Quantitative texture analysis of glaucohanite deformed under eclogite facies conditions (Sesia-Lanzo Zone, Western Alps): comparison between X-ray and neutron diffraction analysis

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Abstract: X-ray and neutron diffraction techniques have been applied to quantitative texture analysis of a glaucohanite from the Sesia-Lanzo Zone (Western Italian Alps), naturally deformed under eclogite facies conditions. The comparison has been carried out in order to reveal the limits and problems of texture analysis related to strongly deformed polymineralic. Different methods of measuring and computing the orientation distribution function from diffraction data have been tested, in particular X-rays, direct peak integration, and neutron diffraction using Rietveld-texture analysis. Due to grain-size problems and heterogeneity of individual amphibole mineral, neutron radiation is shown to be the best probe for characterizing the whole rock: being more penetrative than conventional X-rays, a larger volume of the mineral aggregate is sampled, giving better statistics. However, results obtained by summing the corresponding individual spectra of at least three X-ray diffraction experiments on parallel slabs of the same specimen also give statistically valid, semi-quantitative results that reproduce the overall textures. The quantitative texture analysis shows the strong texture of the two generations of amphiboles (AmphI and AmphII), which are mainly characterized by [001] directions at an angle of about 10° to the mineral lineation and by (M00) planes describing girdles around the lineation. The texture is comparable to those described in the literature for amphibole deformed under different temperature and pressure conditions, and the pronounced asymmetry of the [001] directions with respect to the mineral lineation is consistent with a non-coaxial component that occurs during the deformation.

In the recent past, quantitative texture analysis has been used in incredibly diverse applications in Earth Sciences (Weak 1985; Bunge et al. 1994; Kocks et al. 1998; Leiss et al. 2000). For instance in structural geology, tectonics, deformation processes and glaciology, texture analysis can be used to describe the anisotropy of fabrics (Baker et al. 1969; Baker & Weak 1972; Gapaï & Brun 1981; Benoët et al. 1997; Leiss et al. 2000). In palaeontontology, texture analysis brings new insights into to the phylogeny of molluscs and fossils (Chatagnier et al. 2000). In geophysics, texture analysis aids interpretation of the anisotropic seismic wave propagation in the Earth’s inner core (Weak 2000). Several techniques have been used to carry out texture analysis: the former optical U-stage has progressively been complemented by X-ray and neutron diffraction experiments, and more recently by the local electron back scattering diffraction approach (e.g., Prior et al. 1999). In the case of X-ray and neutron diffraction, photographic films have rapidly been replaced by point detectors which have allowed the first real quantitative texture analyses by measuring diffraction pole figures. However, such detectors only measure one pole figure at a time and do not allow the separation of several textures in multiphase samples of the type commonly present in geological settings.

Bunge et al. (1982) proposed using neutrons to overcome the multiphase problem in texture analysis. Recently, Ricote & Chatagnier (1999) used X-rays in which several pole figures were simultaneously acquired by use of a curved position sensitive detector. So far, however, quantitative texture studies of rocks composed of more than one phase of low crystal symmetry are rare

Microstructural investigations, using optical microscopy, X-ray and neutron diffraction, scanning electron and transmission electron microscopy show that (100)[001] and (hk0)[001] are the most common slip systems in amphiboles (Table 1). Dynamic recrystallization (Cumhust et al. 1989), rigid body rotation (Idéfoni et al. 1990; Siegesmund et al. 1994) and cataclastic deformation (Nyman et al. 1992) may also occur. The most frequently recurrent amphibole textures consist of [001]-direction and (hk0) planes parallel to the stretching lineation (e.g., Schwerdtner 1964; Gapais & Brann 1981; Siegesmund et al. 1994). These studies also showed that the role of intracrystalline plasticity, fracture, rigid body rotation and chemical forces.

