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Internal geometry of a thrust sheet, eastern Proterozoic belt, Godavari Valley, South India

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Abstract. A small thrust sheet, named Pedda Gutta thrust sheet, consisting of calcareous to cherty argillites and cherts, and juxtaposed against tidal-intertidal cross-bedded quartzites and stromatolitic and sileceous limestone in the eastern Proterozoic belt, Godavari Valley, exhibits structures comparable in style to those of the external zone of a fold-thrust mountain belt. A wide spectrum of periodic and aperiodic mesoscopic folds varying from upright ones with rounded hinges and attenuated limbs, through noncylindrical kinks to whalebacks and sheath-like forms have developed within the small volume of the thrust sheet, the preserved thickness of which is of the order of 50 metres (comparable in scale to cleavage duplexes). Cleavage development is also heterogeneous across the width of the sheet. Displacement transfer from faults to folds and vice-versa is a common feature.

On the basis of the distribution of the mesoscopic structures of varying style within the sheet and localization of fault rocks, three slices (wedges) have been recognized, each bounded on the east by a thrust which is steep at the current erosion level but interpreted to be of listric form making the thrust network comparable in architecture, though not in scale, to a hinterland (west) dipping imbricate fan.

Keywords. Cleavage duplex; external zone; Godavari Valley; imbricate fan; mesoscopic folds; thrust sheet; Proterozoic.

1. Introduction

The *contorted and sheared rocks* of Sironcha country and Enchapalli ranges (cf. Inchampalli village in Survey of India 1 inch toposheet no. 65 B/6) belonging to *Pakal* subdivision of *Pakal* Series are distinctive as compared to the flat-lying Albaka sandstones of the Albaka range occurring to the west of Indravari and Godavari rivers (King 1881). With regard to deformation of the little metamorphozed sediments as also their distinctive lithologic association these rocks stand out amongst the middle Proterozoic Pakhal Group (as defined by Basumallick 1967; Chaudhuri 1985) of rocks (see Saha and Ghosh 1986; Saha 1988; Saha and Ghosh 1988). Deformed Proterozoic rocks of Sironcha country and Enchapalli ranges are also interesting with respect to the question of a palinspastic collisional suture between the Bhandara craton and the Eastern Dharwar craton along the Godavari join (Rogers 1986; Rogers and Callahan 1987; Saha 1989). In the mapped area (figure 1) attention is focussed on two* lithostratigraphic (strictly speaking tectono-stratigraphic) units which outcrop as two adjacent belts running NNW–SSE. A sequence of quartzarenite, interlaminated to interbedded sandstone-shale, calcareous argillites, and subordinate stromatolitic or oolitic carbonates (Somnur Formation) occur to the east of a strip of cherty argillite-chert-calcareous argillite. The structural details of the latter, tentatively named as the Pedda Gutta Chert Formation, form the subject

