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On the measurement of plagioclase lattice preferred orientations

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Abstract—There are two major difficulties in measuring plagioclase lattice preferred orientations (LPOs) by U-stage. The first, which is caused by dependence of the LPO determination on anorthite content, cannot be overcome using the U-stage method at present. The second difficulty, which is caused by the dependence on orientation of thin sections, can be overcome by measuring all twinned grains in any two orthogonal sections. Compared with previous methods published in the literature, the present method using two rather than three orthogonal sections is more statistically meaningful and time-saving. In practice, this method was used for measuring LPOs of plagioclase ($\sim An_{50}$) from a typical anorthosite mylonite deformed under the granulite facies conditions in the Morin ductile shear zone within the Canadian Grenville Tectonic Province.

ANALYSIS

PLAGIOCLASE is the most abundant mineral in the Earth's crust (Ronov & Yaroshevsky 1969). Knowledge of the lattice preferred orientation (LPO) of plagioclase may further our understanding of its rheological behavior and deformation mechanisms (Wenk *et al.* 1986, Ji *et al.* 1988, Benn & Allard 1989) as well as its contribution to seismic anisotropy of the crust (Barruol *et al.* 1992, Ji *et al.* 1993, Seront *et al.* 1993). Reports on LPOs of plagioclase (e.g. Wenk *et al.* 1986, Kruhl 1987a,b, Ji & Mainprice 1988, Benn & Allard 1989, Ague *et al.* 1990, Barruol 1993) are relatively rare compared to those of other minerals such as quartz, calcite and olivine. This is mainly due to the following two difficulties in LPO measurement of plagioclase using a Universal stage (U-stage) mounted on a petrographic microscope.

Dependence of the LPO determination on anorthite content

Because plagioclase is triclinic, the axes of the optical indicatrix (N_p, N_m and N_g) are not parallel to the crystallographic axes. Thus, the LPO cannot be inferred directly from the measurements of optical axes. A complete LPO of plagioclase must be constructed using U-stage measurements of both optical axes and planar structural elements such as cleavage planes or compositional planes of twinning. Such a construction is based on the angular relationship between the optical axes and crystallographic directions and planes as a function of anorthite content on a stereogram (Burri *et al.* 1967), and involves several stereographic rotations of orientation data. As the manual construction is very time consuming, Benn & Mainprice (1989) developed an interactive computer program to facilitate the treatment of U-stage data.

Because U-stage measurements do not indicate positive or negative directions of the optical axes, there are four possible orientations for each of the measured planes [e.g. (010), (001) or the pericline twin plane] to be plotted onto the plagioclase determinative diagram of Burri *et al.* (1967). These four orientations are distributed symmetrically with respect to N_m (Fig. 1). But only one of these orientations is correct. If more than one of these four orientations in a plagioclase with a given

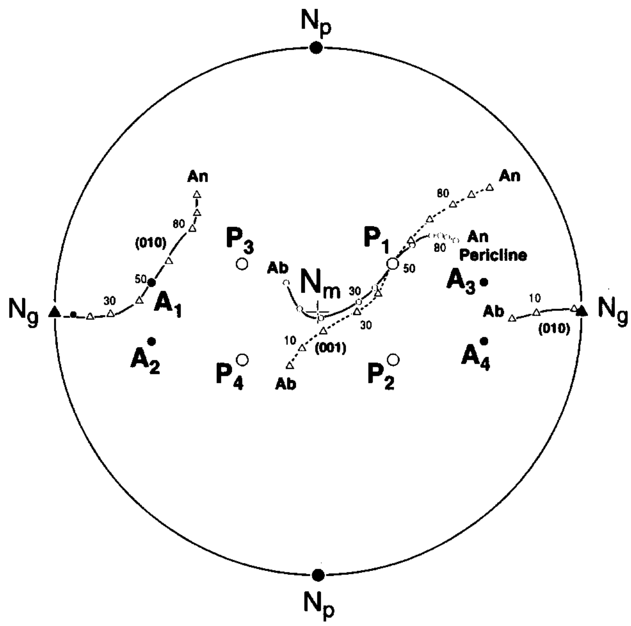

Fig. 1. Plagioclase determinative diagram modified from Burri *et al.* (1967). Migration curves give orientations of planar elements with respect to three optical axes (N_p, N_m and N_g). Black circles A1, A2, A3 and A4, and open circles P1, P2, P3 and P4 represent four possible orientations for albite and pericline twin planes or for (010) and (001), respectively, with respect to N_p, N_m and N_g directions in a plagioclase An_{50}. For anorthite contents An_{10}–An_{35}, the angular distance between A1 and A2, A3 and A4, P1 and P2, or P3 and P4 is too small ($\leq 5°$) to discern these orientations by U-stage method, causing ambiguity in the determination of complete crystallographic orientations. For anorthite contents An_{75}–An_{85}, orientations A1 and P3, A2 and P4, A3 and P1, or A4 and P2 are too close ($\leq 5°$) to be distinguished by U-stage method, making the identity of (010) and (001) cleavages underminable.

