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EXPERIMENTAL GROWTH OF FIBERS AND FIBROUS VEINS

by

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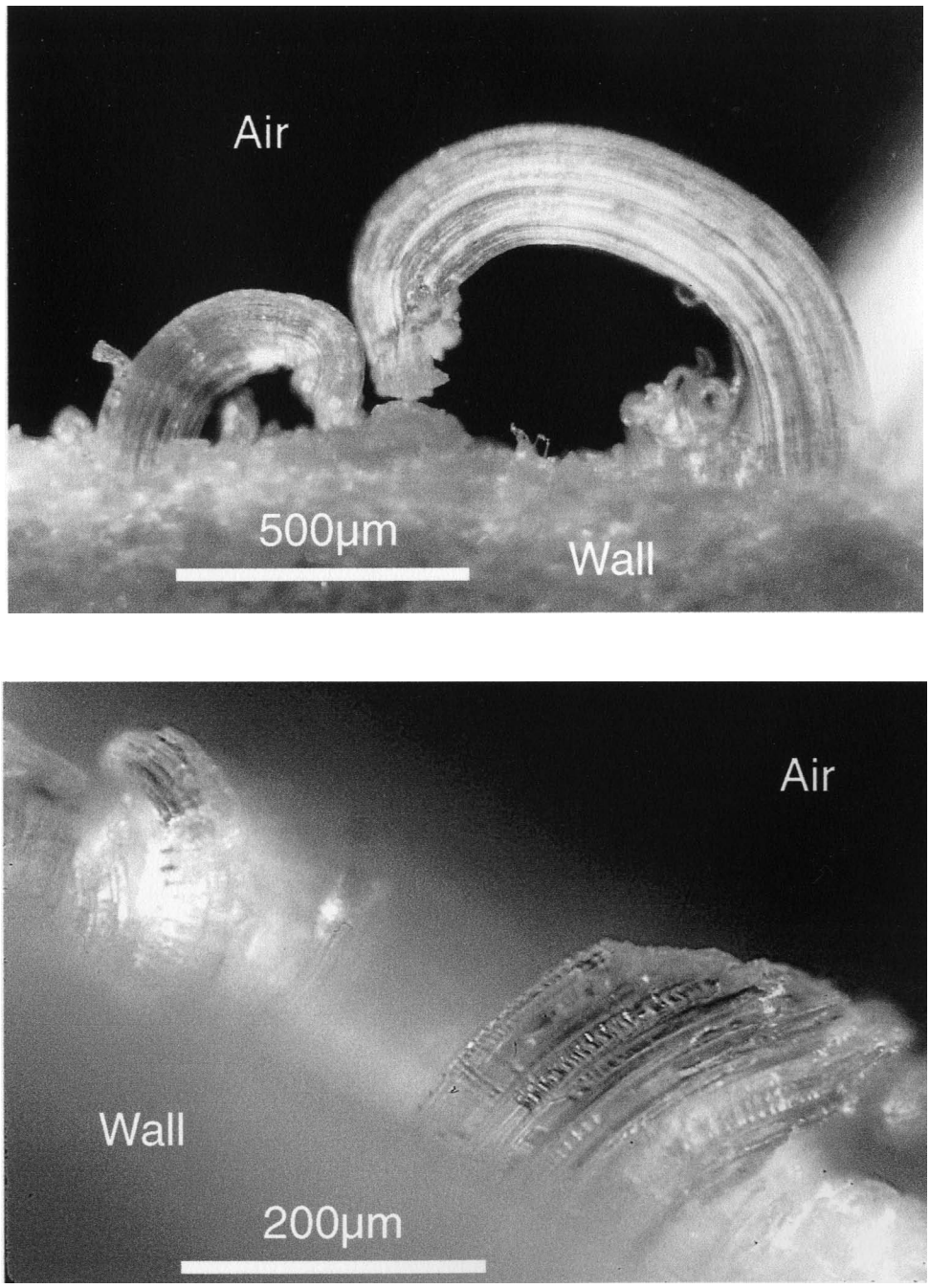
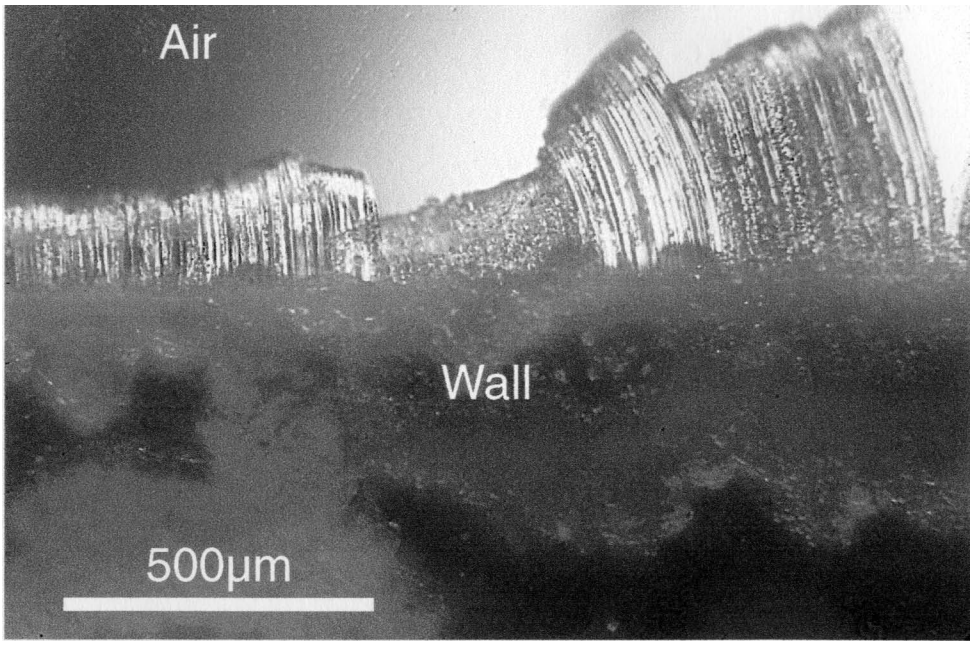


Fig. 3.1 Growth of individual curved or curled fiber bundles in single-block experiments when fibers are loosely packed. (**a**) Strongly curled fiber bundles of NH_4SCN grown on the edge of a piece of Millipore cellulosic filter membrane (with a nominal pore size of 0.025µm) in experiment *SM-02*. Although the older fibers are highly oblique to the wall or even curved back at the tip, the new growth at the base is roughly normal to the substrate. (**b**) Isolated curved fiber bundles of $CuSO_4.5H_2O$ grown on a piece of wax-coated ceramic (*Big Disc*) in a single-block experiment *NFB-42*. Growth occurred in an ambient relative humidity of 68% over a period of about 5 days. Some Type II transverse features can be seen across the fibers.

(a)



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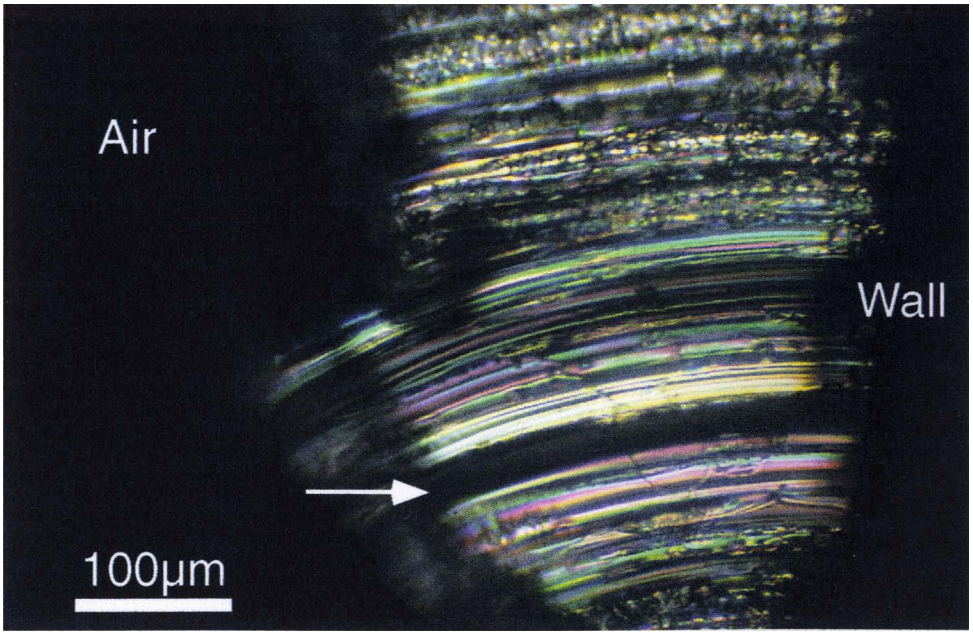
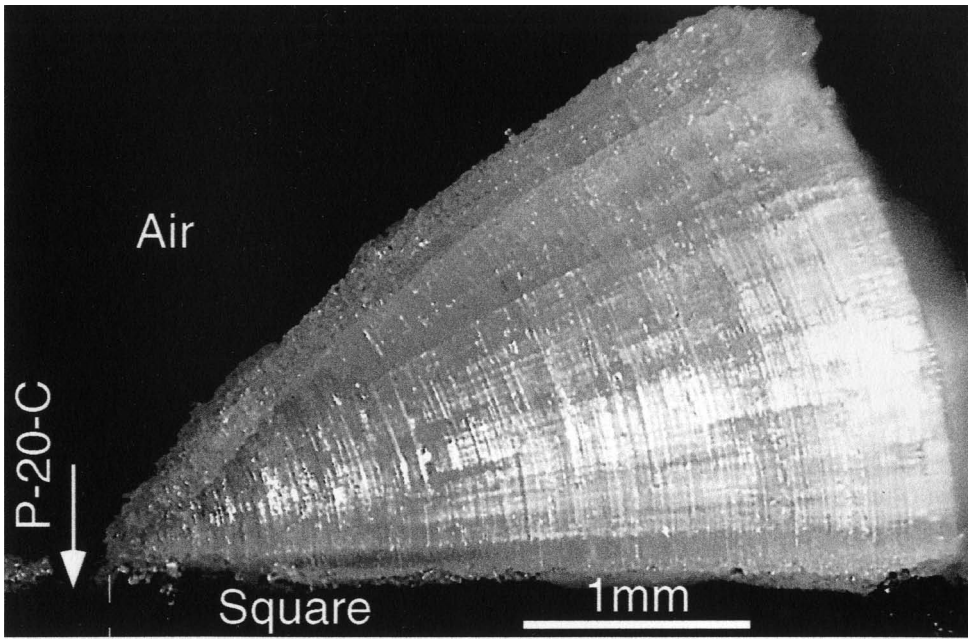


Fig. 3.2 Growth of curved fibers of NH_4SCN on the edge of a piece of Millipore cellulosic filter membrane (with a nominal pore size of 0.025µm) in experiment *SM-03*. (**a**) Micrograph showing that the linear growth rate of the curved fibers increases towards the right so that they are curved towards the left. Note also a sharp discontinuity in fiber lengths indicating relative slip between the fibers during the growth. Photo taken in reflected light. (**b**) Enlarged view of the curved fibers in (a) in transmitted light under crossed nicols. Arrow indicates one fiber or fiber bundle that shows maximum extinction.

Fig. 3.3 Growth of curved fibers of *NH_4SCN* due to a growth rate gradient along the wall of a ceramic block made of two different ceramic materials (*P-20-C* & *Square*) welded together. Growth rate is zero on the *P-20-C* portion due to its large pore size (Chapter 2) but increases to the maximum on the right end of the *Square* portion, so that while the younger growth is always roughly normal to the substrate the older fibers are constantly being lifted and rotated to become increasingly oblique away from substrate. (**a**) Micrograph showing growth over the first 87 hours. (**b**) Micrograph showing the lengthened curved fibers about 13 days later. Notice the concentric shape of the fibers and the radially extending Type I transverse features across them, the point of center close to the point of junction between *P-20-C* and *Square*.

(a)



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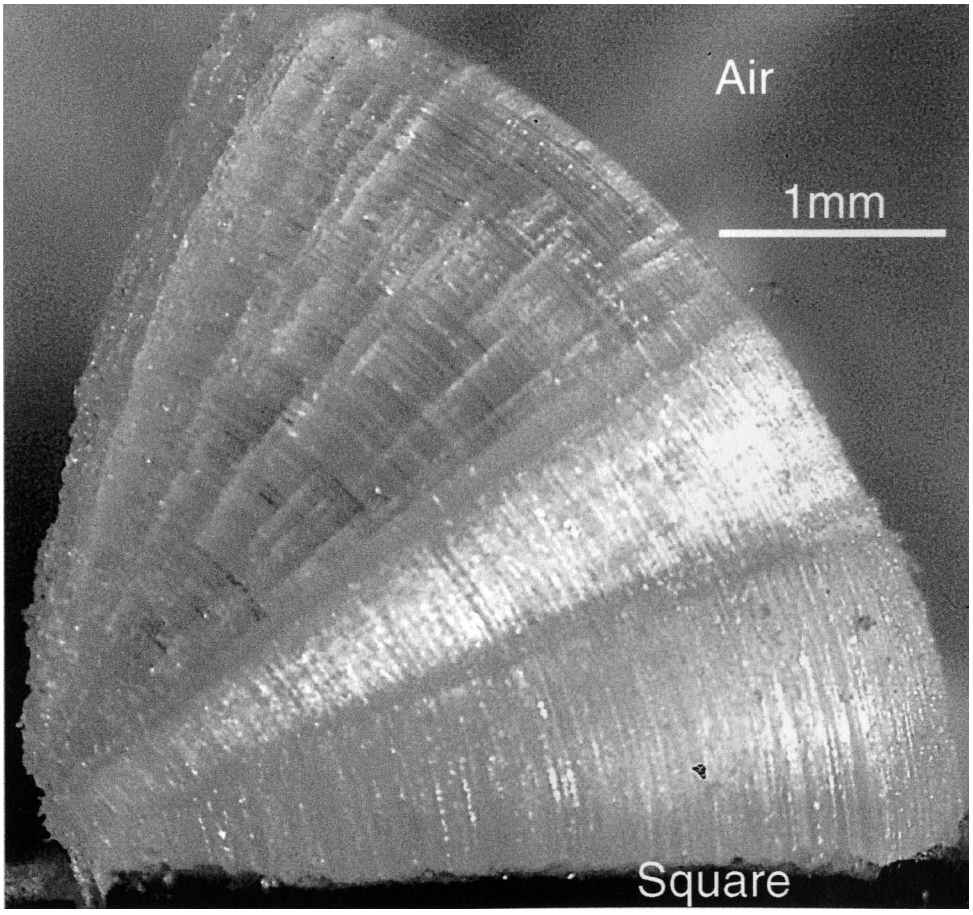


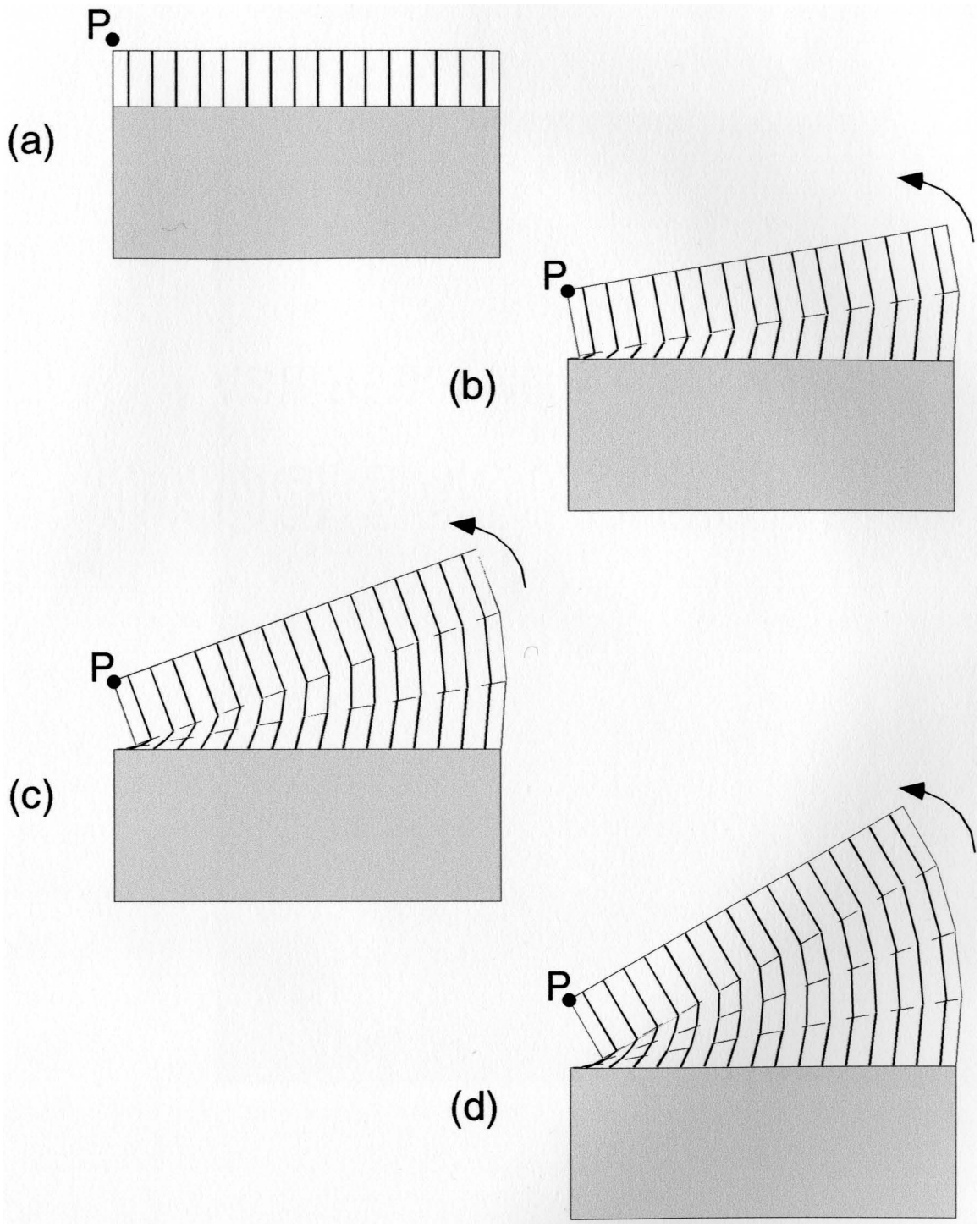


Fig. 3.4 Growth of curved fibers due to body rotation of the old fibers around a fixed point away from the wall. (**a**) Initial growth of fibers normal to the substrate until the upper left coner of the fiber aggregate touches a fixed point (P) on an object of constraint (not drawn). (**b**) Next increment of growth lifting and causing a body rotation of the old fiber aggregate around P. Both the growth rate and growth direction vary systematically along the growth interface. Maximum obliquity angle of growth occurs on the left. (**c**) Third increment of growth causing further rotation of all the old fibers. Growth direction of each fiber remains the same as long as rotation occurs around P. (**d**) Fourth increment of growth with the same growth direction variation pattern as before.The largest curvature of fibers is found on the left.

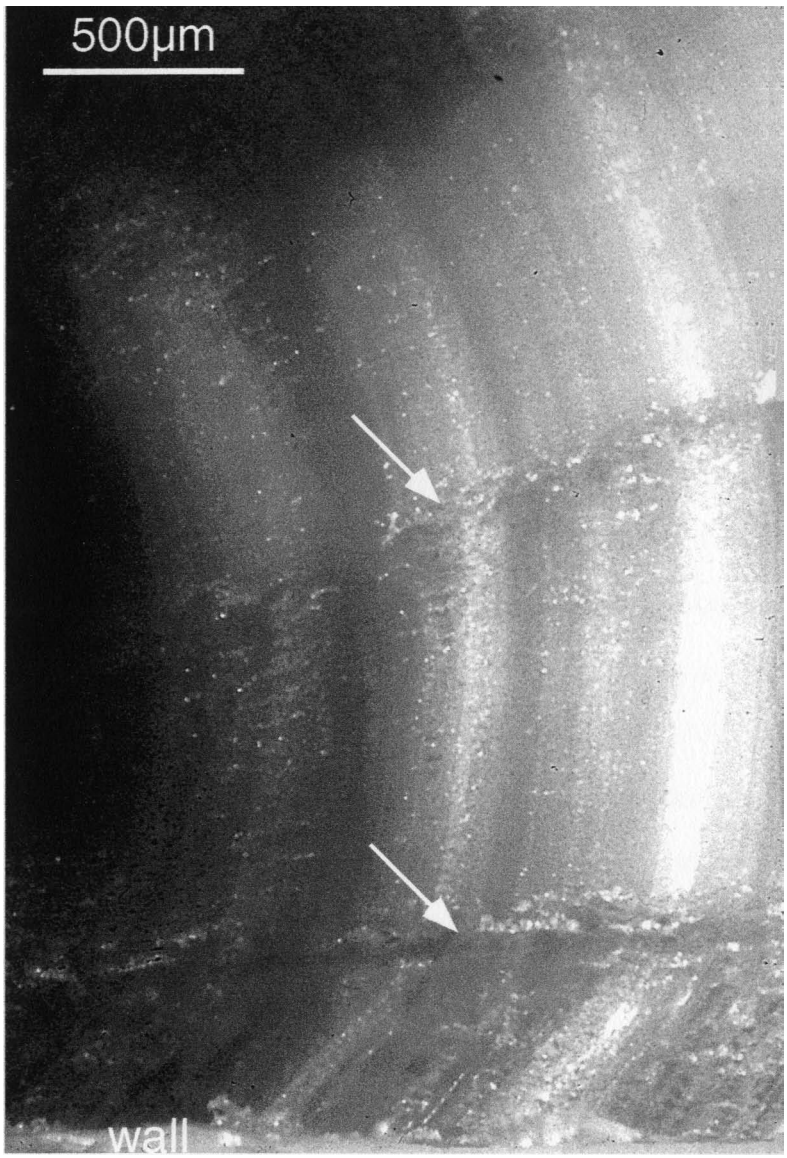
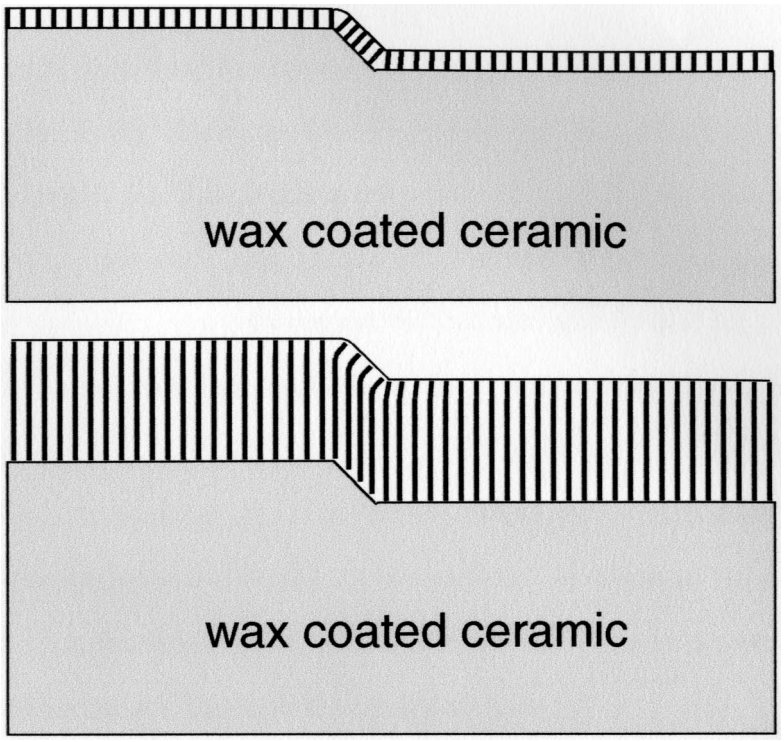


Fig. 3.5 Micrograph showing part of the curved fibers of NH_4SCN grown in a single-block experiment (*NFB-7c*) due to body rotation of the fibers around a fixed point of resistance imposed by an object of constraint placed in the way of the lengthening fibers (somewhere to the left of the photo). Two major Type I transverse features (arrows) are visible across the fibers. It can be seen that both the linear growth rate and the fiber orientation within each of the growth bands vary systematically from the left to the right. Photo taken in reflected light.



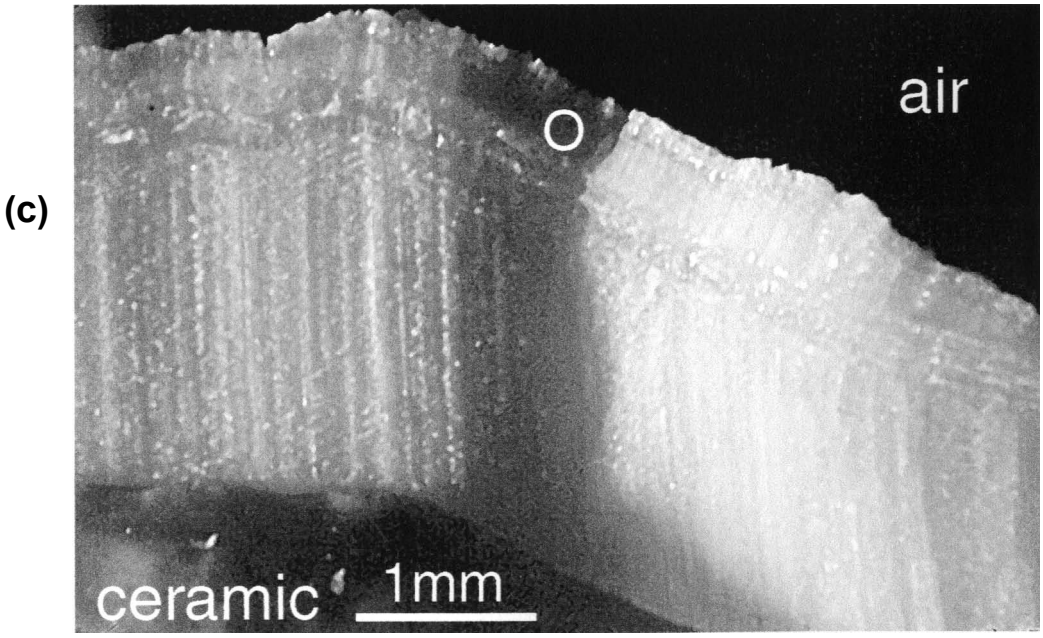


Fig. 3.6 (**a**) & (**b**) Cartoons illustrating growth of oblique fibers on a small step intentionally cut on the growth surface of a single-block experiment (*NFB-14*). (**a**) Initial growth of fibers in a roughly normal direction on the local step as well as on the rest of the growth surface. (**b**) Subsequent change of local fiber growth direction from normal to oblique on the step due to constraints or resistance from adjacent fibers on the right of the step which are still growing in a normal direction to the overall growth surface. (**c**) Micrograph of oblique fibers of NH_4SCN on the step. Notice that the oldest fibers (**O**) representing growth at the beginning of experiment are more or less perpendicular to the local growth surface of the step, while younger fibers are parallel to the predominant growth direction of all fibers (vertical).

