A collection of time-lapse movies from transmitted light deformation experiments

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Abstract

Since the late nineteen seventies, deformation experiments in transmitted light have been used by geoscientists to help understand the complex dynamics of microstructural evolution during ductile creep. This contribution presents a collection of digitized time-lapse movies of experiments with a variety of model materials. Most of these experiments have served as a basis of publications, and the movies can serve as background information for these papers. In addition they are useful as a teaching resource.

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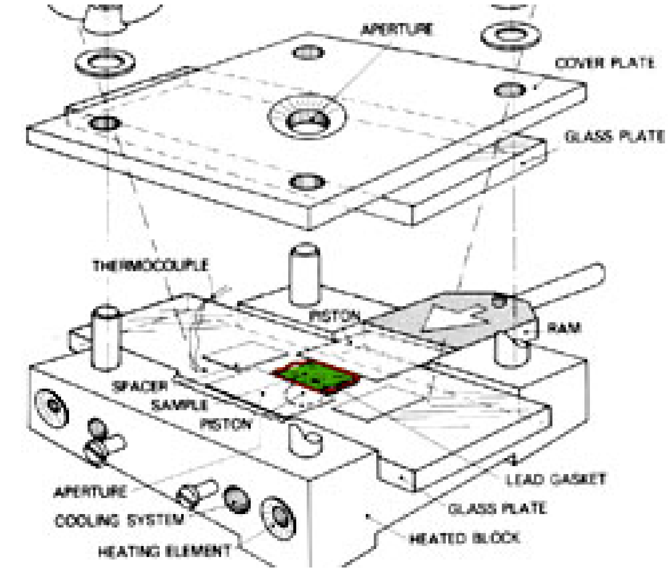
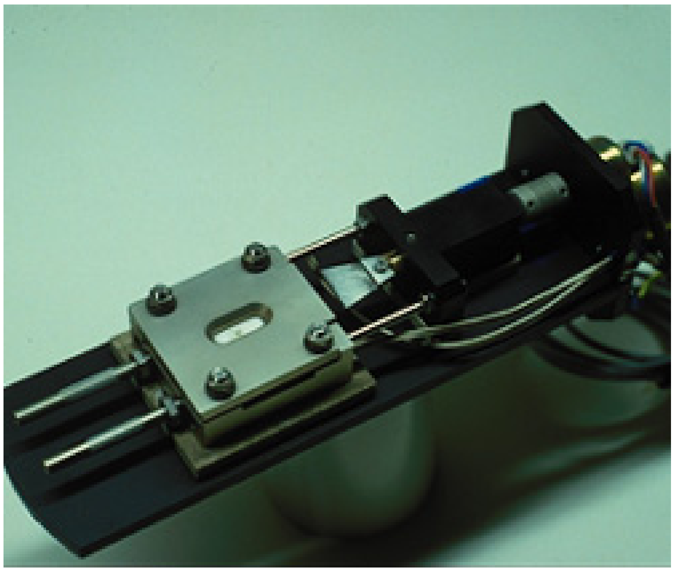
Introduction

Deformation experiments in transmitted light have been used by geoscientists since the late nineteen seventies as an aid to better understand the complex dynamics of microstructural evolution during creep.

Building on pioneering work in the sixties, the experiments used thin (usually around 0.1 mm thick) samples of a transparent crystalline material sandwiched between two glass plates, to generate plane strain. A large variety of model materials were tried (e.g. Wilson, this volume, Hafner and Passchier, this volume, McLaren, this volume, Ree, this volume, Park, this volume, and the apparatus and the technique was slowly improved over the years. Improvements to the cell design were made to deform samples containing pore fluid and to allow very high shear strains in a ringshear arrangement (Jessell and Lister 1991).





A landmark paper was presented by Means (1983) who inserted inert markers into the sample to simultaneously observe the displacement path of many points in the sample and the miscrostructural evolution. Reviews of early work are presented in Urai et al., 1986, Means 1990 and Bons 1993. Modern work has explored the deformation of polyphase materials, combined the microstructural data with accurate measurement of mechanical properties in bulk samples, and developed further refinements to control the stress in the samples, together with the pore fluid pressure. Measurements were compared with finite element models of the experiment. Major advances were the development of analytical tools to analyse the displacement field with high resolution (Bons et al., 1993) and simultaneously the change in crystallographic orientation (Heilbronner, this volume).

Work is in progress to develop cells for use at high pressure and temperature deformation experiments. The latest paper using this technique is that of Bauer et al., (2000). It seems therefore that transmitted light deformation is now a well-established and useful tool in structural geology, with a potential for further contributions.

In a number of early studies cine cameras were used to prepare time lapse movies of the experiments. These movies were a useful basis for further analysis, and in addition to being excellent teaching tools. Videotapes based on this material have been in circulation over a decade, but with the advent of digital video it has become much easier to distribute such material.

This contribution presents a collection of digitized time-lapse movies of experiments with a variety of model materials. Most of these experiments have been carried out more than fifteen years ago, and were describe in detail in publications. The movies can serve as a useful resource base for these papers. In addition the movies are useful as teaching resource. Where appropriate, reference is made to the relevant publications, and therefore the descriptions are kept short.

Camphor movies

Introduction

The movies presented below were recorded in 1979 at Imperial College, London, in cooperation with Sue Burrows and supervised by John Humphries. Results were published in Urai et al., (1980) and Urai and Humphries (1981). Most of the processes seen in the movies were described in detail in these two papers.

Camphor ($C_{10}H_{16}O$) occurs in several forms. It melts above 425 K, it is Cubic below 425 K, Rhombohedral I below 365 $\pm$ 7 K, and Rhombohedral II below 243 K. The actual transformation temperatures are dependent both on the purity of the material and the proportions of d- and l-isomers present.

