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Quantitative texture analysis of slates: An insight into slate's elastic properties and their contribution to the understanding of seismic wave reflections in anisotropic materials

Análisis cuantitativo de texturas de pizarras: Una visión de las propiedades elásticas de las pizarras y su contribución a la interpretación de las reflexiones sísmicas en materiales anisótropos

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ABSTRACT

Slates are low-grade metamorphic rocks characterized by an alignment of the phyllosilicates, resulting in the development of a marked foliation. A consequence of this is a strong directional dependence of their elastic properties, which are tightly bound to their texture. The Rietveld analysis applied to synchrotron x-ray diffraction images of slates from the Truchas Syncline (NW Iberian Peninsula) will provide us with the orientation distribution function (ODF) of the principal minerals that constitute the rock. This textural analysis shows an exceptional alignment of phyllosilicates (muscovite and chlorite) in contrast with a poor orientation of other minerals such as quartz. In a later treatment of the data, the elastic properties of the slates, as well the variations of the seismic wave velocities, have been calculated from the ODF and the single crystal stiffness tensors. The results of both the elastic properties and the wave velocities can be used for the construction of models that allow to understand the reflections of seismic waves in markedly anisotropic materials, which is a matter of a great interest in the studies of the Earth's lithosphere with seismic methods.

Key-words: *Slates, crystal preferred orientation (CPO), stiffness tensor, seismic anisotropy, reflection coefficient.*

RESUMEN

Las pizarras son rocas metamórficas de bajo grado caracterizadas por un alineamiento de los filosilicatos que resulta en el desarrollo de planos de foliación muy acentuados. El método de Rietveld aplicado a datos de difracción de radiación de sincrotrón en pizarras del Sinclinal de Truchas (NO Península Ibérica) permitirá obtener la función de distribución de orientaciones (FDO) de sus principales constituyentes minerales. Este análisis textural muestra un alineamiento excepcional de los filosilicatos, que contrasta con la orientación más pobre de los tectosilicatos. En un tratamiento posterior, se han calculado los tensores de elasticidad, y las velocidades de propagación de las ondas P y S en las pizarras. La caracterización de las propiedades elásticas y de la anisotropía sísmica puede usarse para la construcción de modelos que permitan entender las reflexiones de las ondas sísmicas en materiales anisótropos, lo cual es un asunto de gran interés en los estudios de la litosfera terrestre mediante métodos sísmicos.

Palabras clave: *pizarras, orientación cristalina preferente (OCP), tensor de elasticidad, anisotropía sísmica, coeficiente de reflexión.*

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Introduction

Several quantitative textural studies of slates have been carried out in the recent years in order to understand the anisotropic physical properties of these materials and the formation conditions of their remarkable fabric (Wenk et al., 2019, 2020; Cárdenes et al., 2021).

The aim of the present study is to accomplish a quantitative textural analysis of slates from the Truchas Syncline (NW Iberian Peninsula) by means of the Rietveld refinement method applied to x-ray synchrotron diffraction data obtained from the European Synchrotron Radiation Facility (ESRF) (Rietveld, 1969; Lutterotti et al., 2014). The strong crystal preferred orientation (CPO) of the phyllosilicates turns out to be the property that determines the remarkable cleavage of these materials (Wenk et al., 2019). Rigid minerals such as quartz or feldspar also appear as an important fraction in slates but, in spite of the well-defined shape preferred orientation (SPO) of the grains, the Rietveld analysis do not reveal an important CPO; in fact, the crystal orientations seem random in most samples (Wenk et al., 2019).

The elastic properties of the rocks, like seismic velocities, are defined by those of their constituent minerals and the CPO. In this way, seismic anisotropy is strongly related to the CPO. Therefore, these studies are especially relevant to understand the seismic anisotropy of the upper crust and to stablish a link between the laboratory and field measurements. The results also evaluate the validity of different models (e.g., Tsvankin, 2001).

