

Kyanite deformation in whiteschist of the ultrahigh-pressure metamorphic Kokchetav Massif, Kazakhstan

R. J. BEANE AND C. K. FIELD

Bowdoin College, 6800 College Station, Brunswick, ME 04011, USA (rbeane@bowdoin.edu)

ABSTRACT Microstructures in minerals from ultrahigh-pressure metamorphic (UHPM) terranes are keys to understanding the rheological properties and the exhumation mechanisms of rocks from subduction zones. Kyanite-bearing whiteschist, associated with eclogite lenses, is part of UHPM unit II located south-west of Lake Zheltau in the Kulet region of the Kokchetav Massif. The equilibrium assemblage is kyanite + garnet + talc + phengite + coesite/quartz. Previously reported peak pressure–temperature (P – T) conditions are ~ 3.5 GPa at 750 °C. A strong foliation is defined by the talc and phengite, with a corresponding weak shape preferred alignment of kyanite. Crystallographic orientation maps and analysis of kyanite blades were performed using electron backscatter diffraction methods. The data are consistent with a (100)[001] slip system for the formation of undulose extinction and kink bands in kyanite. Rotations measured across individual kink bands are 10–50° about $\langle 010 \rangle$, and rotations along kyanite with undulose extinction are up to 50° about $\langle 010 \rangle$ with variations between adjacent points typically $< 2^\circ$. The undulose extinction is interpreted to have developed through crystal plastic deformation by dislocation creep. Kink bands mark the development of high-angle grain boundaries by dislocation climb. The deformation of kyanite occurred in the fault-bounded terrane during the exhumation of the Kokchetav Massif.

Key words: electron backscatter diffraction; Kokchetav; kyanite; microstructures; ultrahigh-pressure metamorphism.

INTRODUCTION

Kyanite is a common mineral formed in regionally metamorphosed pelitic sediments and in ultrahigh-pressure (UHP) metamorphosed whiteschists. In this paper, orientation maps of kyanite collected by electron backscatter diffraction (EBSD) methods are presented for the first time to characterize the internal microstructures of this important Al_2SiO_5 polymorph. The analysed kyanite, displaying undulatory extinction and kink bands, is from the UHP metamorphosed whiteschists of the Kokchetav Massif, Kazakhstan (Fig. 1a).

Ultrahigh-pressure metamorphism refers to the metamorphism of crustal rocks in subduction zones at pressures high enough to crystallize the index mineral coesite (a high-pressure polymorph of quartz requiring a minimum pressure of > 2.7 GPa at > 600 °C) or diamond. Prior to the initial discoveries of coesite in upper crustal rocks (Chopin, 1984; Smith, 1984), coesite and diamond were thought to occur only in meteorite-impact craters and mantle xenoliths. The discovery of upper-crustal rocks metamorphosed to UHP has changed our understanding of crustal-scale processes in continental collision zones (cf. Liou *et al.*, 1994; Hacker & Liou, 1998; Ernst & Liou, 2000), by

challenging existing views about subduction and exhumation.

Recently, microstructural analyses of minerals in UHP metamorphic terranes by electron microscopy have begun to lend new insights into the deformation mechanisms of the minerals, and into the strain rates and stress limits in subduction zones. For example, Hwang *et al.* (2001) used analytical electron microscopy to document defect microstructures produced by semi-brittle deformation in minerals from the Sulu UHP terrane; they interpret these to indicate a high strain rate $> 10^{-11} \text{ s}^{-1}$ corresponding to rapid and episodic exhumation. Zhao *et al.* (2005) further noted that strain in the Sulu UHP terrane is localized into narrow shear zones in which omphacite, phengite and kyanite accommodate strain through plastic deformation, concluding that the requisite stress in the subduction zone is much higher than previously thought, on the order of tens of MPa. Similarly, Terry & Heidelbach (2005) used EBSD methods to analyse microstructures of plagioclase, omphacite, garnet and ilmenite from the UHP Western Gneiss Region of Norway to derive upper stress limits of 100–150 MPa and lower strain rate limits of 10^{-12} s^{-1} within shear zones of the UHP terrane. Turning to the UHP Dora Maira Massif in the Western Alps, Lenze *et al.* (2005)

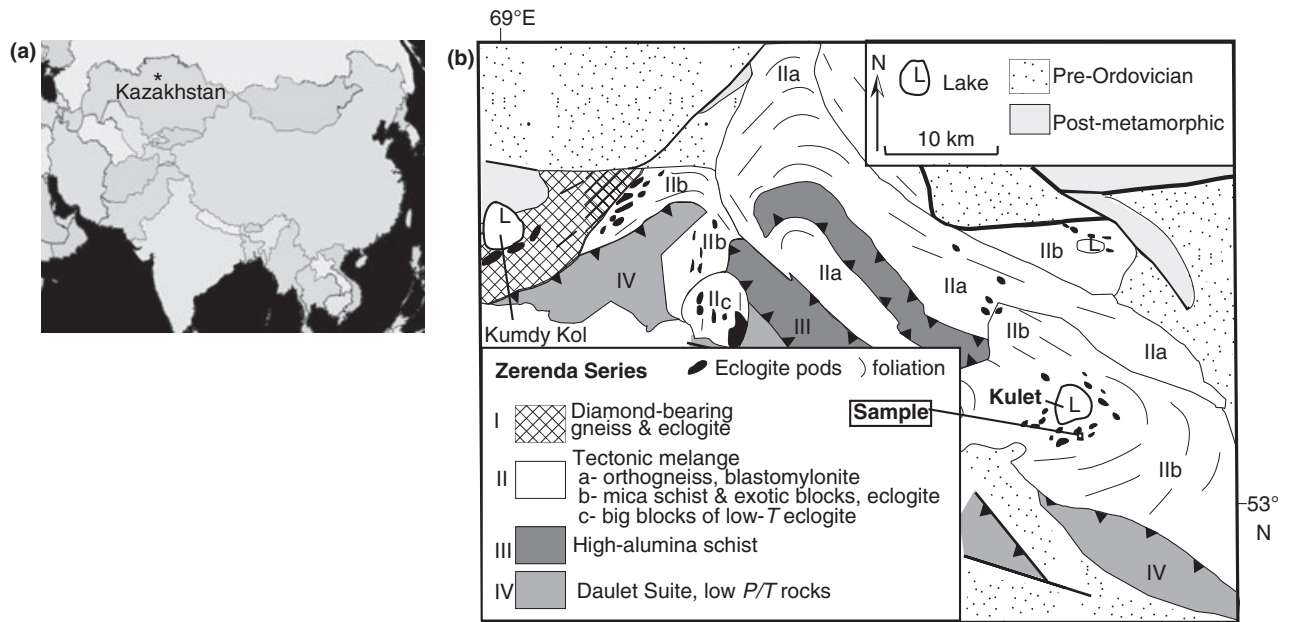


Fig. 1. (a) Location map of the Kokchetav Massif (*) in northern Kazakhstan. (b) Geological map (simplified from R. Zhang, personal communication) of the Kokchetav Massif. The whiteschist sample described in this study is from the Zerenda series, unit IIb, as indicated, south of Kulet lake.

used EBSD methods to document mechanical twins in jadeite and kink bands in kyanite concluding that deformation took place in an inhomogeneous stress

field with local differential stress >0.3 GPa. These examples show that microstructures in minerals from UHP metamorphic terranes are keys to understanding

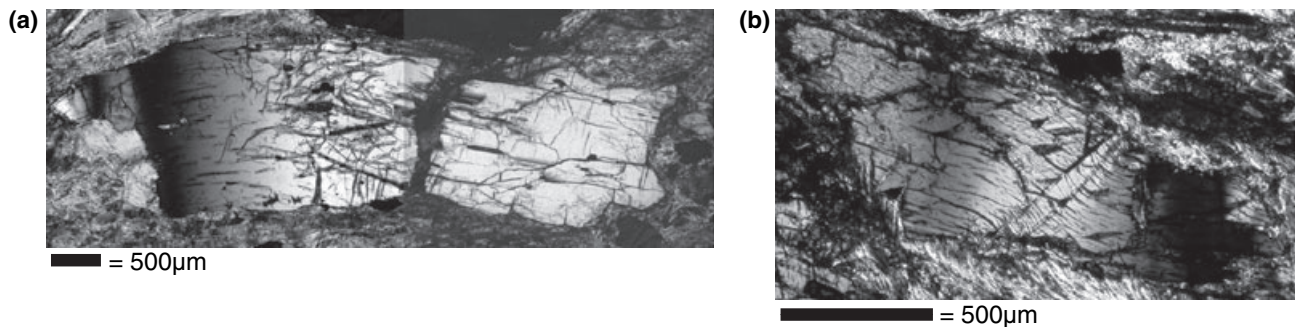


Fig. 2. Photomicrographs of kyanite taken in cross-polarized light. (a) Undulatory extinction in kyanite; photomicrograph corresponds to Fig. 4. (b) Undulatory extinction and kink band in kyanite; photomicrograph corresponds to Fig. 8.

