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A study of deformation phases in slates of Manki Formation, Eastern Attock-Cherat Range, Pakistan

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Abstract

The Manki slates constitute the bulk of the Manki Formation. Its thickness has variously been quoted to be in excess of several kilometers in various parts of the Attock-Cherat Range. Many workers while characterizing the Manki slates attribute its extra-ordinary thickness to multiple folding events. However, there is no structural evidence to support this assumption.

Pelitic rocks tend to cleave as they shorten (a folding precursor). The Manki slates exhibit exceptionally good exposures of cleavage development. This paper summarize the results of a study that measured, analyzed and interpreted more than 1000 cleavage and associated bedding orientations from with in the Manki slates. Our analysis recognized five distinct phases of folding through D_1 to D_5 deformation events. As such this paper provides first ever structural evidence to explain the extra-ordinary thickness of the Manki slates through multiple folding events.

Keywords: Manki Formation; Attock-Cherat Range; deformation phases; bedding-cleavage angle; slates

1. Introduction

The geometric and genetic relationship between cleavages and folding has long been recognized (Sedgewick, 1835; Darwin, 1846; Rogers, 1856). This relationship in the form of axial plane parallel feature is more pronounced in low grade metamorphic rocks e.g. slates. Some deviation from this axial plane parallel behavior has also been noted by several authors (e.g. Ramsay, 1967; Powell, 1974; Phillips et al., 1979). Geometric relationship between cleavage and folds remain a strong indicator of deformation and thus recognition of multiple phases of cleavage formation indicates multiple phases of folding (i.e. deformation).

The Attock-Cherat Range, which borders the Peshawar Basin on the south exposes more than 5km thick sequence of low-grade metamorphic slates of the Precambrian Manki Formation (Fig. 1). The apparent thickness of the slates of the Manki Formation seems much exaggerated. To explain the extraordinary thickness of the Manki slates, most workers (Tahirkheli, 1970; Calkins et al., 1975; Hussain, 1984; Raynolds and Johnson, 1985; Hussain et al., 1990; Hylland et al., 1988; Yeats and Hussain, 1987, 1989; Riaz et al., 1991) conveniently assume multiple episodes of folding with in these argillites. However, to our knowledge this assumption is not supported by any structural evidence. The present study was initiated with a view to either augment the above assumption with structural evidence or provide an alternate explanation. Accordingly we measured more than 1000 cleavage and bedding orientations within a portion of the Manki slates to assess multiple folding phenomenon through geometrical relationships.

