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FOLD-FAULT STRUCTURES OF THE NALLAMALAI RANGE, DIGUVAMETTA-NANDI KA NAMA PASS, PRAKASAM DISTRICT, ANDHRA PRADESH, SOUTH INDIA

DILIP SAHA
Geological Studies Unit, Indian Statistical Institute, 203 B. T. Road, Calcutta-700 035

ABSTRACT

A new structure section across the Nallamalai Range around Diguvametta-Nandi ka Nama Pass, Prakasam district, Andhra Pradesh is presented. Fold-thrust related shortening across the range is accompanied by development of cleavage indicating homogeneous layer parallel shortening (LPS). A high angle fault along the western boundary of the range juxtaposes the flat-lying Nandyal Shale (Kurnool Group) against folded Bairenkonda Quartzite. The geometry of structures varies in this section from east to west. In the western part the folds are of relatively low amplitude, but those in the centre and eastern part show close to tight geometry and relatively high amplitude. The attitude of fold axial planes and cleavage also show a variability, easterly dips being more prevalent in the eastern side. LPS strain is heterogeneous across the range.

Fold development is largely by flexural slip, though later stages are marked by development of bedding parallel slip horizons into break thrusts. Variation in fold morphology and cleavage development may be accounted for in terms of large decollements developing at formation boundaries. Other fold-fault interactions arise out of reactivation of high angle normal faults, or thrusts transporting early formed folds. The thrusts are marked by a ramp-flat geometry with an overall easterly dip.

Key-words: Detatchment folds, blind thrust, layer parallel shortening, buckling instability, basement uplift and gravity gliding.

INTRODUCTION

The Proterozoic rocks of the eastern half of Cuddapah basin have experienced tectonic deformation. The hill ranges occurring along the eastern margin, namely Vellikonda Range and the better known Nallamalai Range running in an arcuate fashion through the central part, bear testimony to an inversion of the basin. The Nallamalai Range defines a marked topographic feature separating the generally flat-lying to gently dipping beds of Kurnool Group in the west from the folded and faulted Nallamalai Group in the east.

The overall structure of the basin infill has been worked out in a general way (Meijerink *et al.*, 1984 ; Nagaraja Rao *et al.*, 1987). Detailed knowledges of the structural geometry of the deformed sectors of the basin is, however, lacking (cf. Narayanaswamy, 1966). Such knowledge would be essential for addressing issues relating to kinematic evolution of structures in the inverted basin and the tectonics in an intracontinental set up. Vellikonda Range and Nallamalai Range are examples of partially exhumed intracontinental hill ranges. As such an understanding of the kinematic evolution of the structures in these ranges contribute towards a solution of more general problems of deformation in the continental interior.

With the above questions in mind a structure section of the Nallamalai Range has been worked out from rock outcrops along parts of the Ongole-Kurnool state highway (SH53) and railway cuttings of Bezwada-Guntakal metre gauge line which cut across the Nallamalai Range between Diguvametta (15 kms west of the subdivisional town of Giddalur, Prakasam dt.) and Nandi ka Nama Pass (about 30 kms east of Nandyal, Kurnool dt.). The section covers a distance of 25 kms along an E-W line across the range trending N-S in this region. As the railway line or the road mentioned above winds through a hilly terrain the actual observation points are located within a zone 9000 ft (2743 m) wide on either side (north or south) of the 566000 grid line on one inch toposheet nos. 57 I/11 and 57 I/15 (Survey of India 1922-23).

STRATIGRAPHIC OUTLINE

The Nallamalai Group consists of Bairenkonda Quartzite and Cumbum Formation and is exposed in the Nallamalai Range between Giddalur in the east and Nandi ka Nama Pass in the west. The Group is nowhere in direct contact with Nandyal Shale (Kurnool Group) within the region. The westernmost exposure of Bairenkonda Quartzite is obtained at the crossing of a track leading to Mahadevapuram and the west flowing Gandileru River (grid intersection 562000 N : 2843000 E). The local stratigraphic succession is given in Table 1.

