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Preface

Recent developments and goals in texture research of geological materials

B. Leiss[a,*], K. Ullemeyer[a], K. Weber[a], H.G. Brokmeier[b], H.-J. Bunge[c], M. Drury[d], U. Faul[e], F. Fueten[a], A. Frischbutter[f], H. Klein[g], W. Kuhs[g], P. Launeau[h], G.E. Lloyd[i], D.J. Prior[j], Ch. Scheffzük[f], T. Weiss[a], K. Walther[f], H.-R. Wenk[k]

[a]*Institut für Geologie und Dynamik der Lithosphäre (IGDL), University of Göttingen, Goldschmidtstr. 3, 37077 Göttingen, Germany*
[b]*GKSS-Forschungszentrum, Max-Planck-Str., Geb. 03, 21502 Geesthacht, Germany*
[c]*Physical Metallurgy, Grosser Bruch 23, D-38078 Clausthal, Germany*
[d]*Geodynamics Research Institute, Faculty of Earth Sciences, Utrecht University, PO Box 80.021, 3508TA Utrecht, The Netherlands*
[e]*Research School of Earth Sciences, The Australian National University, Canberra, ACT 0200, Australia*
[f]*GeoForschungsZentrum (GFZ), Telegrafenberg, 14474 Potsdam, Germany*
[g]*Mineralogisch-Kristallographisches Institut, University of Göttingen, Goldschmidtstr. 3, 37077 Göttingen, Germany*
[h]*Laboratoire Planetologie et Geodynamique, Université de Nantes, 2 rue de la Houssiniere BP 92208, 44322 Nantes CEDEX 3, France*
[i]*School of Earth Sciences, The University, Leeds LS2 9JT, UK*
[j]*Department of Earth Sciences, University of Liverpool, Liverpool L69 3BX, UK*
[k]*Department of Geology and Geophysics, University of California, Berkeley, CA 94720, USA*

1. Introduction

A main objective of the conference on 'Textures and Physical Properties of Rocks' held at the University of Göttingen in October 1999 (Leiss et al., 1999; www.Rock-Textures.de) was the creation of a forum which comprises all aspects of texture and property analysis of rocks. As documented in the editorial of this Special Issue "Textures and Physical Properties of Rocks", the contributions to this Special Issue address a wide range of topics, however, not all of the conference topics could be included in this Special Issue. To fill this gap, this part of the preface presents summaries of most of the keynote talks and conference workshops.

2. Recent experimental and methodical developments

2.1. New experimental and mathematical methods in texture and property analysis (by H.-J. Bunge, Clausthal)

Texture analysis developed in several stages. The initial stage was fabric analysis by means of polarized light microscopy which gives in principle the most complete information about a polycrystalline aggregate, i.e. size, shape, orientation, and mutual arrangement of the constitutive crystallites. The method requires, however, great experimental effort (manually, grain-by-grain) and it does not work in cubic materials. The main application of this method is in transparent, optically uniaxial, materials such as quartzite where it supplies the distribution of *c*-axes of the crystallites (e.g. Sander, 1950).

The next step was the measurement of crystal direction distribution functions (pole figures) by polycrystal diffraction, mainly X-ray diffraction, but also neutron diffraction. This method was developed to a high degree of perfection for metals (e.g. Wassermann and Grewen, 1962). Its drawbacks are that it cannot distinguish a rotation of the crystallites about the normal direction of the reflecting lattice plane, it does not distinguish the location of the crystallites and it was restricted to simple crystal structures, e.g. cubic metals with non-overlapping diffraction peaks. The latter restriction has been overcome recently by the use of position-sensitive detectors, which allow the separation of overlapped peaks by mathematical deconvolution (e.g. Wcislak and Bunge, 1996).

Texture analysis took a great step forward by the calculation of the three-dimensional orientation distribution function (ODF) from two-dimensional direction distribution functions (pole-figures; e.g. Bunge, 1993). But even the ODF does not tell us all about the distribution in space of crystals with different orientations.

The most recent and most important step ahead was reached by the technique of automated crystal orientation mapping (ACOM) based on wide angle electron diffraction (Kikuchi patterns; Adams et al., 1992; Schwarzer, 1997). This method gives the complete *orientation–location function* $g(x)$, i.e. the 'orientation stereology', with high location as well as orientation resolution, high statistical relevance, and in reasonably short time. The method is

* Corresponding author.

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available for the scanning, as well as for the transmission electron microscope.