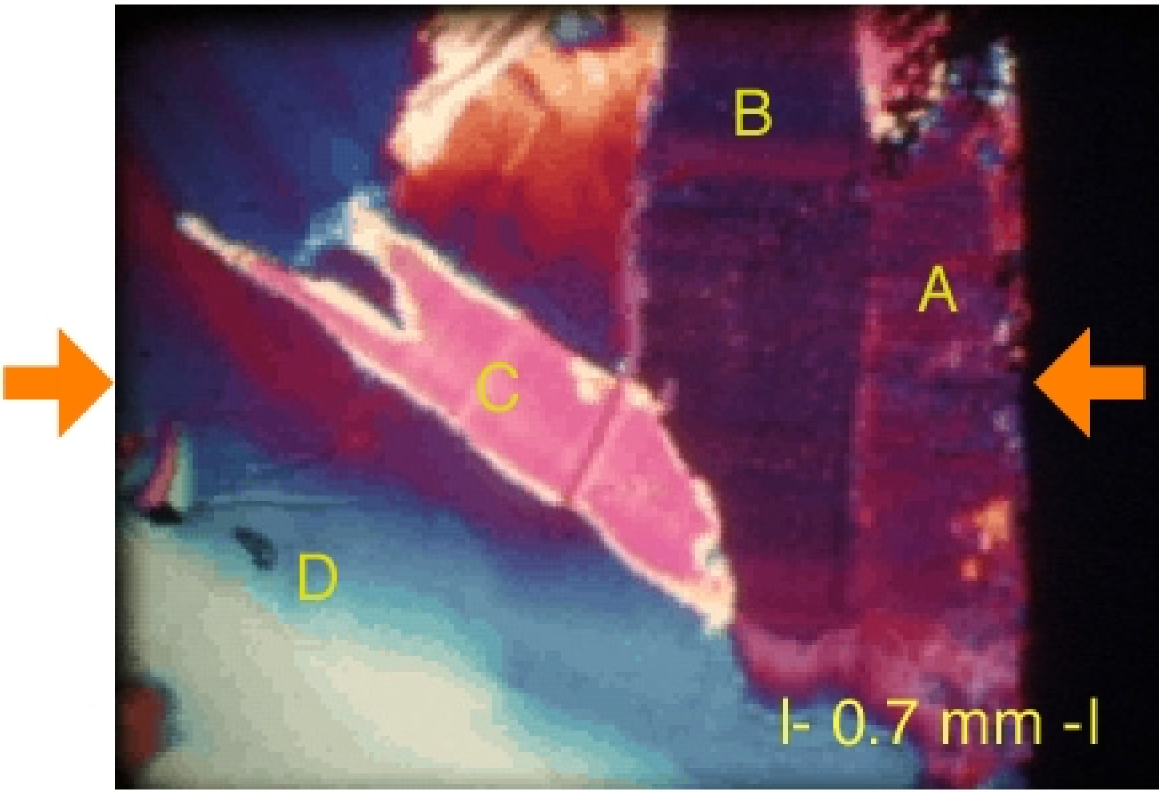
Camphor of commercial purity from two sources (Hopkin and Williams, and BDH) vas used. Although the deformation mechanisms were similar in both, the phase transition temperatures varied by about 10 K.

The granular material was cold-pressed into sheets ~ 0.15 mm thick between moist polished steel plates. The main "trick" of this technique is to get the camphor wafer to detach from both steel plates upon unloading and separating the plates. This was mostly a trial and error process, yielding a usable wafer after several tries. Specimens of approximately 7 x 7 mm were cut from these wafers and placed in the deformation cell. Silicon oil was used to minimize friction between specimen and glass, giving a more homogeneous deformation. First, the glass plates were pressed together very gently, taking care not to break the wafer which was usually slightly non-planar at this stage. Then the sample was heated into the cubic phase field where it became very soft and ductile, and the pressure on the glass plates slowly increased to iron out small irregularities in the sample surface, and slowly cooled. The phase transition produced large grains of the rhombohedral phase which were generally elongated but without preferred orientation.

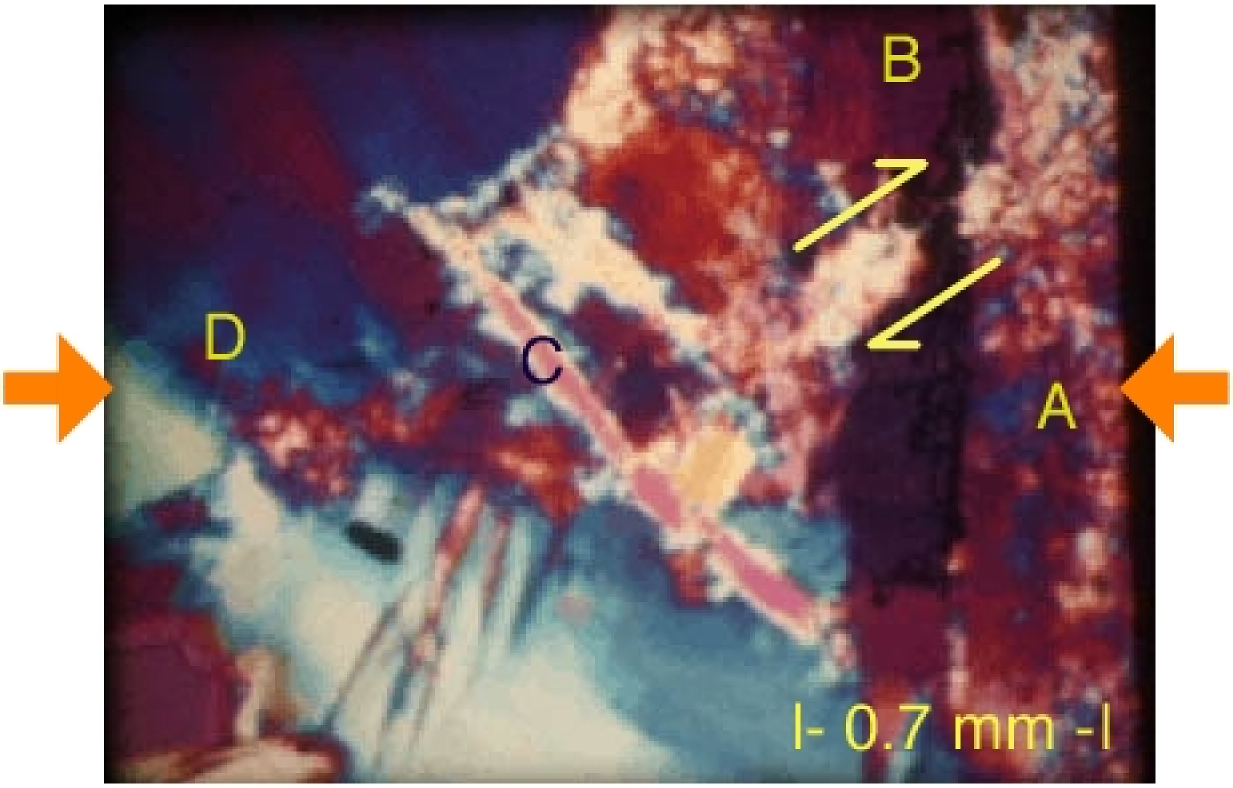
The movies presented here were initially recorded on 16 mm film using a Bolex time-lapse camera. Most experiments were run at a strain rate of approximately 10^{-4} sec^{-1}. The experiments shown in the movies typically lasted about 5 hours. Field of view in the movies is approximately 2 mm.

1 Heterogeneous deformation and dynamic recrystallization

This movie is presented in two parts. The initial microstructure is shown in the first frames of the movie, shot at room temperature with crossed polarizers and the gypsum plate. The movie was recorded in the part of the (larger) sample which was closest to the moving piston. Slip in this temperature range only occurs on the (001) plane, and thus only grains in an easy glide orientation (grain C) could undergo substantial glide. Therefore grains oriented with their (001) plane parallel or perpendicular to the specimen plane deformed in different ways. Grains in easy glide orientation first show fine linear features interpreted as slip lines, and later develop kink boundaries which slowly migrate through the grain; this can be compared with fig. 2 of Urai et al., 1980. Grains in a hard orientation (grain A and B with the slip plane parallel to the line of sight but perpendicular to the shortening direction, grain D with the slip plane paralell to the shortening direction) deformed by twinning. Already at low strains, small equiaxed grains formed by dynamic recrystallization at regions of strain heterogeneity such as kink boundaries, twins and grain boundaries.



With further deformation grain A starts to recrystallize, and finally a dextral shear zone (arrows) oriented at 45 degrees to the shortening direction is formed, cutting through the "hard" grains A and B.