A narrow (c. 3000 ft=914 m wide) strip of colour laminated shale with persistent lamination is exposed along the railway cuttings track at Bogada R. S. and further east in stream sections (the upper tributaries of Saggileru River). Shales (locally sileceous) of similar lithology also occur in road section southwest of Dorapalli viaduct between 161.4 km post and 162.4 km post on Ongole-Kurnool road. Such colour laminated shales which do not contain any coarse sandy intercalation are in sharp contrast to the green shales/slates of Cumbum Formation, which are characterised by thin sandy intercalations. The laminated shales bear resemblance to fine tuffs reported from middle to upper Tadpatri Formation (Murthy, 1982). East of 2859000 grid line there is significant structural discordance between thick bedded units of Bairenkonda Quartzite and the underlying colour laminated shales (Tadpatri Formation). It may be recalled here that the Nallamalai Group is regarded as unconformable to the underlying Chitravati Group (Nagaraja Rao *et al.*, 1987); the Tadpatri Formation constitutes the upper part of the latter Group.

THE STRUCTURE SECTION

The state highway SH53 connecting

Table 1

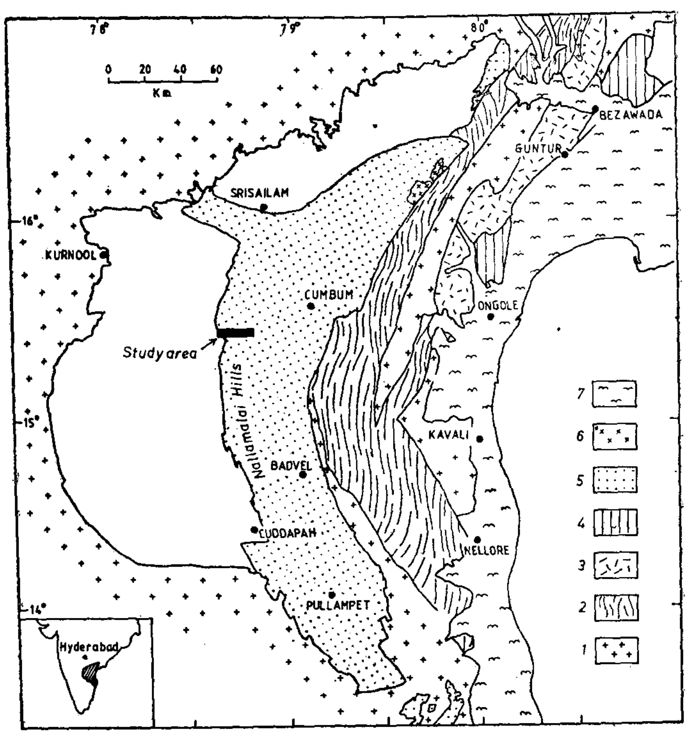
Outline of the lithostratigraphic sequence of Nallamalai Group of rocks

Group	Formation	Lithology
	Nandyal Shale	shales and limestone
——fault——		
Nallamalai Group	Cumbum Formation	shales, slates (limestone intercalation in the lower part), minor quartzite
	Bairenkonda Quartzite	mainly thick bedded quartzite, feldspathic around Diguvametta, grading upward to an alternation of quartzite and quartzite-shale intercalation
——unconformity——		
Chitravati Group	Tadpatri Formation	color laminated (sileceous) shale (cf. ash beds), minor quartzite
	Pullivandla Quartzite (not exposed)	

Ongole with Kurnool offers a transect of the Nallamalai Range between Diguvametta and Mahadevapuram. The Ghat section of the above highway is associated with a topographic relief of 800 feet (244 m). The Bezawada-Guntakal section of the South-Central Railways also offers some excellent railway cuttings in this generally hilly terrain with dense forest cover. The structure section is constructed on the basis of observations along the above road and railway cuttings and other spot observations restricted to a 4500-5500 m wide strip of ground centred around 566000 grid line (Fig. 1).

The western slopes of the Nallamalai Range in this sector is aproachable via Nandi ka Nama Pass (NKNP) which follows the westerly flowing Gandileru River. The latter cuts across the formidable hill range through the Kota Konda peak of 2278 feet (694 m). Further east the road (SH53) passes through the village Pachcherla (PCHL) occurring in an intermontane region between the Kota Konda range and the main Nallamalai Range including the Gali Konda peak of 2415 feet (2208 m). The railway tunnel off Bogada R. S. cuts through the Gali Konda hill range. The Bogada-Diguvametta sector is on the eastern slopes of the Nallamalai Range. For the purpose of description three sectors are recognized. From west to east these are : i) Nandi ka Nama Pass—Pachcherla sector (NKNP-PCHL) ; ii) Kunti R. S.—Bogada R. S. sector (K-B) ; iii) Bogada R. S.—Diguvametta sector (B-META). Kunti R. S. is just outside the area in Fig. 1(b).

