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Authors
Gómez Barreiro, J
Wenk, HR
Vogel, S

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Texture and elastic anisotropy of a mylonitic anorthosite from the Morin Shear Zone (Quebec, Canada)

Juan Gómez Barreiro a,*, Hans-Rudolf Wenk b, Sven Vogel c

a Departamento de Geología, Universidad de Salamanca, Pza. de los Caídos s/n, 37008 Salamanca, Spain
b Department of Earth and Planetary Science, University of California, Berkeley, CA 94720, USA
c Los Alamos Neutron Science Center, Los Alamos National Laboratory, NM 87545, USA

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A B S T R A C T
A sample of anorthosite from the granulite facies Morin Shear Zone (Quebec, Canada) was investigated for crystal preferred orientation and elastic anisotropy. Time-of-flight neutron diffraction data obtained with the HIPPO diffractometer at LANSCE were analyzed with the Rietveld method to obtain orientation distribution functions of the principal phases (plagioclase, clinopyroxene and orthopyroxene). Texture and microstructures are compatible with the plastic deformation of the aggregate under high-T conditions. All mineral phases depict a significant preferred orientation that could be related to the general top-to-the north shearing history of the Morin Shear Zone. Texture patterns suggest that (010)[001] in plagioclase and (110)[001] in clinopyroxene are likely dominant slip systems. Using preferred orientation data P- and S-waves velocities and elastic anisotropy were calculated and compared with previous studies to explore elastic properties of rocks with different pyroxene-plagioclase mixtures. P-wave velocity, S-wave splitting and anisotropy increase with clinopyroxene content. Seismic anisotropy is linked to the texture symmetry which can lead to large deviations between actual anisotropy and that measured along Cartesian XYZ sample directions (lineation/foliation reference frame). This is significant for the prediction and interpretation of seismic data, particularly for monoclinic or triclinic texture symmetries.

1. Introduction
It has been proposed that the deformation of continental lithosphere is mainly driven by the mechanical response of the lower crust (e.g. Royden et al., 1997; Ranalli, 1995, 2003; Rutter and Brodie, 1992). Geophysical observations (e.g. Chen and Molnar, 1983; Wong and Chapman, 1990), thermomechanical models (e.g. Beaumont et al., 2001) and extrapolation of experimental flow laws (e.g. Brace and Kohlstedt, 1980; Kohlstedt et al., 1995; Dimanov et al., 2007) point to a model of long-term strength for the lithosphere with a relatively weak lower crust, placed between a stronger upper crust and mantle (Burov and Watts, 2006). Thermal and compositional heterogeneity of the lithosphere result in a variety of rheological behaviors across tectonic plates and alternative models could play a significant role in some geodynamic contexts (e.g. Maggi et al., 2000; Jackson, 2002). Those features evolve with time and one should consider rheological boundaries as dynamic entities in the Earth system (e.g. Bürgmann and Dresen, 2008).

High-strain zones are recognized as essential pieces of that architecture, but the proportion of localized to distributed strain-flow with depth is not well understood (Ellis and Stöckhert, 2004; Bürgmann and Dresen, 2008). The existence of a laminated lower crust, as revealed by seismic surveys, could be interpreted as the result of localized strain, supporting the role of shear zones (e.g. Franke, 1995; Rey, 1995; Cook et al., 1997; Ji et al., 1997). It is clear that interpretations of seismic data, both in structural and lithological terms, has to rely on a quantitative knowledge of the mechanical properties of shear zones.

Most rock-forming minerals are elastically anisotropic. When deformed in a high-strain zone, crystal preferred orientation or texture often develops. Therefore the aggregate of minerals in deformed rocks will show macroscopic anisotropy (e.g. Kocks et al., 2000), and potentially become a highly reflective volume in the lithosphere (e.g. Ji et al., 1997).

The dominant mineral phases in the lower crust are plagioclase and pyroxene (e.g. Tullis, 1990; Ji et al., 2004a;b; Dimanov et al., 2007). Both exhibit strong anisotropy of their physical properties.
Exploring the crystallographic preferred orientation of deformed pyroxene-plagioclase aggregates could lead to a better understanding of the mechanical and seismic properties of lower crust shear zones. Previous work has focused on texture development of plagioclase aggregates, both naturally and experimentally deformed (e.g., Ji and Mainprice, 1988; Ji et al., 1997; Rybacki and Dresen, 2000; Xie et al., 2003; Feinberg et al., 2006; Gómez Barreiro et al., 2007; Homburg et al., 2010). By comparison, relatively little is known about texture in metabasites (e.g., Mehl and Hirth, 2008; Kanagawa et al., 2008; Gómez Barreiro et al., 2010; Gómez Barreiro and Martínez Catalán, 2012). Moreover, our knowledge of deformation mechanisms of plagioclase and pyroxene are incomplete (e.g., Dornbusch et al., 1994; Bascou et al., 2002; Gómez Barreiro et al., 2007).