The properties of polycrystalline aggregates depend on the orientation stereology of the constitutive crystallites, i.e. on the 'orientation–location' function. This is due to *crystal anisotropy* and its *discontinuity* across the grain boundaries. Knowing only the ODF, only upper and lower bounds of polycrystal properties (Voigt–Reuss bounds) can be calculated. The usual practice is to average these bounds (known as the Hill-value). The Voigt–Reuss bounds may deviate considerably from each other (e.g. up to 25% in the case of elastic properties) and the 'Hill-value' is only a 'guess' inside this uncertainty margin. On the basis of the orientation stereology (using for example the *cluster model* of Kiewel and Fritsche, 1994), the exact property values can be calculated with (principally) no restriction of accuracy.

Besides the (static) materials properties also the physical texture-forming process must be studied ('dynamic' properties of materials). Both, properties as well as processes, play an important role in materials and earth sciences (e.g. Bunge, 1997). Both are to be understood quantitatively in terms of mathematical models (e.g. Raabe and Bunge, 1997). Mathematical models and quantitative experimental methods rely upon each other and must be developed simultaneously.

2.2. Determination of volume textures-advanced methods (by H. Klein and K. Ullemeyer, Göttingen, and H.-G. Brokmeier, Geesthacht)

Volume texture measurements with different radiations are commonly applied in order to determine bulk textures. Whereas the low absorption of neutrons in matter is a well-known property, knowledge of current measuring techniques at the neutron facilities (which are manifold) is not very widespread in geosciences and it seemed to be appropriate to give an overwiew. Furthermore, 'statistical' methods using conventional X-rays or synchrotron radiation are more and more applied in order to characterize local textures. Equipment for high resolution texture measurements has been recently developed and was outlined in the workshop.

It has been demonstrated by *Helmut Klein* that high location resolution X-ray texture measurements may be performed applying glass capillaries. The typical accessible sample volume is in the order of $0.1 \times 0.1 \times 0.01$ mm^3, and an *xyz* sample stage allows surface scans of the sample (Klein and Bunge, 1999). Area detectors may be applied to achieve better angular resolution in the pole figure. The angular resolution is typically 0.1° for both the pole figure angles and the Bragg angle Θ as well (Klein, 1994). Applications are due to the scanning of 2d texture variations ('texture fields') and texture investigations of line-rich samples, respectively.

Also hard synchrotron X-rays in connection with special texture measurement equipment and an area detector may be used for quantitative texture analyses (e.g. Heidelbach et al., 2000). A new instrument at HASYLAB BW5-Station has been described by *Leszek Wcislak* (Hamburg). The large penetration power of the high energy X-rays in matter combined with a powerful detecting technique opens new possibilities of structural analysis in polycrystalline materials. These measurements allow the quantitative determination of textures or internal strains. Because of high energy X-rays, a set of several high-resolution pole figures can be measured from bulk samples in a short exposure time.

An overview on neutron texture measurements using angular dispersive techniques has been given by *Heinz-Günter Brokmeier*. As an expansion of the classical single-detector technique (Brokmeier, 1994) position sensitive detectors (PSDs) in Θ may be applied to record diffraction patterns. First pole figure measurements with PSD have been performed already in 1982 (Bunge et al., 1982). The main advantages are that several pole figures can be measured simultaneously and peak fit procedures are applicable in order to deconvolute overlapping Bragg reflections. Alternatively, a PSD may be arranged such that several pole figure directions are measured simultaneously (Juul Jensen, 1992). Speeding up the measurements in this way allows the study of deformation processes ('kinetic texture measurements').

As outlined by *Klaus Ullemeyer*, neutron time-of-flight (TOF) diffraction offers several advantages for pole figure measurements. A 'white' neutron beam is analyzed with respect to the flight time of the neutrons, leading to diffraction patterns like PSDs. Neither the pole figure grid nor the peak shape are distorted in contrast to PSDs, however, a pulsed neutron source is required (Wenk, 1994; Walther et al., 1995). The ROTAX instrument at ISIS can be equipped with up to three PSDs to measure a number of sample directions simultaneously (Schäfer et al., 1995). The SKAT texture diffractometer at Dubna applies multiple detectors to cover the whole pole angle range at constant scattering angle ($2\Theta = 90°$). By this, all wavelength and Θ dependent corrections can be avoided (Ullemeyer et al., 1998). The TOF high pressure preferred orientation instrument at Los Alamos (still under construction) is designed as a multifunctional instrument and will be equipped with detectors covering a large area at various scattering angles Θ minimizing sample rotations for texture measurements (Bennett and Von Dreele, 1999).