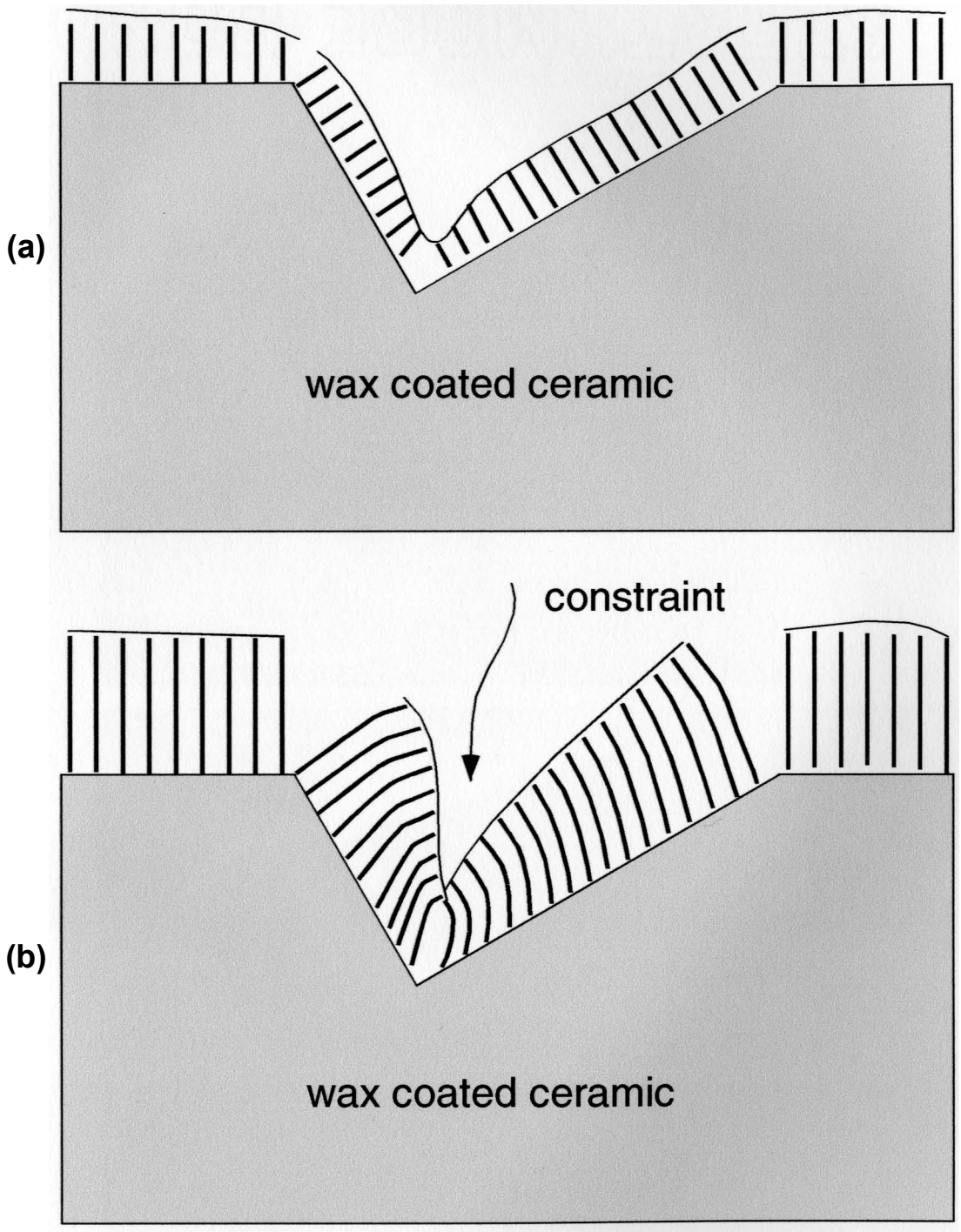
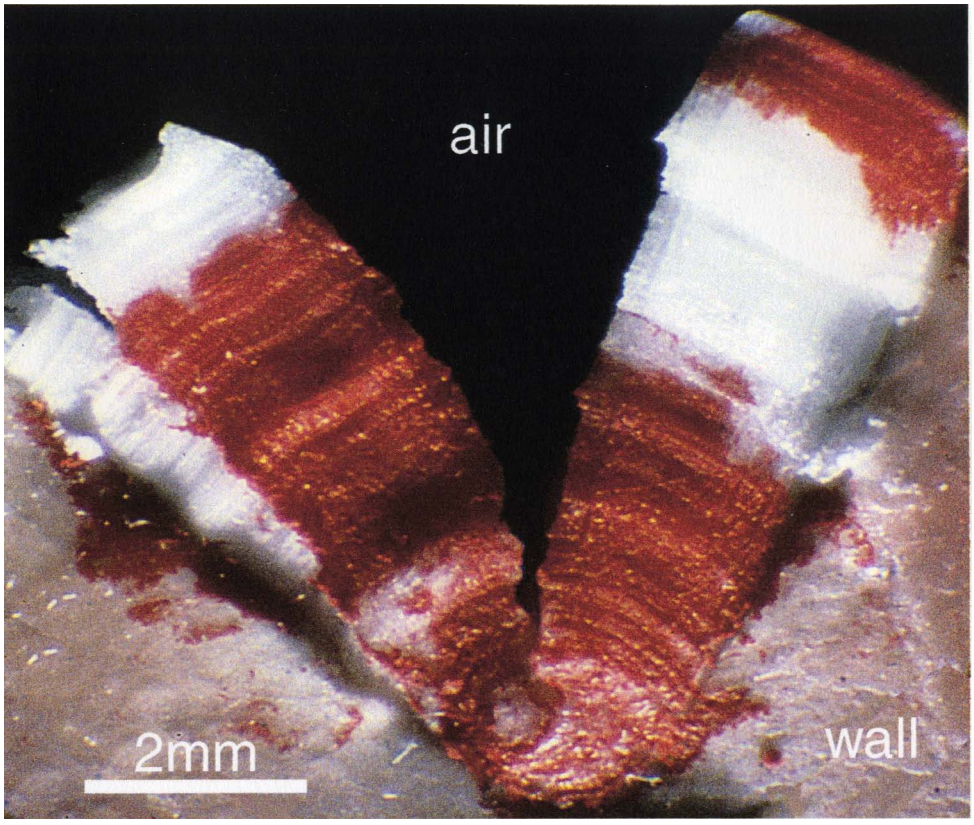


Fig. 3.7 Cartoons illustrating growth of curved fibers in a notch intentionally cut on the growth surface of a single-block experiment (*NFB-7a)*. Direction of fiber growth becomes increasing oblique towards the corner due to competition for space of growing fibers on either limb of notch or constraint arising from mutual intereference of fibers that always tend to grow in a normal direction as far as possible. (**a**) Initial growth of fibers roughly normal to the local growth surface. (**b**) Subsequent growth of fibers in increasingly oblique directions towards the corner due to lack of space there, resulting in growth of curved fibers.

(a)



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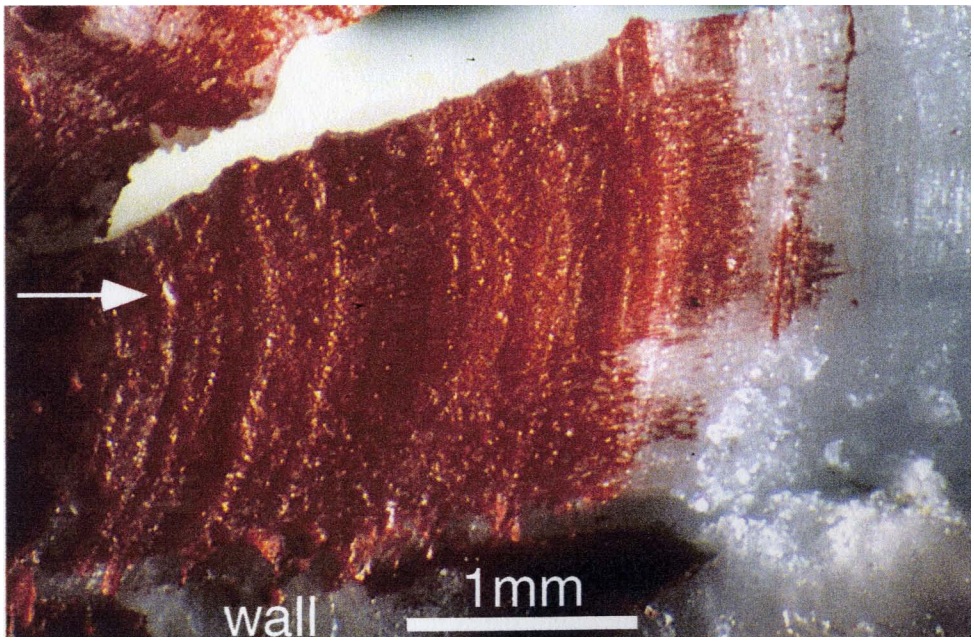
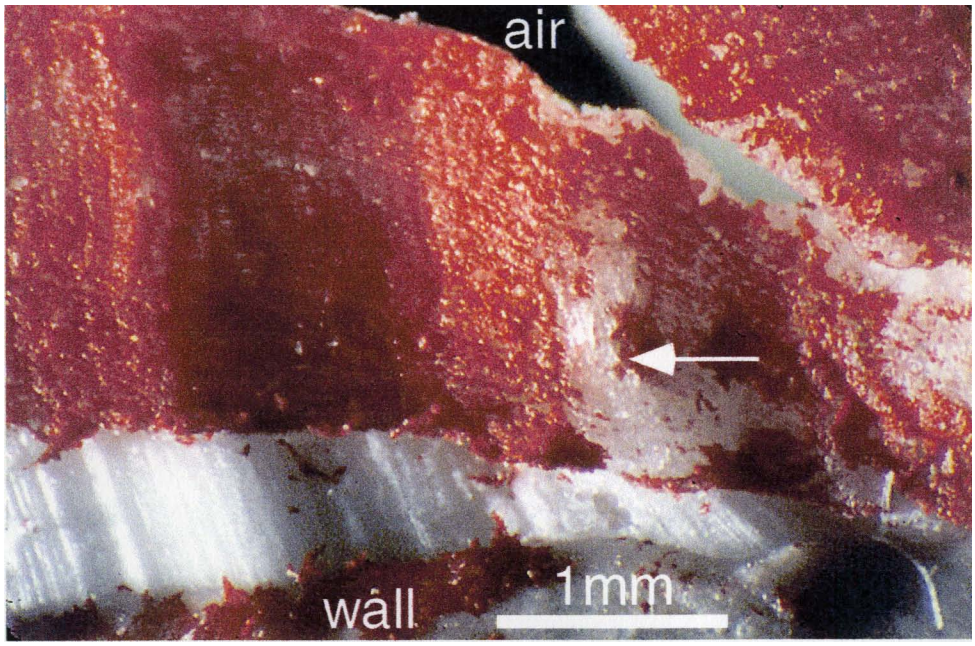


Fig. 3.8 Micrographs showing growth of curved fibers of NH_4SCN in a notch intentionally cut on the growth surface of a single-block experiment (*NFB-7a).* (**a**) Whole view of the fiber aggregates grown in the notch for a period of 22 days. Red pen ink on part of the fibers was put on the fiber-wall interface about 24 hours before. It has been broken apart by fresh fiber growth only on the left limb. (**b**) Close-up of the curved fibers on the right limb. They grew curved as they were forced to grow in an increasingly oblique direction due to lack of space at the corner (on the left). At the same time the older fibers were displaced to the right (arrow).

(c)



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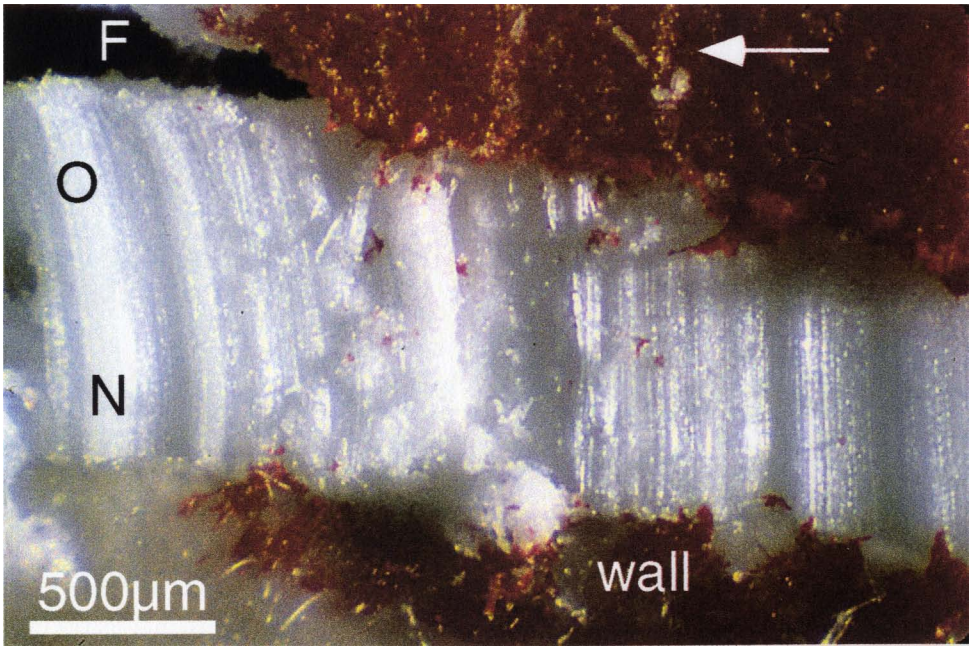
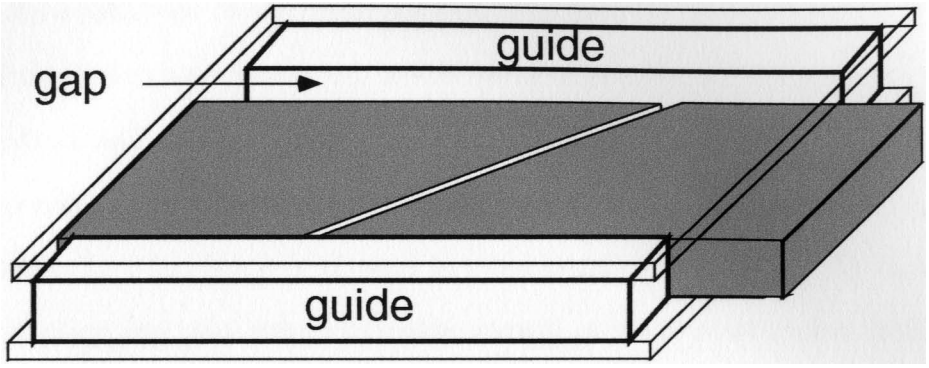


Fig. 3.8 (continued) (**c**) Close-up view of the fresh fibers grown during the last 24 hours on the left limb of the notch, close to the corner. They clearly show an increasingly oblique growth direction with respect to the wall towards the corner on the right, due to increasing lack of space and stronger growth-induced left-lateral shear (arrow) towards the corner. (**d**) Close-up view of the fresh fibers grown on the left limb of the notch, farther away from the corner. Notice a fracture has appeared between the new fibers and the red ink-marked older fibers due to the above growth-induced left-lateral shear (arrow) and consequent restoration of fiber growth direction from oblique (O) back to normal (N) where the fracture appeared. All photos taken in reflecting light.



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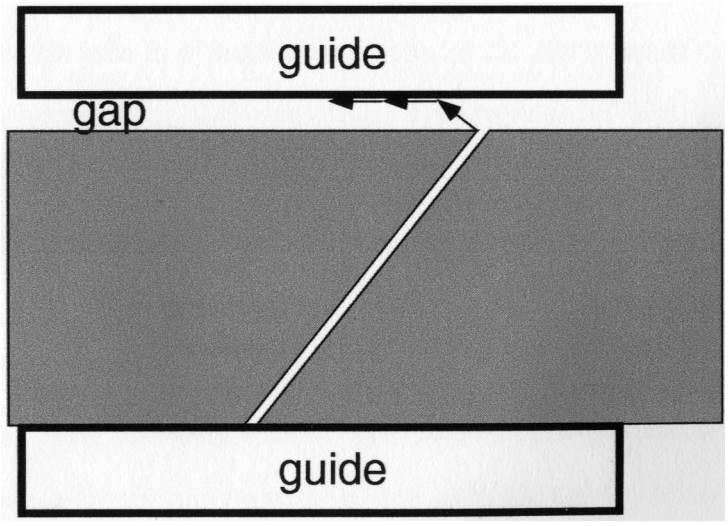
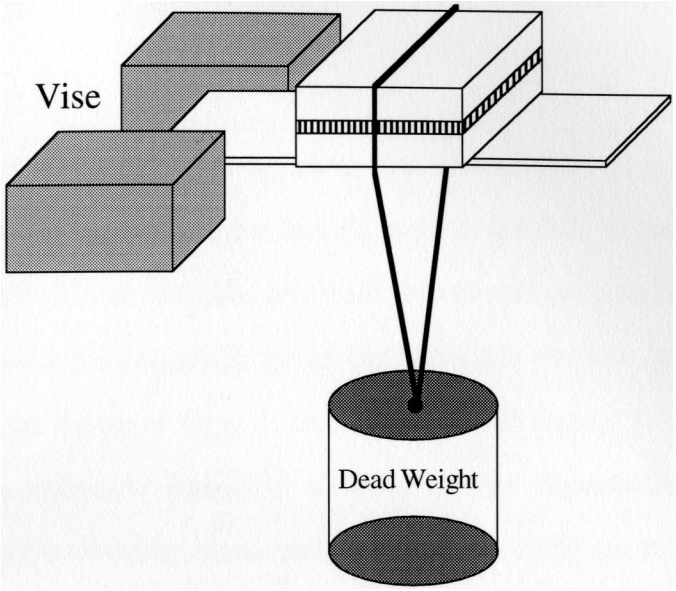


(b)

Fig. 3.9 Cartoons illustrating the set-up for growth of fibers in veins of changing displacement direction. (**a**) Ceramic blocks (shaded), glass plates above and below ceramic blocks, and guide blocks to constrain later displacements. Total length of ceramic blocks about 3 cm; vertical thickness about 5mm. (**b**) Top view of ceramic and guide blocks showing diagonal vein site and successive displacements (arrows) of left-handed ceramic block relative to right-hand block.

(a)



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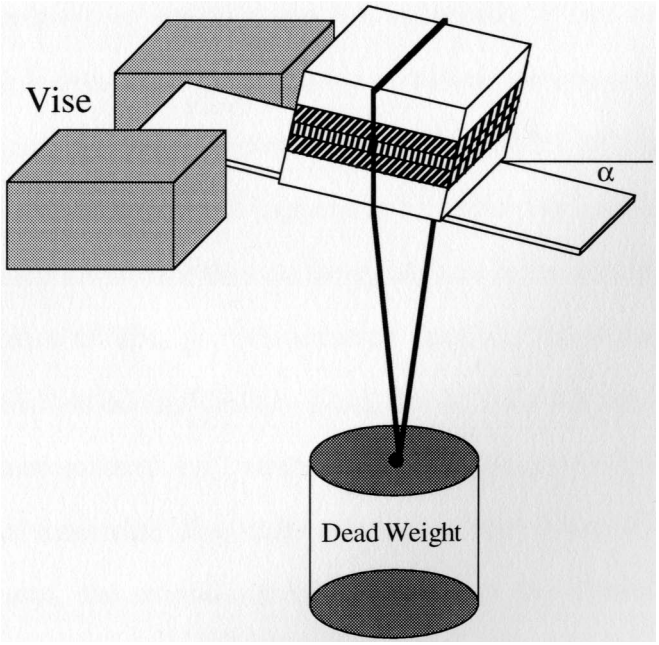
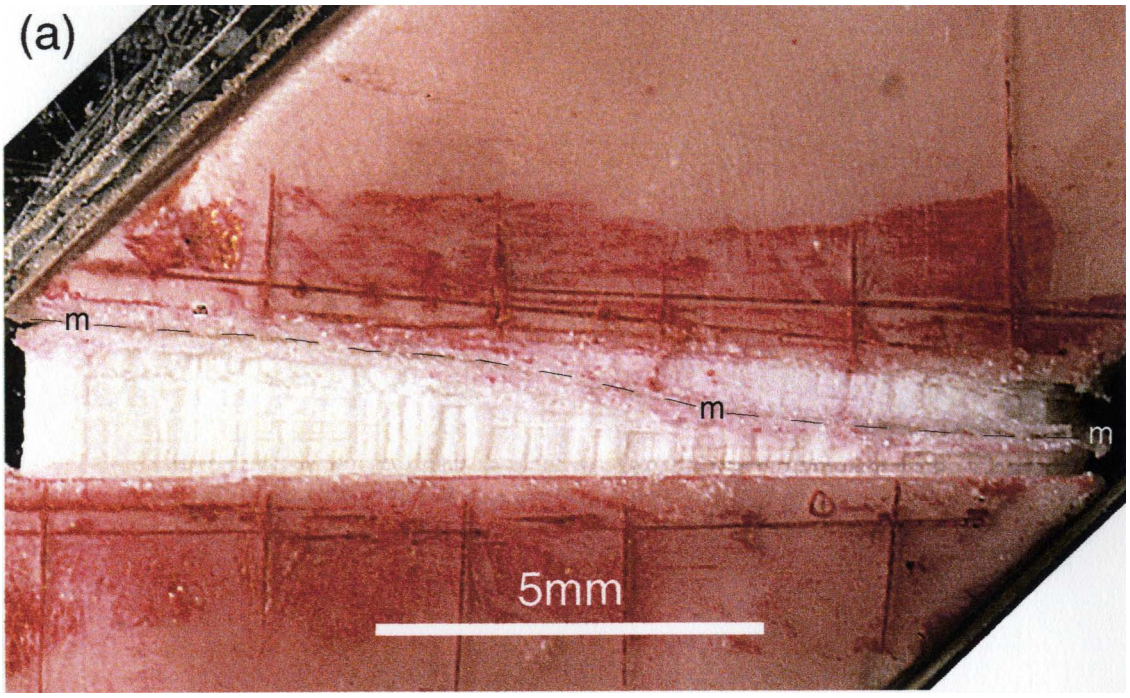


Fig. 3.10 Set-up for growth of veins of curved fibers under compressive loading of changing directions relative to the vein. (**a**) Initial state of sample. A wooden plate to which the bottom block of sample is cemented is held by the jaws of a vise in a horizontal position. Fibers initially grow and dilate the vein in a direction normal to the vein. (**b**) The plate and sample is held in an increasingly inclined position so that the direction of compression or maximum principal stress becomes increasingly oblique relative to the vein. Fibers also grow obliquely due to the oblique compression. Length and thickness of ceramic block are about 2 cm and 5 mm, respectively.

