Journal of Structural Geology, Vol. 12, No. 8, pp. 1005 to 1011, 1990
Printed in Great Britain

0191-8141/90 $03.00+0.00

The behavior of shape preferred orientations in metamorphic rocks: amphiboles and jadeites from the Monte Mucrone area (Sesia-Lanzo zone, Italian Western Alps)

BENOIT ILDEFONSE,* JEAN-MARC LARDEAUX and JEAN-MICHEL CARON

U.A. 726, UCB Lyon I and ENS Lyon, 46 allée d'Italie, 69364 Lyon Cédex 07, France

(*Received* 20 *April* 1989; *accepted in revised form* 27 *March* 1990)

Abstract—In the eclogitic micaschists of the Monte Mucrone area (Sesia-Lanzo zone, Italian Western Alps), we have measured in detail the eclogitic lineation at several outcrops. We present observations at the markers scale, this scale allowing the whole range of progressive deformations to be described. Populations of glaucophanes and jadeites show different statistical features which must be, at least for a part, produced by the distinct mechanical behavior for these markers during the alpine history. The glaucophanes show a positive correlation between the intensity of preferred orientation and their aspect ratio, due to a mainly rigid behavior. The observed differences in shape and orientation of jadeites also show different behavior, related to different retromorphic overprints. We briefly discuss the implications of these observations on the significance of metamorphic lineations.

INTRODUCTION

POPULATIONS of elongate, more or less competent inclusions, defining an overall 'mineral lineation' or 'stretching lineation' within a tectonic foliation are widespread and on a regional scale are used as fundamental data for several recent kinematic syntheses (e.g. Shackelton & Ries 1984, Choukroune *et al.* 1986, Ratschbacher 1986, Burg *et al.* 1987). The understanding of their development, that is of the markers behavior, is therefore critical.

Any progressive deformation lies within the continuum between coaxial straining and rigid-body rotation (Fig. 1) (Ramberg 1975, McKenzie 1979, Means *et al.* 1980, De Paor 1983, Lister & Williams 1983, Ramsay & Huber 1983, Passchier 1986, 1988). Deformation may be partitioned between strain and rigid-body rotation at various scales, as a function of mechanical heterogeneity (McKenzie 1979, Means *et al.* 1980, Lister & Williams 1983, Passchier 1986). In the case of Shape Preferred Orientations (SPO), such heterogeneity may occur between the marker and the matrix. The way marker populations record the progressive strain undergone by the matrix depends on various terms, such as the 'viscosity contrast' between marker and matrix (e.g. Gay 1968), or the concentration of markers when they are rigid (Ildefonse 1987, Ildefonse & Fernandez 1988). This short contribution considers some data obtained from detailed observations on lineations in eclogitic micaschists of the Monte Mucrone area of the Sesia-Lanzo zone, Italian Western Alps (Fig. 2). Amphibole and jadeite SPO has been measured in detail in the foliation plane at four outcrops. Optical microscopic and statistical data from these samples demonstrate different mechanical behaviors for amphibole and jadeite. This

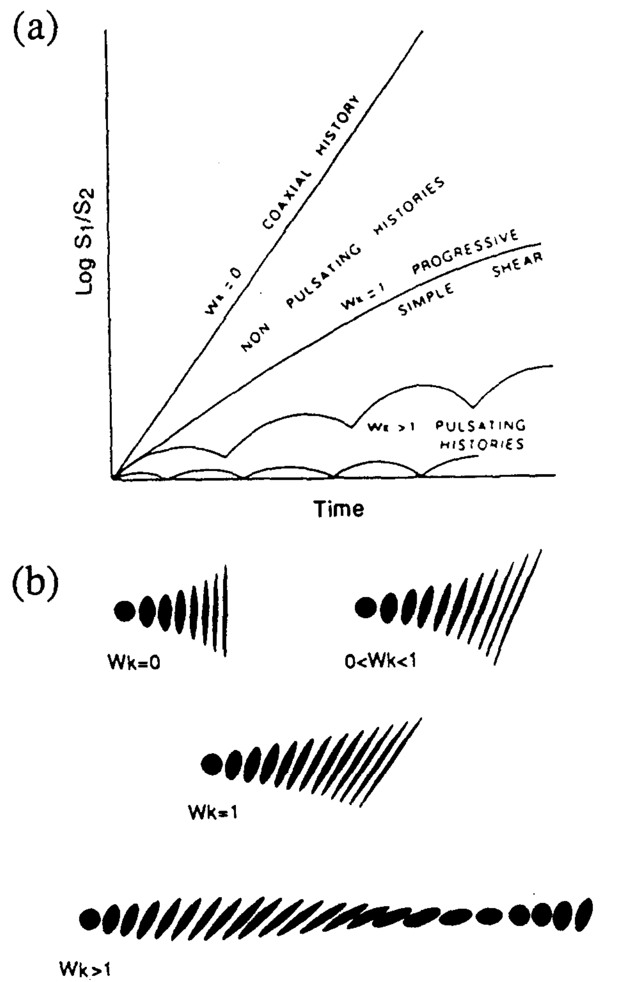

Fig. 1. Range of possible progressive deformation between coaxial deformation (Wk = 0) and rigid-body rotation (Wk = ∞). Wk is the kinematic vorticity number (ratio of the rotational to stretching components of the velocity field. See Means *et al.* 1980, Lister & Williams 1983, Passchier 1987). (a) Plot of logarithm of the ratio of the maximum to minimum principal stretches against time (Means *et al.* 1980). (b) Finite strain ellipse sequences for various Wk (after Ramsay & Huber 1983).