In previous studies mylonites from an anorthositic shear zone in Canada (Morin Shear Zone) have been analyzed. Only the texture of plagioclase was investigated in some detail (e.g., Ji et al., 1994, 1997; Zhao, 1997; Xie et al., 2003). Since then texture analysis evolved from the limited and time consuming U-stage procedures and pole figure goniometry to electron backscatter diffraction (EBSD), synchrotron X-ray diffraction and neutron diffraction. Here we are revisiting this natural laboratory to apply time-of-flight (TOF) neutron diffraction and advanced data analysis to quantify the texture of not only plagioclase but also pyroxene (e.g., Gómez Barreiro and Martínez Catalán, 2012). Based on preferred orientation patterns we then model elastic properties of anorthosite mylonite and finally extend the results to explore elastic anisotropy of rocks with different plagioclase-pyroxene contents to discuss the compositional effect on the physical properties of mafic mylonites (Lloyd et al., 2011).

2. Geological context

The Morin Terrane is part of the Allochthonous Monocyclic Belt, in the SE of the Grenville Province, Canada (Rivers et al., 1989). The Morin Terrane is composed of a Mid-Proterozoic anorthosite suite, surrounded by charnockites, granulites and metasediments (Doig, 1991). For a discussion of the tectonic setting and tectonothermal evolution of the Morin Terrane see Martignole and Friedman (1998), Wodicka et al. (2000) and McLelland et al. (2010).

The Morin anorthosite suite is bounded on the east, by the 5 km-wide Morin Shear Zone (Zhao et al., 1997), which contains a variety of igneous and metasedimentary lithologies. The mylonitic fabrics are defined by quartz ribbons, and flattened aggregates of plagioclase and pyroxene, with a penetrative subhorizontal N0-160E lineation and a west-dipping foliation (Zhao et al., 1997; Ji et al., 1997). Deformation conditions reached granulite facies (630–750 °C/550–750 MPa; Indares and Martignole, 1990). Kinematic criteria at different scales indicate a top-to-the north sense of shear (e.g., Zhao et al., 1997).

3. Sample description

A sample was collected 10 km NW the town of Rawdon (Quebec, Canada) in a mylonitic–ultramysonitic band of meta-igneous rocks. The composition is between a leuconorite and anorthosite, with about 90% plagioclase, 7% clinopyroxene and 3% orthopyroxene. The lineation is defined by elongated pyroxene aggregates and some

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**Fig. 1.** A) Sample reference system. X parallel to the Lineation and foliation define the XY plane. The cylinder for TOF neutron diffraction was coring perpendicular to the foliation and with an arrow parallel to X-axis. B) Thin section (gypsum plate inserted) to show microstructure and qualitative alignment of plagioclase (blue). Note that the plagioclase crystallographic preferred orientation is heterogeneous. A detail of the mylonitic fabric (XZ section) is presented, with fine bands made up of pyroxene. Some asymmetric aggregates of pyroxene indicate a top-to-the North sense of shear. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
porphyroclasts give the sense of shearing to the north (Fig. 1A). Pervasive recrystallization is recognized in thin sections (Fig. 1B). Also a view with polarized light and a gypsum plate inserted demonstrates strong crystal alignment (uniform blue color). Plagioclase is fine-grained, with an estimated average grain-size of $d = 50 \mu m$ and a shape ratio ($SR = long/short$ dimension) of 1.5. Some plagioclase ribbons ($d = 400 \mu m$, $SR = 6$) are locally preserved. Evidence of intracrystalline deformation like undulatory extinction, deformation twins and subgrains are abundant in plagioclase. Pyroxene is concentrated along fine bands with grains that range between 1 mm and 200 $\mu m$. Similar microstructures have been described by Ji et al. (1994, 1997), Zhao (1997) and Xie et al. (2003).

