dominant cleavage, S_1, approximately parallel to the axial surfaces of the D_1 folds. The second phase, D_2, caused large-scale

			Asturoccidental-Leonesa Zone			Centro-Ibérica Zone					
						Truchas Domain					
			Navia & Alto Sil Domain	Mondoñedo Nappe Domain	Caruel Domain	TRUCHAS syncline	RIAZA ATIENZA Sector	MONTE RANDE Sector	ALCAÑICES Syncline	St^a MARIA LA REAL Massif	CODOSERA Syncline
DEVONIAN									MANZANAL Formation Unexploited		GEVORA Unit < 3 quarries
SILURIAN											
ORDOVICIAN	Ashgill					CASAIO & ROZADAIS Formation > 10 quarries	RODADA 4 Formation Unexploited				
	Caradoc										
	Llandeilo		LUARCA Slates Formation <3 quarries		LUARCA Slates Formation 3 - 10 quarries						
	Llanvirn					LUARCA Slates Formation <10 quarries					
	Arenig										
	Tremadoc	Pre-Arenig								< 3 active quarries	
CAMBRIAN				CANDANA F. < 3 quarries							

Fig. 2 Spanish roofing slate lithotects of Palaeozoic age. West Asturian–Leonese (Asturoccidental–Leonesa) and Centroibérica zones are different tectonic units of Hesperian Massif, which forms southernmost part of West European Hercynian orogen

thrusts, which carried internal zones eastward over external zones. The third phase, D_3, produced major folds, commonly having wavelengths greater than those of D_1 folds. Suites of minor structures associated with the D_2 and D_3 phases, when strongly developed, reduce the economic viability of the affected slate bodies by causing an increase in the proportion of waste. Thus, for example, crenulation and crenulation cleavage (S_2) are commonly developed in the hanging-wall blocks adjacent to D_2 thrusts; and S_3 is preferentially developed in the short limbs of asymmetrical D_3 folds adjacent to major faults of Hercynian age.

Combinations of structural factors, including fold style and discontinuities introduced by joints, veins, bedding, etc., limit the natural block size that it is possible to extract from a quarry and, therefore, the industrial exploitability. The minimum exploitable layer thickness for massive slate is 12 m; for slates interbedded with other lithologies it is 100 m.[9]

The main slate quarries have been opened in the southern limb of a major fold, the Truchas Syncline (Figs. 1 and 2), where, stratigraphically, they occur near the base of the Luarca Slate Formation of Llanvirn–Llandeilo (Ordovician) age.[2] The long-established and important quarries of Casaio

Table 1 Commercially significant properties of main Spanish roofing slates

			Geological unit	Colour	S.G., g/cm^3	Water absorption, %	Shear strength, kg/cm^2	Frost resistance	Thermal shock resistance	Acid resistance	Carbonate contents, %
CENTROIBERICA ZONE	Cordosera Syncline		Grevora unit, Villar del Rey (Badajoz)	Black	2.71	2.7	300–400	–	+	+	0.5
		M.Sta.Ma la Real	Pre-Arenig, Bernardos (Segovia)	Layered grey-green	2.72	1.8	400–550	–	–	–	
		Alcañices Syncline	Manzanal Formation Fradellos (Zamora)	Grey	2.77	1.5	300–450	–	–	+	
		Monte-Rande	Luarca Slates, Cuiña (La Coruña)	Grey	2.71	2.7	300–450	–	–	–	
	TRUCHAS DOMAIN	Riaza-Atienza	Rodada 4 Formation Naharros (Guadalajara)	Black							
		TRUCHAS SYNCLINE	Rozadais Formation, S. Pedro Trones y Benuza (León)	Grey	2.83	1.7	350–500	–	–	+	
			Rozadais Formation Carballeda (Orense) La Baña (León)	Black	2.80	2.0	350–450	–	+	+	
			Casaio, Carballeda (Orense)	Dark grey	2.83	1.4	350–475	–	–	–	
			Luarca Slate Formation Carballeda (Orense)	Black	2.85	1.5	350–550	–	+	+	
ASTUROCCIDENTAL–LEONESA ZONE	CARUEL DOMAIN		Luarca Slate Formation Sierra del Caurel (Lugo)	Grey	2.83	1.8	400–550	–	+	+	0.7
			Tremadoc, S.Vicente de Leira (Orense)	Grey	2 83	1.9	400–550	–	+	+	
	MONDO-NEDO DOMAIN		Candana Formation Mondoñedo-Castro Verde (Orense)	Green	2.79	1.1	300–400	–	+	++	1.0
	NAVI Y ALTO SIL DOMAIN		Luarca Slate Formation Los Oscos Lugo (Asturias)	Grey	2.72	1.7	400–500	–	–	–	0.1
			Luarca Slate Formation Alto Sil (León)	Grey	2.80	2.3	300–400	–	+	–	0.1