2.3. 'EBSD technique and application in Geoscience' and 'Practice and problems of applying EBSP to rock forming minerals' (by D. Prior, Liverpool, and G. E. Lloyd, Leeds)

One of the principal ambitions of structural geologists has been to measure the full crystallographic orientation of all elements of a microstructure. The technology to achieve this, generally and easily, has now been realised (Venables and Harland, 1973; Dingley, 1984; Humphreys, 1999) via

electron backscattered diffraction (EBSD) in the scanning electron microscope (SEM). The orientations can be linked to microstructures by using either qualitative orientation contrast (OC) images (Lloyd, 1987) collected via forescatter (FSE) detectors (Prior et al., 1996) or quantitative maps constructed from grids of EBSD measurements (Juul Jensen and Schmidt, 1990; Adams et al., 1992). The principal advantage of EBSD over more established methods of textural and microstructural analysis is that it can be applied to any crystalline material, such that monomineralic quartz, calcite or olivine rocks will no longer dominate microstructural and textural studies. In addition, statistically significant data sets can be collected from large sample areas. This conference highlighted the potential of SEM/EBSD for geological investigations.

For EBSD analysis the sample is inclined at 60–75° to the incident electron beam (see Prior et al., 1999) and faces towards a scintillator screen imaged by a low-light TV camera. Scattering of the incident electrons by the sample crystal lattice satisfies the Bragg condition for diffraction simultaneously for all lattice planes, resulting in an electron backscatter pattern (EBSP). Indexing EBSPs (e.g. Schmidt and Olesen, 1989) provides the full crystallographic orientation and is facilitated by the availability of several commercial computer programs, which also permit control of beam and/or specimen stage movement for collection and indexing of EBSPs, and subsequent data presentation and manipulation. Thus, synthetic, crystallography-based microstructural images (see papers in this volume: Lloyd, 2000; Mauler et al., 2000; Neumann, 2000; Trimby et al., 2000) can be derived from a grid of EBSD data with step resolution of <1 μm. Alternatively, OC images (see papers in this volume: Bartozzi et al., 2000; Jiang et al., 2000) can be collected via FSE detectors placed under the scintillator. EBSD maps and/or OC images permit microstructures to be linked directly to both orientation and misorientation data (see papers in this volume: Lloyd, 2000; Neumann, 2000; Jiang et al., 2000; Trimby et al., 2000) obtained from EBSD.

Optimum analytical resolutions for EBSD are highly specimen-, sample-preparation- and instrument-dependent. Samples must be free of cold-worked deformation in the surface layers, whilst OC imaging and EBSD mapping also require samples to be flat (Lloyd 1987). Non-conducting materials suffer from specimen charging, which can be prevented by coating samples with a thin (<10 nm) layer of carbon, tilting samples to $>70°$, or via use of charge-dissipation devices. For the first two approaches, it is important to ensure a clear and efficient path to earth exists from the sample surface. Charging or charge avoidance procedures limit the spatial resolution in rocks to ~1 μm (Prior et al., 1999), compared with ~100 nm in metals (Humphreys et al., 1999). EBSD angular resolution is typically $\sim1°$, although the axes of low-angle misorientations are poorly defined (Prior, 1999). In metal samples, automated EBSD can achieve >10 EBSP indexes per second but for rocks the rate is 4–0.25 EBSP per second.

The meeting highlighted some aspects of hardware and working practice that facilitate use of SEM/EBSD. In general, compromises are necessary and maintenance of system flexibility, wherever possible, is advantageous. Measured crystallographic orientations should be defined with respect to a *triclinic* reference crystal of known orientation, the specimen tilt axis, tilt direction and surface normal. Fast, accurate and precise indexing is crucially dependent on good calibration (see Prior et al., 1999) of the EBSP pattern centre (PC), detector distance (DD) and working distance (WD). Reference crystals again provide the easiest calibration procedure. Correct indexing of EBSPs requires that all visible bands are simulated and that there are no bands in the simulation that are not observed. Thus, experience with manual indexing is essential before relying on automated computer indexing. Most established systems use a 70° tilt angle. Lower angles make physical interaction between specimen and scintillator more likely and increase specimen charging problems. At higher angles dynamic focussing and tilt correction become problematic. Pre-tilted sample holders where the sample cannot be moved in the plane of the surface should be avoided. The ability to move the scintillator is definitely advantageous as EBSPs with different DD can be used to locate the PC precisely. Although the minimum possible DD maximises EBSD signal and angular range for automatic indexing, slightly longer DDs enable FSE detectors to be mounted and allow OC and EBSD to be used in tandem. Further lengthening of DD can be used to improve angular resolution by decreasing the angular spread of EBSP. High beam currents (e.g. 1–50 nA) yield clear EBSP but involve large electron probe diameters, reduced spatial resolution and an increased tendency for samples to charge. The opposites apply to lower beam currents. Inevitably, the operator will need to increase beam current until useable EBSPs are obtained in a given acquisition time. Short WDs reduce probe size for a given probe current but also limit the size of samples that can be examined.