Fig. 3.11 History of guide-constrained growth of an asymmetric vein of curved fibers of NH_4SCN in experiment *CFB-10* (side A) as shown by successive fiber growth increments compared with the corresponding opening displacements after early opening displacement perpendicular to the vein. Experiment was run in a closed desiccator with a relative humidity of about 12%. All photographs are reoriented so that the vein is aligned with the horizontal and the guides run diagonally across the upper-left and lower-right corners. The position of the lower block is also fixed in all pictures. Dashed lines mark the locations of the previous vein-wall boundaries. Some cross-cutting scratches were made on both wax-coated ceramic blocks alongside of the vein so that displacements of the upper block relative to the lower block could be easily traced using their intersections as markers. (**a**) State of sample after early displacement perpendicular to vein during the first 126 hours of the experiment. (**b**) Vein with more growth over the next 20 hours. Dark blue lines show the corresponding incremental displacement vectors of the five markers on the upper block relative to the lower block. They are oblique in orientation and increase in magnitude towards the right, thus inducing a small counterclockwise rotation of the upper block relative to the lower block. The new fibers are also oblique, approximately paralell with the displacement vector of the closest marker (within experimental error). (**c**) Further widened vein another 26.5 hours later. The corresponding displacements are shown in green. New growth shows the largest growth rate gradient in all the recorded growth periods so a significant rotation of the upper block relative to the lower block (about 2° counterclockwise) occurred. The new fiber growth direction shows a noticeable discrepancy from (or a greater degree of obliquity than) that of the displacement of the closest marker. For comparison several distinct new fiber segments are also marked with thin green lines and their angles to the horizontal (computer measured) are shown beside them, as are the angles of the displacements of the markers. The difference between the two ranges between 5~7°. (**d**) Further widening of the vein in the next 96 hours. The corresponding displacements are shown in yellow. The opening rate is now quite uniform, and the new fiber growth direction is more or less parallel with the displacements of the markers. (**e**) Further growth in the next 122 hours. Displacements are shown in red, showing uniform opening in a more oblique direction. New fibers are also more oblique, almost exactly parallel with the displacements. (**f**) Further growth in the next 47.5 hours. Displacements are shown in blue. Growth increments are small and are approximately parallel with the displacements. (**g**) Last increment of opening over a period of 8 months. The total displacements are shown in pink. New fiber segments are themselves slightly curved, but their overall orientations are approximately parallel with the displacements. All photos taken in reflected light.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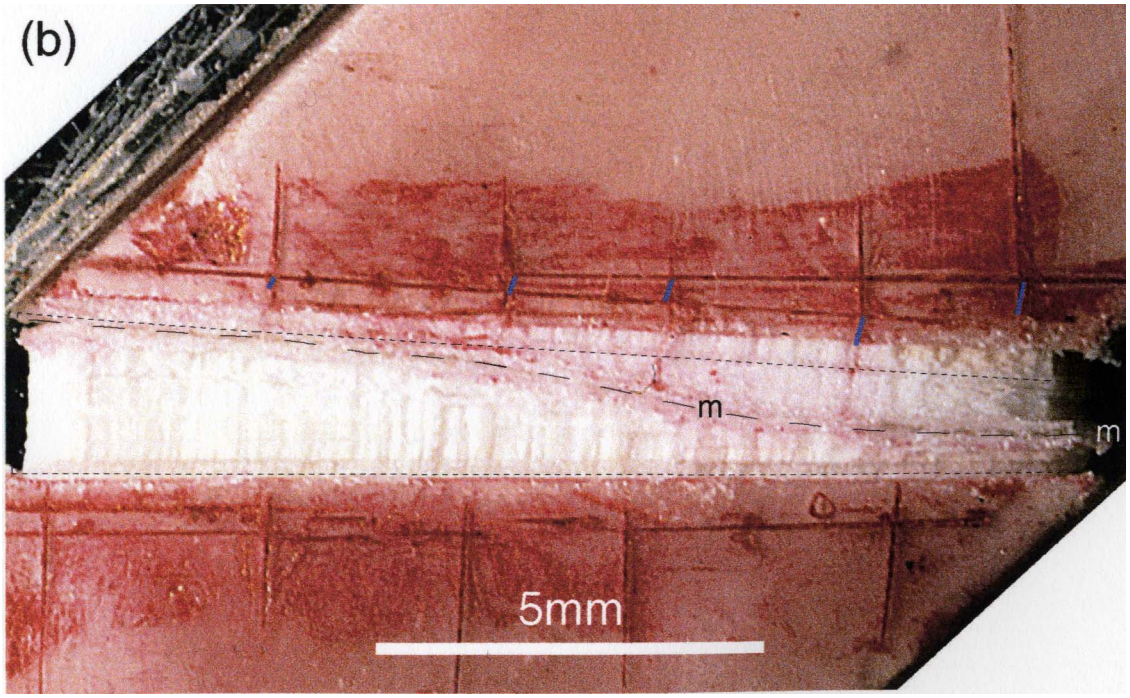
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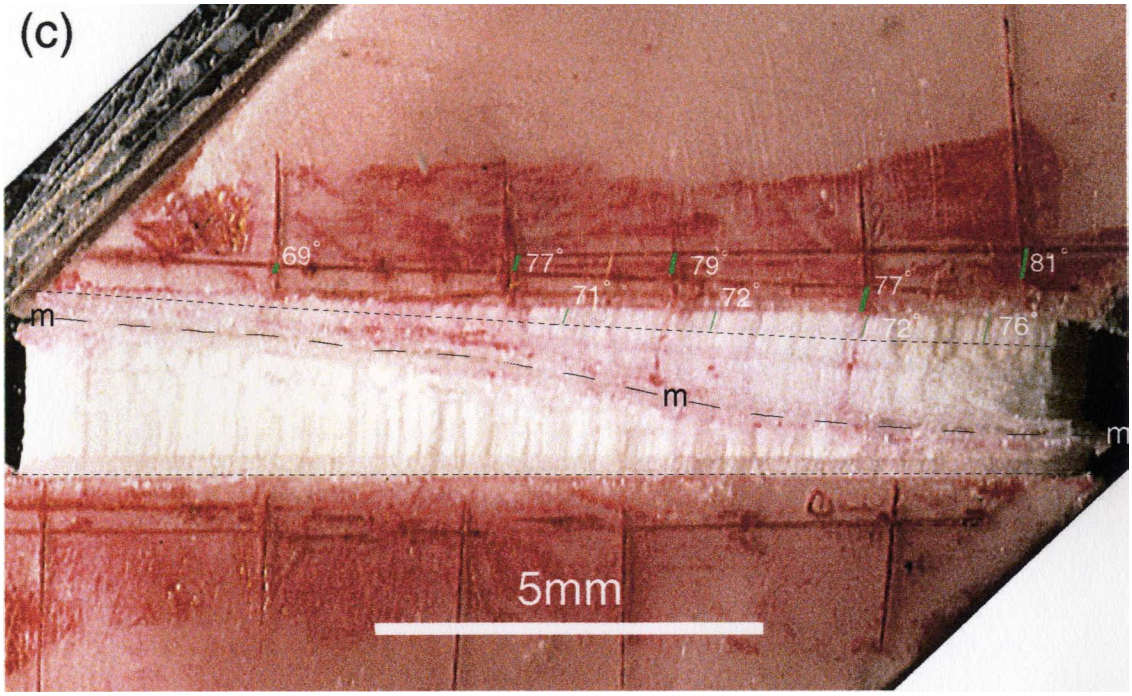
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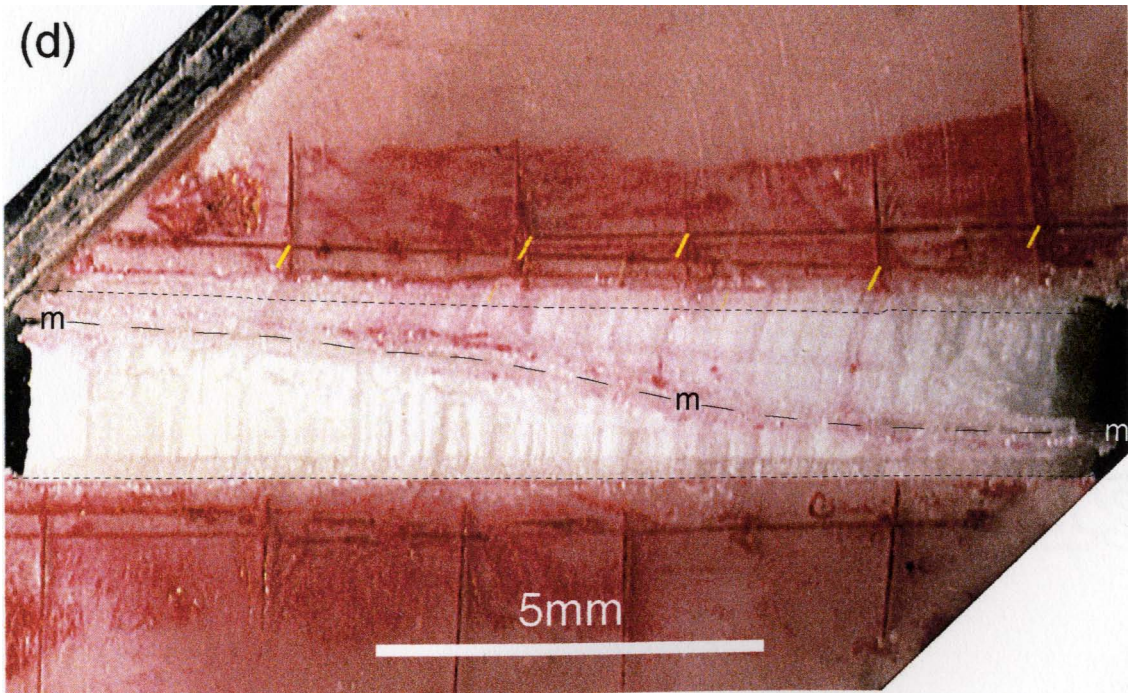
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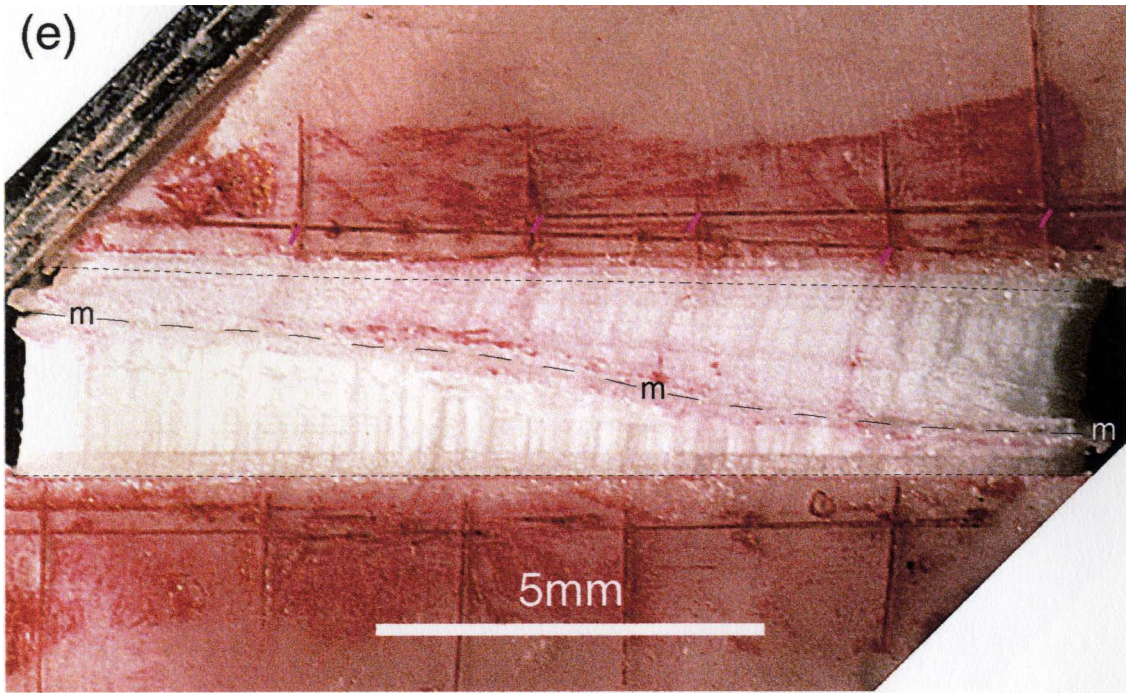
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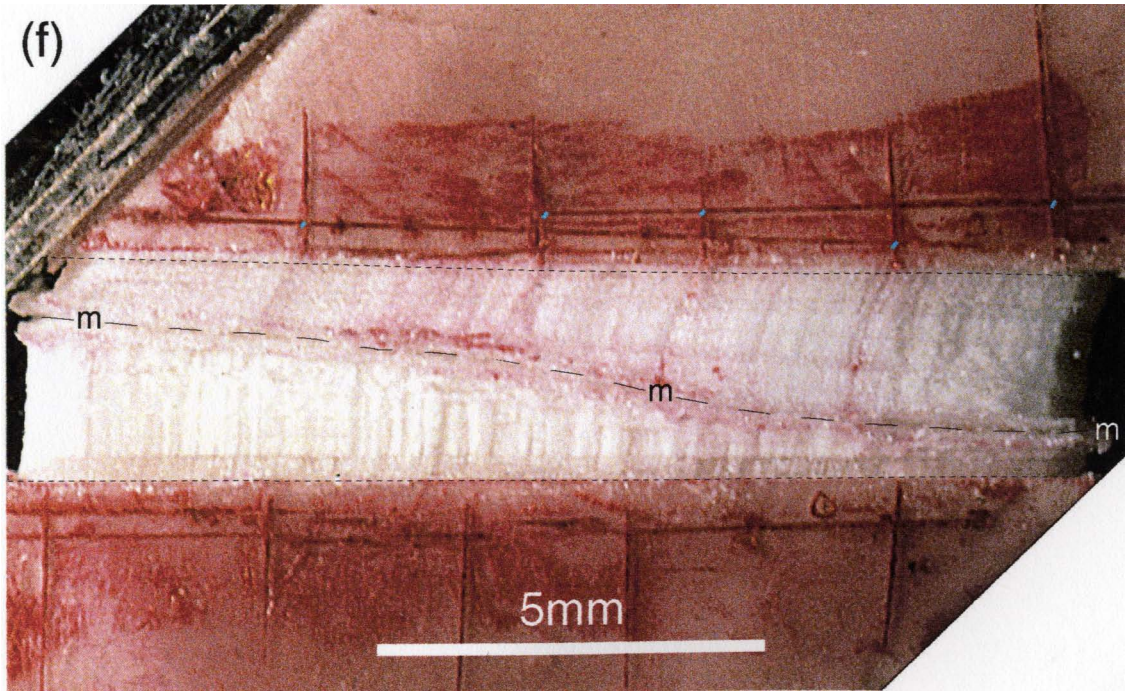
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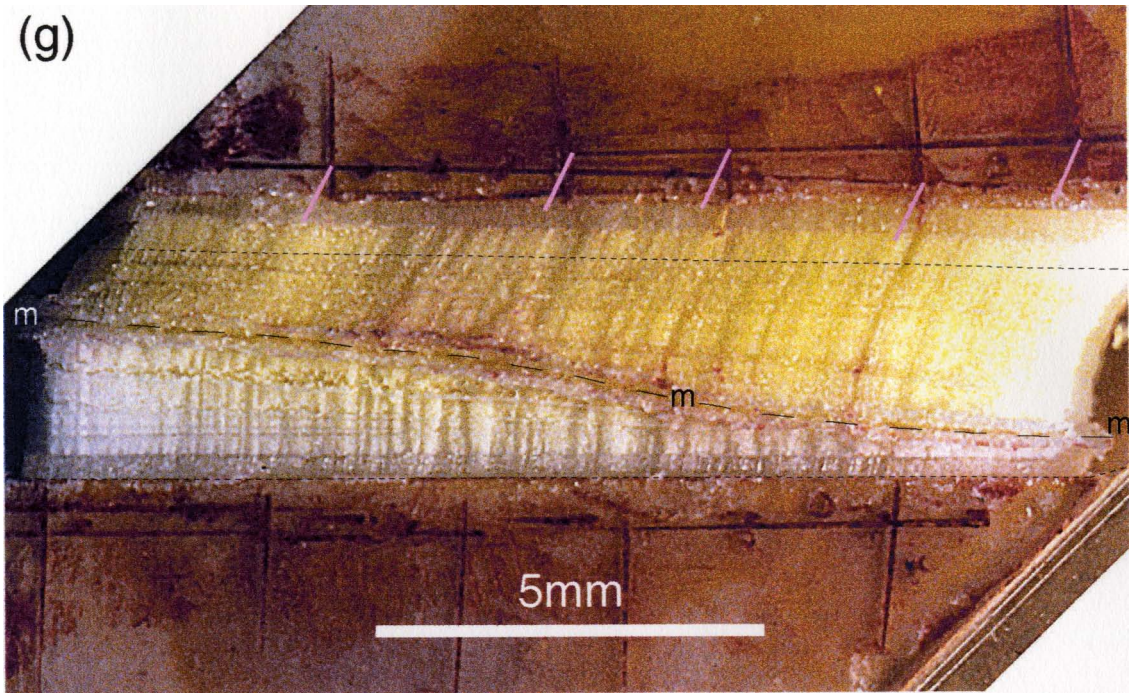
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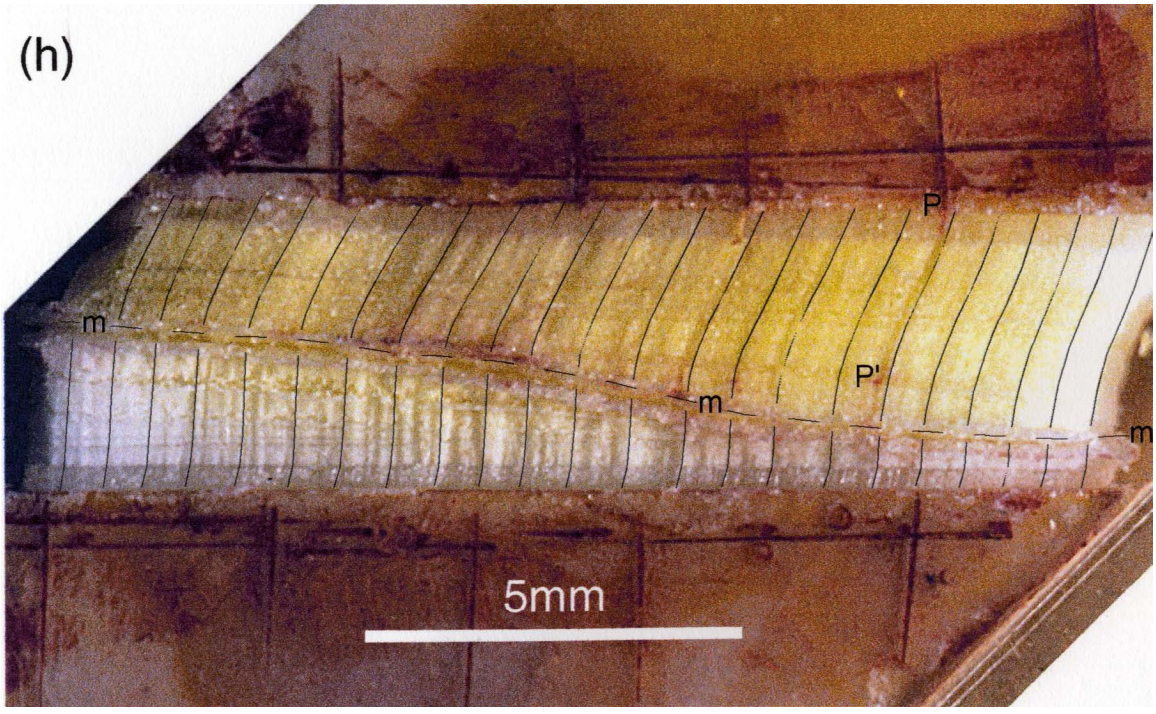
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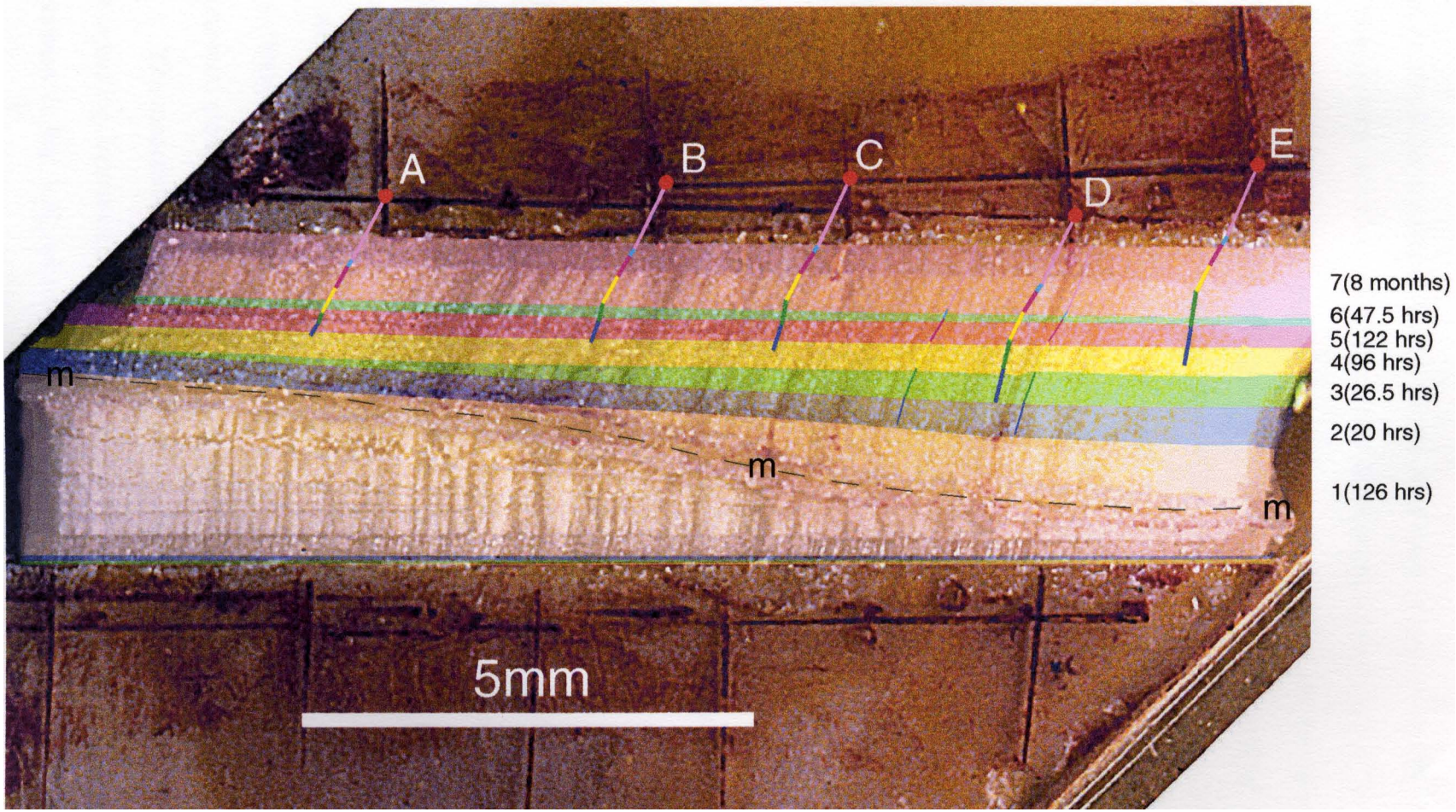
Fig. 3.12 Map of the six successive major fiber growth increments after some early growth in the vein of experiment *CFB-10* (side A) compared with the corresponding displacements of the five scratch intersection markers on the upper block relative to the lower block. The individual fiber growth bands and the corresponding displacements are colored in the same consistent colors as in the corresponding pictures in Fig. 3.12. The displacement increments connect to form five displacement trajectories ending at the five markers (numbered A through E). Also marked in the corresponding colors are the 6 major growth segments of two individual fibers for comparison. While there are large differences between the orientations of the fiber segments and the corresponding opening displacements of the markers for the second stage of growth (shown in green), the fiber segments grown over the other time intervals all show approximate parallelism (within experimental error) with the corresponding trajectory segments. Numbers for each growth band represent the time duration of each growth interval.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5(122 hrs)
4(96 hrs)
3(26.5 hrs)
2(20 hrs)
1(126 hrs)

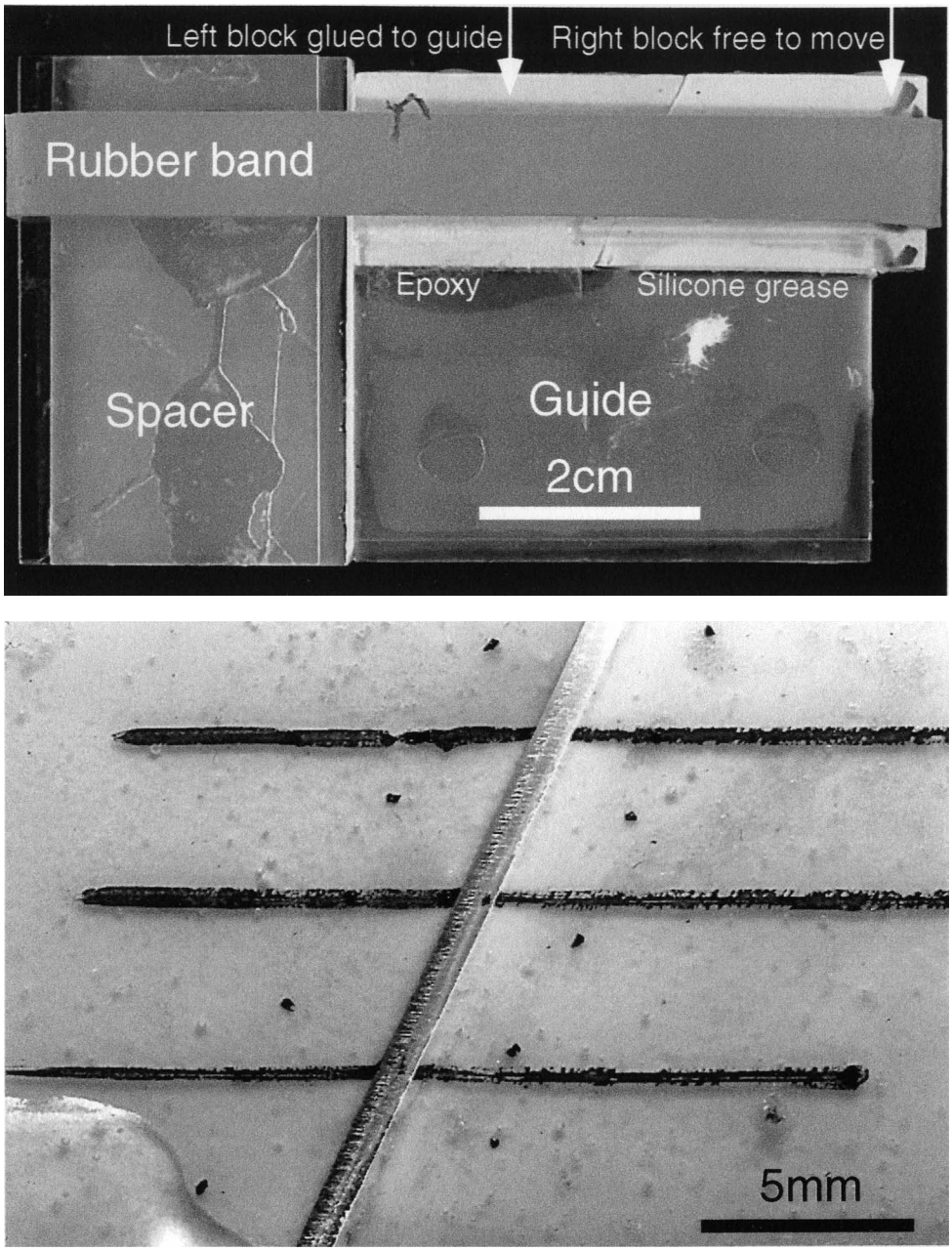
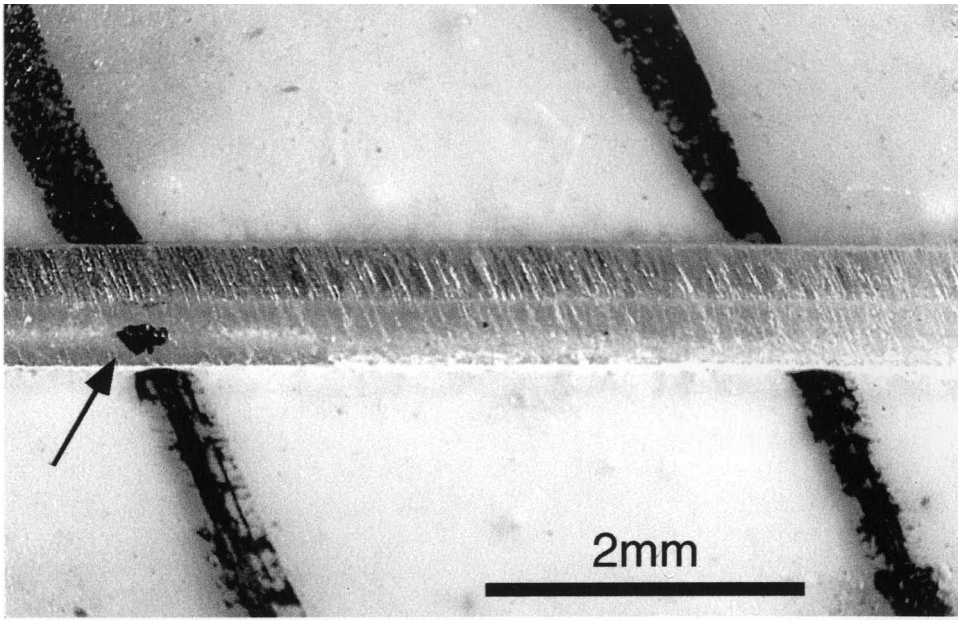


Fig. 3.13 Experimental growth of fibrous veins under compressive loading. (**a**) Rubber-band loading set-up showing how the compressive loading is imposed on the analog wall blocks by means of a rubber band. The spacer on the left is simply used to stretch the rubber band to create a desirable amount of compressive force. Wall blocks (porous ceramic) are coated with epoxy except on the crack side and are saturated with the crystallizing fluid at the beginning of experiment. Crystallization and vein opening occurs at the crack by evaporation of water from the pore fluid under low humidity condtions in a closed jar. (**b**) A vein of fibrous crystals of NH_4SCN grown in a rubber-band loading experiment *DW-07* over a period of 33 days in an ambient air of low humidity (ca. 10%). Fibers grew by pushing the right wall apart from the left wall, against the loading imposed by the rubber band. Black spots alongside of the vein are markers placed for the purpose of monitoring opening displacement, and horizontal lines indicate the orientation of the guide. Fibers in the vein are seen to be roughly parallel to the guide.