The NKNP-PCHL sector shows low amplitude and large wavelength folds in Bairenkonda Quartzite and the lower part of Cumbum Formation (Fig. 1b). This sec-


0 20 40 60
Km
SRISAILAM
KURNOOL
CUMBUM
ONGOLE
BEZAWADA
GUNTUR
Study area
Nallamalai Hills
BADVEL
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NELLORE
PULLAMPET
Hyderabad
7
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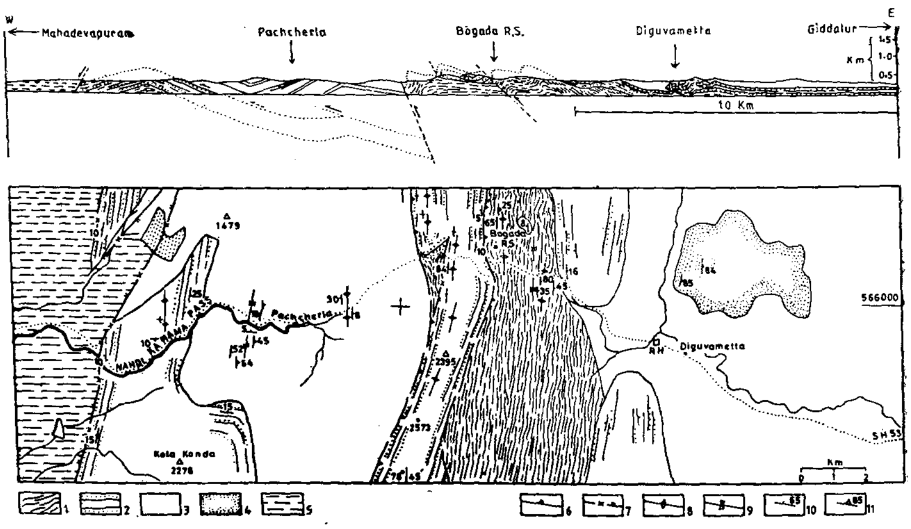
3
2
1

Fig. 1(a).


W
E
Mahadevapuram
Pachcherla
Bogada R.S.
Diguvametta
Giddalur
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SH 53
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Fig. 1(b).

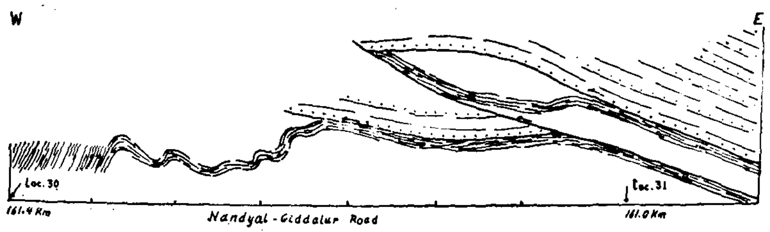

Fig. 1(c).

Fig. 1. (a). Regional geological framework of the Nallamalai Range and location of the study area. 1 = Archaean (unclassified), 2 = Dharwar schists, 3 = Charnockites, 4 = Khondalites, 5 = Nallamalai Group, 6 = Granite diapirs, 7 = alluvium ; after G.S.I. map. (b). Geological map of the study area and an E-W cross-section across the Nallamalai Range around Diguvametta, Prakasam dt., S. India. 1 = Tadpatri Formation, 2 = Bairenkonda Quartzite, 3 = Cumbum Formation (Shale/calc. shale), 4 = Cumbum Formation (sandstone), 5 = Nandyal Shale, 6 = thrust, 7 = normal fault (downthrown side dented), fold axial trace, 8 = antiform, 9 = synform, 10 = bedding dip, 11 = cleavage dip. (c). Cross-section showing in detail the influence of decollements along formation contact, K-B sector. Note deformation in the footwall of individual decollement ; legend as in (b).

tor is bounded on the east by a high angle thrust along which shales of Tadpatri Formation are juxtaposed against Cumbum Formation. Folds in thick bedded units of Bairenkonda Quartzite have a relatively smaller wavelength and higher amplitude in the K-B sector. These folds are disharmonic with respect to structures developed within the underlying Tadpatri Formation. The contact between the two formations act as a decollement. As such fold structures in Bairenkonda Quartzite are comparable to *detachment folds* of Jamison (1992). However, as evident from the section (Fig. 1b), the volume of rock below the decollement is also affected by contractional deformation (see a later section for implications).