Apart from Badajoz and Segovia, which are of lesser importance, all units are located in northwest Spain. The new Sobradelo de Valdeorras Technological Centre for Slate (Orense, northwest Spain) supplies these data to establish commercial standards.
– Without alteration; + with alteration; ++ important alteration.

and Carballeda de Valdeorras are located in this geological setting. The slates exploited occur as beds 10–100 m thick. They are black with an excellent fissility, but have a variable sulphide content, which increases upwards.

Within the Truchas Syncline the Casaio and Rozadais Formations of Caradoc to Ashgill (Ordovician) age are also exploited. The slates occur as 10- to 100-m grey beds interbedded with quartzite and sandstone. They possess good fissility and have lower sulphide contents than slates from the Luarca Slate Formation.

The formations show abrupt lateral changes in facies,[2] which exercise additional controls on the siting of the quarries. Quarries exploiting the Rozadais Formation are San Pedro de Trones (León), opened in the hinge zone and normal limb of an overturned anticline, and Penedo Rayado and Os Foyos in Carballeda de Valdeorras (Orense), both in the normal limbs of overturned folds. Quarries opened in the Casaio Formation, close to Casaio village, are Mormeau, in

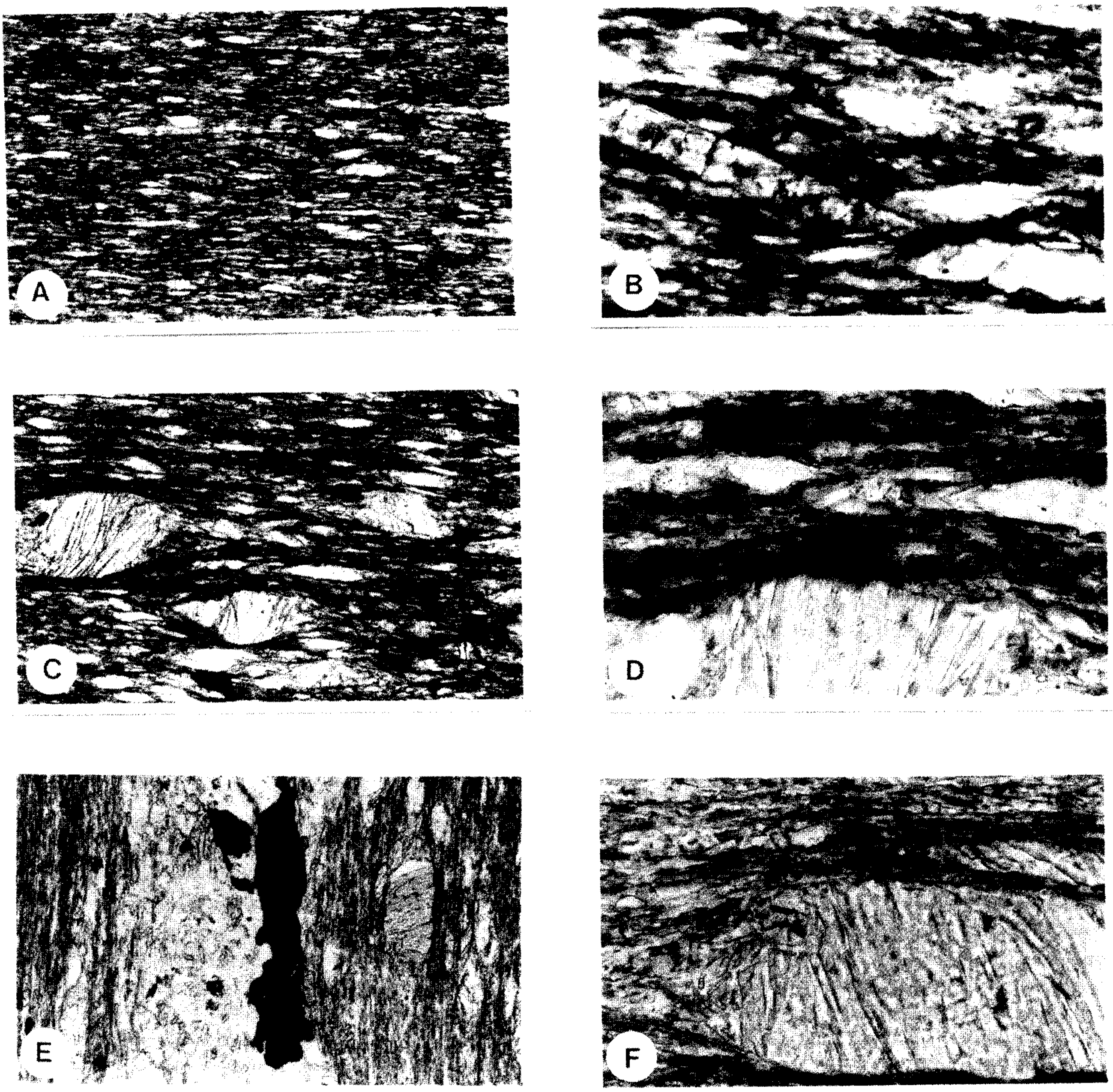

Fig. 3 Photomicrographs, all plane-polarized light. (*a*) *and* (*b*) Sample *H*—slate from Luarca Formation in Navia y Alto Sil Domain (Llanvirn–Llandeilo): (*a*) (long dimension, 860 mm) strongly deformed, small, chlorite–mica stacks and quartz lenses set in very fine-grained, strongly orientated phyllosilicate matrix; micro-porphyroblast of chloritoid set oblique to slaty cleavage slightly above centre; cleavage spacing controlled by *ca* 20 mm wide chlorite–mica stacks; (*b*) (long dimension, 220 mm) detail of chloritoid micro-porphyroblast from centre of field (*a*), deformed chlorite–mica stacks and matrix. (*c*) *and* (*d*) Sample *M*—slate from Casaio Formation in Truchas Domain (Caradoc): (*c*) (long