(c)



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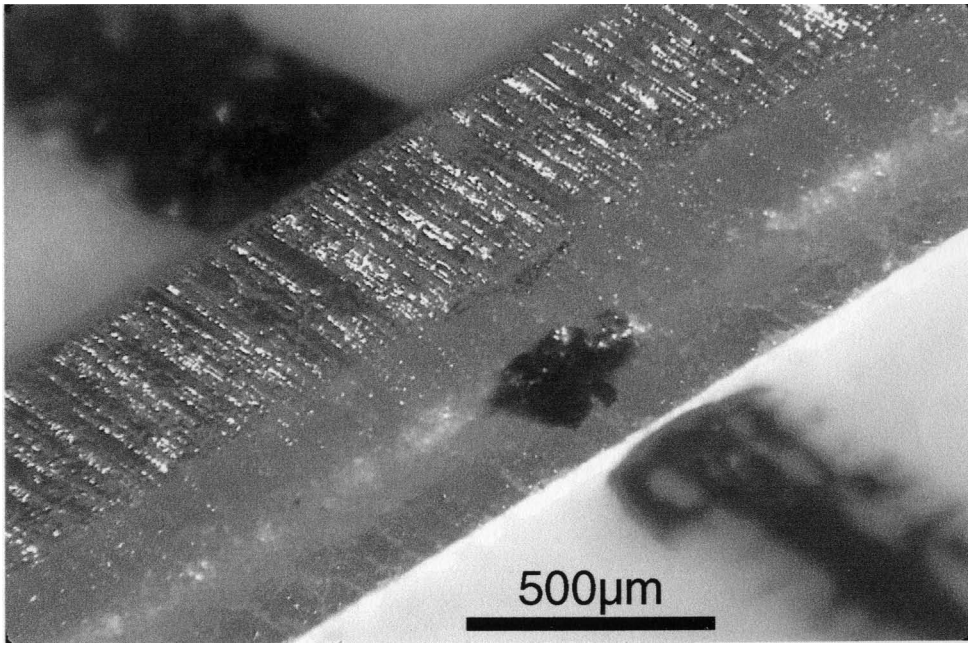
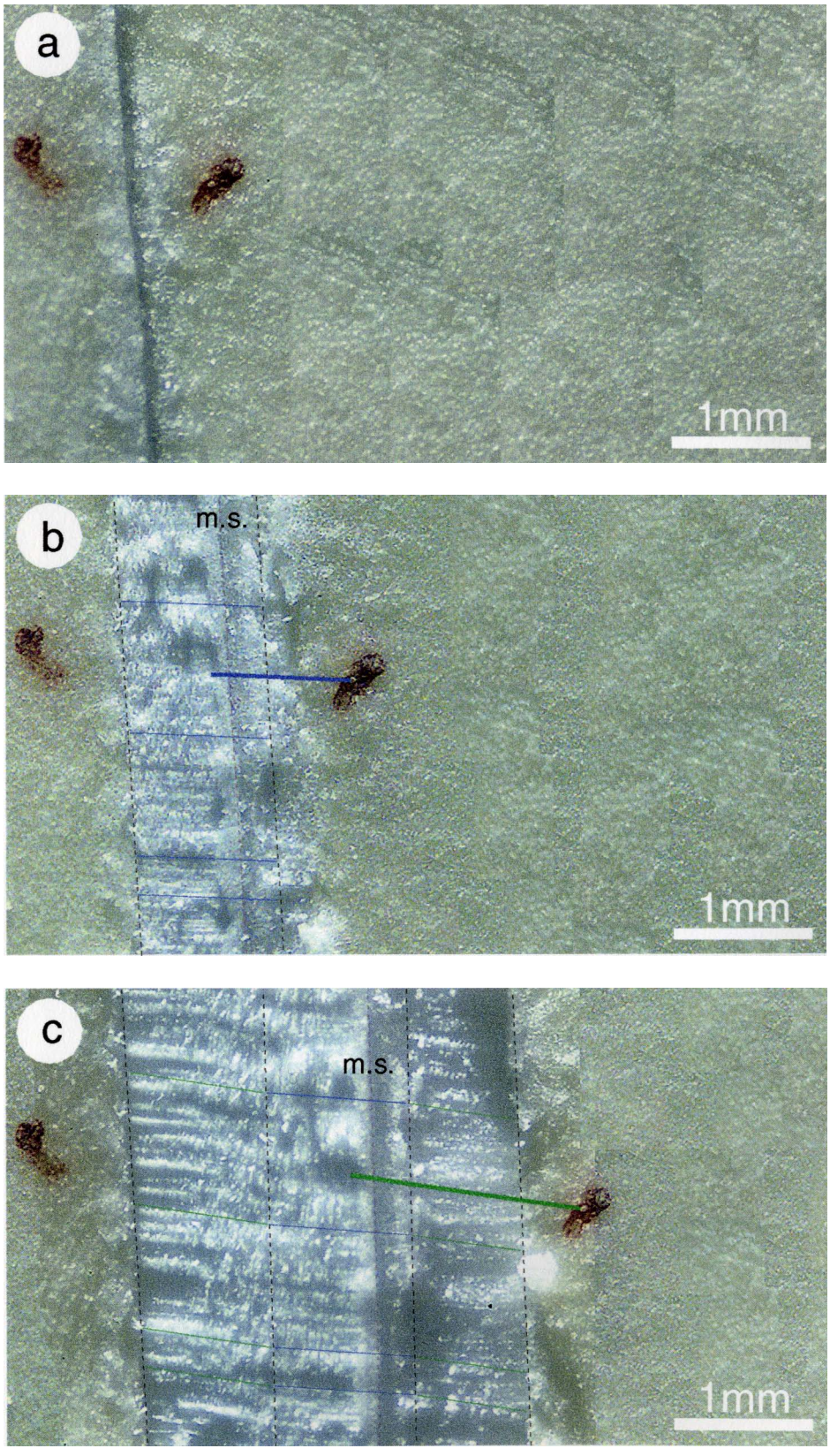


Fig. 3.13 (continued) (**c**) Enlarged view of the same vein as in (b), showing that the vein has an asymmetric geometry with the upper half better developed than the lower half. Note a Type I discontinuity across the fibers in the upper half, which does not mark the suture as it appears. The latter should go somewhere through a pen ink marker pointed to by arrow. The orientation of the guide again is shown by the pen ink marked lines across the vein. (**d**) Micrograph of the same vein at a still larger power. Note the same pen ink marker in the vein as in (c).

Fig. 3.14 History of opening of a vein of curved fibers of $NaNO_3$ in a dead-weight loading experiment *DW-20a* (see set-up in Fig. 3.10). Ceramic blocks were coated with epoxy except on the vein side and growth occurred at room air humidity. As in Fig. 3.11, successive fiber growth increments are compared with the corresponding opening displacements during each growth stage. All photographs are aligned with the position of the left hand block fixed while the right-hand block is displaced by vein opening. Black dashed lines in each picture mark the locations of the previous vein-wall boundaries across the fibers. Red spots alongside of the vein are ink markers placed for the purpose of reconstructing the history of opening displacements. Each reconstructed incremental displacement vector of the right-hand block relative to the left-hand block is shown as a thick colored line ending at the marker in the corresponding picture. For comparison thin lines in the same color and the same orientation as the incremental displacement vector are drawn within the corresponding incremental fiber growth bands. The complete displacement trajectory consisting of all the incremental displacements is drawn in the last picture. Also drawn in the pictures is a pronounced median suture (**m.s.**, shown in a brown dashed line) between the two asymmetric halves of the vein. (**a**) Initial state of sample. (**b**) Initial growth and opening during the first 15 hours. Fibers show approximate parallelism with the incremental displacement (shown in dark blue). (**c**) More growth and opening over the next 22 hours. The displacement (shown in green) has now become more oblique. Although the fiber segments within the new growth bands are slightly curved, their overall orientations are also more oblique than their older counterparts so that they still show approximate parallelism with the displacement. (**d**) More growth and opening in a less oblique direction over the next 32 hours. New fibers again are parallel with the displacement vector (shown in yellow). (**e**) Growth in the next 68 hours. Displacement (shown in red) has become almost normal to vein, while new fibers are almost exactly in accord in orientation. (**f**) The final stage of growth in the last 45 hours with only a small incremental growth on the left-hand side of vein. It does not show much difference from the previous incremental growth direction and still "tracks" the displacement (shown in blue).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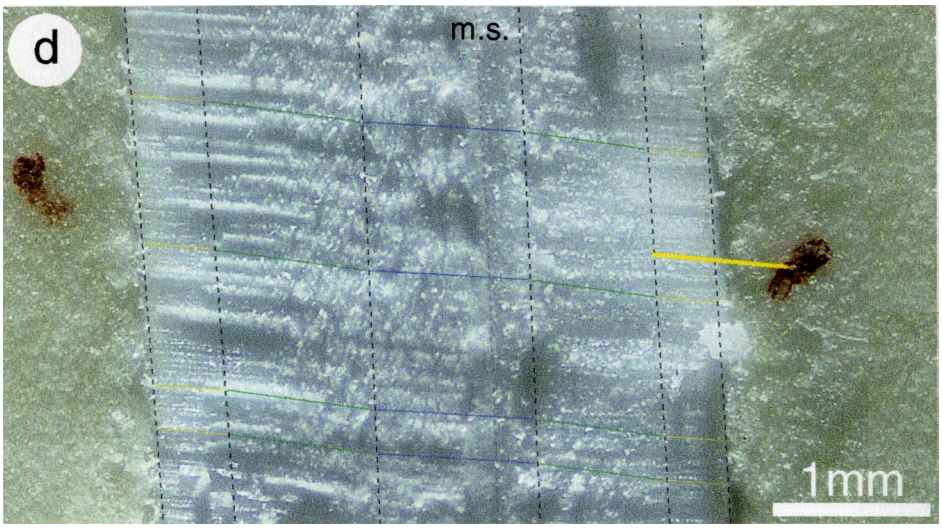
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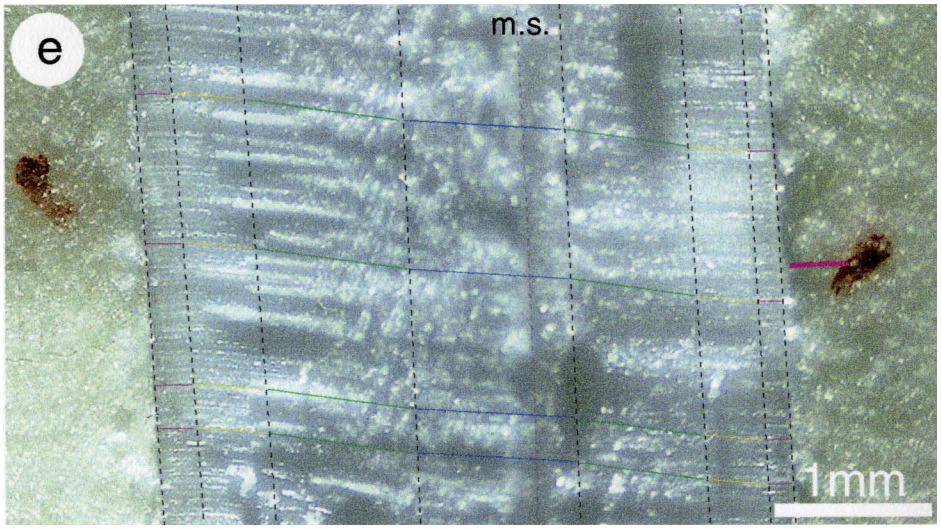
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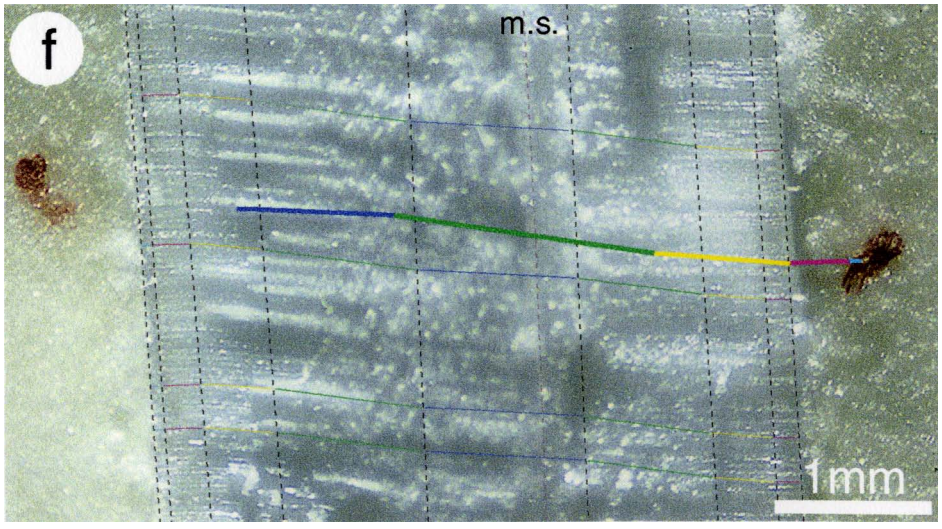
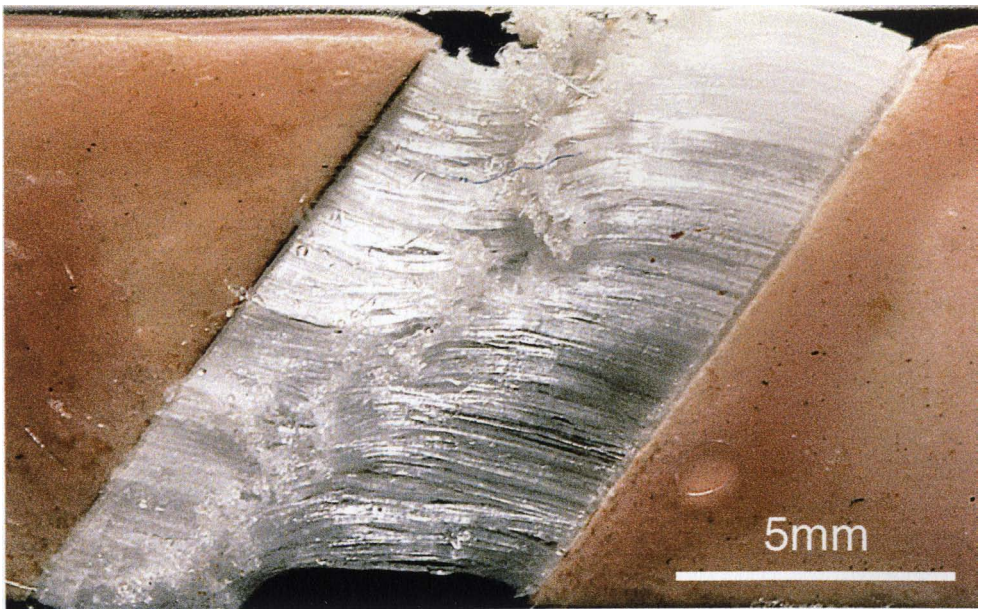

f
m.s.
1mm

(a)



(b)

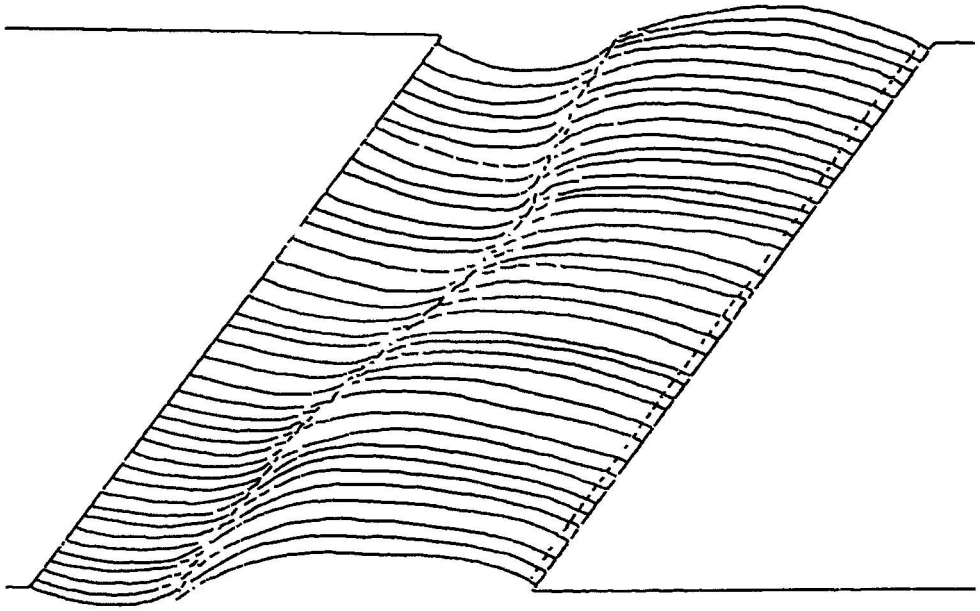
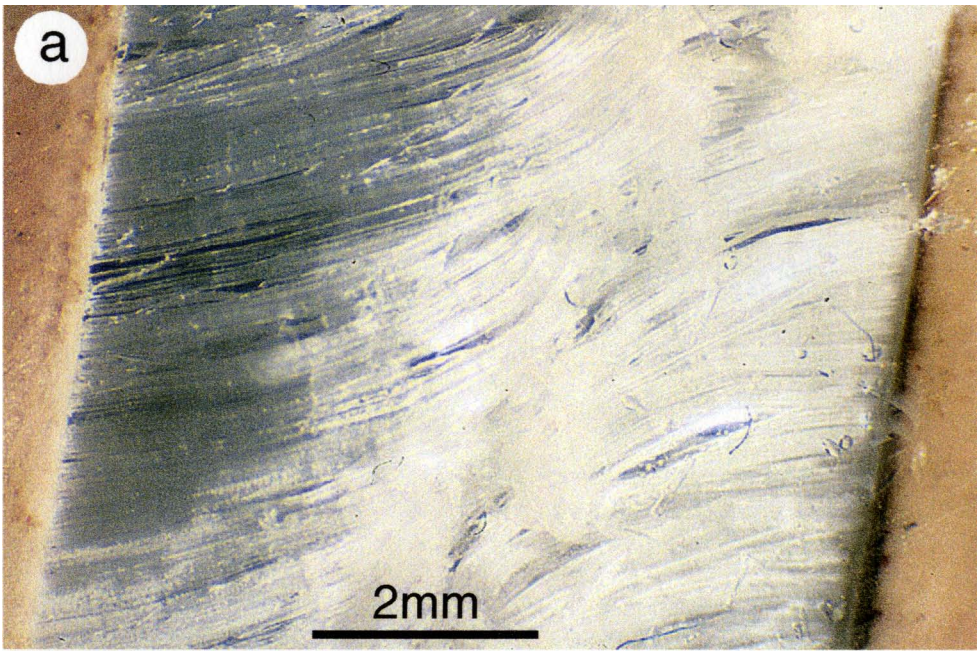


Fig. 3.15 A vein of curved fibers of NH_4SCN with a "syntaxial" pattern of curvature that fails to track displacements. (**a**) Photograph of the vein after displacements all about parallel to the (horizontal) guide blocks. Growth took about 3 days in a closed jar with a relative humidity of about 30%. (**b**) Sketch showing the fiber curvature pattern in (a), despite simple opening history.



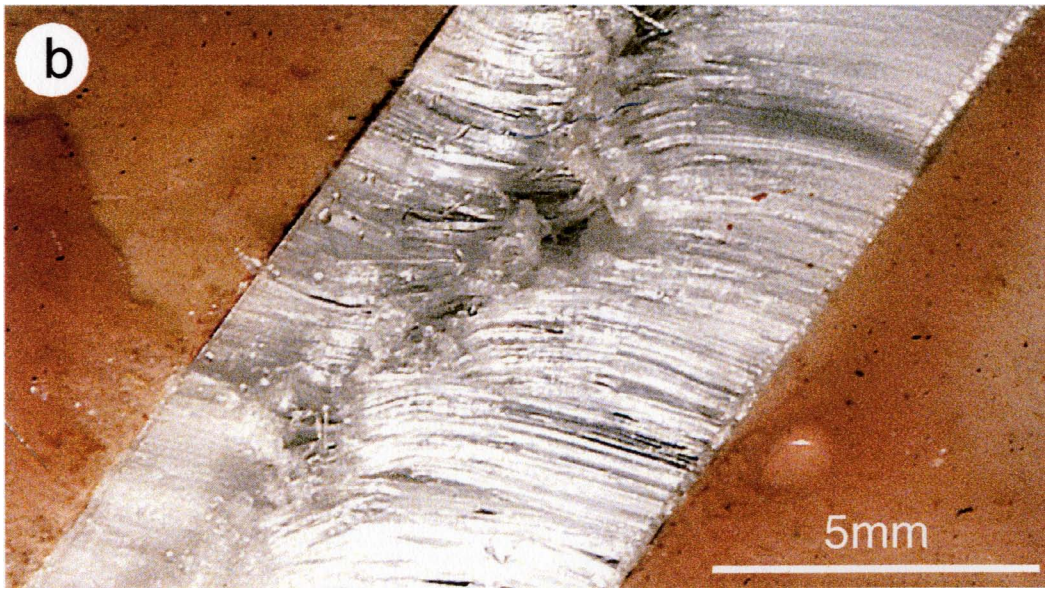
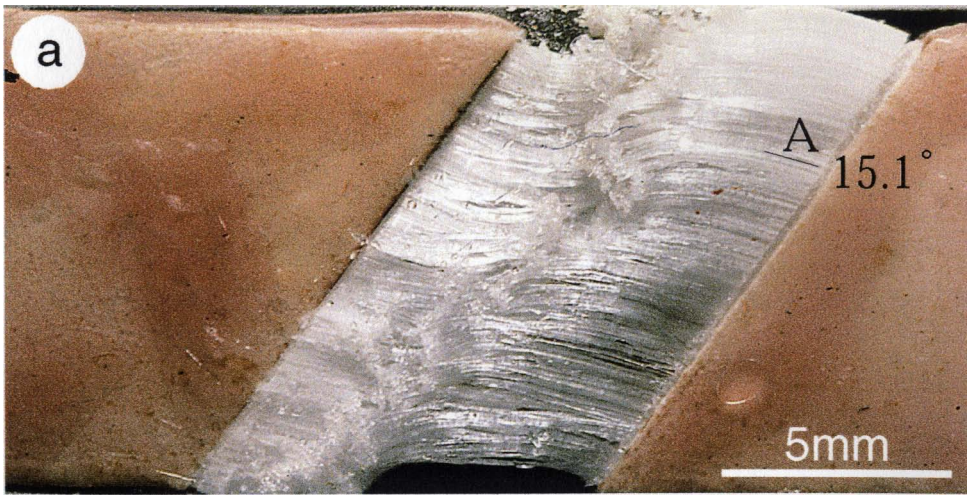
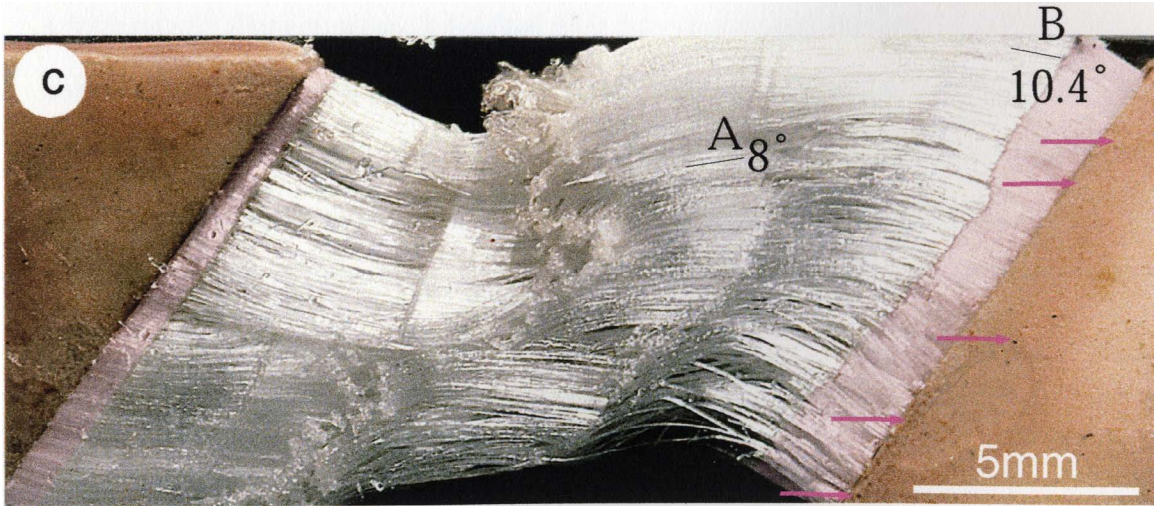


Fig. 3.16 Different views of the same vein as in Fig. 3.15 showing its typical "syntaxial" type of curvature pattern of curved fibers. (**a**) View of the vein lying at a high angle to the horizontal. (**b**) View of the vein with its upper and lower guides (not shown) parallel to the horizontal.