<table>
<thead>
<tr>
<th>References</th>
<th>Deformation conditions</th>
<th>Observation techniques</th>
<th>P–T conditions</th>
<th>Mineral</th>
<th>Deformation mechanisms, slip systems and twin systems</th>
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<tr>
<td>Schwerdtner (1964); Schwerdtner et al. (1971)</td>
<td>NAT</td>
<td>OM</td>
<td>-</td>
<td>Hbl</td>
<td>stress-driven growth; [001] maxima perpendicular to (110) girdle (100) (~101) twinning</td>
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<td>Riecker &amp; Rooney (1969); Rooney et al. (1970)</td>
<td>EXP</td>
<td>OM-XR</td>
<td>400–600°C; 5–15 kbar</td>
<td>Hbl</td>
<td>(100)[001] variable directions</td>
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<td>EXP/NAT</td>
<td>OM</td>
<td>AMP &lt;600°C; &gt;800°C</td>
<td>Gs</td>
<td>(110)/[001] and [011] microstructure</td>
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<td>XR</td>
<td>20–700°C at 2 kbar</td>
<td>Act</td>
<td>[001] lineation</td>
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<td>-</td>
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<td>[001] // lineation</td>
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<td>450–600°C</td>
<td>Clino-Amp</td>
<td>(hk0)[001]</td>
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<td>450–600°C</td>
<td>Clino-Amp</td>
<td>Hbl</td>
</tr>
<tr>
<td>Mainprice &amp; Nicolas (1989)</td>
<td>NAT</td>
<td>OM-XR-TEM</td>
<td>ECL</td>
<td>Gln</td>
<td>(100)[001] (110)[001] (010)[100] (110)[2(110)] (001)</td>
</tr>
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<td>Reynard et al. (1989)</td>
<td>NAT</td>
<td>OM-TEM</td>
<td>ECL</td>
<td>Gln</td>
<td>Rigid body rotation</td>
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<td>Idéfoni et al. (1990)</td>
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<td>OM-TEM</td>
<td>ECL</td>
<td>Gln</td>
<td>[001] lineation</td>
</tr>
<tr>
<td>Skrotski (1990; 1992)</td>
<td>NAT</td>
<td>OM-TEM</td>
<td>T &gt; 650°C</td>
<td>Gr</td>
<td>Cataclastic deformation</td>
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<td>Kuhin &amp; Hunttemann (1991)</td>
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<td>~500°C; 5–15 kbar</td>
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<td>BS</td>
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<td>AMP</td>
<td>Hbl</td>
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<td>Siegesmund et al. (1994)</td>
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<td>OM-TEM</td>
<td>500–670°C</td>
<td>Hbl</td>
<td>Rigid body rotation</td>
</tr>
</tbody>
</table>

NAT, naturally deformed; EXP, experimentally deformed; OM, optical microscopy; XR, X-ray; TEM, transmission electron microscopy; ND, neutron diffraction; AM, amphibole faces; GS, greenschists facies; BS, blueschist facies; ECL, eclogite facies; GR, granulite facies; Hbl, hornblende; Act, actinolite; Amp, amphibole; Gln, glaucophane.
during the deformation of amphiboles under different geological conditions, need more quanti-
tative investigation.

Neutron diffraction is well known as the most reliable experimental technique for quantitative texture analysis (QTA) of naturally deformed rocks when statistics in coarse-grained samples, is a big concern (Bouchet et al. 1979; Wenk et al. 1984; Kocks et al. 1998; Chateigner et al. 1999).

X-ray diffraction suffers from poor statistics when the grain size is not very fine, as is the case in many geological situations. This work first investigates the possibility of using the X-ray diffraction method to achieve a better reliability at least for qualitative results. Secondly, we compare two different methodologies of analysis with respect to their applicability to more complex polymineritic rocks. Finally, amphibole textures obtained with X-ray and neutron diffraction techniques are compared with microstructural features and crystallo-
graphic orientations reported in literature.

