NATURE AND EVOLUTION OF SUBHORIZONTAL CRENULATION CLEAVAGE IN THE TYPE ARAVALLI ROCKS AROUND UDAIPUR, RAJASTHAN

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A set of crenulation cleavage subparallel to the axial planes of small- and intermediate-scale recumbent folds (representing the third phase of deformation, F_3) has developed quite extensively in the early Precambrian (Aravalli) phyllitic rocks and metagreywacke units around Udaipur in southern Rajasthan (western India). These are unevenly spaced planar discontinuities which separate thin slices of plicated rocks (microlithons) of variable thickness. The crenulation cleavage planes deviate from being parallel to the axial planes of fold in passing from one bed to another of different competency, within a single bed of gradational lithologic character (e.g. metagreywacke with graded beds), and at the contact of folds in competent units. Generally, crenulation cleavage appears as mica-chlorite-rich domains bounded by surfaces parallel to the axial planes of microfolds. The domains develop across the sharply bent limbs of asymmetric microfolds. The other morphological forms include those defined by parallelism of layer silicates and trails of magnetite or graphite along axial planes and straight limbs of tight chevron folds, and those appearing as clean-cut faults.

The crenulation cleavage planes indicate directions of maximum finite extension; and upto 43 per cent shortening has been noted in the folds in quartz veins which are oriented normal to the cleavage planes in phyllite. The shortening of the rock column initially leads to the formation of symmetrical open folds (F_3) which, with further tightening accompanied by layer-parallel shear, become asymmetrical. Removal of quartz, leading to the development of mica-chlorite-rich domains across the sharply bent shorter limbs of these asymmetric folds, starts when these limbs make an angle of less than 40° with the direction of maximum finite extension. The shorter limbs ultimately become flattened parallel to the length of the domains of concentrated layer silicates. Metamorphism ushers in late and outlasts the deformation. The subhorizontal crenulation cleavage planes, parallel to the axial planes of recumbent folds, are believed to have developed because of flattening in response to excessive vertical stresses resulting from the weight of steeply dipping layered complex.

INTRODUCTION

A set of quasi-horizontal crenulation cleavage has developed quite liberally, over a large region in the type Aravalli rocks around Udaipur (lat. 24°35′ N: long. 73°41′ E) in southern Rajasthan. The Aravalli rocks here are represented by feldspathic metagreywacke grading to phyllite and micaschist, crystalline limestone including metamorphosed calc-arenites, and quartzites. Crawford (1970) suggested that these rocks are between 2,500 and 2,000 m.y. old.

Recent studies around Udaipur have served to emphasize a complex architecture of these early Precambrian rocks resulting from the impress of three distinct periods of folding (Roy *et al.* 1971; Roy 1972). The earliest folding movement (F_1) produced extremely compressed isoclines with attenuated hinges. The second folding movement (F_2) refolded the F_1 folds to open, tight or even isoclinal folds with veritcal or steeply inclined axial planes striking approximately north-south. The latest deformation (F_3) produced small- and intermediate-scale folds and crenulations with subhorizontal axial planes on the limbs of larger earlier folds. Corresponding to these phases of deformation at least three cleavage structures have developed in the rocks of this region, of which the earliest is of slaty cleavage type and the later ones are crenulation cleavages (*compare* Ramsay 1967, p. 180). The discussion in this paper is limited to the type of crenulation cleavage associated with F_3 crenulations and folds with subhorizontal axial planes (Pl. III, Figs. 1, 2).

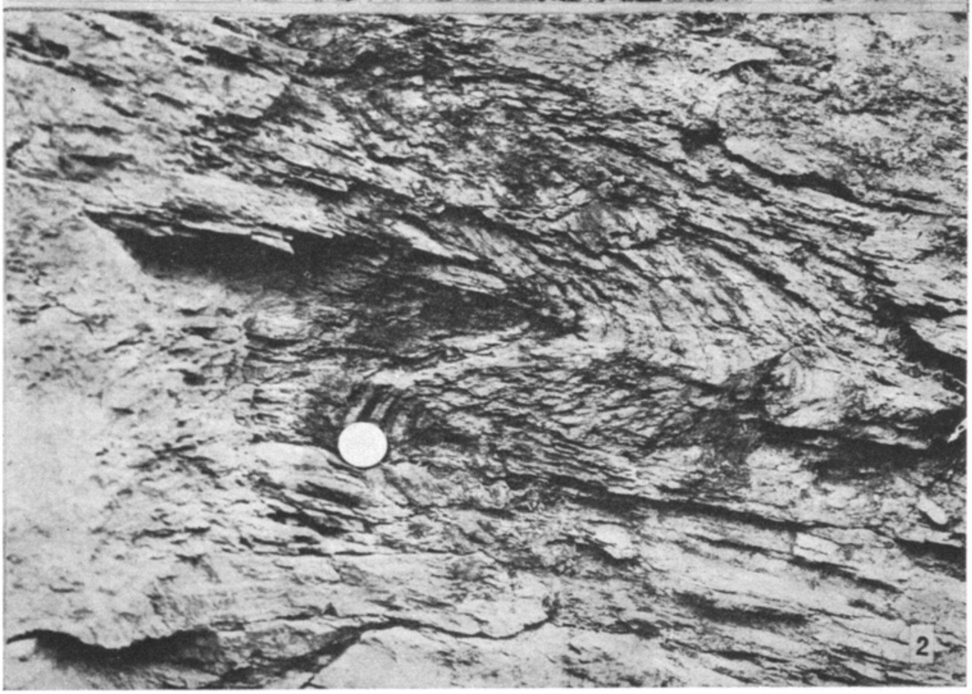
Field Description of Crenulation Cleavage