4. Neutron diffraction texture analysis

Texture analysis by neutron diffraction is the preferred technique for coarse-grained rocks (e.g. Ullemeyer et al., 1998; Wenk et al., 2010). Due to low absorption of neutrons for most elements, neutrons can easily penetrate large volumes, which results in better grain statistics than surface analysis such as thin sections, X-ray pole figure goniometry, and EBSD (e.g. Gómez Barreiro et al., 2010). The experiment was performed at the Los Alamos Neutron Science Center (LANSCE) with the HIPPO TOF neutron diffractometer (Wenk et al., 2003). HIPPO has excellent counting statistics, which is critical for quantitative texture determinations of rocks. The HIPPO diffractometer has 720 $^3$He-detector tubes, distributed over 30 panels arranged on three banks at different diffraction angles ($150^\circ$, $90^\circ$ and $40^\circ$). The different banks have different resolution. The pole figure coverage relative to the incident neutron beam is shown in Fig. 2A.

Oriented cylindrical samples of 10 mm in length and 8 mm in diameter, were drilled perpendicular to the foliation ($Z$). The lineation ($X$) is marked and the sample coordinate system $X$, $Y$ and $Z$ is used as reference to define crystal preferred orientation (Fig. 1A). The sample was rotated around the cylinder axis (perpendicular to the incident neutron beam) into four positions ($0^\circ$, $45^\circ$, $67.5^\circ$, $90^\circ$) to improve pole figures angular coverage (Fig. 2B). At each position, data were collected for 30 min, resulting in a total exposure time of 120 min. TOF diffraction spectra were analyzed with the Rietveld method as implemented in the software MAUD (Material Analysis Using Diffraction; Lutterotti et al., 1997; Wenk et al., 2010). It provides information about phase proportions and preferred orientation. For texture extraction we were using the E-WIMV algorithm. The orientation distribution function (ODF) cell size was $15^\circ$. Crystallographic structures are required in the Rietveld refinement and were loaded in ‘cif’ format. For monocline phases, the first setting has to be used, in both MAUD and BEARTEX, which requires some transformations (Matthies and Wenk, 2009). For plagioclase we use the structure of andesine (P-1; Fitz Gerald et al., 1986), for clinopyroxene diopside (C2/c1; Tribaudino et al., 2005), and for orthopyroxene enstatite (Pbca; Gatta et al., 2007). Lattice parameters were refined. The ODF was exported from MAUD and then used in BEARTEX to calculate and plot pole figures (Wenk et al., 1998). In this article we use labels for second monoclinic setting for labels in pole figures (i.e., [010] is the 2-fold axis).

It should be noted that due to the low crystal symmetry of major components, for example, clinopyroxene (monoclinic) and plagioclase (triclinic), $[010] \ [001]$ and $[001]$ directions do not correspond to the pole of the respective crystallographic plane ($100$) (010) (001), except for [010] in the monoclinic system. To approximate [100] [010] and [001] directions, poles of (20-1) (010) and $(-102)$

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**Fig. 2.** Pole figure coverage. A) Single rotation. B) Combined sample rotations to improve coverage ($0^\circ$, $45^\circ$, $67.5^\circ$, $90^\circ$). MAUD coordinates system is indicated with three orthogonal axes and corresponding rotations, $\chi$, $\omega$, $\phi$. System has been rotated around $\chi = -90^\circ$ and $\phi = -180^\circ$ to bring HIPPO rotation axis to the center of the pole figure and the arrow on top of the sample pointing to the neutron beam at 6 o’clock (Conventional setting). Coverage is plotted relative to sample coordinates.
were used for plagioclase and (−601) (010) (−205) for clinopyroxene (Gómez Barreiro et al., 2007).

Some experimental and calculated diffraction spectra are shown in Fig. 3. Because of the low symmetry of the minerals there is a large number of diffraction peaks, indicated at the bottom, with extreme peak overlaps. Variation of relative intensities of spectra parallel and perpendicular to the foliation is indicative of texture. This is even more evident in the map plot (Fig. 4) which shows a stack of experimental (bottom) and Rietveld model (top) diffraction spectra. The good agreement between experiment and model suggests that the Rietveld fit is reliable.

5. Elastic properties calculations

The elastic properties of the mylonite have been calculated based on averages of single crystal properties over the ODF of each mineral phase, using BEARTEX. Simple averaging schemes, assuming constant stress or strain, provide estimates of the upper and lower bound (Reuss and Voigt averages respectively). Calculation of arithmetic (Hill, 1952) or geometric means (Matthies and Humbert, 1995) is intermediate. These averaging procedures do not consider the influence of grain size, shape, and distribution of phases (microstructure) and particularly the effect that porosity has on the elasticity of rocks. For this, self-consistent and finite element methods have been applied for shales with extreme shape anisotropy and significant porosity (e.g. Vasin, 2013), but for a sample like anorthosite this was not necessary.