Geological setting and sample description

The M26 sample is a glaucophane, mainly con-
tituted of winchitic amphiboles (2-97%) (Table 
2). It crops out along the divide between Monte Murcone and Mombarone, in the Eclectic Micaschists Complex (EMC) of the Sestia-Lanzo 
Zone (Austroalpine domain — Western Alps, 
Italy) (Fig. 1). This zone consists of two main tectonic units distinguished on the base of their lithological and metamorphic differences (e.g. Compagnoni 1977): the upper unit (IIa Zone Diorto-Kinzigítica) and the lower unit (Gneiss 
Minuti Complex and the EMC). The EMC 
shows a dominant Alpine imprint under eclogite facies conditions. The EMC consists of small lenses of biotite–garnet–Al silicates–metapelites (kinzigites), garnet–omphacite–glaucophane-
metapelites, large omphacite–glaucophane–
metaquartzidolite bodies (metagranitoids and metaquartzidolite of Monte Mars Complex, wes-
tern part of the Monte Murcone intrusion 
emplaced at 293 ± 1 Ma (Bussy et al. 1998)), lenses of metabasites (amphibole-bearing eclo-
gites, eclogites and glaucophanites), pure and impure marbles, kyanite–chloritoid–garnet–
quartzites, metre-size peridotitic lenses and an-
destic dykes (Grossi 1977; Pognante et al. 1980; Panshetier et al. 1981; Spalla et al. 1983; Williams 
& Compagnoni 1983; Lardeux & Spalla 1991; 
Venturini et al. 1991). All lithologies, except Oligo-
ocene anadestic dykes (Dal Piaz et al. 1979; De 
Capitani et al. 1979; Beccaluva et al. 1983) show 
a penetrative structural and metamorphic Alpine re-equilibration under eclogite facies con-
ditions. The age of the eclogitic metamorphism has been dated as Late Cretaceous—Early Paleo-
cene (Inger et al. 1996; Duchene et al. 1997; 
Ruffet et al. 1997; Rubeatto et al. 1999).

The structural framework of the EMC, along the Monte Murcone–Mombarone divide, is the result of seven deformation phases (Pognante et al. 1980; Panshetier et al. 1981; Williams & Compagnoni 1983). The most penetrative is D2: it consists, within micaschists and gneisises, of a 
penetrative foliation (S2, 265°/40°) marked by 
eclogite facies minerals, as omphacite, blue-
amphibole and phengite; in eclogites, amphi-
bole-bearing eclogites and glaucophanites, D2 
mainly consists of an S2 foliation, defined by a 
compositional layering associated with a mineral 
lineation (Lc, 25°/35°); the latter lineation (L1) is 
defined by shape preferred orientation of 
omphacite and glaucophane. Subsequent defor-
mation phases (D3 and D4) produced large-
scale isoclinal and recumbent folds. Glaucophan-
ites are metre-scale lenses or boudins within 
eclogitic micaschists and gneisises; they are 
characterized by centimetre to millimetre scale grain 
variations. The macroscopic lineation (L2) 
lies within the S2 compositional layering and is 
marked by the shape preferred orientation of 
eclogophanes and by the preferred orientation 
of lenticular aggregates of glaucophanes (Fig. 
2). No syn-D3 fabric gradients occur at the 
mesoscopic scale within the glaucophanites and 
around micaschists and gneisises. The

Table 2. Chemical analyses of M26 amphiboles

<table>
<thead>
<tr>
<th>Element</th>
<th>Am</th>
<th>AmII</th>
<th>AmIII</th>
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<tbody>
<tr>
<td>SiO₂</td>
<td>59.717</td>
<td>59.658</td>
<td>57.343</td>
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<tr>
<td>TiO₂</td>
<td>0.111</td>
<td>0.043</td>
<td>0.101</td>
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<tr>
<td>Al₂O₃</td>
<td>12.112</td>
<td>11.946</td>
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<tr>
<td>FeO</td>
<td>6.163</td>
<td>6.303</td>
<td>5.801</td>
</tr>
<tr>
<td>MgO</td>
<td>0.007</td>
<td>0.000</td>
<td>0.009</td>
</tr>
<tr>
<td>CaO</td>
<td>13.406</td>
<td>15.353</td>
<td>19.993</td>
</tr>
<tr>
<td>K₂O</td>
<td>2.111</td>
<td>2.166</td>
<td>13.254</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.064</td>
<td>0.000</td>
<td>0.075</td>
</tr>
<tr>
<td>Total</td>
<td>92.293</td>
<td>98.475</td>
<td>98.837</td>
</tr>
<tr>
<td>Si</td>
<td>7.945</td>
<td>8.035</td>
<td>7.875</td>
</tr>
<tr>
<td>Ti</td>
<td>0.008</td>
<td>0.008</td>
<td>0.008</td>
</tr>
<tr>
<td>Al</td>
<td>1.899</td>
<td>1.895</td>
<td>0.322</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>0.690</td>
<td>0.707</td>
<td>0.669</td>
</tr>
<tr>
<td>Mn</td>
<td>0.008</td>
<td>0.000</td>
<td>0.008</td>
</tr>
<tr>
<td>Mg</td>
<td>2.664</td>
<td>2.791</td>
<td>4.095</td>
</tr>
<tr>
<td>Ca</td>
<td>0.299</td>
<td>0.316</td>
<td>1.940</td>
</tr>
<tr>
<td>K</td>
<td>0.008</td>
<td>0.000</td>
<td>0.017</td>
</tr>
<tr>
<td>Na</td>
<td>1.160</td>
<td>1.280</td>
<td>0.041</td>
</tr>
</tbody>
</table>