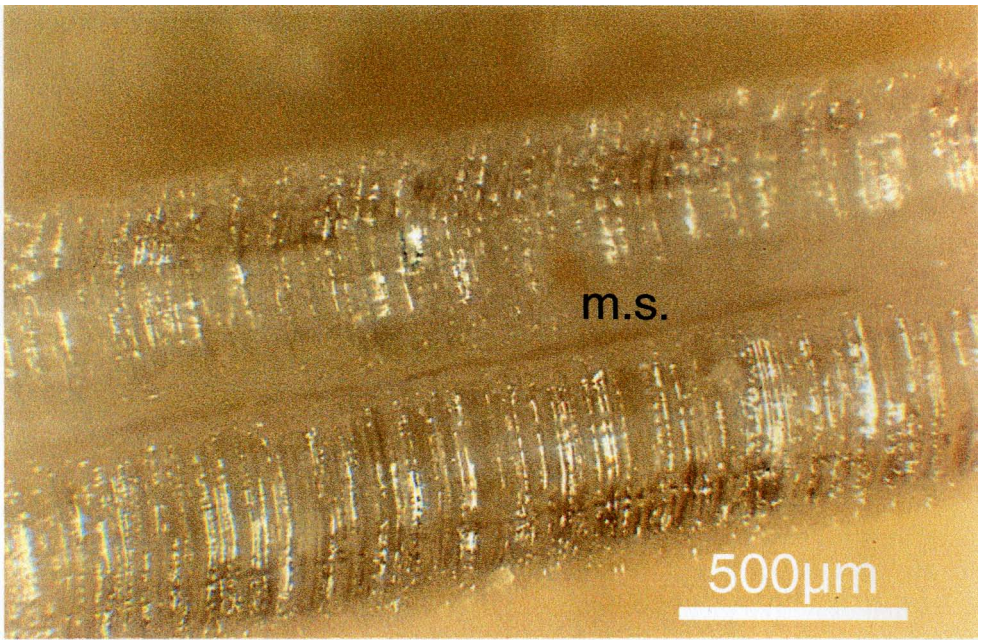
Fig. 3.17 Further opening of vein *CFB-04* and new growth of curved fibers compared with relative displacements between the walls. All photographs are aligned with the long edges of the sample or the upper and lower guides (not shown) parallel to the horizontal. (**a**) Vein grown over the first 80 hours, the same as shown in Fig. 3.15. (**b**) Widened vein 45 hours later. (**c**) Further widened vein another 70 hours later. Red lines with arrows show the relative displacement vectors of several distinct particles on the right-hand wall (pointed to by the arrows) with respect to the left-hand wall, which occurred during the corresponding time interval. The corresponding incremental fiber growth is colored in pink for comparison. Orientaions of one fiber trace A in the first increment and another fiber trace B in the second increment are traced and compared. See text for more details.


a
A
15.1°
5mm


b
B
21.5°
A
4.7°
5mm


c
B
10.4°
A
8°
5mm

(a)



(b)

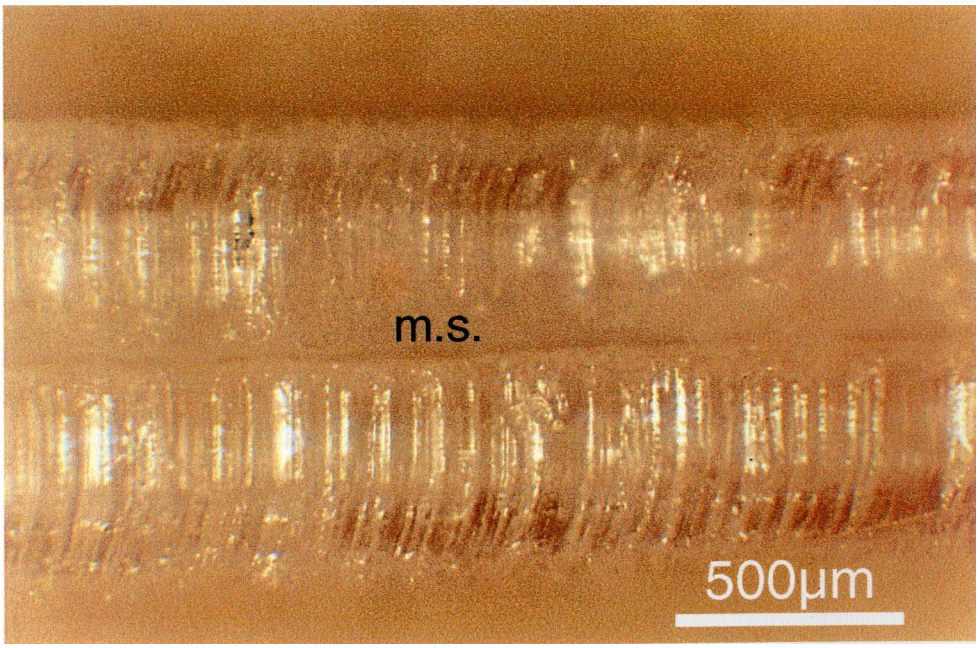
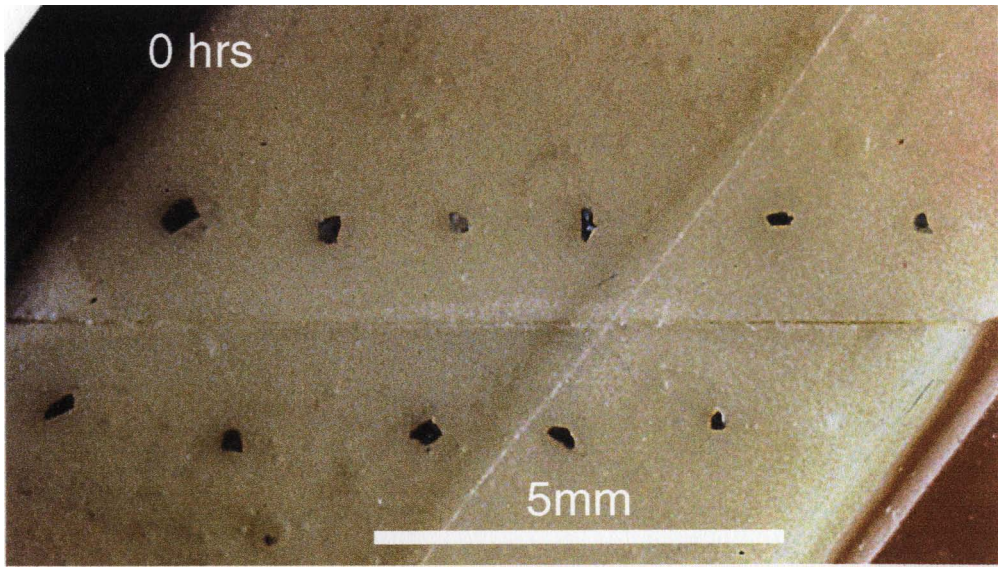


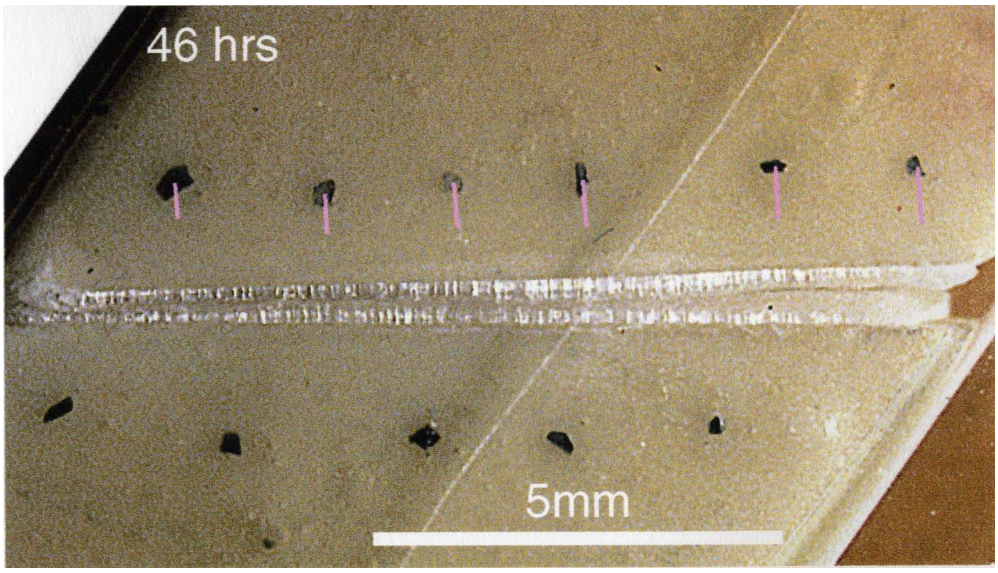
Fig. 3.18 Views of a vein of curved fibers of NH_4SCN with an antitaxial type of curvature pattern, grown in a guide-constrained vein experiment (*CFB-47*) (refer to Fig. 3.9 for the set-up). Growth occurred over a period of 10 days in a closed desiccator with a relative humidity of about 10%. Ceramic blocks (*Square*) were coated with epoxy except on the crack side. Note the median suture is a sharp discontinuity (**m.s.**). Photos taken in reflected light.

Fig. 3.19 History of vein growth in experiment *CFB-47* as shown by successive fiber growth increments compared with the corresponding opening displacements. All photos are reoriented such that the vein is aligned with the horizontal and the guides run diagonally across the upper-left and lower-right corners. Also, the position of the lower block is fixed with respect to the picture and the displacements of the upper block relative to the lower block are traced. Black spots alongside of the vein are tiny powder particles embedded into the wet epoxy-coating during the sample preparation process and are used as markers for tracing displacements. The number in the upper-left corner of each picture represents the length of time of the corresponding growth interval. A vague line running diagonally across the pictures is a thin crack in the cover slip over the sample. (**a**) Initial state of sample. (**b**) Opened vein of fibers 46 hours later. Pink lines show the incremental displacement vectors of the six markers on the upper block relative to the lower block, occurred during the corresponding time interval. They show significant deviations from the overall orientation of fibers (normal to vein) due to rotation. (**c**) Further widened vein 16.5 hours later. The displacements of the markers (shown in green) started to turn clockwise, due to the constraint of the guides. At least some new growth on the lower side of vein begins to show corresponding changes in growth direction.

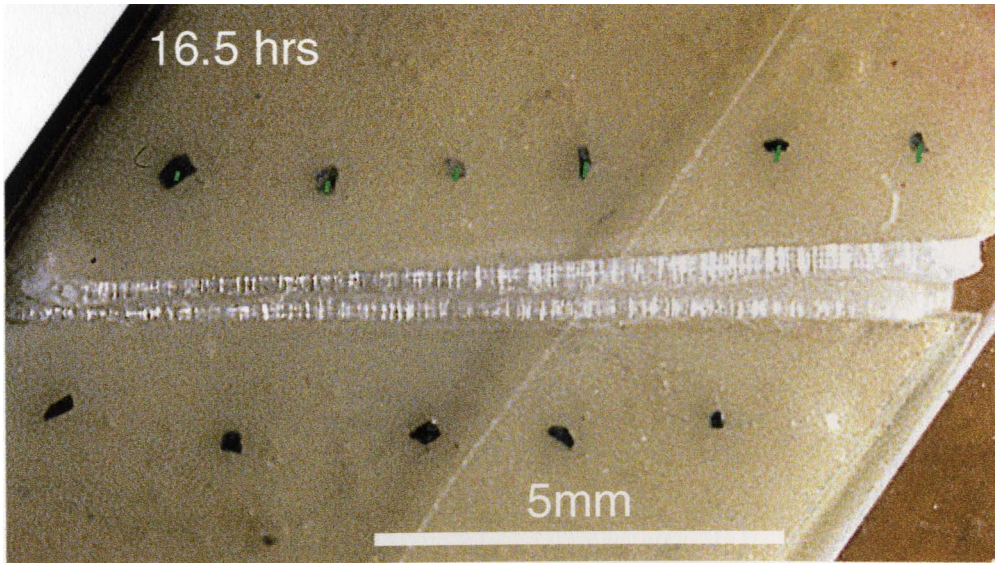
(a)



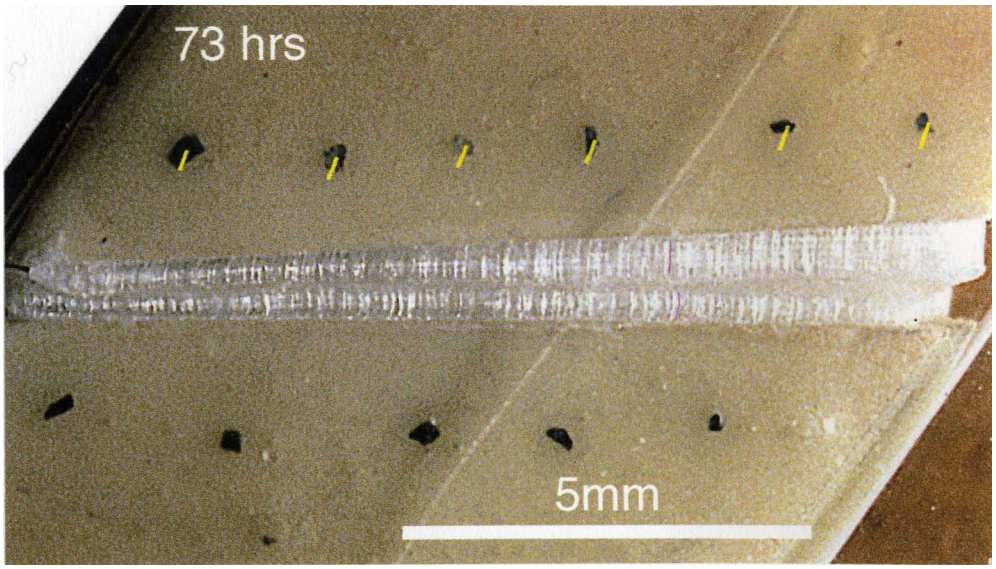
(b)



(c)



(d)



(e)

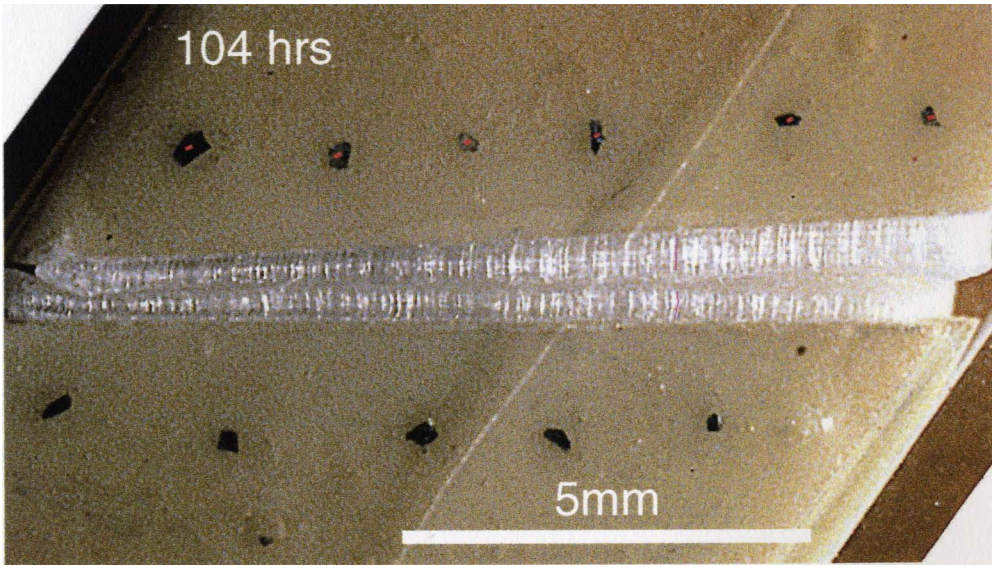


Fig. 3.19 (continued) (**d**) Significant changes in fiber growth direction during the next 73 hours, in response to the changed displacement vectors (shown in yellow) due to the guide constraint. Fibers are significantly curved because of new growth in an oblique orientation, roughly correlatable with the displacements. Red lines mark two distinct fibers for later comparison. (**e**) Last stage of experiment during the next 104 hours. The upper block was forced to further displace right-laterally, but the displacements (shown in red) were NOT completely accommadated by growth of oblique fibers but mainly produced by a slip along the median suture, as can be seen from the changed relative positions of the fibers on either side of vein. For instance, the current relative positions of the same two fibers (also marked with red lines) as in (d) clearly show a right-lateral silp (about 84 μm) along the median suture. All photos taken in reflected light.

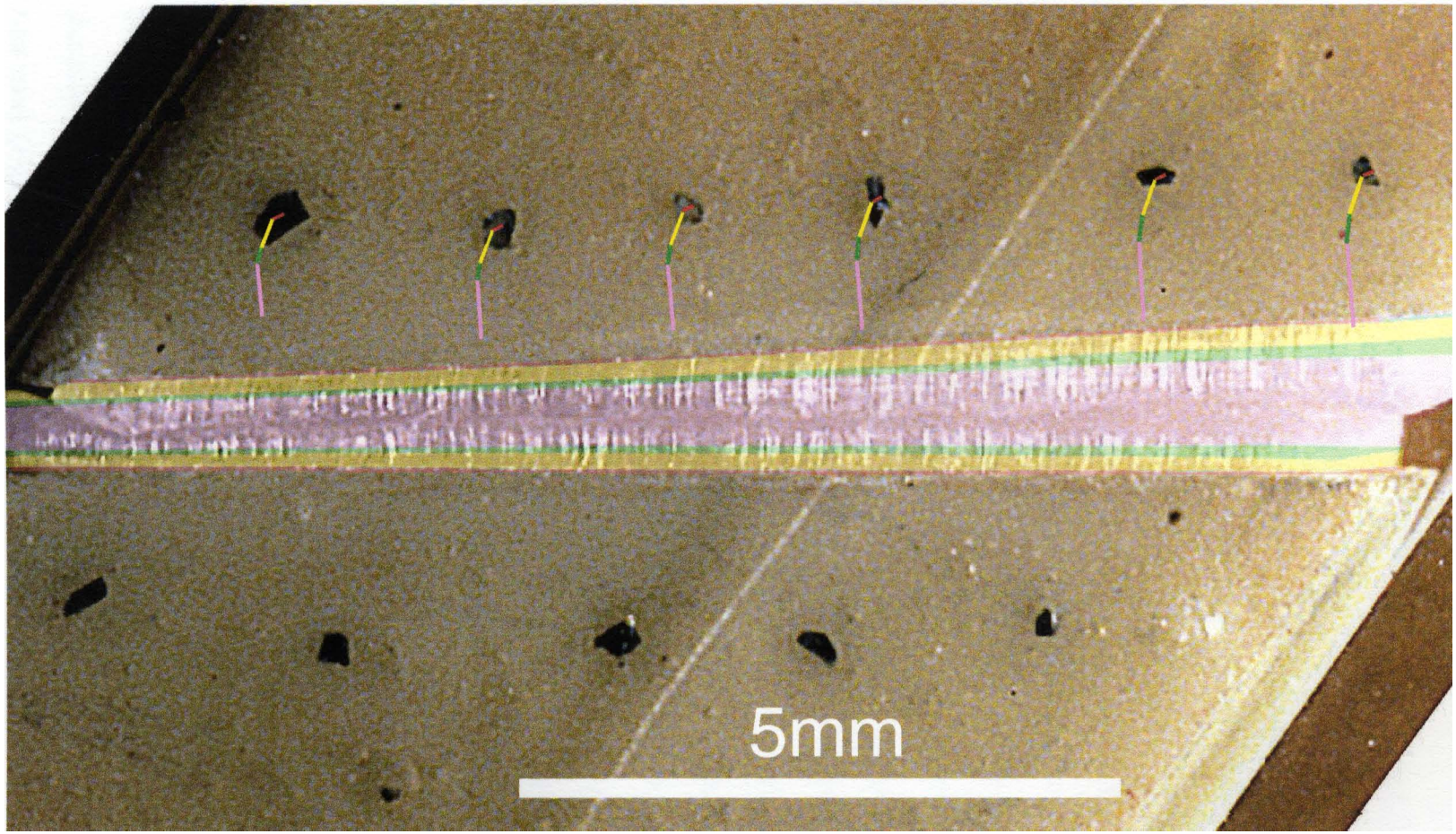
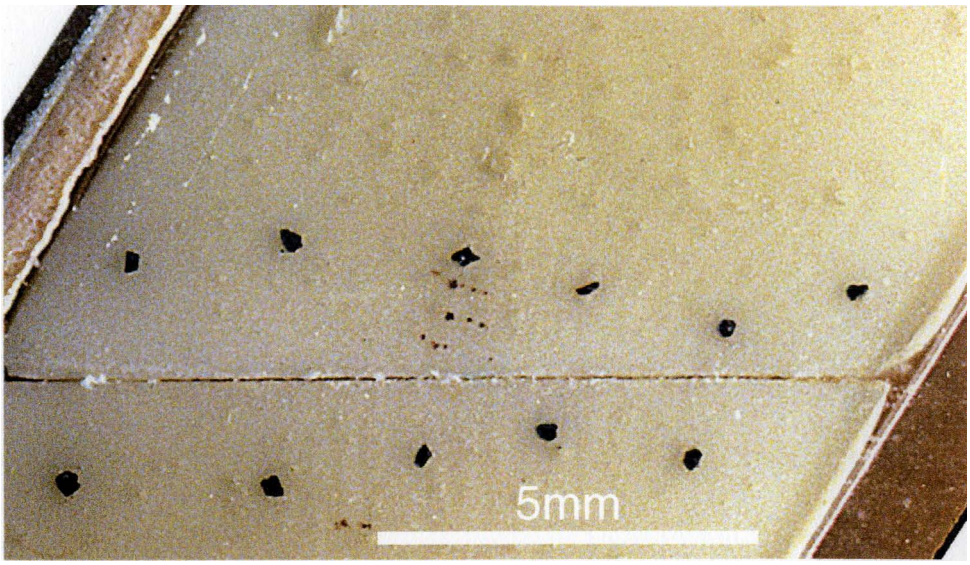


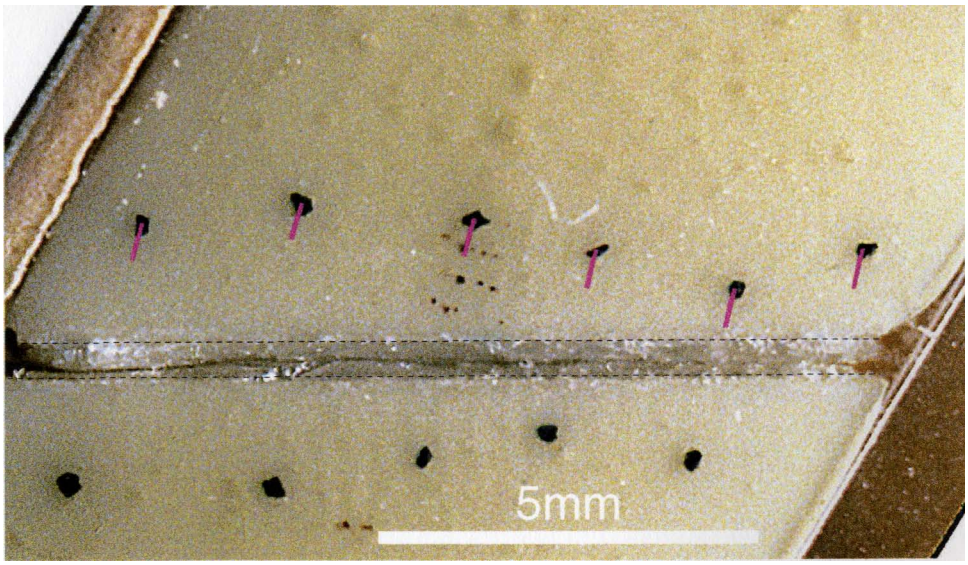
Fig. 3.20 Map of the successive fiber growth increments in the vein of experiment *CFB-47* compared with the corresponding displacements of the six markers on the upper block relative to the lower block. Individual fiber growth increments and the corresponding displacements are colored in the same color as in corresponding pictures in Fig. 3.19. The displacement increments thus connect to form the six trajectories ending at the six black markers. While there are large deviations between fiber orientations and opening displacements of the markers for the first stage of growth (shown in pink), the fibers grown over the second and third time intervals (shown in green and yellow) show parallelism (within experimental error) with the corresponding trajectory segments.

Fig. 3.21 History of growth of a vein of curved fibers of NH_4SCN in experiment *CFB-40*. Experiment was run in a closed desiccator with a relative humidity of about 10%. As in Fig. 3.19, successive fiber growth increments are compared with the corresponding opening displacements during each growth stage. All photographs are reoriented so that the vein is aligned with the horizontal and the guides run diagonally across the upper-left and lower-right corners, and the position of the lower block is fixed in all pictures. Dashed lines again mark the locations of the previous vein-wall boundaries, and black spots alongside of the vein are tiny powder particles embedded into the wet epoxy-coating during the sample preparation process so that displacements of the upper block relative to the lower block could be easily traced using them as markers. (**a**) Initial state of sample. (**b**) Initial growth and opening during the first 102 hours. Red lines show the corresponding displacement vectors of the six markers on the upper block relative to the lower block. They are oblique in orientation, but the fibers are of a poor quality and their orientations are not well defined. (**c**) More growth of better fibers over the next 69.5 hours. The corresponding displacements, shown in green, have become more oblique. Although the new fibers are also obliquely oriented, they are clearly less oblique than the displacements. (**d**), (**e**), (**f**), (**g**), (**h**) & (**i**) Further incremental growths during the following 43.5, 31.5, 47, 69, 121 & 195 hours. The corresponding incremental displacements are shown in dark blue, orange, blue, yellow, purple and pink, respectively. As in (c), the incremental fiber growths in each of these stages are less oblique than the incremental displacements which have become increasingly more oblique on the whole. In (**h**) and (**i**) the two same individual fibers on both halves of the vein are marked in red to show any changes in their relative positions from (h) to (i). It can be seen that there is a significant right-lateral shift in the positions of the fibers in the upper half relative to the fibers in the lower half, reflecting a right-lateral slip along the median suture to accommodate the highly oblique opening displacement during this last stage of vein development.