As part of the averaging procedure, single crystal elastic constants are required. For intermediate plagioclase elastic constants of triclinic andesine based on ab initio simulations (Kaercher et al., 2014) were used. For pyroxene we use diopside elastic constants from Sang et al. (2011), and for orthoenstatite experimental data by Jackson et al. (2007). Single crystal stiffness coefficients are listed in Table 1A.

6. Results

6.1. Volume fraction

Volume fractions for each mineral phase have been obtained with the Rietveld refinement. The best fit was obtained with 88% of andesine, 8% of diopside and 4% of enstatite. These fractions will be used for the calculation of the elastic properties in Section 6.3.

6.2. Texture

The plagioclase in the analyzed mylonite shows moderate crystallographic preferred orientation with a maximum of 2.9 m.r.d. (multiples of a random distribution, 2.89/0.22 m.r.d.;

![Fig. 3. Selected time-of-flight neutron diffraction spectra, for different angles from the 90 bank. The variation on peak intensity is due to texture. Note the strong peak overlapping at lower d-spacing. The positions of some crystallographic planes are indicated. Crosses are measured data, the lines are the Rietveld fit.](image-url)
The clinopyroxene texture is strong, with a maximum of about 10 m.r.d. and a very low minimum (0.03 m.r.d.). The (010) planes are parallel to the mylonitic foliation, depicting an orthorhombic fabric symmetry (Fig. 5). The poles of the (110) planes define a slightly

Fig. 5. The (010) plane defines an asymmetric maximum close to the foliation pole (Z-axis). The [001] direction displays a principal maximum close to the lineation of the sample. The [100] axes do not display a clear texture pattern (Fig. 5).

Table 1

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asymmetric small circle around the foliation pole. The [001] axes define an elongated principal maximum close to the lineation (X-axis). The poles of (100) planes define an elongated maximum about the foliation.

Orthopyroxene shows a moderate texture, similar in strength to plagioclase (2.52–0.26 m.r.d.). Poles of (010) planes define a small circle around the Z-axis, and [100] axes are close to the lineation (Fig. 5). The [001] directions define a complex pattern with several maxima. An orthorhombic symmetry dominates the patterns.

6.3. Elastic properties

From the texture of the different phases and their volume fractions the elastic properties of the aggregate can be calculated by averaging. The elastic properties of the single crystal must be taken into account for each mineral phase. In Table 1A [change Kaercher to 2014. Also in the table have a footnote for diopside that this is averaged. The elastic properties of the single crystal must be taken into account for each mineral phase. In Table 1A [change Kaercher to 2014. Also in the table have a footnote for diopside that this is averaged. The elastic properties of the single crystal must be taken into account for each mineral phase. In Table 1A [change Kaercher to 2014. Also in the table have a footnote for diopside that this is averaged. The elastic properties of the single crystal must be taken into account for each mineral phase. In Table 1A [change Kaercher to 2014. Also in the table have a footnote for diopside that this is averaged. The elastic properties of the single crystal must be taken into account for each mineral phase. In Table 1A [change Kaercher to 2014. Also in the table have a footnote for diopside that this is averaged. The elastic properties of the single crystal must be taken into account for each mineral phase. In Table 1A [change Kaercher to 2014. Also in the table have a footnote for diopside that this is averaged. The elastic properties of the single crystal must be taken into account for each mineral phase. In Table 1A [change Kaercher to 2014. Also in the table have a footnote for diopside that this is averaged. The elastic properties of the single crystal must be taken into account for each mineral phase. In Table 1A [change Kaercher to 2014. Also in the table have a footnote for diopside that this is averaged. The elastic properties of the single crystal must be taken into account for each mineral phase. In Table 1A [change Kaercher to 2014. Also in the table have a footnote for diopside that this is averaged. The elastic properties of the single crystal must be taken into account for each mineral phase. In Table 1A 1992; Ji and Salisbury, 1993; Ji et al., 1997; Zhao, 1997]. The Geometric Mean is a robust estimation of the mean value (Matthies and Humbert, 1995). For these calculations and plotting we use programs in the BEARTEX package (Wenk et al., 1998).