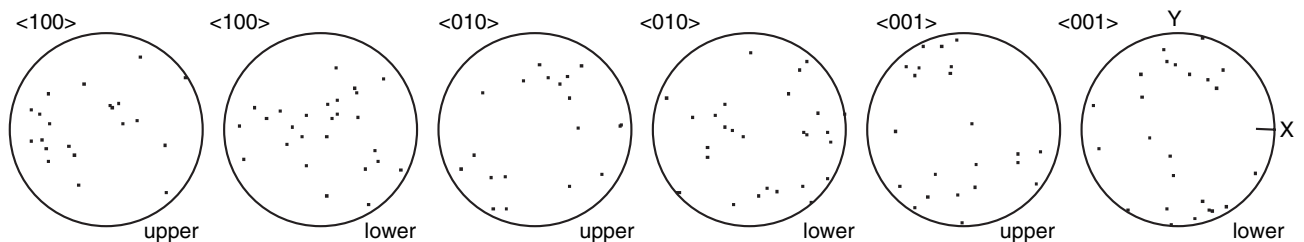


Fig. 3. Kyanite pole figures (equal-area) show no strong crystallographic-preferred orientation. Pole figures were constructed using one point per grain for the 47 kyanite grains observed in a single thin section of whiteschist.

the rheological properties and the exhumation mechanisms of rocks from subduction zones in so far as the microstructures reflect the deformation processes.

REGIONAL GEOLOGY AND SAMPLE DESCRIPTION

The whiteschist sample under study was collected south of Lake Zheltau in the Kulet region from ultrahigh-pressure metamorphic (UHPM) unit II of the Kokchetav Massif (Fig. 1b). The UHPM unit II includes the well-studied diamond bearing rocks of the Kumdy-Kol area and coesite-bearing whiteschist and eclogite of the Kulet area. Diamond-bearing dolomitic marble from Kumdy-Kol underwent peak metamorphism of 4–6 GPa, $\sim 1000^\circ\text{C}$ (Zhang *et al.*, 1997) at 530 ± 7 Ma (Claoue-Long *et al.*, 1991). Peak conditions for whiteschist of the Kulet area are 3.5 GPa, 720–760 $^\circ\text{C}$ (Parkinson, 2000) with monazite inclusions in garnet of associated eclogite dated at 500 ± 3 Ma. Detailed mapping of Parkinson (2000) revealed that the composite lenses of whiteschist and eclogite are restricted along a fault bounded terrane south of Lake Zheltau.

Equilibrium assemblage for the whiteschist is kyanite + garnet + talc + phengite + coesite/quartz. Kyanite grains, up to 10 mm in length, display a weak shape preferred alignment that corresponds to a strong foliation defined by talc and phengite. Most kyanite grains in the matrix are euhedral and exhibit undulose extinction (Fig. 2a). A few kyanite blades contain one or more kink bands (Fig. 2b). Kyanite inclusions in garnet are rounded, subhedral with no undulose extinction or kink bands. Garnet, ~ 2 mm in diameter, is equant and sub-euhedral.

ANALYTICAL METHODS

An EBSD system uses backscattered electrons emitted from a specimen in a scanning electron microscope (SEM) to form a diffraction pattern that is imaged on a phosphor screen. Analysis of the diffraction pattern allows measurement of the crystallographic orientation of a mineral, and the calculation of misorientation angles between any two measurements (Prior *et al.*, 1999). The EBSD studies were conducted at Bowdoin College on a LEO 1450VP SEM outfitted with an HKL Nordlys II detector and CHANNEL 5 software (software details in Schmidt & Olesen, 1989). The sample was prepared by taking a standard polished thin section weighted with a halved brass rod and polished an additional 6 h in a non-crystallizing colloidal silica suspension on a Buehler Vibromet2 vibratory polisher (SYTON method of Fynn & Powell, 1979). The thin section was not carbon coated; charging was minimized by using a chamber pressure of 10 Pa, combined with the 70° tilt. Operating parameters for collecting EBSD patterns were an accelerating voltage of 20 kV, a working distance of 25 mm, and a beam current of 2.2 nA. CHANNEL 5 acquisition and indexing

settings were 4×4 binning, high gain, Hough resolution = 75, 7 bands, and 80 reflectors. Lattice parameters for the kyanite match unit (reflector file) were from Comodi *et al.*, 1997. Mean angular deviations (MAD) between the detected Kikuchi bands and the match unit simulations were $< 1^\circ$. Data were post-processed by removing observed systematic misindexing ($180 \pm 5^\circ$ about $\langle 411 \rangle$ and $\langle 003 \rangle$) and by removing wild spikes. A wild spike is an isolated measurement point with a wrong indexing solution that is recognized because it differs significantly from adjacent measurements; it can occur when poor patterns are generated, such as when there is sample damage, a crack, or dislocation cluster (Day & Trimby, 2004). Pole figures show upper and lower hemisphere direction projections that contain data, because all crystal directions may be

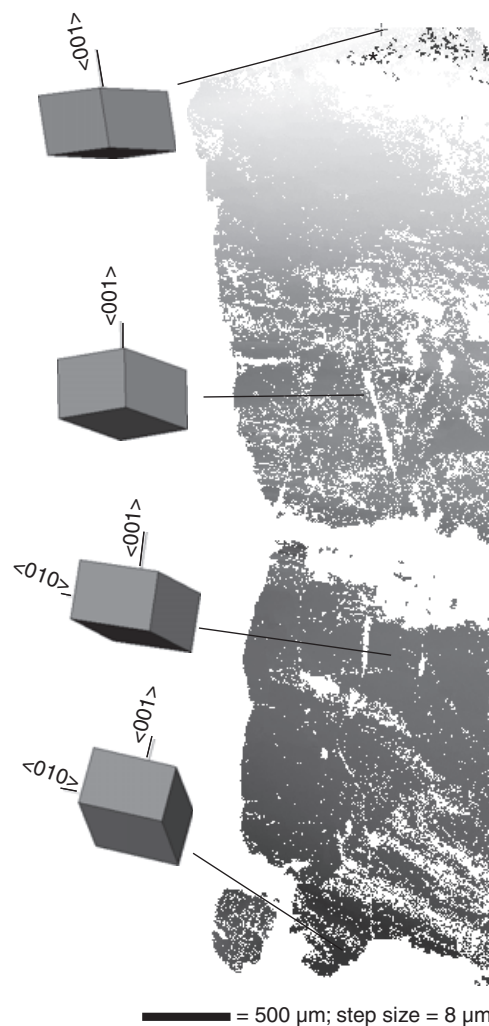


Fig. 4. Orientation map of undulatory kyanite (same grain as Fig. 2a) is grey scaled with a texture component from 0–50° (light grey to black) relative to the Euler angles of the * point at the top centre of the grain. The black spots in the top right are misindexing. The 3D crystals, with labelled crystallographic axes, show orientations as viewed looking down on the thin section.

distinguished in triclinic crystals; most figures also show projection of poles to planes, because in triclinic crystals the low-index directions are not parallel to the poles of these planes (cf. Prior & Wheeler, 1999 and Wenk *et al.*, 1986).