dimension, 860 mm) large, deformed, chlorite–mica stacks and smaller quartz lenses against which slaty cleavage develops contact–strain relationship; cleavage spacing controlled by deformed chlorite–mica stacks (about 150 mm wide) and by transposed siltstone lenses up to 400 mm thick (*not shown*); (*d*) (long dimension, 220 mm) detail of part of chlorite–mica stack and matrix from lower, central part of field (*c*). (*e*) *and* (*f*) Sample *L*—slate from Casaio Formation in Truchas Domain (Caradoc): (*e*) (long dimension, 860 mm) area of transposed, quartz-rich, very fine sand, 420 mm thick; pyrite elongate in plane of cleavage; deformed chlorite–mica stacks and quartz lenses; phyllosilicate-rich matrix; cleavage spacing controlled by thickness of sand lenses; (*f*) (long dimension, 220 mm) detail of chlorite–mica stack (*right of centre in* (*e*)) showing development of quartz and phyllosilicate-rich beard and contact–strain relationship to slaty cleavage

the hinge zone of a syncline, and Juanita–Los Molinos, in an anticlinal hinge zone.

A number of isolated quarries, including the important Armadilla (Benuza) quarry, are also found in the southern limb of the Truchas Syncline in the Sierra de la Cabrera (Leon). Most exploit the Rozadais Formation and the Luarca Slate Formation (Truchillas). The quarries of La Bana have been opened in the inverted limb of an overturned fold in the Rozadais Formation and because the angle S_0/S_1 is high, slates commonly show a bedding stripe (L_1) on S_1.

A group of quarries of Pacios de la Sierra (Quiroga, Lugo) exploits the Luarca Slate Formation where it forms the inverted limb of the major recumbent Caurel fold. In this geological setting the slaty cleavage, S_1, is near horizontal. On the other hand, in the Navia y Alto Sil Domain the slaty cleavage in the Luarca Slate Formation is near vertical. Here a number of isolated quarries, such as Anllares (León), Lamas in Fonsagrada (Lugo) and Los Oscos in Asturias, produce very uniformly textured, fine-grained, highly fissile, dark-grey slates.