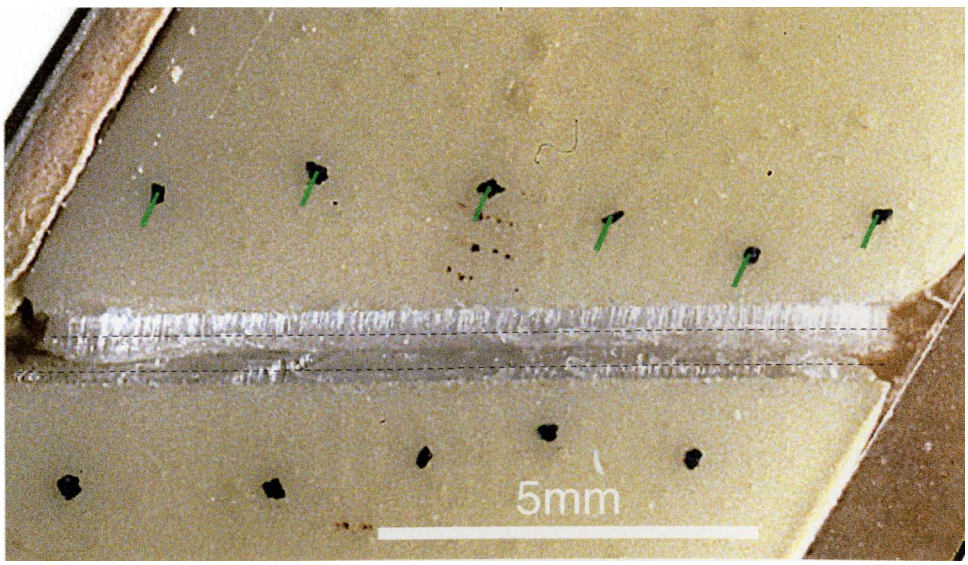
(a)



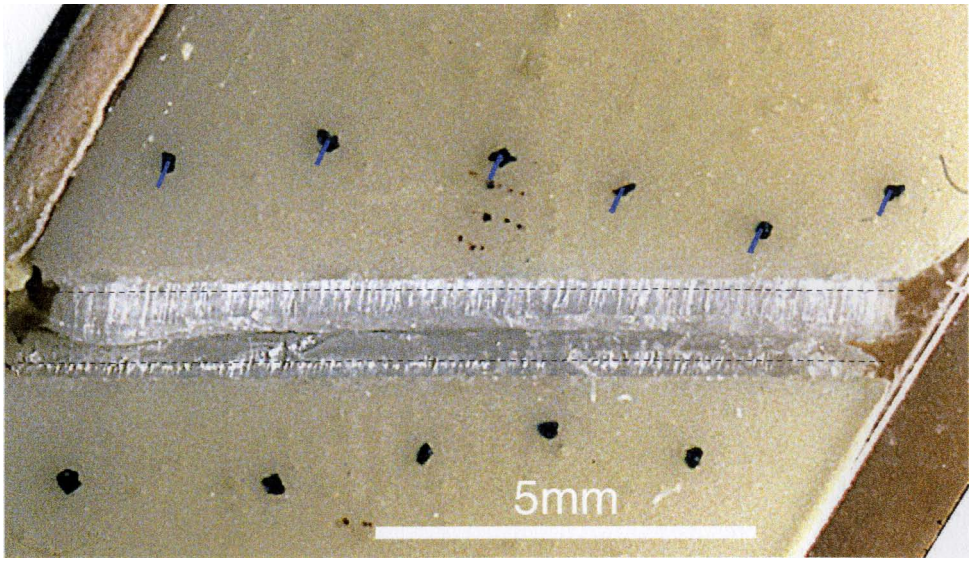
(b)



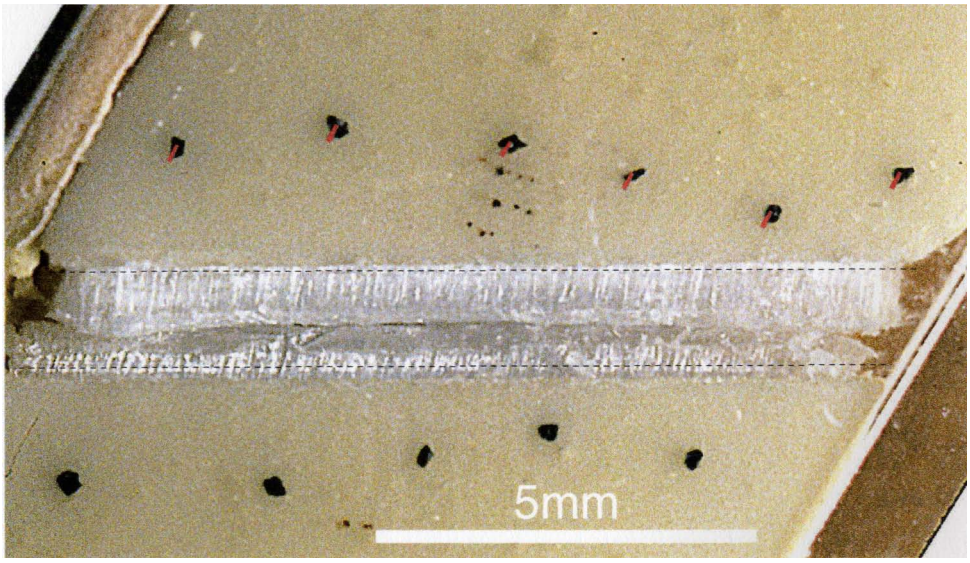
(c)



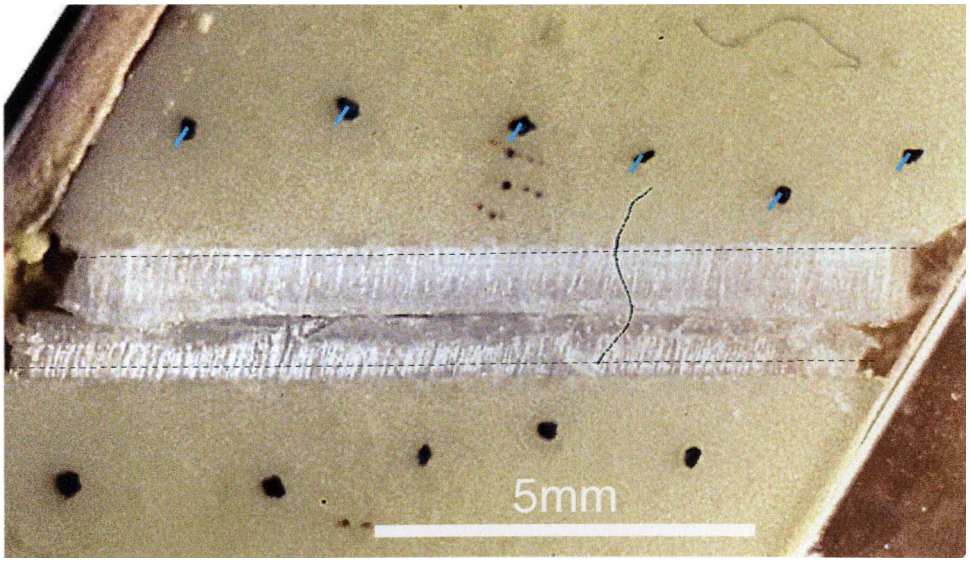
(d)



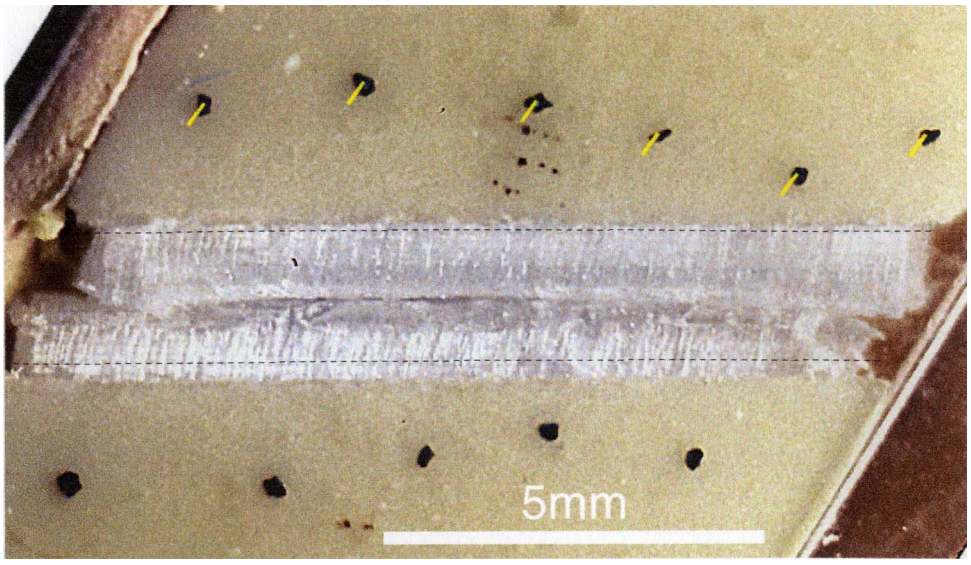
(e)



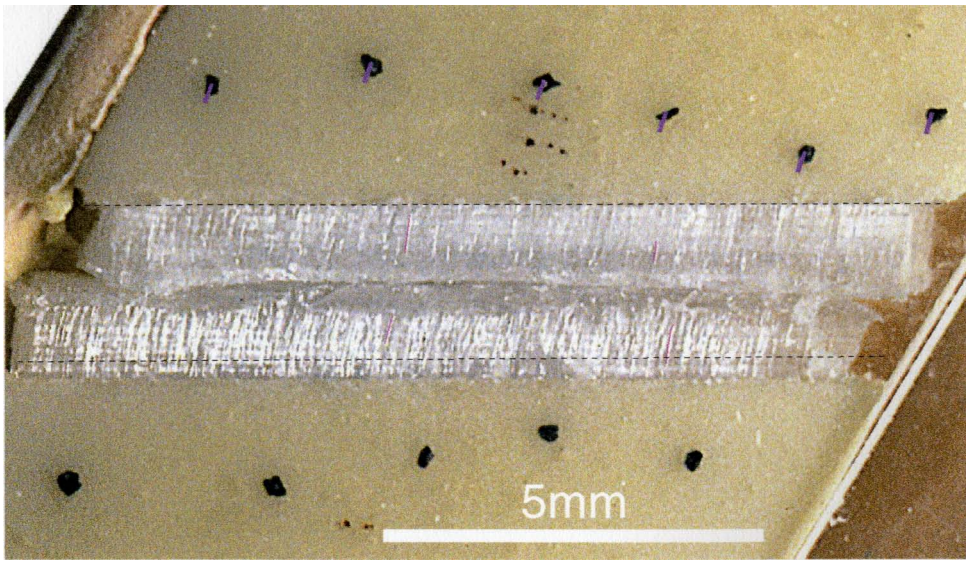
(f)



(g)



(h)



(i)

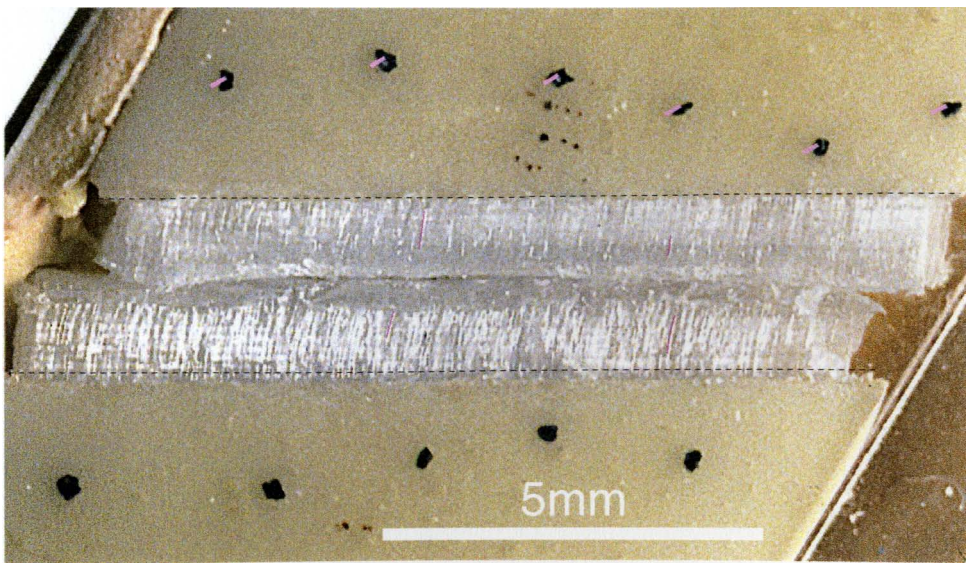


Fig. 3.22 Map of all the eight successive fiber growth increments in the vein of experiment *CFB-40* compared with the corresponding incremental displacements of the six markers on the upper block relative to the lower block. The individual fiber growth increments and the corresponding displacements are colored in the same colors as in the corresponding pictures in Fig. 3.21. The displacement increments thus connect to form the six displacement trajectories ending at the six black markers. It can be seen that the direction of opening displacement becomes increasingly oblique over time except for the second to last opening increment (shown in purple) which shows a sharp bent towards the normal not in accord with the overall trend of the trajectories. Despite such changes and the overall increasingly more oblique trend of opening displacements, the corresponding incremental fiber growths do not show correlated changes. On the contrary they show an overall reversed trend in their orientations; the younger fiber segments (closer to margins) on the whole are LESS oblique than the older fibers (near the center), thus forming a curvature pattern that should belong to the syntaxial type of Durney & Ramsay (1972). Photo taken in reflected light.

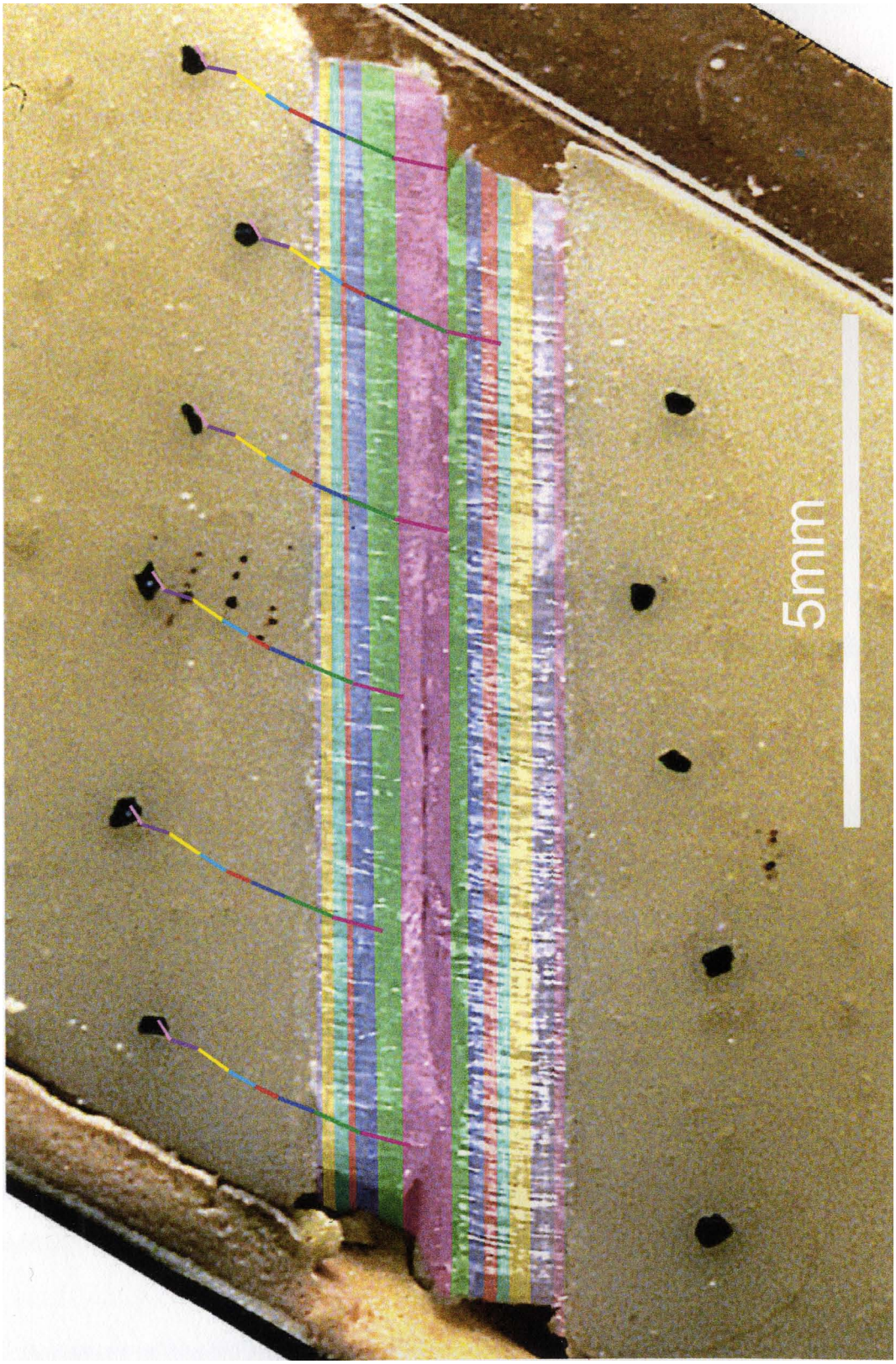
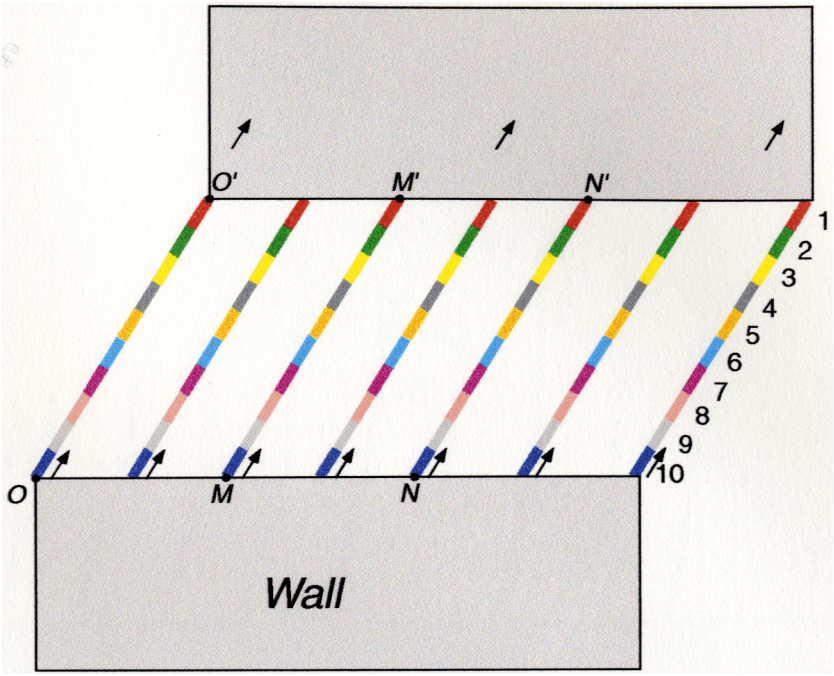
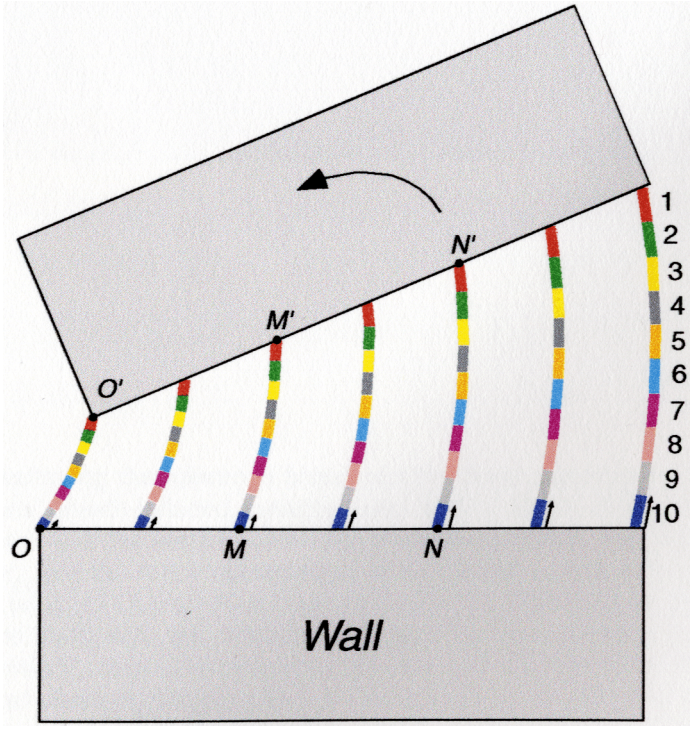

5mm

Fig. 3.23 Diagrams illustrating two basic types of growth-induced motion in Taber growth. In (**a**), fibers grow with a uniform rate and direction of growth along the wall (shown by arrows along the wall) so that the fiber aggregate and the other wall (or the fibers on the other side of vein) are being displaced in a simple body translation. In (**b**), fibers grow with a varying growth rate and direction along the wall (shown by arrows near the wall) so that the old fibers and the other wall are undergoing both a translation and a rotation. For simplicity, only growth from the lower wall is drawn. The upper block can be either viewed as the older fibers grown from the lower block or the fibers grown from the upper block in the case of a vein. Three pairs of originally adjacent points are marked on both blocks. Successive incremental growth bands (shown in various colors) are numbered from the oldest (in red) to the youngest (in blue).

(a)



(b)



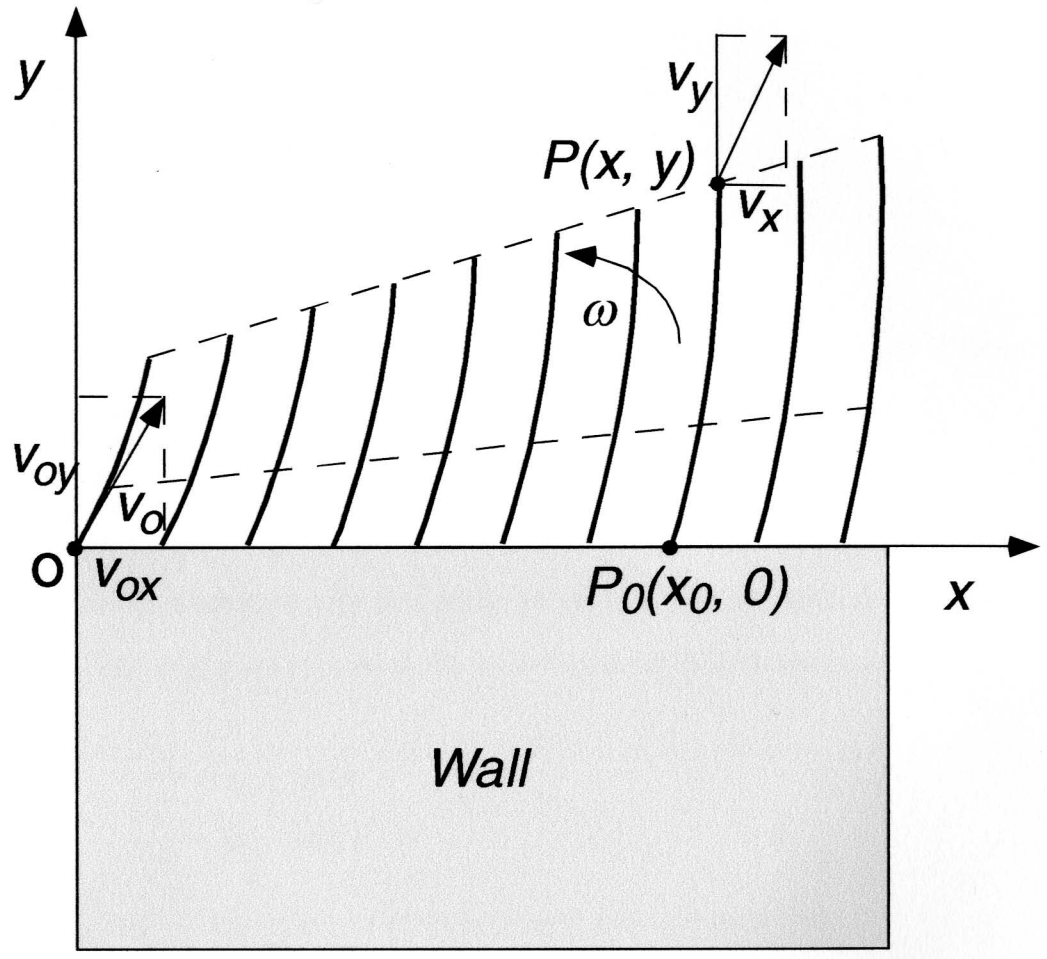
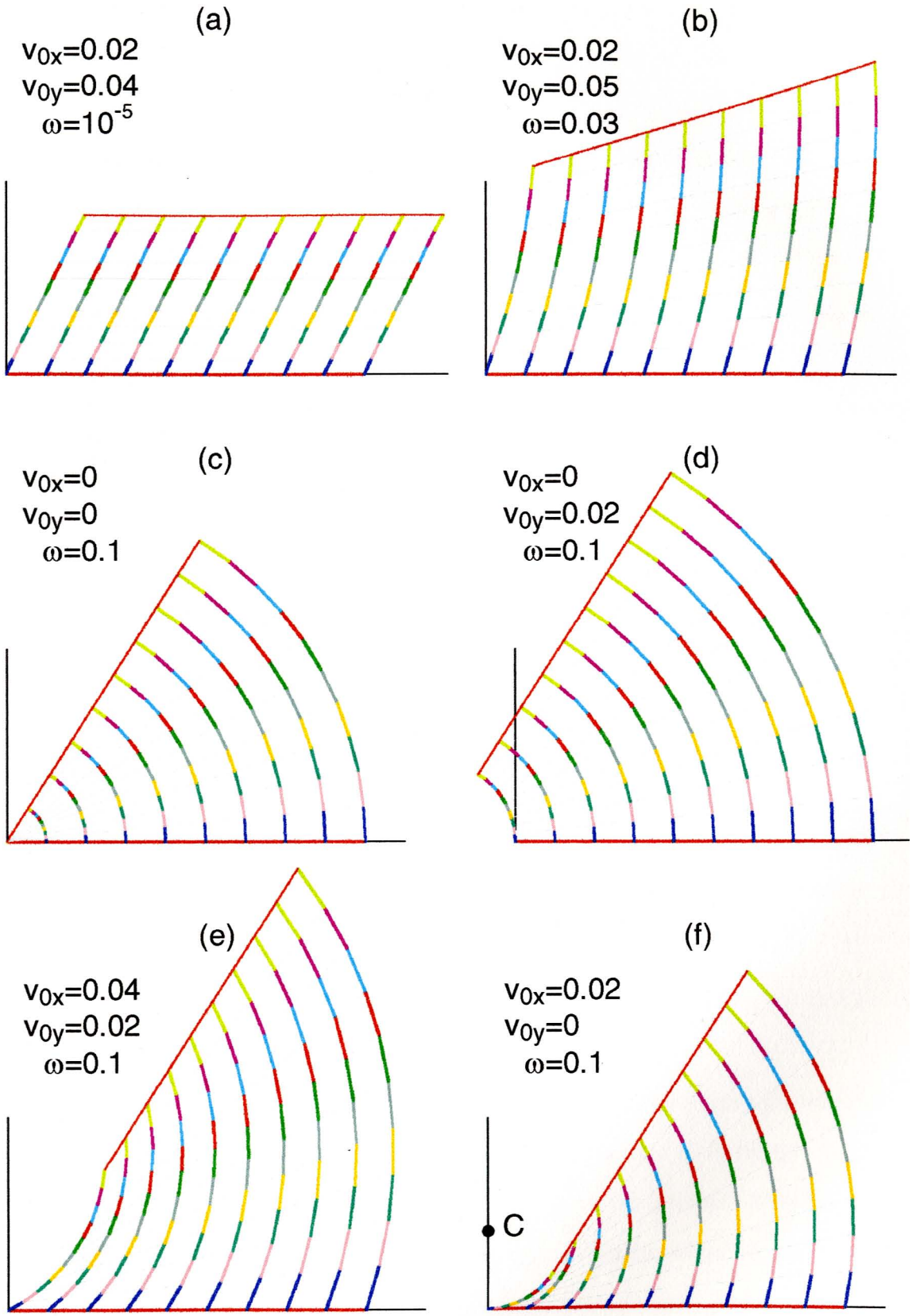


Fig. 3.24 Diagram illustrating the reference frame and the three parameters (ω, v_{ox} & v_{oy}) used to describe the general growth-induced instantaneous motion of the fiber aggregate relative to the wall in Taber growth. ω is the instantaneous angular velocity of the fiber aggregate relative to the wall, and v_{ox} & v_{oy} are the *x* & *y* components of the instantaneous velocity vector (or fiber growth vector) at the origin *O*. Curved thick lines represent the displacement paths of particles or fiber segments carried along with the moving fiber aggregate (and also the actual traces of the curved fibers if the velocity field is at steady state, see text for details). For example, a fiber segment that grew and was incoperated into the fiber aggregate at P_0 at *t=0* has been displaced to point *P*(*x*, *y*). Dashed lines represent successive locations of the boundary between the fibers and the other wall (not drawn) or the median suture if this is one half of a vein, or isochronous linear features such as Type I transverse features across the fibers.