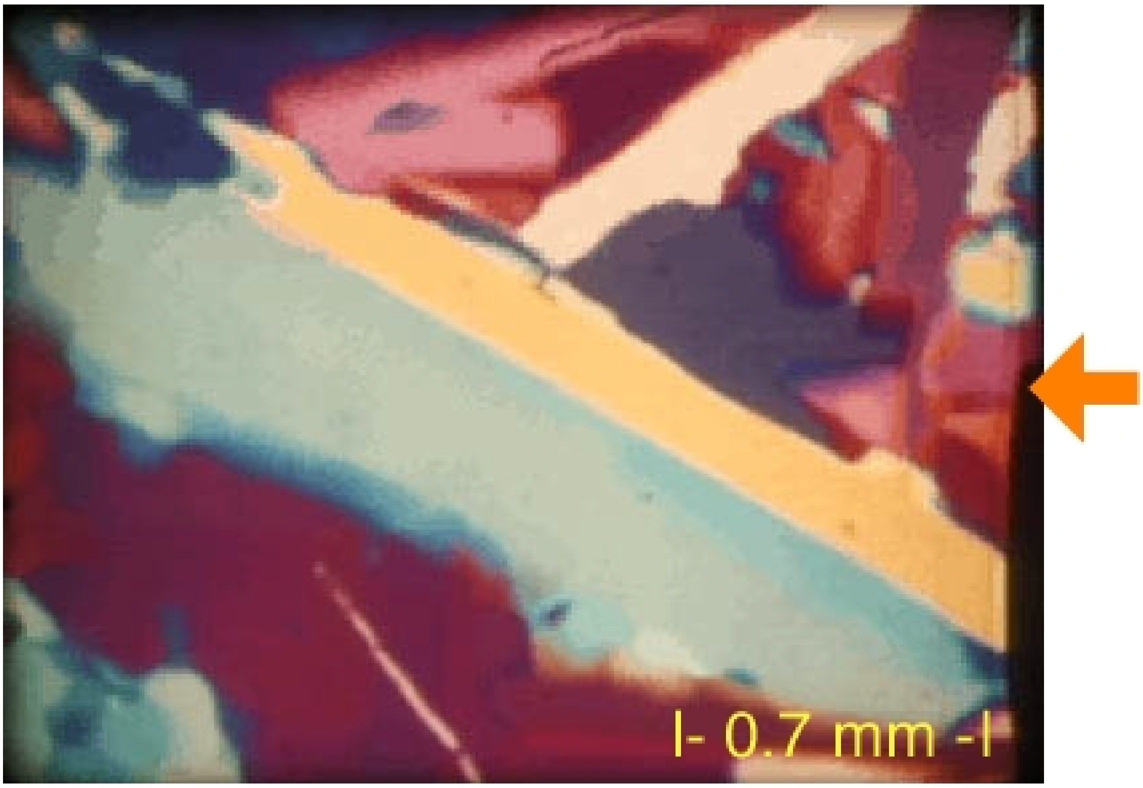


2 Homogeneous deformation and dynamic recrystallization

This experiment is similar to the previous one in its initial microstructure. The difference lies in the slightly higher temperature of about 35 degrees C. This makes the material less anisotropic and deformation becomes more homogeneous. Also here the movie was taken from the part of the sample close to the moving piston coming from the right. This experiment can be best compared with fig. 6 of Urai et al., 1980.

Immediately after the start of the deformation recrystallization starts with the migration of existing grain boundaries. This produces an increasing amount of dynamically recrystallized material, in which a steady state grainsize is maintained.

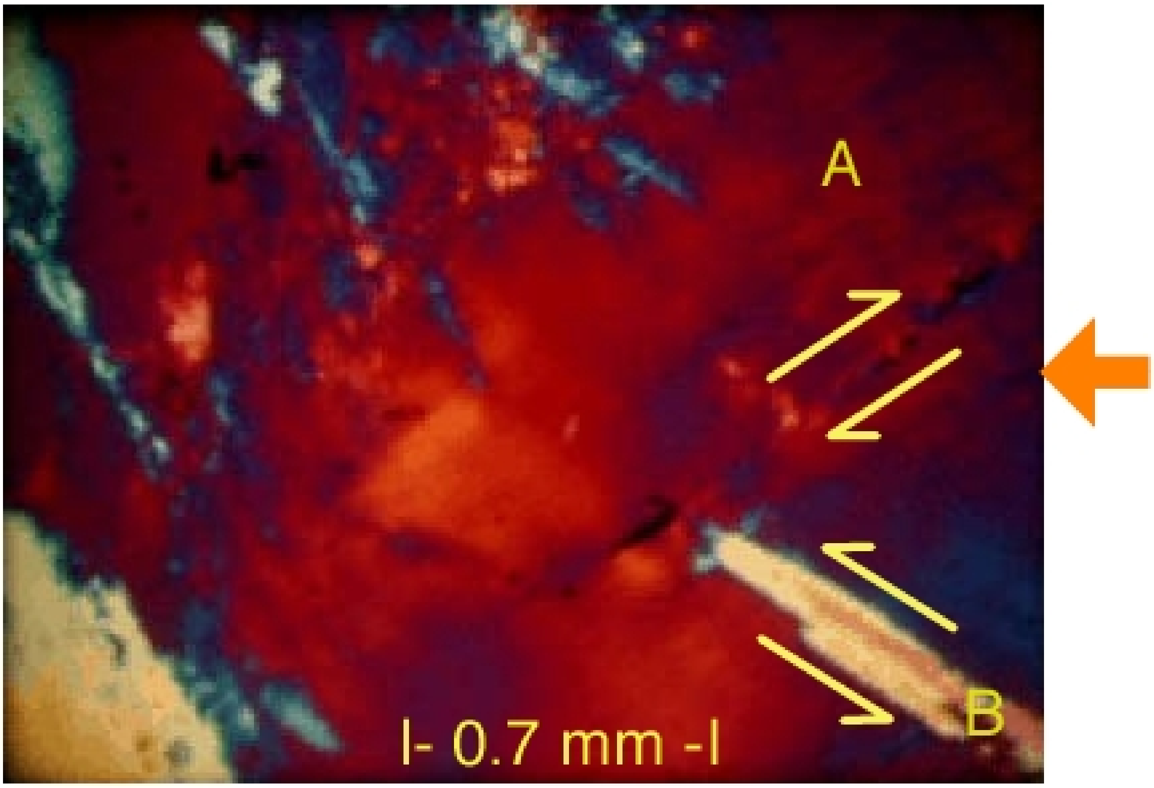
Further deformation leads to a steady increase in the fraction of recrystallized material, until finally after about 50 % shortening the material is completely recrystallized. It is noteworthy that the recrystallized mass shows a spatially organized (domainal) crystallographic preferred orientation shown by the regions consisting of many grains with the same colour. Due to the small size of recrystallized grains (these are smaller than the sample's thickness) details of this microstructure are not clear. The movie is presented in four different sections. These follow each other without a time lap, and show slightly different parts of the sample.