Lithotects of lesser importance include the Lower Ordovician (Tremadoc) slate–sandstone formations of San Vincente de Leira (Orense) and the Lower Cambrian green slates of the Candana Slate Formation in the Mondoñedo Nappe Domain, which are quarried at Castroverde and Pastoriza (Lugo). The Gevora Unit includes slates of Devonian age that are quarried at Villar del Rey (Badajoz, southwest Spain). The quarry has been opened in vertically cleaved slates in a minor syncline associated with the La Codosera Synclinorium. The silty and sandy slates of Santa Maria la Real de Nieva are worked for floor tiles in two quarries near Bernardos, Segovia. Finally, a slate quarry was opened in 1993 in Huelva province, southwest Spain, in a thick volcaniclastic sequence of Carboniferous age. The slates produced are greenish-grey owing to the abundant volcanic detritus.

The technological characteristics of Spanish slates from the main slate formations and structural units are given in Table 1. Fissility is not included in the table because there is, as yet, no completely satisfactory way of quantifying this property.

Mineralogy and microstructure: influence on fissility

Three slate samples (*L*, low-fissility; *M*, medium-fissility; and *H*, high-fissility) were examined by the use of optical, X-ray diffraction, scanning-electron microscope and electron-microprobe techniques. All three are from the Truchas Domain and are Ordovician in age.

The samples consist, in order of decreasing abundance, of white micas, chlorite, quartz, feldspars, ilmenite, pyrite, rutile, apatite and tourmaline. Texturally, all consist of silt-sized clasts of detrital quartz, feldspars, chlorite–mica stacks, muscovite and ilmenite in a recrystalline matrix of white micas, chlorite and quartz lenses, all showing strong preferred orientation.

Sample *H* (Fig. 3(*a*) and (*b*)) contains widely dispersed detrital grains of quartz and chlorite–mica stacks elongated within a very fine-grained, highly orientated, phyllosilicate-rich matrix. Detrital quartz and feldspar average 10 × 30 mm, whereas chlorite–mica stacks average 20 × 100 mm. The sample also contains porphyroblasts of chloritoid up to 15 mm × 150 mm. The spacing of the cleavage is controlled largely by the width of the chlorite–mica stacks and the chloritoid porphyroblasts.

Sample *M* (Fig. 3(*c*) and (*d*)) contains former laminae of coarse siltstone to fine sandstone, which have been transposed into cleavage-parallel lenses up to 400 mm thick. Chlorite–mica stacks average 150 mm × 150 mm and detrital quartz, feldspar and calcite average 50 mm × 100 mm. The matrix is similar to that of *H*. The spacing of the cleavage is controlled largely by the thickness of the transposed lenses of siltstone and sandstone.

Sample *L* (Fig. 3(*e*) and (*f*)) contains continuous and lens-like laminae of siltstone (S_0) that have not been transposed. The cleavage (S_1), due to the preferred orientation of phyllosilicates in the pelitic laminae, intersects S_0 at 13°. The relatively poor fissility is due both to the interruption caused by the siltstone laminae and to the angle S_0/S_1.

The two major controls on fissility in the samples are, therefore, lithology and deformation accompanied by metamorphism.

Slate extraction

Quarried blocks of slate, termed dimension stone, are usually bounded by natural discontinuities, such as bedding planes, joints, veins, kink bands and cleavage surfaces. The minimum size extracted is 0.6 m^3.[19] Estimates of the suitability of particular slate horizons for slate extraction are based on geotechnical properties.[1,20,21,32] Three parameters are involved: the minimum productive volume of a block, V_m; the percentage of blocks in the slate horizon with a volume greater than V_m, V_b; and J_v, defined by the number of discontinuities in a cubic metre of the slate horizon.

Quarries are cut into thick slate horizons, the aim being to extract large dimension stone that is as uniform as possible. Powerful explosives are avoided because their use shatters the slate, though they may be used to clear unwanted overburden. The current method of dimension-stone extraction is based on step cutting, which results in the production of regular blocks of commercially exploitable size from the working face. The oldest technique—rapidly becoming obsolete—uses helicoidal wire, which is a special steel cable several hundreds, or even thousands, of metres in length. The cable is introduced into the rock mass through two connected, perpendicular drill-holes. The helicoidal cable is then pulled out by an engine. The addition of quartz sand and water assists the cutting of the slate and in cooling the cable. Diamond wire is used in a similar way: an engine drives a wheel 0.8–2 m in diameter, which winds in a steel cable that is tensioned with springs. The cable comprises small diamond-coated beads that are separated by springs and plastic segments. Mechanical chain saws and diamond disk saws are commonly used to make vertical, horizontal and inclined cuts and a pneumatic wedge, the *darda*, is used to split blocks from the quarry bench.