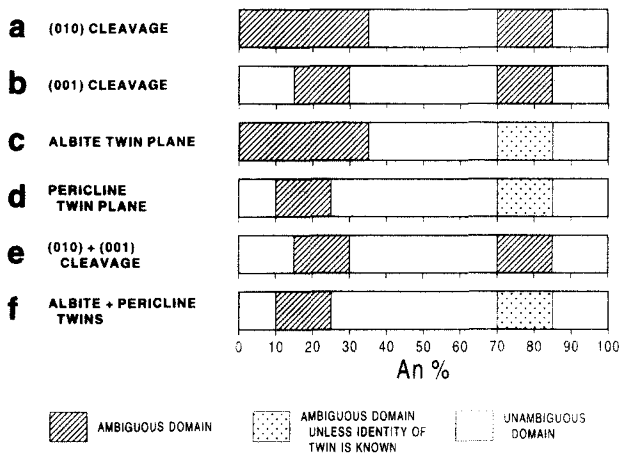

Fig. 2. Schematic illustration of the dependence of plagioclase lattice orientation determination by U-stage on the anorthite content of a given plagioclase and the nature of the visible planar elements.

anorthite content coincide with the migration curve for the corresponding plane within an angular range of U-stage measurement error (±5°), all other crystallographic directions are not unequivocally determinable. Similarly, if any one of the four orientations for (010) is indiscernible from any one of those for (001) within the measurement error, the identity of these crystallographic planes and further the complete LPOs are not unambiguously determinable.

On the basis of the above considerations, in the following paragraphs we will analyze whether the orientation of one plagioclase with a given anorthite content can be unambiguously determined using U-stage method (Fig. 2).

(a) Within the ranges of An_{35-70} and An_{85-100}, an unambiguous, complete determination of the plagioclase crystallographic orientation requires orientation information from only a set of twin planes (either albite or pericline) or a set of cleavages [either (010) or (001)] in addition to the orientation of the three optical directions (Figs. 1 and 2). This feature may facilitate the LPO measurements of plagioclase in high temperature mafic mylonites deformed under upper amphibolite and granulite facies conditions where most plagioclase composition ranges from An_{35} to An_{70} (Smith & Brown 1988).

(b) Crystallographic orientation of plagioclase An_{75-85} may not be unambiguously determined using one or two sets of cleavages because in this compositional range it is impossible to distinguish between (100) and (001) cleavages on the basis of their relative orientation to the three optical directions (Jensen & Starkey 1985, Kruhl 1987b). The migration curves for albite and pericline twins are symmetric with respect to the optical directions (Fig. 1), making the determination of the crystallographic orientation ambiguous if identity of the twins is unknown. Therefore, identification of twin laws using the independent optical methods presented in Roubault *et al.* (1982), will allow the determination of the crystallographic orientation of all grains which contain only one set of twins (Seront *et al.* 1993).

(c) For anorthite contents $\leq An_{35}$, measuring only the (010) cleavage or the compositional plane of albite twin is not enough to permit unambiguous determination of the plagioclase orientation (Fig. 1). This is because more than one crystallographic orientation out of four possible orientations can fit the angular constraints for these plagioclases. For the same reason, measuring one set of (001) cleavages does not allow the orientation of plagioclase An_{15-30} to be determined nor will measuring the pericline twin plane alone allow one to determine the crystallographic orientation of plagioclase An_{10-25}. In a worse situation, within the compositional range of An_{10-30}, complete LPOs of plagioclase cannot be determined unambiguously even if the orientation of two sets of twin planes or two sets of cleavages as well as the axes of optical indicatrix have been measured (Fig. 1). Point (c), coupled with the usual low twin frequency in albite and oligoclase explains why previous authors (e.g. Shelley 1977, 1979, 1989, Ji & Mainprice 1988, White 1990, Kruhl 1993), were obliged to use optical indicatrix orientation to infer indirectly the crystallographic orientation of these plagioclases.

Dependence of the LPO determination on orientation of thin sections

The second problem is derived from a fact that only grains with visible twinning or cleavage can be used for LPO determination. Because the degree of rotation possible with the U-stage is limited to 45°, it is impossible to measure the orientation of twin or cleavage planes which make angles lower than 45° with respect to the thin section. The section is generally cut parallel to the XZ, XY or XY plane, where X is parallel to the stretching lineation, Z is normal to the foliation, and Y is normal to the lineation and located on the foliation. The number of measurable grains in a given section depends on the pattern and intensity of LPO. For example, if (010) planes are strongly oriented parallel or subparallel to the foliation (XY-plane), one would expect a high frequency of visible (010) planes as indicated by cleavage or compositional plane of albite, albite-Carlsbad and Carlsbad twins on the XZ section. If such a frequency is higher than 90% [e.g. in sample BN12 of Ji & Mainprice (1988) measurable (010) plane frequency is as high as 92% in the XZ section], the measured LPO can be considered to be representative of the bulk fabric of the sample.