CRYSTAL PREFERRED ORIENTATION

No crystallographic preferred orientation (CPO) for the matrix kyanite in the sample was discernible. Kyanite shows a weak shape preferred alignment that corresponds to a strong foliation defined by talc and phengite. To evaluate whether the weak shape preferred alignment corresponded with a CPO, pole figures were constructed using one point per grain for the 47 kyanite matrix grains observed in a single thin section of the whiteschist (Fig. 3). The distribution on the pole figures does not appear to be completely random, but with 47 data points, the statistics are not sufficient to determine whether or not the CPO is indeed random.

ORIENTATIONS FOR KYANITE SHOWING UNDULOSE EXTINCTION

Most kyanite blades in the sample matrix exhibit undulose extinction when observed under crossed polars in a petrographic microscope. Orientation maps for portions of five such kyanite were obtained by EBSD methods. One kyanite showing undulose extinction (Fig. 2a) is fully analysed and presented here (Figs 4–7); data for other grains are comparable.

This example of an undulose kyanite ($\sim 5000 \times 1500 \mu\text{m}$) shows a 50° change of orientations along its length (Figs 4 & 7c). The grain is fractured; the orientation of the lower and upper portions of the grain have been shifted relative to each other (crystal models

on Fig. 4). Points from the upper portion of the grain plot in distinct clusters on the $\langle 010 \rangle$ and $[010]$ equal angle pole plots. There is $\sim 38^\circ$ dispersion of orientations for the $\langle 100 \rangle$, $\langle 001 \rangle$, $[100]$ and $[001]$ contoured pole plots (Fig. 5a,b).

The clusters of data on the $\langle 010 \rangle$ and $[010]$ plots suggest that rotation is about one of those. The misorientation (rotation) axis was determined by bisecting the $[001]$ and $[100]$ data dispersions (Fig. 6a). The intersection of these two bisections marks the misorientation axis. The uncertainty of the misorientation axis is influenced by the misorientation angle and by the accuracy of the orientation measurement; error estimate for the misorientation axis can be calculated as $\sin \delta_{\text{max}} = \sin r / \sin(\theta/2)$ where δ_{max} is the maximum deviation, r is the measurement accuracy, and θ is the rotation angle (methods of Kruse *et al.*, 2001). For this kyanite, the rotation angle is taken as the dispersion of the contoured data (38°) and the measurement accuracy as 1° (maximum MAD for this sample, and also the estimate for absolute orientations by Trimby *et al.*, 1998) calculating δ_{max} of 3.1° . A circle of error around the graphically determined misorientation axis intersects $\langle 010 \rangle$ and does not intersect $[010]$. Rotation about $\langle 010 \rangle$ is consistent with the $(100)[001]$ glide (Fig. 6b) suggested by previous researchers (cf. Mügge, 1898; Raleigh, 1965; Lenze *et al.*, 2005).

To further evaluate the rotation about $\langle 010 \rangle$ with $(100)[001]$ glide necessitates graphically determining the (100) postulated slip plane and the pole to that plane (Fig. 6c), and evaluating whether the observed dispersion of data are consistent with a twist or tilt boundary plane. Small circle dispersion about $\langle 010 \rangle$ as well as a twist boundary plane drawn through the pole to (100) do not completely model the dispersion of $[001]$ and $[100]$ (Fig. 6d,e). A boundary containing

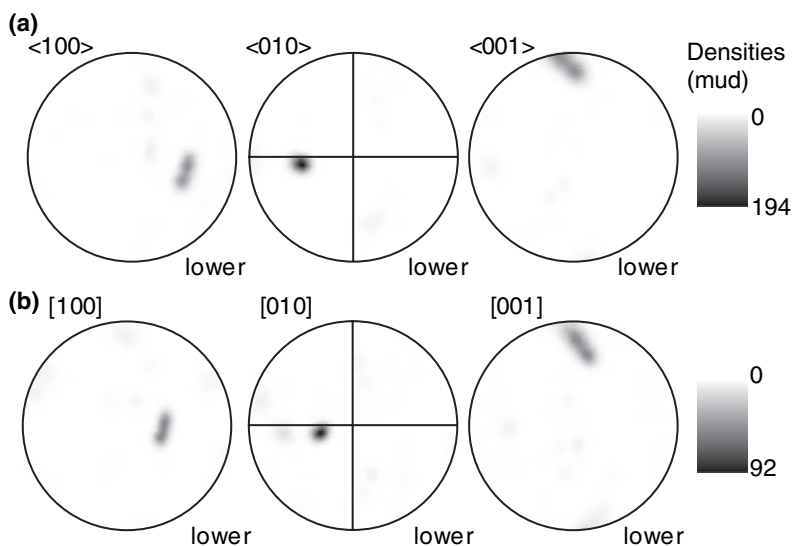


Fig. 5. Pole figures (equal angle) for the upper portion (above fracture) of the undulatory kyanite in Fig. 4. Contoured data for (a) crystallographic directions and (b) plane normals are plotted from 53 653 analysis points on equal angle stereonet. Note that the poles to planes are not the same as the crystal directions for monoclinic crystals; specifically, the $[010]$ plot is noticeably different than the $\langle 010 \rangle$ plot. All upper and lower hemisphere crystal directions were plotted, only plots with data are shown. Grey scale contours show densities for the mean unit deviation (mud) which is the ratio of the frequency of a specific orientation to the frequency of equally partitioned orientations. Points cluster on the $\langle 010 \rangle$ and $[010]$ plots and show 38° dispersion on the $\langle 100 \rangle$, $\langle 001 \rangle$, $[100]$, and $[001]$ plots.