Geological setting

The slate samples of this study were collected in the NW of the Iberian Massif (Spain), in the Truchas Syncline, which crops out in the Ollo de Sapo Domain of the Central Iberian Zone (CIZ) near the boundary with the West-Asturian Leonese Zone (WALZ), as delimitated by the Courel-Peñalba Syncline (Martínez-Catalán et al., 2009). According to these authors, the Truchas Syncline is a synclinorium originated during the C1 phase of the Variscan orogeny and it is built up by smaller recumbent folds. In its core the Ordovician and Silurian pre-orogenic terrigenous deposits can be found, while the Armorican Quartzite appears in the outer regions. The syncline structure was affected by a later re-folding during the

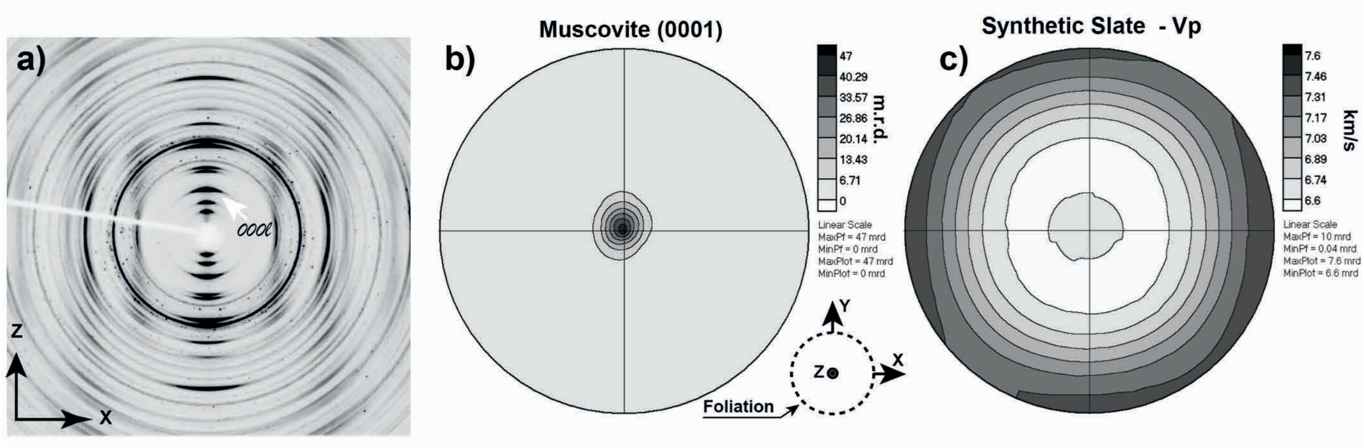

Fig. 1.- a) 2D diffraction image of a slate @ID11- ESRF, 000l mica's planes are indicated. b) (0001) muscovite pole figure obtained after Rietveld refinement with MAUD, showing a strong texture (m.r.d.: multiples of a random distribution). c) Velocity distribution of compressive seismic waves (Vp) as calculated with BEARTEX, where a quasi-transversal isotropy is depicted. XYZ sample reference system, with XY // slaty cleavage and Z= foliation pole.

Fig. 1.- a) Imagen 2D de difracción de una pizarra obtenida en la línea ID11 -ESRF, La familia de planos 000l de las micas se marca con una flecha. b Figura de polos del plano basal de la moscovita, mostrando una fuerte textura, obtenido del análisis Rietveld en MAUD. c) Distribución de velocidades de ondas P (Vp) calculadas con BEARTEX para una pizarra sintética, donde se aprecia un comportamiento aproximadamente transversalmente isótropo. XYZ definen el sistema de referencia de la muestra, con XY paralelo al clivaje pizarroso y Z paralelo al polo de dicha foliación.

C3 deformation phase (Martínez-Catalán et al., 2009).

The slaty cleavage is another characteristic of the materials of this region: it was formed during the C1 contractional phase and the resulting foliation planes align parallel to the axis of the recumbent folds (ibid.).

The sedimentation of these materials occurred in the continental margin of Gondwana (ibid.), developing alternating layers of sandstones and shales that would later become quartzites and slates during the low-grade metamorphism following the barrovian sequence of the C1 deformation phase. The materials reached the lower greenschists facies (chlorite zone), with temperatures no higher than 400ºC and pressures between 20 and 40 MPa (García-Guinea et al., 1997).