*Present address: Geologisches Institut, ETH-Zentrum, CH-8092 Zürich, Switzerland.

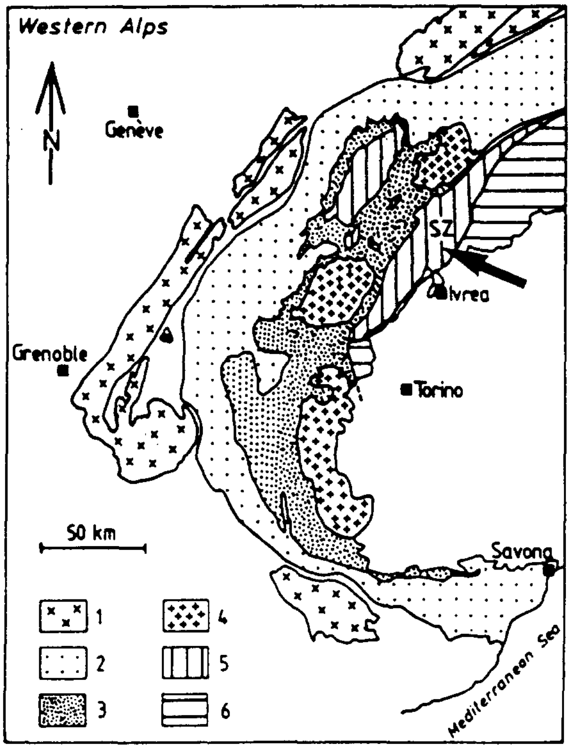

Fig. 2. Geographical and geological situation of the Monte Mucrone area (after Stöckert 1985). SZ = Sesia zone. 1 = Helvetic basement; 2 = Penninic realm, undifferentiated; 3 = Piemonte zone (Penninic); 4 = Monte Rosa, Gran Paradiso and Dora Maira nappes (Penninic basement); 5 = Austroalpine units; 6 = Southern Alpine basement. The Mucrone area is indicated by the arrow.

has to be considered in future work about the way eclogitic lineations reflect the structural history of the Monte Mucrone area. In a more general way, this paper demonstrates the necessity for marker-scale investigations when considering the significance of SPO in relation to the structural history of metamorphic rocks.

GEOLOGICAL CONTEXT

The studied lineation lies within the foliation plane of eclogitic micaschists in the Monte Mucrone area (Fig. 2). The Sesia-Lanzo zone represents a slice of continental crust subducted and then uplifted during the alpine orogeny (Dal Piaz *et al.* 1972, Hunziker 1974, Compagnoni *et al.* 1977). Various lithotypes such as micaschists, marbles, metagranites and metabasites were subjected to high-pressure and low-temperature (eclogite-facies) metamorphism (Compagnoni 1977, Reinsch 1979, Lardeaux 1981, Vuichard & Ballèvre 1985). An important characteristic of these metamorphic rocks is the good preservation of the high-pressure mineralogical assemblages, through the retrogressive *P–T* path followed during uplift of the Sesia-Lanzo zone (Lardeaux *et al.* 1982, Rubie 1984). Stünitz (1989) explains the preservation of high-pressure assemblages by a fluid deficiency during the retromorphic (greenschist-facies) overprint, resulting in incomplete reactions. At the scale of the Sesia zone, the heterogeneity of the greenschist-facies overprint is related to differences in initial lithologies (Stünitz 1989) and in the intensity of the late-alpine deformation (Spalla *et al.* in press). Four main generations of structures have been recognized (Gosso 1977, Gosso *et al.* 1979, 1982, Pognante *et al.* 1980, Passchier *et al.* 1981, Lardeaux *et al.* 1982, 1983, Spalla *et al.* 1983, Williams & Compagnoni 1983, Stünitz 1989). The first (D_1) deformation event gave rise to the development of a strong transposed foliation plane and isoclinal rootless folds under eclogitic conditions. This event is described as a composite one, with successive structures developing in a major non coaxial-strain zone related to subduction. The second (D_2) and third (D_3) events produced coaxial open folds and axial foliation planes. The structures of the second generation show only weak or no retrogressive transformation. A combination of eclogitic foliations (D_1 and D_2) leads to the main regional foliation plane in the eclogitic micaschists (Williams & Compagnoni 1983, Hy 1984). The retrogressive greenschist-facies overprint is mainly related to third generation structures. A fourth generation, represented by open kink folds with sub-vertical axial planes, is locally developed.