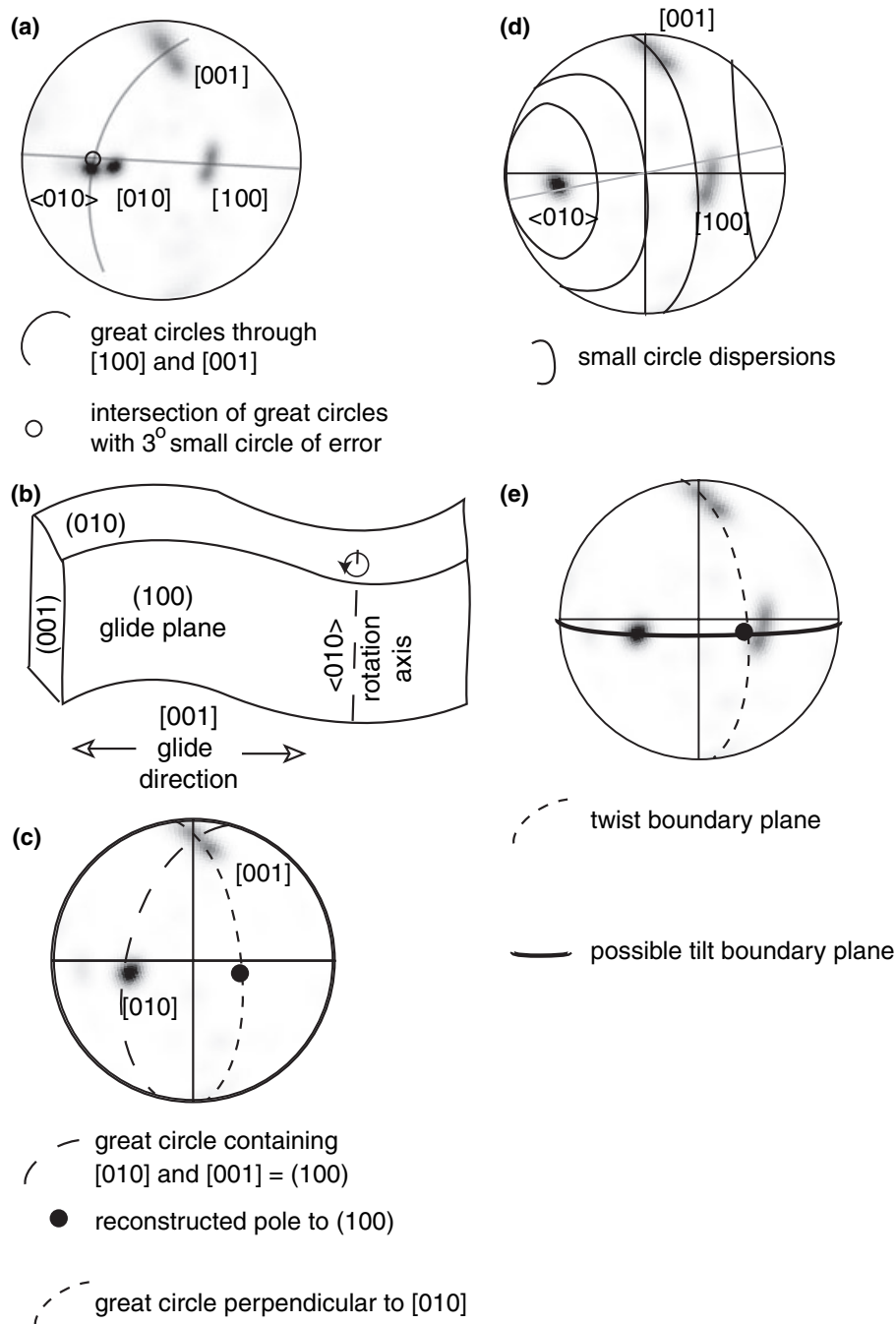


Fig. 6. Combined data from Fig. 5 on lower hemisphere equal angle pole figure for analysis. (a) Misorientation axis graphically determined as the intersection of great circles bisecting [001] and [100], and indicated with a 3° small circle of error. The <010> crystallographic direction is interpreted to be the rotation axis, because it overlaps with the misorientation axis. (b) Simplified sketch (modified from Lenze *et al.*, 2005, Fig. 8) of how kyanite blades may exhibit undulatory rotations about <010> consistent with a (100)[001] glide. (c) Interpretation of lower hemisphere projections of [010] and [001] with reconstructed (100) pole and great circles. (d) Possible rotation axis <010> with lower hemisphere projections of [001] and [100] and small circle dispersion. The dispersion of [001] nearly matches the small circle; the dispersion of [100] does not match the small circle. (e) A twist boundary plane alone cannot fully explain the dispersion of [100]. The constructed tilt boundary plane intersects the dispersion of [001], the reconstructed (100), and the rotation axis <010>, and the dispersion of [001] might be more fully explained by a boundary containing both twist and tilt components.

both twist and tilt components (Fig. 6e) seems to more fully describe the dispersion of orientations observed in this undulatory kyanite.

Orientations along a linear transect through both portions of the fractured undulatory kyanite show a progressive change accommodating over 50° rotation

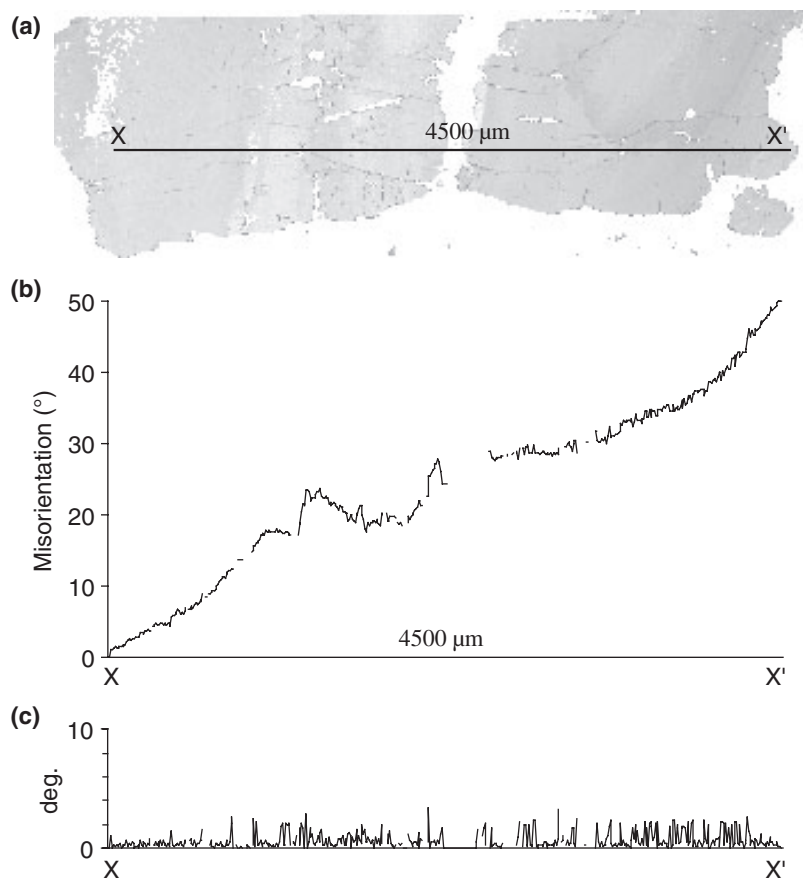


Fig. 7. (a) Band contrast map of kyanite showing location of transect used for misorientation profiles. (b) Misorientation profile from X to X' along undulatory kyanite (same grain as Figs 2a & 4) relative to first point. (c) Misorientation profile from X to X' showing point-to-point variations. Data are not plotted for points which could not be indexed or for which there was systematic misindexing of $\sim 180^\circ$. Note that the error for EBSD measurements is approximately $\pm 1^\circ$.

(Fig. 7a,b). Point-to-point variations ($8 \mu\text{m}$ step size) along the transect are all $< 4^\circ$, with most $< 2^\circ$ (Fig. 7c). These small point-to-point variations yield no mappable low-angle boundary traces ($> 2^\circ$).

ORIENTATIONS FOR KINK BANDED KYANITE

While nearly all kyanite grains in the sample matrix show undulose extinction, few have kink bands as observed with light microscopy. One kyanite blade ($\sim 1500 \times 400 \mu\text{m}$; Fig. 2b) exhibits undulose extinction, has one kink band that completely crosses its width, and has two partial kink bands that extend only $\sim 150 \mu\text{m}$ from each side. These observed characteristics suggest it is an appropriate grain to evaluate for the development of kink bands in kyanite.

The kyanite shows up to 45° change of orientations along its length (Fig. 8). Crystal direction models show apparent rotation of axes about $\langle 010 \rangle$ (Fig. 8). Points from the top, kink, and bottom portions of the grain plot in distinct clusters on the $\langle 010 \rangle$ and $[010]$ equal angle pole plots (Fig. 9). There is $32\text{--}34^\circ$ dispersion of orientations for the $\langle 100 \rangle$, $\langle 001 \rangle$, $[100]$ and $[001]$ contoured pole plots for the above and below kink portions of the grain (Fig. 9).

Similar to the undulose kyanite example, the data cluster on the $\langle 010 \rangle$ and $[010]$ plots for the kink-banded kyanite. The misorientation (rotation) axis was graphically determined as the intersection of great circles bisecting the $[001]$ and $[100]$ data dispersions (Fig. 10a) with a calculated error estimate of 3.4° (method as outlined for the undulose kyanite). A circle of error around the misorientation axis intersects $\langle 010 \rangle$ and does not intersect $[010]$ (Fig. 10a).