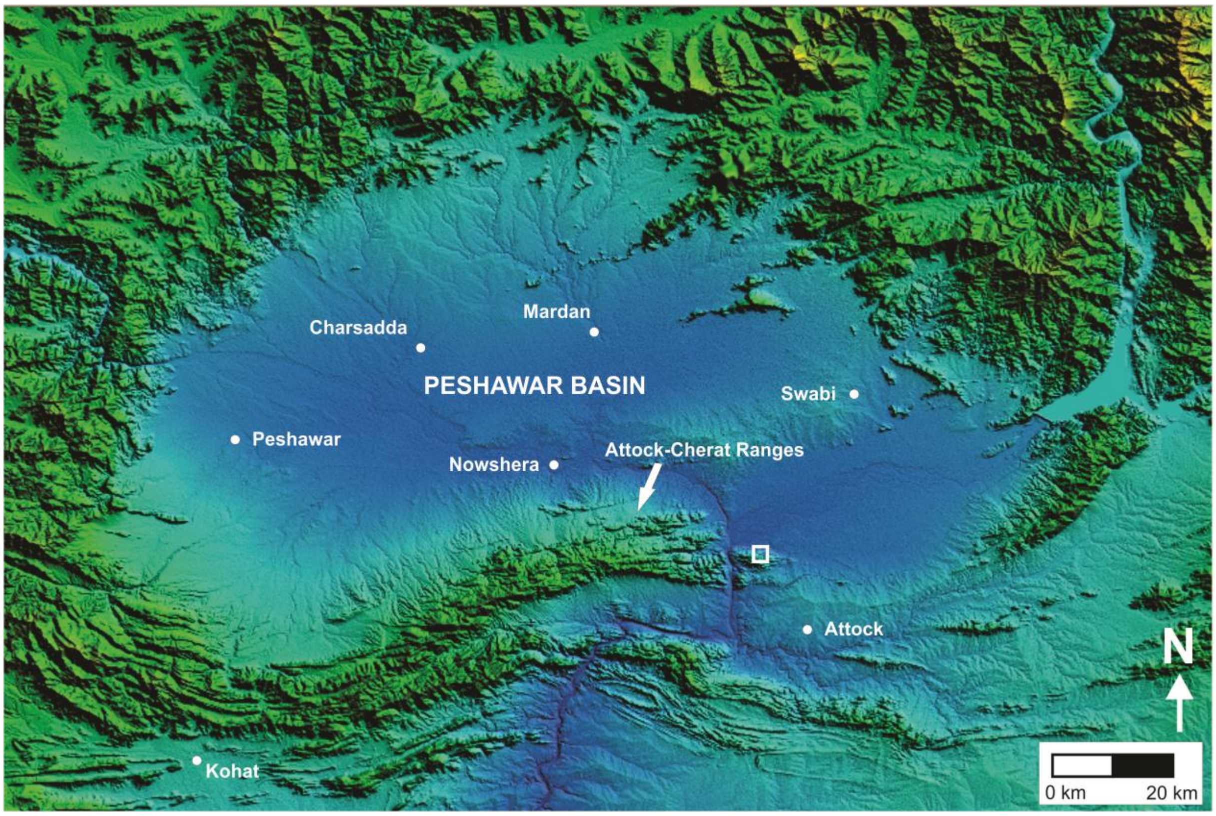

Fig. 1. Location map of Attock-Cherat Range with study area (white rectangle) plotted on SRTM DEM file.

2. Geology of Attock Cherat Range

Attock-Cherat Range (ACR) borders the Peshawar Basin on the south (Fig. 1). The western end of ACR merges into Kohat mountains near Darra Adam Khel tribal territory while the eastern end terminates in the Peshawar Basin, west of Kamra.

The ACR is divided into three tectonic units (Yeats and Hussain, 1987) separated by two major thrust faults: the Khairabad fault to the north and the Hissartang fault to the south. The northern and central tectonic units predominantly comprise of argillaceous rocks belonging to Manki and Dakhner Formations. The southern tectonic unit is composed of Paleozoic and Mesozoic carbonates and arenaceous rocks.

The Manki Formation constitutes the thickest stratigraphical unit in the metasedimentary suite. It is composed of slate, phyllitic slate and phyllite with subordinate lenticular limestone. The sandy and gritty bands are note worthy throughout the formation. A strongly developed slaty cleavage is prominent near Manki, Ziarat Kaka Sahib, Attock, Khairabad and on the left bank of Indus River. Ripple marks are locally observed which are usually present in sandy bands. Some small scale cross bedding and graded bedding is also present in sandy beds. Manganese dendrites, conchoidal fractures and pyrite cubes are also present in abundance in lower portions of the Formation.

Bedding-cleavage intersection produces the conspicuous pencil-cleavage and may locally form rectangular chips. At places variation in lithological composition of the slates make the cleavage refraction. The weathered surfaces of the Manki slates exhibit grey, greenish grey and brownish grey colors and light grey or light greenish grey colors on the fresh faces.

Limestone of the Manki Formation occurs as pockets and lenses. The exposures of Manki slates in the northern portion of the ACR show a higher proportion of quartz veining.

3. Structural data

Our structural data sets include recognition and documentation of 249 bedding orientations in addition to other primary structures e.g. grading and syn-depositional folding. Similarly we recorded a total of 756 cleavage orientations along with other secondary structures like folds, faults, joints and fractures.

Cleavage is present throughout the area in great abundance and occurs in a variety of orientations, while bedding is not clearly recognizable in all places. Bedding is clear in sandy portions of the outcrops and is difficult to recognize in clay-rich portions of Manki slates. However, at places bedding is exceptionally clear (Fig. 2) with exceptionally good recognizable sedimentary features. Such features include syn-sedimentary folding, graded bedding etc. On the other hand cleavages are easily recognizable in the whole area due to their pervasive occurrence and fissile nature. The clear-cut relationship between cleavages and bedding surfaces was also documented from several localities. The more than 756 cleavages and about 249 bedding plane orientations were collected from 24 different stations along a NE-SW traverse, starting from GT road near Mansar Camp and ending at about 3 km south of the road (Fig. 3).

This data was subsequently sorted and plotted on Stereonet using Stereoplot software of Rick Allmendinger (Dept. of Earth & Atmospheric Sciences, Cornell University, New York) for further analysis.