In hand-specimens and in outcrops, crenulation cleavage appears as glossy surfaces, smeared with micas and chlorite, which enclose plicated rock slivers of variable thickness (less than a millimeter to several centimeters). The planes are usually subparallel to each other, but they do not, as a rule, run for long distance. Where uniformly well-developed, their spacing seems to be dependent on the grain size and composition of the rock. Thus, a fine grained phyllite cleaves into thin laminates, a millimeter or less in thickness, whereas quartzose phyllite or metagreywacke forms thicker slabs three to five centimeters thick.

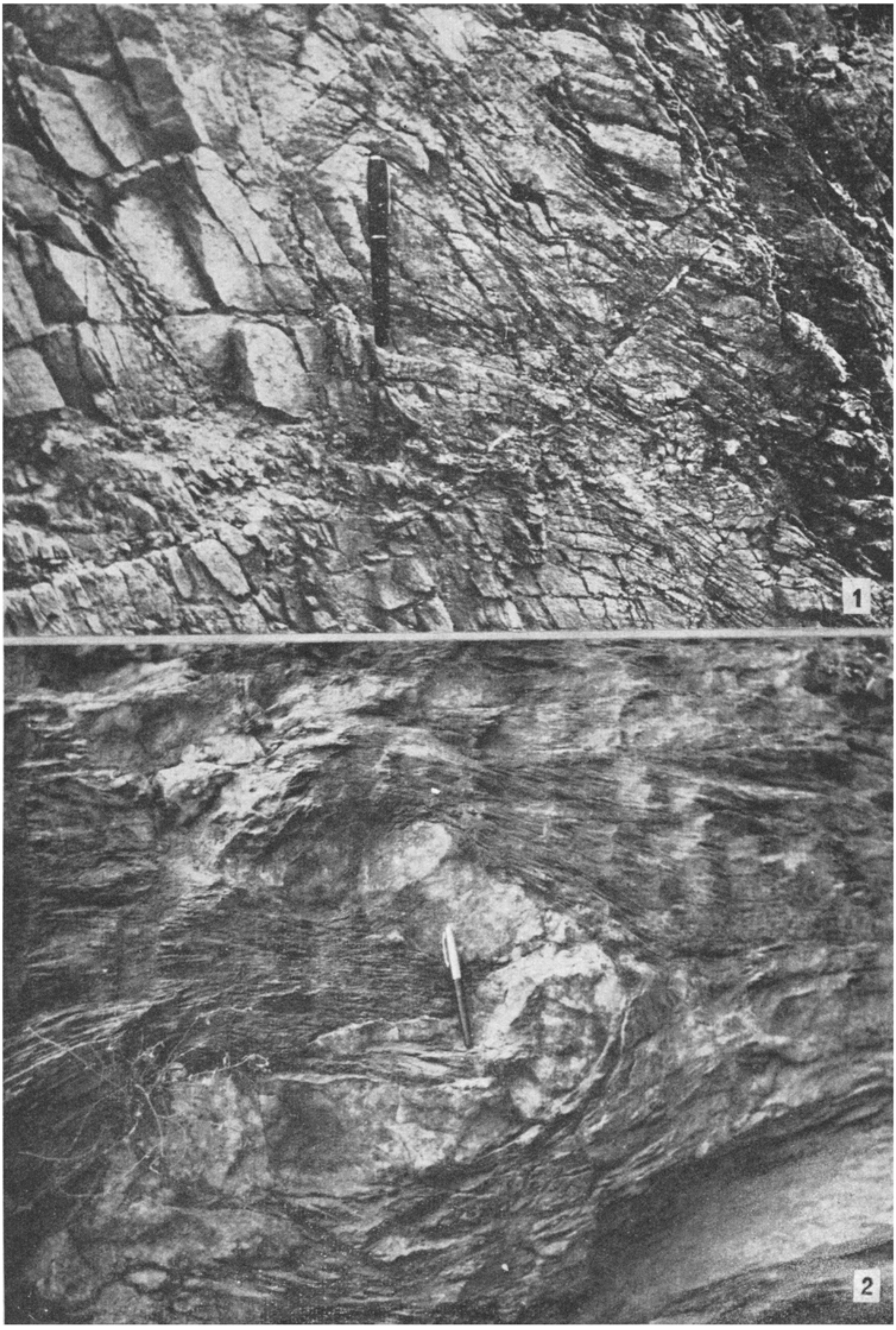
Crenulation cleavage is planar and uniform in rocks of more or less homogeneous lithologic composition. Change in the orientation of the cleavage resulting in refraction, occurs where phyllitic rocks alternate with metagreywacke. Where the alternate layers are thin, the angle between crenulation cleavage and bedding plane is always higher in competent psammitic layers than that in incompetent pelitic layers. Curved crenulation cleavage planes have formed in the graded units in metagreywacke. The microlithons bounded by successive curved cleavage planes in these rocks, closely resemble foreset beds in cross-laminated sedimentary strata (Pl. IV, Fig 1; *compare* Wilson 1946, p. 279; and Ramsay 1967, p. 405).