Rotation about $\langle 010 \rangle$ for the kink-banded kyanite is consistent with the $(100)[001]$ glide discussed for the kyanite with undulose extinction. However, for this example, a twist boundary appears to model the dispersion of orientations fairly well without necessitating a substantial tilt component (Fig. 10b,c). The orientation data for the kink band fits the same modelled twist boundary as that for the non-kink portions of the kyanite (Fig. 10d).

Orientations along a linear transect across the kink-banded kyanite show a generally progressive change corresponding to dispersion with a discrete jump in orientation across the kink band (Fig. 11a,b). With the exception of the kink band, point-to-point variations ($3 \mu\text{m}$ step size) along the full length transect typically are $< 2^\circ$, with a few just under 6° (Fig. 11c). At the kink band boundaries, the point-to-point variations

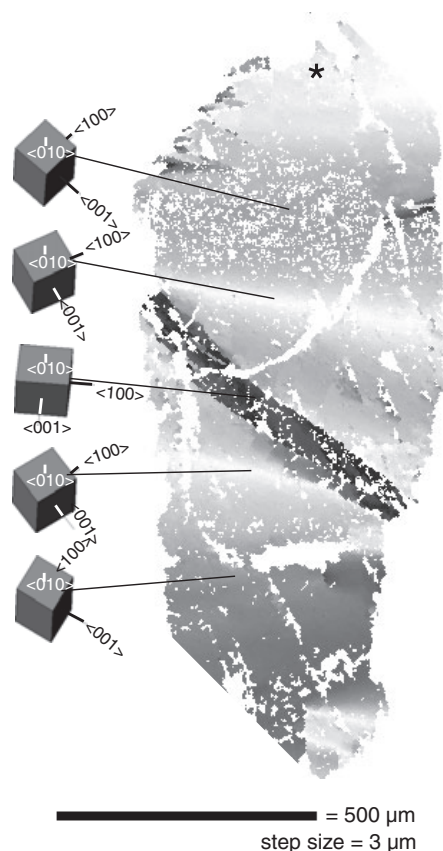


Fig. 8. Orientation map of kink-banded kyanite (same grain as Fig. 2b) is grey-scaled with a texture component from 0 to 45° (light grey to black) relative to the Euler angles of the * point at the top centre of the grain. The 3D crystals, with labelled crystallographic axes, show orientations as viewed looking down on the thin section.

are much higher, 29° and 18°; between the boundaries the point-to-point variations in the kink band are < 2° (Fig. 8b). A short (170 µm) transect across a partial (possibly incipient?) kink band on the edge of the kyanite blade shows several spikes of orientation changes > 15° relative to the first point (Fig. 11d); no such spikes are observed on the corresponding positions on the full-length transect along the midline of the grain. A short (180 µm) transect across the kink band at the edge of the grain shows an orientation change of 50° relative to the first point (Fig. 11d) and corresponds to the spikes of orientation changes observed along the midline transect.

The crystal lattice misorientations between two points analysed by EBSD are expressed by a rotation angle and a rotation axis (Wheeler *et al.*, 2001). The map of high-angle (misorientation angles > 10°) grain boundaries (Fig. 12a) mirrors the map of misorientations about the <010> axis (Fig. 12b). The lines on both maps mark the prominent kink band across the full width of the kyanite blade and the partial kink bands near one end of the kyanite. There are multiple

subparallel high-angle grain boundaries near the edge of the kyanite for the full-width kink band and for the partial kink bands. The high-angle boundary traces for the partial kink band are approximately perpendicular to the maximum orientation gradient along the length of the kyanite. However, the boundary traces for the full-width kink band are at an angle to the maximum orientation gradient and thus initially seem inconsistent with the previously suggested twist boundary (Fig. 10d). For this full-width kink band, multiple subparallel high-angle grain boundaries on the edges of the grain reduce to one boundary on either side of the kink band. It may be possible that during the development of the full-width kink band, partial kink bands near both edges propagated towards each other to form the observed full-width kink band.

These high angle misorientations that mark the kink bands (Fig. 12) are about the <010> axis, the axis closest to the graphically determined misorientation axis (Fig. 10a). A few of the high-angle grain boundaries correspond to fractures observed in the kyanite. Other observed fractures do not correspond with high-angle grain boundaries. Pre-existing grain boundaries may facilitate the development of fractures, perhaps related to decompression during exhumation.

KYANITE INCLUSIONS IN GARNET

Kyanite inclusions in garnet are 100–500 µm in diameter, anhedral, and not kink banded. Orientation maps of inclusions do not show the large variations in crystal lattice orientations that the matrix kyanite grains exhibit. Minor misorientations (2–3°) between lattices seem limited to the edges of the inclusions. Although the garnet surrounding the kyanite is extensively fractured, orientation maps by EBSD show no variations of lattice orientation within individual garnet.

DISCUSSION

Rotation axis and slip system

For kyanite exhibiting undulose extinction and/or kink bands the data, presented in this paper and in previous papers, are consistent with a (100)[001] slip system. Mügge (1898) first suggested the (100)[001] slip system based on optical observations. Then, Raleigh (1965) used experimentally produced slip lines to evaluate glide plane and direction for slip in kyanite strained 5–10% at 5–7 kbar confining pressure. (Slip lines are linear markings formed from the offset by glide on slip planes intersecting the polished mineral surface.) Using incident light to observe slip lines, Raleigh (1965) noticed traces of (100) slip planes and kink bands trending approximately normal to slip lines with rotation about [010] defining a slip direction of [001] and confirming the observation of Mügge (1898).