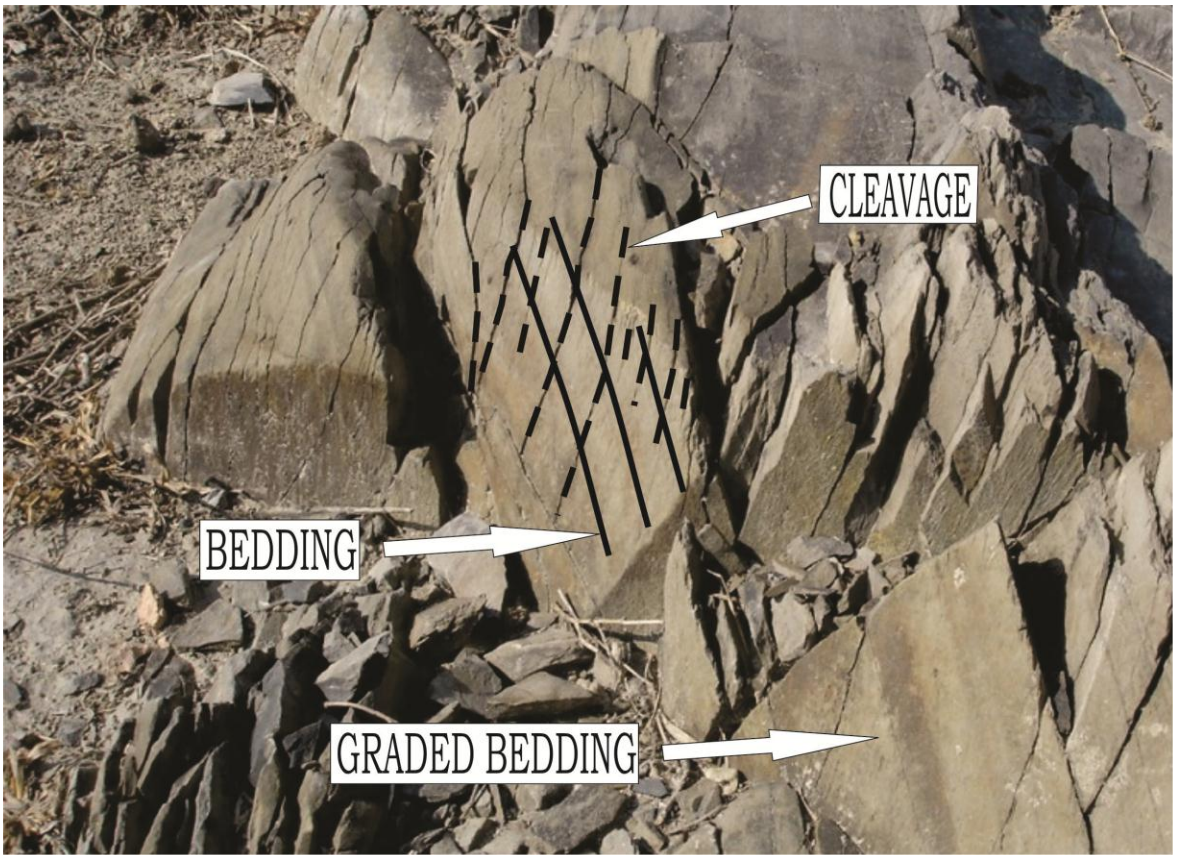

Fig. 2. Manki slate exhibiting strong cleavages that cross-cut the bedding planes. Graded bedding is shown by alternating light & dark bands.

