Journal of Structural Geology, Vol. 13, No. 3, pp. 243 to 259, 1991
Printed in Great Britain

0191-8141/91 $03.00+0.00

Mobile-hinge kinking in layered rocks and models

KEVIN G. STEWART

Department of Geology, University of North Carolina, Chapel Hill, NC 27599-3315, U.S.A.

and

WALTER ALVAREZ

Department of Geology and Geophysics, University of California, Berkeley, CA 94720, U.S.A.

(*Received* 4 *January* 1990; *accepted in revised form* 21 *June* 1990)

Abstract—An unresolved question in structural geology is whether kink folds grow by the gradual rotation of the fold limbs about a fixed hinge, by the nucleation of kink bands that grow by fold-hinge migration or by some combination of these mechanisms. The importance of mobile-hinge kinking has previously been recognized in experimentally deformed slate and phyllite as well as decks of paper cards, but its importance in the folding of multilayers consisting of alternating competent and incompetent layers has been uncertain. This study shows that mobile-hinge kinking can be an important folding mechanism in both natural and experimental multilayers. The natural folds are in pelagic limestones from the Umbria–Marche Apennines of Italy. The geometrical properties of these folds, as well as the small-scale structures in the rocks, indicate that these folds formed by the nucleation and expansion of kink bands with mobile hinges, not by a fixed-hinge folding mechanism. The experimental folds were produced by the deformation of multilayered models consisting of layers of lead separated by layers of wax-impregnated cloth. The progressive growth of these folds by the nucleation and expansion of kink bands was directly observable. A rough estimate of the rate at which fold hinges migrated through the Apennine limestones was obtained indirectly using the displacement history recorded by calcite fibers on a fault, which cuts a kink fold and was active during the formation of the fold. It appears that the rate at which fold hinges migrated was approximately 100 times greater than the displacement rate along a fault that was moving by pressure-solution slip.

INTRODUCTION

THE MECHANISM by which kink folds form is a long-standing question in structural geology. The mechanisms that have been proposed can generally be divided into two categories: those that involve rotation of the limbs about fixed fold hinges and those that involve the nucleation of kink bands that expand by the lateral migration of the fold hinges. Most workers who have studied kink folds have either concluded or assumed that the folds were formed by gradual rotation of the limbs about fixed hinges (e.g. Anderson 1964, 1968, Donath 1968, Dewey 1969, Ramsay 1974, Verbeek 1978). Theoretical studies of folding based on buckling theories by Biot (1964, 1965), Johnson (1977) and Latham (1985a,b) also assumed fixed-hinge folding. Folding by the nucleation and growth of kink bands has been inferred in experimentally deformed cylinders of phyllite (Paterson & Weiss 1966) and directly observed in experimentally deformed modeling materials (e.g. Weiss 1968, Honea & Johnson, 1976), but has rarely been demonstrated in natural kink folds (Cobbold 1976, Stewart *et al.* 1984, Beutner & Diegel 1985). Theoretical models of folding by the nucleation and growth of kink bands in mechanically continuous materials with a strong planar anistropy have been presented by Weiss (1980) and Cobbold *et al.* (1984), although Weiss (1980) warned that the mechanical behavior of such materials may be very different from the mechanical behavior of multilayers.

The purpose of this study was to demonstrate the mechanism by which kink folds form in certain kinds of natural and experimental multilayers. The natural folds in this study occur in a sequence of bedded pelagic limestones located in the Umbria–Marche Apennines of central Italy (Fig. 1). The experimentally generated folds were produced by deformation of multilayered models in a hydraulic press. Experiments are particularly useful in the study of folding because they allow direct observation of the mechanisms by which folds are produced. The experimental apparatus used in this

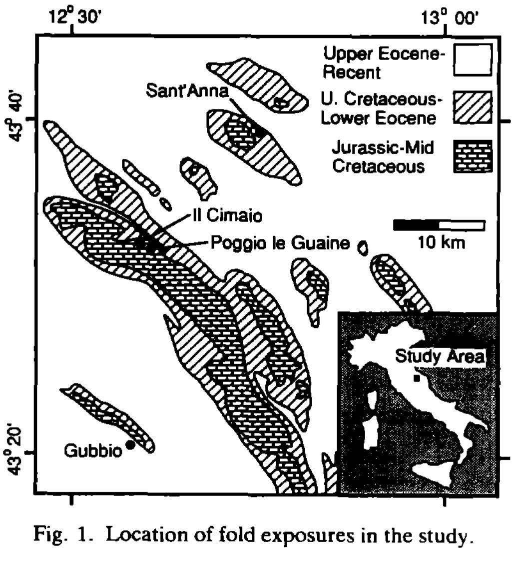

Fig. 1. Location of fold exposures in the study.

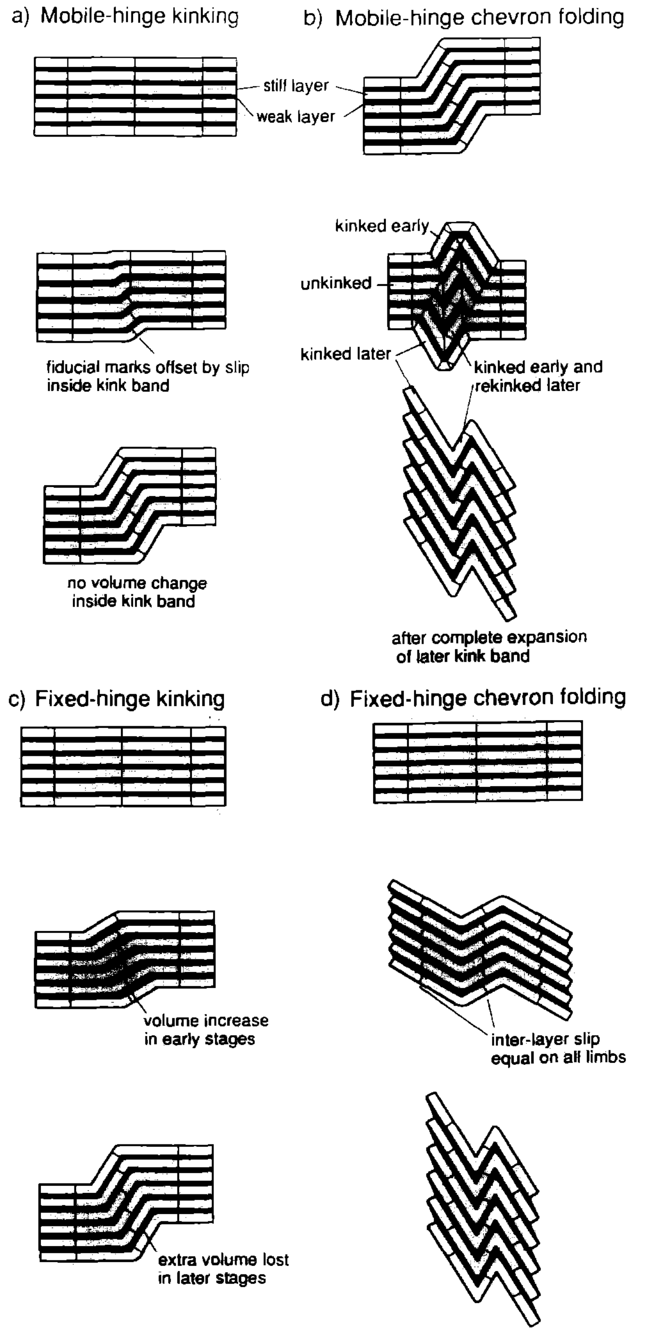

Fig. 2. Four idealized mechanisms for generating kink and chevron folds. White layers represent competent, mechanically isotropic layers which do not shear internally; black layers are incompetent and able to shear internally. (a) Mobile-hinge kinking and (b) mobile-hinge chevron folds produced by intersection and expansion of mobile-hinge kink-bands. (c) Fixed-hinge kinking—layers rotate between fixed boundaries. (d) Fixed-hinge chevron folding—layers buckle and folds tighten by rotation of the layers about fixed hinges.

study was originally built for the studies of Weiss (1968) and Gay & Weiss (1974) and is described in the Appendix. The Appendix also contains descriptions of the models and the experimental conditions under which they were deformed.

In this study the importance of four different folding mechanisms are evaluated, here called mobile-hinge kinking (Fig. 2a), mobile-hinge chevron folding (Fig. 2b), fixed-hinge kinking (Fig. 2c) and fixed-hinge chevron folding (Fig. 2d). Mobile-hinge kinking (Fig. 2a) occurs by the nucleation of a kink band, which propagates across the multilayer and expands by migration of the kink-band boundaries. Paterson & Weiss (1966) showed that a chevron fold can be produced when two mobile-hinge kinks meet or intersect (Fig. 2b). Fixed-hinge kinking involves rotation of a part of the multilayer defined by two immobile boundaries (Fig. 2c). Fixed-hinge chevron folding creates a fold by buckling the layers and gradually tightening the fold by rotation of the fold limbs about a fixed hinge (Fig. 2d). Fixed-hinge kinking differs from fixed-hinge chevron folding in that the axial planes of the former need not bisect the interlimb angle of the folds, such as is shown in the intermediate stage of Fig. 2(c). This requires a volume change inside the kink band.

The terms 'kink fold' and 'kink band' are used in the broadest sense in this paper. Classically these terms have been used to describe only those folds with very sharp hinges and planar limbs. In this study we will use the terms to describe folds that have a monoclinal geometry or have formed by one of the kinking mechanisms described above. The kinks may have either sharp or gently curved hinges. In the terminology used by Suppe (1985), these would be called angular or curved folds.

GEOMETRICAL AND STRUCTURAL FEATURES OF THE DIFFERENT FOLDING MECHANISMS

Each of the folding mechanisms shown in Fig. 2 should produce folds with certain geometrical and structural features. Folds produced by either mobile-hinge or fixed-hinge kinking should appear as a network of individual kink bands that are separated by regions of unrotated layering, whereas fixed-hinge chevron folding should produce a more regular system of folds with no domains of unrotated layering. In addition, each of the folding mechanisms implies a unique strain history. In the field, one should be able to discriminate among the different mechanisms by noting which of the predicted structural features are present. These features are summarized in Table 1.