Change in the orientation of crenulation cleavage even in a single lithologic unit has been observed near the contact of fold hinges of competent rocks. This feature is conspicuous in certain sections where phyllite beds enclose folded veins of quartz (Pl. IV, Fig 2). The crenulation cleavages in phyllites in the concave core of the fold are more closely spaced and uniformly developed than away from it, resulting in wedging of microlithons, whereas on the convex side, the crenulation cleavage planes are almost normal to the vein boundary just near the hinge zone. Away from the hinge zone the planes wisp around the fold and become subparallel to the limbs. There is, however, a "shadow" zone immediately at the contact of the quartz vein on the convex side, where no new cleavage has formed.

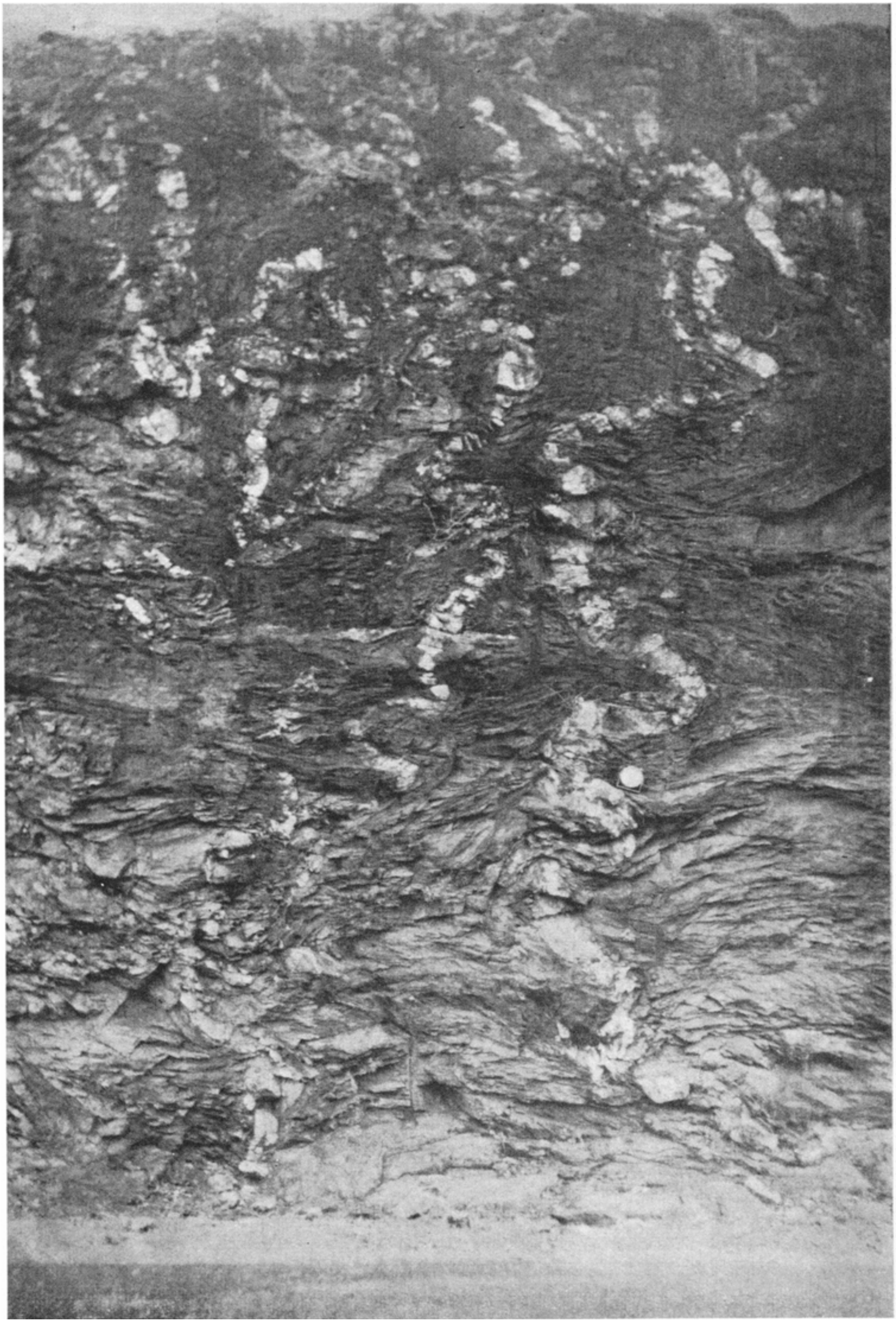
The folds on competent layers associated with subhorizontal crenulation cleavage show variable shapes on the profile planes, but their geometry is almost universally concentric. A few, however, appear to have been slightly flattened. Some of