Current research into the cutting of slate is concentrated on improved diamond-wire devices and water-jet techniques. In the latter high-pressure jets of water containing abrasive garnet powder are forced through long-lasting diamond or ceramic nozzles.

Fissility decreases as the slate blocks dry out. The dimension stone (or *rachon*) is transported rapidly from the quarry face to the factory because slate that has been allowed to dry is consequently much more difficult to split. Temperatures below −8°C damage the slate blocks, and this can constitute another reason why slate must be processed within a few hours of its removal from the quarry face.[27] In the factory the *rachons* are split first into smaller blocks some 30–40 cm thick. These are then cut with diamond disk saws into rectangular blocks, which are stored in water to await splitting. Further splitting into millimetric slate sheets is carried out by hand using a small chisel called a *uñeta*. Finally, the slate sheets are cut to size with hand-operated shearing machines.[19]

Prospecting—Dominio de Truchas, central Spain

A general approach to prospecting for slate deposits was developed in France by Le Corre[16,17] and Castaing and Rabu.[6] Subsequently the Spanish Geological Survey (Instituto Tecnologico Geominero, ITGE) began several projects on slate deposits in northwestern Spain. As a result, Barros *et al.*[1] published a methodology of slate prospecting, which proposed four phases: (1) exploration based on 1 : 25 000 scale geological mapping; (2) geological mapping at 1 : 5000 scale and construction of stratigraphic logs; (3) detailed investigation, at 1 : 2000 scale, of geology and structure, allowing the siting of boreholes; and (4) control of exploitation by means of boreholes, working face controls and an extension of structural studies.

A specific example of a slate prospecting study is presented here for a region in central Spain, on the border of Guadalajara, Segovia and Madrid provinces. The starting point was a 1 : 100 000 scale geological map[12] and 1 : 33 000 scale aerial photographs. The data obtained were used to select ten geological traverses, on a scale of 1 : 25 000, totalling 103 km in length. The photogeological study indicated that 44 km^2 of outcrop of the Upper Ordovician R4 Formation provided the most likely site for the finding of roofing slate deposits.

The second phase began with geological mapping of the selected area and the construction of six geological cross-sections at the 1 : 10 000 scale. A set of 126 orientated samples was collected for microscopic study to identify or confirm the presence and attitudes of bedding, crenulation cleavages and otherwise undetectable microfissures. Some of the microstructures were used to infer the presence of larger-scale structures. A borehole 115 m deep penetrated the R4 Formation and the core provided information on thickness, lithology, degree and depth of the weathering profile, sedimentary structures, slaty cleavage, secondary foliations, sulphides and the presence of discontinuities and the nature of their fillings, if any. Some 151 discontinuities were identified and their *in-situ* orientations were determined. These, combined with discontinuities measured at the surface, totalled 240.

The discontinuity data were divided into two populations because that at depths above 30 m included unsystematic discontinuities that had originated through unloading, whereas that below 30 m consisted of fewer and more systematic discontinuities. A total of 134 determinations were made on bulk specific gravity, water absorption, resistance to freezing and thermal changes, acid resistance, flexural strength and carbonate contents. The sampling of blocks for fissility experiments was difficult because of the dryness of surface samples. The lower part of the R4 Formation proved less suitable because of the presence of sandy laminae and carbonate microclasts, but the rest of the formation proved suitable, despite a relatively high water absorption rate and rapid oxidation during thermal changes. Completion of the second phase allowed the selection of seven favourable areas where the geological conditions for quarrying, quality of slaty cleavage and slope ratio were met.

Detailed structural investigation of the seven favourable areas, or rock bodies, constituted phase three. Continuous cores were examined from a series of boreholes mainly to assess the fracture pattern and its intensity. Measurements were made of bedding (S_0), slaty cleavage (S_1), joint sets (J), faults (F) and quartz veins (Q). Two fracture parameters were used: J_v and V_b.[32] To calculate the threshold values of J_v and V_b, the values that differentiate exploitable rock bodies from others, several quarries of the Valdeorras area (northwest Spain) were previously studied. The maximum J_v value was 2 and the smallest dimension stone was 0.6 m^3. The cal-