The colour laminated shales of Tadpatri Formation are exposed throughout the cuttings adjoining the railway track with a N-S bearing over a distance of 6000 ft through Bogada R. S. This outcrop of Tadpatri Formation is marked by vertical to steeply dipping beds with local overturning towards west. The western limb of a hanging wall asymmetric antiform is dislocated here by a thrust on the western side (Bogada thrust). The latter juxtaposes Tadpatri Formation against Bairenkonda Quartzite. The above hanging wall antiform is followed on the eastern side by a markedly asymmetric synform-antiform pair in the B-META sector. Near Iskagondam (lat. 15°24′50″N : long. 78°47′45″E), moderately dipping shales of Tadpatri Formation is overlain by thick bedded units of Bairenkonda Quartzite with a bedding dip of 10-15 degrees towards east. Structural discordance between the two formations is evident here.

North of Diguvametta feldspathic quart-

Table 2

Comparison of geometry of different structural features in three different sectors across the Nallamalai Range (see Fig. 1)

structural feature	NKNP-PCHL sector	K-B sector	B-META sector
limb dip	10°–25°	0–90°	0–90°
minimum interlimb angle	145° (Bairenkonda Qzt)	75°	155° bqz 35° tdp
dip of axial plane	70°–90° (E)	40°–45° E	40°–45° sh 80°–90° qz
wavelength (s)	upto 9140 m	640 m	914 m
δ/s	0.07	0.5	0.2–0.4
hinge	angular to slightly rounded in all sectors		
fold-fault interaction	decollement and blind thrust taking off as a ramp on decollement (cf. fault propagation fold) high angle reverse fault (? reactivation)	decollement; transported fold thrust dipping 40°E displaces formation	blind thrust; intra-formational decollement

bqz—Bairenkonda Quartzite; tdp=Tadpatri Formation; δ=fold amplitude; sh=shale; qz=quartzite.

zite horizons are folded into relatively upright folds with much smaller wavelength compared to those in the NKNP-PCHL sector. The quartzites and intervening shaly intercalations show well developed cleavage here. These folds in quartzite-shales are probably underlain by a blind thrust. The basic similarity and/or difference in the structural geometry of the three sectors is summarized in Table 2. The ground between Diguvametta and Krishnamsattepalle is relatively flat and mostly under cultivation. Cleaved shales of Cumbum Formation is locally exposed in stream sections.

CLEAVAGE DEVELOPMENT

As described earlier shortening across the Nallamalai Range is mainly registered by folds and thrusts. The development is evidently heterogeneous as one moves from B-META sector in the east through K-B sector to NKNP-PCHL sector in the west. An analysis of this variation is presented later. However, apart from fold and/or thrust shortening the strata also show development of cleavage in this belt. The development of cleavage is rock selective. In general, cleavage is prevalent in most outcrops of Cumbum Formation or Tadpatri

Formation shales/slates. The cleavage morphology in all three sectors varies from a slaty cleavage or fracture cleavage to crenulation cleavage.

Morphologic variation of cleavage does not seem to be related to either the tightness of folds or the size and form of cleavage duplexes. Fracture cleavage, however, is more common in shales of Cumbum Formation exposed in NKNP-PCHL sector. Thinly laminated shales of Tadpatri Formation are more often marked by crenulation cleavage, whereas all the three morphologic types are found in shales of the Cumbum Formation in the K-B sector. Quartzites show cleavage only locally, such as those exposed north of Diguvametta or the hills around Giddalur; the thick bedded quartzites exposed in the K-B sector or those of NKNP-PCHL sector are without any cleavage. Cleavage in rocks is thought to represent homogeneous layer parallel shortening (LPS of Geiser, 1988) component of contractional deformation. Evidently, LPS is heterogeneous spatially across different sectors.