Movie 02_0 **Movie 02_1** **Movie 02_2** **Movie 02_3**

3 Shearzone development

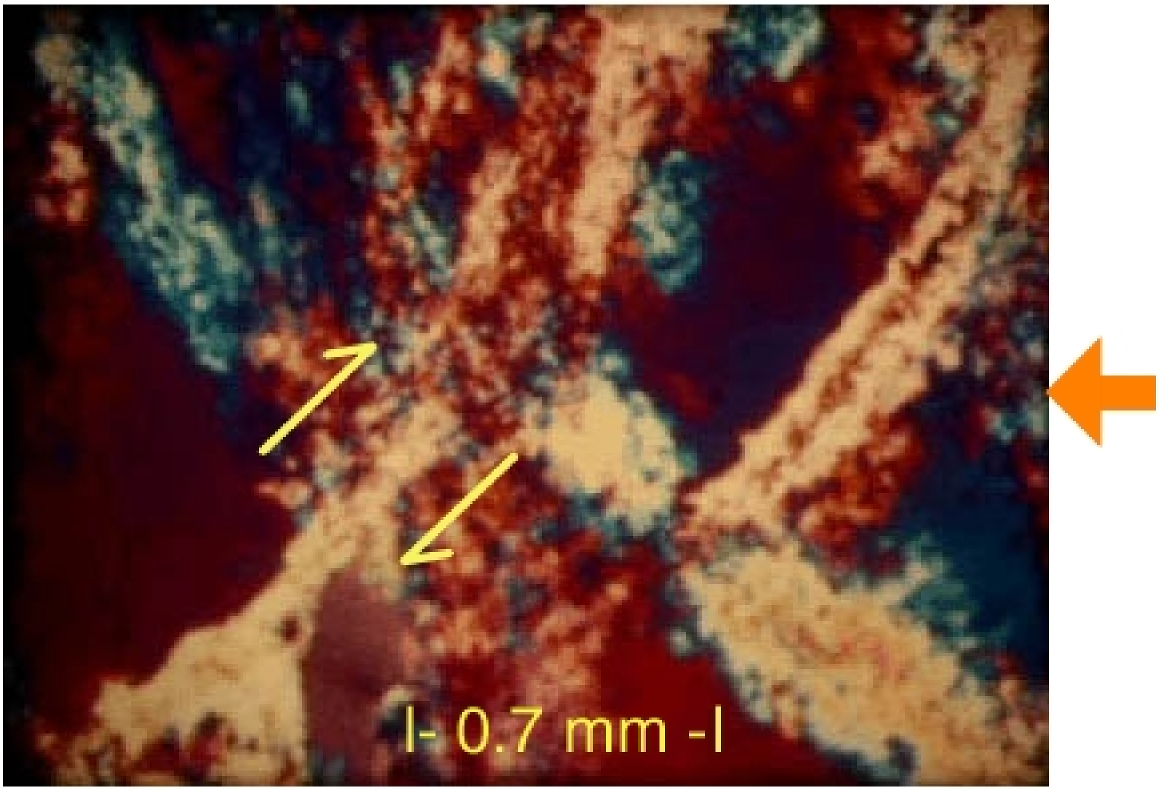
In some experiments, the heterogeneous distribution of the deformation resulted in the formation of shear zones. The initiation of these zones usually occurred in grains favourably oriented for slip: with the slip plane perpendicular to the glass plates and at high angles to the shortening direction. Such a grain constitutes a plane of weakness in a direction of high shear stress. In the experiment shown here, an easy slip grain is embedded in a large one in a hard orientation as shown by its colour. Stress concentration at the tip of this grain results in the initiation of a shear zone. In the conjugate direction, after some initial plastic deformation, another shearzone is initiated after a shortening of about 10 %. The initial rapid movement here could have been along an intragranular fracture. The shear zones rapidly recrystallize into a fine grained mass with a very good preferred orientation, one of easy glide. The deforming piston is seen to be moving in from the right side. This room temperature experiment was discussed in detail in fig. 2 of Urai and Humphreys 1981.



After shear zone initiation most of the deformation occurred by shear flow in the shear zones.

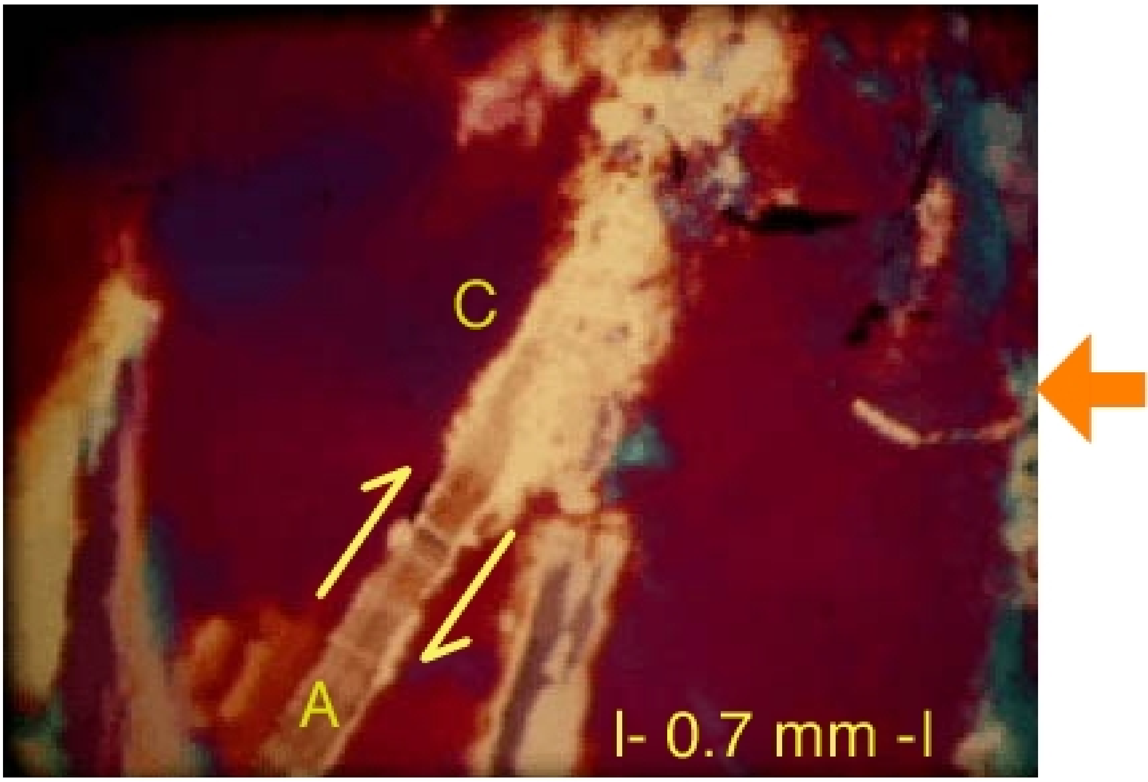
Mature shear zones consisted of fine grains (~10µm) due to the relatively high strain rate in the shear zone, with a strong preferred orientation. Often a darker contrast was observed along the centre.

In the second movie of this experiment the interaction between shear zones can be followed. Earlier shearzones become kinematically unfavourable for slip and new shear zones are initiated, passively carrying the earlier, now inactive shearzones along: these undergo metadynamic recrystallization in this stage. This process is strongly controlled by the geometry of the deformation which favours coaxial flow.

