The influence of plagioclase LPO on P-wave anisotropy and seismic reflectivity of metabasites from the lower continental crust

Influencia de la OCP de plagioclasa en la anisotropía de ondas P y en la reflectividad sísmica de metabasitas de la corteza continental inferior

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RESUMEN

En este trabajo se han obtenido valores de velocidad y anisotropía de ondas-P, con distintas proporciones hornblenda-plagioclasa, en muestras generadas a partir de anfibolitas naturales, en las que una única orientación cristalográfica preferente (OCP) de hornblenda se combina con distintas OCPs de plagioclasas. Los resultados sugieren que, aunque las propiedades sísmicas de la corteza inferior están controladas principalmente por la OCP de hornblenda, la plagioclasa, incluso apareciendo en proporciones bajas, puede modificar dicho comportamiento. Su grado de influencia depende de la intensidad y la orientación de la OCP. Así, variaciones en la OCP de plagioclasas pueden producir modificaciones en la magnitud, la distribución espacial y la anisotropía de Vp, lo que podría tener efectos en la reflectividad de la corteza continental inferior.

Palabras clave: *Anfibolita, corteza continental inferior, OCP, plagioclasa, ondas P.*

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Introduction

The seismic behaviour of the lower continental crust is beyond the influence of cracks and fractures and, therefore, it mainly depends on some intrinsic petrophysical properties of the transmitting material (Mainprice *et al*., 2000): density (which results from the relative volume fraction between constituent phases and their respective densities), single-crystal seismic properties, and the lattice preferred orientation (LPO) of the constituent phases, specially that of anisotropic minerals such as hornblende and plagioclase (e.g., Mainprice *et al*., 2000; Meissner *et al*., 2006 and references therein). Therefore, modelling the seismic properties of the lower continental crust can be achieved, using plastically deformed amphibolites as an analogue material (e.g., Rudnick and Fountain, 1995), via either direct velocity measurements or using computed LPO of the main constituents (e.g., Mainprice and Humbert, 1994; Barberini *et al*., 2007). One of the advantages of the latter is the contribution of different mineral phases can be isolated or modified (Tatham *et al*., 2008).

Seismic properties of ductile deformed amphibolites in the lower continental crust are largely controlled by hornblende LPO (e.g., Tatham *et al*., 2008). It is widely assumed the presence of plagioclase within these rocks results in a simple decrease in the velocity and anisotropy magnitudes (e.g., Siegesmund *et al*., 1989) and minor changes in their orientation (Tatham *et al*., 2008). However, plagioclase presents a high single-crystal seismic anisotropy (e.g., Siegesmud *et al*., 1989). Therefore, its influence on the seismic properties of amphibolites could be more complex than expected when it shows a well-developed LPO. The relationships between plagioclase LPO (in terms of strength and orientation) and P-wave velocity and anisotropy of amphibolites are analysed in this paper.

Samples and methods

Samples analysed in this study belong to the Acebuches metabasites, lying at the boundary between Ossa-Morena and South Portuguese zones, two of the main units of the Iberian Massif (SW Iberian Peninsula). The analysed samples are medium-to-high temperature/low pressure amphibolites, with Mg-hornblende and plagioclase (oligoclase – andesine) as the main phases. They show a foliation (of either metamorphic or mylonitic nature) defined by the preferred orientation of hornblende prismatic blasts and, in the mylonitic one, by plagioclase ribbons also (see more details at Díaz Azpiroz *et al*., 2007).

Hornblende and plagioclase LPO have been obtained via automated electron backscattered diffraction (EBSD) in a CamScan scanning electron microscope (SEM) at the University of Leeds (see analytical details at Díaz Azpiroz *et al*., 2007). EBSD data were processed into conventional LPO pole figures (Fig. 1) using program PFch5 (Mainprice, 2003). In this case, plagioclase fabric strength has been defined by the average fabric strength parameter *C* (Woodcock, 1977) of spherical distribution of [100] and [010] directions.