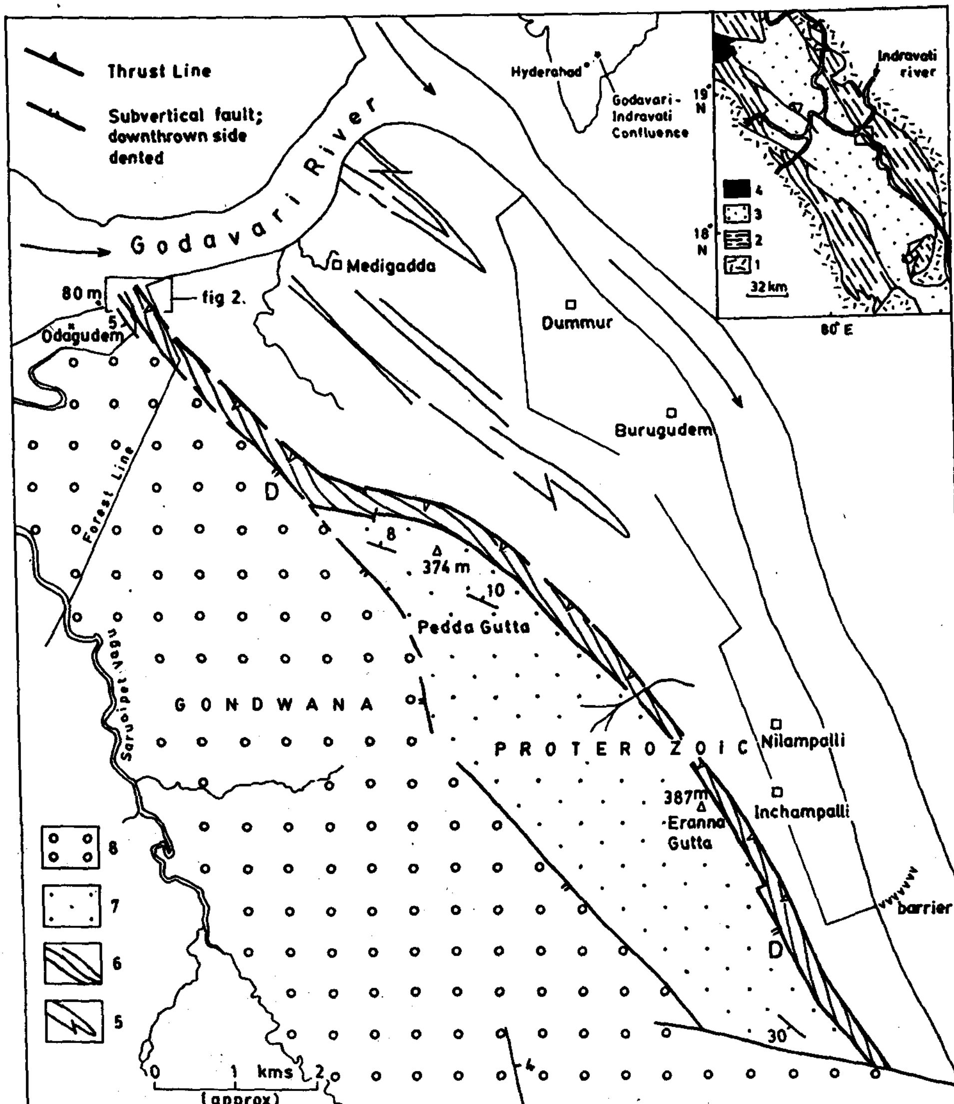

Figure 1. Geologic setting of the Pedda Gutta thrust sheet, eastern Proterozoic belt, Godavari Valley. Inset shows the Proterozoic outcrops of the Pranhita-Godavari Valley. 1 = Precambrian crystalline basement; 2 = Proterozoic sedimentary sequences; 3 = Gondwana rocks; 4 = Tertiary rocks; 5 = Somnur Formation; 6 = Chert-shales of Pedda Gutta sheet; 7 = Undifferentiated sandstone-conglomerate (Proterozoic); 8 = Polymict conglomerate (Chikiala).

matter of this contribution. Table 1 gives the general stratigraphic position of the rocks of the area.

That a sequence of thrust with slices of varying litho-stratigraphic character and/or structural style forms an imbricate network is suggested by an examination of rock outcrops with a topographic relief of 250 metres between the Godavari River bed and the northern slopes of Pedda Gutta (374 m peak) and an excellent subhorizontal

Table 1. Stratigraphy of the Sironcha country and Enchapalli (cf. Inchampalli village) rangers.

		Generalized sequence of Godavari Valley	Sironcha country and Enchapalli ranges[1]		
			West of Indravati river		
		William King (1881)	S of Godavari	N of Godavari	E of Indravati-Godavari rivers
MESOZOIC		Gondwana rocks	Chikiala breccia	Chikiala breccia	
		angular —unconformity—	—fault—	—fault—	
PROTEROZOIC		Sullavai sandstones			
		angular —unconformity—			
	Pakal Series	Albaka subdivision			Albaka Sandstone
			Eranna Gutta sandstone with conglomerate interbeds	Po Gutta sandstone	Infra-Albaka quartzites, shales[4]
				—unconformity—	—fault—
				Kopela Shale Formation[2]	Kopela Shale Formation
				Bodela Vagu Formation[2]	Bodela Vagu Formation
					—dislocation—
		Pakhal subdivision			Tarur Nala Formation[3]
			Pedda Gutta cherty argillites cherts, slates		
			—dislocation—	—dislocation—	—dislocation—
		angular —unconformity—	Somnur Formation	Somnur Formation[2]	Somnur Formation
		Basement (AZOIC)			