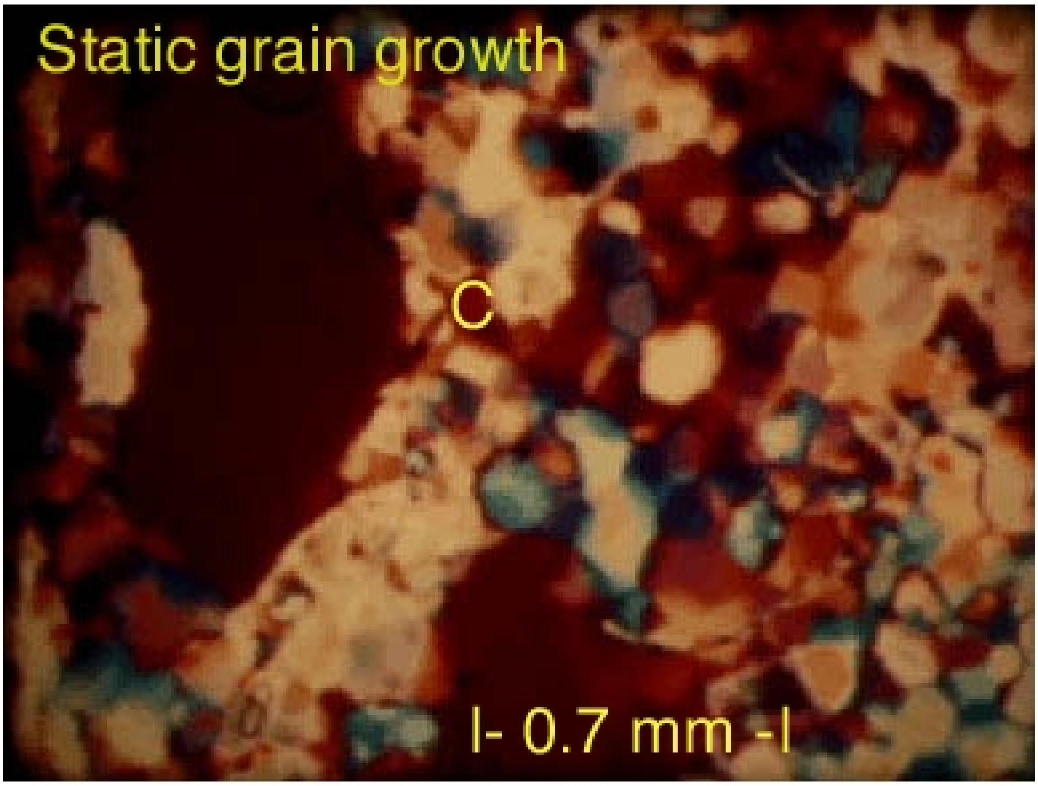


4 Metadynamic recrystallization

This movie is included to illustrate the effect of metadynamic recrystallization. The first part of the room temperature experiment is similar to the previous one: deformation is dominated by a long grain in soft orientation (A) which develops into a shearzone at high angle to the compression direction. Although deformation in this grain is strong, it recrystallizes very slowly, perhaps because of the low strain energy built up in grains oriented favourably for slip on one system.

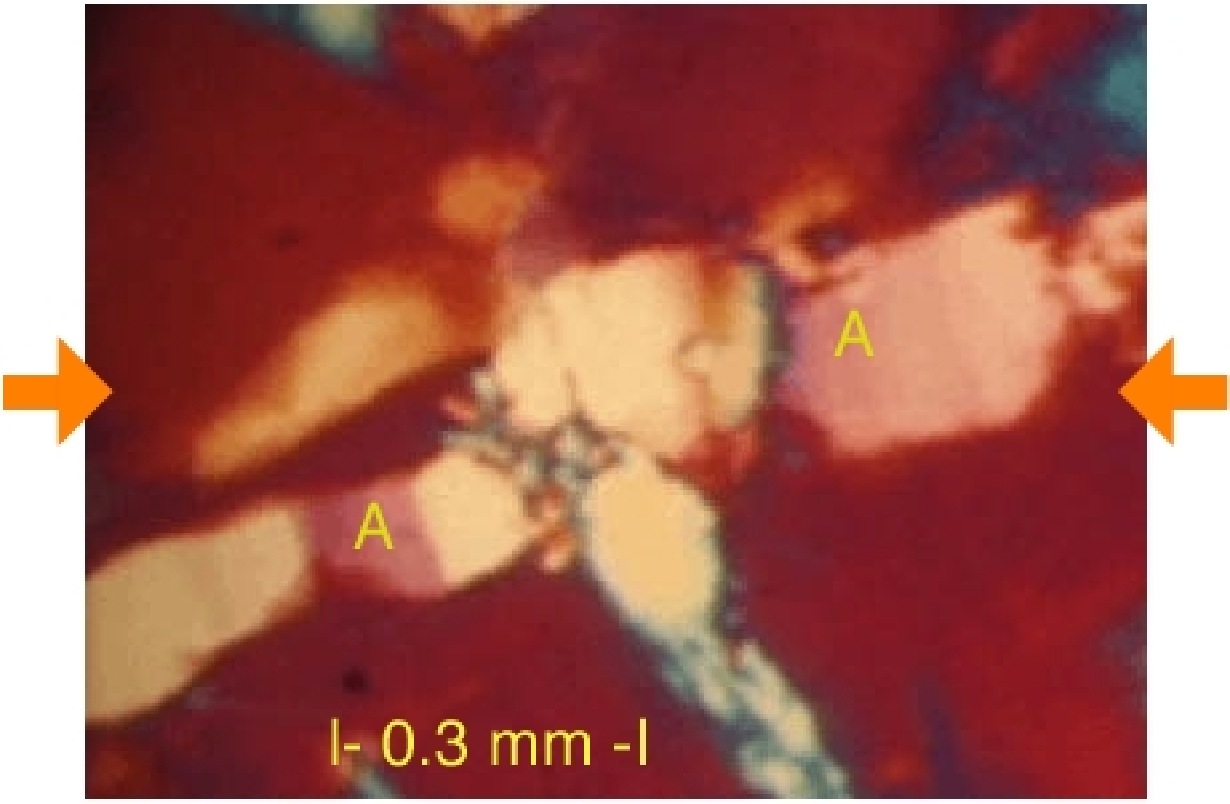


After this deformation the loading piston was stopped and the sample allowed to statically recrystallize. The movie was recorded at a 10x slower rate, over a period of approximately 15 hours. The grain growth process strongly increases the size of the recrystallized grains and produces a good foam texture. It is noteworthy that some of the old grains which did not deform because they were located close to the soft grain A did not recrystallize either, presumably because they did not accumulate significant strain energy.