In the whole Sesia-Lanzo zone, the eclogitic linear fabric is generally strong, well preserved and trends about NW–SE (Vuichard 1986). Nevertheless, the last three events of deformation are represented by large-scale structures, so that the overall geometry is very complex, and early lineation and fold directions vary, sometimes considerably as in the Monte Mucrone area, because of redistribution by later deformation events (Compagnoni *et al.* 1977, Gosso *et al.* 1979, Passchier *et al.* 1981, Hy 1984, Ildefonse 1987). The lineation is in fact a composite fabric, defined by quartz rods, pressure shadows around garnets, and the shape preferred orientation of glaucophanes and jadeites. The latter, in the Monte Mucrone area, are defined by very large grains (at the scale of several centimeters), particularly suitable for data collection in the field. Both jadeite and glaucophane porphyroblasts are associated with the first generation of structures, but in detail the relative timing of growth is unclear. From several studies in different areas of the eclogitic micaschists, it is argued that glaucophane porphyroblasts are slightly younger than jadeite (Compagnoni & Maffeo 1973, Dal Piaz *et al.* 1973, Pognante *et al.* 1980), but glaucophane can also be older because the early alpine pre-eclogitic assemblage has been shown to be of blueschist facies (e.g. Reinsch 1979, Pognante *et al.* 1980, Lardeaux 1981). It is seen from all the studies that jadeite destabilization started between D_1 and D_2, whereas glaucophane remained stable during D_2 (e.g. Dal Piaz *et al.* 1973, Gosso 1977, Hy 1984).

RESULTS

The two-dimensional distribution of glaucophane and jadeite on the foliation plane has been systematically measured in four outcrops localized between Monte Camino and Monte Rosso, north of Monte Mucrone (Fig. 3). Outlines of markers were drawn on large sheets

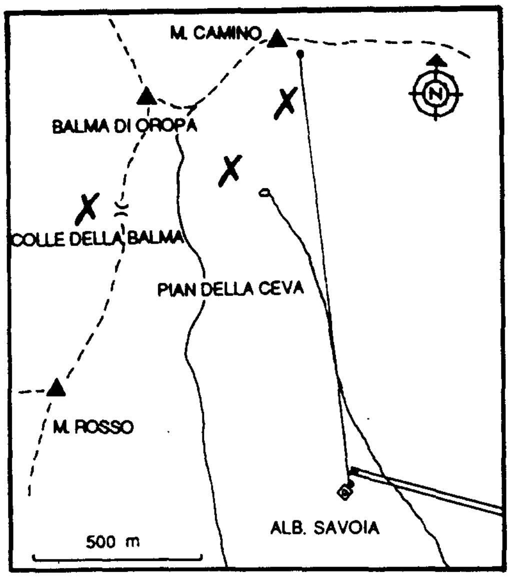

Fig. 3. Location of the studied outcrops (indicated by crosses). Cartographic maps: "Ivrea-Biela e bassa valle d'Aosta", 1:50,000, Istituto Geografico Centrale, Torino. "Lillianes", 1:25,000, Istituto Geografico Militare Italiano.

of tracing paper and these tracings subsequently digitized and analyzed in the laboratory. The collected data have been statistically analyzed to obtain aspect ratio and orientation frequency distributions for each measured population. The program also gives the fabric ellipse axial ratio (R_F) and orientation (α), using the eigenvalue method described in Harvey & Laxton (1980).

Glaucophane populations

The glaucophanes show a wide range of aspect ratios, and their preferred orientation is rather weak (Fig. 4) in contrast with, for instance, the good alignment of the quartz rods. When classifying the glaucophane populations with respect to aspect ratios, the higher this ratio, the stronger the preferred orientation (Fig. 5). The explanation for this must be found in the behavior of glaucophane in the flowing rock. Many theoretical and experimental works (e.g. Jeffery 1922, Gay 1966, Ghosh & Ramberg 1976, Freeman 1987) have demonstrated that the rotation of isolated rigid markers, in a given flow regime, is a function of their aspect ratio (Fig. 6), and the intensity and the orientation of fabrics defined by rigid markers must, therefore, also depend on the aspect ratio of the markers (e.g. Willis 1977, Fernandez 1984, 1987). Glaucophanes do not show any optical features of intragranular deformation, except for very minor undulose extinction. Pressure shadows develop around some of them and very frequently, they are boudinaged, the microfractures being sealed by quartz, phengites and retrogressive amphiboles. Thus, both optical and statistical observations indicate that the glaucophane acted as a rigid marker during at least the retrogressive part of the alpine history.

Jadeite populations

The two measured jadeite populations show very different patterns (Fig. 7). The squat porphyroblasts (A86-Hj) are unretrogressed jadeites. They may be affected by both intracrystalline strain (undulose extinction, subgrains) and microfractures, but Hy (1984) reported that fresh jadeites are rarely strained in the Mucrone area. Most commonly, jadeite porphyroblasts are replaced by albite to a great extent. This is the case for the elongate porphyroblasts defining the population A86-J. The elongate jadeite was thus stretched during