The meeting also highlighted several problems that might beset geological EBSD analysis. EBSP misindexing and/or non-indexing are both functions of pattern quality, although some minerals have misindexing problems even with high-quality patterns. Misindexing typically increases as crystal symmetry decreases. Only few minerals (e.g. calcite, garnet, halite and some cubic ore minerals) are indexed with $\sim99\%$ reliability. For other minerals (e.g. quartz) it may be possible to optimise software parameters to maximise success, or to eliminate unreliable analyses on the basis of some confidence index. Thus, any use of automated EBSD must include an assessment of the degree of misindexing and a discussion of their possible effects. Assessment of specimen charging, and the use of appropriate charge prevention techniques, is needed for each sample, based on sample characteristics and the density of sampling points required. Because any automated EBSD grid contains points that are not indexed (e.g. an indexing success rate of $\sim50\%$

is good for minerals), interrogation of geological data sets raises the problem of how to deal with the missing data. A common practice is to apply noise reduction routines that assign orientations to points with no data (e.g. based on orientations of neighbouring points). Although such practices make maps look microstructurally authentic, it is important to realise that they can introduce artefacts into both the maps and any crystal orientation database. Thus, the raw map should accompany publication of processed maps.

Perhaps the biggest challenges confronting SEM/EBSD are in learning how to optimise data collection and how to use the data. It is important to consider the most appropriate data collection method to address a given problem. An optical microscopy or OC image together with a few carefully selected EBSD analyses may provide as much scientific information as several hundred thousand automated measurements over a grid. Finally, whilst pole figure, inverse pole figure and orientation distribution function diagrams are well established in textural studies, the same cannot be said for misorientation data and distributions (Wheeler et al., 2000), nor parameters that link texture and microstructure. All such data can be readily derived via EBSD analysis and it is these aspects, rather than the EBSD technique itself, which will provide the new tools of microstructural analysis in the future.

2.4. Advanced methods for optical texture determinations (by F. Fueten, St. Catharines, and P. Launeau, Nantes)

Despite the availability of a variety of high-tech techniques, optical measurements retain their relevance today. Microscopes, thin sections as well as computers with video capture boards are readily available and familiar to most geologists. Many important geological questions can be addressed through a number of optical techniques.

Optical measurements that are aimed at determining some aspect of the orientation of the mineral lattice depend upon the symmetry of that lattice. Traditionally, these measurements have been carried out using a Universal Stage (e.g. Turner and Weiss, 1963) and the nature of possible measurements depends on the mineral. Arguably, optical texture measurements have most commonly been performed on quartz in which case optical methods do not yield a full description of the orientation of the structure but are restricted to measuring the orientation of the *c*-axis only.

Measuring *c*-axes with the universal stage (e.g. Turner and Weiss, 1963) is a time-consuming and laborious process. It does, however, allow the operator to keep track of a measured grain's position as well as its *c*-axis, conveying more information. This method, called AVA or Achsenverteilungsanalyse (Sander, 1950) maintains the link between orientation and position by means of a map of colour coded grains in which specific colours correspond to specific *c*-axis orientations.

The photometric method (Martinez, 1958; Price 1973, 1980) improves upon that manual universal stage technique and yields volume-weighted pole figures. While the direct link between position and *c*-axis of a grain is lost, the problem can be overcome by analyzing small areas (Price, 1978).