A series of folds from two exposures in the Umbria–Marche Apennines of Italy were examined to see if the folding mechanism could be determined by recognizing any distinctive geometrical and structural features. Figure 3 is a sketch of a part of the 150 m-high cliff at Poggio le Guaine (near the town of Secchiano, in Italy, 43°32′40″N, 12°35′08″E of Greenwich, 0°8′0″E of Rome). This exposure contains an array of folds with kink and chevron shapes developed in the Aptian–Albian Fucoid marls and Cenomanian Scaglia Bianca limestones. These particular folds lie in a continuous belt of folds located on the frontal (northeast) limb of a large anticline. The basal detachment for the folds is the contact between the top of the thick-bedded Lower Cretaceous Maiolica limestone and the base of the weaker Fucoid marls. The Maiolica is not folded and served as a rigid lower constraint. The folded rocks consist of micritic limestone layers, 20–40 cm thick,

Table 1. Structures produced by different folding mechanisms, from Ramsay & Huber (1987) and Stewart (1987)

Deformation Feature	Folding mechanism: Mobile-hinge kinking	Mobile-hinge chevron folding	Fixed-hinge kinking	Fixed-hinge chevron folding
Sheared incompetent layers	Present only inside kink band	Present on both fold limbs	Present only inside kind band	Present on both fold limbs
Volume change inside kink band	Possible*	Possible*	Yes†	No
Structures inside kink band produced by fold-hinge migration	Yes‡	Yes‡	No	No

*Mobile-hinge kinks may contain evidence of dilation within the kink band if the hinge zones were dilated during hinge migration.
†Volume change may disappear in final stage of kinking.
‡Development of structures depends on the amount of strain in the migrating hinge zones (see text for a discussion of the types of structures).

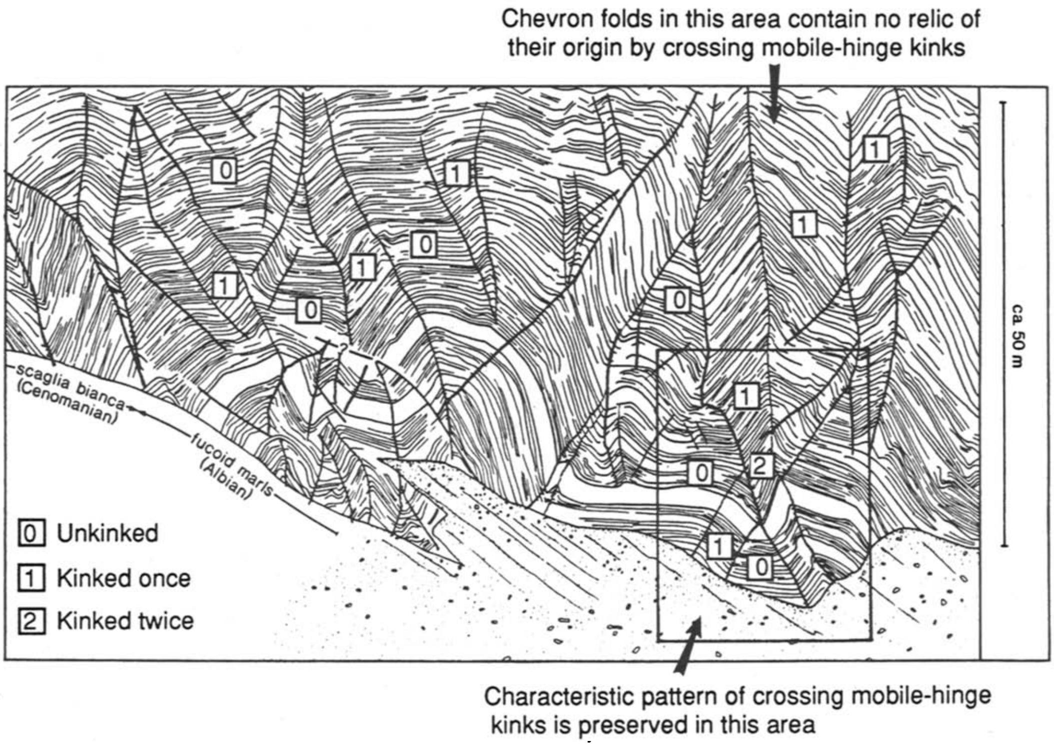

Fig. 3. Drawing of a part of cliff exposure at Poggio le Guaine. Traces of axial planes reveal a complex pattern of unkinked (examples marked with a '0'), singly kinked ('1'), and doubly kinked ('2') domains. Area inside rectangle shows intersecting kink bands forming a chevron fold. Area above rectangle shows complete chevron folding with no unkinked areas remaining. (Drawing by Joan Gabelman.)

separated by 1–5 cm-thick shale layers. The second set of folds are exposed in the cliff at Il Cimaio, which is along trend approximately 1.5 km northwest of Poggio le Guaine (Fig. 1). The folds here are part of the same belt of folds exposed at Poggio le Guaine, however the overall shortening is less; the shortening at Il Cimaio is about 7% compared to 35% at Poggio le Guaine. This relationship is especially fortunate insofar as the folds at Il Cimaio provide a natural model of what the folds at Poggio le Guaine were like at an earlier stage in their formation.

Geometrical properties

In Fig. 3 it is possible to distinguish domains consisting of approximately planar bedding that are separated from adjacent domains by axial surfaces of folds. The traces of most of these surfaces have been drawn on the sketch. The pattern of undeformed domains, single kink bands and chevron folds present in Fig. 3 strongly resembles the patterns of folds obtained by Weiss (1968) in experimentally deformed decks of paper cards, and in all of our experiments (an example from one of our experiments is shown in Fig. 4; see Appendix for description of model). In these experiments, the folds unquestionably formed by mobile-hinge kinking. This pattern of undeformed domains, single kink bands and chevron folds is expected for folds produced by mobile-hinge and fixed-hinge kinking. It is not the expected pattern, however, for folds produced by fixed-hinge chevron folding.

The most commonly used test of fixed-hinge vs mobile-hinge kinking uses the 'inner' and 'outer' kink angles, β and α (see Verbeek 1978, fig. 11). Ideally, mobile-hinge kinks should have equal inner and outer kink angles, whereas fixed-hinge kinks should generally have $\beta > \alpha$, if there is an overall volume increase (see intermediate stage of folding depicted in Fig. 2c). To assess the validity of this test, β and α were measured for 196 kink bands in models consisting of paper cards and other models consisting of thin layers of lead (Fig. 5). The angles β and α are rarely equal in these model folds, which definitely formed by mobile-hinge kinking, and there is a wide scatter of the data points about the $\beta = \alpha$ line. Inspection of the kinks in these models showed that the differences in β and α are due primarily to minor amounts of layer-parallel slip either inside the kink band, resulting in $\beta < \alpha$, or outside the kink band, resulting in $\beta > \alpha$ (Fig. 6). Small amounts of slip can produce a fairly large difference between β and α (up to 30° or more in the card decks). Because β and α can be significantly altered by a relatively small amount of deformation not necessarily related to kinking, we believe that scattered data points in a β vs α plot do not rule out any of the kinking mechanisms. Measurements of β and α for 25 kink bands at Poggio le Guaine and Il Cimaio are also plotted on Fig. 5. As was the case for the model kinks, there is a large scatter of the data points. Part of the scatter may be due to alteration of the angles by layer-parallel slip or other kinds of deformation, but we believe that most of the scatter was caused by measuring the angles on photographs where the plane of the photograph was not exactly perpendicular to the fold hinges. Unfortunately, the inaccessibility of most of these kinks prohibited direct measurement of the kink angles.

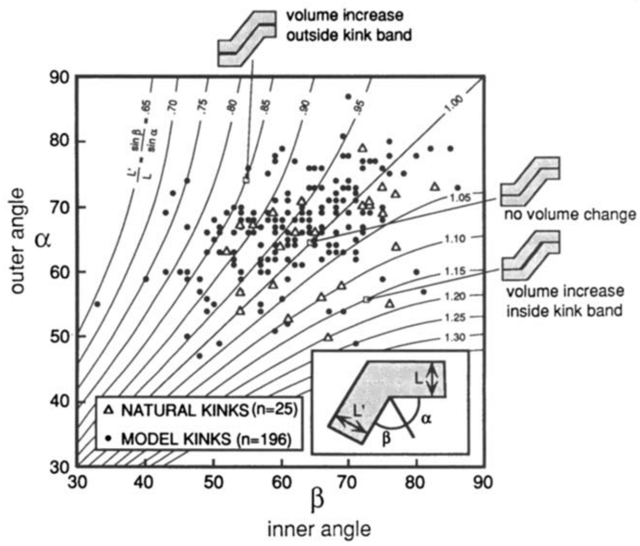

Fig. 5. Plot of inner kink angle, β, vs outer kink angle, α, for natural and experimental kink bands. Contours are L'/L (= sin β/sin α) indicating the value of the volume increase or decrease within a kink band with respect to the material outside the kink band. Mobile-hinge kinks should ideally lie along the $\beta = \alpha$ line ($L'/L = 1.0$). Fixed-hinge kinks should generally fall below the $\beta = \alpha$ line ($L'/L > 1.0$). The points for the mobile-hinge kinks generated experimentally, however, are not clustered about the $\beta = \alpha$ line, indicating changes in volume inside and/or outside the kink bands. The scatter of values associated with mobile-hinge kinks limits the usefulness of a plot such as this one as a test of folding mechanisms in natural materials.

A different, and perhaps more useful, geometric test involves plotting a histogram of the fold interlimb angles. In the cases of mobile-hinge and fixed-hinge kinking we would expect to find a bimodal distribution of interlimb angles with one peak centered on the interlimb angle of a monoclinal kink and the second peak centered on the interlimb angle of a fold consisting of two adjacent or intersecting kink bands. In the case of

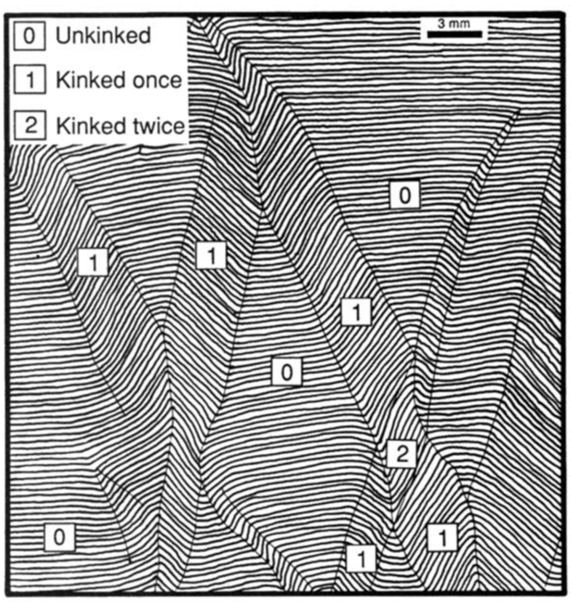

Fig. 4. Drawing of kinked deck of paper cards showing single kink bands, kink intersections, chevron folds and undeformed material. Folds were produced by mobile-hinge kinking.