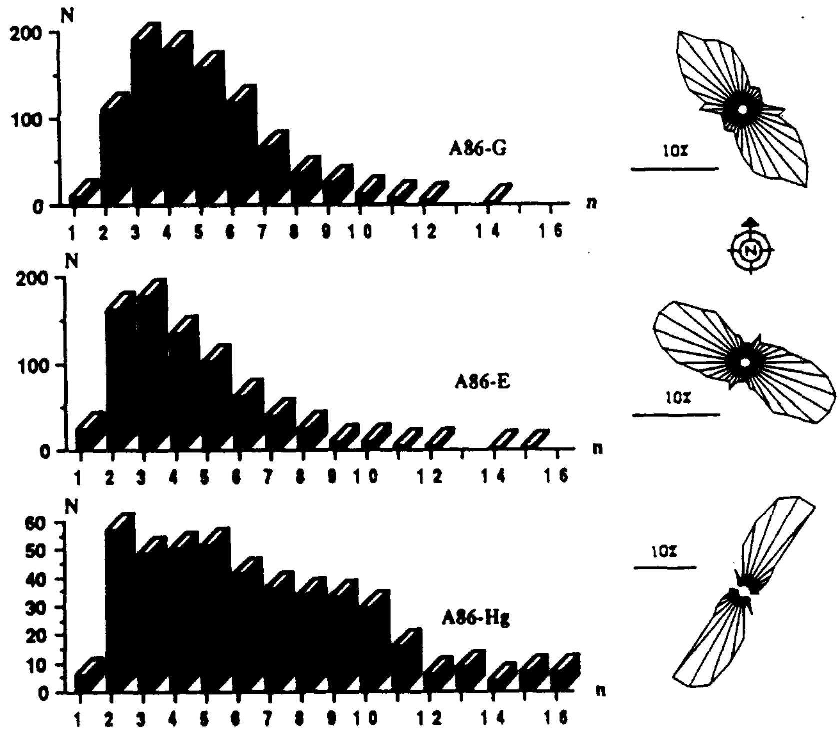

Fig. 4. Orientation frequency (roses) and aspect ratio (histograms) distributions for the glaucophane populations. A86-G:920 measures, A86-E:762 measures, A86-HG:442 measures. n = aspect ratio, N = number of markers.

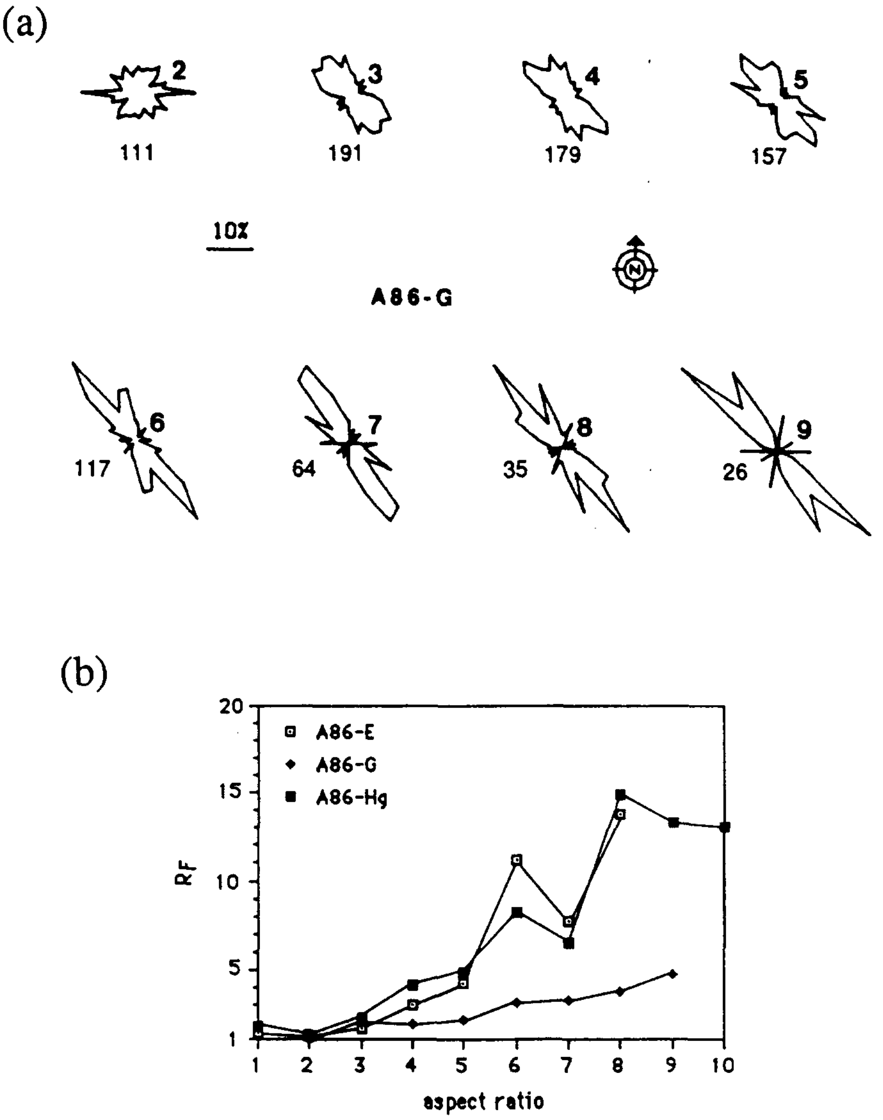

Fig. 5. Increase of the SPO intensity with the axial ratio in glaucophane populations. (a) Roses drawn for A86-G subfabrics corresponding to each value of aspect ratio (±0.5) from 2 to 9. The number of markers is indicated for each rose. (b) Plot of the subfabric ellipses axial ratios against the glaucophanes aspect ratio.

the retrogressive deformation and acted as a rather passive marker compared to glaucophane, although it sometimes shows significant competency contrast with the matrix (pinch-and-swell structures). In fact, there is no evident correlation between the aspect ratio and fabric intensity (Fig. 8).

