Available online at www.sciencedirect.com
SCIENCE DIRECT®
Tectonophysics 372 (2003) 135–145
TECTONOPHYSICS
www.elsevier.com/locate/tecto

Critical shear stress for mechanical twinning of jadeite—an experimental study

Jens Orzol[a,*], Claudia A. Trepmann[a,1], Bernhard Stöckhert[a], Guanghai Shi[b]

[a] *Institute of Geology, Mineralogy and Geophysics, Ruhr-University Bochum, Bochum, Germany*
[b] *Institute of Geology and Geophysics, Chinese Academy of Science, Beijing, China*

Received 19 September 2002; received in revised form 19 June 2003; accepted 23 June 2003

Abstract

Coarse-grained natural jadeitite samples from Myanmar were experimentally deformed in a Griggs-type solid-medium apparatus at strain rates of $2 \cdot 10^{-5}$ and $5 \cdot 10^{-6}$ s^{-1} and temperatures of 900 and 1000 °C. The microfabrics of the deformed samples are investigated by scanning electron microscopy (SEM) using the electron backscatter diffraction (EBSD) technique. The critical shear stress for twinning in the (100) [001] system is derived from the orientation distribution of jadeite crystals with and without mechanical twins. The results indicate a homogeneous stress field within the sample and a critical shear stress of 150±25 MPa, which compares well to that determined by Kollé and Blacic [J. Geophys. Res. 87 (1982) 4019] for mechanical twinning of other clinopyroxenes. With the critical shear stress known, mechanical twinning of jadeite can be used as a paleopiezometer for high stress tectonic environments.

Keywords: Deformation experiments; Mechanical twinning; Jadeite; Paleopiezometry

1. Introduction

The microstructural record of deformed rocks provides information on the activated deformation mechanisms and can be used—if an appropriate experimental or theoretical calibration is available—to constrain the past conditions in terms of temperature or stress. Recorded information on the state of stress at depths unaccessible for direct measurement, and on the stress history, are of particular interest in geoscience, as predictions are otherwise based on a number of assumptions and subject to considerable uncertainty. Following the principle of uniformitarism, paleopiezometers (e.g. Twiss, 1977) applied to the microstructural record of exhumed rocks thus provide useful constraints on the present-day conditions at unaccessible depths, and for modeling and simulation in geodynamics.

Mechanical twinning is a widespread deformation mechanism in minerals of low symmetry, including carbonate minerals, plagioclase and clinopyroxene.

* Corresponding author. Present address: Leibniz Institute for Applied Geosciences (GGA), 30631 Hannover, Germany.
E-mail addresses: j.orzol@gga-hannover.de (J. Orzol), trepmann@unb.ca (C.A. Trepmann), bernhard.stoeckhert@ruhr-uni-bochum.de (B. Stöckhert), ghshi@mail.c-geos.ac.cn (G. Shi).
[1] Present address: Department of Geology, University of New Brunswick, Fredericton, Canada.

0040-1951/03/$ - see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/S0040-1951(03)00242-7

For instance, in calcite twinning is ubiquitous because a low shear stress of less than 10 MPa is required for twinning (e.g. Tullis, 1980). In contrast to calcite, mechanical twinning of clinopyroxenes is not common and is suggested to be a deformation mechanism restricted to low temperature and very high strain rates (Raleigh and Talbot, 1967; Carter and Raleigh, 1969; Wenk, 1970; Kirby and Christie, 1977; Avé Lallement, 1978; Kollé and Blacic, 1982; Godard and van Roermond, 1995; Laurent et al., 2000).

In accordance with theory (e.g. Tullis, 1980), Kollé and Blacic (1982) demonstrated that the twinning stress does not depend on temperature or strain rate. If the critical resolved shear stress (CRSS) is known, in a homogeneously deformed volume of rock the differential stress can be derived from the analysis of the orientation distribution of twinned crystals (Kollé and Blacic, 1982). The method is referred to as dynamic analysis (Raleigh and Talbot, 1967).

In the present study, the same method is applied to samples of natural jadeitite that were experimentally deformed in a Griggs-type apparatus. For the given maximum differential stress and orientation of the maximum principal stress direction, the orientation distribution of jadeite crystals with and without mechanical twins is used to derive the critical resolved shear stress for twinning.

2. Mechanical twinning of clinopyroxene

Mechanical twinning can be described as a homogeneous simple shear, with the shear strain and shear sense fixed for a given twin law (Fig. 1). By definition, the shear plane is normal to K_1 and contains the shear direction η_1. The direction η_2 parallels the intersection of the shear plane and K_2.