However, in most cases, the fraction of measurable grains is much less than this (Table 1) in any given section, and hence the measured LPO (e.g. Suwa 1979, Wenk *et a.*. 1986, Olesen 1987, Ague *et al.* 1990) may not be representative for the bulk rock. In order to overcome such difficulties related to the measurement of crystallographic planes by U-stage, Kruhl (1987) proposed to simply sum all measurements from three orthogonal sections. This method has been applied to plagioclase LPO studies by many authors (e.g. Kruhl 1987a, Benn & Allard 1989, Siegesmund & Kruhl 1991, Barruol 1993, Seront *et al.* 1993). However, it should be pointed out that such an integrated fabric is not necessarily

Table 1. The frequency percentages of planar elements (twin planes or cleavages) in plagioclase in an anorthosite mylonite (sample 917) from the Morin ductile shear zone within the Canadian Grenville Tectonic Province (Quebec, Canada). In a given area of about 6 mm^2, 222 and 248 grains were measured on the thin sections parallel to XZ-and YZ-planes, respectively

	Observation plane	
	XZ-section	YZ-section
	Frequency	Frequency
Grains with two sets of twins or cleavages	57/222 = 25.7%	42/248 = 16.9%
Grains with only albite twin or (010) cleavages	95/222 = 42.8%	109/248 = 44.0%
Grains with only pericline twin or (001) cleavages	22/222 = 9.9%	27/248 = 10.9%
Grains without twins or cleavages	48/222 = 21.6%	70/248 = 28.2%
Grains with albite twins or (010) cleavages	152/222 = 68.5%	151/248 = 60.9%
Grains with pericline twins or (001) cleavages	79/222 = 35.6%	69/248 = 27.8%
Measured area	6 mm^2	6 mm^2

representative of the LPO of the bulk rock. As shown in Figs. 3(a)–(c), domains B, D and F represent the planar-element-unmeasurable areas, respectively, on the XZ, XY and YZ sections, due to the maximum possible inclination of the U-stage of 45°. The diameter of these unmeasurable circles is 90°. In Fig. 3(d), grains for which the pole to a given crystallographic plane [e.g. pole to (010)] is located in region G are counted twice, while the grains for which the pole to the crystallographic plane is located in domain H (12.1% of the hemispherical area) are counted three times in the compiling process. This means that grains plotting in region H are artificially overestimated whereas grains plotting in domain G are underestimated.

Some authors (Wenk *et al.* 1986, Ji & Mainprice 1988, Benn & Allard 1989, Ague *et al.* 1990) used only the grains showing two sets of cleavages {(010) and (001)} or

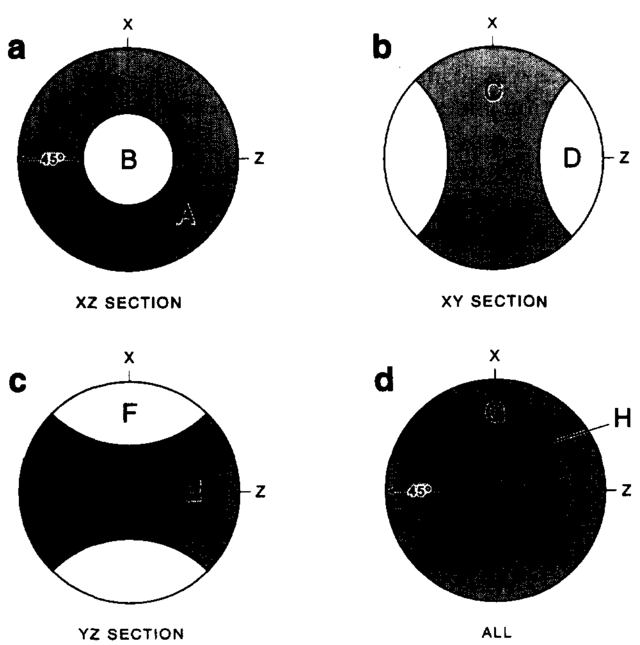

Fig. 3. Distribution of planar-element-unmeasurable domains (blank) on the XZ (a), XY (b) and YZ (c) sections due to the maximum inclination of the U-stage of 45°. The unmeasurable domain is about 29.3% of the total hemispherical area. Diagram (d) is formed by simply accumulating (a), (b) and (c). In so doing, the concentration of the plane poles located in domain G is underestimated and the concentration of those located in domain H is overestimated. Domain H is about 12.1% of the total hemispherical area.

twin planes (albite and pericline) for the measurements of plagioclase LPO. The LPO measured by this method, however, represents a selective, sub-fabric that is not necessarily representative of the bulk fabric. The reason is not difficult to find. As the intersection between (010) and (001) planes is the [100] direction, one can, using this method, measure only the grains whose [100] direction is located in domains B, D and F (Figs. 3a–c), respectively, in the XZ, XY and YZ sections. Even though all the measurements from these three sections are summed (B+D+F), the grains whose [100] direction is oriented in four triangular regions (domain H in Fig. 3d) are completely omitted. Yet not all grains possess at the same time two sets of twins or cleavages (Table 1, also see Jensen & Starkey 1985).