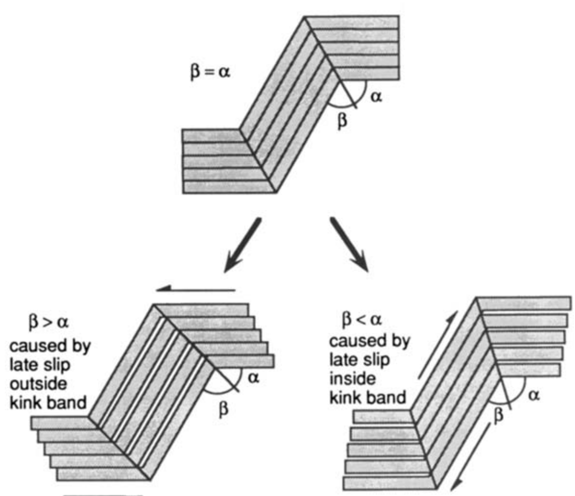

Fig. 6. Two ways in which the relationship between the inner and outer kink angles can be changed by later layer-parallel slip.

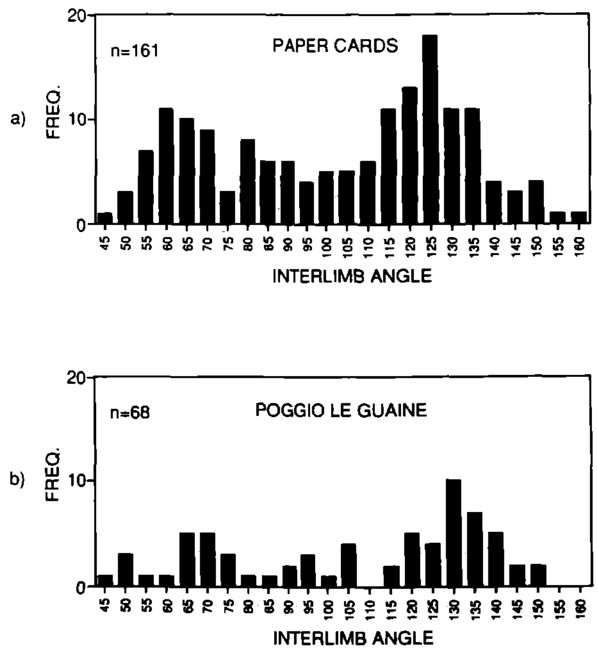

Fig. 7. Histogram of interlimb angles of folds (a) in card decks and (b) at Poggio le Guaine. Note the peaks at about 125° in the cards and 130–135° in the natural folds corresponding to single kink bands, and the secondary peaks at about 60° (cards) and 65–70° (natural folds) corresponding to folds formed by kink intersections.

fixed-hinge chevron folding we would expect to see one peak with a more or less 'Gaussian' distribution about the mean. Figure 7(a) is a plot of the interlimb angles of 161 folds that formed by mobile-hinge kinking in decks of paper cards. There is a wide scatter in the interlimb angles but the two maxima predicted above can be seen at about 60°, which corresponds to mobile-hinge chevron folds, and at about 125°, which corresponds to single mobile-hinge kink bands. The same pattern can be seen in a plot of the interlimb angles of 68 folds at Poggio le Guaine (Fig. 7b). There is a strong peak centered at about 130–135° corresponding to single monoclinal kink bands and several other minor peaks, although the strongest of these minor peaks is centered at about 65–70°, which is close to the value expected for folds resulting from two crossing kink bands. The weaker peaks in the Poggio le Guaine data at 50° and 95–105° correspond to particularly tight chevron and kink folds, respectively. A χ^2 test of goodness of fit that compared the similarity of the Poggio le Guaine distribution (Fig. 7b) with the distribution obtained from the card decks (Fig. 7a) yielded a value of $\chi^2 = 29.09$ with 23 degrees of freedom. (Note: for this calculation the Poggio le Guaine data were shifted to the left one increment. This provided a better match to the card data and seemed reasonable since we were only interested in the shapes of the curves, not whether the peaks were at the same values.) In a χ^2 test, the lower the value of χ^2, the closer the match between the two curves. In order to assess the significance of this value of χ^2 we compared it to χ^2 values obtained from random distributions. Using a computer we generated 32,000 random distributions of 68 interlimb angles lying between 45° and 160°. χ^2 was then calculated for each random distribution. The value of χ^2 for the Poggio de Guaine folds was lower than that for 99.8% of the computer-generated random distributions, indicating, we believe, that there is a good match between the distribution of interlimb angles at Poggio le Guaine and the distribution of interlimb angles of mobile-hinge kinks in the card decks. Although this geometric test cannot discriminate between fixed- and mobile-hinge kinking, it can distinguish folds formed by either of these two mechanisms from folds formed by fixed-hinge chevron folding.

Sheared incompetent layers

If a fold has formed by fixed-hinge chevron folding there should be evidence of interlayer slip on both limbs of the fold. Interlayer slip only inside the kink band rules out fixed-hinge chevron folding, but is consistent with mobile-hinge and fixed-hinge kinking. Slip outside the kink band, however, does not rule out mobile-hinge or fixed-hinge kinking because this slip may have occurred either before or after the folding in an unrelated deformation episode.

As mentioned earlier, the limestone sequences in this study consist of interbedded limestone and shale. On the fold limbs, individual limestone layers show no evidence of mesoscopic penetrative flow or ductile deformation. The only evidence of penetrative deformation occurs in vein calcite, which is usually twinned. The rocks seem to have been folded under brittle conditions, which is expected given that they were probably buried no deeper than 2 or 3 km when deformed (Alvarez *et al.* 1976, D'Argenio & Alvarez 1980). The only identifiable mesoscopic and microscopic deformation mechanisms within these rocks are pressure solution, fracture, vein formation and twinning of the calcite within filled fractures. There is no evidence that any of these deformation mechanisms accommodated internal, layer-parallel shearing, within the limestone layers on the limbs of the folds. Interlayer slip, if it has occurred, is localized in the shale layers. Figure 8(a) is a photograph of a part of the fold complex at Poggio le Guaine with the boundaries of a single, large kink band marked. If this fold formed by mobile-hinge or fixed-hinge kinking, only the shale layers inside the kink band should show evidence of shearing. Following a single shale layer from outside the kink band (Fig. 8b) to inside (Fig. 8c) shows that only the part of the shale layer inside the kink band has been sheared. Inside the kink band the original depositional layering of the shale has been disrupted and a strong cleavage is present, whose orientation is consistent with the sense of shear predicted by the fold shape. The lack of evidence for shear in the shale layers outside the kink band is incompatible with fixed-hinge chevron folding.

Volume change inside the kink band

A feature of fixed-hinge kinking is that the volume of the material between the axial planes changes during rotation of the layers (Fig. 2c). The volume of the material gradually increases as the layers rotate to the point where they are perpendicular to the axial planes. The volume then gradually decreases as the layers rotate past this orientation until finally, when the axial planes bisect the interlimb angles of the fold, the volume is equal to its original value. For the folds at Poggio le Guaine and Il Cimaio, the increase in volume would most likely occur by increasing the separation between the limestone layers and opening gaps in the intervening shale layers. The amount of separation in a fold is a function of the interlimb angle as well as the thickness of the competent layers. Using Ramsay's equation (7-52) (1967, p. 449), the maximum separation between each pair of adjacent limestone layers at Poggio le Guaine would have been about 8 cm, using a layer thickness of 25–30 cm, an angle of 60° between the kink-band boundary and the undeformed layering, and an initial separation due to the presence of the intervening shale layers of 3–4 cm. If the folds at Poggio le Guaine had formed by fixed-hinge kinking, then there would have been gaps 4–5 cm thick between each pair of limestone layers when the volume was the greatest. As mentioned earlier, the rocks at Poggio le Guaine were buried several kilometers deep when they were folded and it seems likely that any such gaps would have been closed by collapse of the layers, although this depends upon the strength of the layers. Collapse of the layers could be prevented if they had been supported by fluids or by calcite precipitated in the open spaces. If the spaces had been filled by calcite, this additional material would have had to have disappeared later, as the layers rotated to their final position and the spaces closed. The removal of the material would most likely have occurred by pressure solution. In these rocks, and in limestones in general, the calcium carbonate present in clay-rich zones tends to dissolve more easily than the calcium carbonate in clay-poor zones (Alvarez *et al.* 1978, Marshak & Engelder 1985). If the space between each pair of adjacent limestone layers contained 4 cm of sparry, secondary calcite and 4 cm of the original clay-rich calcareous shale when the separation was the greatest, then the space between the limestone layers should contain mostly sparry calcite and insoluble clay residue after the space had closed back to its original thickness. There is some sparry calcite in the shale layers inside the kink bands but these layer-parallel, fibrous crystals were produced by layer-parallel shear, not by separation of the limestone layers. These fibers fill gaps produced during slip inside the shale, and may represent a slight volume increase, although if the calcite was produced by pressure solution within the same shale layer there may be no net change in the volume.

Calcite crystals that would have grown to fill the spaces resulting from a volume increase caused by fixed-hinge kinking would not be layer-parallel but would be oriented along lines that track the paths of points on the layers that were originally in contact with one another (Durney & Ramsay 1973). During the first stages of folding (middle drawing in Fig. 2c), these fibers would record an oblique separation of the layers. If the layers continued to rotate, the gaps between the layers would close (bottom drawing in Fig. 2c). At this final stage, points on adjacent limestone layers that were originally together would lie along a line that was layer-parallel, but the calcite fibers produced during the folding should record only the initial separation and would be oriented obliquely to the layers.

There is no direct evidence for or against the limestone layers having been separated and propped open by fluids. If this had occurred one might expect the shale layers inside the kink bands to be brecciated as well as sheared, which they are not.

Evidence for migration of kink-band boundaries

Another potentially useful criterion for discriminating between mobile-hinge kinking and the fixed-hinge mechanisms is the presence of structures inside the kink band recording the migration of the fold hinge. In their experimentally kinked phyllite samples, Paterson & Weiss (1966) found fractured quartz grains inside large kink bands and unbroken grains outside the kind bands which they cited as evidence for migrating fold hinges. We examined the natural folds in this study to see if features analogous to those seen by Paterson & Weiss (1966) are present in the rocks.