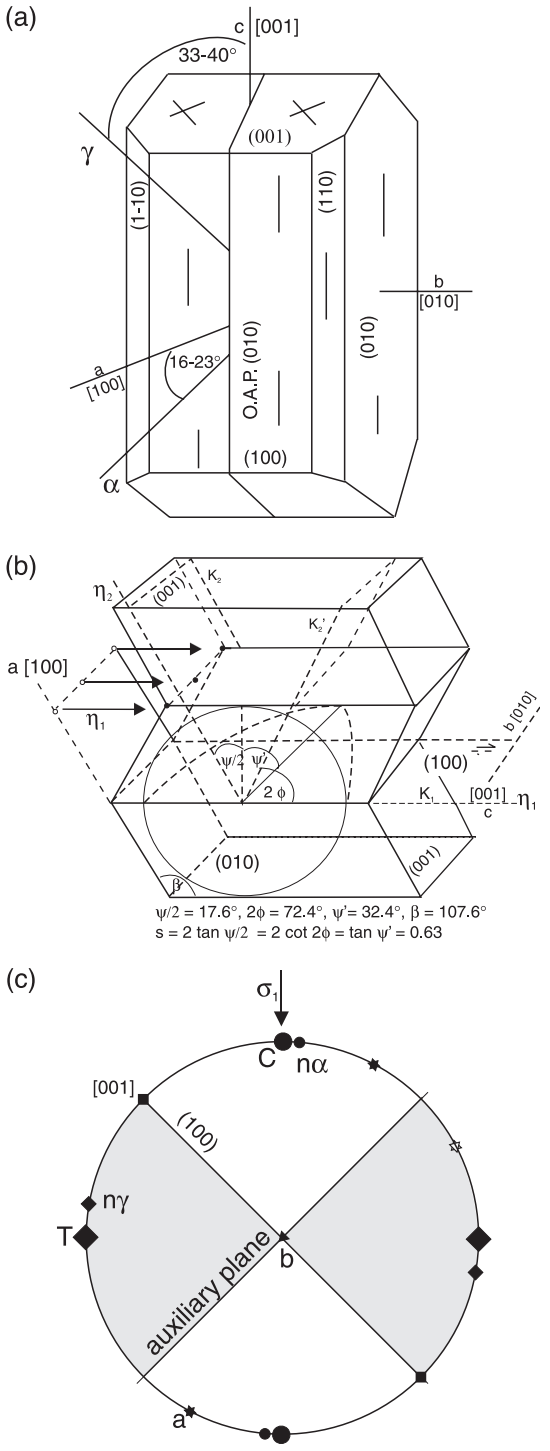

Fig. 1. (a) Crystallographic planes and directions in jadeite; (b) scheme of (100) twinning in jadeite. The (100) plane is the twin and composition plane. The shear direction is [001]; (c) stereographic projection of crystallographic planes and directions for a twinned jadeite. The most favourable orientation of the crystal for twinning on (100) is that with the σ_1 direction at 45° to (100) and [001], and at 27.4° to the *a*-axis, all directions being parallel to (010). The σ_1 and σ_3 directions most favourable for twinning are termed C and T, respectively.

The angle γ between K_2 and K_2', and therefore the amount of shear $s = 2\tan(\gamma/2)$, are defined by crystallography, with $\gamma/2 = \beta - 90°$. For the angle $2\Theta = (180° - \beta)$ between the two circular sections the amount of shear is given by $s = 2\cot(2\Theta)$. During twinning, the plane oriented perpendicular to η_1 is rotated by the angle γ' and $s = \tan\gamma'$. Specification of the elements K_1 and K_2 is sufficient to define a twin, but usually the four elements K_1, η_1, K_2 and η_2 are cited.

The twin glide elements of two reciprocal mechanical twins in clinopyroxenes were determined by Raleigh and Talbot (1967) as:

(1) lamellar twins parallel to (100): composition plane K_1=(100), K_2=(001), shear direction η_1=[001], η_2=[100]
(2) basal twins parallel to (001): composition plane K_1 = (001), K_2 = (100), shear direction η_1=[100], η_2=[001].

Because all four indices are rational, the twins are labelled compound twins.

Jadeite is monoclinic with the space group $C2/c$ (Fig. 1a). The idealized clinopyroxene structure can be described as (100) layers containing chains of $[SiO_4]^{4-}$ tetrahedra, stacked alternately with (100) layers of cations in eight- and six-fold coordination, respectively. Therefore, the main structural change that occurs during mechanical twinning on (100) is the reorientation of the cation coordination polyhedra. The structure of the (100) twin boundary is described by Kirby and Christie (1977) by a displacement of 1/2 [001] of the tetrahedral-chains. For the host grain and a (100)-twin lamella, only the orientation of the $\langle a \rangle$-axis is different (Fig. 1b,c). The amount of shear related to twinning is determined by the angle β = 107.6°, where $s = 2\tan(\beta - 90°) = 0.63$. The twin orientation can be considered as the result of either a 180° rotation about η_1 (i.e. a reflection on (100)) or a 180° rotation about the normal to K_1 (i.e. a reflection on a plane perpendicular to (100)) (Fig. 1c). The latter symmetry operation is mechanically not relevant because the indices of this element are caused by the monoclinic symmetry of jadeite being irrational. If the first rotation axis is the [001] direction, the second one is approximately [201].

Using a Griggs-type solid medium apparatus, Kollé and Blacic (1982) have experimentally determined a critical resolved shear stress (CRSS) of 140 ± 10 MPa for (100) [001] twinning of hedenbergite and of 100 ± 30 MPa for chrome diopside. These authors suspect that the numerous mineral inclusions and (001) growth twins in their chrome diopside samples may account for the apparently lower CRSS value and the scatter in the data. They conclude that the CRSS of 140 ± 10 MPa determined for hedenbergite represents a reasonable value for the twinning stress in clinopyroxene and that the composition of pyroxene does not notably affect the CRSS.