Stoichiometric ratios of elements based on 23 O. Fetot as Fe₂O₃.
glauconephane has been sampled where minor overprinting by subsequent deformation and metamorphic transformations occurred (e.g. D3 and D4 folds).

Thin sections for optical microscopy were cut parallel to the mineral lineation (L2) and perpendicular to the foliation S2 (XZ plane in Fig. 2). Glauconephane exhibits a compositional layering defined by alternating domains (<5 mm thick). Domains I have a lenticular shape; large AmphI occur as ellipsoidal grains (0.4–1 mm) within domains I, showing undulose extinction, deformation bands and in some places subgrains (Fig. 2). Domains I are discontinuous, and wrapped by domains II, parallel to S2. AmphI grains do not have a shape preferred orientation with respect to S2 and L2. AmphI porphyroblasts, displaying undulose extinction and marginal subgrains, occur in the core of the domains I. The misorientation angle between adjacent subgrains is often higher than 5° (Fig. 2). Subgrains at the rims of the domains I display shape preferred orientation close to S2 and L2 directions. Domains II are defined by aggregates of AmphII. AmphII are mainly strain free with grain sizes <0.4 mm. Shape preferred orientation of AmphII is parallel to the mineral layering (S2) (Fig. 2a) and the AmphII grains are similar in size to AmphI marginal subgrains. AmphII shows rutile, zircon, opaques and quartz inclusions. A third generation of amphibole (AmphIII) occurs locally at the grain boundaries between amphiboles (Fig. 2). Chlorite and white mica partially replace AmphI and AmphII or fill small fractures with quartz and carbonates. Garnet appears as small porphyroblasts (<1 mm) and forms less
Fig. 2. (a) Alternating domains I and II, marking the mineralogical lineation (L2). Domain I is defined by an elongated aggregate of Amph with no shape preferred orientation; domain II is defined by shape preferred orientation of Amph grains, elongated parallel to the mineral lineation (L2). Amph subgrains at the domain boundary show shape preferred orientation parallel to L2. (b) Continuous white and black lines define the Amph grain boundaries, while stippled white lines define Amph subgrain boundaries; a1 grains preserve shape and crystallographic orientation of Amph; a2 sub-grains show different degrees of misorientation with respect to Amph crystal orientation. (c) and (d) Amph, within domain I, with elongate strain free subgrains (a2); shape preferred orientations of subgrains mainly lie parallel to the X direction.

Less than 1% of the rock volume. Micro-fractures (2 mm thick), occurring at high angles (70°) with respect to the layering, are mainly filled by fine aggregates of quartz, carbonates, diopside and white mica.

Mineral chemistry and quantitative diffraction analyses

Quantitative chemical analyses were performed on polished samples using an Applied Research
Laboratories electron microprobe fitted with six wavelength-dispersed spectrometers and a Tracor Northern Energy Dispersive Spectrometer 5600, using natural silicates as standards. An accelerating voltage of 15 kV, a sample current 20 nA and a beam current 300 nA were used. Matrix corrections were calculated using the ZAF procedure (Colby 1988). Table 2 shows representative mineral compositions of AmplI, AmplII and AmplIII. While Ampl and AmplII display the same chemical composition (winchite), AmplIII (actinolite) is characterized by a decrease in Al and Na content and an increase of Mg and Ca content.