In order to measure the LPO of plagioclase in a statistically correct manner, we propose the use of any two of the three orthogonal sections. The present method using two rather than three sections also results in saving 1/3 of the time with respect to Kruhl's method. Our method is shown schematically in Fig. 4. The reasoning in this method is that the grains unfavorable for measuring the planar element [e.g. (010) plane] in a given section will become measurable in any one of the two other orthogonal sections (see Appendix). For instance, the orientation of the grains whose (010) planes cannot be measured in the domain (d) on the XZ section can be statistically represented by the orientation of the grains whose (010) planes can be measured either from domain (h) on the YZ section or from domain (1) on the XY section (Fig. 4). A composite fabric diagram can be obtained by compiling the measurements from domain (h) or (l) with those from domains (a+b+c) in the XZ section. This method causes neither overlapping nor omission of orientation domains. Unfortunately, the method does not eliminate the problems with plagioclase more sodic than An_{35}.

APPLICATION

Our method is being applied to a systematic study of plagioclase LPOs in a kilometer-wide mylonite zone of the Morin Anorthosite Massif, Grenville Province,

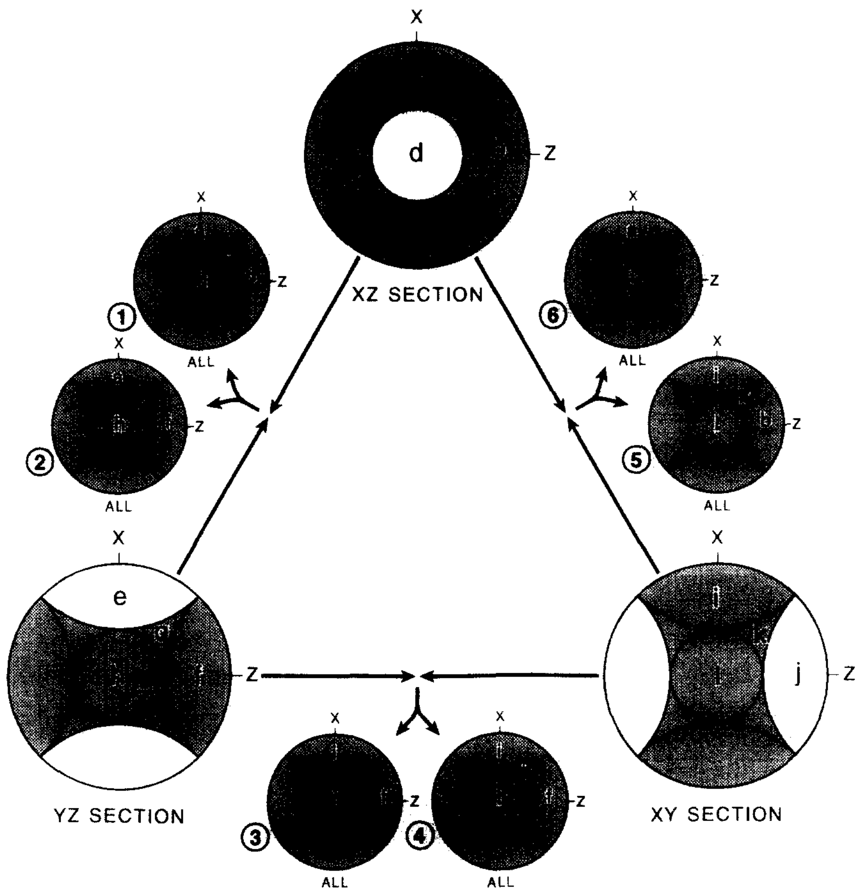

Fig. 4. Summary diagram showing how to obtain a plagioclase LPO by bringing together all the orientation data measured on any two orthogonal sections. The planar-element-unmeasurable domains (d, e and j on the XZ, YZ and XY sections, respectively) are blank. See text for the explanations in detail.

Québec (X. Zhao *et al.* in preparation). This massif is the core of a plutonic complex (Martignole & Schrijver 1970) emplaced around 1155 Ma (Doig 1991) in high-grade metamorphic rocks of the allochthonous monocyclic belt of the Grenville Province (Rivers *et al.* 1989). The dextral strike-slip ductile shear took place in the eastern part of the massif along with its country rocks, under granulite facies conditions, around 1020 Ma (Martignole & Friedman 1992). Anorthosite and norite involved in this ductile shear zone are highly strained with γ-values up to 10 and characterized by a prominent mylonitic foliation and stretching lineations defined by elongated pyroxene porphyroclasts.

Sample 917 is a typical anorthosite mylonite in the Morin ductile shear zone. It consists of about 4% orthopyroxene, 1% clinopyroxene and 95% plagioclase whose compositions range from An_{45} to An_{55}, with an average composition of An_{50}. The foliation within the rock is parallel to the compositional layers with varying pyroxene contents. Although plagioclase (relict) ribbons are occasionally observed, most plagioclase (recrystallized) grains are weakly elongated, with aspect ratios less than 2. Average grain size of the plagioclase crystals in the mylonite is 160 μm, which is much smaller than that (2 cm) in the weakly deformed anorthosite protolith outside the shear zone. Optical evidence for intracrystalline deformation such as lattice distortion, tapering deformation twins, undulatory extinction, subgrains and dynamic recrystallization are abundant in almost all grains. The grain boundaries are generally lobate. These microstructural features indicate that the mylonite was formed by grain size reduction by cyclic (dislocation glide) strain-induced dynamic recrystallization (e.g. Knipe 1989).