3. Description of the natural jadeitite sample

The natural jadeitite used in the present study was taken from the Myanmar (Burma) jadeitite area (Chhibber, 1934), which is located in the western part of the Sagaing strike-slip fault belt in the Parkhan (also referred to as Hpakan or Pharkan) area of the Kachin state, Myanmar (Burma). The coordinates of this jadeitite occurrence are N25°36′91″ E96°18′63″, as determined by GPS measurement. The jadeitites occur as veins with a width of 1.5–5 m and a length of about 10–100 m. The jadeitites show two types of microfabrics. Most jadeitites are fine-grained or reveal coarse-grained domains transected by fine-grained layers, possibly a result of deformation-induced recrystallization. A few jadeitites reveal a primary vein microstructure, with large euhedral to subhedral grains (Shi et al., in press). Most coarse-grained jadeite crystals bear abundant fluid inclusions, whose composition is in the H_2O–CH_4 system (Shi et al., 2000). For the present study, a jadeitite specimen with predominantly coarse grains and minor fine-grained domains was chosen (Fig. 2). It is characterized by a heterogenous grain size distribution, with predominantly anisometric large grains whose long dimension ranges from approximately 0.8–2 mm (Fig. 2), and subordinate domains with smaller grains of about 0.1–0.2 mm in diameter. The chemical composition of the jadeite is remarkably homogeneous, without notable zoning or systematic contrast between large and small grains. The mean and standard deviation of 59 microprobe analyses performed along transects parallel and normal to the sample axis is reported in Table 1; the results are given in wt.% oxide compo-

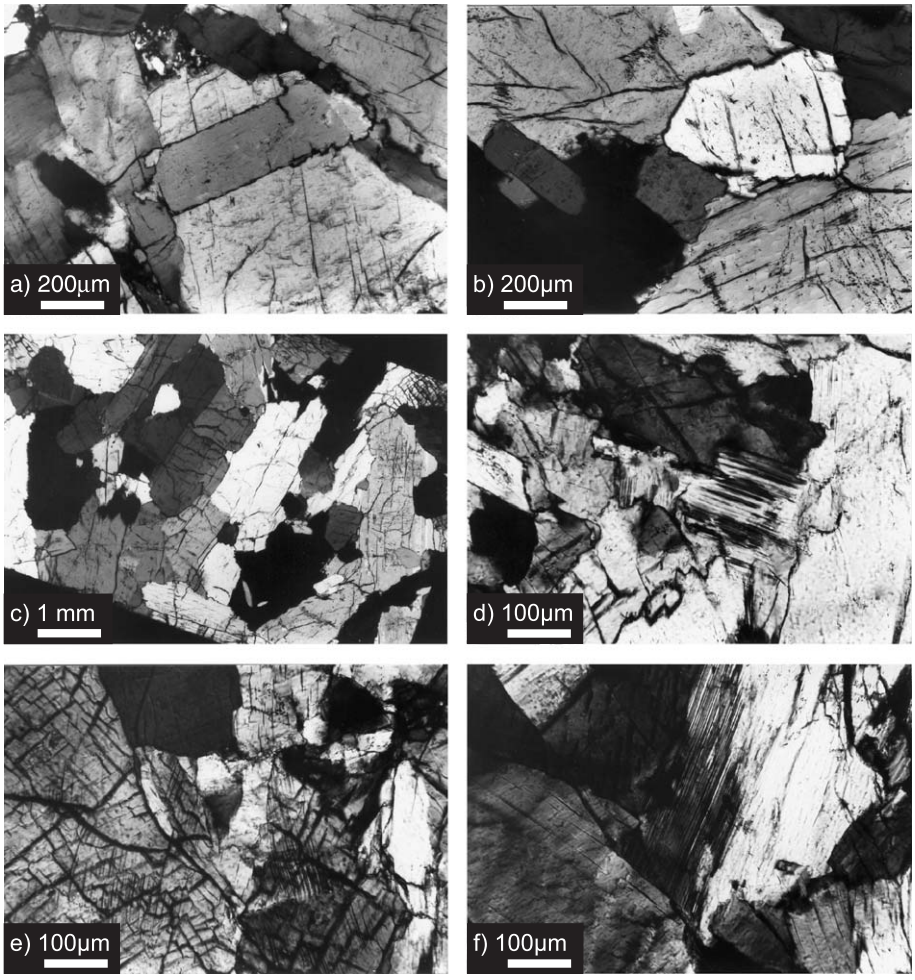

Fig. 2. Optical micrographs of undeformed and deformed samples of natural jadeitite with crossed polarizers. Microstructures of undeformed samples FC3A (a) and FC3C (b, c). Twins are systematically absent. Sample JC2 (d, e, f) deformed at temperatures of 900 and 1000 °C, at a strain-rate of $2 \cdot 10^{-5}$ s^{-1} to a strain of 14%. Lamellar twins have formed in grains of appropriate orientation. Also, the grains show undulatory extinction but no subgrains on the optical scale.

nents. The molar end member proportions are similar to 97% jadeite and 3% diopside, with other components negligible.