DISCUSSION

Mode of Fold-thrust Development

As noted earlier the Bairenkonda Quartzite has been folded on a large scale. Dominated by quartzites and bounded on either side chiefly by shaly/slaty rocks of Tadpatri Formation and Cumbum Formation, this unit acts as a relatively stiff mechanical layer, thereby providing the set up for a buckling instability to develop under contractional deformation. However, instead of a straightforword buckling of the stratigraphic pile as a whole and uniform development of folds across the belt, there is, as described earlier, a spatial variation in the development of structures.

The spatial variation can be explained partly by invoking detachment along the formation boundaries. For example, the folds within the Cumbum Formation in the NKNP-PCHL sector are disharmonic with respect to the major antiformal structure affecting thick bedded units of Bairenkonda Quartzite (Fig. 1b) exposed along Nandi ka Nama Pass; a decollement along the stratigraphic contact is a logical interpretation. Similarly, a decollement between Tadpatri Formation and Bairenkonda Formation has also been invoked in the K-B sector (Fig. 1b-c). A smaller decollement internal to Bairenkonda Formation controls the structures northeast of Diguvametta in the B-META sector. While in the first case, the decollement is largely following the lithostratigraphy, in each of the other two cases the thrust cuts up section along a ramp. In a way these are fold decollements (McClay, 1992); however, departure from the text book model is evident from footwall deformation (cf. 'Kimmeridge model' of Ramsay, 1992).

The two large thrust structures at the eastern and western end of the K-B sector are apparently unrelated to any of the above two decollements. (It is assumed that the present structure section is correct to a depth of 1.8 kms). The high angle thrust at the western boundary of the K-B sector has an apparent displacement of a few hundred meters emplacing the Tadpatri Formation shales at their present level. The other thrust is apparently associated with