More recently, several computerized techniques (Beyna et al., 1990; Heilbronner and Pauli, 1993; Stöckhert and Duyster, 1999; Fueten and Goodchild, 2000) have been developed to determine quartz *c*-axis orientations using a set of images taken from thin sections placed on a flat microscope stage. While these methods vary in implementation and the amount of special equipment required, they all depend upon the same physical properties of uniaxial minerals. Light propagating at an angle to the *c*-axis is split into two vibration directions perpendicular to the wave normal. One vibration direction lies in the (001) plane and is perpendicular to the *c*-axis while the projection of the second vibration direction is parallel to the *c*-axis. Hence, for quartz, the maximum intensity or brightness occurs when the *c*-axis is at angles of 45° and 135° with respect to the lower polarizer vibration direction. The plunge of the *c*-axis is calculated from the brightness, which varies from dark for *c*-axis parallel to the light path to bright for *c*-axis perpendicular to the light path. Optical measurements from thin sections placed on flat stages alone can not completely resolve the plunge direction of the *c*-axis. The optical information obtained for a pixel with trend X is the same as for a pixel of trend $X + 180°$. Heilbronner and Pauli (1993) overcome this problem by tilting the section and taking a second measurement.

Computerized methods have several advantages. Lattice orientations are calculated for every pixel of the image and the continuity of the data makes it ideal for AVAs. Furthermore, the resultant captured images can be subjected to further image processing routine for segmentation (Heilbronner and Pauli, 1993; Goodchild and Fueten, 1998). When the grains are segmented and identified, their shape-preferred orientation (SPO) can be analyzed in various classes of grain sizes, shapes or aspect ratios (Launeau and Cruden, 1998). This analysis of sub-fabric within a population of minerals is particularly suitable to the study the flow patterns in magmas. One example of this type of measurement is the crystal size distribution (CSD), which may be performed on thin sections, on scanned images of polished slabs or even directly on the outcrop. CSDs are developed during solidification and recrystallisation of rocks and, hence, can directly address questions related to these processes. Most CSD studies have used very simple data acquisition techniques: direct measurement of intersection lengths in thin sections, blocks or even outcrops, followed by transformation to three-dimensional CSDs (Higgins, 2000). Such studies have addressed problems as diverse as the residence time, mixing and dynamics of magmas in chambers, the origin of megacrysts, and role of grain size coarsening in igneous rocks.

2.5. Diffraction methods for strain measurements on geological samples (by A. Frischbutter, K. Walther, and Ch. Scheffzük, Potsdam)

The last decades of geological research were characterized by the progressive incorporation of methods from engineering, chemistry, mathematics and physics. This process was based on rapidly developing experimental possibilities, which allow access to e.g. submicroscopic rock parameters. Also, neutron diffraction has reached an advanced stage of experimental maturity. The first intracrystalline strain measurements using TOF neutrons have been recently carried out on geological samples (Frischbutter, 1998). Strain measurements applying X-rays have not been very successful in geosciences due to the small accessible sample volume of X-rays. Reik (1976) is the only published example. However, such investigations are important also from the economical point of view. Stresses are generated within the earth's crust by different processes and the breaking down of accumulated stresses results in earthquakes. Earthquake generation is a complex process which is not yet well understood and fundamental research in the field of the stress/strain behaviour of rocks may help to improve our knowledge. Furthermore, the stress state in compacted sediments is of interest for oil and gas mining because it determines the mobility of fluids.

Numerous studies confirm that the large-scale generalization of stress data (derived from fault plane solutions, hydrofractures, breakouts) characterizes the stress state at the borders of large tectonic units (plates) quite well. However, such stress data do not necessarily fit the requirements of stress investigations at the local scale and certainly not at the micro scale. Intracrystalline strain measurements using (neutron) diffraction methods may significantly contribute to the evaluation local/small scale stresses since they offer a new dimension of observation. In situ experiments may be performed directly in the (neutron) beam, and the effect of load, relaxation, even at changing experimental conditions, can be investigated. Furthermore, residual stresses of first (macro) and second (micro) order can be accessed only by means of diffraction methods. Residual microstresses are preserved in any composite or polycrystalline solid after plastic deformation and depend upon the elastic and thermal properties of the constituents and on the lattice orientations. All these properties are usually different, e.g. residual microstresses never vanish.