Table 1
Average of 59 microprobe analyses on samples of natural jadeitite

Oxide component	Wt.%
SiO_2	59.43 ± 0.37
Al_2O_3	24.53 ± 0.86
Na_2O	14.68 ± 0.45
CaO	0.75 ± 0.67
MgO	0.56 ± 0.48
Total	99.96

4. Deformation apparatus and experimental techniques

Pressure and temperature conditions for deformation experiments on jadeite are constrained by the stability field of jadeite (e.g. Holland, 1980; Waterwiese et al., 1995). At temperatures of 900 °C, a minimum pressure of 1.8 GPa is required to prevent the breakdown of jadeite to nepheline and albite. Thus, deformation experiments can at present only be performed using a solid-medium apparatus. The apparatus used in the present study has been described in detail by

Rybacki et al. (1998) and has been used for systematic studies on high-pressure minerals (Renner et al., 2001; Orzol, 2002; Rybacki et al., 2003). It is equipped with a fast reacting servo-hydraulic system for the control of both the confining pressure and the axial load. A straight graphite furnace is used for internal heating of the assembly in connection with a programmable controller. Two NiCr–Ni thermocouples are used to measure the temperature. The eutectic mixture of CsCl and NaCl was used as a pressure-transmitting medium in the vicinity of the sample. This salt mixture is only moderately hygroscopic and its melting temperature is approximately 1000 °C at a pressure of 2.5 GPa (Kim et al., 1972). The use of a molten or low-viscous salt is advantageous compared to a solid salt assembly, as friction is drastically reduced allowing a significantly improved stress resolution (Green and Borch, 1990; Gleason and Tullis, 1995).

Samples were cored from the natural jadeitite specimen using a diamond drillbit, and the cores were ground to yield cylinders with a diameter of 3.8 mm and a length of approximately 7.0 mm. The samples were dried at 150 °C for 24 h to remove surface water. Then, they were fit into platinum capsules with a wall thickness of 0.1 mm, and a somewhat higher thickness at the top and bottom surfaces. Optical inspection after the experiment did not reveal any damage to the capsules.

All tests were carried out at a nominal confining pressure of 2.5 GPa. Temperature and pressure conditions were built up simultaneously to final conditions, employing a heating rate of 5 °C/min. With the chosen path, the stability field of jadeite is entered at 250 °C, which precludes decomposition of jadeite. At final run conditions, the axial piston is advanced into the assembly at a constant velocity. After hitting the sample, the piston is stopped when the desired strain is accumulated. The piston is then retreated by 1 mm and pressure and temperature are lowered simultaneously to room conditions within 20 min.

5. Mechanical data and correction procedure

Force versus displacement data were recorded during advance of the axial piston into the assembly and subsequent axial shortening of the samples. These were transformed into stress strain curves (Fig. 3). The displacement is first corrected for the stiffness of the axial loading column. The true strain is calculated from the measured axial shortening. The differential stress is determined by subtracting the confining pressure and the frictional forces. In view of the high contrast in the strength between the sample and the confining medium a dynamic friction correction (Rybacki et al., 1998) is applied. The linear portion of the force versus displacement curve prior to the hit-point is fit with a straight line obtained by a linear regression that serves as the baseline for the correction of the force. Finally, for transformation into stress, the residual load is divided by the changing cross-sectional area of the sample, which is determined assuming a constant volume during deformation.

Sample FC3-2 was deformed at a temperature of 900 °C and a strain-rate of $5{\cdot}10^{-6}$ s^{-1} to a strain of 9%. The experiment on sample JC2 involved two deformation cycles, one at a temperature of 900 °C and one at a 1000 °C, both at a strain-rate of $2{\cdot}10^{-5}$ s^{-1} leading to an overall strain of 14% (Fig. 3). Mechanical twinning occurs instantaneously and is assumed to reflect the stage of maximum differential stress. These maximum stresses were 1260 MPa for FC3-2 and 1340 MPa for JC2. The difference between the temperatures recorded by the two thermocouples was below 5 °C in both experiments. An average strain-rate is obtained from the amount of axial shortening and the piston velocity.

The uncertainty in the differential stress is not only related to the uncertainty of the employed gauges, but is dominated by the procedure used for the friction correction. Applying the dynamic friction correction assumes that the increase of frictional forces, represented by the linear increase of force prior to the hit-point, does not change with ongoing displacement after hitting the sample. In calibration experiments the piston was retracted after deformation of the sample and was subsequently readvanced into the assembly without renewed deformation of the sample. This allowed to measure the friction at displacements corresponding to a typical sample strain of 20%. Comparison of the directly measured friction with the friction contribution obtained by extrapolation of the linear portion of the force displacement curve of the deformation cycle shows that, on average, the change in background friction amounts to about 80 MPa. This can be taken as an upper limit of the uncertainty in