The difference in shape and orientation between the two measured jadeite populations can be related to the differing degree of retromorphic overprint. The occurrence of both fresh and retrogressed jadeite in the same unit is probably due to different reaction kinetics and/or fluid activity (see geological context above).

DISCUSSION

If populations of minerals with different time-behaviors can be described in a common time and space reference frame, like feldspars and their recrystallization tails (Passchier 1987) or quartz *c*-axis fabrics and rotated garnets (Vissers 1989), analyzing their relationships has been shown to provide useful information about the kinematics of progressive deformation. Nevertheless, care should be taken in the present case when comparing glaucophane and jadeite SPO, because of lack of information about the initial distributions and relative ages. Indeed, as pointed out above, it seems likely that the two minerals did not appear at the same time in the eclogitic assemblages. It is also clear that the time-behavior, at least for the retrogressed jadeite, has changed during the deformation history.

Because of the complex relations between rigid markers and the deformation history (Fig. 6), the SPO cannot be simply related to the finite strain of the matrix. In the case of intermediate behavior between rigid and passive markers, this relation is particularly complex; the velocity field in the marker may be of the pulsating type (see Fig. 1) when the strain in the matrix is non-coaxial (e.g. Gay 1968, Bilby *et al.* 1976, Lisle *et al.* 1983). Mechanical interactions between competent markers must also be considered in natural SPO. As shown experimentally, this phenomenon can strongly

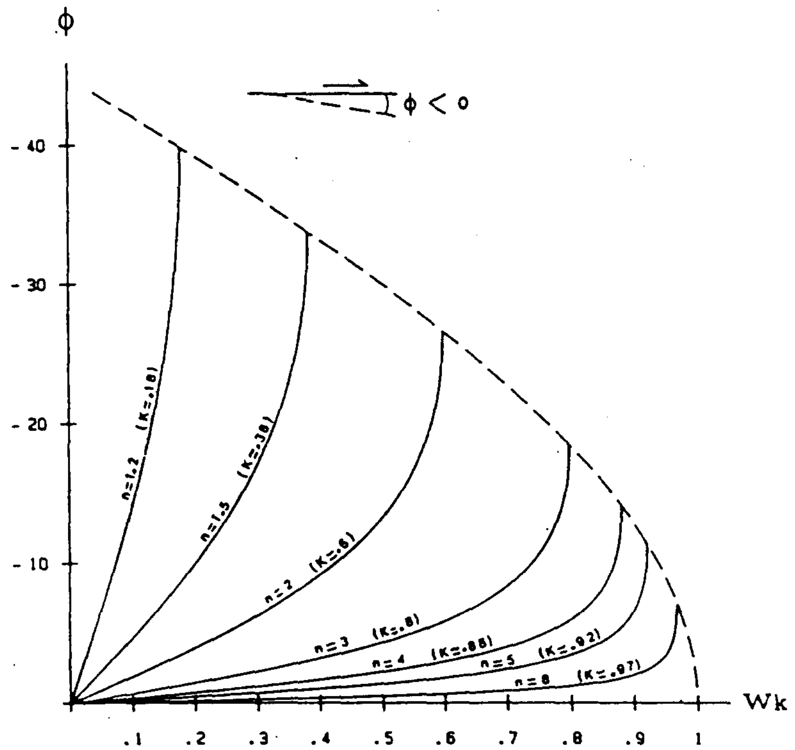

Fig. 6. Stable and metastable positions (ϕ) of rigid markers as a function of their aspect ratio (n) and of vorticity number (Wk) (Ildefonse 1987, from the equations given in Ghosh & Ramberg 1976). Continuous curves are for stable positions and dashed one is for metastable positions. When the vorticity is greater than the shape factor ($K = (n^2 - 1)/(n^2 + 1)$), markers cannot reach stable positions and undergo periodical rotation.

reduce the intensity and change the orientation of the fabric (Ildefonse 1987, Ildefonse & Fernandez 1988). So, SPO defined by competent markers are most useful as kinematic indicators (e.g. Fernandez 1984, Passchier 1987, Blumenfeld & Bouchez 1988). Nevertheless, theoretical studies show that very elongate rigid markers have a behavior very close to the one of passive markers; for aspect ratios >10, the rotation of a rigid marker is almost identical to that of a passive marker line. It was pointed out in Ildefonse & Fernandez (1988) that, for likely geological strain (axial ratios ranging between 1 and 25, Pfiffner & Ramsay 1982), the behavior of rigid markers SPO may be approximated to the one of passive markers SPO when their aspect ratio is >5. This is probably illustrated by the fact that in two of the measured glaucophane populations, the subfabric intensity increases very significantly for aspect ratios >5 (Fig. 5). Moreover, the R_F values are then comparable to the ones obtained for the elongate jadeite population (Fig. 7).