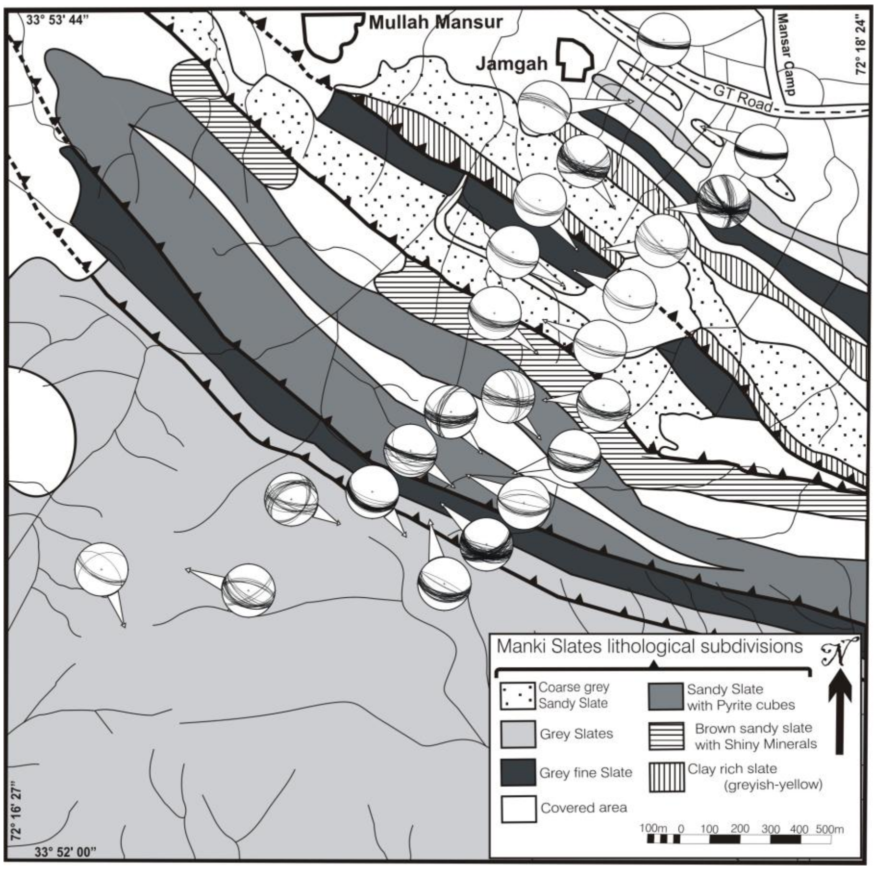

Fig. 3. Geological map of the study area with beach ball plots of all cleavages as recorded at respective stations.

4. Data Analysis and Deformation Phases

Geological deformation events are characterized by shortening and flattening. Cleavages are formed in response to shortening and flattening (Sorby, 1856; Flinn, 1962; Donath & Parker, 1964) and preferentially develop in folded rocks. Geometric relationship between the orientation(s) of cleavage surfaces and the configuration of folded beds makes them interesting and important in structural studies (e.g. Sintubin et al., 1998). The cleavage surfaces lie in the S_1S_2 plane of the strain ellipsoid perpendicular to the direction of minimum finite stretch (S_3) (Ramsay 1967). In most cases cleavage surfaces are parallel to axial surface of a fold. However, they are arranged symmetrically about the axial surface in a fan of orientations if there is a strong mechanical competence contrast between successive beds. In either case, the cleavage surfaces do contain an axial plane cleavage. In an upright fold, cleavages are everywhere steeper than the inclination of bedding. While in overturned folds, cleavage can dip less steeply than bedding. This information is used to determine the "younging" direction of bedding (Bell, 1981). The same information is also used to figure out the 'facing' of beds, and to construct the configuration of folds in profile view.

To determine deformation phases, we needed to establish the number of folding events by statistically sorting the entire data set in subsets or domains. In the first step of sorting we discarded all those cleavage orientations that were clearly part of a refraction fan and preserved only those that were penetrative on the scale of the outcrop. This assured that the preserved cleavages are more or less axial plane parallel. In the second step cleavages were separated into small groups such that each group would contain a concentration cluster of cleavages effectively making a distinct domain. This sorting of the cleavage data yielded eight different domain concentrations (Fig.4a-h)