Fig. 3.25 Calculated paths of displacement or traces of curved fibers for different steady-state velocity distributions of the growth-induced motion in Taber growth. The meanings of ω, v_{ox} & v_{oy} are the same as in Fig. 3.24. Line segments with the same color across different lines can be either viewd as incremental displacements of the ten oldest fiber pieces or particles moving away from the wall, or as isochronous bands of incremental fiber growth formed during the same interval of time. Note that their ages should be viewed oppositely, For example, the red color either represents the youngest incremental growth or the oldest (first) incremental displacement of the whole displacement paths. (**a**) Pure translation (ω is infinitely small). (**b**) Translation with only a small amount of rotation. (**c**) Rotation about the origin. (**d**) Rotation and translation in a normal direction. (**e**) Rotation and translation in an oblique direction. (**f**) Rotation and translation in a horizontal direction. The center of rotation (C) happens to be on the vertical axis in (f).


(a)
v_{0x}=0.02
v_{0y}=0.04
ω=10^{-5}
(b)
v_{0x}=0.02
v_{0y}=0.05
ω=0.03
(c)
v_{0x}=0
v_{0y}=0
ω=0.1
(d)
v_{0x}=0
v_{0y}=0.02
ω=0.1
(e)
v_{0x}=0.04
v_{0y}=0.02
ω=0.1
(f)
v_{0x}=0.02
v_{0y}=0
ω=0.1
C

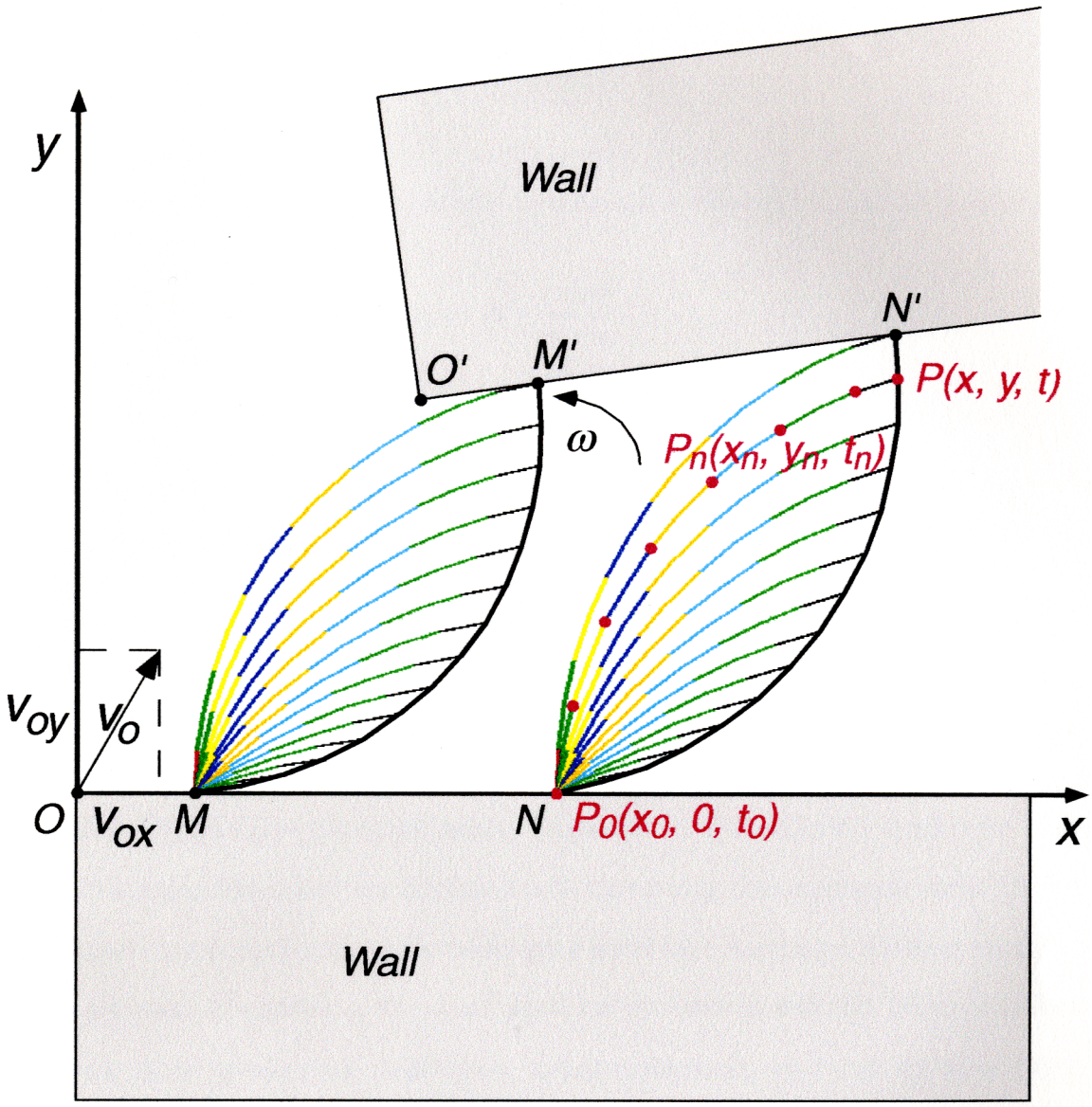
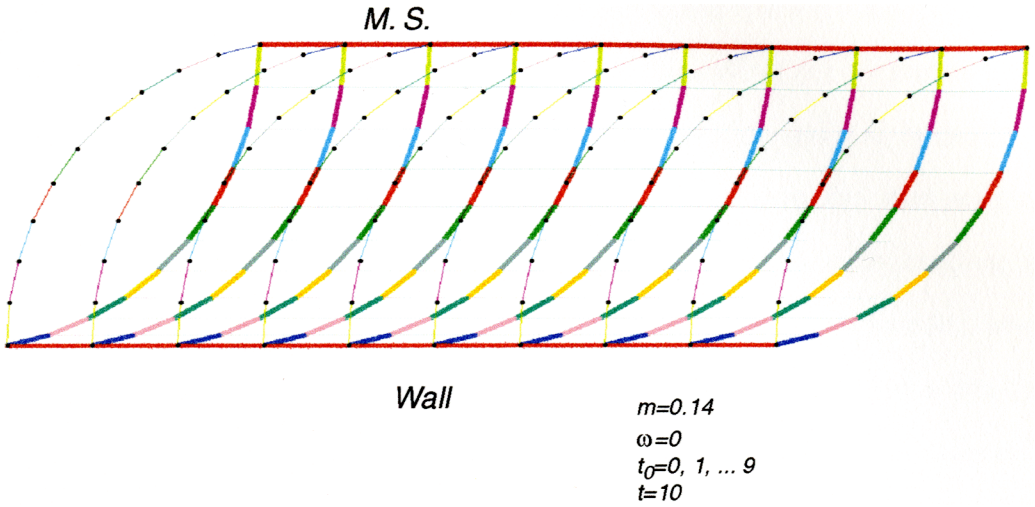


Fig. 3.26 Diagram illustrating different displacement paths of successive incremental fiber segments grown from the same point on the wall due to the non-steady state motion of the fiber aggregate relative to the wall in Taber growth. ω v_{ox} & v_{oy} have the same meanings as in Fig 3.24, except that v_{ox} & v_{oy} are assumed to vary with time such that the growth rate vector at the origin changes from normal to increasingly oblique while ω is still taken as a constant. Thin shaded lines represent the displacement paths of successively younger fiber segments grown from the same point (*M* or *N*) on the wall as they are carried along with the moving fiber aggregate. For instance, line P_0P with red dots marked on it is the displacement path of a fiber segment that grew from *N* (or P_0) at $t=t_0$ and was subsequently displaced through various points to finally arrive at point *P*(*x*, *y*) at current time *t*. Thus the longest line (*N* to *N'*) represents the path of the oldest fiber segment grown at $t_0=0$, while the other lines are paths of successively younger fiber segments originated at the same point at successively later times (t_0=1, 2, ..., t). Thick black lines that connect the end points of all the paths represent the actual traces of the whole curved fibers as seen at present time. To show the accumulative effect of a rotation component, the outline of the other wall (or the fibers grown on the other wall) is also shown, so are the points on it (*O'*, *M'* & *N'*) that were originally adjacent to *O*, *M* & *N* on the lower block .

Fig. 3.27 Diagrams showing modeled half-vein displacement paths and curved fiber traces in Taber growth under different non-steady state conditions. As in Fig 3.26, the instantaneous growth rate vector components (v_{ox} & v_{oy}) at the origin are assumed to vary with time according to trigonometric functions such that the instantaneous growth direction at the origin changes from normal to increasingly oblique, while the rotaional component ω is assumed to remain constant. Thin curved lines represent the calculated displacement paths of the tips of fibers on the median suture (M. S.) while thick lines represent the traces of the whole fibers, as seen at current time t. For correlation successive fiber growth increments of the fiber traces are marked in the same colors as the corresponding incremental displacements that occurred at the same time as the growth of the fiber segments. Thus, the oldest fiber segment at the upper end of the fiber traces (in red) grew at the same time as the first incremental displacement (also in red) at the lower end of the displacement paths of the oldest tips of fibers (or the adjacent point on the median suture). (**a**) Special case of non-steady state translation with a zero rotaional component (ω=0). The current orientations of the various fiber segments of the fiber traces are exactly parallel to the corresponding incremental displacements on all the displacement paths, and all fiber tips or points on the median suture have the same incremental displacement at any given time. (**b**) General case of non-steady state fiber growth. The current orientations of the fiber segments do not agree with the the correponding incremental displacements due to a non-zero rotational component in the displacement field (ω=0.012). The incremental displacement vectors of different points on the median suture are also different for any given interval of time.

(a)



(b)

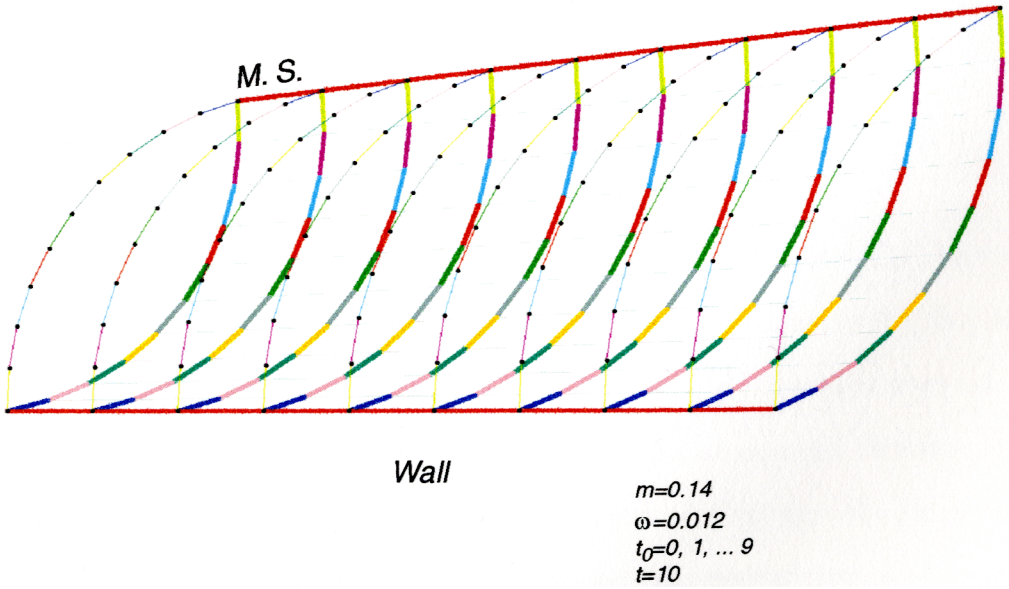


Fig. 3.28 Diagrams showing distinct fiber morphological characteristics and curvature patterns of the different modes of growth of curved fibers in one side of an antitaxial vein. Thin lines across fibers represent isochronous lines of growth, while curved colored lines represent the displacement trajectories of the median suture of the vein (**M. S.**) relative to the wall. For the purpose of visual comparison, the successive segments of fibers are marked with thin line segments on the fiber boundaries in the same colors as the corresponding incremental displacements. Thus, the lowest segment of the displacement trajectories corresponds to the uppermost (oldest) increment of growth (in red). (**a**) Steady-state rotation mode of growth. The fiber traces and displacement trajectories are exactly identical in shape, but the fiber segments are progressively different in orientation from the corresponding incremental displacements. Fibers show a shape similar to that of a parallel fold. (**b**) Non-steady-state translation growth mode. The fiber traces are different from the displacement trajectories, but fiber segments are exactly parallel to the corresponding displacements. Fibers show a shape similar to that of a similar fold. (**c**) General non-steady-state growth mode involving rotation as well as changes in instantaneous direction of growth. The fiber traces are different in shape from the displacement trajectories, and the fiber segments are also different from the corresponding displacements. Fibers show a shape intermediate between that of (a) and (b).

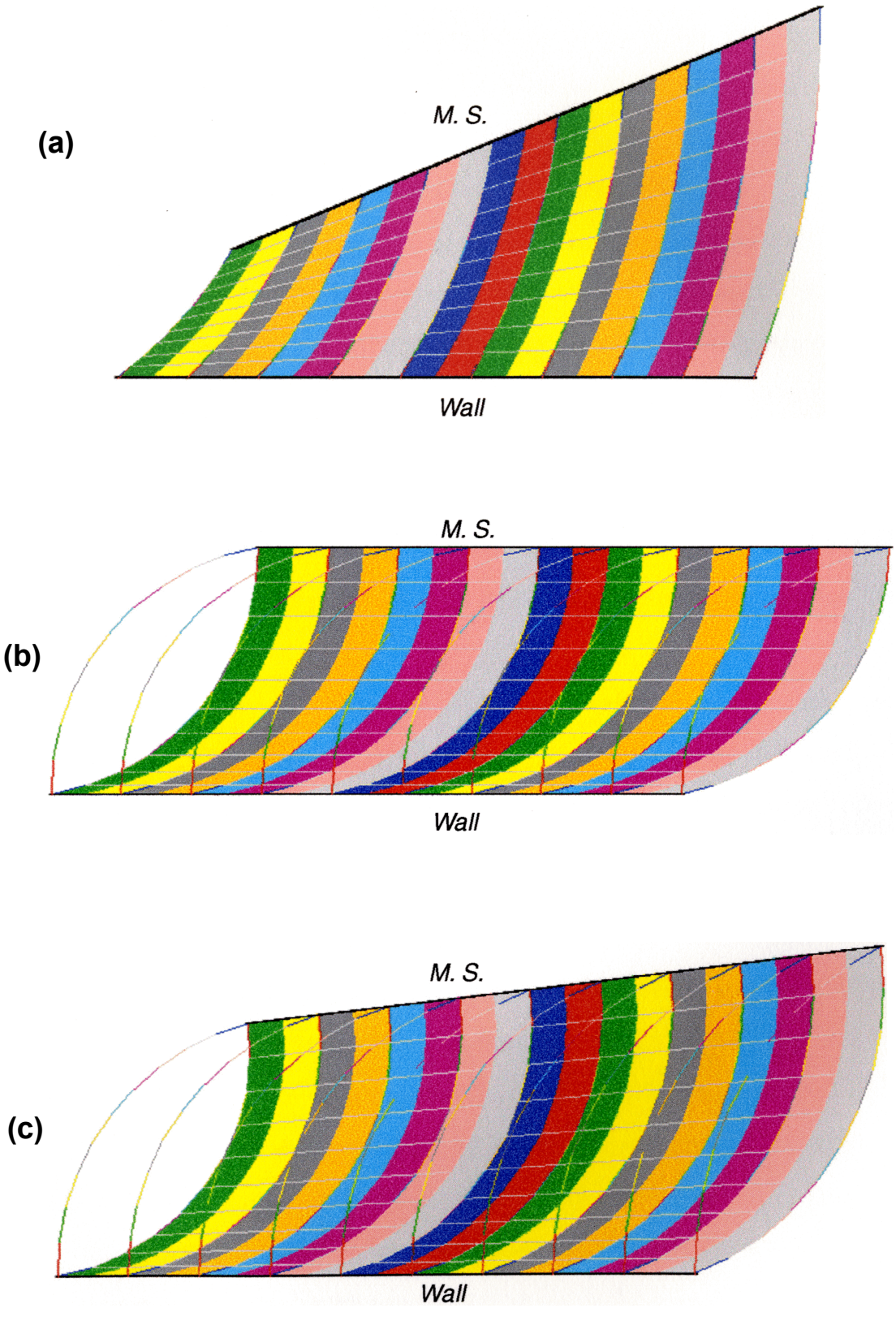
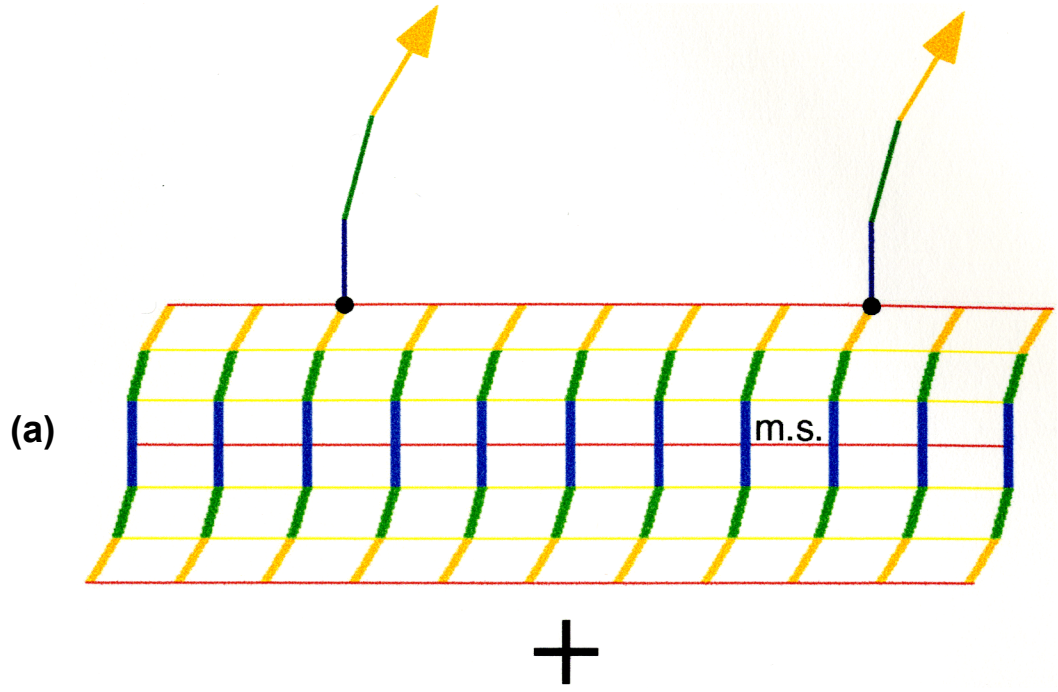
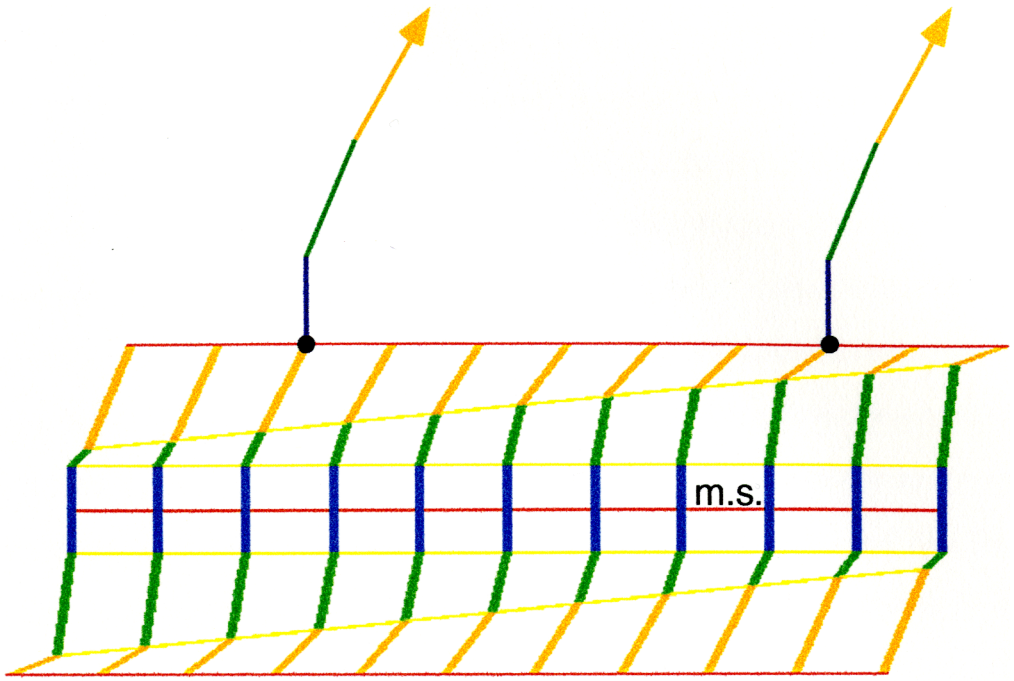

(a)
M. S.
Wall
(b)
M. S.
Wall
(c)
M. S.
Wall

Fig. 3.29 Diagrams comparing different apparent tracking characteristics of fibrous veins as seen in two different reference frames. (**a**) Opening history of a vein involving symmetric opening increments without rotation is represented by incremental displacements of the upper wall relative to the lower wall (lines with arrow above the vein). The lower wall is used as the reference frame (symbolized with a '+'). Fiber segments are drawn parallel to, and shown in the same color as the corresponding incremental displacements. (**b**) The same opening history is alternatively represented by relative displacements between the two walls and the vein median suture (**m.s**) (line segments with arrow within the vein). The reference frame is now fixed on the median suture. The fibers drawn parallel to these displacements are also parallel to the corresponding wall-wall displacements shown in (a). (**c**) Opening of a vein invloving rotational increments. Incremental fiber segments are drawn exactly parallel to the corresponding incremental displacements (not shown) of the walls relative to the median suture of the vein, but they are no longer 'track' the correponding incremental displacements of the upper wall relative to the lower wall except for the first increment. (**d**) Opening of a vein invloving asymmetric opening increments in that the directions of displacements of one wall relative to the vein are different from those of the other wall. Again the fibers drawn parallel to the vein-wall displacements are not parallel to the wall-wall displacements except for the first increment.


(a)
m.s.
(b)
m.s.

(c)



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(d)

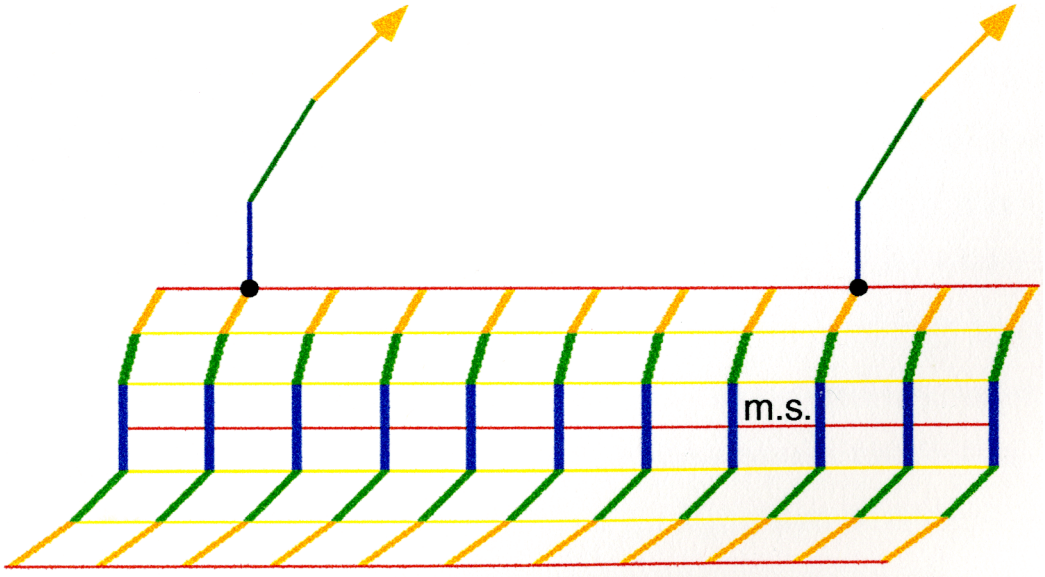

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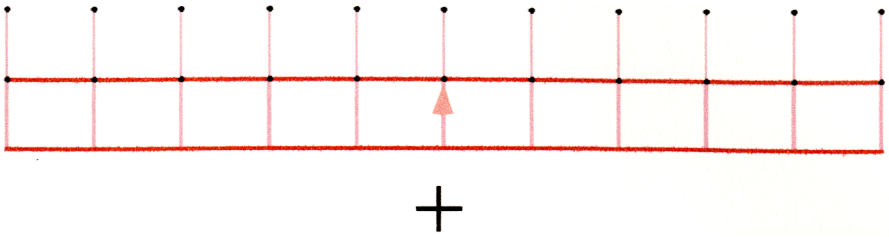
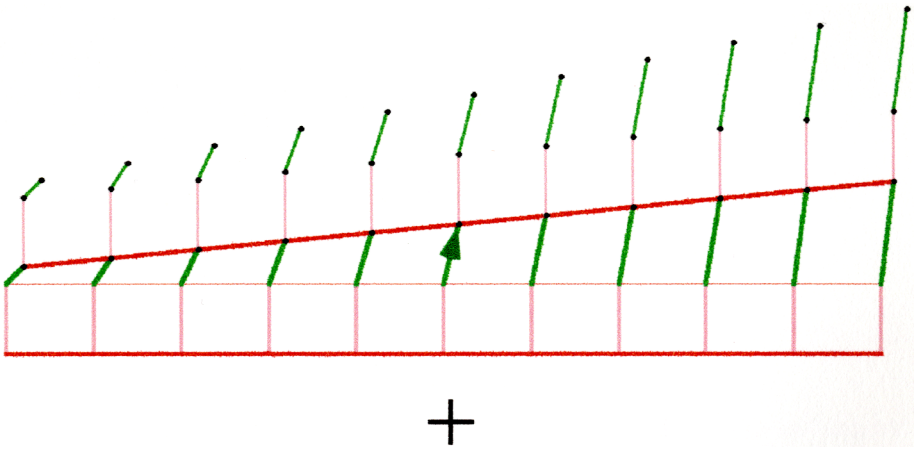
Fig. 3.30 Diagrams illustrating different apparent tracking characteristics of a one-sided vein as observed in different wall reference frames. Thick lines within the vein represent fiber segments that are drawn parallel to the incremental displacements of the upper or lower wall relative to the vein, while thin lines above vein are trajectories of displacements of the upper wall relative to the lower wall. Gray lines across the fibers are boundaries of the successive growth increments. In (**a**) the wall on the side of no growth is the reference frame (placed at the bottom side of vein) and the younging direction of growth is upward (arrow). Fibers drawn parallel to the displacements of the upper wall relative to the vein are identical to the displacements of the upper wall relative to the lower wall. Note the continuous variation of both the magnitude and direction of the incremental displacements during the second and third increments of opening. In (**b**) the same opening history of the one-sided vein is alternatively described by the incremental displacements of the wall on the side of no growth (now placed at the top) relative to the wall of growth (placed at the bottom). Younging direction is downward. Thin light gray lines within vein at the second and third stages show the outline of vein at the previous stage relative to the lower wall so that the displacements of different points of the upper wall relative to the lower wall can be directly found. Only one such displacement is drawn between the previously adjacent points (A to A' for the second and B to B' for the third increment of opening). They are no longer parallel to the corresponding fiber segments drawn parallel to the displacements of the lower wall relative to the vein due to the growth-induced rotation of the upper wall relative to the lower wall during the second and third increments of opening. The shapes of the whole displacement trajectories in this reference frame are also different from those in (a). Furthermore, the orientations of the older fiber segments relative to the lower wall are also changing at each stage of opening as a result of rotation of the vein relative to the lower wall (e.g. fibers of the first increment become oblique at the second stage and further change back to their orignal normal direction at the third stage of opening).