[1] Mostly unpublished works of Geological Studies Unit, ISI; [2] Saha and Ghosh (1988); [3] Ghosh (1986); [4] Saha (1988)

section brought out by flood erosion on the southern bank of Godavari river between Sarvaipet Nala mouth and the NNW trending forest line west of Medigadda village (figure 1); the latter section transects through considerable structural relief. Here, a 300 m × 40 m strip of ground is mapped on scales up to 2 cm = 1 m for structural details. These two-dimensional map information, in conjunction with those gleaned through outcrop examinations in a belt of structural and topographic relief, are used to obtain a first approximation answer to the following questions: Is there any distinctive variation in mesoscale structural style in different slices (wedges) from the highest to the lowest structural level? Is it possible to relate the internal deformation, having expressions in mesoscopic folds, faults and cleavages, with the displacement on the bounding thrust? What are the roles of higher level detachments and minor fault arrays in semipervasive displacement transfers within the thrust slices? How are the different thrusts connected in a sequence? How far does a model of hinterland dipping piggyback sequence explain the observed geometry? There is no attempt here to reconstrust balanced cross-sections for want of stratigraphic offsets on a scale finer than thrust imbrication. Although one of the important tools in unravelling the structure of a thrust belt is not in the armoury while attempting structural analysis of the Pedda Gutta thrust sheet, this work follows Boyer and Elliot (1982) in finding a solution to the thrust belt problem by referring to the "logic" of the fault network.

2. The Pedda Gutta thrust sheet

Between the Somnur Formation rocks in the east and the Chikiala conglomerates (breccia) or a sequence of Proterozoic sandstone-conglomerate on the west, the Pedda Gutta thrust sheet extends for a strike length of 15 km (figure 1). Although the exposure is poor, the same band of the cherty argillites and associated rock strata continues in the NNW direction across the Godavari river bed and further north for another 10 km. Apparently the Pedda Gutta Chert Formation is largely dismembered due to rifting during the deposition of the late Proterozoic sandstone-conglomerate sequence as well as during the Mesozoic Gondwana sedimentation event. This is responsible for the present narrow width (c. 0·8 km) of the thrust sheet outcrop.

The internal constitution of the Pedda Gutta thrust sheet is largely worked out from an excellent subhorizontal section on the southern bank of the Godavari river at the mouth of the Sarvaipet nala (Vagu). Here, the section cuts through considerable structural relief and the details are mapped on scales up to 2 cm = 1 m scale. In spite of the obvious scale difference, the terminology used in the description of thrust belts of classical areas (e.g. Bally *et al* 1966; Boyer and Elliot 1982; Butler 1982) is borrowed for better description.

The contact between the Somnur Formation rocks and those of the Pedda Gutta Chert Formation is considered here as a line of major structural dislocation, the Pedda Gutta Thrust. Noticeably, the Somnur Formation rocks represent shallow water tidal-intertidal to subtidal environment (Saha and Ghosh 1988), whereas the calcareous to cherty argillites and cherts of the other formation have definitely originated below the wave base with a limited contribution from terrigenous clastics. The juxtaposition of stratigraphic units with a marked difference in their depositional environments leads one to believe in the horizontal translation of the Pedda Gutta Chert Formation across the strike borne on the Pedda Gutta Thrust. Coupled with this stratigraphic mismatch across a line of dislocation, the structural style of the two rock units have a tell-tale difference. The Somnur Formation rocks are internally folded and cleaved, but the development of cleavage is often rock-selective. For example, the quartizites occurring immediately to the east of the Pedda Gutta Thrust are dipping steeply towards west (stratigraphic facing also towards west) but any penetrative tectonic fabric is poorly developed and the original sedimentary structures like cross-bedding are still well preserved (figure 2). In contrast to this, the calcareous and cherty argillites of the Pedda Gutta Chert Formation are highly cleaved; transposition of the bedding lamination is the rule here; mesoscopic fold trains are often dismembered by small thrusts, oblique or strike slip faults; development of mylonitic/phyllonitic or cataclasite bands is common both in the vicinity of the Pedda Gutta Thrust as well as internally within the thrust sheet.

On the basis of a variation in the style of development of mesoscopic folds, cleavage as well as lithostratigraphic heterogeneity across the thrust sheet, three slices (wedges) are recognized internally within the preserved part of the Pedda Gutta thrust sheet.