The LPO measurements were undertaken on two perpendicular sections: one parallel to XZ and another parallel to YZ sections. Both sections are perpendicular to the foliation and compositional layers within the sample. The XY section was not chosen because it is restricted to a single compositional layer which in general is not representative of the anisotropic bulk rock. An identical area (6 mm^2) was selected for the measurements on each thin section. Such an area contains 222 plagioclase grains with size greater than 30 μm in the XZ section, and 248 such grains in the YZ section (Table 1). The grains finer than 30 μm (thickness of the thin section) were too small to be measured. The plagioclase grains are twinned dominantly according to the albite law, commonly according to the pericline law, and with rare examples of the albite-Carlsbad and Carlsbad laws. These twin frequencies suggest a metamorphic or mechanical origin for the twins. Plagioclase grains with the albite-Carlsbad and Carlsbad twins are considered as relict grains from the igneous protolith (Suwa 1979). A similar situation has been reported by Onyeagocha & Seifert (1971) and Kehlenbeck (1972) in Adirondack

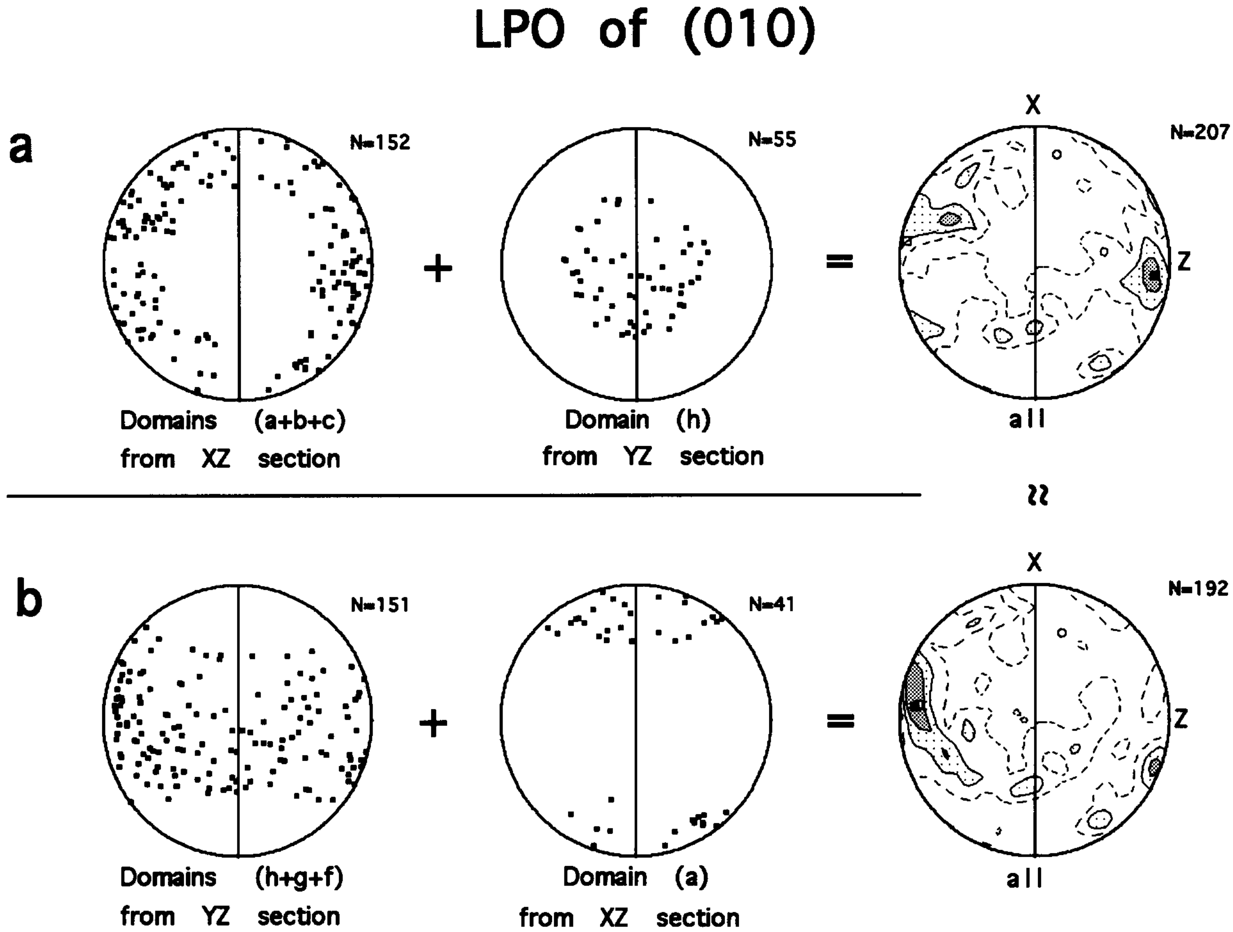

Fig. 5. Preferred orientation of plagioclase (010). Similar fabric patterns are obtained although two different methods were used for data treatment. Contours are 1%, 2% and 3% of the number of measurements per 1% of the hemispherical area. The contour interval >3% is shaded. N is the number of poles plotted. Equal-area, lower hemisphere projection. The XY plane (foliation) is the N–S solid line and is perpendicular to the page; the *X* direction (lineation) is N–S. The black and open squares as well as the open circle indicate the maximum density, the calculated best fabric axis and the pole to the best fabric plane (Bouchez *et al.* 1971).