In Fig. 6 we show the single crystal propagation surfaces for seismic P-waves (A) and shear-wave splitting (B) for plagioclase, clinopyroxene and orthopyroxene. Standard conventions have to be used for averaging calculations: Z = c, Y = (c × a), X = (Y × Z); where X, Y, Z are axes of the right-handed Cartesian crystal coordinate system and a, b, c are crystal axes (Fig. 6). For monoclinic diopside, the first setting (Z = c = [001]) has been used (Matthies and Wenk, 2009). For shear-wave splitting we also show the orientation of the fast shear wave.

Seismic velocity data for the combined rock are summarized in Table 2. P-wave anisotropy (A; %) is defined as AVP = 200*(Vmax − Vmin)/(Vmax + Vmin). When the anisotropy is calculated from VP measurements along X, Y, Z sample axes (Fig. 1), it is calculated as AVPXZ = 100*(Vmax − Vmin)/Vmean, where Vmean = (VPX + VPY + VPZ)/3. The two are different when textures are asymmetric. Elastic wave surfaces for P-waves and shear-wave splitting are also displayed in Fig. 7.

The maximum P-wave velocity for the polyphase aggregate is very close to the pole of the mylonitic foliation, and almost parallel to the plagioclase (010) pole maximum (Figs. 5 and 7). As expected, the Voigt average results in higher values than the Geometric Mean. VP anisotropy, based on actual maximum and minimum, is moderate AVP = 2.6–2.4%. The anisotropy based on actual maximum and minimum, is moderate AVP = 2.6–2.4%. The anisotropy based on actual maximum and minimum, is moderate AVP = 2.6–2.4%. The anisotropy based on actual maximum and minimum, is moderate AVP = 2.6–2.4%. The anisotropy based on actual maximum and minimum, is moderate AVP = 2.6–2.4%. The anisotropy based on actual maximum and minimum, is moderate AVP = 2.6–2.4%.

Fig. 5. Pole figures for clinopyroxene (diopside), plagioclase (andesine) and orthopyroxene (enstatite). Reference system is indicated. Contours are in multiples of random distribution (m.r.d.). Equal area projection.
dependent on the selected average (Voigt-Geometric Mean; Fig. 7) with four principal maxima. Values are moderate ($dV_{\text{max}} = 97 - 86 \text{ m/s}$; Table 2). The maximum splitting occurs at about $15^\circ$ to the lineation and a second one at $15^\circ$ to the foliation pole, with the first enhanced by Voigt average and the second by the Geometric Mean (Fig. 7). Both the shape of the P and S – wave propagation surfaces correlate well with the plagioclase single crystal and polycrystal patterns (Figs. 5–7).

7. Discussion

7.1. Texture of phases and slip systems

Neutron diffraction analysis of a mylonitic anorthosite from the Morin Shear Zone provides quantitative texture data for plagioclase, clinopyroxene and orthopyroxene (Fig. 5). Previous texture studies on similar rocks from Ji et al. (1994, 1997), Zhao (1997) and Xie et al. (2003) depicted similar patterns for plagioclase. To date very limited information existed for pyroxene (Zhao, 1997) or were assumed to be randomly oriented.

Plagioclase texture patterns are compatible with dislocation activity on (010) planes and [001] directions (Gómez Barreiro et al., 2007, and references therein). A secondary maximum close to the periphery in the [001] figure could be related to twinning (Fig. 5). The (010)[001] slip system is common in natural plagioclase-rich mylonites at medium to high-grade metamorphic conditions (Kruhl, 1987; Ji et al., 1988, 1994; Zhao, 1997). Dynamic recrystallization is an important process in the Morin Shear Zone and could contribute to the texture (e.g. Ji and Mainprice, 1990; Kruse et al., 2001, 2002). The monoclinic asymmetry of the patterns is coherent with a top-to-the north shearing.