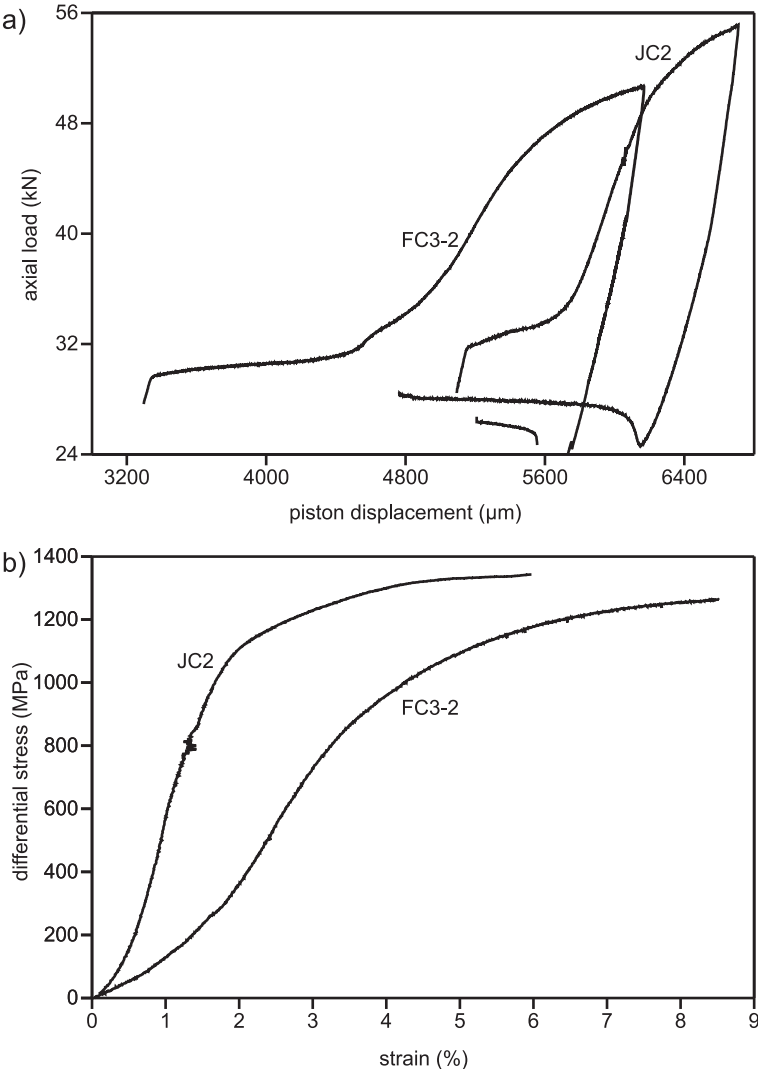

Fig. 3. (a) Uncorrected force versus displacement curves for deformation experiments on samples JC2 defomed at 900 °C and $2{\cdot}10^{-5}$ s^{-1} and FC3-2 deformed at 900 °C and $5{\cdot}10^{-6}$ s^{-1}. (b) Stress strain curves, corrected for friction and stiffness of the axial loading column (see text for details).

differential stress determination, as for the experiments presented here the induced strain is much lower and extrapolation is consequently required over a smaller displacement.

6. Microfabrics of deformed specimens

The absence or presence of twinning is analysed by optical polarizing microscopy and SEM analysis. Thin sections are oriented parallel to the axis of shortening. Thus, shear stress is at a minimum parallel to the section plane and no grains with twin lamellae parallel to the section plane—which may not be identified—are expected. In view of the rotational symmetry, twins in grains of any other equivalent orientation in the stress field, but with (100) at a higher angle to the plane of the thin section, would be readily identified. As twinning in such grains is systematically absent, the analysis is unlikely to be affected by orientation

dependent visibility of twin lamellae in the thin section.

The grain size of the deformed samples corresponds to that of the undeformed material. In contrast to the undeformed material, a marked inhomogeneous crystal plastic deformation is documented by undulatory extinction in most grains (Fig. 2). Fine lamellar (100) [001] twinning is restricted to grains with a specific crystallographic orientation (Fig. 2). Due to the limited strain, no shape or crystallographic preferred orientation is developed. In many cases, the twin lamellae are lense- or wedge-shaped with a characteristic width of about 1 μm. The microstructure indicates a combination of twinning and deformation by dislocation glide. Grain boundary bulging appears possible in some places, but cannot be related to experimental deformation with certainty, as the high-angle grain boundaries are quite irregular in the starting material (Fig. 2). The most conspicuous difference compared to the undeformed microstructure is the extensive microcracking (Fig. 2). All samples exhibit microcracks oriented perpendicular to the direction of shortening. These cracks are transgranular and their spacing is on the order of 100–150 μm. According to their orientation, these cracks are attributed to unloading following the deformation stage, and thus are not effective at the stage of plastic deformation and twinning. In addition, suitably oriented grains contain networks of nearly perpendicular (87°; Deer et al., 1978) microcracks, corresponding to the {110} cleavage of jadeite. Their orientation is not correlated to the direction of compression. The spacing of the cleavage cracks is approximately 10 μm.

The complex microstructure of the starting material with a coarse grain size (Fig. 2) favours inhomogeneous deformation. Also, the small strain precludes formation of a homogeneous microstructure.

7. Orientation measurement

The twin law (100) [001] and the orientation of the jadeite crystals were determined by electron backscatter diffraction (EBSD). For this procedure, mechanically polished thin sections were additionally chemically polished using a colloidal silicon suspension (SYTON) (Prior et al., 1999) to reduce the surface damage. For inspection by SEM, the thin sections were then coated with carbon. The EBSD patterns and the orientation contrast images (OCI) were acquired using a scanning electron microscope (SEM) LEO 1530 with field emission gun and forescatter detector, operated at an accelerating voltage of 25 kV, with the section tilted over 70° and a working distance of 25 mm. The EBSD patterns were indexed with the HKL software ''CHANNEL 4'' (Schmidt and Olesen, 1989).