Alvarez *et al.* (1976) have found that the dominant deformation mechanism in the hinges of the mesoscopic tectonic folds in the Italian limestones is pressure solution. There is negligible strain of the rock bounded by the stylolites and calcite-filled extension fractures, as shown by the undeformed state of the preserved foraminifera. In our study of the folds at Poggio le Guaine and Il Cimaio we found that the intensity of pressure solution in the competent limestone layers is generally greater in the hinges of the folds than inside the kink bands; although in folds with gently curved fold hinges, the intensity of the pressure solution in the hinge zones is comparable to the intensity of the pressure solution both inside and outside the kink band. It is difficult to quantify the amount of strain due to pressure solution in these rocks because there are no markers. The only other structures seen within the rock layers are small faults and extension cracks, both filled and unfilled. These structures seem to be concentrated in the hinge zones of the folds, much like the pressure solution effects, but they are also more common inside the kink bands than outside. This pattern is not completely clear because of the highly non-uniform distribution of these structures within the layers. Inside the kink bands there are zones that are highly fractured next to zones that are relatively undeformed. If these folds have formed by mobile-hinge kinking, it seems that the migrating hinges would have been accommodated by brittle fracturing instead of pressure solution. At this point in our studies, however, we do not feel that there is a clear record of migrating hinges present in the rocks inside the kink bands.

This particular evidence seems to suggest that the folds formed with fixed hinges, yet the other evidence

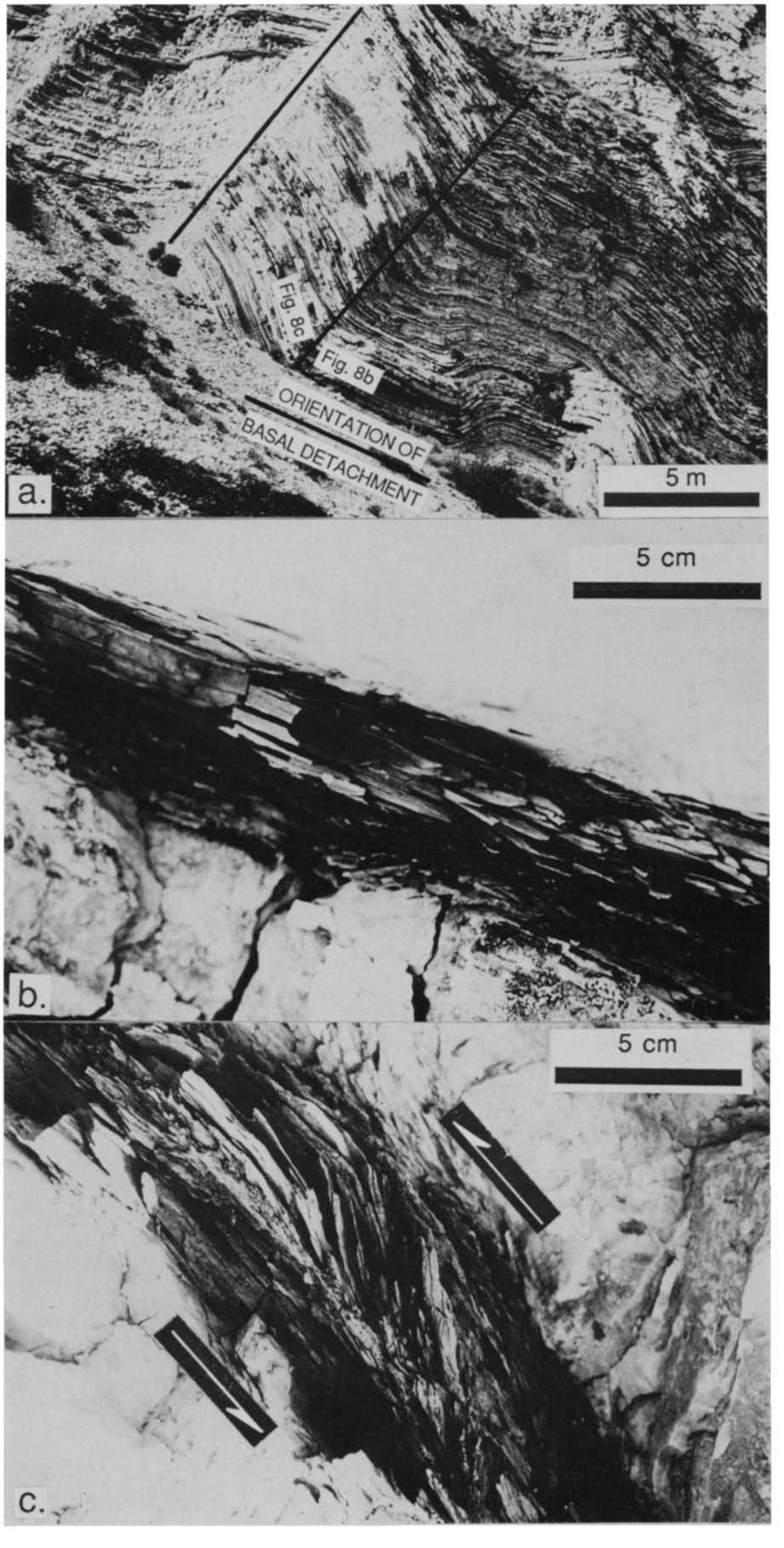

Fig. 8. (a) Single kink band at Poggio le Guaine, in Fucoid marls. Décollement level between Fucoid marls and Maiolica limestone is 20 m below photograph and is parallel to line labeled "Orientation of basal detachment". Black lines mark kink-band boundaries. Locations of shale layers shown in (a) & (c) are marked. Kink band is about 6 m wide. (b) Unsheared 3–5 cm thick shale layer outside kink band. (c) Same shale layer as in (b) but inside kink band with inclined cleavage showing shear in the predicted sense.

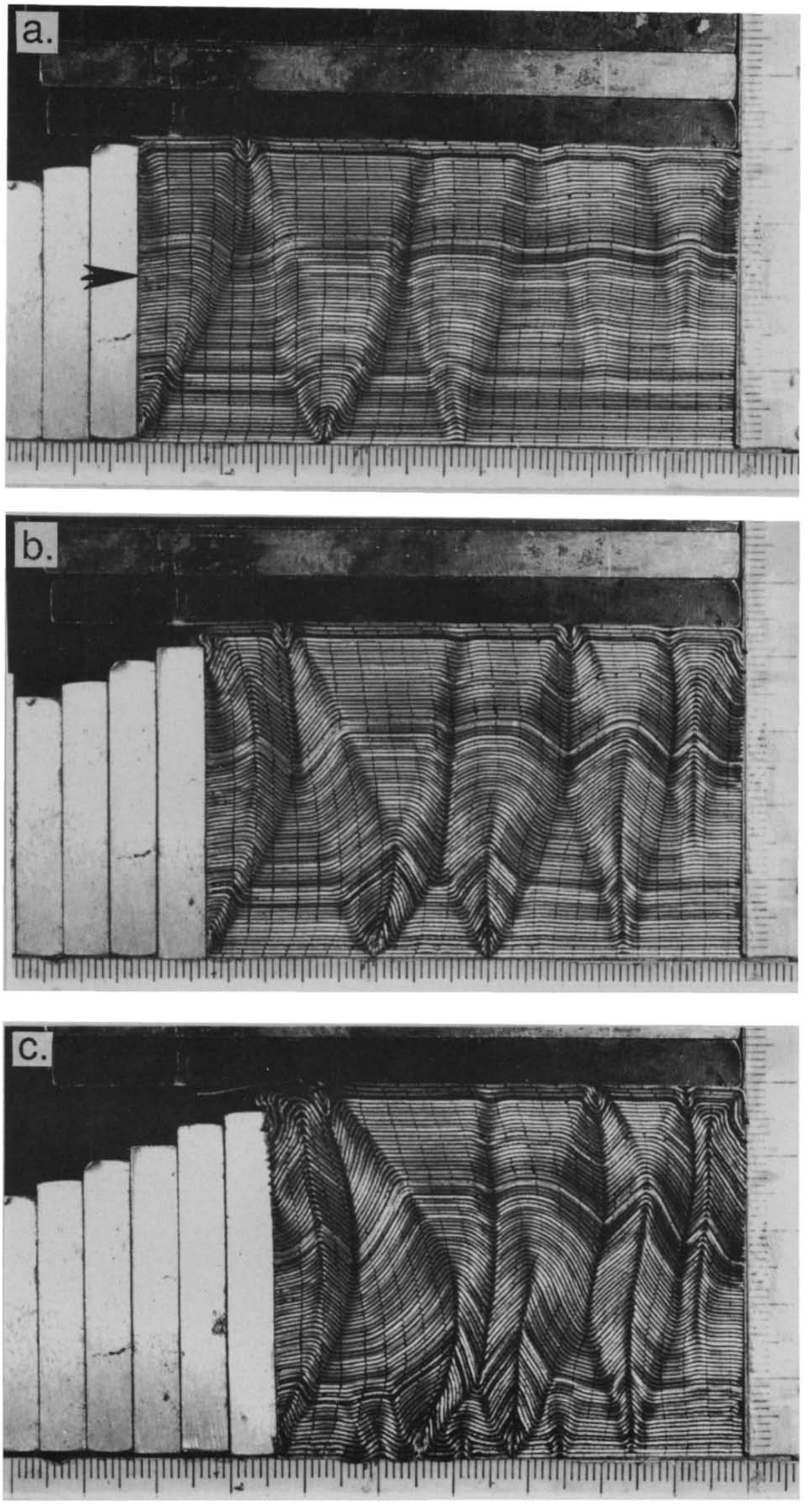

Fig. 9. Progressive stages in the deformation of a model consisting of 0.5 mm-thick lead layers separated by wax-impregnated cloth. Arrow marks layer used in Fig. 10. (a) Shortened 5%. (b) Shortened 15%. (c) Shortened 26%. Notice that the hinges tighten as they migrate. Scale divisions are mm.