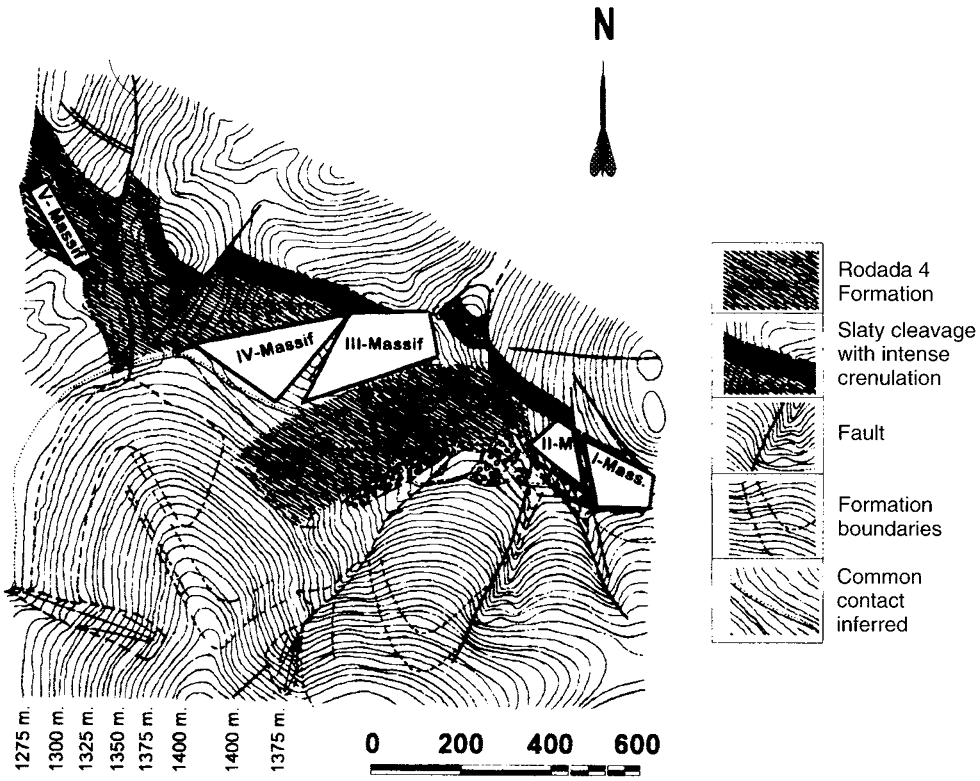

Fig. 4 Map of area of slate exploration exercise near border of Guadalajara, Segovia and Madrid provinces, central Spain. Rock body V ('V-Massif') was selected for drilling and further study (scale in metres)

