Journal of Structural Geology, Vol. 9, No. 5/6, pp. 585 to 590, 1987
Printed in Great Britain

0191–8141/87 $03.00 + 0.00

A newly recognized type of slickenside striation

W. D. Means

Department of Geological Sciences, State University of New York at Albany, 1400 Washington Avenue, Albany, NY 12222, U.S.A.

(*Received* 3 *June* 1986; *accepted in revised form* 11 *March* 1987)

Abstract—This note summarizes current views on the origin of slickenside striations and points to the existence of a type of striation not readily explained by established genetic ideas. Such striations have been seen on fault surfaces in naturally deformed shale and in experimentally deformed paraffin wax. They are defined by arrays of shallow, slip-parallel ridges and grooves of millimetric width and below. On any given slip-surface, the ridges are as common as the grooves and display similar dimensions and profile shapes. Across any pair of slip-surfaces in contact at the end of faulting, ridges protruding from one surface fit into or nest with grooves on the other surface. The origin of these features is not yet understood.

INTRODUCTION

Classical slickensides are smooth or shiny fault surfaces commonly striated in the slip direction. Some workers refer to the striations themselves as slickensides (Hills 1972, p. 179, Angelier 1979, p. T18) but this is probably not a good idea, for reasons explained by Fleuty (1975).

Closely related to slickensides in the classical sense are other kinds of fault surfaces which are not particularly smooth or shiny but which do bear a prominent, slip-parallel lineation. These include fault surfaces covered with mats of parallel crystal fibers (Durney & Ramsay 1973), vein-bearing surfaces with a slip-parallel lineation but no present crystal fibers, and surfaces of lineated, cemented or uncemented gouge (Engelder 1974). Many field workers thus extend the term slickenside (as I do in this paper) to cover all of these features, from classical slickensides where surface shine is the essential feature, to less shiny types where the lineation dominates.

Slickensides are familiar in fault zones and on the surfaces of rock layers that have been folded by flexural slip. They have been used by generations of mappers to ascertain the *direction* and, in some cases the *sense* of slip, but they have never been exploited much to estimate the *rate* and *depth* of slip events, or the *magnitudes* of incremental and total slip displacements. The problem has been that not enough is known about the various kinds of slickensides that exist, the processes by which they form, and the ways in which their measurable properties correlate with slip processes and parameters. With seismological and tectonic interest in fault rocks increasing, the time seems ripe for a new wave of research on the structure and significance of slickensides. Indeed a start has already been made, by Petit *et al.* (1983), Gamond (1983), Gray (1984), Petit & Laville (1985), Guiraud & Seguret (1985), and by several papers in the present Special Issue.

CURRENT VIEWS ON THE ORIGIN OF SLICKENSIDE LINEATIONS

There have been at least five distinct explanations for slickenside lineations. They are illustrated schematically in Fig. 1, where the resulting elongate features are referred to informally as 'scratches', 'streaks', 'tails', 'fibers' and 'spikes'.