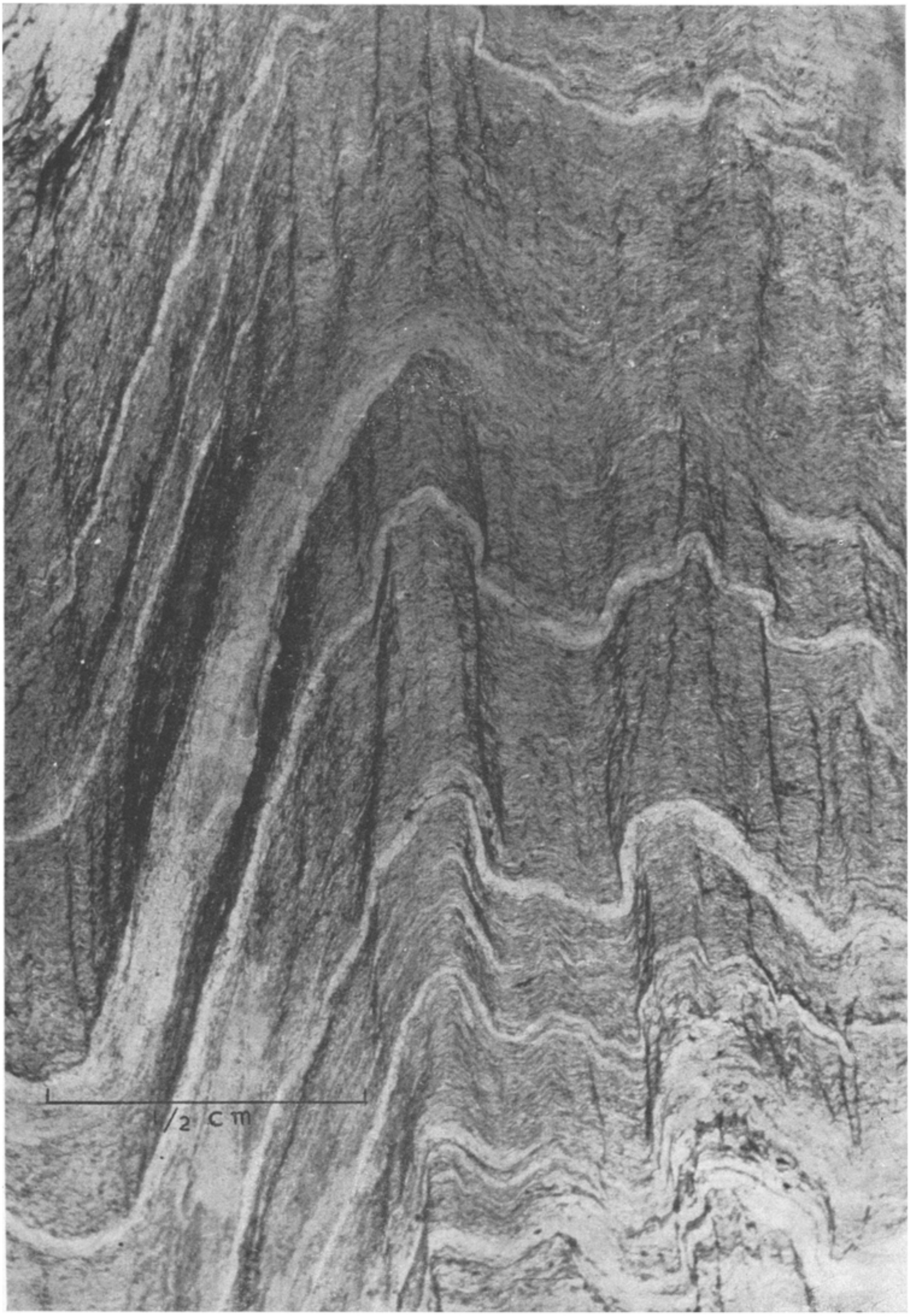
FIGS. 1, 2. Development of crenulation cleavage parallel to axial planes of recumbent folds.