5 Kink boundary migration

This movie shows a detail of one of the movies. It shows a nice example of the formation of kink boundaries in a grain (A) in easy glide orientation. With progressive deformation the grain is folded, and the kink boundaries migrate. After sufficient misorientation across the kink boundary, recrystallization starts with the growth of new grains in the kink boundary. The exact process of nucleation is unclear. This movie can be compared with fig. 2 of Urai et al., 1980.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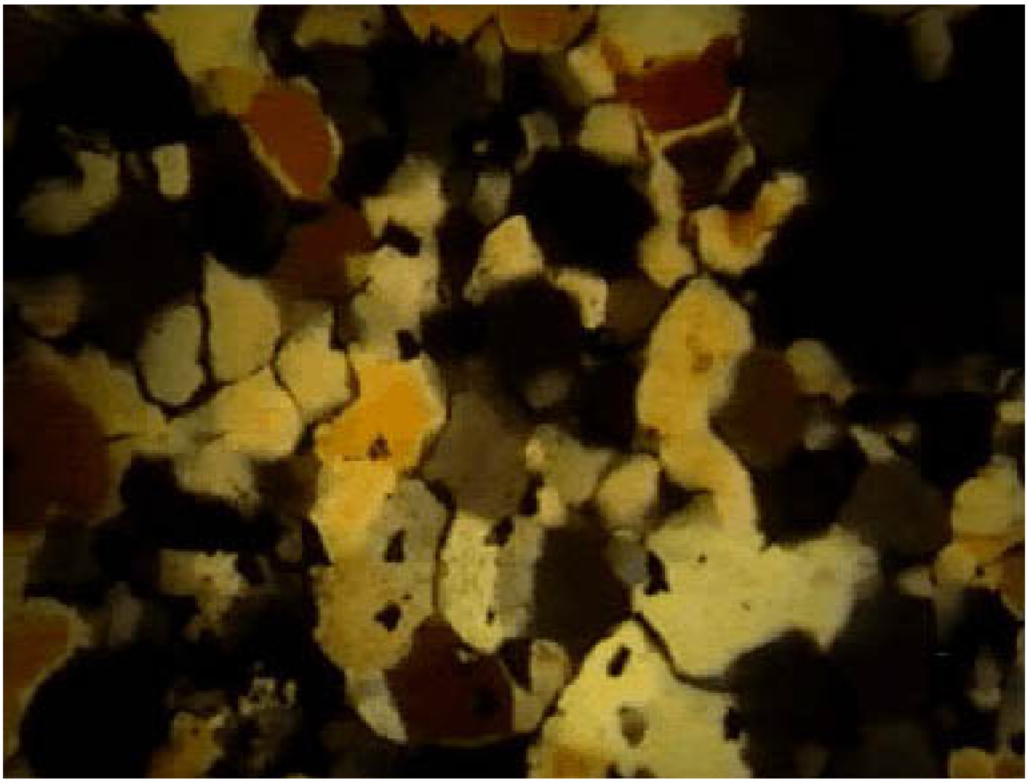
Octachloropropane movies

Visser et al., (1989) published an abstract based on Peter Visser’s MSc. Thesis. This study reports measurements of grain boundary migration velocities in deforming Octachloropropane (OCP). Two experiments from this study were recorded in time-lapse movies, these are included here. Samples were prepared by cold pressing the OCP plus marker grains into a thin sheet and annealing the sample in the deformation apparatus at around 60 degrees C. This resulted in a sample with a good foam texture and a weak preferred orientation. The experiments were run at lower strain rates than the usual see-through experiments. Field of view in both experiments is about 2 mm.

1 Slow dynamic recrystallization

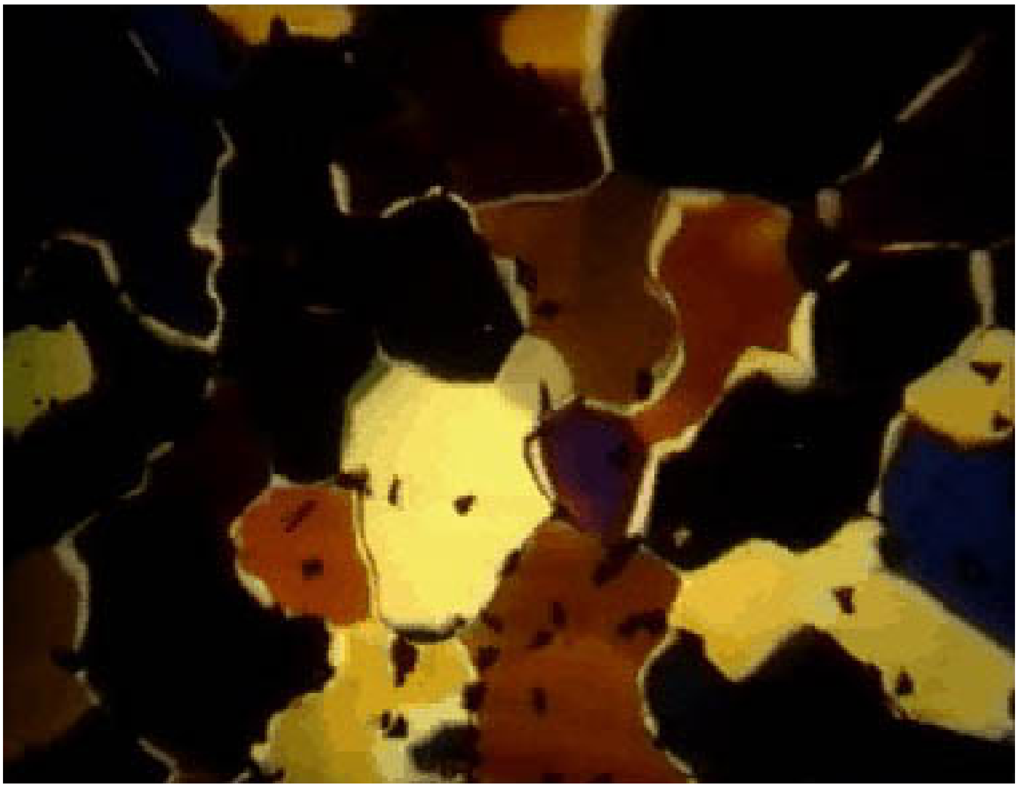
This room temperature experiment, recorded with crossed polarizers and with a few large inert markers in the sample shows dynamic recrystallization in a sample where the initial grainsize happens to be the same as the dynamically recrystallized one. From the onset of deformation grain boundaries start migrating, but relatively slowly with respect to the rate of deformation (compare for example with the camphor movies presented earlier in this paper). After a large amount of deformation the grainsize has decreased somewhat but not dramatically. In triple junctions, grain boundaries meet at approximately 120 degrees during the experiment, indicating the local role of grain boundary energy driven grain boundary migration.



2 Dynamic grain growth

This experiment was run at about 60 degrees C. Here the grains undergo strong grainsize increase during deformation, and a strong crystallographic preferred orientation develops. For most of the experiment the sample has a reasonable foam texture, and most still pictures exported from this movie would be interpreted as due to static recrystallization. The process of grain growth is partly the same as during static recrystallization where grains with less than six sides shrink and eventually disappear, and partly due to massive coalescence of grains with the same orientation. At the end of the experiment the sample is very coarse grained, with a strong crystallographic preferred orientation.

Note that the movie was recorded off the center line of the sample and shows material flowing through the field of view for this reason. The "jerky" movement in the first part of the experiment is due to an unstable camera, and is not related to changes in deformation rate.