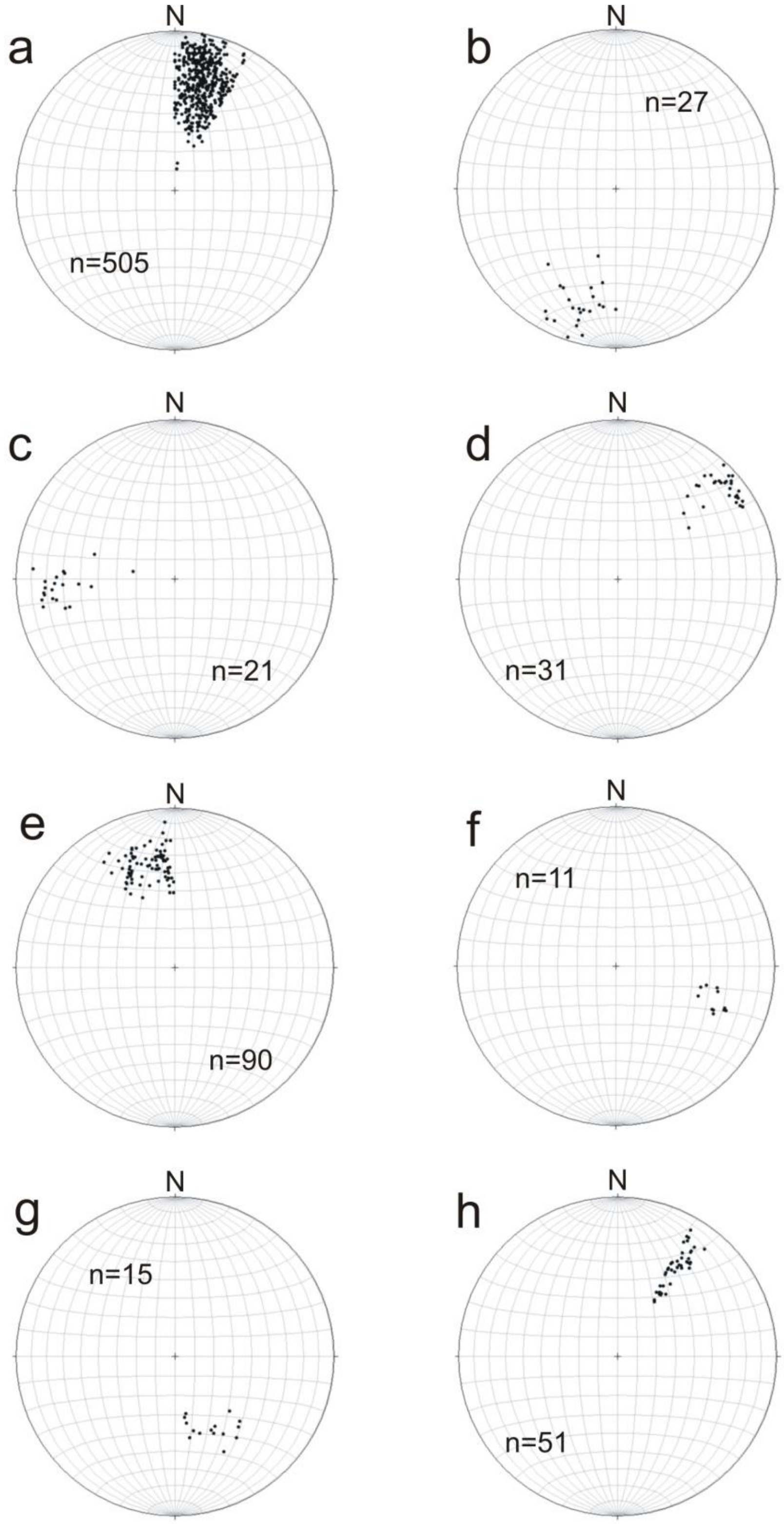

Fig. 4. Clusters of cleavages into domains after second-step sorting of raw data. a-h represent the resultant domains (see text for explanation).

4.1. Cleavage Domain 1

This domain is widely present and is well preserved throughout the area. This domain is comprised of 505 cleavage orientations (Fig. 4a). The general strike orientation of the cleavages with in this domain ranges from N60ºW to N70ºW with steep dips towards south and southwest. The dip angle averages between 70º to 80º. This domain of cleavages seems to be younger in age as it cross cuts all the other domains and is very prominent.

4.2. *Cleavage Domain 2*

This domain has almost the same strike as that of the domain 1 but it dips towards north rather than south. It has 27 cleavage orientations (Fig. 4b) as measured in the field. The average dip angle for cleavages of this domain is 65º to 75º.

4.3. Cleavage Domain 3

This domain is not well preserved in the area and has the general strike ranging from NS to N10ºW and has dip angle of 60º to 80º towards east (Fig. 4c). There are 21 cleavage orientations with in this domain that have been recorded in the field.

4.4. Cleavage Domain 4

This domain has strike ranging from N30ºW to N50ºW and dips towards south-west with angles from 75º to 85º (fig. 4d). There are 31 data points in this domain that have been recorded in the field.

4.5. Cleavage Domain 5

This domain is distributed throughout the area. It has general strike ranging from N70ºE to N85ºE and dips with angle from 45º to 65º towards SSE (Fig. 4e). The domain contains 90 data points that have been documented from field observation.