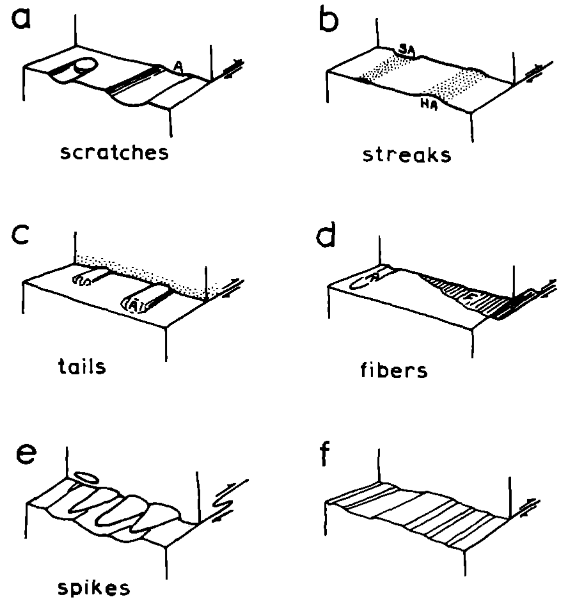

Fig. 1. Types of slip-parallel linear features on slickensides. (a) Grooves or scratches resulting from asperity (A) ploughing. Upper groove with sheared-off asperity at its down-slip end. (b) Debris streaks trailing soft asperity (SA) or accumulated in lee of hard asperity (HA). (c) Tails of erosion-sheltered material on the down-slip side of hard asperities. (d) Fibers (F) and rod (R) of vein material filling potential voids behind steps or asperities, respectively. (e) Spikes on a slickolite surface. (f) Newly-recognized type explained in text.

Asperity ploughing

This is the original idea to account for lineations defined by furrows, grooves or scratches on slickensides. A protuberance moving with one side of a pair of shearing surfaces interfaces geometrically with the other side and scores a groove in it (Fig. 1a). The protuberance may be a part of the surface with which it moves or a piece of debris from either surface, moving at a velocity intermediate between the velocities of the two surfaces. Excavation of the groove may be accomplished by a variety of brittle or ductile deformation processes. The term 'ploughing' is sometimes reserved for ductile cases, but I use it here in a more general way. Grooves scored by asperity ploughing are commonly called 'wear grooves', 'wear tracks' or 'tool tracks'. They are familiar from frictional sliding experiments on rocks (e.g. Engelder 1974, LaFountain *et al.* 1975).

Debris streaking

Debris streaking produces slip-parallel elongate bodies of gouge or consolidated gouge, by at least two mechanisms (Fig. 1b). A soft asperity may wear down, leaving a debris track on the other surface, or debris may become piled up fore and aft of an asperity, in the manner claimed for some glacial drumlins.

Erosional sheltering

When a surface bearing hard particles is eroded by a moving layer of cataclastic debris, elongate ridges on the down-slip (cf. 'down-wind') side of each such particle will be sheltered from erosion (Fig. 1c). J. R. Andrews (work in preparation), refers to the face of the hard particle and the remnant ridge trailing it as 'crag and tail' structure. Tjia (1967) referred to such features as 'trails'.

Fiber growth

Lineations of this kind develop by growth of elongate crystals (commonly quartz or calcite) parallel to the local displacement direction across slowly dilating potential voids on fault surfaces (Durney & Ramsay 1973). Most commonly, the fibers compose mats or sheets of many individuals, but a similar process can produce single-crystal or polycrystalline rods of the vein material completely surrounded by the native rock or its cataclastic derivatives (Fig. 1d).

Slickolite formation

Slickolites (Bretz 1940) are like stylolites in being dissolution surfaces with spikes and columns pointing in the displacement direction. Unlike ordinary stylolites, however, the spikes and columns of slickolites point subparallel to (rather than subnormal to) the surface as a whole (Arthaud & Mattauer 1972). They are thus the inverse of crystal fiber slickenside lineations (Fig. 1e). Dissolution rather than precipitation causes them, and they indicate slip with local volume decrease instead of volume increase. Slickolite lineation and crystal fiber lineation may occur close together on the same fault surface (Mattauer 1973, p. 347) if the surface undulates about the slip direction. A striking illustration of slickolite lineation is provided by Mattauer (1973, p. 345).

THE NEW TYPE OF STRIATION

The new type of striation was recognized first in paraffin wax sheared experimentally in a direct shear jig (Fig. 2), at room temperature, 3×10^{-3} ms^{-1} slip rate. The wax used was a relatively hard white wax (MP 62°C) made black with candle dye. The fault surfaces are shiny dark surfaces (classical slickensides) with a pronounced slip-parallel striation. The distinctive features of these striations are: (1) that ridges are as common as grooves and have similar dimensions and shapes in profile as the grooves; and (2) that the topography on one side of a pair of slickensides in contact at the end of shearing nests congruently with topography on the other side. Thus ridges on one side fit perfectly into grooves on the other side, and vice versa (Fig. 1f).