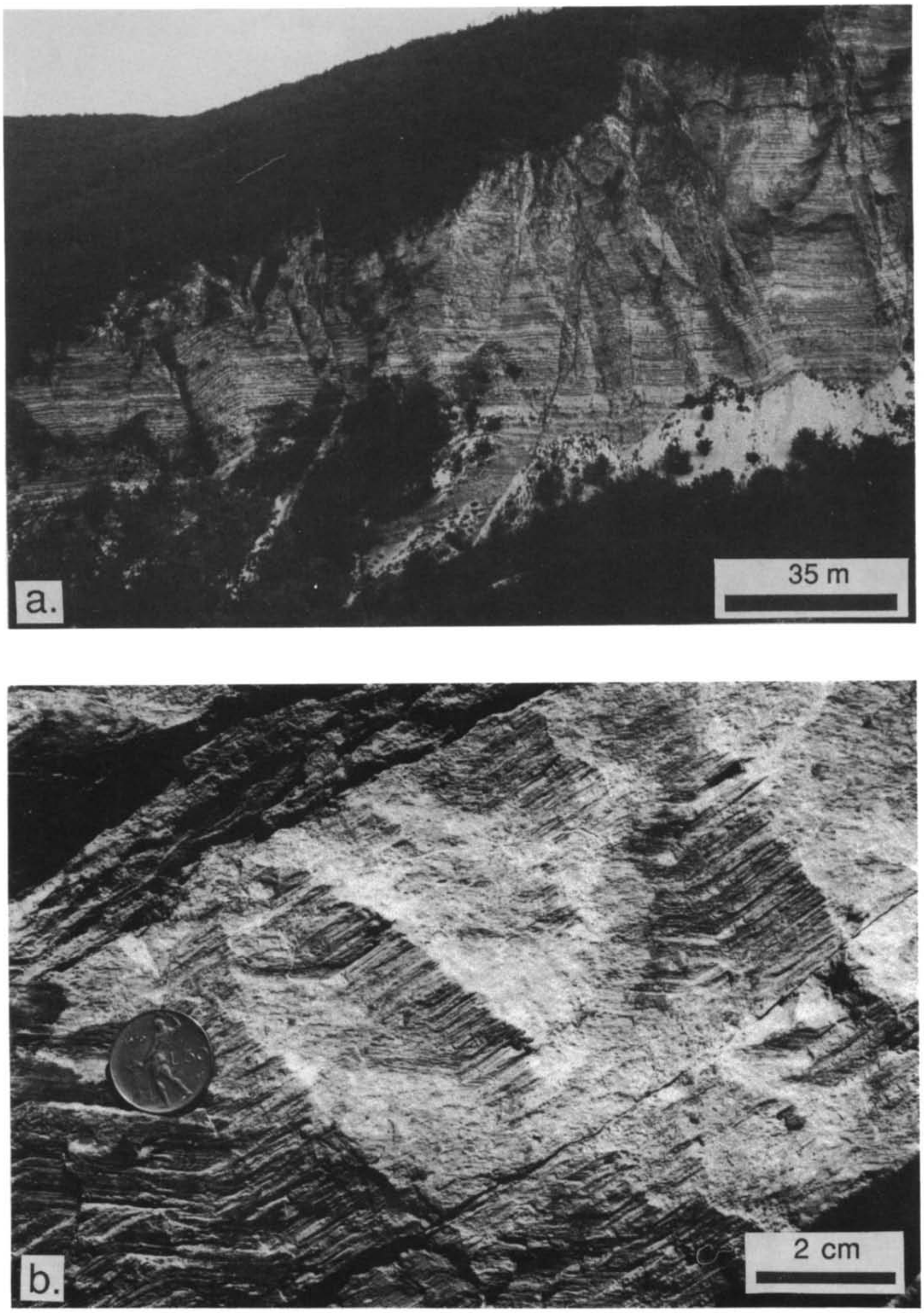

Fig. 10. Kink bands at Il Cimaio with gently curved hinges. These kinks are in the same belt of folds as the sharp-hinged kinks exposed at Poggio le Guaine, but have been shortened less. This suggests that the kinks at Poggio le Guaine may have started with gently curved hinges that tightened as the shortening increased, as was seen in the model shown in Fig. 9. (b) Calcite fibers and dissolution grooves on fault surface. Sharp change in orientation of fibers records change in slip direction relative to bedding, interpreted as the moment at which sudden kinking occurred.

presented so far (the geometrical properties, interlayer slip and volume change inside the kink band) is consistent with mobile-hinge kinking. The question of deformation in the layers caused by hinge migration is examined more closely in the next section.

HINGE MIGRATION IN EXPERIMENTAL AND NATURAL FOLDS

The amount of deformation in the rocks inside a kink band left by a pair of migrating fold hinges depends on the angularity of the fold hinge. If the shape of the fold hinge varies during migration then the deformation in the rocks at different places will be unequal. Also the fold hinges may sharpen after they have finished migrating, in which case the deformation in the fold hinges may be much greater than inside the kink band. Unfortunately, in natural folds the shape of the folds and fold hinges can be seen at only one instant in the folding history. In experimentally deformed multilayered models, however, it is possible to observe the complete evolution of folds that form by mobile-hinge kinking, and to see how the angularity of the fold hinges can vary during the deformation.

Experimental folds

This section presents the results of one in a series of experimental deformations of multilayered model consisting of layers of lead separated by layers of wax-impregnated cloth (see Appendix for a description of the experiment). This model material was chosen as a better approximation to the Apennines bedded limestone–shale sequences than was given by the decks of paper cards used by Weiss (1968). Figure 9 shows three stages in the deformation of the model. In the first photograph (Fig. 9a), a single kink, which nucleated in the lower left corner of the model, has propagated across the layers, reflecting back when the upper and lower boundaries were encountered. In the subsequent photographs (Figs. 9b & c), continued shortening causes the kink bands to widen by migration of the fold hinges. These folds have therefore formed by mobile-hinge kinking. As the fold hinges migrated, they became sharper. This progressive sharpening of the fold hinges is presented quantitatively in Fig. 11. Figure 11 is a plot that shows, at different stages, how much of a single lead layer from the model in Fig. 9 remained undeformed, how much had been incorporated into a straight kink-band segment and how much was part of a curved fold hinge. The lengths of these different sections were measured on photographic enlargements of the model and the breaks between the different regions were gotten by visual inspection of the layers. No analytical functions were used in this process. A layer near the center of the model was used in order to minimize the influence of the rigid upper and lower boundaries on the behavior of the layer. Layers above and below would yield plots different from that in Fig. 11.

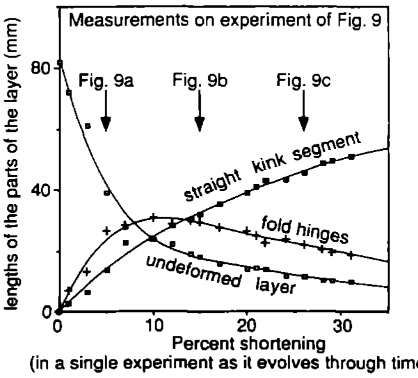

Fig. 11. Plot showing geometrical evolution of a single lead layer from model in Fig. 9. The three curves show lengths of layer that were undeformed, part of a fold hinge (measured around the fold hinge) and part of a straight kink segment, vs shortening. Notice that the arc length of the fold hinges increases from 0% shortening to about 10% shortening, but then decreases indicating a sharpening of the fold hinge with increased shortening. Expansion of the kink band after about 10% shortening is due to a combination of hinge sharpening and hinge migration out into the undeformed layer.

Inspection of Fig. 11 reveals the following two-stage history:

(1) 0–10% shortening—undeformed material is being consumed to form straight kink segments bounded by gently curved fold hinges (see Fig. 9a). Fold hinges are produced as new kink bands nucleate. Straight kink segments are formed as the hinges migrate outward into the undeformed layers. During this stage, undeformed material is being incorporated into fold hinges at a slightly higher rate than into straight kink segments, indicating that nucleation of kink bands is accommodating more of the shortening than expansion of existing kink bands;

(2) 10–35% shortening—during this stage no new kink bands have nucleated (compare Figs. 9b & c with Fig. 9a). Existing kink bands are expanding, as shown by the continued consumption of undeformed material and production of straight kink segment, but the fold hinges are also sharpening. This is shown by the progressive decrease in the fold-hinge component in Fig. 11 and by comparing the curvature of the hinges in Figs. 9(b) & (c), especially in the chevron folds. At this stage, about half of the quantity of material added to the straight kink segments in each shortening increment comes from migration of the hinges out into the undeformed layer, and the other half comes from straightening the layers near the fold hinges. The reduction in the size of the fold hinges results in transfer of material only into the straight kink segments. Material in the hinge zones is not transferred back into the undeformed parts of the layer, which would cause the kink bands to shrink, and require overall extension, rather than continued shortening.

As the fold hinges sharpen, the strain in the hinge zones increases. If it were possible to see the structures that formed in the lead as a result of the migration of the fold hinges, they would be concentrated near the final position of the hinges.

Relation between fold-hinge sharpness and mode 1 and mode 2 kinking

Mobile-hinge kinking can progress by either of two modes, and the mode of growth probably influences the sharpness of the fold hinges. One mode proposed by Rondeel (1969) requires the kink-band boundaries to rotate as they migrate so that the angle between the layers inside and outside the kink band, ϕ, increases as the kink band expands (Fig. 12a). In the other mode (Fig. 12b), the kink-band boundaries migrate with a fixed angle. Weiss (1980) refers to the growth modes shown in Figs. 12(a) & (b) as 'mode 1' and 'mode 2', respectively. For a hypothetical kink band forming in a mechanically anisotropic continuum, Weiss (1980) showed that mode 1 growth is more important than mode 2 growth when ϕ is less than about 60°. Once the layers inside the kink band have rotated to about 60°, mode 2 growth seems to be more important for continued growth of the kink band (Weiss 1980). Mode 1 growth is probably restricted to thin multilayers or small kink nuclei in thicker bodies, because for kinks involving many beds, the volume of material incorporated into the kink band—even with very small changes in the kink angle—would be prohibitively large (Fig. 12a) (Weiss 1980).

Mode 1 growth can be seen in the model of Fig. 9 during the early stages of folding (compare the fold interlimb angles in Figs. 9a & b). The mode of growth influences the sharpness of the hinges because a large interlimb angle may not cause enough strain in a layer to induce a localized yielding in the hinge zone. If a kink has formed only by mode 1 growth, there may not be clear evidence of the fold hinge migration inside the kink band, particularly of migration during the early stages of folding when the strain in the hinge zones was low.