A representative sample of M26 glaucophane (1 cm²) was powdered with an agate mortar and a powder diffraction pattern was collected using Cu Kα radiation, from 5° to 70°, in steps of 0.01° and 8 seconds per step. A quantitative phase analysis using the Rietveld method was performed using a richterite (Hawthorn et al. 1997) and a clinochlore (Snyth et al. 1981) as starting structural models. The atomic fractions were deduced from chemical analysis. The quantitative phase analysis confirmed that the total amount of chlorite and AmplIII is less than 5%. The other phases, observed using optical microscopy, are below the detection limits of the X-rays.

Texture measurements

Measuring single pole figures does not allow a quantitative texture analysis, even when measured completely; in order to compare between samples independently (e.g. porosity, stress/strain states, particle sizes and phase ratios) normalization of pole figures is needed (Bunge & Eibling 1982). Normalization involves refining the orientation distribution function (ODF), which defines the texture strength and all components of the texture. The same single pole figure can be generated by many different ODFs, which means that interpretation of texture from a single pole figure is ambiguous.

X-ray diffraction

X-ray diffraction texture measurements were carried out using a Huber four-circle goniometer (closed eulerian cradle +θ-2θ movements) mounted on an INEL X-ray generator, and Cu Kα wavelength radiation, monochromatized by an incident flat graphite monochromator. A curved position sensitive detector (PSD) with a 2θ resolution of 0.03° (INEL CPS-120) was used to acquire complete diffraction patterns at different positions of the sample in the 0°-120° 2θ range. The flat samples were measured in reflection geometry. The incident angle on the sample ω, and the PSD position were chosen to maximize coverage in orientation space. The spectra were measured using a coverage from 0° to 355° in ϕ and from 0° to 70° in χ (Fig. 3) with incremental steps of 5° for both angles, which corresponds to 72 x 15 = 1080 measured 2θ patterns. Each pattern was acquired for 180 seconds.

We chose an X-ray beam size of 1 x 1 mm, collimated to provide sufficient resolution for peak separation and for an average grain size of 0.1-0.4 mm; larger Ampl grains (0.5-0.8 mm) correspond to less than 2% of the sample. The irradiated surface was increased by oscillations of the sample perpendicular to the lineation direction (±3° of amplitude) (Fig. 3). A further increase of the irradiated area could be provided by lowering ω, but such a procedure would give rise to more severe peak overlap due to a defocusing effect, particularly at high 2θ values, where much of the orientation information is located. Compared to a set-up with a point detector, this experimental design allows an optimized incident angle value of ω = 16°.

To further increase the grain statistics, three slabs of the same sample, cut perpendicular to the mineral layers and parallel to the mineral lineation, were measured. The respective raw intensities for each pole figure direction obtained from the three different experiments were summed before the ODF calculation.

Figure 3a shows the sum of 1080 diagrams of M26 used for the phase identification and peak indexing at the ω = 16° position, and Fig. 3b is an example of such a summed diagram for a lower incidence angle (ω = 5.3°). Such diagrams are close to random powder patterns, but only approximately since the pole figures were incompletely measured. The summed diagrams confirms that the Ampl and AmplII chemical compositions are similar. The increased overlap for the lower ω value can be clearly seen (Fig. 3b), leading to unreliable integration for 2θ values larger than 40°. For this reason only the experiments at ω = 16° have been used. Indexing of the diagrams used shows that at least twenty pole figures are theoretically usable for the ODF determination. Some peaks are however weak, closer to the background counts, and these would decrease the overall reliability of the ODF; therefore, only thirteen have been used in the analysis, removing peaks lower than 8% of the maximum.

To obtain these pole figures for texture analysis, data treatment was operated through direct
Fig. 3. Summed X-ray diffraction diagrams at 16° (a) and 5.3° (b) ω angles. (c) Instrument angles in reflection geometry.
cyclic integration of the diffracted intensities and corrections for absorption using an INEL-LPEC software program (INEL 1986). The WIMV (Matthies & Vinel 1982) iterative method was subsequently used to compute the ODF from the selected pole figures. The quality of the result was assessed with reliability factors (RP0 and RPI, for global and above 1 m.r.d., or multiple of random distribution, values respectively). From the ODF, we can recompute any pole figures, even those that are not available experimentally, and calibrate parameters indicative of the texture strength: the texture index \( F^2 \), and the texture entropy \( S \) (after Burge 1982; Matthies 1991).