FIGS. 1, 2. 1, Curved crenulation cleavage in graded-bedded metagreywacke. The cleavages show refraction in passing from metagreywacke to phyllite; 2, Changes in the orientation of crenulation cleavage at the contact of a folded quartz vein.



Concentrically folded quartz veins in phyllite showing 40–42% buckle shortening.



Crenulation cleavage appearing as dark lines and zones parallel to the axial planes of microfolds.

the concentrically folded quartz veins in phyllites (Pl. V) having almost uniform layer thickness indicate 40–42 per cent buckle shortening.

Microscopic Study of Crenulation Cleavage

In thin sections crenulation cleavage appears as dark lines subparallel to the axial planes of microfolds (Pl. VI). Their development is restricted to the bands composed mainly of layer silicates. In rocks of alternate lithology of contrasted types, crenulation cleavage appears as discontinuous lines, terminating abruptly at the contact of competent layers composed of granular minerals, mainly quartz (Pl. VII, Fig. 1). Even within layer silicate bands the cleavage planes are only statistically parallel, the details however show dying out and branching of planes.

The stages of deformation leading to the formation of crenulation cleavage can be studied in rocks which show all variations between slightly crenulated schistosity to well-developed crenulation cleavage. The first stage in the development of cleavage is the formation of microcrenulations with low amplitude/wave length ratio. Initially the crenulations are in the form of symmetrical open folds (Pl. VII, Fig. 2). As the microfolds tighten up, the new cleavage planes make their first appearance as incipiently developed mica-chlorite-rich domains parallel to axial planes of microfolds. These mica-chlorite-rich domains (differentiated crenulated cleavage of Williams 1972) have variable width from less than 0.2 mm to over one mm. Initially the individual flakes of mica and chlorite remain askew to the length of the domain (Pl. VIII; *compare* Rickard 1961). The angle between them is sometimes as high as 35° or even more. With progressive tightening of the folds the flakes become oriented parallel to the new cleavage direction.

The differentiated crenulation cleavage described above is the principal morphological form of axial plane cleavage associated with F_3 microfolds in Udaipur area. The two other morphological types are sometimes seen in thin sections. In one of these types, the crenulation cleavage is defined by parallelism of layer silicates and trails of granular dark minerals (magnetite or graphite) along the axial planes and straight limbs of tight chevron folds. The crenulation cleavage of this type appear near the hinges of folds on competent beds. In the third type the cleavages coincide with planes of clean-cut faulting displacing the contacts of different lithologic layers usually into a series of steps (Pl. IX).

Evolution of Crenulation Cleavage

The most important point that emerges from the description of crenulation cleavage is that there is a strict geometric relationship between the cleavage and F_3 folds. This evidently favours a close genetic connection also. The geometric characteristics of F_3 folds and the style of cleavage in different parts of folds, particularly in mutilayers of different competency and thickness, can be explained satisfactorily by assuming variable states of strain in different parts of folds during buckling of the layers (Ramsay 1967; Ramberg and Ghosh 1968).

The crenulation cleavage planes indicate directions perpendicular to the maximum finite shortening. This relationship has been brought out clearly, where large number of buckle-folded quartz veins of unlike orientation cross crenulation cleavage planes (Text Fig. 1). The different veins show systematic variation in the degree of folding depending on their orientation with respect to the cleavage planes (*compare* Ramberg and Ghosh 1968). The veins which are at high angles to the cleavage show maximum degree of folding (up to 43 per cent shortening in veins almost normal to the cleavage direction). Those which are subparallel to the cleavage are straight and show pinch-and-swell structures.

The microscopic studies have shown that crenulation cleavage appears as domains of concentrated layer silicates bounded by planes parallel to the axial planes of microfolds. The domains develop across sharply bent shorter limbs of asymmetric microfolds. The deformation stages leading to their development can be outlined as follows :

(1) Shortening of rock column parallel to early cleavage, resulting in the formation of symmetrical open folds;

(2) Tightening of the folds due to continued shortening and development of asymmetric folds due to layer parallel shear;