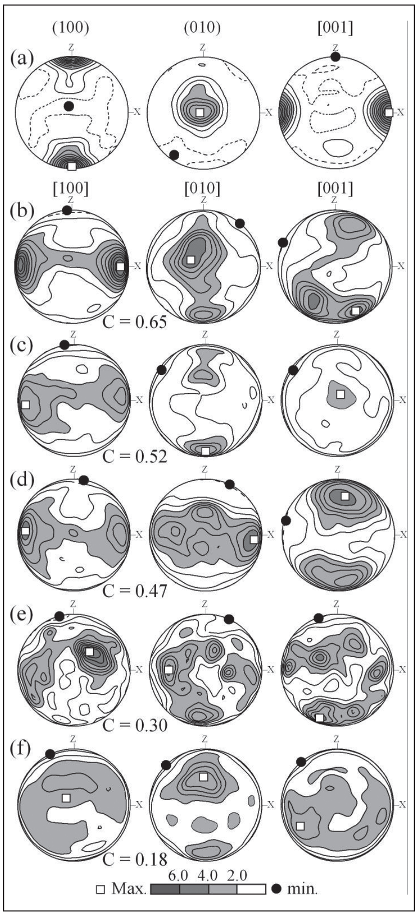

Fig. 1.- Equal area, lower hemisphere projections showing LPO of Mg-hornblende from sample V1 (a) and plagioclases (b) to (f) used in this study: V1 (b), V3 (c), A3 (d), A1 (e) and PV7 (f). Contours correspond to 0.5 m.u.d. (multiples of uniform distribution). C: average fabric strength parameter of spherical distribution of plagioclase [100] and [010] directions.

Fig. 1.- Proyecciones equiareales (hemisferio inferior) mostrando la OCP de Mg-hornblenda de la muestra V1 (a) y las plagioclasas (b) a (f) usadas en este estudio: V1 (b), V3 (c), A1 (d), A3 (e) y PV7 (f). Los contornos corresponden a 0.5 m.u.d. (múltiplos de la distribución uniforme). C: parámetro de intensidad de fábrica media de la distribución esférica de las direcciones [100] y [010] de plagioclasa.

LPO-derived seismic properties have been calculated using programs Anisch5 and VpG (e.g.¸ Mainprice and Humbert, 1994), considering, for each constituent phase (hornblende and plagioclase), the measured LPO, the single crystal stiffness tensor (Aleksandrov and Ryzhova, 1961, for hornblende; Aleksandrov *et al*., 1974, for plagioclase) and density. In this study, the «rock recipe» approach (e.g., Tatham *et al*., 2008) is used, so seismic P-wave properties are computed introducing variable plagioclase-hornblende volume fractions (in 10 % steps). For each case, the azimuthal distribution of P-wave velocity (*Vp*), which includes maximum (Vp_{max}) and minimum (Vp_{min}) velocities, velocity in the kinematic framework (X-Y-Z) and P-wave velocity anisotropy (*AVp*), are calculated. This methodology works out well when examining the relative importance of highly influent phases, such as hornblende and mica (Tatham *et al*., 2008; Lloyd *et al*., 2009). In contrast, changes derived from variations in plagioclase are obscured by these other dominant phases. To avoid the influence of hornblende in LPO-derived seismic properties of the analysed amphibolites, composite samples have been created from natural samples of the Acebuches amphibolites. These composite samples are defined by a unique, well developed, hornblende LPO and five different plagioclase LPOs (Fig. 1).

To compare the obtained *Vp* fabrics with hornblende and plagioclase LPO it must be remarked that the fastest *Vp* direction in hornblende single crystals is [001], [010] is intermediate and the slowest is [100]. [100] is also the slowest *Vp* direction in plagioclase single crystals but, in this case, the fastest direction is [010] and [001] is intermediate (e.g., Siegesmund *et al*., 1989). Therefore, Hb fastest direction [001], which is parallel to the kinematic X-direction, is between plagioclase fastest and slowest directions in sample A3, it seems subparallel to the intermediate direction of plagioclase in sample PV7, and it is parallel to plagioclase slowest direction in samples V1 and V3. In sample V3, in addition, plagioclase fastest direction is parallel to hornblende slowest direction also. The relationship with plagioclase of sample A1 is unclear. These combinations are useful to test how the Pl LPO orientation affects *Vp* and *AVp*.

Results and interpretation

P-wave velocity (Vp)

As plagioclase volume fraction (*PVF*) increases Vp_{max} decreases and Vp_{min} increases (Fig. 2). These evolutions are not linear, such as there is a $PVF \leq 1$, where the difference between both velocities (related to *AVp*) reaches a minimum.

The influence of plagioclase LPO on *Vp* azimuthal distribution can be appreciated comparing plagioclase and hornblende LPOs (Fig. 1) with computed seismic fabrics (Fig. 2). Additionally, a more quantitative approach can be achieved by measuring angles between the fastest and slowest crystallographic directions of single crystals of plagioclase ([010] and [100]) and hornblende ([001] and [100]), and the orientation of Vp_{max} and Vp_{min}, respectively. These angles have been represented against *PVF* (Fig. 2).