The different calculations have been carried out using the Berkeley Texture Package (BEARTEX, Wenk et al. 1998). Depending on the sample composition several diffraction peaks coming from different phases can be present at close 2θ positions. For X-ray data analysis where only the direct integration method was used to obtain pole figures, we only used single peaks, or peak overlaps coming from the same phase as a summed multi-pole figure. The overlaps can be treated by the WIMV method, assigning intensity contributions to each component of the multi-pole figure (weight in % in Table 3).

**Neutron diffraction**

Neutron diffraction experiments were carried out at the Institut Laue-Langevin (ILL, Grenoble, France) high flux reactor using the position-sensitive detector of the D1B beamline. The detector spans a 2θ range of 80° with resolution of 0.2° and the wavelength used was 2.523 Å. The sample (1 cm\(^2\)) was mounted in a transmission Debye-Scherrer geometry and measured with the same scan grid as for X-ray experiments, but the pole figure coverage extended to 90° in \( 2\theta \) thanks to the low absorption of neutrons in this type of material. The \( 2\theta \) value was 10° and the counting time was 50 seconds per spectrum. A total of 72 × 19 = 1368 measured scans over the accessible 2θ range were made. Figure 4a shows the summed neutron diffraction pattern of the M26 sample for the 1368 scans. Since no defocusing effect occurs in transmission geometry and the full \( 2\theta \) range is measured, such a diagram is closer to a powder diffraction pattern than an X-ray diffraction pattern, even when a blind area exists for pole figures at \( 2\theta > 60° \). The neutron diffraction pattern shows an agreement between AmpI and AmpII chemical compositions. The smaller range of 2θ values, due to the larger wavelength used, gave fewer peaks. The MIMA function of BearTex, a subroutine based on the Minimal Pole Density Set (MPDS) criterion (Helming 1991), was used to compute the minimum requirement in experimental data to fulfill the condition that any ODF cell is determined by at least three points coming from the experimental pole figures. MIMA results show that the orientation space was completely covered by both the X-ray and neutron data sets, allowing reconstruction of the quantitative textures using the WIMV algorithm.

Changes ok?
the Rietveld Texture analysis (Mathies et al. 1997). A Rietveld texture analysis (Latterotti et al. 1997) was performed for all patterns with the software package MAUD (Latterotti et al. 1999), considering amphibole as the only phase present. MAUD uses a Rietveld core routine to compute spectra and a so-called Le Bail algorithm (Mathies et al. 1997) to extract the differences between random and textured intensities for each computed peak. These spectra form the basis for computing the ODF using WIMV. Finally, the spectra were recomputed using the results from the ODF for the next Rietveld iteration step. Initially, lattice parameters (Table 4), a five-parameter background function, 28 displacement of the peaks and the three-parameter Caglioti for the peak shape function, were simultaneously refined for five cycles assuming the sample was not textured. The discrepancy in fitting after these first steps suggests how strong the texture is (Fig. 4a). Then, the Le Bail-WIMV routines for the ODF computation were activated and texture was iteratively refined with crystal structure, yielding a better agreement between observed and calculated patterns (Fig. 4b). A first attempt to refine atomic positions as well as B_{eq} led to unusual values and these were replaced by values found in the literature for the next steps. Crystallographic results are compared with those of glaucoaphane (Comodi et al. 1991) and winchite (Ghose et al. 1986) in Table 4.

Table 4. Lattice parameters for amphiboles

<table>
<thead>
<tr>
<th>Lattice parameters</th>
<th>Estimated standard deviation</th>
<th>Glaucoaphane (Comodi et al. 1991)</th>
<th>Winchite (Ghose et al. 1986)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a (Å)</td>
<td>9.535</td>
<td>7.72517E-05</td>
<td>9.5310</td>
</tr>
<tr>
<td>b (Å)</td>
<td>17.706</td>
<td>1.66699E-05</td>
<td>17.7590</td>
</tr>
<tr>
<td>c (Å)</td>
<td>5.2823</td>
<td>7.16033E-05</td>
<td>5.3030</td>
</tr>
<tr>
<td>beta (°)</td>
<td>103.78</td>
<td>8.19599E-05</td>
<td>103.59</td>
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Fig. 5. Experimental normalized (exp.) and recalculated (rec.) X-ray (a) and neutron (b) pole figures for amphibole. Equal area projections. Logarithmic density scale. Intensity values are in m.r.d. x 100.