anorthosite in which the albite law (74%) and the pericline law (23%) predominate in the recrystallized matrix with minor amounts of other laws only in the porphyroclasts. The frequency percentage of plagioclase grains favorably oriented for measurement of the (010) plane [the contact plane for albite, albite-Carlsbad and Carlsbad twins or (010) cleavage] to permit the necessary crystallographic constructions was 68.5% in the XZ plane and 60.9% in the YZ plane (Table 1). Obviously, neither the fabric measured from the XZ section nor that from the YZ section alone can be representative of the LPO of the bulk rock.

There are two ways to obtain a composite (010) fabric diagram (Fig. 5). Figure 5(a) is drawn by combining all orientation data of (010) measured on the XZ section and those measured from domain (h) (Fig. 4) on the YZ section while Fig. 5(b) is drawn by bringing together all orientation data of (010) measured on the YZ section and those from domain (a) on the XZ section. The composite (010) fabric diagrams shown in Fig. 5(a) and in Fig. 5(b) are very similar regardless of some minor differences. The differences come from the fact that what we measured on different sections are actually different grains rather than the same grains. The similarity between the skeletons of these two composite fabric diagrams confirms a stability of the measuring method. Statistically, it is reasonable to postulate that the results are independent of the methods used for making the composite fabric diagram.

Based on the orientation data of (010) shown in Fig. 5(a) and those of the three optical axes (not shown here), we can determine the complete crystallographic orientation for about 93% of the plagioclase ($\sim An_{50}$) grains within the sample. Contoured fabric diagrams for 12 crystallographic planes and nine crystallographic directions are presented in Figs. 6 and 7, respectively. Positive and negative crystallographic axes (Wenk *et al.* 1986) have not been differentiated. Contouring of the diagrams was performed using an unpublished computer program written by D. Mainprice and J.-L. Bouchez, using a 1% counting circle. Inspection of Figs. 6 and 7 shows that the plagioclase LPO strength is intermediate in this sample. The crystallographic planes (010), $(01\bar{1})$, $(02\bar{1})$, $(1\bar{2}1)$ and $(03\bar{1})$ (using c = 1.4 nm) tend to be aligned parallel or subparallel to the foliation (XY-plane). In contrast, the poles to (100), (001), (110), (101), (111) and (120) tend to be located at high angles (>60°) with respect to the normal to the foliation (Z-direction). Fabrics of the crystallographic directions are relatively more complex. [001], [111] and [012] direc-