This region is of a special importance because it hosts an extensive slate mining activity, whose production happens to be one of the largest in the world (Cárdenes et al., 2014).

Eight samples were collected in quarries settled in two different formations of the Ordovician. Seven of them were from the Rozadais Formation (Upper Ordovician) and one of them from the Luarca Formation (Middle Ordovician).

Methodology

Synchrotron x-ray diffraction

The synchrotron x-ray diffraction experiments were carried out in transmission geometry, at the European Synchrotron Radiation Facility (ESRF) in Grenoble (France). Contrary to regular x-ray tube apparatus, the high energy and intensity of the synchrotron radiation allow a good penetration into the sample and the recording of low 2θ diffraction angles (Wenk et al., 2020).

Since our objective is to characterize the texture of the slates in all spatial directions, several diffraction images were collected at different rotation angles (fig. 1a).

Texture and elasticity of slates

The Rietveld analysis was performed with the software MAUD (Lutterotti et al., 2014), which calculates the orientation distribution function (ODF) with the E-WIMV algorithm (Lutterotti et al. 2014; Forjanes et al. 2020).

The quantitative information of the relative abundance of the main mineral phases and their texture can be used to calculate the elastic properties of the aggregate. Slate's stiffness tensors, which characterize the elasticity of the materials in three dimensions, can be calculate by averaging the ODFs with the single crystal stiffness tensors that can be found in the scientific literature (e.g., Mookherjee and Mainprice, 2014).

Once the stiffness tensor of each sample is defined, the velocity of the seismic waves is calculated for all directions inside the rock, as well as the birefringence. These calculations are based on Christoffel (1877) equation as implemented in the software BEARTEX (Wenk et al., 1998). This procedure will allow us to understand the seismic anisotropy of these materials.

For that purpose, we have calculated seismic properties of a synthetic slate, with a high percentage of muscovite and chlorite (90%), to study how anisotropy changes with the abundance of phyllosilicates and its distribution in the aggregate.

Results

The Rietveld refinement indicates a predominance of muscovite and chlorite for all samples, while quartz and albite are found in a smaller proportion. The texture analysis shows a remarkable alignment of the phyllosilicates (muscovite and chlorite) in contrast with the poor CPO of quartz and albite (fig. 1b).

P-waves travel faster along the foliation plane than perpendicular to it, and the P-wave anisotropy is >12% for the synthetic slate (fig. 1c). Spatial distribution of Vp shows some azimuthal variations (fig. 1c).

Discussion

The (0001) pole figures of muscovite and chlorite show an exceptional alignment that build up the macroscopic cleavage plane of the rock. In contrast, CPOs of quartz and albite are very poor, with low maximum values of multiples of random distribution (m.r.d.) for all crystallographic planes.

Even though the textural strength of

phyllosilicates cannot always be easily related to tectosilicate abundance, this last parameter has proved to have an important relevance in conditioning the anisotropy of the sample. The higher is the tectosilicates abundance, the lower is the anisotropy.

One important remark is the existence of an azimuthal variation of Vp within the foliation plane (XY). This is in fact a deviation of a pure transversally isotropic elastic medium behaviour, a very common assumption when modelling this kind of lithologies (Aki and Richards, 1980; Blangy, 1994), which needs to be revisited.

Concluding remarks

Slates from the Truchas Syncline (NW Spain) show a remarkable anisotropy in the direction of the cleavage plane as a result of the crystal preferred orientation of its constituent phyllosilicates. This property allows the fissility of the slate and its use as roofing material, but it also conditions its elastic properties and the direction-dependence of the seismic velocities.

The understanding of the propagation of seismic waves in these anisotropic materials is critical to understand Earth's deep structures by means of seismic reflection techniques. Our analysis suggests that simple assumptions like pure transverse isotropy need to be re-evaluated.

Author contributions

The data presented in this Scientific Session corresponds to the M.Sc. thesis of SAA. ESRF experiments were performed by JGB and JMSM.

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