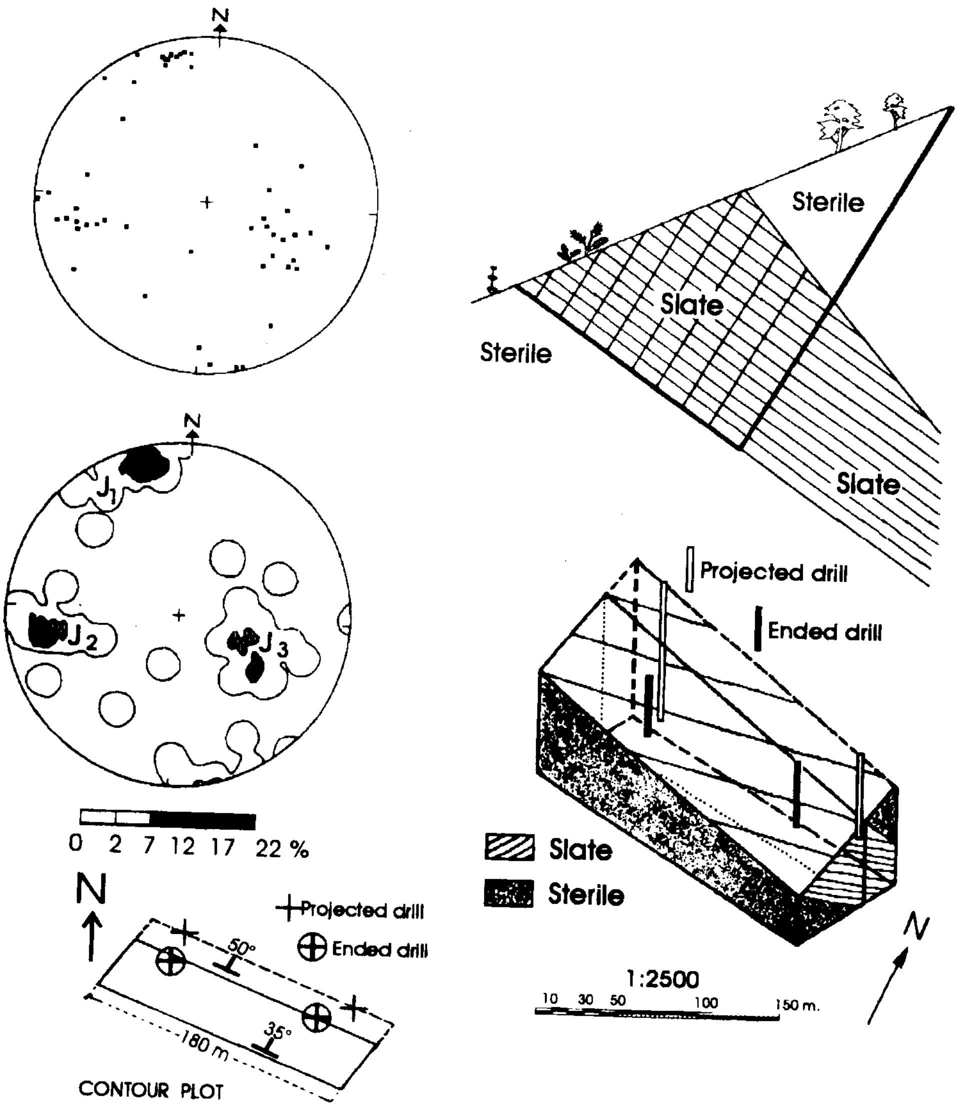

Fig. 5 Rock body V. Lower hemisphere stereographic plot of poles to discontinuities and contoured stereogram of data; plan, vertical cross-section and block diagram showing positions of boreholes

culated value of V_b is 0.7—hence 70% of the natural blocks must exceed 0.6 m^3. It should be noted, however, that when smaller saws are used at the quarry bench some quarries are able to operate successfully with a smaller dimension stone of 0.4 m^3.

In the final phase eight boreholes yielding 450 m of core were sunk to depths ranging from 30 to 80 m and measurements were made as in phase 3. J_v and V_b values were determined for each of the seven rock bodies. When the discontinuities alone are considered five rock bodies exceeded the threshold values (Fig. 4), but two of these (III and IV) had secondary foliation present at very low angles to the slaty cleavage, which makes extraction very difficult. This left bodies II, V and VII, of which V proved to be best (Fig. 5). The slate horizon of body V is underlain by carbonate sands, the contact bedding plane dipping at 35° inwards from the slope. The upper part of the slate horizon dips at 50°, is strongly crenulated (S_2) and is unusable. This geometry is a disadvantage because the overburden increases waste as the working face cuts deeper (Fig. 5). The predictions for the final state of the quarry were: (*a*) quarry face sloping at 60° and 70 m high; (*b*) 25% yield of dimension stones (blocks) from the total slate mass; (*c*) 240 000 m^3 (66 000 t) of useful slate; and (*d*) 300 000 m^3 of waste in the quarry and 73 000 m^3 in the factory. The final slope and height of the face on abandonment of the quarry are considered very safe. The extraction of dimension stones requires the use of diamond wire.

Discontinuity calculations—Casaio quarry model

A slate quarry from Casaio (Orense) was studied[31] by using the recommendations of the International Society for Rock Mechanics to quantify the rock body discontinuities[4] and the formulae of Castaing and Rabu.[5,6] The main structural elements are a slaty cleavage (S_1) and two sets of systematic joints (J_1 and J_2). The sets are approximately orthogonal to each other (S_1 = 175/25; J_1 = 100/90; J_2 = 000/70, dip direction/dip). A third systematic joint set is parallel to S_1, but therefore does not limit the dimension stone size. It was necessary to undertake a study before quarrying because the discontinuities form a dense, homogeneous network.

Two frequency histograms were constructed using the distances between joints of the two sets (Fig. 6). The parameters J_v = 2.20 and V_b = 0.38 were determined for a cube of side 1.1 m as the estimated minimum block. For the analysis a minimum block of dimensions $A \times B \times C$ was assumed, C (height) being a constant 0.3 m. This value of C was dictated

[redacted]