8. Derivation of critical resolved shear stress for twinning

The Schmid formula yields the resolved shear stress on the glide plane and glide direction for twinning as a function of differential stress and crystal orientation, using the direction of axial shortening (corresponding to the σ_1 direction) as a reference. For each mechanically twinned jadeite crystal, the resolved shear stress on (100) in direction [001] must have exceeded the CRSS for twinning. The resolved shear stress on the (100) plane in the [001] direction, in the sense that allows twinning, can be derived by the following equation for each individual crystal

$$\sigma_{\mathrm{RSS}} = (\sigma_1 - \sigma_3)(\cos\gamma \cdot \cos\theta),$$

where σ_1 and σ_3 denote the maximum and minimum principal stress, respectively; γ is the angle between the σ_1 direction and the normal to the (100) plane and θ the angle between σ_1 and [001]. The derived resolved shear stress values for crystals with and without mechanical twins are displayed in Table 2. In this analysis, we assumed a homogenous stress field (Sachs model), as a first approximation.

It is presumed that twinning occurred wherever the critical shear stress was reached and that for crystals without twins the resolved shear stress on (100) in direction [001] in the sense allowing twinning remained below the CRSS. Twinning is not possible when the direction of σ_1 is at an obtuse angle between (100) and the $\langle a \rangle$-axis. Using this method, a surprisingly uniform value for the critical resolved

Table 2
Resolved shear stress on the (100) plane in the [001] direction, with sense appropriate for twinning, derived for crystals with and without twins

Data point	Resolved shear stress (MPa)	
Sample JC2		
13-3	26	nt
12-1	35	nt
4-7	64	nt
4-27	132	nt
4-26	143	nt
4-16	150	nt
8-3	155	t
7-3	175	t
12-3	183	t
10-3	210	t
4-20	277	t
4-17	330	t
4-18	332	t
9-3	350	t
4-29	371	t
4-19	413	t
4-12	473	t
4-2	546	t
4-1	561	t
4-15	626	t
3-2	643	t
4-4	649	t
4-23	663	t
4-24	671	t
4-25	685	t
Sample FC3-2		
14	51	nt
7	116	nt
6	165	t
15	167	t
45	175	t
5	203	t
11	217	t
4	229	t
12	234	t
16	234	t
3	235	t
8	235	t
2	240	t
13	266	t
1	282	t
46	293	t
18	311	t
17	376	t
20	394	t
19	410	t
40	470	t
39	471	t
Sample FC3-2		
22	483	t
42	488	t
41	490	t
9	495	t
10	497	t

The stress data are arranged according to increasing resolved shear stress. Crystals subject to a resolved shear stress exceeding 150 MPa show twinning (labelled t), while no twins (labelled nt) are observed for shear stresses below 150 MPa.

shear stress is indicated (Table 2). Wherever the shear stress on (100) in the direction of [001], with σ_1 at an acute angle between (100) and the $\langle a \rangle$-axis, exceeded 150 MPa, mechanical twins are observed. The twins are systematically absent in all crystals with an orientation that keeps the respective shear stress below 150 MPa.

9. Discussion

The fact that the orientation distribution of a statistically sufficient number of crystals (Table 2) shows a remarkably sharp boundary between the fields of crystals with and without twins, bears two important implications. First, the stress field in the experimentally deformed sample must be sufficiently homogeneous, despite the anisotropy of the crystals and the coarse grain size. Second, the critical resolved shear stress for twinning has a specific characteristic value, in accordance with theory (Tullis, 1980). For (100) [001] twinning of jadeite, the sharp threshold between the twinned crystals and those of appropriate orientation but lacking twins suggests a critical resolved shear stress of 150 MPa.

The uncertainty of the critical resolved shear stress is given by the uncertainty in the determination of the resolved shear stress ($\delta\sigma_{RSS}$). It can be estimated using a standard Gaussian error analysis based on the Schmid's formula, which uses the maximum differential stress achieved during deformation of the sample and the angles γ and θ that were introduced above. From the uncertainties in the differential stress $\Delta(\sigma_1 - \sigma_3)$ and in the angles $\Delta\gamma$,$\Delta\theta$

the uncertainty of the resolved shear stress is obtained by:

$$\delta\sigma_{RSS} = ((\cos\gamma\cos\theta)^2(\Delta(\sigma_1-\sigma_3))^2 + ((\sigma_1-\sigma_3)\sin\gamma\cos\theta)^2(\Delta\gamma)^2 + ((\sigma_1-\sigma_3)\cos\gamma\sin\theta)^2(\Delta\theta)^2)^{1/2}$$

Obviously, the terms arising from the uncertainty in the angles are subordinate and the uncertainty in the resolved shear stress is governed by that of the differential stress. It also depends on the orientation of the crystals, but is of interest only for the limiting orientation, where twins can form. Taking $\Delta\gamma$ and $\Delta\theta$ as 2°, and using the upper bound to the error on differential stress ($\Delta(\sigma_1-\sigma_3)=80$ MPa), a conservative estimate for the uncertainty in the critical resolved shear stress for (100) [001] twinning is 25 MPa. This uncertainty includes the 140 MPa proposed by Kollé and Blacic (1982) based on their experiments on clinopyroxene single crystals with a composition close to the hedenbergite ($CaFeSi_2O_6$) clinopyroxene end member. These authors derived an uncertainty of 10 MPa from the standard deviation of critical resolved shear stresses determined from a set of experiments. Considering the uncertainty in the stress measurement of that earlier study, in particular for the experiments on diopside, the coincidence with the results of the present study should not be taken to indicate that the critical shear stress for twinning of clinopyroxenes may be independent of composition.