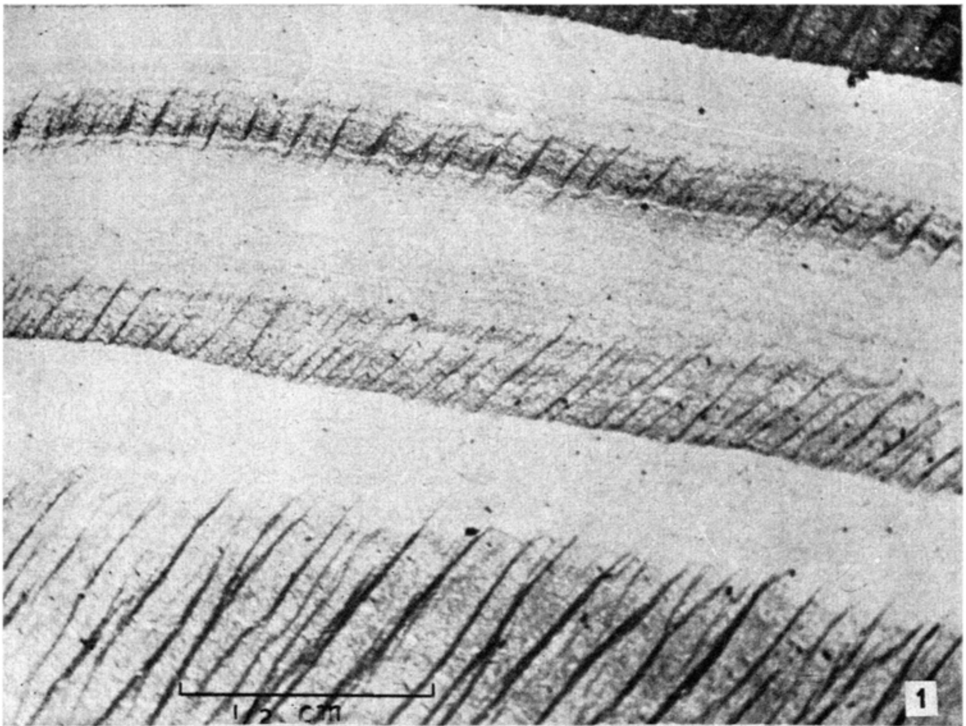
(3) Development of domains of concentrated layer silicates, bounded by planes parallel to the axial planes of microfolds, across sharply bent shorter limbs of asymmetric folds; and

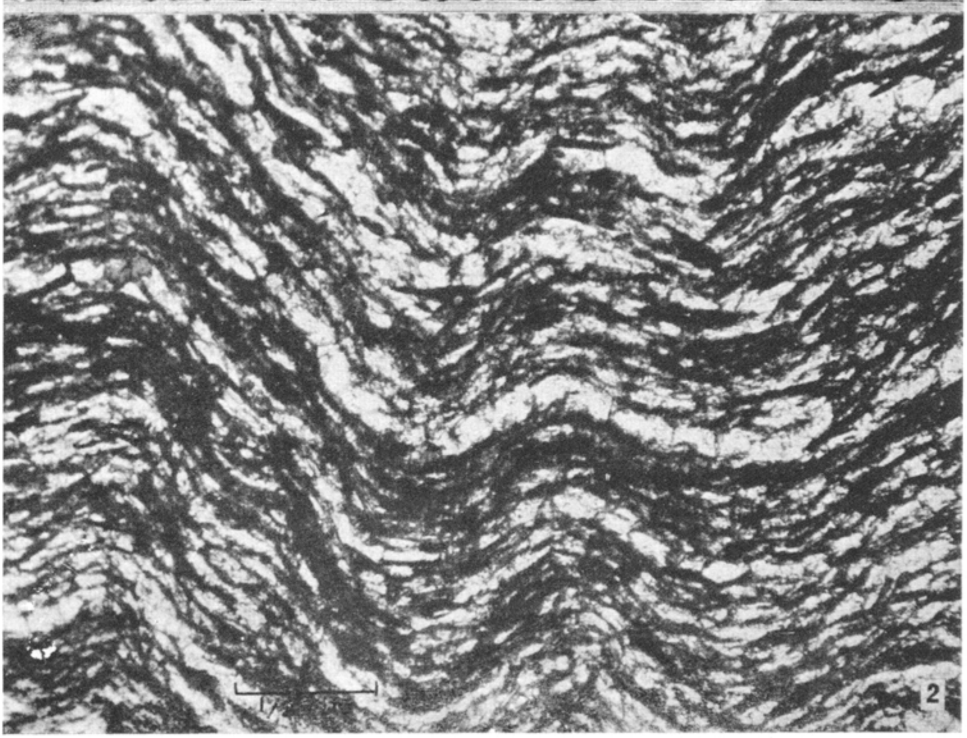
(4) Flattening of the shorter limbs of microfolds parallel to the length of the domains and recrystallization leading to the development of zones of concentrated layer silicates cutting across earlier cleavage structures.