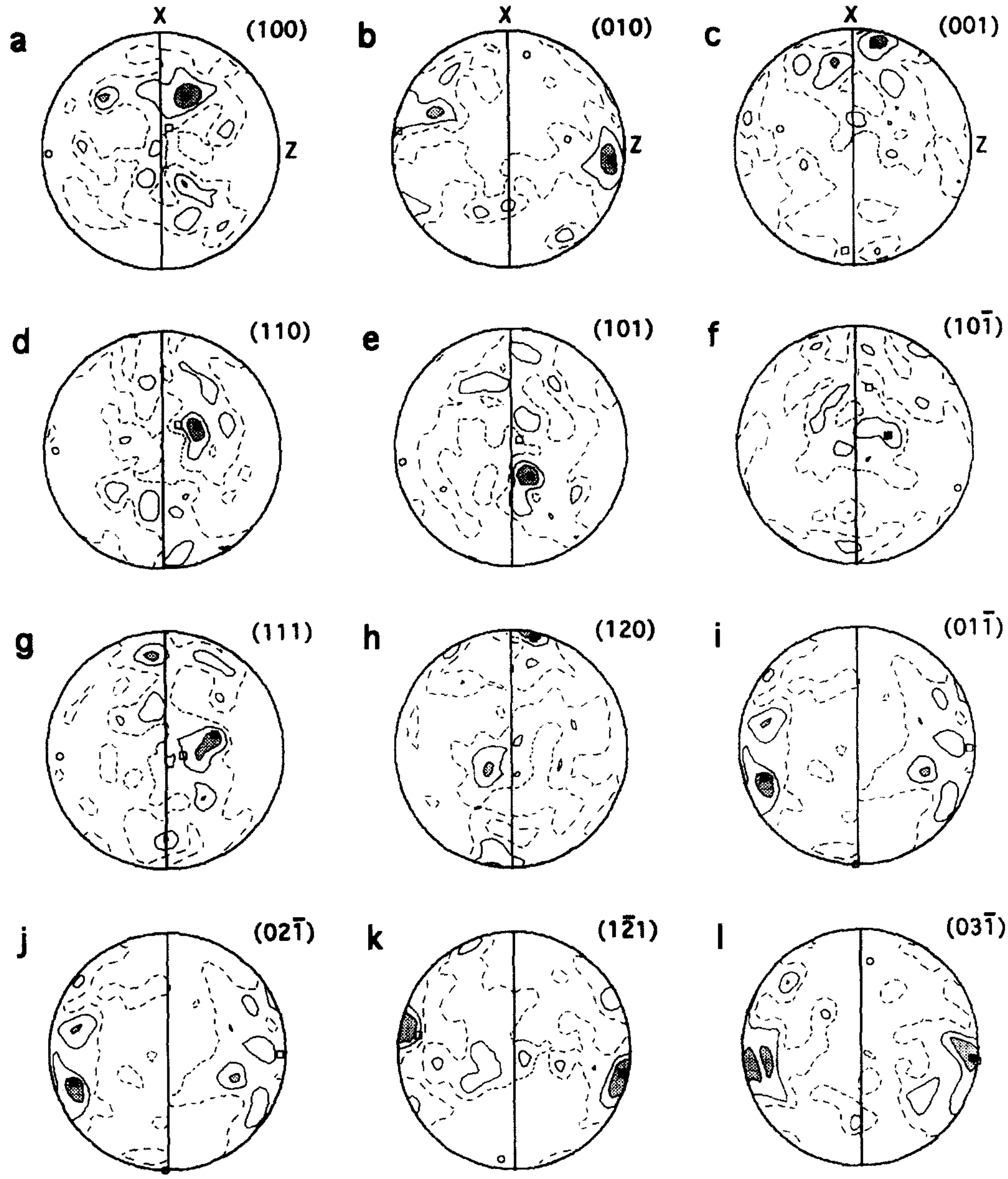

Fig. 6. Preferred orientation of 12 plagioclase (An_{50}) crystallographic planes in the anorthosite mylonite from the Morin shear zone. Two-hundred and seven grains representative of 93% volume of the sample were measured. Symbols as in Fig. 5.

tions appear to have their high concentrations at small angles to the extension lineation (X), and the [100] direction has a high concentration near the Y-direction.

From only LPO data without TEM constraints on dislocation substructures we hesitate to draw general conclusions about slip systems in plagioclase deformed in the granulite facies mylonites. In the present sample, if the LPO was formed by intracrystalline slip (Bouchez *et al.* 1983, Wenk & Christie 1991), (010)[001], (01$\bar{1}$)[111], (02$\bar{1}$)[012] and/or (1$\bar{2}$1)[012] may be the potential slip systems responsible for the fabric pattern. (010) and (1$\bar{2}$1) may be the most possible operative glide planes since their LPOs display a clear obliquity with respect to the extension lineation (X) and the normal to the foliation (Z), which indicates a dextral rotational movement. This shear sense agrees with that given by quartz *c*-axis fabrics (Ji & Martignole 1994) and field kinematic indicators such as asymmetrical extensional shear bands and winged porphyoclasts of pyroxene (Martignole 1992).

CONCLUSIONS

Previous methods used in measuring plagioclase LPOs by U-stage, published in the literature, are statistically incorrect to some extent, and the resulting LPOs must be considered with caution. Using the method presented here, we avoid most of the problems encountered by the existing methods (e.g. Wenk *et al.* 1986, Kruhl 1987a,b, Ji & Mainprice 1988, Ague *et al.* 1990, Barruol 1993). If the frequency of twinning is high, we are able to measure more than 90% of the grains. However, we have not been able to measure the orientation of untwinned plagioclase grains. The fraction of untwinned grains among the fine grained recrystallized