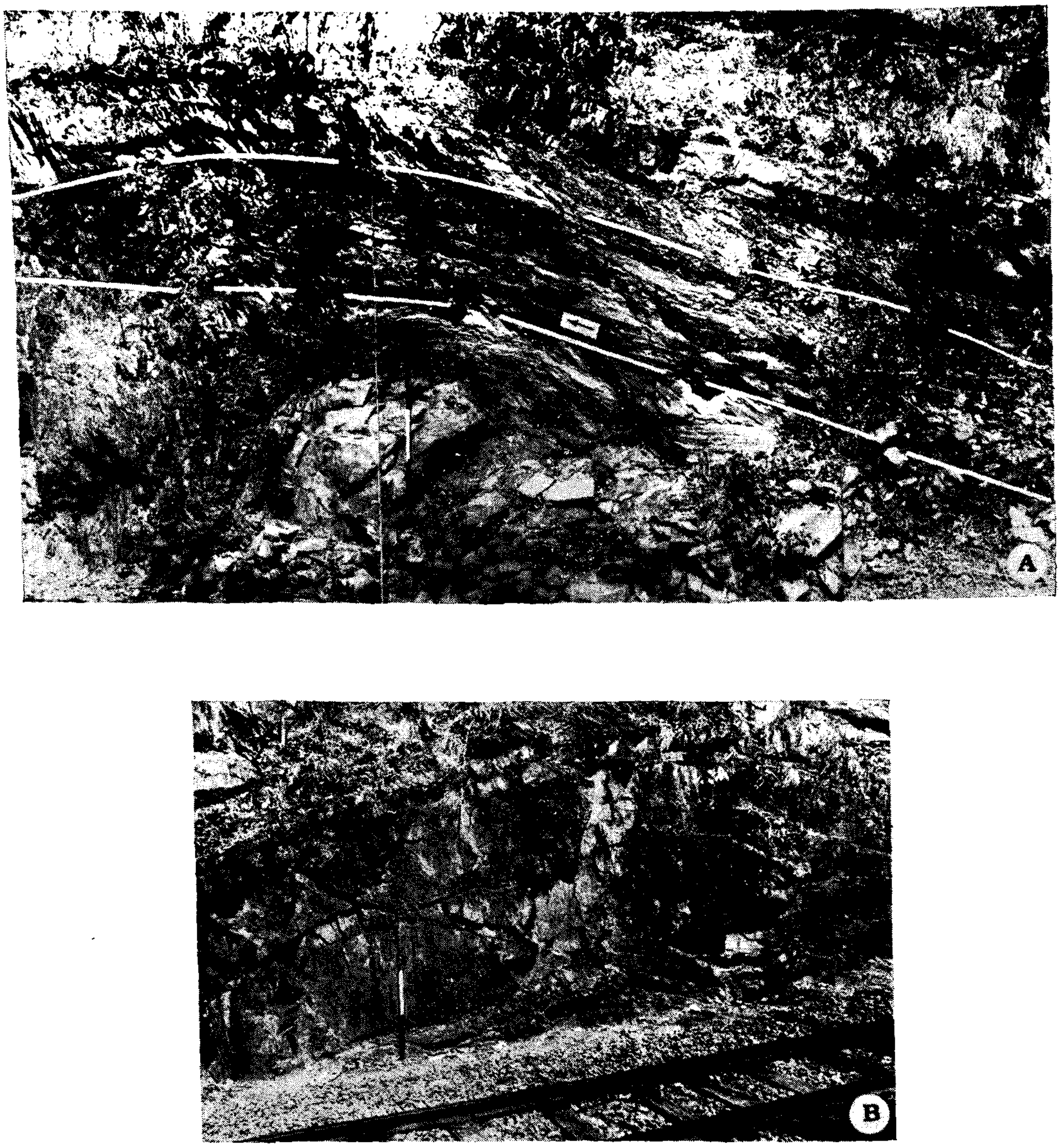

Fig. 2. Break thrusts with different degrees of fold tightness. (a) Gentle asymmetric antiform with thrust originating on the eastern limb cutting as a ramp through a thick quartzite bed in the western limb (forelimb). (b) Open to close asymmetric antiform with one vertical limb (forelimb) severed by a thrust parallel to the gentle limb (eastern limb). Note another thrust (decollement) higher up in the section. E-W sections looking north, railway cuttings near Dora Palli viaduct.

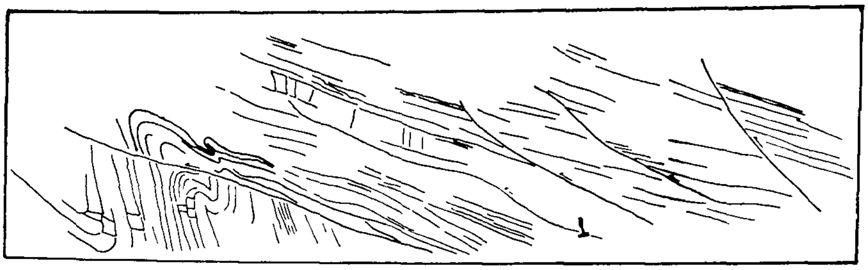

Fig. 3. A series of converging thrusts with the lowest one transporting overturned folds on the hanging wall. Sketch after a photomosaic, railway cutting on the eastern end of the Dora Bhavi viaduct.

a displacement of about 100 meters. The reactivation of a pre-existing normal fault bounding the shales of Tadpatri Formation may explain the steep attitude of the western bounding thrust.

Buckle Strain accommodated by Flexural Slip

The largest fold in thick-bedded quartzites of Bairenkonda Quartzite is at Nandi ka Nama Pass. However, a series of folds developed in the quartzites are exposed along road and railway cuttings west of Bogada R. S. and around Dorapalli viaduct. Examination of small scale structures in these places clearly reveal that flexural slip was involved in the development of these folds. Small flexural slip duplexes (Tanner, 1992) in the K-B sector also attest to a bedding parallel slip. Other bedding parallel dislocation surfaces are marked by slickensides, slickencrysts or fault gouges. In some cases thrusts take off as a decollement on the gently dipping eastern limb of an asymmetric antiform but cross the axial region of the fold as a break thrust (Fig. 2) ; in still others the hanging wall structure is essentially those of transported folds (Fig. 3). Some degree of flexural flow in thick quartzite beds is indicated by sigmoid tension gashes with opposite sense of shear on two limbs of an open antiform ; the structures occur within a thick apparently massive quartzite unit.

Rotational Deformation

Folds on different scales are generally west verging. The axial plane changes from vertical in the west to easterly dipping at 25-30° towards east. Although the thrust faults are marked by ramp-flat geometry, majority of these thrusts have an overall easterly dip (Fig. 1). Westerly dipping reverse faults or shear zones, however, are not altogether absent on a small scale.