Results

Figure 5 shows the experimental normalized and recalculated pole figures from the X-ray and neutron analyses with respect to lineation direction and foliation plane. For X-rays, the high X range was not completely covered and characteristic rings appear at unmeasured regions in recalculated pole figures (Fig. 5a). Such rings prove that, for the X-ray case, the MPDS is at the lower limit for the full ODF coverage.

X-ray pole figures (Fig. 5a) display symmetric and asymmetric girdles around mineral lineation for most pole figures (e.g. (111), (131), (340) and (221)). The quality assessment of the ODF is given by a comparison of the experimental and recalculated pole figures and by the RP0 and RP1 values in Table 5. We can clearly see in this case that the orientation density values are not as low as those revealed by neutrons. This is mainly due to the low grain statistics, which intrinsically force the WIMV algorithm to

<table>
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<th>Number of pole figures</th>
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<th>Neutron pole figures</th>
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<tr>
<td>OD minima (m.r.d.)</td>
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<td>OD maxima (m.r.d.)</td>
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<td>6.61</td>
</tr>
<tr>
<td>S</td>
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<td>P0 (m.r.d.)</td>
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<tr>
<td>RP0 averaged (%)</td>
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<td>13.69</td>
</tr>
<tr>
<td>RP1 averaged (%)</td>
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<td>10.74</td>
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enhance the overall texture strength. However, these strong densities are obtained through an ODF refinement, the convergence of which ensures coherency between pole figures. A qualitative interpretation of the results is then made possible, with the grain-size problem affecting only the density values. Recalculated pole figures do not perfectly reproduce the experimental ones, as seen from the quite high RP factors. This is a consequence of the presence of some large grains. The strong amphibole texture is clearly shown by recalculating some special pole figures from the ODF focusing on principal crystal directions (Fig. 6a). The non-measurable (001)$^*$ directions are close to the lineation and (010)$^*$ and (100)$^*$ are mainly scattered within a plane perpendicular to the lineation direction. The (001)$^*$ directions make an angle lower than 10° with the lineation and display an angle of <15° with respect to the XZ plane as shown by the asymmetry of maxima.

Similar features to those described above can also be observed in the neutron pole figures (Figs 5b and 6b). Here, experimental pole figures are smoother than those obtained with X-rays, and recalculated pole figures (Fig. 5b) closely reproduce the experimental ones, with corresponding lower RP values. Experimental and recalculated pole figures exhibit great and small circle distributions close or perpendicular to the lineation direction. As for the X-ray pole figures, a small angle between the lineation and (001)$^*$ directions is apparent, as shown by the low Miller indices pole figures (Fig. 6b). The [001]$^*$ directions are strongly oriented, with an angle slightly deviating from the lineation: approximately 10° and 15° with respect to the XZ plane. The [010]$^*$ and [100]$^*$ directions mainly describe maxima normal to the lineation direction.

**Discussion and conclusions**

The M26 glauconaphite exhibits a strong texture, as shown by the pole density distribution of the amphibole and the texture indices reported in Table 5. The texture is comparable with those described in amphiboles deformed at different pressure and temperature conditions: the [001]$^*$ and [110]$^*$ directions lie parallel and perpendicular to the lineation respectively (e.g., Schwerdtner 1964; Schwerdtner et al. 1971; Gapaï & Brun 1981; Mainprice & Nicolas 1989; Kruhl & Huntemann 1991; Siegesmund _et al._ 1994), where the [110]$^*$ orientation is a function of the fabric components (Gapaï & Brun 1981). In the M26 glauconaphites, [100]$^*$ and [010]$^*$ directions scatter within the YZ-plane of the strain ellipsoid, and [001]$^*$ directions lie at an angle with respect to the lineation and foliation. This can be interpreted as due to a dominant constrictional component of the finite strain (Gapaï & Brun 1981). The symmetry of the [001]$^*$ directions with respect to the fabric elements could be interpreted as having developed during a non-coaxial deformation (e.g., simple shear), as observed in other materials (Nicolas & Poilier 1976; Gapaï & Cobbold 1987; Mainprice & Nicolas 1989; Law 1990; Wenk 1998).