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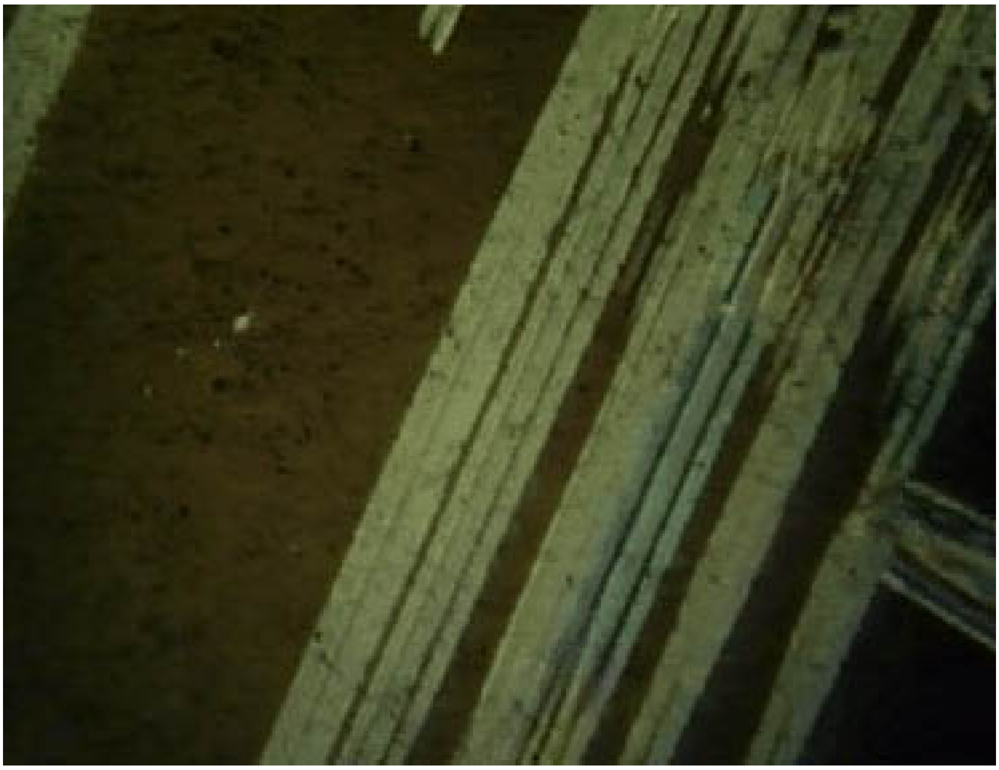
Bischofite movies

The bischofite and carnallite experiments were described in detail in Urai (1987). These experiments were carried out using samples cut from coarse grained natural samples. The experiments were done with a pore fluid of saturated aqeous solution, in a closed system with a moving seal between the glass plates. These movies were recorded in 1982 at the Institute for Earth Sciences, Utrecht University.

1 Twinning in dry Bischofite single crystal

This experiment starts with a single crystal of bischofite, without a pore fluid. It is shortened horizontally, and develops a set of twin lamellae. With further shortening the twin lamellae widen and coalesce into a completely twinned crystal, except in the right side of the sample where the early formation of a second twin set prevents twinning to go to completion. Field of view is approximately 3 mm.

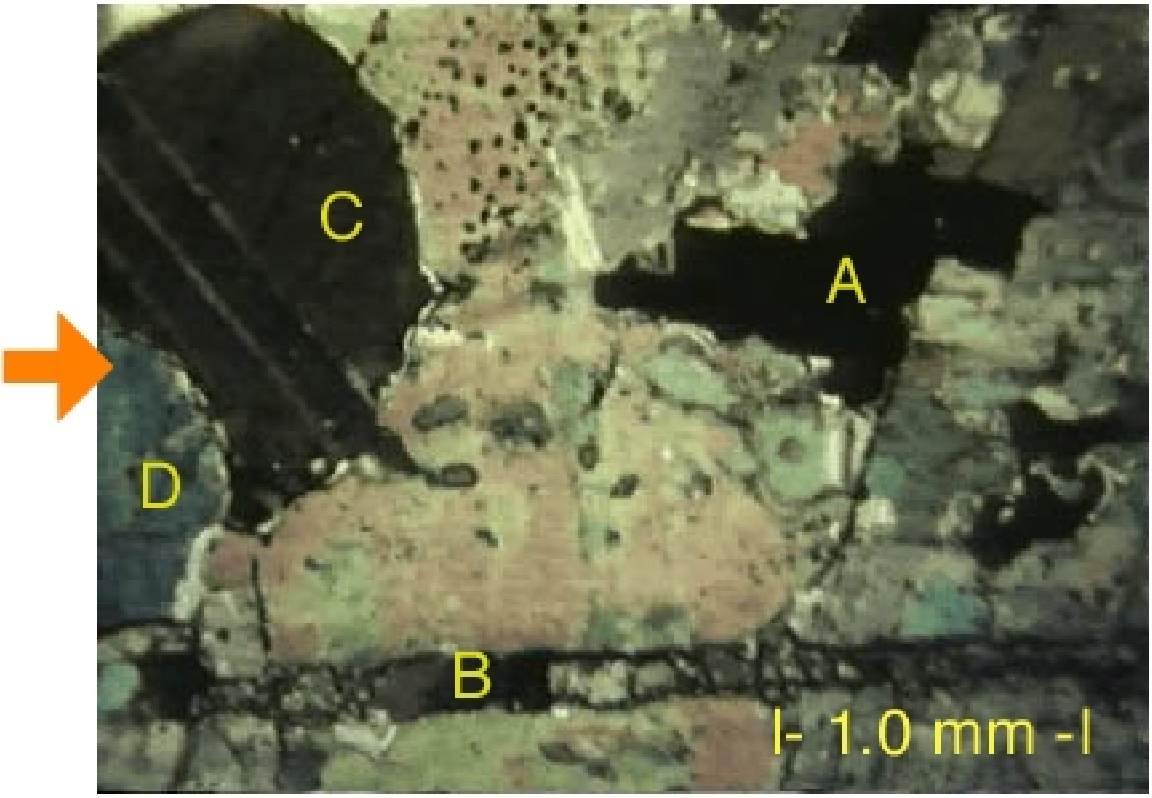


2 Deformation of wet Bischofite

In the presence of a saturated solution, bischofite recrystallizes readily at room temperature. This movie was taken from a deformation experiment using wet bischofite, at 80 degrees C and $5x10^{-5}$ s^{-1} strain rate. It was described in detail in Urai (1987).

Several interesting features can be seen, such as the large changes in migration rate of the grain boundaries (fast and slow migration), twinning of newly grown grains, and the oscillatory motion of grain boundaries.

The figure shown corresponds to the second frame of fig. 5 in Urai (1987). Old grains (C and D for example) and a string of finer recrystallized grains formed during sample preparation (B) are features of the starting material. Grain A is a recrystallized grain studied in detail in fig. 6 of Urai (1987).