CONCLUSION

In the Monte Mucrone area, the eclogitic lineation is a composite fabric. The glaucophane and jadeite SPO

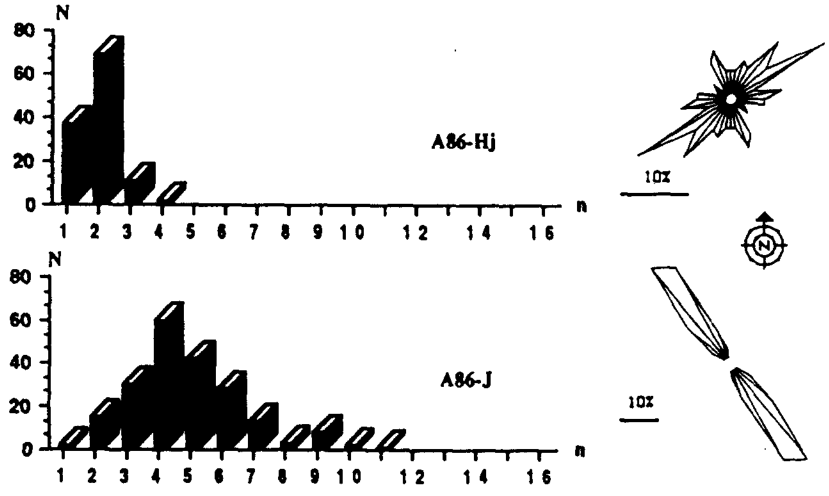

Fig. 7. Orientation frequency (roses) and aspect ratio (histograms) distributions for the jadeite populations. A86-Hj: 119 measures, A86-J: 204 measures. n = aspect ratio, N = number of markers.

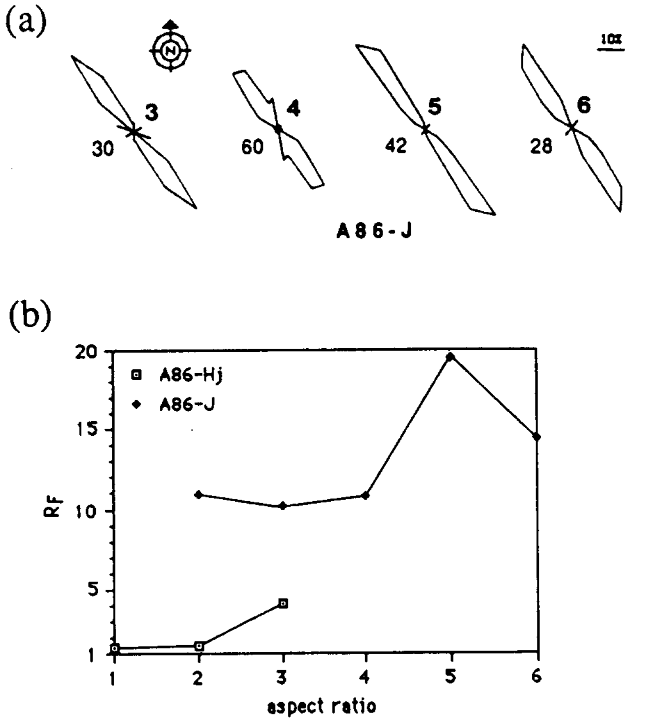

Fig. 8. Subfabrics of jadeite populations. (a) Roses drawn for A86-J subfabrics corresponding to each value of aspect ratio (±0.5) from 3 to 6. The number of markers is indicated for each rose. (b) Plot of the subfabric ellipses axial ratios against the jadeites aspect ratio.

show different statistical features which result partly from the different mechanical behavior of the porphyroblasts. The two populations cannot be quantitatively compared because there are too many unknown parameters (relative timing of appearance, initial distribution, time-changing behavior). Nevertheless, the present measurements and observations demonstrate that in metamorphic rocks, the mechanical behavior of minerals has a major influence on the SPO developed during progressive deformation. Depending on this behavior, metamorphic lineations may show various relationships, both in orientation and intensity, with bulk finite strain and motion. In the case of glaucophanes (rigid markers), the correlation between fabric intensity and markers aspect ratio is weaker when they are elongate. This confirms that, as previously shown by theory, the behavior of elongate rigid markers with aspect ratio >5 approaches that of passive markers and may be then used for finite strain or regional-scale kinematic analyses.

Acknowledgements—We thank the very careful and critical review of D. J. Sanderson, G. E. Lloyd and one anonymous reviewer, which considerably helped to improve this paper. N. S. Mancktelow is gratefully acknowledged for checking the English text.

REFERENCES

Bilby, B. A., Eshelby, J. D., Kolbuszewski, M. L., Kundu, A. K. & Gay, N. C. 1976. The change of shape of viscous ellipsoidal region embedded in a slowly deforming matrix having a different viscosity. A discussion. *Tectonophysics* **35**, 403–409.

Blumenfeld, P. & Bouchez, J.-L. 1988. Shear criteria in granite and migmatite deformed in the magmatic and solid states. *J. Struct. Geol.* **10**, 361–372.

Burg, J.-P., Balé, P., Brun, J.-P. & Girardeau, J. 1987. Stretching lineations and transport direction in the Ibero-Armorican arc during the Silurio-Devonian collision. *Geodin. Acta* **1**, 71–87.

Choukroune, P., Ballèvre, M., Cobbold, P., Gautier, Y., Merle, O. & Vuichard, J. P. 1986. Deformation and motion in the western alpine arc. *Tectonics* **5**, 215–226.

Compagnoni, R. 1977. The Sesia-Lanzo zone: high pressure–low temperature metamorphism in the austroalpine continental margin. *Rc. Soc. Ital. miner. Petrol.* **33**, 335–374.