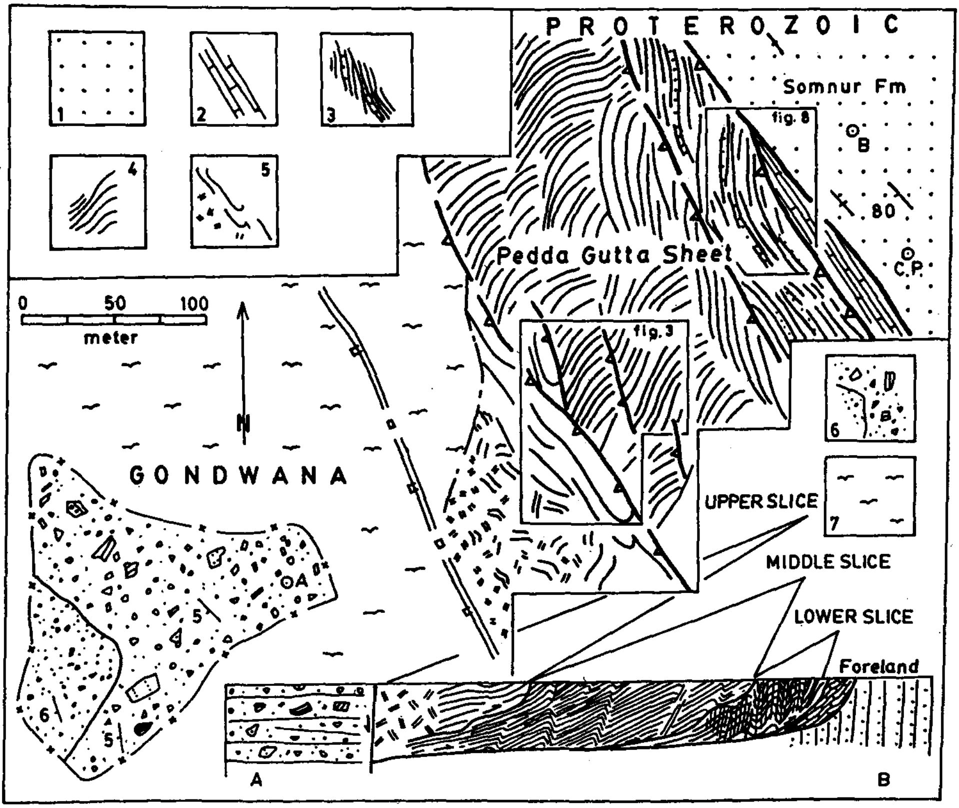

Figure 2. Broad structural make-up of the Pedda Gutta thrust sheet, for location see figure 1. Schematic section along *AB* shows an interpretation of the structure as a hinterland dipping imbricate fan (for details see text). 1 = quartzite (Somnur Formation); 2 = sileceous and stromatolitic limestone (Somnur Formation); 3 = calcareous and cherty argillites; 4 = cherty argillites; 5 = cherts and cherty argillites, breccia zone near the boundary fault with the Gondwana; 6 = polymict conglomerates and grits (Gondwana); 7 = alluvium; 3–5: units of Pedda Gutta Chert Formation.

These are referred to as the Upper, Middle and Lower Slices (wedges) respectively exposed in this order from west to east (figure 2), and each bounded by a thrust on its eastern margin.

2.1 *The Upper Slice* (*wedge*)

Bounded by the boundary fault with the Gondwana rocks on the west and lying above the western most thrust on figure 2 the Upper Slice consists of cherty argillites and cherts. A zone measuring a few tens of metre wide of highly brecciated rocks (derived from Pedda Gutta Chert Formation) marks the western boundary fault. This tectonic brecciation apparently has had little influence on the Chikiala conglomerates and presumably represents the Mesozoic or earlier rifting episode. Away from the zone of influence of this brecciation the Upper Slice rocks show a subhorizontal parting plane (transposed bedding) on which shallow fold structures take the form of whalebacks (figures 3 and 4). Internal deformation is accommodated by common bedding detachments which form an imbricate network. A spaced cleavage, cataclasite/mylonite bands are common in the vicinity of small ramps connecting bedding parallel flats (figure 5). The movement direction as indicated by slickensides and slickencrysts on subhorizontal parting planes is at a high angle to the local NNW strike of thrust at the bottom of the Upper Slice (wedge) (figure 6a). Microfault arrays, mostly of steep orientation and with a consistent movement sense form anastomozing network in a certain volume of rocks bounded by bedding detachments (figure 6b). The dominant set of microfaults in this array has a strike at 60–70° with the movement direction (figure 6).