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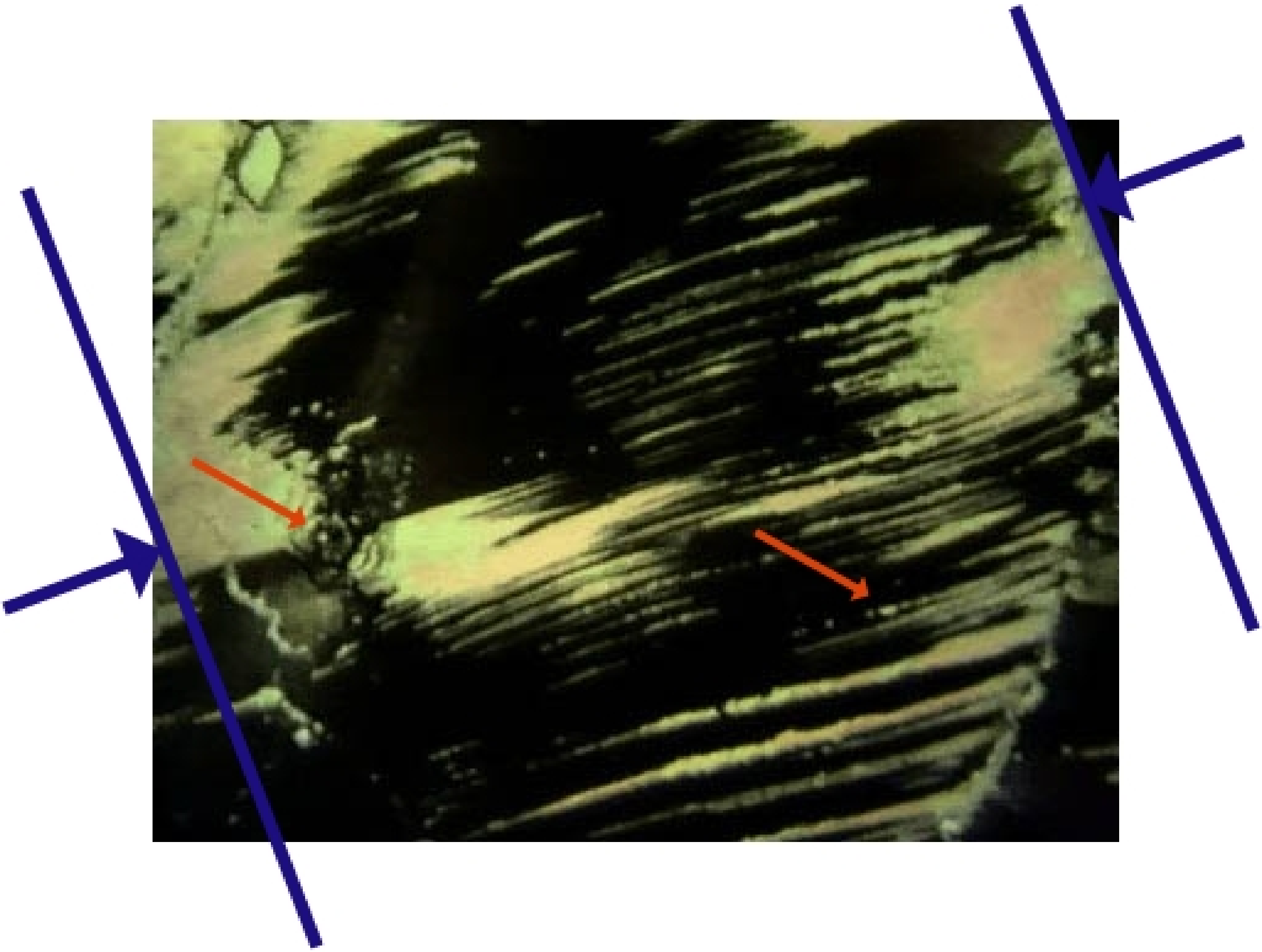
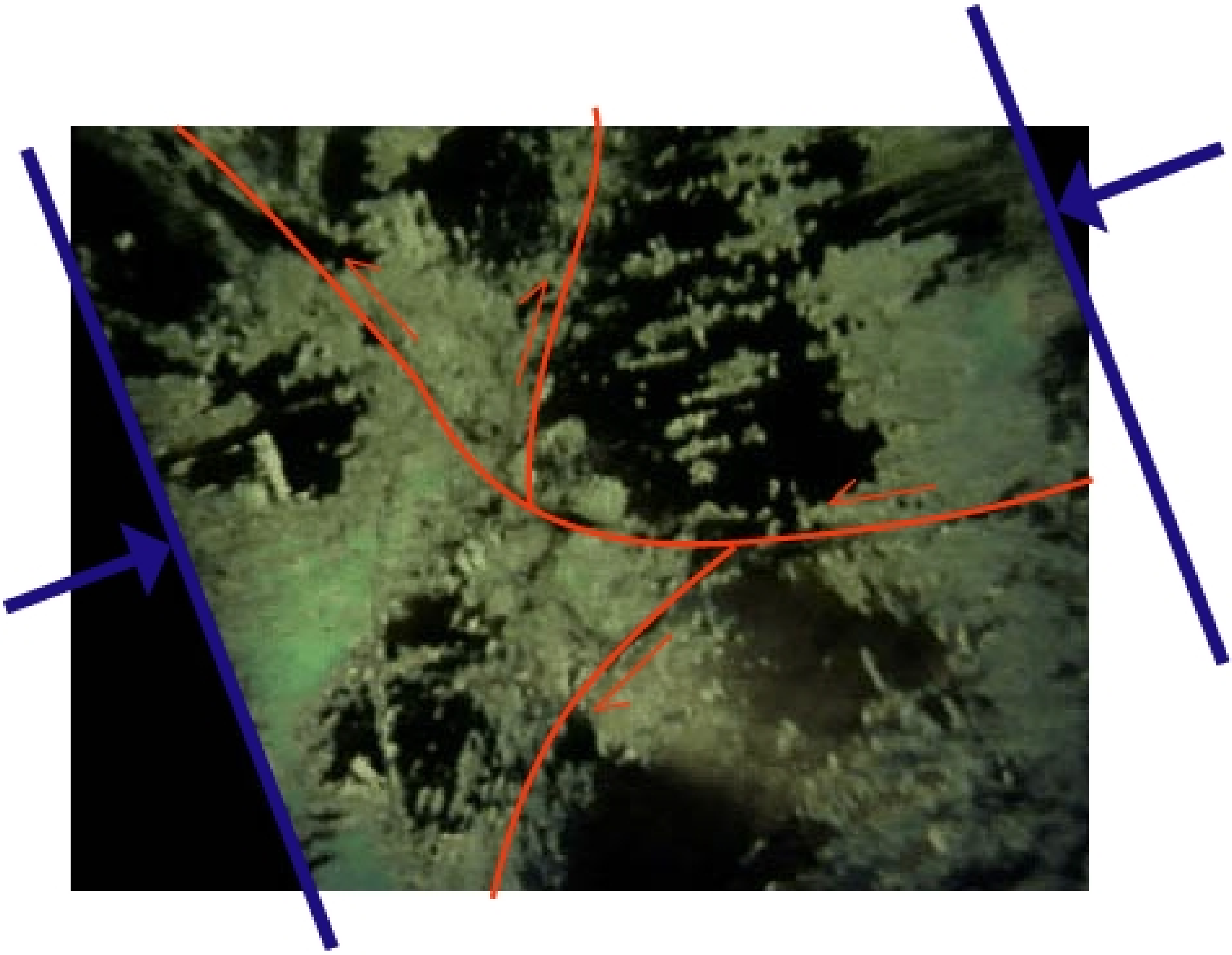
Carnallite movies

1 Twin boundary migration

This movie is comparable to the experiment shown in fig. 3 of Urai (1987). Wet carnallite, deformed at 100 degrees C and $5x10^{-5}$ s^{-1} strain rate usually develops a set of twins at the onset of deformation. These twins replace the ones which developed during sample preparation and are un-twinned by the new stress directions. Twinning is accompanied by dislocation creep. Note that the twins do not propagate into areas of undulose extinction. In the left side of the sample there is a small hard halite inclusion. After about 10% strain the twin boundaries become mobile and twin boundary migration is the main process of recrystallization at this stage.



After considerable shortening and recrystallization, strain is localized into a network of semibrittle shear zones, originating at the small halite grain mentioned above. Carnallite in these zones is recrystallized into a very fine grained aggregate, and movement along the shearzones is accompanied by ductile deformation of the moving fragments.



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