Compagnoni, R., Dal Piaz, G. V., Hunziker, J. C., Gosso, G., Lombardo, B. & Williams, P. F. 1977. The Sesia-Lanzo zone, a slice of continental crust with alpine high pressure–low temperature assemblages in the Western Italian Alps. *Rc. Soc. Ital. miner. Petrol.* **33**, 335–374.

Compagnoni, R. & Maffeo, B. 1973. Jadeite-bearing metagranites s.l. and related rocks in the Mount Mucrone area (Sesia-Lanzo zone, Western Italian Alps). *Schweiz. miner. Petrogr. Mitt.* **53**, 355–378.

Dal Piaz, G. V., Hunziker, J. C. & Martinotti, G. 1972. La Zona Sesia-Lanzo e l'evoluzione tettonico-metamorfica delle Alpi nord-occidentali interne. *Mem. Soc. geol. Ital.* **11**, 433–466.

Dal Piaz, G. V., Hunziker, J. C. & Martinotti, G. 1973. Excursion to the Sesia zone of the Schweizerische Mineralogische und Petrographische Gesellschaft. *Schweiz. miner. Petrogr. Mitt.* **53**, 477–490.

De Paor, D. G. 1983. Orthographic analysis of geological structures—I. Deformation theory. *J. Struct. Geol.* **5**, 255–277.

Fernandez, A. 1984. Etude théorique et expérimentale du développement de la fabrique dans les roches magmatiques. Application à l'analyse structurale des granitoïdes. Unpublished thèse ès Sciences, University of Clermont-Ferrand.

Fernandez, A. 1987. Preferred orientation developed by rigid markers in two dimensional simple shear strain: a theoretical and experimental study. *Tectonophysics* **136**, 151–158.

Freeman, B. 1987. The behaviour of deformable ellipsoidal particles in three-dimensional shape slow flows: implications for geological strain analysis. *Tectonophysics* **132**, 297–309.

Gay, N. C. 1966. Orientation of mineral lineation along the flow direction in rocks: a discussion. *Tectonophysics* **3**, 559–564.

Gay, N. C. 1968. Pure shear and simple shear deformation of inhomogeneous viscous fluids—I. Theory. *Tectonophysics* **5**, 211–234.

Ghosh, S. K. & Ramberg, H. 1976. Reorientation of inclusions by combination of pure shear and simple shear. *Tectonophysics* **34**, 1–70.

Gosso, G. 1977. Metamorphic evolution and fold history in the eclogitic micaschists of the Gressoney Valley (Sesia-Lanzo zone, Western Alps). *Rc. Soc. Ital. miner. Petrol.* **33**, 389–407.

Gosso, G., Dal Piaz, G. V., Piovano, V. & Polino, R. 1979. High pressure emplacement of early nappes, post nappe deformation and structural levels (internal Northwestern Alps). *Mem. Inst. Geol. Univ. Padova* **32**, 5–15.

Gosso, G., Kienast, J. R., Lardeaux, J. M. & Lombardo, B. 1982. Replissement intense et transposition (en climat métamorphique de haute pression) des contacts tectoniques majeurs dans l'édifice supérieur des nappes alpines (zone Sesia-Lanzo). *C. r. Acad. Sci., Paris* **294**, 343–348.

Harvey, P. K. & Laxton, R. R. 1980. The estimation of finite strain from the orientation distribution of passively deformed linear markers; eigenvalue relationships. *Tectonophysics* **70**, 285–307.

Hunziker, J. C. 1974. Rb–Sr and K–Ar age determinations and the alpine tectonic history of the Western Alps. *Mem. geol. Miner. Univ. Padova* **31**.

Hy, C. 1984. Métamorphisme polyphasé et évolution tectonique dans la croûte continentale éclogitisée: les séries granitiques et pélitiques du Monte Mucrone (zone Sesia-Lanzo, Alpes italiennes). Unpublished thèse 3ème cycle, University of Paris.

Ildefonse, B. 1987. Les linéations et la déformation. Aspects naturels, théoriques et expérimentaux des orientations préférentielles de forme. Unpublished thèse de doctorat, University of Lyon 1.

Ildefonse, B. & Fernandez, A. 1988. Influence of the concentration of rigid markers in a viscous medium on the production of preferred orientations. An experimental contribution, 1. Non coaxial strain. In: *Geological Kinematics and Dynamics* (*In honor of the 70th Birthday of Hans Ramberg*). *Bull. geol. Instn Univ. Uppsala* **14**, 55–60.

Jeffery, G. B. 1922. The motion of ellipsoidal particles immersed in a viscous fluid. *Proc. R. Soc. Lond.* **102**, 161–179.

Lardeaux, J. M. 1981. Evolution tectonométamorphique de la zone nord du massif de Sesia-Lanzo (Alpes occidentales). Un exemple d'éclogitisation de la croûte continentale. Unpublished thèse 3ème cycle, University of Paris VI.

Lardeaux, J. M., Gosso, G., Kienast, J. R. & Lombardo, B. 1982. Relations entre le métamorphisme et la déformation dans la zone Sesia-Lanzo (Alpes occidentales) et le problème de l'éclogitisation de la croûte continentale. *Bull Soc. geol. Fr.* **26**, 793–800.