Metamorphism, however, ushers in late in the stage and in all probability outlasts the deformation. Thus, alongwith the development of zones rich in mica and chlorite, mimetic recrystallization of the layer silicate minerals defining earlier cleavage structures, results in the formation of polygonal arches between successive new cleavage structures.

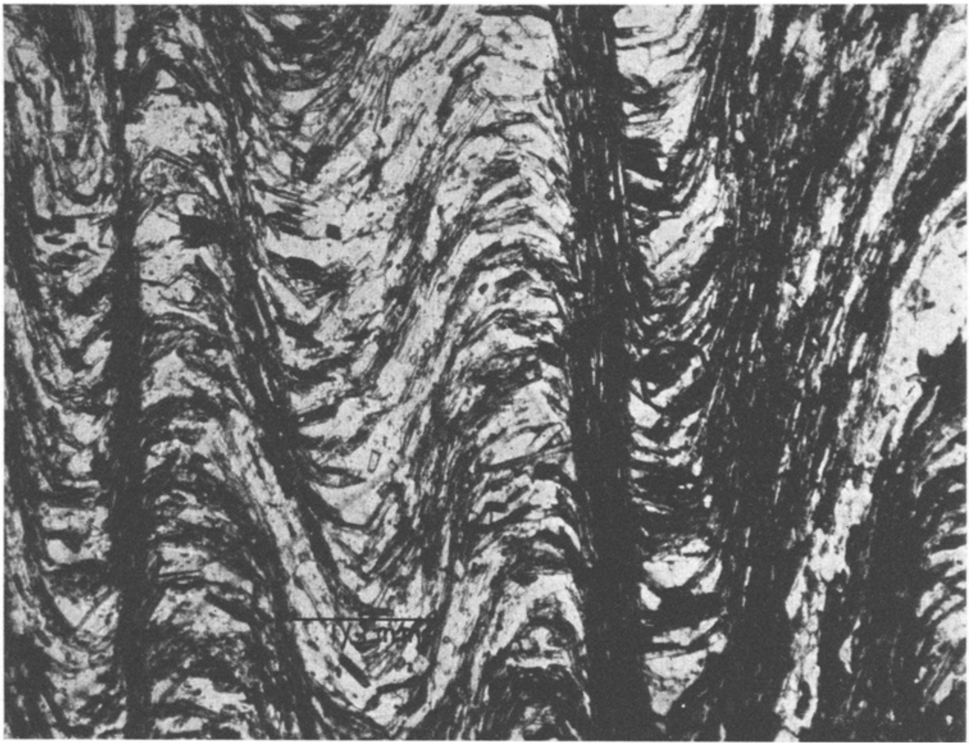
The factors which control the formation of mica-chlorite-rich domains are thus : (1) the mechanical rotation of the layer silicates to subparallelism with the axial planes of microfolds, and (2) the selective removal of quartz. The problem of removal of quartz from certain limbs to form mica-rich domains has been discussed at length by Williams (1972), who suggested that mica-rich domains involve selective solution of quartz by fluid migrating along movement zones. It is possible that a chemical gradient is set up for the removal of quartz when any one of the two limbs of microfolds comes in the quadrant of extension during rotational strain. Measurements show that this process starts when the limbs make an angle of less than 40° with the direction of maximum finite extension.

The development of crenulation cleavage does not change the shapes of associated folds. There is also little evidence of any decipherable slip along most of these planes. A limited amount of slip might have taken place where the cleavage planes coincide with thin kink bands. In rare instances, crenulation cleavage planes develop into clean-cut microfaults displacing marker beds (Pl. IX). The microfaults are not always strictly parallel to the cleavage planes but are at low angles to them, and are often marked by concentration of micas and chlorites. The displacements along the faults are not uniform, but the component of movement has in all





FIGS. 1, 2. 1, Development of crenulation cleavage in bands composed mainly of layer silicates: The cleavage planes show irregularities such as abrupt termination and branching; 2, Development of microcrenulations as symmetrical open folds in phyllites.