2.2 *The Middle Slice* (*wedge*)

Consisting mainly of cherty argillites and argillites the Middle Slice is bounded by an upper thrust at the bottom of the Upper Slice and a lower thrust separating the calcareous and cherty argillite unit below. There is a significant development of phyllonitic rocks at the base of this slice. The contact zone with the Upper Slice is marked by isolated fold hinges with a steep plunge, curved fold hinges or some assuming sheath-like forms (figure 3). Noticeably a number of steep faults, with reverse or oblique slip movements, disturb the footwall rocks immediately below the upper thrust at the bottom of the Upper Slice. However, the bedding parallel parting shows an overall 25–30° NNW dip. Away from the upper bounding thrust mesoscopic kink folds dominate the structure (top right corner of figure 3). Such folds are often modified in form due to transition of fold displacement to a fault displacement or otherwise later faults (shear zones) reorienting fold hinges. These folds seem to have a consistent asymmetry with narrow N–S steep short limbs making the structure an open '*Z*' in plan. Folds possessing a kink band geometry with narrow hinges and long planar limbs have been described from fold-thrust belts of Jura (Laubscher 1976, 1977); Valley and Ridge Province (Faill 1973; Roeder *et al* 1978; Rocky Mountains of the western United States and Canada, and southern Appalachians of the eastern United States (Boyer 1986). However one must keep in mind the scale difference—the folds of the Rocky and Appalachian examples have wavelengths up to a few kilometres and amplitude of up to a few hundred metres.

Kink-folds of the Middle Slice have an axial trace at a high angle to the overall