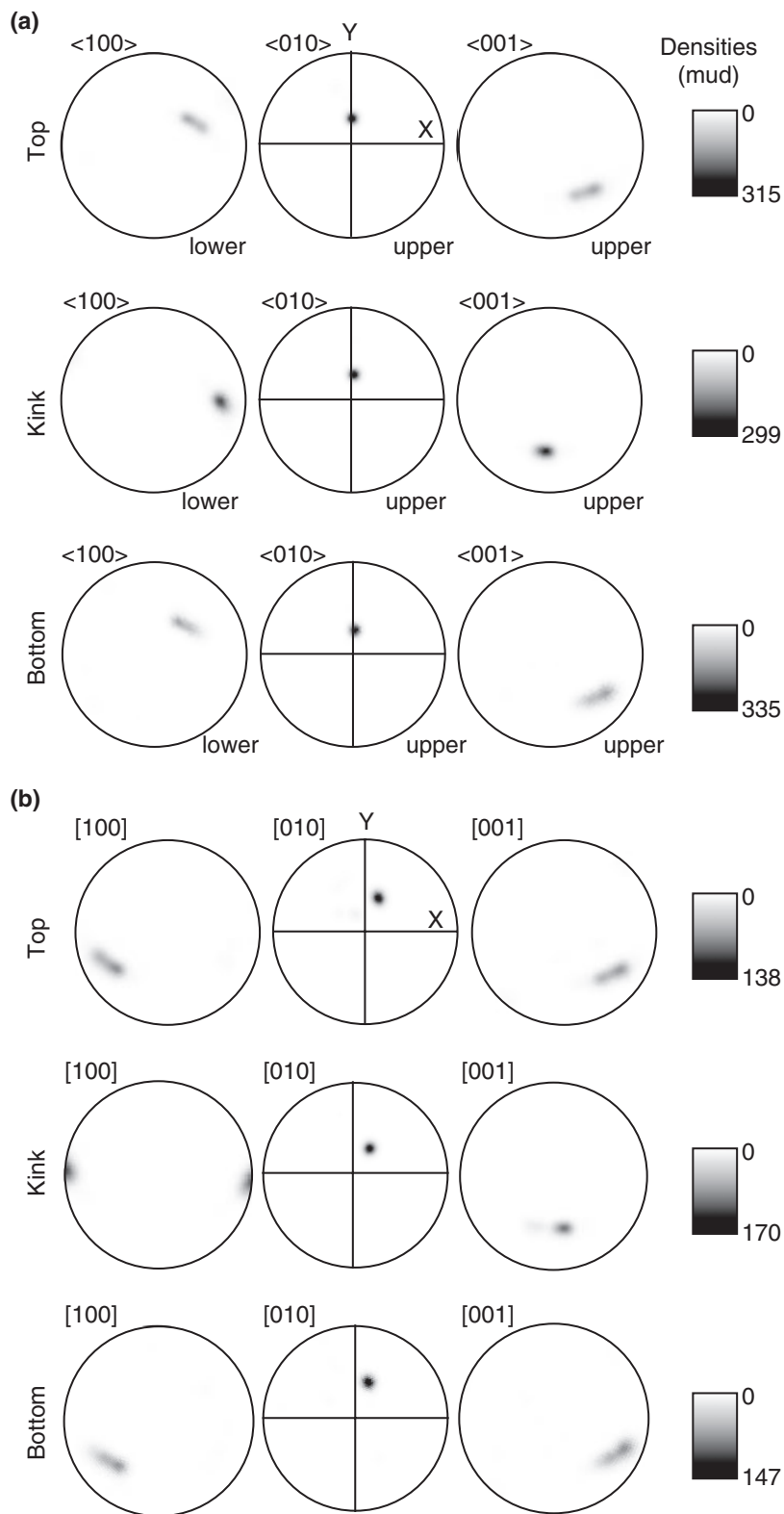
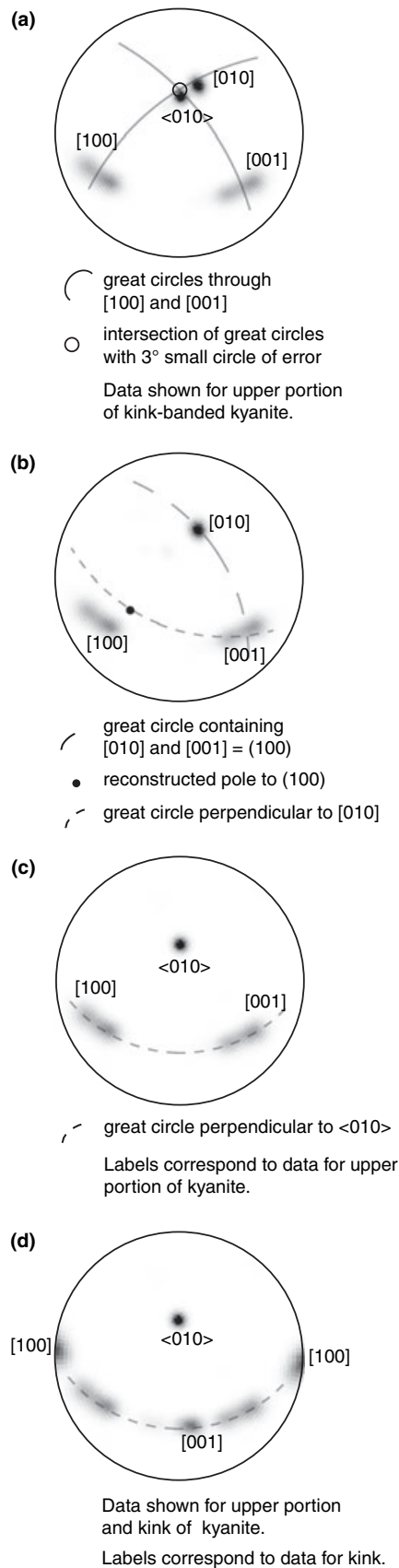


Fig. 9. Pole figures (equal angle) for the kink-banded kyanite of Fig. 8. (a) Crystal directions for the top (above kink), kink, and bottom (below kink) portions of the grain. All upper and lower hemisphere crystal directions were plotted, only plots with data are shown. (b) Upper hemisphere poles to planes. Note that the poles to planes are not the same as the crystal directions for monoclinic crystals; specifically, the [010] plot is noticeably different than the $\langle 010 \rangle$ plot. Grey scale contours for all pole figures show densities for the mean unit deviation (mud) which is the ratio of the frequency of a specific orientation to the frequency of equally partitioned orientations. Data points (22 188) were contoured for the top portion of the grain (34° dispersion for [001] and [100]); 1979 for the kink; and 10 733 for the bottom portion of the grain (32° dispersion for [001] and [100]). Contours for the top and bottom portions of the grain are nearly identical.

Raleigh (1965) suggested that the slip occurred in 'closest packing directions' such that the strong Si-O bonds of kyanite remained unbroken. More recently,

Lenze *et al.* (2005) used EBSD point analyses to suggest a (100)[001] slip system for the formation of kink bands in kyanite of the UHP Dora Maira massif.



This study presents the first published orientation maps by EBSD for kyanite. Data are consistent with a (100)[100] slip system for the formation of kink bands and identify the same system for the formation of undulose extinction. The undulose extinction in the kyanite does not appear to be caused by microfracturing as has been described in feldspar by Tullis & Yund (1987); however, it should be noted that if microfracturing rather than plastic deformation was involved in forming undulatory extinction in kyanite, then analysis of the misorientation in terms of a slip system would not be valid.

The large data sets collected in the orientation maps of the kyanite allow determination of the misorientation axis, and an evaluation of whether this axis is more likely to be <010> or [010] (not the same in triclinic crystals). For both the undulose, and the kink-banded kyanite, the circle of error about the misorientation axis intersected with the collected data in the <010> crystallographic direction, but did not match the data plotted for [010] leading us to interpret the misorientation axis as <010>.

Dislocation creep

Undulose extinction in minerals, such as described for kyanite in this paper, suggests plastic deformation by dislocation creep (White, 1986; Zhao *et al.*, 2005). The dispersion of EBSD data about rotation axes also points to plastic deformation by dislocation creep (Lloyd *et al.*, 1997; Prior *et al.*, 2002; Bestmann & Prior, 2003). The data presented for kyanite with undulose extinction show > 50° dispersion about <010> (Figs 6 & 7), consistent with this process.

Angular rotations across kink bands are > 10° about <010> (Fig. 11) signifying the development of high-angle grain boundaries. Zhao *et al.* (2005) surmised that high-angle grain boundaries observed in kyanite from the UHP Dora Maira massif formed through 'climb-accommodated dislocation creep' resulted in the rotation of subgrains. This model builds on work of Poirier & Guillope (1979) who described deformation-induced recrystallization involving the rotation of subgrains to develop high-angle grain boundaries and kink bands. The orientation map data presented in this paper from the UHP Kokchetav

Fig. 10. Combined data from Fig. 8 (top portion of grain) on one upper hemisphere equal angle pole figure for analysis. (a) Misorientation axis graphically determined as the intersection of great circles bisecting [001] and [100], and indicated with a 3° small circle of error. The <010> crystallographic direction is interpreted to be the most probable rotation axis, because it overlaps with the misorientation axis. (b) Interpretation of lower hemisphere projections of [010] and [001] with reconstructed (100) pole and great circles. (c) Probable rotation axis <010> with lower hemisphere projections of [001] and [100]. The dispersion of [001] and [100] lie on the twist boundary plane perpendicular to <010>. (d) The data for the kink-banded portion of the grain lie on the same twist boundary plane.