In consonance with the above, cleavage developed in various lithologies across the belt is also generally dipping towards east (Fig. 4) at an angle varying from one place to the other. The variation in cleavage dip may simply reflect a general heterogeneity of LPS strain. But this may indeed reflect diminishing angle between shear direction and finite XY plane in a progressive strain history where the bulk strain is simple shear, or simple shear compounded with flattening.

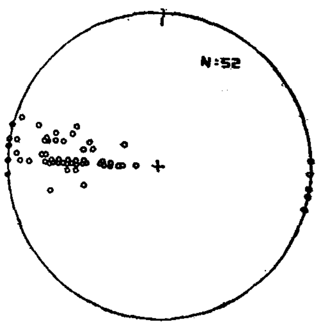

Fig. 4. Equal-area plot showing easterly dip of cleavage irrespective of spatial position on the mapped sector shown in figure 1.

The following are examples of small scale structures indicative of rotational strain :

a) The forelimb of an asymmetric antiform is disrupted by small east dipping reverse faults, the limb segment bounded by a fault pair rotating in a clockwise sense (Fig. 5). The rotation is similar to that of a rigid body in a ductile matrix, the forelimb having been affected by a shear zone with discrete failure surface.

b) Zones of sigmoid tension gashes internal to thick quartzite beds indicate a sense of shear conforming to "upper layer moves towards antiformal hinge relative to a lower one". However, easterly dipping zones of this type are more common than

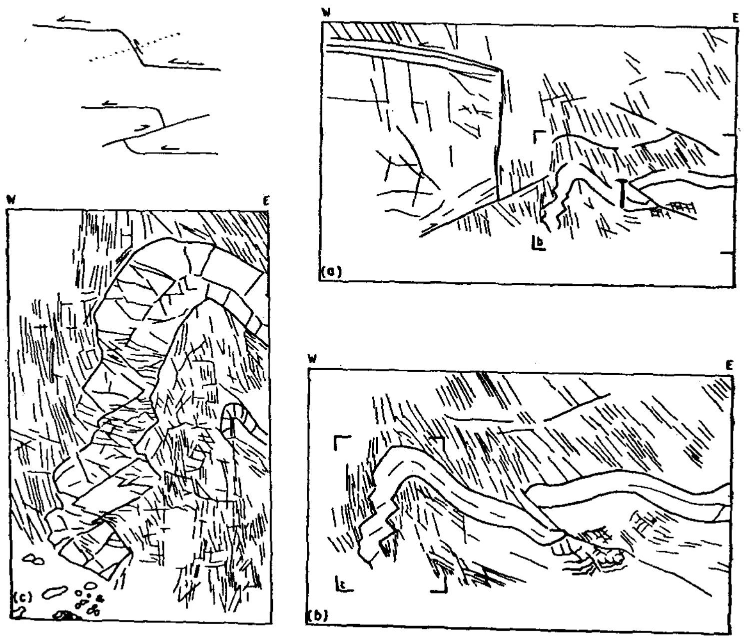

Fig. 5. (a)-(c). Rotation of quartzite rhombs within a segmented forelimb in the hanging wall of a mesoscale thrust. Railway cutting off western end of the railway tunnel, Bogada R. S. Overall structural set-up for (a)-(c) are on top left.

those with westerly dips. Strain accommodation by internal brittle flow is thus marked by an asymmetry, west directed flow being more prevalent.

Nallamalai Folds by a Push from East ?

The westerly vergence of folds, the prevalence of east dipping thrusts and shear zones, and easterly dip of cleavage is quite marked across the Nallamalai Range. It may also be noted that the amplitude of the largest mappable fold from NKNP is low compared to folds in the K-B sector. One may explain the observed features in terms of a push from the east, the buckles on Bairenkonda Quartzite developing as the stress front moves west. However, LPS strain is significant even in the westernmost NKNP-PCHL sector as attested by the development of cleavage in shales.

Comparing with other deformation set up in analog models, or the proposed models of development of Jura structures (Price and Cosgrove, 1990, p. 258), the folds in the Nallamalai Range could equally well be explained by basement uplift further east and an west directed gravity gliding from this high. In the latter case one would expect basement material at higher structural levels in the east. It remains to be examined whether the granite domes of Vellatur, Ipur and Nekarikallu (Nagaraja Rao *et al.*, 1987) along the eastern margin of the Cuddapah basin represent remobilized basement diapirs (*c.f.* Qureshi *et al.*, 1968).

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