Comparing the data for calcite, dolomite and clinopyroxene single crystals and aggregates, Tullis (1980) proposed that the stresses for twinning of grains in aggregates are systematically higher at lower temperatures, probably because of the interference with surrounding grains. In experiments conducted at higher temperatures, the stresses approach those derived from single crystal experiments Tullis (1980). As the experiments of this study were performed at relatively high temperature, allowing concomitant deformation by other crystal plastic mechanisms and thus relaxing the interference problems at grain boundaries, a comparison with the single crystal data of Kollé and Blacic (1982) seems to be justified.

We are aware of two examples, where mechanical twinning of natural jadeite has been investigated so far. The orientation distribution of jadeite crystals with and without mechanical twins was determined in exhumed high pressure metamorphic rocks of the Sesia Zone (Western Alps), by Trepmann and Stöckhert (2001). Tentatively using a critical resolved shear stress of 140 MPa (Kollé and Blacic, 1982), they obtained a differential stress of at least 0.5 GPa and possibly up to 1 GPa. The value of 150 ± 25 MPa derived in the present study is identical within the limits of error to the 140 MPa (Kollé and Blacic, 1982) used by Trepmann and Stöckhert (2001). Thus, the new experimental results on clinopyroxene with a composition nearly identical to that of the Sesia Zone pyroxenes support the validity of the derived differential stresses of at least 0.5 GPa, which was attributed to quasi instantaneous loading of the uppermost plastosphere due to stress redistribution in a major seismic event (Küster and Stöckhert, 1999; Trepmann and Stöckhert, 2001, 2002, in press).

Another example of mechanical twinning in jadeite in natural rocks has been studied by Lämmerhirt and Stöckhert (2001). In ultrahigh pressure metamorphic rocks from the Dora Maira Massif, Western Alps (e.g. Schertl et al., 1991) mechanically twinned jadeite crystals are found embedded in a coarse-grained quartz matrix with a typical foam-microstructure and devoid of indications of late-stage crystal plastic deformation on the optical scale. Lämmerhirt and Stöckhert (2001) proposed that in this case twinning of jadeite has occured in a short episode of high stress deformation related to rapid transformation of coesite to quartz, with the microstructural record of this stage erased in the quartz matrix due to extensive grain growth and annealing.

10. Conclusions

The critical shear stress for (100) [001] mechanical twinning of jadeite is determined as 150 ± 25 MPa, which corresponds to the value of 140 ± 10 MPa given for hedenbergite by Kollé and Blacic (1982). With the given critical resolved shear stress, the occurence of mechanically twinned clinopyroxene in natural rocks suggests that these rocks were subject to exceptionally high differential stresses of at least 0.3 GPa. Such stress levels may be reached for a very short time, as during synseismic loading (Trepmann

and Stöckhert, 2001) or during rapid phase transformation (Lämmerhirt and Stöckhert, 2001). When a homogeneous stress field on the sample scale can be assumed, the orientation distribution of crystals with and without mechanical twins, combined with the experimentally determined critical shear stress can then be used as a paleopiezometer (e.g. Raleigh and Talbot, 1967), which—in contrast to recrystallized grain size or dislocation density (e.g. Twiss, 1977; Poirier, 1985; Kohlstedt and Weathers, 1980)—does not indicate a quasi steady state flow stress, but a short term peak stress reached in non-steady state flow. Mechanical twinning is therefore a particularly useful indicator of peak stresses attained during quasi-instantaneous loading, e.g. related to seismic events or rapid phase transformation, with a record that can be preserved during subsequent stages of creep at decreasing stresses or static annealing.

Acknowledgements

Constructive reviews by Philippe Laurent and an anonymous referee, and thoughtful comments by Dorothée Dorner, helped to improve the final version of the manuscript. Funding by the German Science Foundation (DFG) within the scope of the Collaborative Research Center *Rheology of the Earth—from the upper crust to the subduction zone* (SFB 526) is gratefully acknowledged.

References

Avé Lallement, H.G., 1978. Experimental deformation of diopside and websterite. Tectonophysics 48, 1–27.

Carter, N., Raleigh, C., 1969. Principal stress directions from plastic flow in crystals. Geological Society of America Bulletin 80, 1231–1264.

Chhibber, H., 1934. The Mineral Resources of Burma. Macmillan, London.

Deer, W.A., Howie, R.A., Zussmann, J., 1978. Single-Chain Silicates. Longman Group, London.

Gleason, G., Tullis, J., 1995. A flow law for dislocation creep of quartz aggregates determined with the molten salt cell. Tectonophysics 247, 1–23.

Godard, G., van Roermond, H., 1995. Deformation-induced clinopyroxene fabrics from eclogites. Journal of Structural Geology 17 (10), 1425–1443.

Green, H.W., Borch, R.S., 1990. High pressure and temperature deformation experiments in a liquid confining medium. In: Duba, A.G., Durham, W.B., Handin, J.W., Wang, H.F. (Eds.), The Brittle-Ductile Transition in Rocks. Geophysical Monograph, vol. 56. American Geophysical Union: Washington, DC, United States, pp. 195–200, 283–317.

Holland, T., 1980. The reaction albit = jadeite + quartz determined experimentally in the range 600–1200 °C. American Mineralogist 65, 129–134.

Kim, K., Vaidya, S., Kennedy, G., 1972. Effect of pressure on the temperature of the eutectic minimums in two binary systems: NaF–NaCl and CsCl–NaCl. Journal of Geophysical Research 77 (35), 6984–6989.