In general, the angles that Vp_{max} define with Hb[001] and Pl[010], and Vp_{min} define with Hb[100] and Pl[100] are mutually complementary. For low *PVF* values, Vp_{max} and Vp_{min} define small angles with hornblende LPO and large angles with plagioclase LPO. When a critical PVF value is reached, angles defined by Vp_{max} switch, such as that defined with Hb[001] tends to 90º while that defined with Pl[010] tends to 0º. In contrast, angles defined by Vp_{min} change progressively up to a *PVF* where the angle with Hb[100] becomes larger than that with Pl[100]. These two critical *PVF* values do not necessarily coincide in one sample, and vary from one sample to another, depending on plagioclase LPO strength (V1 *vs*. PV7) but probably also on its orientation (V3 *vs*. A3).

Reflectivity is mainly controlled by *Vp* in the vertical direction (e.g., Ji *et al*., 1993). Most lower continental crust reflectors are horizontal or gentle dipping. Assuming that in such cases, the main foliation must be also subhorizontal, *Vp* in the Z direction (Vp_z) would be the best approximation to *Vp* in the vertical. Considering relationships between LPO and *Vp* fabric, it is remarkable Hb LPO is usually defined by the lowest velocity crystallographic direction [100] parallel to the kinematic Z direction, which means that Vp_z is mostly close to Vp_{min} when controlled by hornblende LPO. In contrast, Pl LPOs are more variable and, in any case, its lowest velocity crystallographic direction [100] would be rarely parallel to Z because (100) has not been reported as a slip plane for plagioclase (Stünitz *et al*., 2003 and references therein). As a consequence, Vp_z for *Vp* fabrics dominated by Pl LPO deviate from Vp_{min} and, commonly, approximate Vp_{max}. The resulting Vp_z, when compared with volume fractions of plagioclase and hornblende, shows a linear ($R^2 = 0.953 – 0.996$) decrease from Hb-rich to Pl-rich amphibolites (Fig. 2). The slopes of the regression lines defined by Vp_z range from – 0.17 to –