Several aspects of stress/strain analyses were discussed in the workshop. *Miroslaw Vrana* (Rez, Czech Republic) presented strain investigations on sandstone undergoing uniaxial compression. Whereas *Vrana* applied angle dispersive neutron diffraction, *Christian Scheffzük* reported on the suitability of TOF neutrons in order to determine applied and residual strains and stresses. Both their results are compiled in Frischbutter et al. (2000). Accuracy and limitations of strain measurements on geological samples were addressed by *Lothar Pintschovius* (Karlsruhe). Since very small d- variations in the order of 10^{-5} are to be detected, the spectral resolution $\Delta d/d$ represents an important instrumental parameter of strain analyses (Pintschovius et al., 2000). Theoretical aspects of stress/strain analyses were discussed in three more contributions. The 'inverse' problem of stress analysis—determination of the single crystal elastic constants from polycrystalline measurements—was explained by *Siegfried Matthies* (Dresden). Such an inversion may be required if single crystals of appropriate size are not available in order to determine the elastic constants. A further problem is related to the determination of the strain-free lattice constant d_0. A number of solutions known from the literature was outlined by *Thomas Wieder* (Darmstadt), and a general solution was proposed (Wieder, 2000). *Kurt Walther* gave an overview on the influence of texture on the elastic and thermal properties of polycrystals.

3. Application of texture and property analysis on geological problems

3.1. Melt distributions and textures in rocks (by M. Drury, Utrecht, and U. Faul, Canberra)

Melts and more generally fluids can have important effects on the physical properties of rocks. How much the presence of melt modifies the properties of rocks depends on melt fraction and topology. At high temperature and in the absence of deformation the melt topology is controlled by grain boundary, phase boundary and melt-crystal interfacial energy. These interfacial energies determine the dihedral angle, the angle at the intersection of two crystal-melt interfaces and one grain or phase boundary. Early work on the olivine–basalt system assumed crystalline isotropy, with melt distributed in tubules along three-grain edges and dihedral angles from 20–50°. With this assumption the effect of melt on physical properties is controlled by only two parameters, the melt fraction and dihedral angle. Later studies have demonstrated that interfacial energies in the olivine–basalt system are anisotropic. An important consequence of this anisotropy is that melt distribution is influenced on the local scale by grain orientations and on the bulk scale by the texture (lattice preferred orientation). In the workshop on melt distributions and textures presentations concentrated on the characterization of complex melt distributions in textured materials and the effect of melt on physical properties.

Melt distributions in upper mantle rocks have been studied extensively with experiments on olivine plus melt. These studies were reviewed by *Martyn Drury* who showed that melt microstructures in this system can be roughly subdivided into four features (Cmíral et al., 1998; Faul 2000): nanometre-scale melt films (Drury and Fitz Gerald, 1996; De Kloe et al. 2000) and wider (10–500 nm) melt layers on two-grain boundaries (Faul et al., 1994; Hirth and

Kohlstedt, 1995); tubules at the intersection of three grains, and larger interserts, commonly surrounded by four or more grains. As a result of deformation the melt distribution may become stress controlled and is then aligned at an angle to the maximum compressive stress (at relatively high stresses and strain rates, Daines and Kohlstedt, 1997), or remain surface-energy controlled and become aligned co-parallel to the lattice preferred orientation.

A method to approximate the pore geometry in fluid-saturated partially molten rocks such that physical properties like seismic velocity or permeability can be calculated was described by *Ulrich Faul*. In olivine–basalt samples Faul showed that most of the melt is present in inclusions with small aspect ratios Faul et al. (1994). Low-aspect-ratio inclusions reduce seismic velocities much more efficiently than melt in a network of grain-edge tubes. Recent direct permeability measurements on texturally equilibrated calcite by Wark and Watson (1998) and new experiments by Zhang and Faul confirm that even for relatively uniform pore geometries the isotropic model overestimates the permeability at low porosities ($<1\%$). The permeability of calcite is expected to be higher than that of partially molten dunite due to the much more regular pore geometry and despite the larger average dihedral angel. Assessment of the permeability of complex melt distributions suggests that significant permeability is not attained until a percolation threshold is reached when the low-aspect-ratio inclusions connect at melt fractions of 2–3% (Faul, 1997).

Methods for modeling anisotropic seismic properties of partially molten rocks found at mid-ocean ridges were described by *David Mainprice* (Montpellier). Various effective medium methods (Mainprice, 1997) were discussed by Mainprice and these methods were applied to natural samples of oceanic lower crust and upper mantle from the Oman ophiolite. In harzburgites and dunites the former melt distribution is inferred from the distribution and shape of relict plagioclase and clinopyroxene (Jousselin and Mainprice, 1998). An average melt inclusion shape was defined using an autocorrelation function. Seismic velocities could then be calculated using the observed melt inclusion shapes, melt fraction, and melt and lattice preferred orientations. Similar methods were applied by *Benoît Ildefonse* (Montpellier) to gabbros from the crustal section of the Oman ophiolite (Lamoureux et al., 1999). Ildefonse showed that velocity variations with depth observed at fast spreading ridges could be accounted for by changes in the orientation of the anisotropic melt distribution and lattice preferred orientation while keeping the melt fraction constant.