4.6. Cleavage Domain 6

This domain of cleavages is not well developed in the area and consists of strikes from N10ºE to N20ºE and has very shallow dip angles (Fig. 4f) compared to all other domains. It dips with angles ranging from 40º to 50º towards north-west. A total of 11 data points have been recorded in the field that belong to this domain.

4.7. Cleavage Domain 7

This domain contains cleavages ranging in strike from N60°E to N75°E and dips with angles ranging from 40° to 50° towards NNW (Fig. 4g). A total of 15 data points were recorded in the field that belonged to this domain.

4.8. Cleavage Domain 8

This domain of cleavages have general strike of N50°W to N60°W. This domain has very little variation in strike of cleavages but it shows great degree of variation in the amounts of dips, i.e. dip of this domain ranges from almost vertical to 10° towards SW (Fig. 4h). But majority of cleavages belonging to this domain dip at 40° to 75°. There are 51 data points recorded in the field that belong to this domain.

The above eight domains were sorted again in a way that two domains of more or less similar strike orientation but opposite dip direction were grouped into one set and plotted together on the stereonet. This was based on the assumption that cleavages in folded and mechanically contrasted rocks tend to form in a fan structure that converge into the axial plane of the associated fold. Thus the cleavage strike orientations would be more or less same across the axial plane but with opposite dip directions. This sorting generated sets of cleavages that loosely defined an axial plane and thus a folding event. However, not all domains were matched. This "domains matching" gave three distinct axial planes (thus distinct folding events) and two domains remained unmatched. In case of the unmatched domain, the field evidence (these cleavages were recorded on lithologies that were not repetitive with in the area) indicated that they may be part of some regional scale folding event that may not be represented by the outcrop scale structures found in this area. Thus, the three matched and two independent sets defined five folding events (Fig. 5a-e). This is supported by the field evidence that majority of cleavage and bedding orientations within same layers are not inclined in the same direction indicating refolding or multiple folding. Similarly the field evidence that some of the cleavages cross-cut other cleavage domains (Fig. 6) clearly establishes multiple cleavage forming phases i.e. shortening and thus folding events.

From the stereoplots of these sets one can find approximate orientation of the respective axial planes. For example for the 1st set of folding the axial plane is oriented at N80ºW (Fig. 5a), for the 2nd set it is oriented at N65ºW (Fig. 5b), for the 3rd set it is oriented at N30ºW (Fig. 5c), for 4th set it is at N70ºE (Fig. 5d) and for the 5th set it is oriented at N20ºE (Fig. 5e).

Apart from cleavage orientations we recorded an array of bedding (S_0) orientations with in the same area. One set is spread with orientations range from 290º to 315º and averaging at 300º (i.e. WNW). This WNW set of S_0 has, on average, 45 degrees dip towards NE. The other set is spread from 260 to 285 azimuth direction with averaged orientation at 272 or EW and has average dip of 65 degrees towards north. The switch in orientation direction of the S_0 surface may be associated with the thrust imbrication that has been recognized from the same area. However a detailed analysis of the geometrical relationship of the S_0 (bedding) and S_1 (cleavages) surfaces was not performed.