Figure 3 demonstrates the nesting property. Figure 3(a) shows the footwall slickenside of a mated pair of slickensides. Figure 3(b) shows an epoxy cast of the corresponding part of the hangingwall slickenside. Nesting is demonstrated by the similarity of the two pictures, since the cast (which is known to nest with the hangingwall) matches the footwall closely.

Figure 4 shows transverse striation profiles in two wax specimens, as traced from photographs of sawcuts through epoxy casts of the slip surfaces. The largest ridges and grooves are millimeters across but typically less than a millimeter high or deep. Their flanking surfaces typically make angles of 25° or less with the trace of the fault surface as a whole. Two ridge and groove profiles are common: shallow U-shapes with flat tops or bottoms or V-shapes lacking flat tops or bottoms. Superposed on the coarsest topographic features are various finer striations, often an order of magnitude finer than the coarsest features, and too small to show in

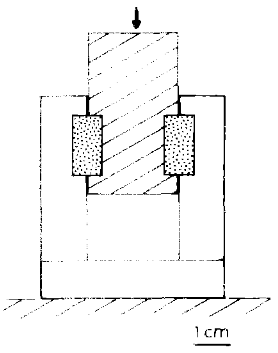

Fig. 2. Direct shear jig for faulting blocks of paraffin wax (stippled). Front and back cover plates removed.

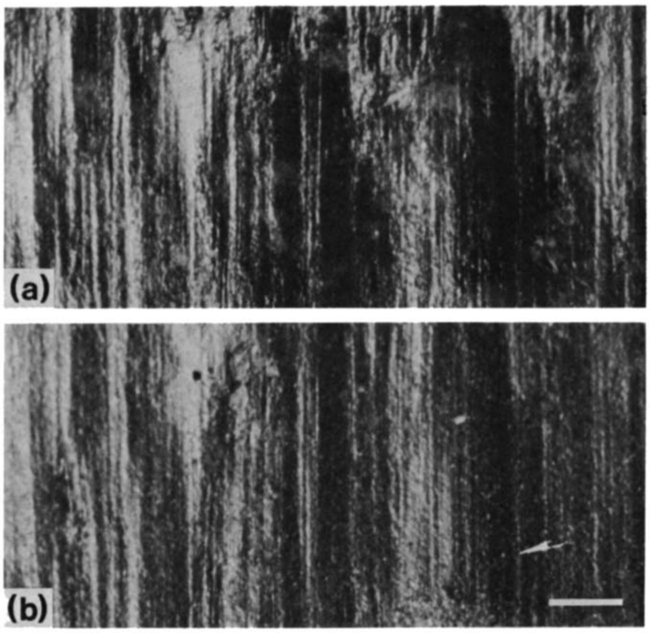

Fig. 3. Nesting of striations on slickensides in wax. (a) Footwall slickenside. (b) Epoxy cast of hangingwall slickenside Equivalence of (a) and (b) demonstrates nesting, as explained in text. Scale bar 1 mm.