3.2. Texture development, recrystallization and viscoplastic behaviour of ice (by W. Kuhs and H. Klein, Göttingen)

Hexagonal ice (ice Ih) is a mineral and glacier ice is an almost monomineralic rock. The interaction of plastic flow and texture is important for the understanding of glacier flow on earth as well as on a number of other celestial bodies. The textures developed in arctic and antarctic ice sheets are usually studied by optical microscopic methods on samples obtained from deep ice core drillings. Ice exhibits a very pronounced visco-plastic anisotropy as well as important recrystallization phenomena (at least at temperatures prevailing on earth); any modelling of the viscoplastic flow needs to take into consideration both effects. The workshop was communicating the latest measurements of deep ice core textures for Dome C, Antarctica, and NGRIP, Greenland (*Thorsteinsson Thorsteinsson,* Bremerhaven), and presented some recent texture simulation results using the visco-plastic self-consistent approach (*Olivier Castelnau* and *Paul Duval*, Grenoble). The role of continuous and discontinuous recrystallisation processes was emphasized (*Paul Duval*) and computational methods for the calculation of texture-dependent physical properties were discussed in detail (*Kolumban Hutter*, Darmstadt, and *Helmut Klein*).

3.3. Textures and physical anisotropies of carbonates (by B. Leiss and T. Weiss, Göttingen)

Carbonate rocks are of particular interest for deformation, texture and property analyses because they have unique characteristics. The relatively high crystallographic symmetry of calcite and the usually monophase composition of carbonate rocks allow unproblematic texture analyses. Due to the low deformation temperature of calcite, carbonate rocks often play an important role as a lubricant in thrust zones and are very suitable for comparative deformation experiments. The intracrystalline slip systems are well known from numerous experiments and are a reliable basis for numerical texture simulations. From experiments and numerical simulations, a variety of texture types is known (Wenk et al., 1987) which has not been found in nature until now. *Bernd Leiss* could now present the missing High-temperature texture type for natural samples from a marble in Carrara, Italy for the first time (Leiss and Molli, 1999; Leiss and Weiss, 2000, this volume). Another, only recently described natural texture type is characterized by regular *c*-axis distributions on a great circle (e.g. Leiss and Ullemeyer, 1999) and can be related to external rotations during deformation. Additional new aspects on the evolution of natural calcite textures were presented by *Michel Bestmann* (Erlangen). A calcite marble shear zone on Thassos Island, Greece, shows the typical microstructural sequence from a protolith to an ultramylonite. The textures, however, are very similar and the *c*-axis maxima do not show the conventionally expected (Wenk et al., 1987) progressive increase and/or deviation from the foliation normal. Only a detailed analysis of the $+<a>$ and $-<a>$ pole figures prove differences in the textures and give evidence that the similar textures are developed by different slip systems (Bestmann et al., 2000, this volume). Natural textures usually develop in a simple shear deformation regime which is difficult to realize

experimentally. Only recently, new experiments were developed which allow deformation in torsion to high shear strains. First data on the rheological and microstructural evolution of marbles deformed in such an experiment and at different temperatures were shown by *Luigi Burlini* (Zürich; Pieri et al., 1999). Especially the observed texture modifications by the different recrystallisation processes will help to understand and interpret the natural textures. The influence of the factor 'time' on the textural evolution of fine grained calcite was investgated by *Tatyana Ivankina* (Dubna). Rapid heating up to 250°C—accompanied by uniaxial compression—led to only minor texture modifications. In contrast, long-time exposition (20 weeks) at slowly decreasing load (60 down to 10 MPa) and room temperature caused significant textural changes. Dynamic recrystallisation as a response on long-acting stress at low temperatures is supposed to be responsible for the modifications.