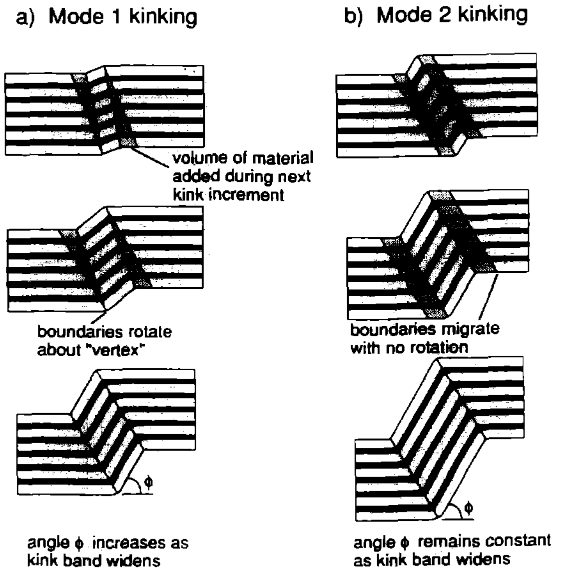

Fig. 12. (a) Mode 1 growth. Angle, ϕ, increases as kink band expands. (b) Mode 2 growth. Angle is fixed as kink band expands.

Natural folds

There is also evidence of fold hinge sharpening in the folds at Poggio le Guaine and Il Cimaio. Recall that the exposures at Poggio le Guaine and Il Cimaio are in the same belt of folds but that the shortening is less at Il Cimaio, thus providing a natural model of what the folds at Poggio le Guaine were like at an early stage. Figure 10(a) shows kink bands at Il Cimaio that have kink angles, ϕ, generally less than 45°. The average kink angle for the folds at Poggio le Guiane is close to 60°. This seems to show that kink band evolution at Il Cimaio was halted while the folds were still expanding by mode 1 growth. The fold hinges in Fig. 10(a) are gently curved so there should not be much evidence of the migration of the kink-band boundaries inside the kink band. Although most of the kink bands in Fig. 10(a) are inaccessible, the few available for study do not have structures clearly indicative of hinge migration. As mentioned earlier, the fold geometry and lack of evidence of separation of the layers is consistent with mobile-hinge kinking. The lack of clear evidence for hinge migration may indicate that the fold hinges at Poggio le Guaine were gently curved for a large part of the folding history. The development of these natural folds would then have been similar to the development of the experimental folds in the model in Fig. 9.

The fold hinges at Poggio le Guaine may also have sharpened during mode 2 growth, but there is no exposure that shows the fold development at a stage intermediate between the stages exposed along trend at Il Cimaio and Poggio le Guaine. It is also possible that the sharper hinges observed at Poggio le Guaine are a result of further rotation of the fold limbs about a fixed hinge. This is expected to occur in mobile-hinge chevron folds because the axial plane of a chevron fold is not mobile (Fig. 2b). Continued shortening only tightens the fold, which can be seen in Fig. 9. The chevron folds near the base of the model change from open folds to nearly isoclinal folds as the shortening progresses.

THE STRAIN HISTORY: MOBILE-HINGE KINKING VS PRESSURE SOLUTION

In the previous section, the lack of pressure solution features in the rocks inside the kink bands could be attributed to low strain in the hinge zones during the early stages of hinge migration. However, the question arises whether the formation of the fold hinges was ever dependent on pressure solution. That is, did mobile-hinge kinking only progress because pressure solution allowed fold hinges to form, or did mobile-hinge kinking and pressure solution operate more or less independently? And if pressure solution was not an important deformation mechanism during hinge migration, why is it now concentrated in the fold hinges?

One way to answer these questions is to investigate the rates at which fold hinges migrate. If pressure solution operates too slowly to accommodate a fast-

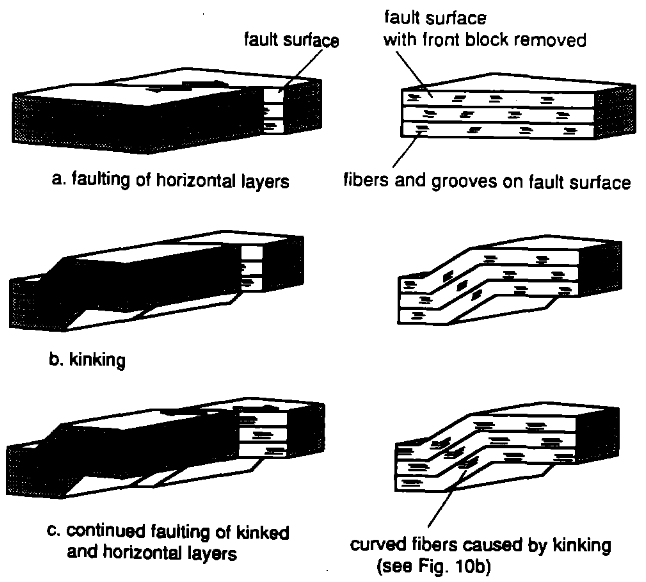

Fig. 13. Model for evolution of calcite fibers shown in Fig. 10(b). (a) A fault with a horizontal slip vector (as shown by the block diagram on the left) would produce horizontal fibers and dissolution grooves on the fault surface (as shown by the sketch on the right where the front block has been removed to expose the fault surface). If the bedding was folded during faulting (b) then the fibers and dissolution grooves within the kink band would be folded along with the bedding. If the fault continued to move with a horizontal slip vector, (c) then the fibers and dissolution grooves inside the kink band would record this folding episode.

moving fold hinge then mobile-hinge kinking and pressure solution would have operated independently.

Hinge migration rates and pressure solution strain rates

The limestone units in the study area are cut by numerous small-displacement faults (Marshak *et al.* 1982). Figure 10(b) shows the surface of one of these faults in the Upper Cretaceous Scaglia Rossa limestone exposed in a roadcut near the church of Sant'Anna (43°39'30"N, 12°44'38"E of Greenwich, 0°17'30"E of Rome). Displacement on this fault is probably less than 10 cm, but what makes it particularly interesting is the sharp bend in the calcite fibers and solution grooves, recording a change in the slip direction on the fault surface, relative to bedding (see Ramsay & Huber 1983 for a discussion of shear-vein orientations and fault-slip directions). The bedding, which is cut by the fault surface, currently dips 50–60° to the left (northeast) and is presumably part of a kink band, although no kink-band boundaries are visible in the outcrop. The presence of solution pits, fiber-encrusted steps, and a lack of cataclasis are evidence that this fault moved by the process of pressure-solution slip (Elliott 1976, Marshak *et al.* 1982). The arrangement of the pits and fiber-encrusted steps permits determination of the slip direction and fiber-growth direction on the fault surface. Using the criteria described by Elliott (1976) and Marshak *et al.* (1982), the last fibers to form are currently horizontal and the first-formed fibers become horizontal when the bedding is rotated back to horizontal. These fibers are optically continuous around their change in orientation and therefore may record continuous movement of the fault before, during, and after folding, with a slip direction that remained consistently horizontal. This sequence is illustrated in Fig. 13.

Movement by pressure-solution slip is accomplished by dissolution of asperities along the fault surface and is often accompanied by deposition of fibrous crystals in voids that open as the fault slips (Durney & Ramsay 1973, Elliott 1976, Marshak *et al.* 1982). This is a type of diffusional creep and the rate of slip on such a fault is controlled by the rate at which obstacles along the sliding surface can be removed by pressure solution (Elliott 1976). For the fault at Sant'Anna, the continuity of the fibers on the fault surface suggests that fiber growth kept pace with fault slip. Since this fault has moved by pressure-solution slip, the average rate of fiber growth was similar to the rate at which pressure solution dissolved obstacles along the fault. Using the bend in the calcite fibers as a record of the folding process, we can compare the rate at which the kink fold grew to the rate of pressure-solution slip along the fault. No information is available that would provide the exact growth rate of the calcite fibers, so only the relative rates can be estimated.

We will consider the situation where the change in fiber orientation is a result of passage of the kink-band boundary during mode 2 growth. The natural kink folds in this study generally have gently curved hinges, so as the hinges migrate, pre-existing fibers do not rotate instantaneously to their final position but go through a number of intermediate orientations (see Fig. 14). New horizontal fibers grown during these intermediate stages will produce a gradual transition from the original to the final fiber orientation (Fig. 14) and the length of the transition is dependent on the rate of hinge migration. If

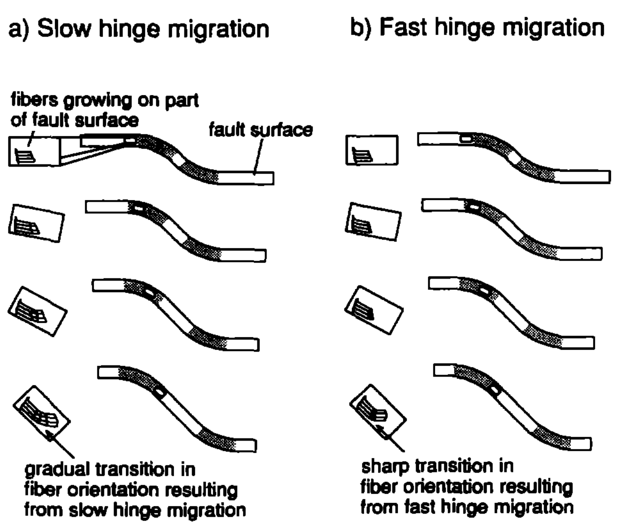

Fig. 14. Schematic evolution of calcite fibers produced by faults that slip during folding for both slow and fast moving hinges. The plane of the page corresponds to the fault plane and new fibers are continually being added to the right edge of the existing fibers. Four progressive stages of faulting are shown in each case. Slip direction on the fault is consistently horizontal. (a) Kink bands with slowly migrating hinges will produce a gradual transition from the initial fiber orientation to the final orientation during passage of the fold hinge. (b) Kink bands with fast migrating hinges or sharp hinges will produce a sharp transition from one fiber orientation to the other. Figure 10(b) is an example of a sharp transition in fiber orientation.

the hinge is migrating slowly (Fig. 14a) the length of the transition will be longer and more gradual than if the hinge is migrating quickly (Fig. 14b). It is important to note that we are considering the average rate of hinge migration. It is certainly possible that hinge migration may be episodic, consisting of a series of relatively rapid jumps punctuated by periods of no- or slow-migration. Episodic migration might show up as a stepwise transition from the original fiber orientation to the final. The hinges of the natural kink folds in this study have arc lengths that are generally greater than 0.5 m or so (see Fig. 8). The fibers on the fault surface in Fig. 10(b) are about 4 cm long and the length of the transition from one fiber orientation to the other, although variable, is always less than 0.5 cm. If the kink-band boundary migrated 0.5 m (the length of a hinge zone) during the time it took the fault to slip 0.5 cm, the displacement rate of the kink-band boundary would have been about 100 times greater than the displacement rate on the fault (50 cm of hinge migration during 0.5 cm of fault slip). Because the fault moves only as fast as pressure solution can dissolve away obstacles, the information from the fibers shows that in the time it took to dissolve 1 cm of limestone along the fault, a fold hinge migrated through 100 cm of limestone. This suggests that pressure solution was not able to operate fast enough to accommodate kink-band boundary migration and fold hinge formation, at least during part of the fold expansion.