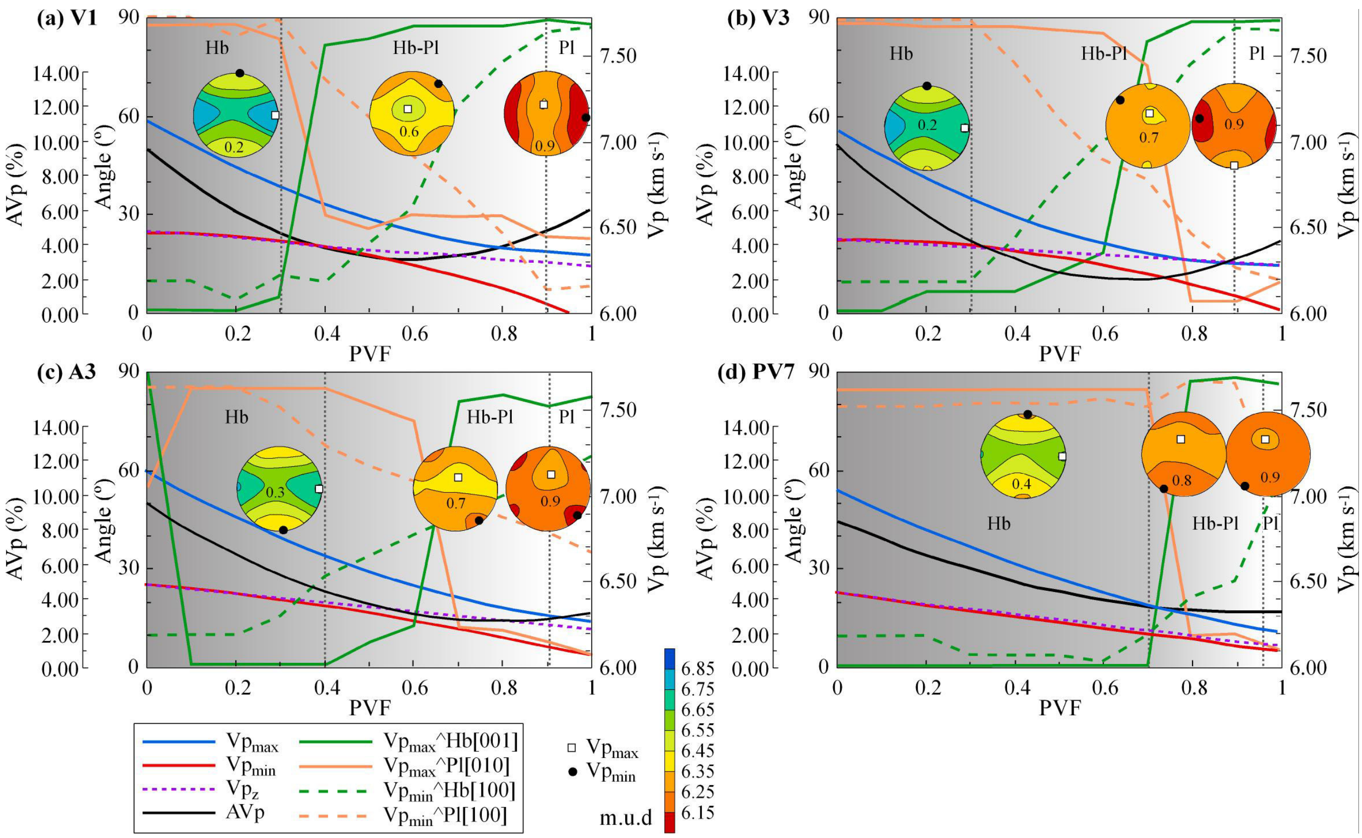

Fig. 2.- Evolution of different seismic parameters and angles between seismic and crystallographic fabrics with increasing *PVF*, for four of the samples analysed in this study. Regions dominated by hornblende (Hb), by plagioclase (Pl) or a combination of the both (Hb-Pl) are distinguished by different shadings. Representative azimuthal distribution of *Vp* for each region are presented also, indicating *PVF*.

Fig. 2.- Evolución de distintos parámetros sísmicos y de ángulos entre fábricas sísmicas y cristalográficas con el incremento en PVF, para cuatro de las muestras analizadas en este estudio. Las regiones dominadas por hornblenda (Hb), por plagioclasa (Pl) o con una combinación de ambos (Pl-Hb) se han distinguido mediante sombreados. También se muestran distribuciones espaciales de Vp significativas de cada uno de estos sectores, indicando la PVF.

0.34, resulting in descents from the maximum Vp_z value of 2.6 – 5.1 % and maximum reflectivity (calculated according to Ji *et al*., 1993) differences (between Hb-pure and Pl-pure amphibolites) of around 0.1.

Hb LPO is unique in this study, thus Vp_z when $PVF = 0$ is the same for all samples. With increasing *PVF*, differences in Vp_z among the samples increase also, reaching its maximum when $PVF = 1$. For a certain *PVF* value, and provided Hb LPO is constant, differences in observed Vp_z can be attributed to Pl LPO. Vp_z for $PVF = 1$ shows a rough positive correlation with Pl fabric strength (Fig. 3a). However, some samples deviate from the regression line suggesting some influence from Pl LPO orientation and its relation with Hb LPO orientation. Sample V3 shows a larger influence on Vp_z than expected from its LPO strength, which is coherent with its unfavourable LPO orientation (Pl [100] and [010] subparallel to Hb [001] and [100], respectively). In contrast, the influence of sample A3 is lower than expected, coincident with its more favourable LPO orientation (Hb [001] between Pl [010] and [100]).

However, differences in Vp_z due only to variations in Pl LPO result in a maximum reflectivity variability, (between V3 and PV7) at $PVF = 1$, of 0.01, which is one order of magnitude lower than reflectivity due only to *PVF* variations. This suggests that, in these samples, changes in Pl LPO can modify slightly reflectivity between layers with different Pl-Hb volume proportions, but cannot produce reflectivity themselves.

P-wave anisotropy (AVp)

Vp_z is the main parameter controlling seismic reflectivity. However, LPO-derived *AVp* can exert some influence on it (e.g. Ji *et al*., 1993), such as high *AVp* values can enhance reflectivity. It has been shown that for plagioclase-hornblende volume fractions of common amphibolites ($PVF = 0.4 – 0.6$), there can be quite low variations in Vp_z values. In such cases, differences in *AVp* can induce significant variations in seismic reflectivity.

The variation of *AVp* with increasing *PVF* defines a curve that adjusts ($R^2 = 0.963 – 0.994$) to a quadratic function with the form:

$$AVp = a\,PVF^2 + b\,PVF + c \qquad \text{(eq. 1)}$$

AVp shows its maximum with $PVF = 0.0$ and decreases with increasing *PVF*. This descent can be estimated by the principal coefficient (a) of eq. 1. *AVp* reaches its minimum (AVp_{min}) with variable *PVF* ($PVF\text{-}AVp_{min}$) depending on the samples.