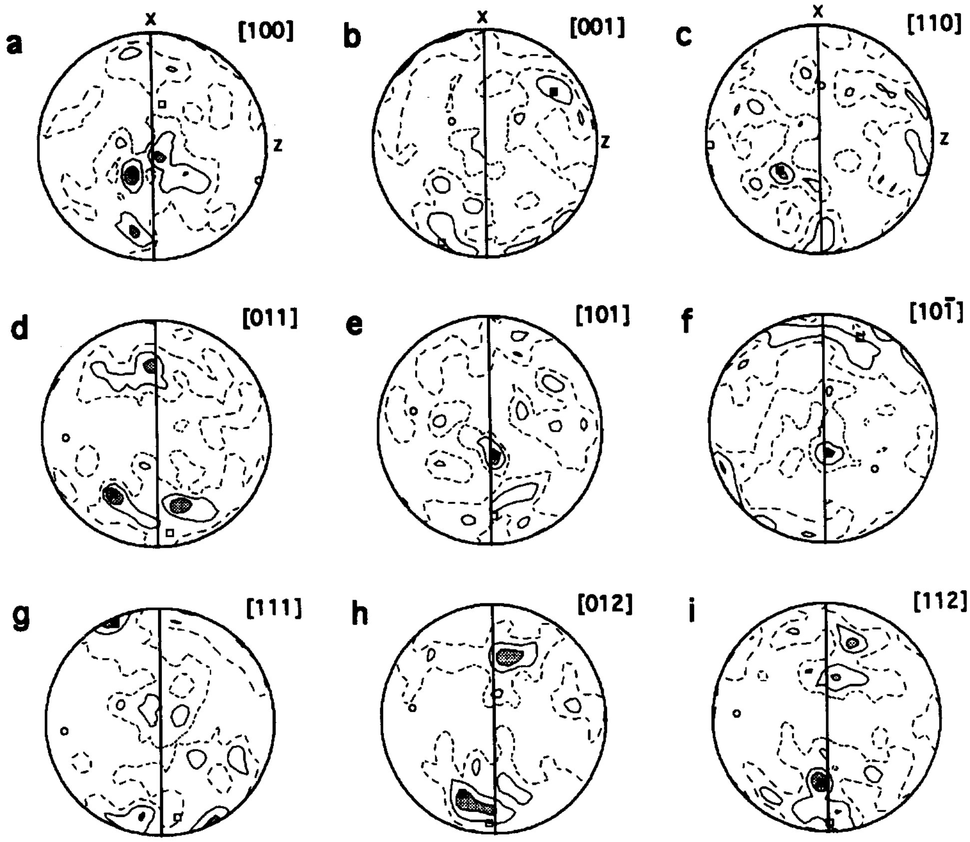

Fig. 7. Preferred orientation of nine plagioclase (An_{50}) crystallographic directions in the anorthosite mylonite from the Morin shear zone. Two-hundred and seven measurements. Symbols as in Fig. 5.

neograins may be high with respect to their porphyroclasts. Yet the complete crystallographic orientation of albite-rich plagioclase ($<An_{35}$) is almost impossible to determine unambiguously by the U-stage method. An X-ray method seems to be unsatisfactory in determining plagioclase LPO due to the large number of overlapping diffraction peaks (Lhote *et al.* 1969). Sophisticated neutron diffraction techniques with high resolution and position-sensitive detectors (Wenk *et al.* 1986, Wenk & Pannetier 1990), which enable the mathematical deconvolution of only a limited part of the spectrum, provide information about volume fractions of grains of specified lattice orientation but no information about grain size, shape morphology and spatial configuration. Computer-controlled transmission electron diffraction technique (Humphreys 1983) in which a diffraction pattern of the selected area, of typical diameter 10 μm, is obtained from a foil thin enough (of the order of 100 nm) to be transparent to the electron beam, is time consuming and difficult to apply for routine LPO analysis of relatively coarse grained rocks. Electron backscattered Kikuchi diffraction patterns with a standard scanning electron microscope (Dingley 1987, Adams *et al.* 1993) seem to be successful and not very time consuming for the LPO analyses of cubic metal materials. These techniques may be applied by geologists in LPO measurements of triclinic minerals such as plagioclase in the future.

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APPENDIX

In a Cartesian co-ordinate system (1, 2, 3; in the case, 1 is parallel to the stretching lineation (X), 2 is normal to the lineation and is located on the foliation (Y), and 3 is normal to the foliation (Z)), the normal (N) to a given plane P is defined by an angle (θ) between N and a reference plane and an angle (α) between N and a reference direction on the reference plane. θ_{ij}, represent, respectively, the angles between N and co-ordinate planes ij ($i = 1, 2, 3; j = 1, 2, 3; i < j$). α^i_{ij} represent, respectively, the angles between the directions i and the projection of N on planes ij ($i = 1, 2, 3; j = 1, 2, 3; i<j$). Because the degree of rotation possible with the U-stage is limited within an angle of ϕ (normally, $\phi = 45°$), plane P can be observed on planes ij only if $\theta_{ij} \leq \phi$. Direction cosines of **N** are thus given by

$$\left.\begin{aligned} \cos\beta_i &= \cos\theta_{ij}\cos\alpha^i_{ij} \\ \cos\beta_j &= \cos\theta_{ij}\sin\alpha^i_{ij} \\ \cos\beta_k &= \sin\theta_{ij} \end{aligned}\right\} \begin{aligned} &(i < j; i \neq k \neq j; i = 1, 2, 3; \\ &j = 1, 2, 3; k = 1, 2, 3) \end{aligned}$$

where β_i are the angles between N and axes i ($i = 1, 2, 3$), respectively. Since $\cos^2\beta_i + \cos^2\beta_j + \cos^2\beta_k = 1$ ($i \neq j \neq k; i = 1, 2, 3; j = 1, 2, 3; k = 1, 2, 3$) and $\phi = 45°$, any two of these three angles (β_i, $i = 1, 2, 3$) cannot be simultaneously less than 45°. In other words, any two of the three angles θ_{ij} of **N** with respect to the three co-ordinate planes ij ($i = 1, 2, 3; j = 1, 2, 3; i<j$) should not be simultaneously greater than 45°. Therefore, the grains unfavorable for measuring a given planar element on a given co-ordinate plane will become measurable on any one of the two other co-ordinate planes.