Origin and consequences of the anisotropic physical properties of carbonate rocks were reviewed by *Thomas Weiss*. Due to the high single crystal anisotropy of calcite most physical properties, such as thermal dilatation and thermal conductivity, elastic wave propagation, mechanical strength and anisotropy of the magnetic susceptibility, are directionally dependent (e.g. Siegesmund et al., 1997; Weiss et al., 2000). The magnitude and type of directional dependence is controlled by the texture and can be predicted using model calculations. However, in most cases the texture-related properties are overprinted by other fabric characteristics (Weiss et al., 2000). The magnitude and anisotropy of elastic wave velocities are strongly influenced by pre-existing microcrack systems, which tend to lower elastic wave velocities significantly (Weiss et al., 2000). *Luigi Burlini* contributed to this topic with case studies of the seismic properties of natural carbonate mylonites and experimentally deformed calcite rocks and discussed the relative contribution of the texture and grain-shape preferred orientations. Weiss illustrated that the thermal properties (dilatation and conductivity) are clearly controlled by the texture. The correlation of the thermal conductivity with the texture pattern is much more complicated than the comparison between texture and thermal dilation. However, even the thermal dilatation of carbonates is strongly influenced by other fabric properties like i) pre-existing microcracks and ii) thermally induced crack systems (Leiss and Weiss, 2000, this volume; Siegesmund et al., 2000a,b). *Helga de Wall* (Heidelberg) used samples from the same shear zone as Bestmann for the comparison of experimentally determined and texture-derived anisotropy of magnetic susceptibility (AMS) of diamagnetic calcite. She could establish a clear correlation and show the suitability of a diamagnetic mineral for the fabric characterization by means of AMS (De Wall et al., 2000).

The application of quantitative fabric analyses to coal and ore deposit exploration were demonstrated in two other contributions. *Alexander Emetz* (Lviv) investigated the evolution of silver-bearing galena ores from the Muzievo deposit in the Ukraine. He could establish a correlation between the semiconducting properties and the silver content and suggests to use the semiconducting properties for characterising the ore quality. *Igor Kurovets* (Lviv) presented a systematic analysis of the petrography, microstructure and the physical properties of sandstones and limestones from the Lower Carboniferous coal deposits of the Dnjeper–Donets depression. The samples originate from a depth of 4.0 to 6.0 km. In contrast to the sandstones, the limestones are characterized by a considerable anisotropy of the physical properties.

An application of quantitative fabric analyses in archeology and historical science was demonstrated by *Karl Ramseyer* (Bern). In order to verify origin and old trade routes of white marbles, statues, buildings and sarcophagus have been characterized by fabric analyses, cathodoluminescense and stable isotopes, and have been compared with the marbles from ancient quarries in the area of the Mediterranean. For a quantitative comparison of the fabric parameters (e.g. grain size distributions, length, orientation and ratio of the major and minor axes, perimeter/area) a canonical discriminant analysis was introduced.

All the results of these contributions are based on recent progress in the quantification of microstructures, textures and physical properties. This is a necessary precondition to go new ways in e.g. the analysis of the evolution of geological structures at all scales and in the characterization and evaluation of building stones and carbonate-related deposits.

4. Summary and outlook

4.1. The Future of Fabric Analysis in Geosciences (by H.-R. Wenk, Berkeley)

Ever since the discovery of directionality in rocks by D'Halloy (1833), have structural geologists been fascinated with the alignment of crystals in rocks. The alignment may be due to growth or due to deformation and causes anisotropy of physical properties, such as seismic wave propagation in the Earth. There have been many books (including the famous by monograph Sander, 1950; Turner and Weiss, 1963; Nicolas and Poirier, 1976; Wenk, 1985; Kocks et al., 1998) and a multitude of scientific papers published on various experimental and theoretical aspects of preferred orientation in rocks, yet many questions remain. While much is known about monomineralic rocks such as quartzite, marble and olivinite, we still know practically nothing about polymineralic rocks and do not understand in any quantitative way such basic questions as to how hornblende aligns in an amphibolite, or mica in a gneiss. While the theoretical framework to deal with such materials is still in its infancy (having to balance growth, deformation, chemical reactions, and recrystallization), it is also difficult

to characterize the orientations of crystals and orientation relationships between neighbors. New techniques, such as EBSP, synchrotron X-rays, and neutron diffraction will become increasingly important. It can not be overemphasized how important experiments will be. Not only do they have to be complex enough to reproduce stress, strain, temperature and pressure conditions in the Earth, but they also have to include the influence of chemical reactions that accompany deformation during metamorphism. Clearly there is a wealth of opportunities for theoretical as well as experimental research to improve our understanding of rock-forming processes. It is impressive that we can now deform rocks at conditions corresponding to the moons of Jupiter (Bennett et al., 1997), as well as the center of the Earth's core (Wenk et al., 2000), but much work remains to be done. One of the big attractions of texture research has been the stimulating interaction between structural geologists, petrologists, geophysicists, mineralogists, materials scientists and biologists. A close collaboration will be essential in the future.

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