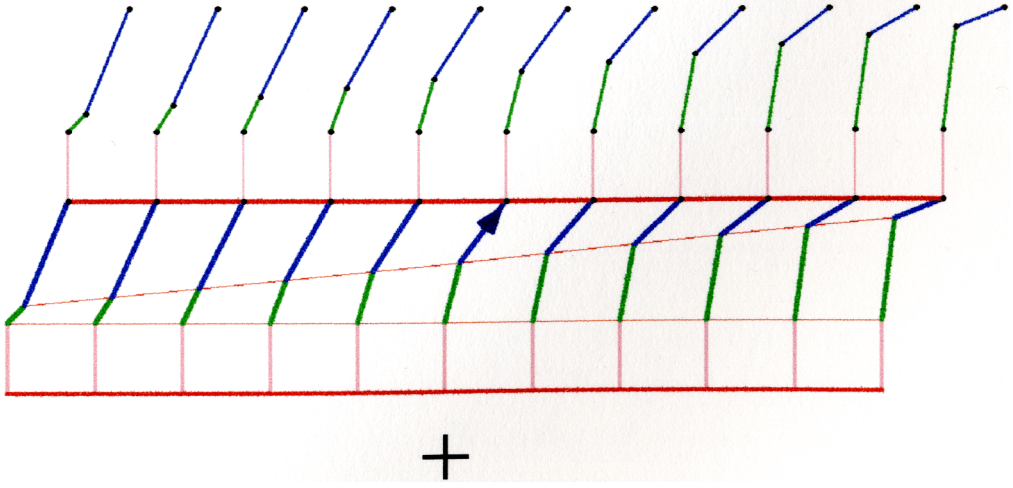
(a)



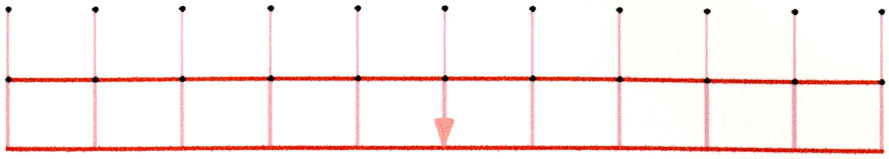
(b)



(c)



(d)



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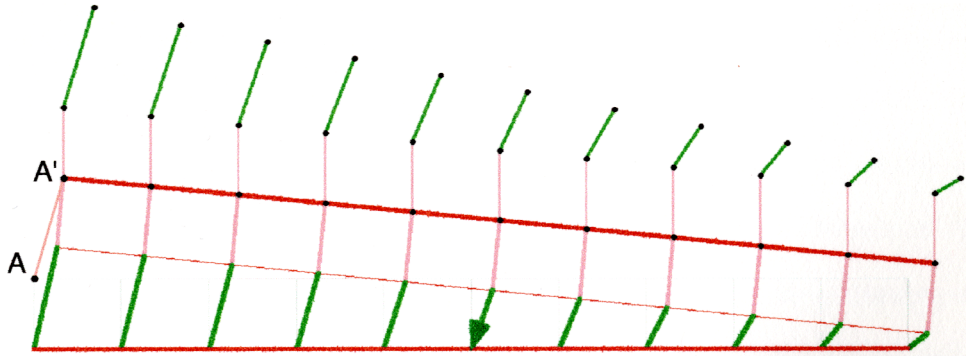
(e)



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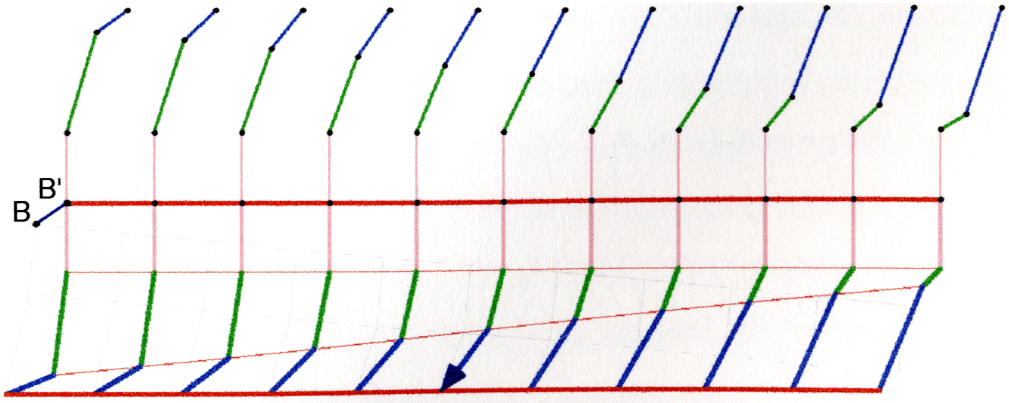
(f)



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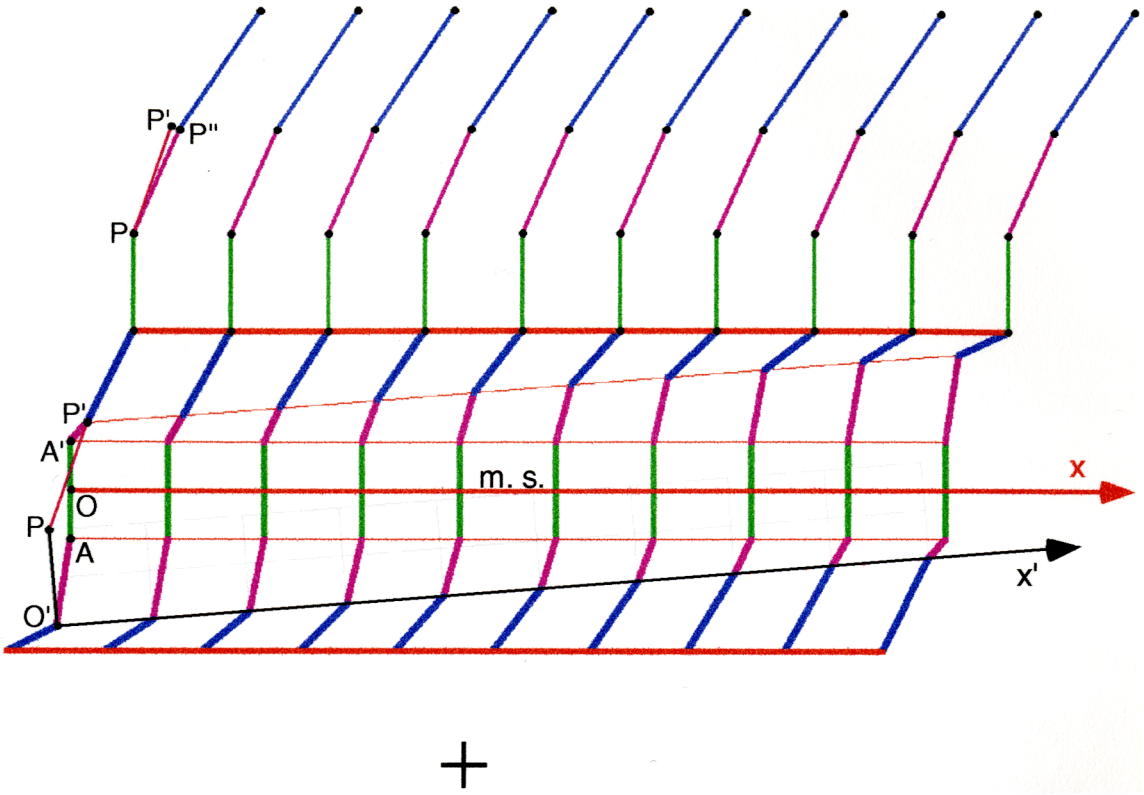
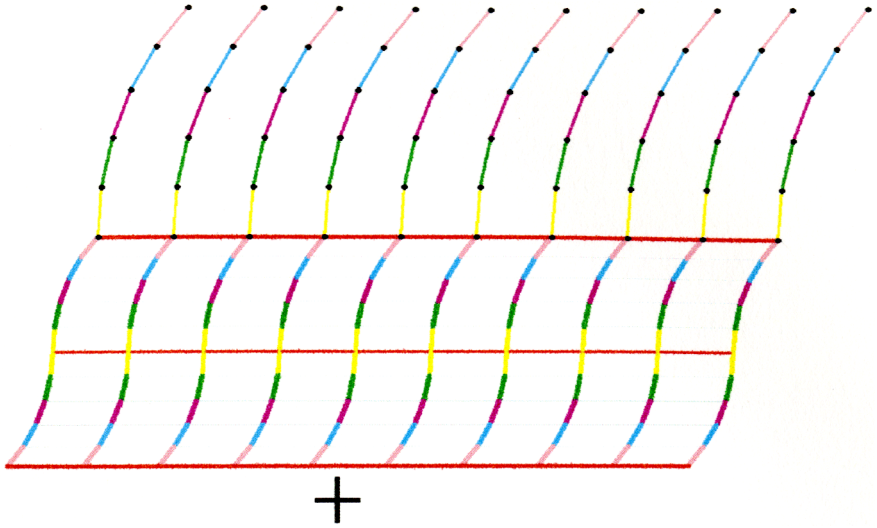


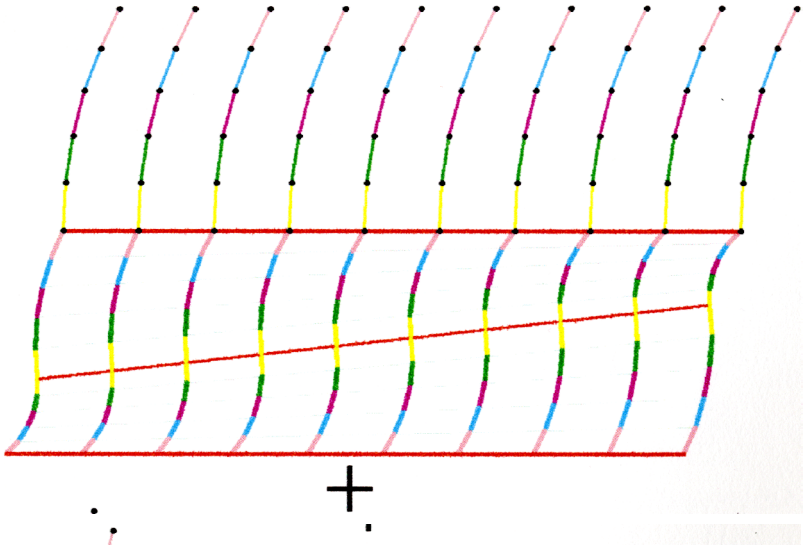
Fig. 3.31 Diagram illustrating how a given displacement history of the walls relative to the vein median suture (m. s.) is converted into the displacement history of one wall relative to the other for an antitaxial vein. Thin red lines represent the successive positions of the upper and lower walls relative to the vein reference frame fixed on the median suture (coordinate axis x shown in red), while thick colored line segments within the vein represent the corresponding incremental displacements of the walls relative to the vein (or tracking fibers) at different points along the vein. Colored lines with dots above the vein are the reconstructed displacement trajectories of the upper wall relative to the lower wall. As illustrated for the second increment of opening for the leftmost point of the vein, the incremental displacement of the upper wall relative to the lower wall is the difference vector (**PP'**) between the location vector of the point of the upper wall at that instant (i.e. 2nd increment) (**O'P'**, not drawn) and the location vector of the same point at the previous instant (i.e. 1st increment) (**O'P**) as expressed in the reference frame fixed on the lower wall at the time (coordinate axis x' shown in black). This difference vector can also be directly seen by comparing the outline of vein at the previous stage relative to the lower wall (thin light gray lines) with the outline of the vein at the current stage (i.e. second stage). Since the coordinate system of the lower wall reference frame was inclined with respect to the horizontal at that moment, this vector has to be further transformed into what should be seen in the lower wall reference frame at its current position (horizontal) at the final stage of opening. The actual wall-wall displacement vector shown relative to the lower wall at its final position (**PP''**) thus differs from **PP'** by a small angle of the same magnitude as the angle between the past orientation of the lower wall and its final horizontal orientation.

Fig. 3.32 Diagrams showing computer-reconstructed displacement trajectories of the upper wall relative to the lower wall for some veins with arbitrarily assumed wall-vein displacement histories. Thin lines represent the successive positions of the upper and lower walls relative to the median suture of vein, while thick colored line segments represent the corresponding incremental displacements of the walls relative to the vein. Colored lines with dots above vein are the reconstructed displacement trajectories of the upper wall relative to the lower wall. (**a**) Incremental displacements of the two walls relative to the vein are identical. (**b**) Incremental displacements of the two walls relative to the vein are rotation-symmetric. (**c**) Incremental displacements of the two walls relative to the vein are reflection-symmetric. (**d**) Incremental displacements of the upper wall relative to the vein are simple translations while those of the lower wall relative to the vein invlove clockwise rotation. (**e**) Incremental displacements of the upper wall relative to the vein involve rotaion while those of the lower wall relative to the vein are simple translations. (**f**) Incremental displacements of both walls relative to the vein involve rotaion but the displacements of the last two increments of the upper wall relative to the vein are zeros.

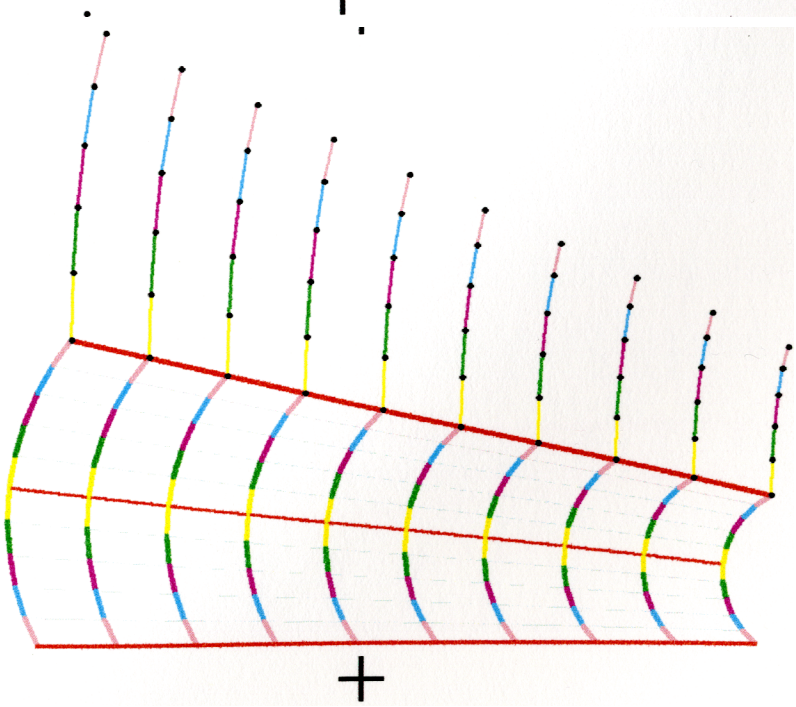
(a)



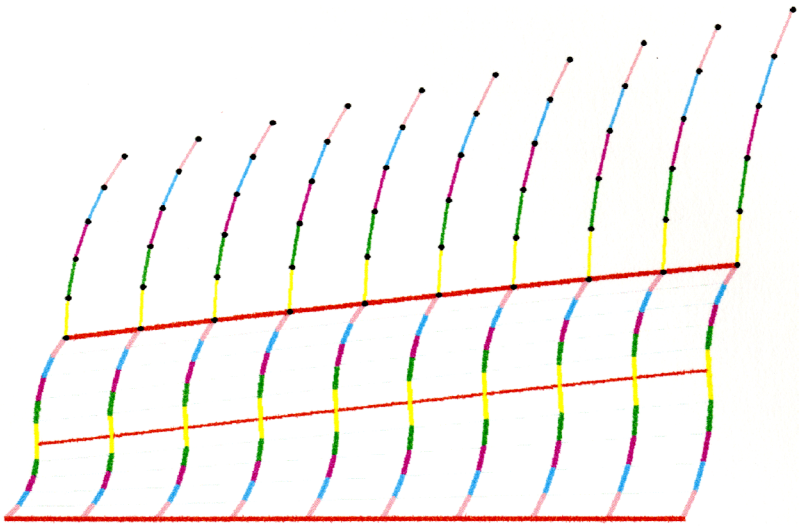
(b)



(c)



(d)



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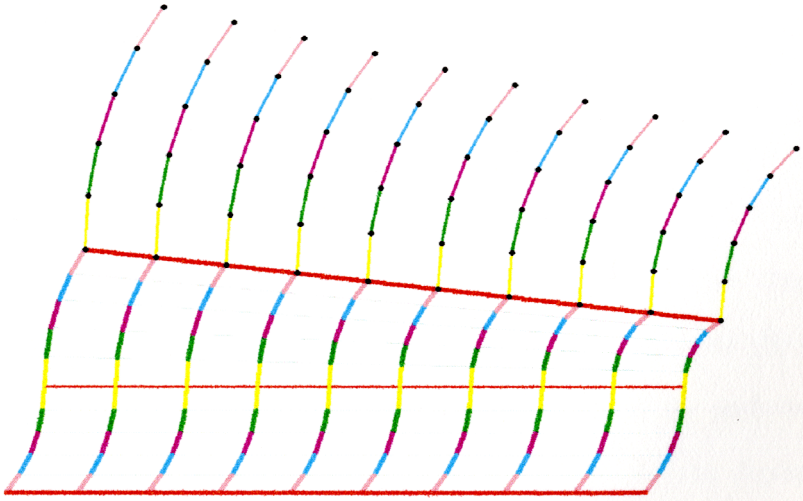
(e)



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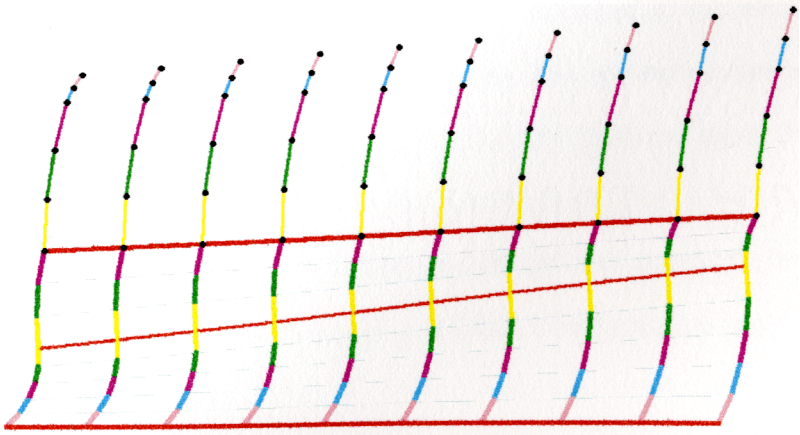
(f)



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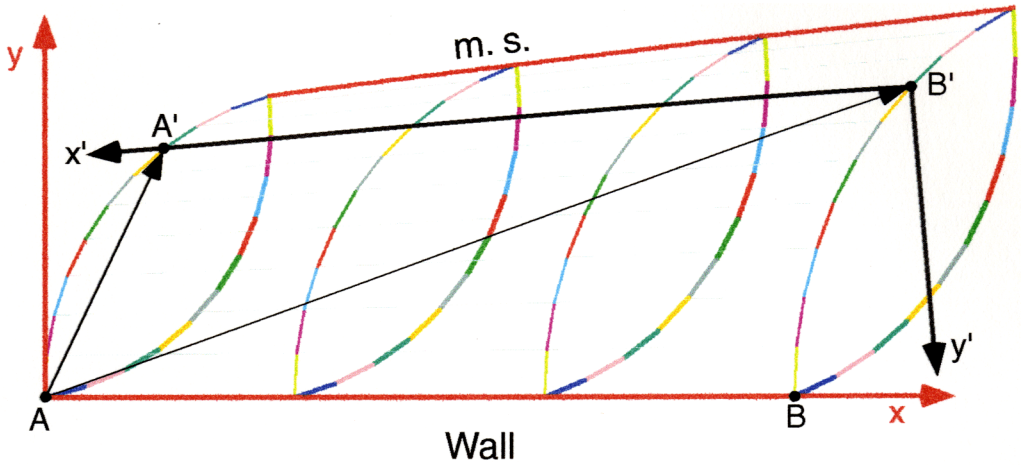
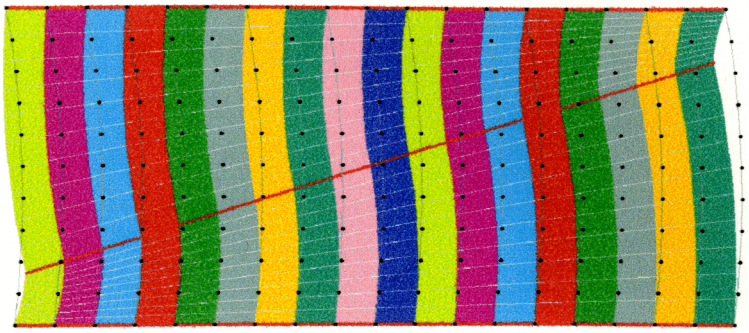


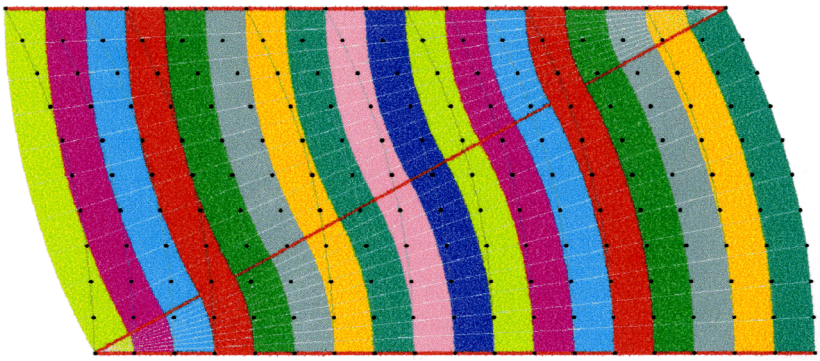
Fig. 3.33 Diagram illustrating how a displacement history of the vein median suture relative to the wall is converted into the displacement history of the wall relative to the vein for one half of an antitaxial vein. As in Fig. 3.27, thin colored lines represent the displacement paths of the median suture (M. S.) with reference to the wall, while thick colored lines represent fiber traces. The successive positions of the median suture relative to the wall are also shown by a series of thin gray lines, defined by vectors **AA'** and **AB'** (lines with arrow), which thus gives the displacement history seen in the reference frame fixed on the wall (coordinate system shown in red). The displacement history of the wall relative to the vein seen in the reference frame moving with the median suture (coordinate system shown in black) can also be thought of consisting of a series of successive positions of the wall relative to the median suture, defined by vectors **B'B** and **B'A** (not drawn) represented in terms of the components on the axes of the moving reference frame. Both vectors can be directly obtained in the wall reference frame (**B'B**=**AB**-**AB'** and **B'A**=-**AB'**) and these can then be transformed into their representations in the vein reference frame by simple coordinate transformations.

Fig. 3.34 Diagrams showing modeled fiber curvature patterns and displacement trajectories of the upper wall relative to the lower wall for two-sided antitaxial veins of different steady-state or non-steady state modes of growth with respect to the walls. Thin lines represent the successive positions of the upper and lower walls relative to the median suture of vein, defining the different displacement histories of the two walls relative to the vein that are derived from, and correspond to the different displacement histories of the median suture relative to the wall as modeled in Figs. 3.25 and 3.27. Lines with dots are the reconstructed displacement trajectories of the upper wall relative to the lower wall, with the lowest segment representing the first increment of opening while the highest the last increment. (**a**), (**b**) and (**c**) correpond to the steady-state displacement histories (with reference to the wall) in Fig. 3.25b, c and d, respectively, while (**d**) and (**e**) correspond to the non-steady state displacement histories in Fig. 3.27a and 3.27b, respectively.

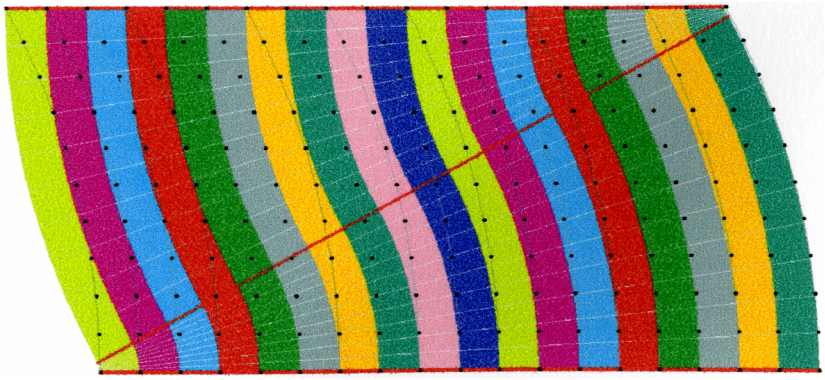
(a)



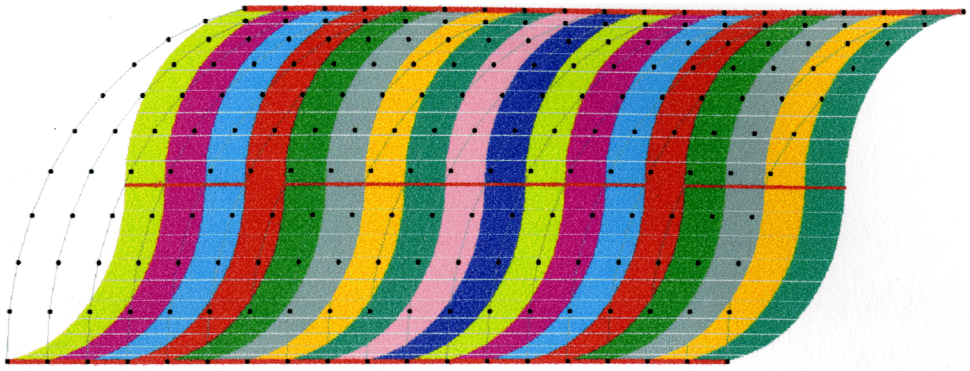
(b)



(c)



(d)



(e)