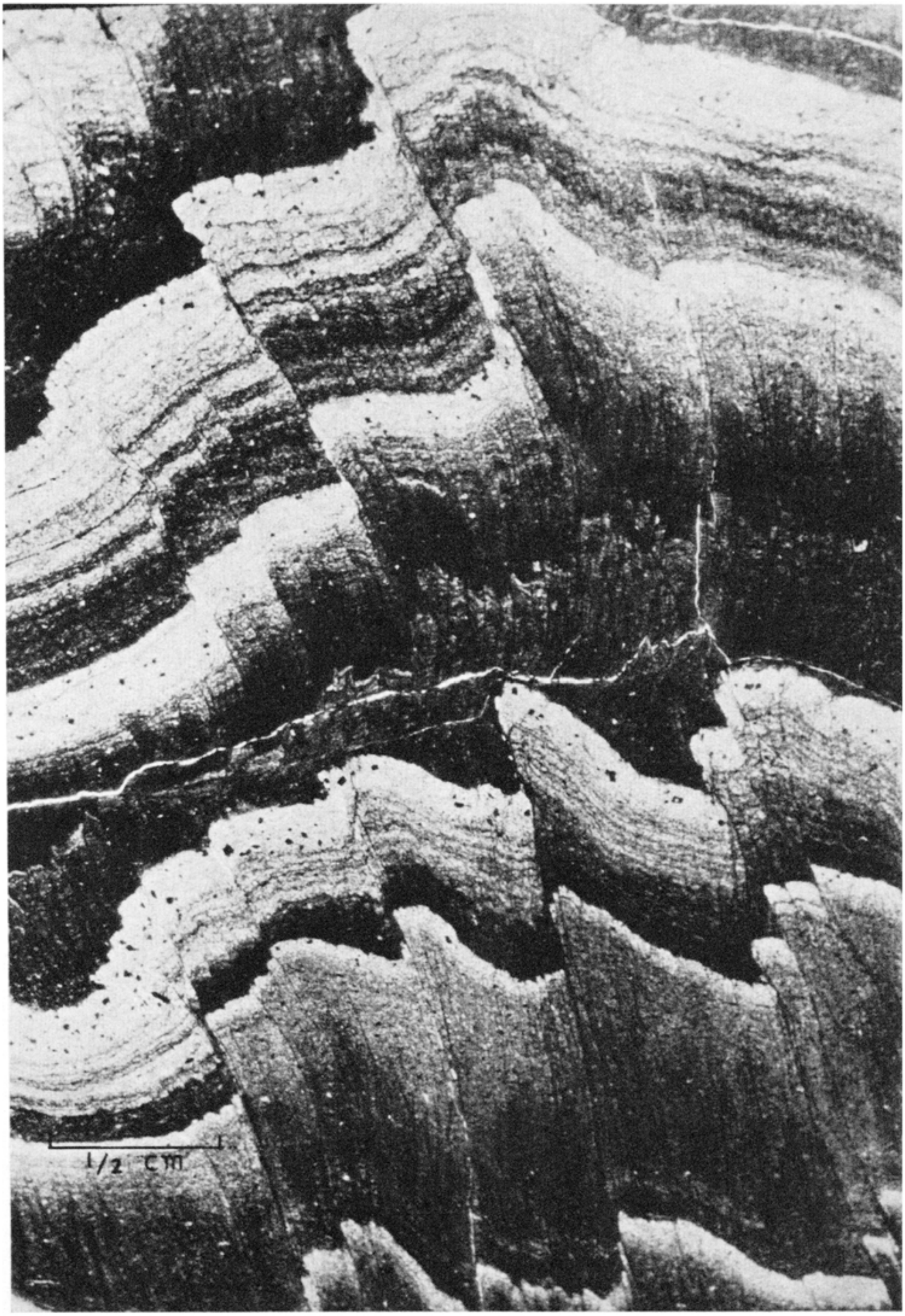
Stages of development of crenulation cleavage in different zones.

probability a same sense. Noticeable slip can also be seen along the crenulation cleavage planes at the contact of fault planes.

TECTONIC IMPLICATIONS OF SUBHORIZONTAL CRENULATION CLEAVAGE

The subhorizontal crenulation cleavage along the axial planes of a set of small- and intermediate-scale recumbent folds is a common feature in the rocks around Udaipur, Rajasthan. The present analysis implies that these crenulation cleavage planes are the result of compressive strain in the vertical direction subparallel to the layering.

The geometry of the earliest folds (F_1) is indeterminate to a great extent, yet it is thought that these were initially in the form of overturned to recumbent folds with approximately east-west axial trend (Roy *et al.* 1971; Roy 1972). The second deformation (F_2) refolded them to form upright folds with north-south axial trend. The F_2 folds, with continued deformation, became close to tight sometimes even isoclinal, resulting in the subvertical positions of beds and schistosity subparallel to them. The stresses responsible for the formation of the recumbent folds (F_3) on the limbs of upright folds (Pl. V) were in all probability vertically directed, which implies that the gravity was the main motive force in their formation. The



Clean-cut faulting along crenulation cleavage planes displacing the beds of different lithology.

TEXT FIG. 1. Variations in the degree of folding in buckle-folded quartz veins of unlike orientations.

crenulation cleavage planes probably developed owing to flattening in response to excessive vertical stresses resulting from the weight of steeply dipping layered complex. The other possibility is that these subhorizontal cleavages and recumbent folds have been formed due to simple shear down an inclined plane (*compare* Ramberg and Ghosh 1968).

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