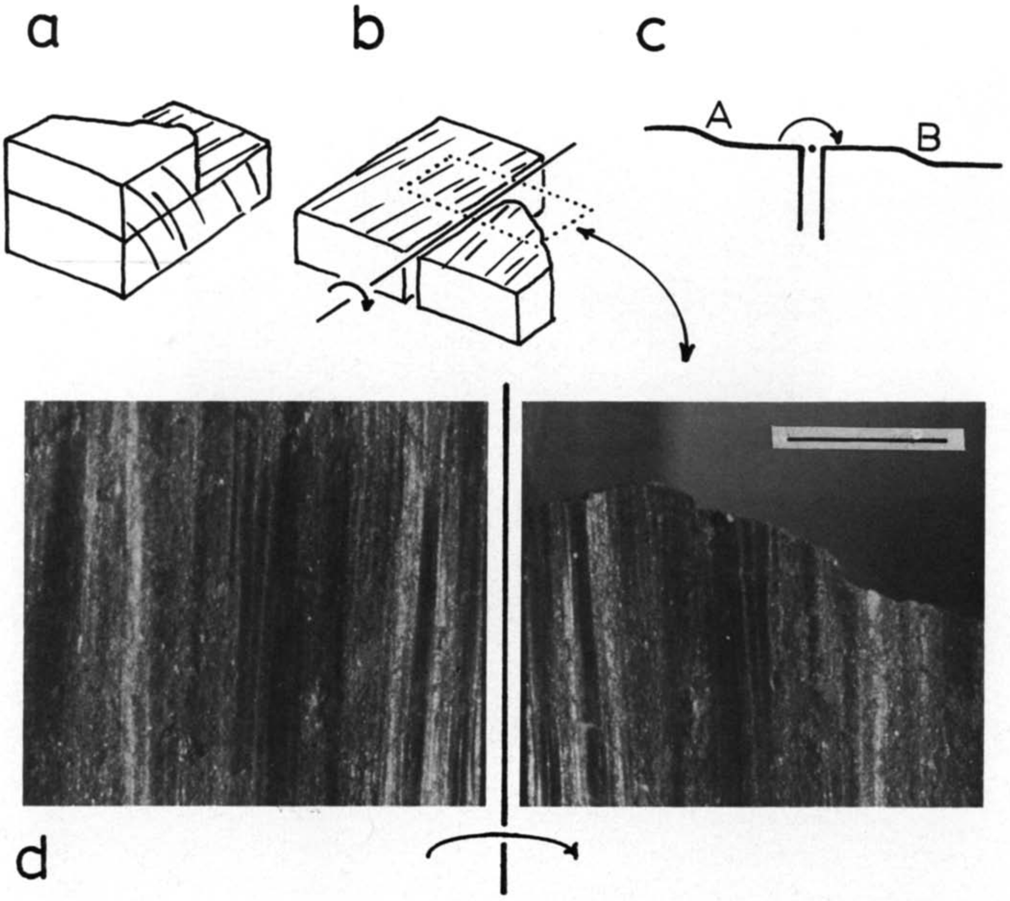

Fig. 6. Nesting of striations on natural slickensides from Latham, New York. (a) Specimen as collected, with sawcut perpendicular to slickensides and approximately parallel to striation. (b) Specimen parted on slickenside and opened like a book. (c) Schematic view in plane normal to axis of opening, showing how features that nest, like surfaces A and B, are parallel and therefore reflect light equally when the fault is opened up as shown. (d) Photograph of slickensides showing mirror symmetry of light and dark stripes across the axis of opening, indicating a high degree of nesting. Scale bar 1 mm. Techniques used here and in Fig. 3 are alternative ways to examine slickensides for nesting.

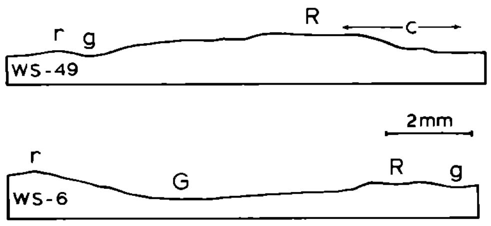

Fig. 4. Striation profiles from two wax specimens, showing shallow U-shaped ridges (R) and groove (G), V-shaped ridges (r) and grooves (g), and a cascade (c). No vertical exaggeration.