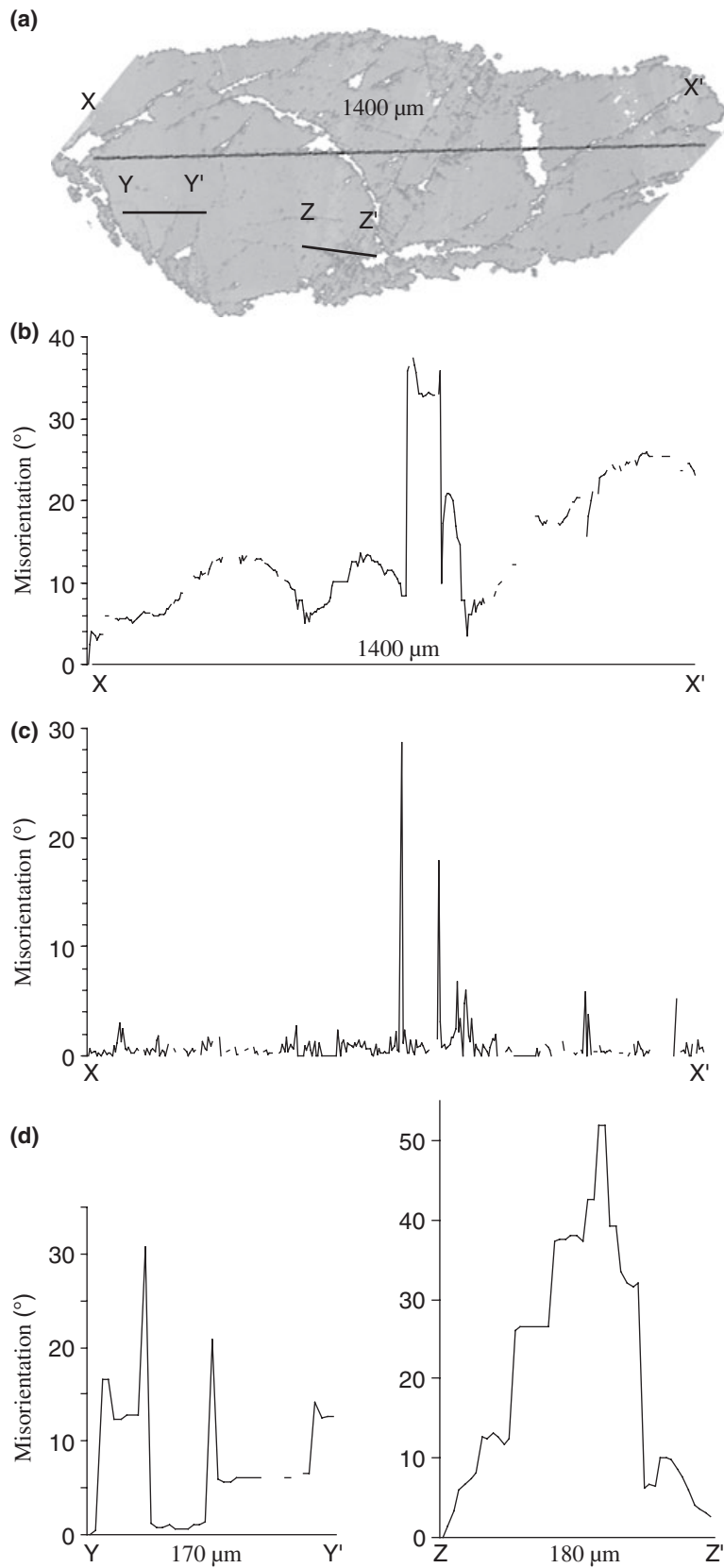


Fig. 11. (a) Band contrast map of kink-banded kyanite showing location of three transects used for misorientation profiles. (b) Misorientation profile from X to X' along kink-banded kyanite (same as Figs 2b & 6) relative to first point. Data are not plotted for points which could not be indexed or for which there was systematic misindexing of $\sim 180^\circ$. Note that the error for EBSD measurements is approximately $\pm 1^\circ$. (c) Misorientation profile from X to X' showing point-to-point variations. (d) Misorientation profiles from Y to Y' and Z to Z' relative to first point with 3 $\times$ horizontal exaggeration.

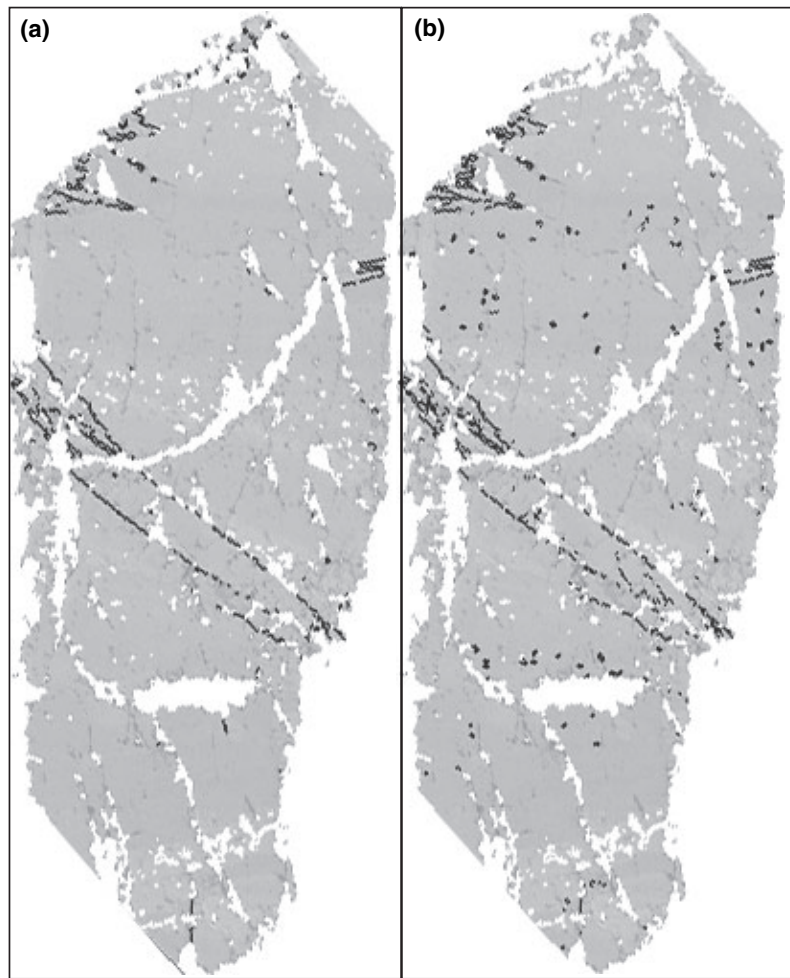


Fig. 12. (a) Map of high-angle grain boundaries (misorientation angles $> 10^\circ$; indicated as black lines) developed within kink-banded kyanite (band contrast map kyanite; same crystal as Figs 2b & 8–11). (b) Map of misorientations about $\langle 010 \rangle$ as indicated with black lines.

complex substantiate the development of high-angle grain boundaries and kink bands in kyanite by dislocation climb. Within the kink bands there is no observed undulatory extinction and little variation in crystallographic orientation. The formation of the kink band created a relatively strain-free region between the grain boundaries, a potentially significant process in accommodating large strain observed in geological processes (cf. White, 1977).

Multiple high-angle boundaries are observed along the edge of kyanite grains (Fig. 11). High interfacial strain at the kyanite grain boundaries may have led to higher dislocation densities and resulted in the initiation of the multiple high-grain boundaries observed. Multiple parallel profiles (collected during data analysis) across the high-grain boundaries show angular variations $> 40^\circ$ at the edge of the kyanite (see for example, Z–Z', Fig. 11d) that decrease towards the centre of the grain. Within $150 \mu\text{m}$ from the edge towards the centre, most of these boundaries have angular misorientations $< 2^\circ$. Only the boundaries immediately adjacent to the kink band are observed to persist as high-angle grain boundaries ($> 10^\circ$) across the width of the kyanite. This suggests the

presence of fewer dislocations away from the edge of the grain.