Table 2

<table>
<thead>
<tr>
<th>Morin anorthosite</th>
<th>Texture based models</th>
<th>Ultrasonic measurements</th>
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<tr>
<td>%</td>
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<td>95 Pl</td>
<td>MT-8</td>
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<td>8 Cpx</td>
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<td>90 Pl</td>
</tr>
<tr>
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<td>5 Cpx</td>
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<td>2 Bt</td>
<td>2 Bt-op</td>
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<td>GM</td>
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<td>$dV_{\text{min}}$ (m/s)</td>
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<td>$AV_{\text{P}}$ (%)</td>
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</tr>
<tr>
<td>$\rho$ (g/cm$^3$)</td>
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Fig. 6. Single crystal elastic wave propagation surfaces for andesine (An50), diopside, and Enstatite. (A) P-waves and (B) Shear-wave splitting. [001] is in the center (Z’) and pole to (010) to the bottom (Y’). Equal area projection. Contours are with linear scale. For (B) a velocity difference 10 means 1000 m/s.
The crystallographic preferred orientation of clinopyroxene shows a distribution with (010) planes parallel to the foliation and [001] directions parallel to the rock lineation (Fig. 5B). This is a very common texture, both in natural and experimentally deformed clinopyroxene (e.g. Van Roermund and Boland, 1981; Van Roermund, 1983; Buatier et al., 1991; Skrotzki, 1994; Godard and Van Roermund, 1995; Bascou et al., 2001; Brenker et al., 2002). TEM investigations of omphacite (e.g. Godard and Van Roermund, 1995) and diopside (e.g. Amiguet et al., 2010) have not observed dislocation activity on the (010)[001] system. The activation of other slip systems at different temperatures was documented in experiments. Below 800 °C and high stress/strain rate mechanical twinning on planes (100) and (001) dominates (e.g. Avé Lallemant, 1978). At higher temperatures dislocation and diffusion creep control the deformation, depending on microstructure and stresses (e.g. Bystricky and Mackwell, 2001). The systems (100)[001], (010) [100] and {110}C<110> have been documented when deformation is carried out at 800–900 °C (Ingrin et al., 1991). At higher temperatures (>1000 °C) {110}C<110> and {100}[001] slips dominate (Ingrin et al., 1991; Raterron et al., 1994; Amiguet et al., 2010).

Bascou et al. (2002) attributed the (010)[001] texture in clinopyroxene to a geometrical effect. In a series of Viscoplastic Self Consistent (VPSC) texture simulations on omphacite, those authors demonstrated that even with no slip activity allowed on (010)[001], (010) planes align with the foliation in different strain regimes. Simulation results are compatible with TEM observations and support that slip on (110) controls the orientation of (010) poles normal to the foliation. In our sample, clinopyroxene (110) (010) [001] patterns correlates with simulations of Bascou et al. (2002) and are compatible with a slip on the (110)[001] system.

The dispersion of maxima in the orthopyroxene texture precludes a clear interpretation in terms of slip systems. While (100) [001] and (010) [001] have been suggested as important slip system for high-grade metamorphic conditions (Avé Lallemant, 1978; Ross and Nielsen, 1978; Christensen and Lundquist, 1982; Dornbusch et al., 1994), the contribution of other mechanisms like grain boundary sliding could result in different textures (e.g. Sundberg and Cooper, 2008). In our sample a combination of several processes may be responsible of the texture. However, due to the low volume fraction of the orthopyroxene, we should be cautious about any inferences. Some correlation could be established with the orthopyroxene texture in sample A6 (Zhao, 1997), a porphyroclastic mylonite from Morin Shear Zone.

### 7.2. Velocities of phases an composite

For single crystal P-waves, andesine is most anisotropic ($V_P = 44.1\%$; $V_{Pmax} = 7.82$ km/s; $V_{Pmin} = 5.89$ km/s), clinopyroxene is intermediate ($V_P = 39.8\%$; $V_{Pmax} = 9.35$ km/s; $V_{Pmin} = 7.16$ km/s), and orthopyroxene is least anisotropic ($V_P = 23.2\%$; $V_{Pmax} = 8.62$ km/s; $V_{Pmin} = 7.38$ km/s). The strongest shear wave splitting ($dV_s$) is shown by single crystal plagioclase, with a maximum of 1855 m/s about 45° to $Z$ (Fig. 6).

Seismic velocities for individual phases of the textured Morin mylonitic anorthosite are calculated from the polycrystal elastic tensor of each phase (Geometric mean, GM; Table 1B. In plagioclase and clinopyroxene the distribution of P-wave velocity is asymmetric with respect to sample axes XYZ, while for orthopyroxene the pattern is more symmetric (Fig. 8). In general $V_{Pmax}$ is at a high angle to the foliation (75°–90°) and $V_{Pmin}$ defines an inclined girdle (= 15°) for plagioclase and a relatively wide maximum around the lineation in both pyroxenes (Fig. 8). Shear-wave splitting shows a complex pattern with no simple relationship with the foliation and lineation (Fig. 8). Both the shear-wave splitting and the orientation of the polarization plane for the fastest shear wave ($S_i$) are strongly dependent of the propagation direction.