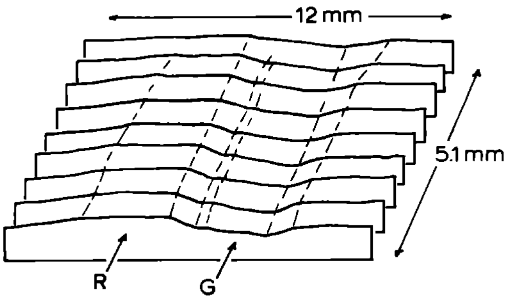

Fig. 5. Profiles normal to striations in shale from Latham, New York, traced from photographs of serial sawcuts, showing a ridge (R) and groove (G). Dashed lines connect main inflection points. No vertical exaggeration.

Fig. 4. These commonly take the form, in profile view, of 'cascades', with the traces of surfaces parallel to the fault as a whole alternating with the traces of surfaces inclined in one direction relative to the fault surface as a whole. Examples of cascades are shown on the right half of the slickenside in Fig. 1(f) and at the right end of profile WS-49 in Fig. 4.

Striations morphologically like the ones in wax are seen in some naturally sheared dark shales and mudstones. Examples are shown in Figs. 5 and 6 of striation profiles and nesting in shale slickensides from Latham, New York. These are black slickensides in black rocks, with no evident quartz or calcite vein material in the plane of the slickensides.

DISCUSSION

The type of slickenside striation described above is new in the sense that it is not readily explained by any of the current ideas about how such features form. It may have been noticed already by many workers, but I know of no published accounts. The most nearly similar feature is represented in a line drawing by Gamond (1985, fig. 33). This shows U-shaped ridges and grooves, similar to those in my Fig. 1(f), but does not indicate whether such features in the footwall nest with similar features in the hangingwall. Hancock & Barka (1987) likewise describe flat-bottomed grooves or 'gutters' on a fault surface, without being able, in the absence of the hangingwall block, to prove or disprove a nesting relationship.

Among the five genetic ideas represented by Fig. 1(a–e), fiber growth and slickolite formation can be ruled out for the wax striations, because clearly no fluid phase is present during deformation of the wax. Debris streaking can also be ruled out, because dark wax turns conspicuously pale-colored when microcracked or comminuted. Excellent striations are often produced across parts of the wax that remain dark and are therefore not microcracked or comminuted. Striation of the erosional sheltering type (Fig. 1c) could produce the observed nesting and subequal development of ridges and grooves, but this process does not account for the observed striation profiles, if one assumes ridge profiles ought to correspond to the profiles of their protector asperities. There is no reason evident why the asperities themselves should have the profiles observed. The same argument can be used against the classic asperity-ploughing model. The observed groove profiles would imply specially shaped asperities, assuming groove profiles mimic those of the 'cutting tool' creating them. Further arguments against asperity ploughing are provided by the nesting of ridges with grooves and the subequal development of ridges and grooves on a given surface. At least in my view of the classical asperity ploughing model, a slickenside striated by asperity ploughing ought to bear grooves, but not ridges of similar area and profile shape between the grooves. Furthermore, grooves produced by classical asperity ploughing should be associated with asperities, or sheared off asperities, at their down-slip ends, not with ridges extending along the entire length of each groove.

To understand the origin of these striations, further experiments are needed to find out how striation properties such as length, nesting and profile shape develop as fault slip accumulates. Also needed are petrographic studies of natural slickensides bearing this type of striation, to establish the microstructure and mineralogy in the slickenside and adjacent host material.

Meanwhile it will be of interest to see whether striations of the newly-recognized type are common in rocks and whether they exist on larger scales than the fine scale observed to date. Field workers with slickensides in their areas may wish to look carefully at the striation types present, bearing in mind that more than one type may coexist on a given slickenside, either because of sequential development under different slip conditions, or because more than one type of striation may develop simultaneously on a given slip surface under a given set of slip conditions. I have noticed, for example, that slickensides with dominant crystal fiber lineation can also bear a lineation that is independent of the fibers, though not necessarily of the type described here. An instance of this may be provided by fig. 13.33 of Ramsay & Huber (1983). Here the dominant linear feature is the fibrous white calcite decorating steps on a slip-surface in limestone, but there also appears to be a second, slip-parallel linear feature on the limestone itself, immediately above many of the calcite patches. This second type of striation, whatever it is, presumably represents slip at an aseismic rate, like the associated, crack–seal, fibrous calcite.