Deformation conditions

The crystal plastic deformation of kyanite blades is interpreted to have occurred in the fault-bounded terrane of UHPM unit II during the exhumation of the Kokchetav Massif. Kyanite inclusions in garnet lack evidence for extensive deformation, signifying that deformation was not prograde and that the rheologically competent garnet may have shielded the kyanite from later deformation. Based on a detailed study of the whiteschists of the Kokchetav Massif, Parkinson (2000) interpreted matrix quartz to be unstrained. The coexistence of unstrained quartz and strained kyanite leads us to tentatively suggest that deformation of kyanite occurred under UHP conditions prior to the coesite-quartz transformation during exhumation. If so, then this study seems to support the Zhao *et al.* (2005) assertion, based on their study of mylonites from a shear zone in the Sulu UHP belt, that stress levels deep in subduction zones are sufficiently high ('on the order of tens of MPa')

for minerals to deform by dislocation creep. The precise quantification of the required stress to create undulose extinction and kink banding of kyanite calls for future laboratory deformation experiments on kyanite that will allow for a rheological comparison with naturally deformed samples.

ACKNOWLEDGEMENTS

This paper is dedicated to J.G. Liou, R.B.'s graduate advisor at Stanford University who introduced her to studies of UHPM. Samples were collected during a survey of the Kokchetav Massif in 1994, funded by National Science Foundation (NSF) grant 9304480 to R.G. Coleman. This material is based upon work supported by NSF grants 0320871 and 9951390 to R.B. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF. We thank the guest editors, L. Dobrzhietskaya and J. Gilotti, for their work on this special volume, and greatly appreciate the constructive comments of the reviewers, D. Prior and H. Stünitz.

REFERENCES

- Bestmann, M. & Prior, D. J., 2003. Intragranular dynamic recrystallization in naturally deformed calcite marble: diffusion accommodated grain boundary sliding as a result of subgrain rotation recrystallization. *Journal of Structural Geology*, **25**, 1597–1613.
- Chopin, C., 1984. Coesite and pure pyrope in high-grade blueschist of the Western Alps. A first record and some consequences. *Contributions to Mineralogy and Petrology*, **86**, 107–118.
- Claoue-Long, J. C., Sobolev, N. F., Shatsky, V. S. & Sobolev, A. V., 1991. Zircon response to diamond pressure metamorphism in the Kokchetav massif, USSR. *Geology*, **19**, 710–713.
- Comodi, P., Zanazzi, P. F., Poli, S. & Schmidt, M. W., 1997. High-pressure behavior of kyanite; compressibility and structural deformations. *American Mineralogist*, **82**, 452–459.
- Day, A. & Trimby, P., 2004. *Channel 5 Manual*. HKL Technology, Inc., Hobro, Denmark.
- Ernst, W. G. & Liou, J. G., 2000. *Ultrahigh-Pressure Metamorphism and Geodynamics in Collision-Type Orogenic Belts*. International Book Series, 4. Geological Society of America, Boulder CO. 293 pp.
- Fynn, G. W. & Powell, W. J. A., 1979. *The Cutting and Polishing of Electro-optic Materials*. Adam Hilger, London. 216 pp.
- Hacker, B. R. & Liou, J. G., 1998. *When Continents Collide: Geodynamics and Geochemistry of Ultrahigh-Pressure Rocks*. Kluwer Academic Publishers, Boston, MA. 323 pp.
- Hwang, S., Shen, P., Yui, T. & Chu, H., 2001. Defect microstructures of minerals as a potential indicator of extremely rapid and episodic exhumation of ultrahigh-pressure metamorphic rock: implication to continental collision orogens. *Earth and Planetary Science Letters*, **192**, 57–63.
- Kruse, R., Stünitz, H. & Kunze, K., 2001. Dynamic recrystallization processes in plagioclase porphyroclasts. *Journal of Structural Geology*, **23**, 1781–1802.
- Lenze, A., Stöckhert, R. & Wirth, R., 2005. Grain scale deformation in ultra-high-pressure metamorphic rocks – an indicator of rapid phase transformation. *Earth and Planetary Science Letters*, **229**, 217–230.
- Liou, J. G., Zhang, R. & Ernst, W. G., 1994. An introduction to ultrahigh-pressure metamorphism. *The Island Arc*, **3**, 1–24.
- Lloyd, G. E., Farmer, A. B. & Mainprice, D., 1997. Misorientation analysis and the formation and orientation of subgrain and grain boundaries. *Tectonophysics*, **279**, 55–78.
- Mügge, O., 1898. Über translation und verwandte erscheinungen in kristallen. *Neues Jahrbuch für Mineralogie, Geologie und Paläontologie*, **1**, 71–158.
- Parkinson, C. D., 2000. Coesite inclusions and prograde compositional zonation of garnet in whiteschist of the HP-UHPM Kokchetav massif, Kazakhstan; a record of progressive UHP metamorphism. *Lithos*, **52**, 215–233.
- Poirier, J. P. & Guillope, M., 1979. Deformation induced recrystallization of minerals. *Bulletin de Mineralogie*, **102**, 67–74.
- Prior, D. J. & Wheeler, J., 1999. Feldspar fabrics in a greenschist facies albite-rich mylonite from electron backscatter diffraction. *Tectonophysics*, **303**, 29–49.
- Prior, D. J., Boyle, A. P., Brenker, F. *et al.*, 1999. The application of electron backscatter diffraction and orientation contrast imaging in the SEM to textural problems in rocks. *American Mineralogist*, **84**, 1741–1759.
- Prior, D. J., Wheeler, J., Peruzzo, L., Spiess, R. & Storey, C., 2002. Some garnet microstructures: an illustration of the potential of orientation maps and misorientation analysis in microstructural studies. *Journal of Structural Geology*, **24**, 999–1011.
- Raleigh, C. B., 1965. Glide mechanism in experimentally deformed minerals. *Science*, **150**, 339–341.
- Schmidt, N. H. & Olesen, N. O., 1989. Computer-aided determination of crystal lattice orientation from electron channeling patterns in the SEM. *Canadian Mineralogist*, **27**, 15–22.
- Smith, D. C., 1984. Coesite in clinopyroxene in the Caledonides and its implications for geodynamics. *Nature*, **310**, 641–644.
- Terry, M. P. & Heidelbach, F., 2005. Deformation-enhanced metamorphic reactions and the rheology of high-pressure shear zones, Western Gneiss Region, Norway. *Journal of Metamorphic Geology*, **24**, 3–18.
- Trimby, P. W., Prior, D. J. & Wheeler, J., 1998. Grain boundary hierarchy development in a quartz mylonite. *Journal of Structural Geology*, **20**, 917–935.
- Tullis, J. & Yund, R. A., 1987. Transition from cataclastic flow to dislocation creep in feldspar: mechanisms and microstructures. *Geology*, **15**, 606–609.
- Wenk, H. R., Bunge, H. J., Jansen, E. & Pannetier, J., 1986. Preferred orientation of plagioclase-neutron diffraction and U-stage data. *Tectonophysics*, **126**, 271–284.
- Wheeler, J., Prior, D. J., Jiang, Z., Spiess, R. & Trimby, P. W., 2001. The petrological significance of misorientations between grains. *Contributions to Mineralogy and Petrology*, **141**, 109–124.
- White, S., 1977. Geological significance of recovery and recrystallization processes in quartz. *Tectonophysics*, **39**, 143–170.
- White, S. H., 1986. The effects of strain on the microstructures, fabrics and deformation mechanisms in quartzites. *Philosophical Transactions Royal Society of London*, **A283**, 69–86.
- Zhang, R. Y., Liou, J. G., Ernst, W. G., Coleman, R. G., Sobolev, N. V. & Shatsky, V. S., 1997. Metamorphic evolution of diamond-bearing and associated rocks from the Kokchetav Massif, northern Kazakhstan. *Journal of Metamorphic Geology*, **15**, 479–496.
- Zhao, Z. Y., Wei, C. J. & Fang, A. M., 2005. Plastic flow of coesite eclogite in a deep continent subduction regime: microstructures, deformation mechanism and rheologic implications. *Earth and Planetary Science Letters*, **237**, 209–222.

Received 25 March 2006; revision accepted 28 November 2006.