In polyphase anorthosite seismic velocity (Fig. 7) is similar to the monomineralic aggregates, particularly to the plagioclase velocity patterns (100% Pl; Fig. 8). While plagioclase dominates the aggregate (88%), the contribution of pyroxenes (12%) to the bulk velocity is significant (Figs. 7 and 8). Comparing P-wave maximum velocity the mylonitic anorthosite shows higher values (7.10 km/s; Fig. 7) than pure plagioclase aggregate (6.71 km/s; Fig. 8). Real anisotropy also increases from $V_P = 2.26$% to $V_P = 2.36$%.

We compared our elasticity data with those measured and calculated in similar samples by Ji et al. (1997), Zhao (1997) and Xie et al. (2003). P-wave velocities are similar, but with some differences due to compositional variations and averaging schemes (Table 2). Considering Voigt and Geometric Mean averages, actual anisotropy in our sample ($V_P = 2.35–2.36$) is lower than calculated values of Xie et al. (2003) (3.33%) and Ji et al. (1997) (2.9%). The difference is larger compared to experiments by Zhao (1997) in terms of anisotropy ($V_P = 4.2–8.5$) and shear-wave splitting (Table 2). In the aggregates from Xie et al. (2003) and Ji et al. (1997) a random pyroxene orientation was assumed. In Zhao (1997) a real texture for pyroxene was obtained for two samples, and then imposed on the rest of samples. Here the method to analyze the texture and the overall composition play an important role to

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**Fig. 7.** P-wave velocity ($V_P$) and S-wave splitting ($dV_s$) propagation surfaces for the mylonitic anorthosite of this study. The results for Voigt and Geometric mean averages are presented. Actual P-wave anisotropy ($AV_P$ %) is indicated. Equal area projection. Contours are with linear scale.

<table>
<thead>
<tr>
<th>Phase</th>
<th>$V_P$ (km/s)</th>
<th>$dV_s$ (km/s)</th>
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<tbody>
<tr>
<td>Plagioclase</td>
<td>6.71</td>
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<tr>
<td>Clinopyroxene</td>
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<table>
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</tbody>
</table>

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**Table 2.** Seismic velocities for individual phases of the textured Morin mylonitic anorthosite are calculated from the polycrystal elastic tensor. The crystallographic preferred orientation of clinopyroxene shows a distribution with (010) planes parallel to the foliation and [001] directions parallel to the rock lineation (Fig. 5B). This is a very common texture, both in natural and experimentally deformed clinopyroxene (e.g. Van Roermund and Boland, 1981; Van Roermund, 1983; Buatier et al., 1991; Skrotzki, 1994; Godard and Van Roermund, 1995; Bascou et al., 2001; Brenker et al., 2002). TEM investigations of omphacite (e.g. Godard and Van Roermund, 1995) and diopside (e.g. Amiguet et al., 2010) have not observed dislocation activity on the (010)[001] system. The activation of other slip systems at different temperatures was documented in experiments. Below 800 °C and high stress/strain rate mechanical twinning on planes (100) and (001) dominates (e.g. Avé Lallemant, 1978). At higher temperatures dislocation and diffusion creep control the deformation, depending on microstructure and stresses (e.g. Bystricky and Mackwell, 2001). The systems (100)[001], (010) [100] and {110}C<110> have been documented when deformation is carried out at 800–900 °C (Ingrin et al., 1991). At higher temperatures (>1000 °C) {110}C<110> and {100}[001] slips dominate (Ingrin et al., 1991; Raterron et al., 1994; Amiguet et al., 2010).

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explain those differences. For example, the U-stage measurements typically result in poor grain statistics and, in the case of plagioclase, a biased orientation/grain selection (e.g. Ji et al., 1994). Therefore some texture components could be artificially enhanced or removed. This is relevant, since both plagioclase and pyroxene fabrics could result in constructive or destructive combinations of their seismic behavior, depending on texture. The effect of the composition will be discussed later.

We can compare seismic data and ultrasonic measurements from previous studies (Ji et al., 1997; Zhao, 1997; Vp mean = 6.9–6.5 km/s; Table 2) with those calculated along the sample coordinates (X, Y, Z; Fig. 1). Results with the same averaging scheme (Voigt) are similar (Vp mean = 7.0 km/s), but even better for the Geometric Mean data (Vp GM = 6.8 km/s). P-wave anisotropy depicts the same trend, with real data that range between AVp = 1.7–12% (Ji et al., 1997; Zhao, 1997), and our Vp GM data between AVp GM = 2.1 and 1.9% (Voigt–Geo Mean). It is clear that the difference between actual anisotropy and XYZ anisotropy (orientation of the cores for ultrasonic measurements in the sample reference system) is due to the effect of texture (e.g. Wenk et al., 2012). The selection of the averaging scheme (Voigt, Reuss, Hill, Geometric Mean) has some effect. In our case the best approximation to real velocity measurements is obtained with the Geometric mean.