Acknowledgements—This work was supported in part by National Science Foundation Grant EAR 8606961. I thank Paul Hancock for suggesting improvements in review.

REFERENCES

Angelier, J. 1979. Determination of the mean principle directions of stresses for a given fault population. *Tectonophysics* **56**, T17–T26.

Arthaud, F. & Mattauer, M. 1972. Sur l'origine tectonique de certains joints stylolitiques parallèles a la stratification; leur relation avec une phase de distension (exemple du Languedoc). *Bull. Soc. geol. Fr., 7 ser.* **XIV**, 12–17.

Bretz, J. H. 1940. Solution cavities in the Joliet limestone of northeastern Illinois. *J. Geol.* **50**, 675–811.

Durney, D. W. & Ramsay, J. G. 1973. Incremental strains measured by syntectonic crystal growths. In: *Gravity and Tectonics* (edited by DeJong, K. A. and Scholten, R.). John Wiley and Sons, New York, 67–96.

Engelder, J. T. 1974. Microscopic wear grooves on slickensides, indicators of paleoseismicity. *J. geophys. Res.* **79**, 4387–4392.

Fleuty, M. J. 1975. Slickensides and slickenlines. *Geol. Mag.* **112**, 319–322.

Gamond, J.-F. 1983. Displacement features associated with fault zones: a comparison between observed examples and experimental models. *J. Struct. Geol.* **5**, 33–45.

Gamond, J.-F. 1985. Conditions de formation des zones de discontinuités cinématiques dans la croûte supérieure. Aspects expérimentaux et naturels. Unpublished thèse Doctorat, l'Université Scientific et Médicale de Grenoble.

Gray, M. B. 1984. Slickensided soil fractures—indicators of strain and deformation processes in the Bloomsburg formation, central Pennsylvania. *Program, 1984 Annual Meeting, Northeastern Section, Geological Society of America, Providence, Rhode Island* (abstract).

Guiraud, M. & Seguret, M. 1985. Compaction-related soft sediment micro-faulting within the fluvio-deltaic fill of the Soria strike-slip basin (Late Jurassic-Early Cretaceous, N. Spain). *Program, 1985 Conference on Deformation Mechanisms in Sediments and Sedimentary Rocks, University College, London* (abstract).

Hancock, P. L. & Barka, A. A. 1987. Kinematic indicators on active normal faults in western Turkey. *J. Struct. Geol.* **9**, 573–584.

Hills, E. S. 1972. *Elements of Structural Geology* (2nd Edn). John Wiley and Sons, New York.

LaFountain, L. J., Swain, M. V. and Jackson, R. E. 1975. Origin of macroscopic wear grooves generated during frictional sliding experiments. *Int. J. Rock Mech. Mining Sci.* **12**, 367–371.

Mattauer, M. 1973. *Les Déformations des Matériaux de l'Ecorce Terrestre*. Hermann, Paris.

Petit, J.-P., Proust, F. & Tapponier, P. 1983. Critères de sens de mouvement sur les miroirs de failles en roches non calcaires. *Bull. Soc. geol. Fr., 7 ser.* **XXV**, 589–608.

Petit, J-P. & Laville, E. 1985. Morphology and microstructure of hydro-plastic slickensides in sandstone. *Program, 1985 Conference on Deformation Mechanisms in Sediments and Sedimentary Rocks, University College, London* (abstract).

Ramsay, J. G. & Huber, M. I. 1983. *The Techniques of Modern Structural Geology, Vol. 1: Strain Analysis*. Academic Press, London.

Tjia, H. D. 1967. Sense of fault displacements. *Geologie Mijnb.* **46**, 392–396.