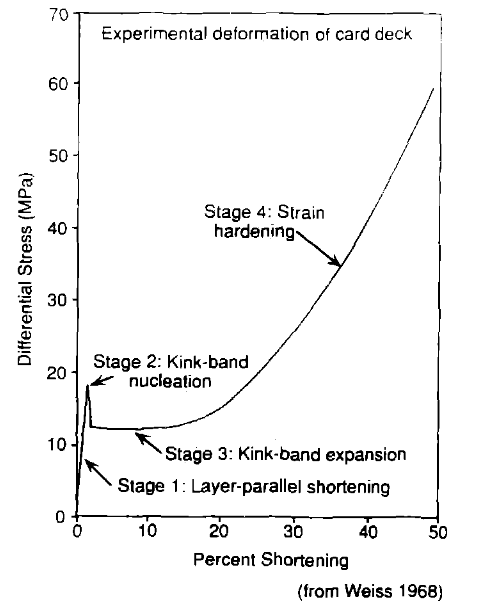

Fig. 15. Differential stress vs shortening for an experimentally deformed card deck. Cards were deformed under a constant vertical load of about 900 kg—a relatively low confining load (adapted from Weiss 1968).

Deformation history of the folded limestones

The large difference in the displacement rates between hinge migration during mobile-hinge kinking and pressure solution suggests that they acted independently during the deformation of the limestones. In places where the same rock units have been shortened but not folded, there is often weak to moderate stylolitization (solution cleavage) and veining. The stylolites are usually perpendicular or sub-perpendicular to bedding (Alvarez *et al.* 1976, 1978). In addition, there are often small faults that have moved by pressure-solution slip (Marshak *et al.* 1982), such as the one described above. At Poggio le Guaine and Il Cimaio, stylolites that are roughly perpendicular to bedding are visible in the limestone layers inside the kink bands as well as outside and were probably formed prior to folding. This 'background' stylolitization is overprinted by more intense pressure-solution effects in the hinge zones of chevron folds and kink folds where the hinges are sharp. Since the present position of the hinges of these folds represents the final position of the migrating kink-band boundaries, it is reasonable to assume that this localized pressure solution occurred after hinge migration had slowed considerably or stopped. This late episode of pressure solution may have helped change the shape of the gently curved fold hinges at Il Cimaio to the more angular hinges seen at Poggio le Guaine.

The following deformation history is based upon the field observations and inferences described above, as well as the deformation histories seen in experimentally deformed models that folded by mobile-hinge kinking. The inferred stress–strain behavior of the rocks is based upon the stress–strain behavior of experimentally deformed decks of paper cards recorded by Weiss (1968). Figure 15 is adapted from one of the stress–strain curves presented by Weiss (1968).

The deformation history can be divided into four episodes:

Stage 1—originally planar layers underwent layer-parallel shortening. During this stage, the stress was below the critical value for kinking but was increasing. Pressure solution was the dominant deformation mechanism producing bedding-perpendicular stylolites and displacement on faults that moved by pressure-solution slip (Marshak *et al.* 1982). The deformation-mechanism map for calcite presented by Rutter (1976) shows that pressure solution can be an important deformation mechanism if the strain rate is low, and the limestones were probably deforming slowly at this point. Marshak *et al.* (1982) estimated that the slip on the pressure-solution slip faults amounted to a local layer-parallel shortening of between 1 and 2%; the overall shortening by stylolitization is probably similar. This part of the deformation is analogous to the shortening that occurs in the models before the first kink bands nucleated. In the cards this is primarily elastic strain, unlike the permanent deformation imparted to the rocks by pressure solution.

Stage 2—the compressive stress reached the critical value required for kink bands to nucleate and propagate. In models, these first kink bands form very rapidly. In rocks, the evidence from Sant'Anna indicates that the displacement rates of kink-band boundaries is much faster than the displacement rates for pressure solution and therefore natural bands may also nucleate rapidly. Since the formation of kink bands was more efficient at relieving the stress in the rocks it became the dominant deformation mechanism during this stage. The rapid stress drop associated with the formation of these first kinks can be seen in Fig. 15. A recent study by Stel & De Ruig (1989) shows a similar relationship between pressure-solution cleavage and kink formation. In their study of a kink band in Spain they found that pressure solution became an insignificant deformation mechanism during the growth of the kink band.

Stage 3—in the multilayered models, continued compressive stress caused the existing kink bands to expand. Figure 15 shows continued shortening at a constant stress during this phase, which also corresponds to the stage in the deformed lead multilayer shown in Fig. 9(b) where the kink bands were expanding with gently curved hinges. For the rocks at Poggio le Guaine and Il Cimaio, the shortening attributable to pressure solution during this stage was probably small in comparison to the shortening accommodated by fold growth.

Stage 4—the final stage in the deformation involved slowing of the expansion of the kink bands. In the deformed models, the slowing of the expansion of the kink bands is accompanied by a rise in stress (see Fig. 15). This is the result of "geometrical" strain hardening (term proposed by L. E. Weiss), which seems to be a result of two different phenomena. One part of the strain hardening is due to the increase in the dip of the fold limbs. When the layers rotate past 45°, the shear stress on the slip surfaces decreases. A kink band expands by slip between the layers and as the shear stress begins to fall, expansion becomes more difficult. This causes the stress to rise and the shortening rate to decrease. The second part of the strain hardening is due to inhibited hinge migration caused by interfering kink bands. Weiss (1968) noted that originally mobile hinges in kink bands tend to get locked when later kinks propagate across the early kink bands.

At Poggio le Guaine, after mode 1 growth ended and the limbs of the folds were dipping about 60°, the sequence as a whole probably became stronger, and subsequent shortening was slower than in the two previous stages of the deformation. Mobile-hinge kinking was no longer an important deformation mechanism and, because the strain rate had decreased, pressure solution had once again become dominant. The post-folding pressure solution seems to have been concentrated in the hinge zones of the folds, which were regions with higher elastic strain energy. Dissolution of material in the hinge zones would allow the rocks to shorten further by sharpening the hinges and the accompanying interlayer slip would allow the folds to tighten. At this point the folding mechanism would become either fixed-hinge kinking or fixed chevron folding. This is analogous to the sharpening of the chevron fold hinges in the lead multilayer (Figs. 9 and 11), although the deformation in the lead layers occurs by crystal plasticity, not pressure solution.

If pressure solution had not been able to dissipate the stress in the limestones fast enough, the critical stresses for faulting or other deformation mechanisms might have been attained and pressure solution might have again become unimportant. In the lead models the stress was dissipated by crystal plastic flow of the lead out of the deformation apparatus.

DISCUSSION AND CONCLUSIONS

Recognition of folds formed by mobile-hinge kinking

Each of the four folding mechanisms—mobile-hinge kinking, mobile-hinge chevron folding, fixed-hinge chevron folding and fixed-hinge kinking—produces characteristic structures in the deformed rock layers and produce folds with characteristic geometries. Geologists studying folds in the field should be able to determine which, if any, of these mechanisms operated during the folding by recognizing these structures and geometries. Fold arrays that include single kink bands, chevron folds and unrotated layers are characteristic of mobile-hinge and fixed-hinge kinking. In the past, a plot of inner vs outer kink angles was the primary test for mobile-hinge kinking. Ideally, mobile-hinge kinks should have equal inner and outer kink angles. Any significant deviation from this ideal has usually been considered sufficient evidence to rule out mobile-hinge kinking as the folding mechanism. We have shown, however, that this test is unreliable. A plot of inner and outer kink angles from mobile-hinge kinks produced in laboratory experiments (Fig. 5) produced a fairly wide scatter of points that seems to be a result of minor amounts of interlayer slip. A more useful geometric test is to plot a frequency distribution of interlimb angles. Folds that have formed by fixed- or mobile-hinge kinking should show a characteristic bimodal distribution (Fig. 7) with the peaks centered on the interlimb angles of single kink bands and chevron folds.

Folds formed by mobile-hinge kinking should show evidence of interlayer slip only in the rocks inside the kink band and no evidence of volume change. In addition, there may be structures in the rocks inside the kink bands that record the migration of the fold hinges. Evidence of hinge migration, however, is dependent on the sharpness of the fold hinges during migration. The natural kink bands in this study probably do not show clear evidence of boundary migration because the hinges for the most part were gently curved.

The folds at Il Cimaio, which have gently curved hinges and shallow limb dips, show that a fold formed by mobile-hinge kinking need not have 60° limb dips and sharp, angular hinges. Many folds in nature with shallow limb dips and gently curved hinges may have formed by mobile-hinge kinking; these features may indicate that folding was arrested during mode 1 growth.

Importance of different folding mechanisms

Fixed-hinge chevron folding was not important in the formation of the folds in either the natural or experimental multilayers. Fixed-hinge chevron folding, however, can be important in certain instances. For example, buckle folds, which form essentially by fixed-hinge chevron folding, can be easily produced by shortening a deck of cards provided there is little or no upper constraint. In our experiments we always had an upper constraint and did not see fixed-hinge chevron folding. Gay & Weiss (1974) found that the first deflections produced in experimentally deformed decks of paper cards often appeared as symmetric or monoclinal buckles. These folds may have been growing initially by fixed-hinge chevron folding but they were very small and rapidly evolved into folds that grew by mobile-hinge kinking. These small buckles seemed to serve as sites for the nucleation of the kink bands.

Fixed-hinge kinking in mechanically continuous materials results in a loss of cohesion at the kink-band boundaries. In a multilayer, however, cohesion across the kink-band boundaries can be maintained by allowing gaps to open between the layers (Fig. 2c). Opening dilational spaces requires additional work and as the confining stress increases so would the amount of work that is expended in opening gaps. Fixed-hinge kinking might, therefore, be expected to become less important at higher confining stress. Anderson (1974) found this to be true for experimentally shortened cylinders of slate. At low confining stress, faulting was most important. At intermediate confining stress, the samples deformed by fixed-hinge kinking, and at high confining stress the samples deformed by mobile-hinge kinking. The change between deformation by fixed-hinge and mobile-hinge kinking should occur when it becomes easier to have hinges migrate through rock layers than to open gaps between them. Fixed-hinge kinking is probably most important when the confining stress is low, when the kink bands are small, and also when the limb-dips, and therefore the gaps between the layers, are small. We found no evidence of the dilation associated with fixed-hinge kinking in the exposures of natural folds at Poggio le Guaine and Il Cimaio. Other authors have found evidence of dilation within both natural (Anderson 1968, Dewey 1969, Collomb & Donzeau 1974, Verbeek 1978) and experimental kink bands (Donath 1968, Anderson 1974), but with the exception of the folds examined by Collomb & Donzeau (1974), these studies were of cm-scale folds.