In the literature, the observed preferred orientations have been mainly interpreted as due to (100)(001) slip, rigid body rotation and oriented growth (see Table 1 for references). The crystallographic preferred orientations of the M26 sample suggest a strong influence of crystal shape, as shown by Ildéfonce _et al._ (1990) for glauconaphite within the Eclogitic Micaschists of the Sesia-Lanzo Zone and for hornblende in amphiboles where the weak matrix is constituted of plagioclase (Gapaï & Brun 1981; Siegesmund _et al._ 1994). Our sample is matrix free, and

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**Fig. 6.** X-ray (a) and neutron (b) pole figures recalculated with BEARTEX. Equal area projections. Logarithmic density scale. Intensity values are in m.r.d. x100.
domains II, mainly constituted by AmpII, wrapping around domains I. Furthermore, AmpII porphyroclasts show undulose to patchy extinction, deformation bands and subgrains (Fig. 2). Subgrains in the core of the domains I show neither undulose extinction nor shape preferred orientations. Subgrains at the rims of the domains I progressively show a tendency to be oriented parallel to the domains II. The grain size and preferred orientation of such subgrains is similar to those of the AmpII defining domains II and both are mainly strain free. These relationships account for a component of subgrain rotation during the development of S2 and for AmpII-rich domains II having mechanically behaved as a ‘weak matrix’ with respect to the domains I (Cum最主要 et al. 1989; Siegesmund et al. 1994).

The relationships between the meso-microstructures and crystallographic textures, described above, do not unequivocally discriminate the dominant deformation mechanism during the development of the glaucophanite preferred orientation. In general, the nature of the deformation mechanisms leading to amphi-
bole textures still remains incompletely resolved (e.g. Stüntz 1989; Siegesmund et al. 1994). Aside from these limitations, the present work shows that similar crystallographic textures occur in amphiboles deformed under amphibolite and eclogite facies conditions, except for the pronounced asymmetries of [001] orientations with respect to the fabric elements. Further investigations on other lithologies of the Sesia-Lanzo Zone, such as eclogite micaschists or eclogites, may provide more quantitative textural data of the deeply subducted slice of continental crust in the Sesia-Lanzo Zone. Such data can be used to study the mechanical behaviour of rock-forming minerals during the important natural process of subduction to mantle depths and their relationships with whole rock deformation mechanisms.

The comparison of the two techniques shows that X-ray data can produce semi-quantitative results, which reproduce the overall texture if a sufficient area of the sample, or different sections of the same sample, are scanned using similar conditions. Neutron results are statistically more reliable (Table 5). The reliability of the different computation techniques is confirmed by the textures obtained: both direct peak integration (X-ray) and Rietveld texture analysis (neutron) produced qualitatively similar results even when starting from raw intensities obtained through different acquisition techniques (Uhlenmeier et al. 2000), and agree with the results reported in the literature. However, it can be seen that, besides the comparatively limited accessibility of neutron experiments to users, the much larger resolution of X-rays using a PSD gives a high potentiality in QTA of geological samples of half-millimetre sized grains. The relatively poor 2θ resolution of thermal neutrons makes the separation of peaks from several phases a hard task, even with a Rietveld-like technique. This can be demonstrated, as in this work, by the strong correlation existing between fitted parameters such as atomic positions or isotropic Debye-Waller factors and texture coefficients, causing the refinements to diverge when all the parameters are refined. No atomic structure variations between samples can be accessed under these conditions, and with the resolution used, this limits the neutron applicability. X-rays offer a better resolution, but their lower χ measurable range illustrates another limitation. The use of a Rietveld texture methodology overcomes this limitation by increasing the number of pole figures used in the QTA analysis, together with a better atomic structure definition than that which is accessible from the better resolution. This methodology requires a high number of diffraction diagrams and a diffraction apparatus equipped with a position sensitive detector or area detector that can realize such measurements in a reasonable experimental time. Indeed, if the grain statistic problem is alleviated by special measuring practices, such as larger oscillations than those used in the present work, X-ray diffraction using the direct integration method suggests that a complete quantitative description of textures and structures of strongly polyphasic rocks can be achieved by implementing the X-ray Rietveld texture analysis.

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