Kirby, S., Christie, J., 1977. Mechanical twinning in diopside $Ca(MG,Fe)Si_2O_6$: structural mechanism associated crystal defects. Physics and Chemistry of Minerals 1, 137–163.

Kohlstedt, D.L., Weathers, M.S., 1980. Deformation-induced microstructures, paleopiezometers, and differential stress in deeply eroded fault zones. Journal of Geophysical Research 85 (B11), 6269–6285.

Kollé, J., Blacic, J., 1982. Deformation of single-crystal clinopyroxene: 1. Mechanical twinning in diopside and hedenbergite. Journal of Geophysical Research 87 (B5), 4019–4034.

Küster, M., Stöckhert, B., 1999. High differential stress and sublithostatic pore fluid pressure in the ductile regime-microstructural evidence for short term post-seismic creep in the Sesia Zone, Western Alps. Tectonophysics 303, 263–277.

Lämmerhirt, A., Stöckhert, B., 2001. Grain scale deformation in ultrahigh pressure metamorphic rocks related to phase transformation. Abstractvolume, Deformation Mechanisms, Rheology and Tectonics. Noordwijkerhout, The Netherlands, p. 98.

Laurent, P., Kern, H., Lacombe, O., 2000. Determination of deviatoric stress tensor based on inversion of calcite twin data from experimentally defomed monophase samples: Part ii. Axial and triaxial experiments. Tectonophysics 327, 131–148.

Orzol, J., 2002. Experimental deformation of jadeite. PhD thesis, Ruhr University Bochum.

Poirier, J.P., 1985. Creep of Crystals. Cambridge Univ. Press, Cambridge.

Prior, D.J., Boyle, A.P., Brenker, F., Cheadle, M.C., Day, A., Lopez, G., Peruzzo, L., Potts, G.J., Reddy, S., Spiess, R., Timms, N.E., Trimby, P., Wheeler, J., Zetterström, L., 1999. The application of electron backscatter diffraction and orientation contrast imaging in the SEM to textural problems in rocks. American Mineralogist 84, 1741–1759.

Raleigh, C., Talbot, J., 1967. Mechanical twinning in naturally and experimentally deformed diopside. American Journal of Science 265, 151–165.

Renner, J., Stöckhert, B., Zerbian, A., Röller, K., Rummel, F., 2001. An experimental study into the rheology of synthetic polycrystalline coesite aggregates. Journal of Geophysical Research 106 (B9), 19411–19429.

Rybacki, E., Renner, J., Konrad, K., Harbott, W., Rummel, F., Stöckhert, B., 1998. A servohydraulically-controlled deformation apparatus for rock deformation under conditions of ultrahigh pressure metamorphism. Pure and Applied Geophysics 152, 579–606.

Rybacki, E., Konrad, K., Renner, J., Wachmann, M., Stöckhert, B.,

Rummel, F., 2003. Experimental deformation of synthetic aragonite marble. Journal of Geophysical Research 108 (B3), 2174.

Schertl, H.P., Schreyer, W., Chopin, C., 1991. The pyrope-coesite rocks and their country rocks at Parigi, Dora Maira Massif, Western Alps: detailed petrography, mineral chemistry and PT-path. Contributions to Mineralogy and Petrology 108, 1–21.

Schmidt, N., Olesen, N., 1989. Computer-aided determination of crystal-lattice orientation from electron-channeling patterns in the SEM. Canadian Mineralogist 27, 15–22.

Shi, G., Cui, W., Wang, C., 2000. The fluid inclusions in jadeitites from Pharkant area, Myanmar. Chinese Science Bulletin 45, 1896–1900.

Shi, G., Cui, W., Tropper, P., Wang, C., Shu, G., Yu, H., 2003. The petrology of a complex sodic- and sodic-calcic amphibole association and its implications for the metasomatic processes in the jadeitite area in northwestern Myanmar (Burma). Contributions to Mineralogy and Petrology (in press).

Trepmann, C., Stöckhert, B., 2001. Mechanical twinning of jadeite—an indication of synseismic loading beneath the brittle-plastic transition. International Journal of Earth Sciences 90 (1), 4–14.

Trepmann, C., Stöckhert, B., 2002. Cataclastic deformation of garnet: a record of synseismic loading and postseismic creep. Journal of Structural Geology 24, 1845–1856.

Trepmann, C., Stöckhert, B., 2003. Quartz microstructures developed during non-steady state plastic flow at rapidly decaying stress and strain rate. Journal of Structural Geology (in press).

Tullis, T., 1980. The use of mechanical twinning in minerals as a measure of shear stress magnitudes. Journal of Geophysical Research 85 (B11), 6263–6268.

Twiss, R.J., 1977. Theory and applicability of a recrystallized grain size paleopiezometer. Pure and Applied Geophysics 115, 227–244.

Waterwiese, T., Chatterjee, N., Dierdorf, I., Göttlicher, J., Kroll, H., 1995. Experimental and thermodynamic study of heterogeneous and homogeneous equilibria in the system $NaAlSiO_4$–SiO_2. Contributions to Mineralogy and Petrology 121, 65–73.

Wenk, H.-R., 1970. Submicroscopical twinning in lunar and experimentally deformed pyroxenes. Contributions to Mineralogy and Petrology 26, 315–323.