After this minimum value, *AVp* increases with increasing *PVF*. In samples where $PVF\text{-}AVp_{min} < 1$ the maximum *AVp* value for the right branch of the function is attained when $PVF = 1.0$. As a result, there is a region within the function where any *AVp* value can be related to two different *PFV* values.

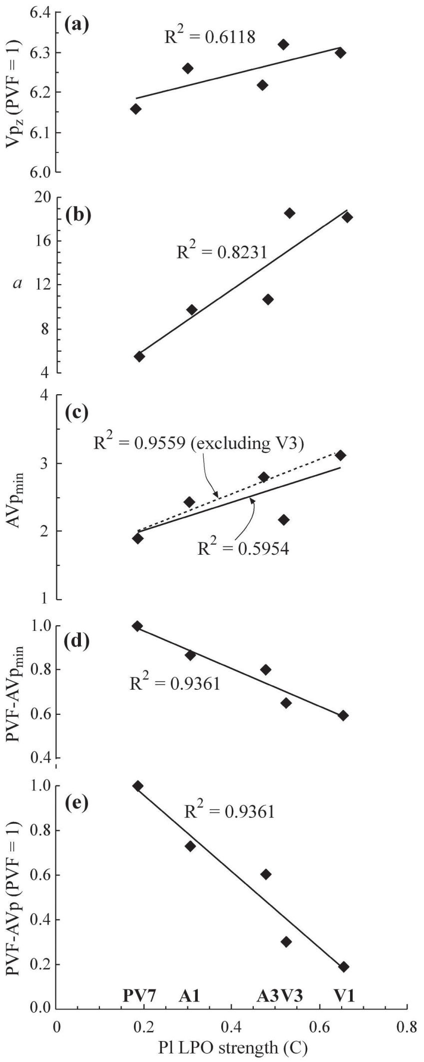

Fig. 3.- Evolution of different *Vp* parameters versus plagioclase LPO strength (*C*, Fig. 1). (a) Vp_z for *PVF* = 1. (b) Principal coefficient of eq. 1. (c) AVp_{min}. (d) *PVF* corresponding to AVp_{min}. (e) *PVF* where *AVp* equals that of *PVF* = 1.

Fig. 3.- Evolución de distintos parámetros de Vp frente a la intensidad de la CPO de plagioclasa (C, Fig. 1). (a) Vp para PVF = 1. (b) Coeficiente principal de la eq. 1. (c) AVp_{min}. (d) PVF en el que se alcanza el AVp_{min}. (e) PVF en el que AVp es igual a AVp para PVF = 1.

The lower limit of this region is defined by the *PVF* where *AVp* equals that of *PVF*=1 (*PVF-AVp(PVF = 1)*), and can be as low as 0.2 (sample V3, Fig. 3e).

The evolution of *AVp* with increasing *PVF* (as characterized by the quadratic function defined by eq. 1 and related parameters), is strongly dependant on plagioclase fabric strength (Fig. 3). Thus, for stronger plagioclase fabrics, *AVp* decreases more rapidly with increasing *PVF* (Fig. 3b), AVp_{min} is higher (Fig. 3c) and it is attained with a lower *PVF* (Fig. 3d), and *AVp* reaches higher values for pure plagioclase aggregates (*PVF* = 1), thus enlarging the uncertainty region of the function (Figs. 2, 3e). Nevertheless, deviations from regression lines can be attributed to orientation of plagioclase LPO. For instance, more rapid *AVp* descents reaching lower AVp_{min} values at a lower *PVF* suggest plagioclase LPO of sample V3 is less favourably oriented respecting to hornblende LPO than the average. In contrast, gentler *AVp* descents and a higher *PVF* corresponding to the minimum value of *AVp* suggest plagioclase LPO of sample A3 is more favourable oriented with respect to hornblende LPO than average. These observations are in accordance with that deduced from variations in Vp_z for *PVF* = 1.

Conclusions

The «rock recipe» approach using composite samples sharing a unique hornblende LPO has proven to be an appropriate way to test the influence of plagioclase on P-wave properties of the lower continental crust.

According to the evolution observed for different seismic parameters of the studied amphibolites, three intervals can be defined, depending on the relative influence that hornblende and plagioclase exert on the resulting *Vp* fabric. The limits of these intervals are affected by plagioclase LPO strength and orientation. Therefore, distinct Pl LPO can produce (with rather low plagioclase volume fractions) noticeable differences in azimuthal distribution of *Vp* in amphibolites, which can result in slight variations in seismic reflectivity derived from Vp_z. Reflectivity enhancing could be generated at high plagioclase volume fractions by *AVp*.

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