The most important folding mechanism in the models and in the natural folds at Poggio le Guaine and Il Cimaio was mobile-hinge kinking. Mobile-hinge kinking is well known in crystals and other materials whose mechanical behavior approaches that of a continuous medium with a strong, planar anisotropy (slates, phyllites, card decks), but the evidence presented in this study shows that mobile-hinge kinking can be an important folding mechanism in mechanically discontinuous multilayers as well, provided they also have a strong planar anisotropy. The only special boundary condition necessary to initiate mobile-hinge kinking in the laboratory was that the model be strongly constrained during the deformation. In the natural folds, competent limestone units provided the rigid constraints. It seems likely that if the confining medium were less competent, such as shale, this would affect the folding mechanism, but to what degree is not clear. In several card deck experiments we used stiff layers of rubber to confine the models. The resulting folds were still mobile-hinge kinks but often had rounder hinges than similar experiments confined with steel plates. The relationship between rigidity of constraint, fold kinematics, and fold geometry needs further study.

Rapid strain rates associated with mobile-hinge kinking

Paterson & Weiss (1966) found that kink-band formation in experimentally deformed phyllite samples occurred rapidly and was associated with a large stress drop. Weiss (1968) also found this to be true for kink-band formation in models (stage 2 in Fig. 15). Paterson & Weiss (1966) speculated that mobile-hinge kinking in nature may occur rapidly enough to generate earthquakes. For the natural folds in this study, the kink-band boundaries appear to have had displacement rates at least 100 times faster than the displacement rates associated with pressure-solution slip along a fault. Whether this was high enough to produce earthquakes is uncertain but remains a possibility.

Acknowledgements—Support for this project was provided by grants from the National Science Foundation (EAR-79-11337, EAR-80-22846 and EAR-83-18660 awarded to Walter Alvarez), Chevron Overseas Petroleum, Inc., and two Geological Society of America Research Grants awarded to Kevin Stewart. We thank Lionel Weiss, David Bice, Virginia Pfaff, Giampaolo Pialli, Alessandro Montanari, Lung Chan, Mark Anders and Mark Hageman for many helpful discussions related to the study of natural and experimental folds. We thank Lionel Weiss and Virginia Pfaff for their comments on an early version of this manuscript, and Roy Kligfield and an anonymous reviewer for their helpful comments on the most recent version. We thank Leonardo Polonara and the Assessorato al Territorio of the Regione Marche, and the Club Alpino Italiano, Sezione San Severino Marche for field support.

REFERENCES

Alvarez, W., Engelder, T. & Lowrie, W. 1976. Formation of spaced cleavage and folds in brittle limestones by dissolution. *Geology* **4**, 698–701.

Alvarez, W., Engelder, T. & Geiser, P. 1978. Classification of solution cleavage in pelagic limestones. *Geology* **6**, 263–266.

Anderson, T. B. 1964. Kink-bands and related geological structures. *Nature* **202**, 272–274.

Anderson, T. B. 1968. The geometry of a natural orthorhombic system of kink bands. In: *Kink Bands and Brittle Deformation* (edited by Baer, A. J. & Norris, D. K.). *Geol. Surv. Pap. Can.* **68–52**, 200–226.

Anderson, T. B. 1974. The relationship between kink-bands and shear fractures in the experimental deformation of slate. *J. geol. Soc. Lond.* **130**, 367–382.

Beutner, E. C. & Diegel, F. A. 1985. Determination of fold kinematics from syntectonic fibers in pressure shadows, Martinsburg slate, New Jersey. *Am. J. Sci.* **285**, 16–50.

Biot, M. A. 1964. Theory of internal buckling of a confined multilayer sequence. *Bull. geol. Soc. Am.* **75**, 563–568.

Biot, M. A. 1965. Further development of the theory of internal buckling of multilayers. *Bull. geol. Soc. Am.* **76**, 833–840.

Cobbold, P. R. 1976. Fold shapes as functions of progressive strain. *Phil. Trans. R. Soc.* **A283**, 129–138.

Cobbold, P. R., Means, W. D. & Bayly, M. B. 1984. Jumps in deformation gradients and particle velocities across propagating coherent boundaries. *Tectonophysics* **108**, 283–298.

Collomb, P. & Donzeau, M. 1974. Relations entre kink-bands decametriques et fractures de socle dans l'Hercynien des Monts d'Ougarta (Sahara occidental, Algerie). *Tectonophysics* **24**, 213–242.

D'Argenio, B. & Alvarez, W. 1980. Stratigraphic evidence for crustal thickness changes on the southern Tethyan margin during the Alpine cycle. *Bull. geol. Soc. Am.* **91**, 681–689.
Dewey, J. F. 1969. The origin and development of kink bands in a foliated body. *J. Geol.* **6**, 193–216.
Donath, F. A. 1968. Experimental study of kink fold development in Martinsburg slate. In: *Kink Bands and Brittle Deformation* (edited by Baer, A. J. & Norris, D. K.). *Geol. Surv. Pap. Can.* **68-52**, 255–287.
Durney, D. W. & Ramsay, J. G. Incremental strains measured by syntectonic crystal growths. In: *Gravity and Tectonics* (edited by DeJong, K. A. & Scholten, R.). Wiley, New York, 67–96.
Elliott, D. 1976. The energy balance and deformation mechanisms of thrust sheets. *Phil. Trans. R. Soc. Lond.* **A283**, 289–312.
Gay, N. C. & Weiss, L. E. 1974. The relationship between principal stress directions and the geometry of kinks in foliated rocks. *Tectonophysics* **21**, 287–300.
Honea, E. & Johnson, A. M. 1976. Part IV, Development of sinusoidal and kink folds in multilayers confined by rigid boundaries. *Tectonophysics* **30**, 197–239.
Johnson, A. M. 1977. *Styles of Folding*. Elsevier, Amsterdam.
Latham, J-P. 1985a. The influence of nonlinear material properties and resistance to bending on the development of internal structures. *J. Struct. Geol.* **7**, 225–236.
Latham, J-P. 1985b. A numerical investigation and geological discussion of the relationship between folding, kinking and faulting. *J. Struct. Geol.* **7**, 237–249.
Marshak, S., Geiser, P. A., Alvarez, W. & Engelder, T. 1982. Mesoscopic fault array of the northern Umbrian Apennine fold belt, Italy: geometry of conjugate shear by pressure solution slip. *Bull. geol. Soc. Am.* **93**, 1013–1022.
Marshak, S. & Engelder, T. 1985. Development of cleavage in limestones of a fold-thrust belt in eastern New York. *J. Struct. Geol.* **7**, 345–359.
Paterson, M. S. & Weiss, L. E. 1966. Experimental deformation and folding in phyllite. *Bull. geol. Soc. Am.* **77**, 343–374.
Ramsay, J. G. 1967. *Folding and Fracturing of Rocks*. McGraw-Hill, New York.
Ramsay, J. G. 1974. Development of chevron folds. *Bull. geol. Soc. Am.* **85**, 1741–1754.
Ramsay, J. G. & Huber, M. I. 1983. *The Techniques of Modern Structural Geology, Volume 1: Strain Analysis*. Academic Press, New York.
Rondeel, H. E. 1969. On the formation of kink bands. *Nederlandse Akademie van Wetterschapper* **72**, 317–329.
Rutter, E. H. 1976. The kinetics of rock deformation by pressure solution. *Phil. Trans. R. Soc.* **A283**, 203–219.
Stel, H. & De Ruig, M. J. 1989. Opposite vergence of a kink fold and pressure solution cleavage, southeast Spain: a study of the relation between paleostress and fold kinematics. *Tectonophysics* **165**, 117–124.
Stewart, K. G. 1987. A study of compressional and extensional structures in the Northern Apennine fold-and-thrust belt. Unpublished Ph.D. thesis, University of California, Berkeley.
Stewart, K. G., Alvarez, W. & Weiss, L. E. 1984. A comparison between kink folds in pelagic limestones and modeling materials: Evidence for migrating kink band boundaries. *Geol. Soc. Am. Abs. w. Prog.* **16**, 669.
Suppe, J. 1985. *Principles of Structural Geology*. Prentice-Hall, Englewood Cliffs, New Jersey.
Verbeek, E. R. 1978. Kink bands in the Somport slates, west-central Pyrenees, France and Spain. *Bull. geol. Soc. Am.* **89**, 814–824.
Weiss, L. E. 1968. Flexural slip folding of foliated model materials. In: *Kink Bands and Brittle Deformation* (edited by Baer, A. J. & Norris, D. K.). *Geol. Surv. Pap. Can.* **68-52**, 294–357.
Weiss, L. E. 1980. Nucleation and growth of kink bands. *Tectonophysics* **65**, 1–38.

APPENDIX

Deformation apparatus and technique

The experimental apparatus used in this paper is described in detail in Weiss (1968). It consists of two hydraulic rams at right angles to one another, which are supported by a rigid steel frame in which the models are deformed. The vertical ram is lowered by means of a hand pump until it comes in contact with the model and the desired confining load is attained. The horizontal ram is driven by an electric pump. The shortening rate is controlled by a valve that regulates the amount of fluid going to the ram. During the deformation, the model shortens horizontally and extends vertically. This necessitates stopping the experiment every so often to place larger and larger steel plates between the model and the horizontal ram, to minimize the size of the unconstrained corner that forms during the deformation (see the experiment in Fig. 9). The confining load is kept constant by means of an adjustable pressure-release valve. The model is shortened the desired amount or until the 18,000 kg load limit of the horizontal ram is attained.

Description of models

The model from which Fig. 4 was sketched was a deck of paper cards of the type used by Weiss (1968). It was deformed under a constant vertical confining load of 1100 kg.

The model in Fig. 9 consisted of layers of lead separated by layers of wax-impregnated cloth. The lead was cut into strips, rolled to the desired thickness, and then stacked and machined to produce an even deck with right angles. The wax-impregnated cloth is available as a reinforcing backing for paper maps and posters under the name Chartex. Each layer in this model consists of one layer of Chartex. The sheets of Chartex were then cut into strips the same size as the finished lead layers. The model was deformed under a constant vertical load of about 1100 kg.