Lardeaux, J. M., Gosso, G., Kienast, J. R. & Lombardo, B. 1963. Chemical variations in phengitic micas of successive foliations within the eclogitic micaschists complex, Sesia-Lanzo zone (Italy, Western Alps). *Bull. Mineral.* **106**, 673–689.

Lisle, R. J., Rondeel, H. E., Doorn, D., Brugge, J. & Van de Gaag, P. 1983. Estimation of viscosity contrast and finite strain from deformed elliptical inclusions. *J. Struct. Geol.* **5**, 603–609.

Lister, G. S. & Williams, P. F. 1983. The partitioning of deformation in flowing rock masses. *Tectonophysics* **92**, 1–33.

McKenzie, D. 1979. Finite deformation during fluid flow. *Geophys. J. R. Astr. Soc.* **58**, 689–715.

Means, W. D., Hobbs, B. E., Lister, G. S. & Williams, P. F. 1980. Vorticity and non-coaxiality in progressive deformation. *J. Struct. Geol.* **2**, 371–378.

Passchier, C. W. 1986. Flow in natural shear zones. The consequences of spinning flow regimes. *Earth Planet. Sci. Lett.* **77**, 70–80.

Passchier, C. W. 1987. Stable positions of rigid objects in non-coaxial flow—a study in vorticity analysis. *J. Struct. Geol.* **9**, 679–690.

Passchier, C. W. 1988. The use of Mohr circles to describe non-coaxial progressive deformation. *Tectonophysics* **149**, 323–338.

Passchier, C. W., Urai, J. L., Van Loon, J. & Williams, P. F. 1981. Structural geology of the central Sesia-Lanzo zone. *Geol. en Mijnb.* **60**, 497–507.

Pfiffner, O. A. & Ramsay, J. G. 1982. Constraints on geological strain rates: arguments from finite strain states of naturally deformed rocks. *J. geophys. Res.* **87**, 311–321.

Pognante, U., Compagnoni, R. & Gosso, G. 1980. Micro-mesostructural relationships in the continental eclogitic rocks of the Sesia-Lanzo zone: a record of a subduction cycle. *Rc. Soc. Ital. miner. Petrol.* **36**, 169–186.

Ramberg, H. 1975. Particle paths, displacement and progressive strain applicable to rocks. *Tectonophysics* **28**, 1–37.

Ramsay, J. G. & Huber, M. I. 1983. *The Techniques of Modern Structural Geology, Volume 1: Strain Analysis.* Academic Press, London.

Ratschbacher, L. 1986. Kinematics of Austro-alpine cover nappes: changing translation path due to transpression. *Tectonophysics* **125**, 335–356.

Reinsch, D. 1979. Glaucophanites and eclogites from Val Chiusella, Sesia-Lanzo zone (Italian Alps). *Contr. Miner. Petrol.* **70**, 257–266.

Rubie, D. C. 1984. A Thermal-tectonic model for high-pressure metamorphism and deformation in the Sesia zone, Western Alps. *J. Geol.* **92**, 21–36.

Shackelton, R. M. & Ries, A. C. 1984. The relation between regionally consistent stretching lineations and plate motions. *J. Struct. Geol.* **6**, 111–117.

Spalla, M. I., De Maria, L., Gosso, G., Miletto, M. & Pognante, U. 1983. Deformazione e metamorfismo della zona Sesia-Lanzo meridionale al contatto con la falda piemontese e con il massicio di Lanzo, Alpi Occidentali. *Mem. Soc. geol. Ital.* **26**, 499–514.

Spalla, M. I., Lardeaux, J. M., Dal Piaz, G. V. & Gosso, G. In press. Métamorphisme et tectonique à la marge externe de la croûte Austro-Alpine: ré-examen des unités de la zone Sesia (Alpes Occidentales). *C. r. Acad. Sci. Paris.*

Stöckhert, B. 1985. Compositional control on the polymorphism ($2M_1$–3T) of phengitic white mica from high pressure parageneses of the Sesia zone (lower Aosta valley, Western Alps; Italy). *Contr. Miner. Petrol.* **89**, 52–58.

Stünitz, H. 1989. Partitioning of metamorphism and deformation in the boundary region of the "seconda zona Dioritico-Kinzigitica", Sesia zone, Western Alps. Unpublished Ph.D. thesis, ETH Zürich.

Vissers, R. L. M. 1989. Asymmetric quartz *c*-axis fabrics and flow vorticity: a study using rotated garnets. *J. Struct. Geol.* **11**, 231–244.

Vuichard, J. P. 1986. Cinématique éoalpine et alpine en zone Sesia-Lanzo (Alpes occidentales). *C. r. Acad. Sci., Paris* **303**, 1333–1338.

Vuichard, J. P. & Ballèvre, M. 1985. Garnet–chloritoid equilibria in eclogitic pelitic rocks from the Sesia zone (Western Alps): their bearing on phase relations in high pressure metapelites. *J. metamorph. Geol.* **6**, 135–157.

Williams, P. F. & Compagnoni, R. 1983. Deformation and metamorphism in the Bard area of the Sesia-Lanzo zone, Western Alps, during subduction and uplift. *J. metamorph. Geol.* **1**, 117–140.

Willis, D. G. 1977. A kinematic model of preferred orientation. *Bull. geol. Soc. Am.* **88**, 883–894.