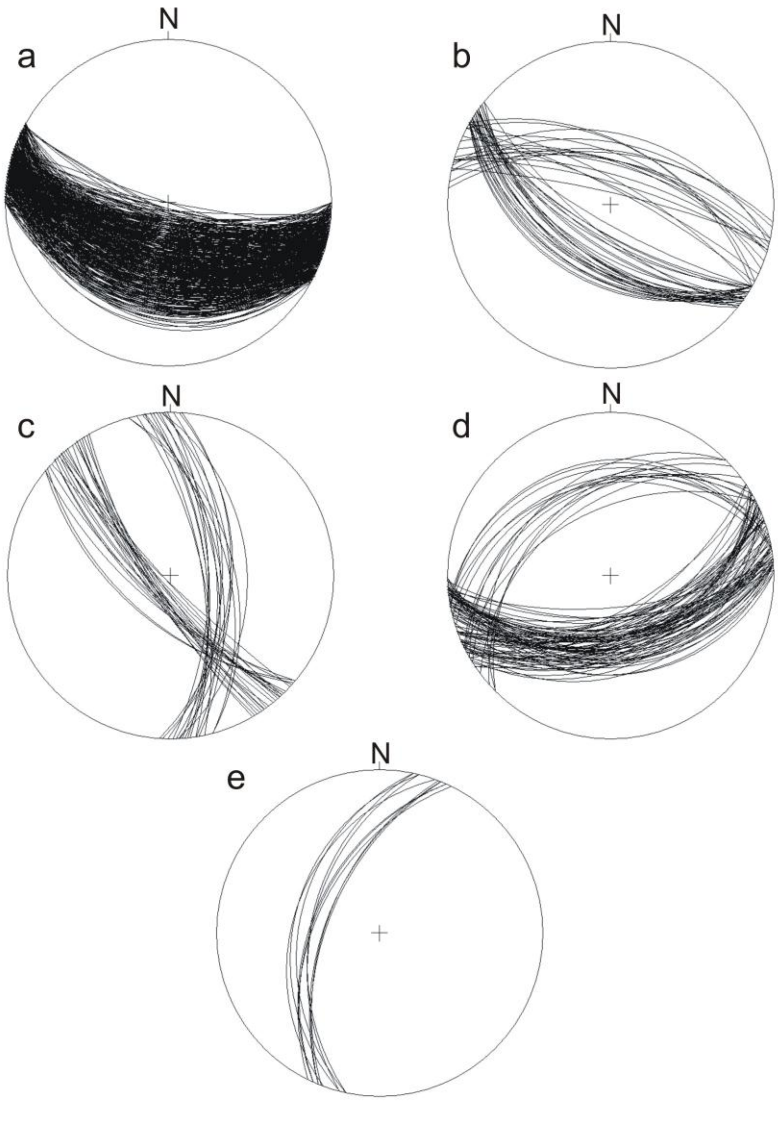

Fig. 5. Mixing and matching of the eight domains of Fig. 4 to sort out cleavages belonging to distinct folding events (see text for explanation).

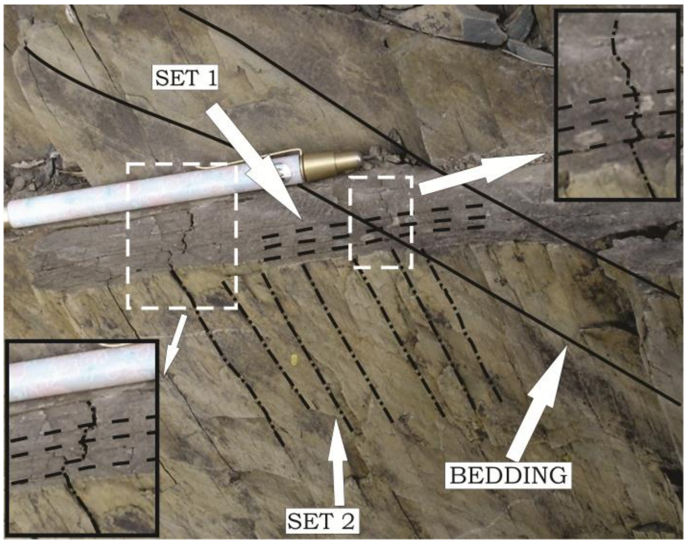

Fig. 6. Field evidence of multiple sets of cleavage development along with the light-dark bands of bedding (S_o) surfaces. Here the age relationship can be established via the fact that Set 1 (N65ºW) truncates the Set 2 (N05ºW) cleavages. Set 1 cleavages are visible on the horizontal plane formed by the floor portion of the step-structure. Inset shows the offsetting of Set 2 cleavages by Set 1 cleavages.

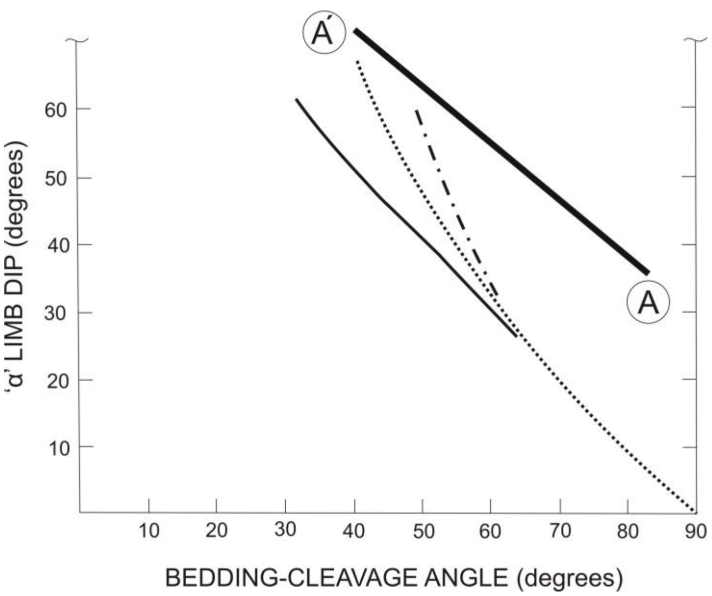

Fig. 7. Bedding cleavage angle vs limb dip graph (after Gray, 1981) showing predicted bedding cleavage angle relationships for flexural flow (dotted line), flattened flexural flow (solid line), and pressure-solution model C (dot-dash line. The heavy line A-A′ denotes our data.