7.3. Rock recipes. Anisotropy of gabbroic rocks

As a next step we are creating hypothetical plagioclase–clinopyroxene mixtures (‘rock recipes’; Tatham et al., 2008), assuming that the phases display the same texture patterns. The results are summarized in Tables 2 and 3 and Figs. 8–11. Orthopyroxene is not considered in the synthetic mixtures.

Elastic tensors for some relevant metagabbroic compositions are shown in Table 1C, and wave surfaces are displayed in Fig. 8. Both velocity and anisotropy increase with the pyroxene volume fraction from 6.7 to 8.3 km/s and from 2.3 to 5.1% respectively (Fig. 9). The trend of S-wave splitting is somewhat more complex but also increases (from 850 m/s to 1560 m/s; Figs. 8 and 9). The effect of texture in seismic properties is also clear in the synthetic mixtures. In Fig. 10, the variation of P-waves at different orientations to the lineation (X-axis), in the XZ sample plane reveal an asymmetric distribution around the foliation pole (75–80° to the Z-axis, Figs. 8 and 10), which could result in discrepancies between ultrasonic and texture-based seismic wave data. The dimension of that discrepancy is computed in terms of anisotropy in Fig. 11 (see also Table 3), where AVp XYZ and AVp anisotropies are plotted against the bulk density of the plagioclase–pyroxene mixture (Pl-Cpx). A deviation of up to 25% from the actual value of P-wave anisotropy is expected if ultrasonic measurements are performed along the
Cartesian axes X, Y, Z (Fig. 11). This effect must be taken into account for the prediction and interpretation of seismic data, when monoclinic or triclinic texture symmetry is suspected (Fig. 5). The results highlight the need to expand the calibration of the seismic response to deformation fabrics for rocks at lower crust and different strain regimes (e.g. Lloyd et al., 2011).

7.4. Reflectivity

Reflection coefficients (R) at lithologic interfaces have been calculated from densities and P-waves velocities along the Z-axis (Geometric mean; Table 3; normal incidence, Sheriff and Geldart, 1995). Results calculated from synthetic mixtures and the mylonitic anorthosite (MSZ) are shown in Table 4. The pair mylonitic pyroxenite–anorthosite returns the highest reflectivity (R = 0.035). Among the gabbroic protoliths, mylonitic melagabbros have the highest contrast with mylonitic anorthosites (R = 0.020). Mylonites from gabbros and leucogabbros show a very low contrast with mylonitic anorthosites (R < 0.011).

Reflectivity results suggest that only when a strong mineral segregation occurs in mafic mylonites a good reflectivity could be reached between layers with pyroxene and layers with plagioclase (R ≈ 0.04; Sheriff, 1975). Mechanical segregation of phases could be favored in high-grade shear zones affecting mafic protoliths because of the contrasting mechanical behavior of e.g. plagioclase and pyroxene (e.g. Mackwell et al., 1998).

8. Conclusions

A sample from the Morin anorthosite shear zone was analyzed with TOF neutron diffraction. Texture and microstructures are compatible with the plastic deformation of the aggregate under high-T conditions. All mineral phases depict a significant preferred orientation that could be related to the general kinematic history of the Morin Shear Zone.
Texture-based elastic properties of the aggregate were calculated and compared with previous calculated and measured data in the area. A good agreement is found, but neutron diffraction, in combination with Rietveld data analysis emerges as a powerful technique to quantify preferred orientation of rocks composed of several low-symmetry phases.

We have explored the elastic properties of gabbroic rocks by using a ‘rock recipes’ approach. There is an increase of P-waves velocity, S-waves splitting and anisotropy for higher clinopyroxene volume fractions. Seismic anisotropy calculations are very sensitive to the texture symmetry. Large deviations (8–25%) were found between actual anisotropy (\(V_{p}\), \(V_{S}\)) and that measured along XYZ sample directions (\(V_{Pp} \), \(V_{Pm}\), \(V_{Pm}\)). This should be considered when interpreting geophysical data and building models of the lower crust, where textures with monoclinic and triclinic symmetries are common. Particularly preferred orientation patterns in more mafic gabbroic rocks should be analyzed with similar techniques.

Acknowledgments

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References