5. Folding Mechanism

Folding in argillaceous rocks has much more complex cleavage-fold relationship. To determine the mechanism of folding we chose Gray (1981) methodology. We plotted the averaged limb dip α (in this case the dip of the associated bedding plane) against the respective cleavage-bedding angle (S_0^S_1 on Gray's (1981) Fig. 6b plot). Our data plotted along line AA′ (Fig. 7) that does not appear to resemble the calculated sequence of flexural flow model rather it transects it at lower angles. Similarly it would transect the calculated sequence of pressure solution model C if the latter is extrapolated to lower angles. On the other hand our data plot mimics the flattened flexural model albeit at much higher angles. The higher cleavage-bedding angles could be due to early-formed dominal microfabric or latter refolding event. Interestingly, an extrapolated line of our data does not intersect at 90° but does so at much higher angle. This suggest that either the cleavage originally did not develop orthogonally to the bedding plane or was rotated, e.g. by a thrusting event.

6. Discussion

The set 1 (Fig. 5a) cleavages are by far the most abundant (505 data points), widespread and cross-cut all other cleavage sets in the field. As such they must be the youngest phase of deformation i.e. D_5. There is no clear evidence to establish chronology of other deformation phases. However, some indirect evidence points to a probable chronological order of deformation. The axial plane of set five (Fig. 5e) fold is oriented more or less in north-south direction, which means that this fold was produced by tectonic forces that compressed these rocks in an east-west direction. This is different from the present day tectonic regime where regional compressive forces are operating in a north-south direction. Hence we assume that the deformation phase which produced these folds is the oldest (i.e. D_{1} = pre-Himalayan). The oldest age of this deformation event is further supported by the fact that this set contains the least no of cleavages indicating obliteration through successive deformations. Using paleomagnetic data, Acton (1999) suggests that the Indian plate during Cretaceous was subjected to north-west directed compressional forces. If that is true then this would indicate that the set 4 (Fig. 5d) cleavages were formed during the Cretaceous folding event. The Cretaceous being very early Himalayan age would make these folds to be D_2 phase of deformation. Similarly Gowd et al., (1992) point out that the current stress field in the Indian plate is oriented at about N23°E. This means that the 2^{nd} set folds (Fig. 5b) are produced by this regime of stress because they are almost perpendicularly oriented to the N23°E stress regime. The fact that this stress regime is current will put this deformation to D_4 phase. This leaves behind the set three (Fig. 5c) folds, which can conveniently be assigned to D_3 folding event.

Field evidence suggests that folding event associated with D_5 deformation phase clearly truncates the D_1 folding event but no clear evidence existed for the mutual relationship of other deformational phases.

7. Conclusions

In the light of the above discussion it is concluded that the slates of the Manki Formation have been subjected to multiple phases of deformation. Each of these deformational phases is manifested by its associated folding as documented by the development of cleavages. The recognition of thrust faults indicates further deformation of these rocks. This implies that the mapped thickness of “Manki Slates” does not represent its true depositional thickness but is rather much exaggerated by the multiple phases of folding. The associated faulting events will have an additional factor in exaggerating the thickness of the Manki slates. Since no absolute timing can be determined for these deformation events it is difficult to assign individual effects to either style of deformation.

Analysis of cleavage data suggests that the slates of the Manki Formation have suffered multiple phases of folding. The folding event associated with D_5 phase (Figs. 4a & 5a) of NS shortening is youngest of all as it is present all over the area and truncates the other cleavages produced during other phases. The stand-alone sets of cleavages (set 1 and 5, Figs. 5a & 5e) may either be associated with very large amplitude folding event or may simply be fault truncated-folds

Analysis of the cleavage-bedding angle and fold limb angle indicates that the dominant folding mechanism closely resembles a flattened flexural flow folding model.

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