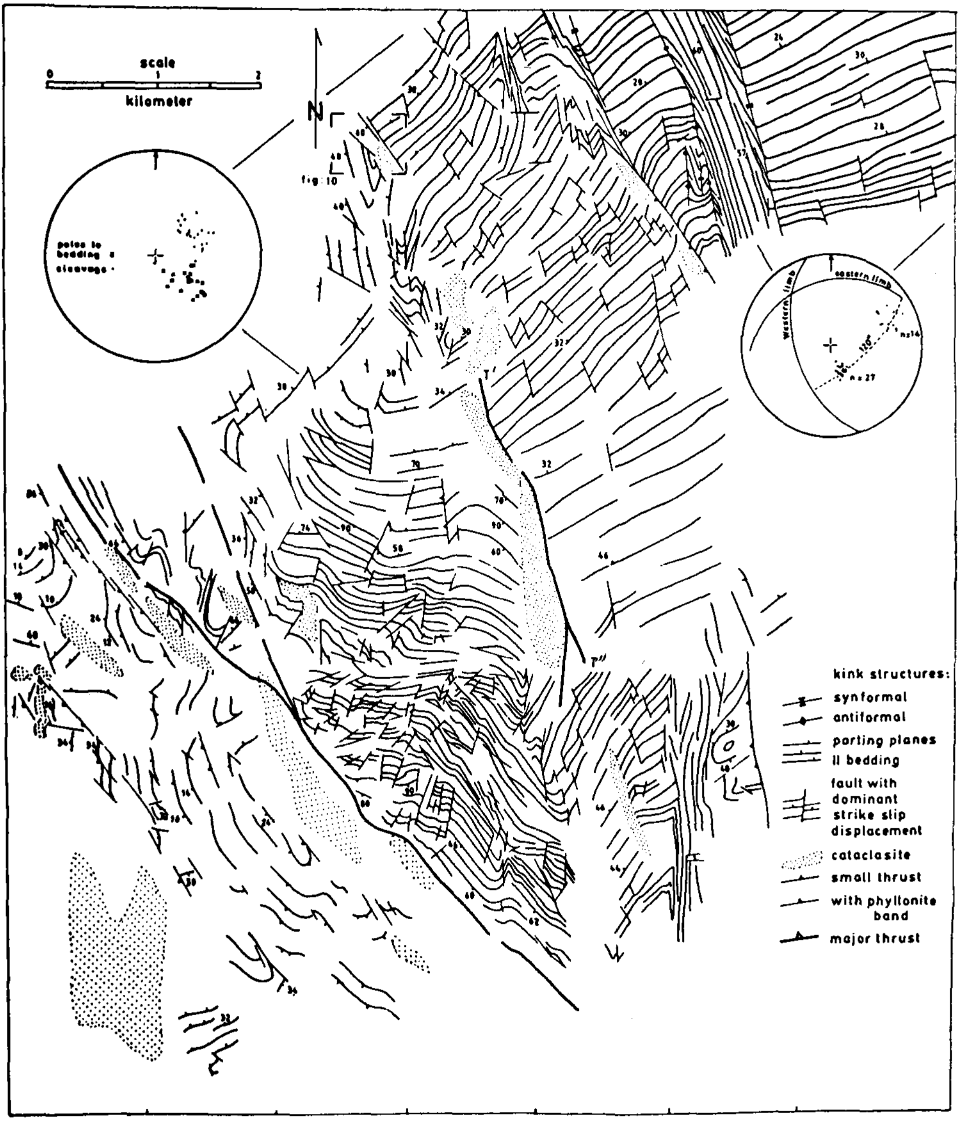

Figure 3. Structural details in parts of the Middle and Upper Slices, Pedda Gutta thrust sheet, for location see figure 2. Equal area plot (top left) shows the orientation of the oblique cleavage in relation to bedding within the Middle Slice. Folds of kink geometry prevail away from bounding thrusts in the Middle Slice, top right quadrant of the structure map and the equal area plot (right).

bedding strike. Still the asymmetry is compatible with a large component of E–W shortening (cf. *intraplate* folds of Boyer 1986) across the thrust sheet. Bulk shortening is also partly accommodated by the development of semi-penetrative fabric having mesoscopic expression in the form of an oblique cleavage even away from the obvious influence of a fold hinge. The dihedral angle between this cleavage and bedding parallel parting is about 30°, but the angle between the average strike azimuths of cleavage and bedding is quite high (c. 60°; equal area plot on the top left hand corner

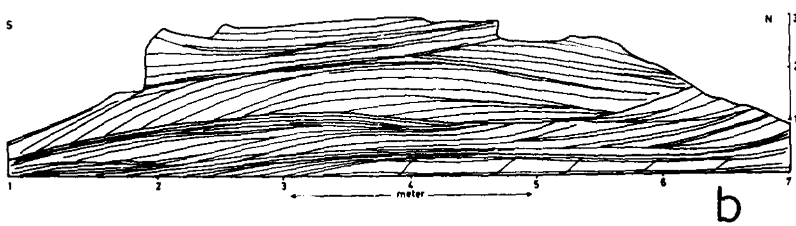

Figure 4. (**a**) Higher order bedding detachments making an anastomozing network (cf. duplex), Upper Slice. (**b**) Line drawing showing a projection of structures in (**a**) to a NNE–SSW vertical plane.

of figure 3; compare with the plot on the top right which gives the orientation of the elements of a kink-fold). These cleavage orientations refer to localities where bedding has a relative constant orientation thus avoiding the short limb of kink folds or locales influenced by breaches by later faults and shear zones.

A number of small steep faults with strike azimuths between NNW and NNE displace the form surface, mostly in a strike slip sense. These have a marked concentration in the footwall immediately below the upper bounding thrust or in the neighbourhood of higher order detachments cutting into the present erosion level through small ramps internal to the Middle Slice.

The lower bounding thrust of the Middle Slice is marked by a zone of phyllonite development; the phyllonitic foliation (possibly transposing the original bedding parallel parting) itself is transposed by a crenulation cleavage (figure 7). The cleavage is subvertical with NNW strike and the apparent offsets across the cleavage have a consistent sense of displacement.

2.3 *The Lower Slice* (*wedge*)

The Lower Slice consists of calcareous and cherty argillites and rests on the Pedda Gutta Thrust. Rocks of the Pedda Gutta thrust sheet rest on two different lithostratigraphic units of the Somnur Formation, namely quartzites (North of branch point *B* on figure 8) and stromatolitic and sileceous limestone (south of branch point *B*, figure 8). An isolated outcrop of the Pedda Gutta thrust sheet occurs within the

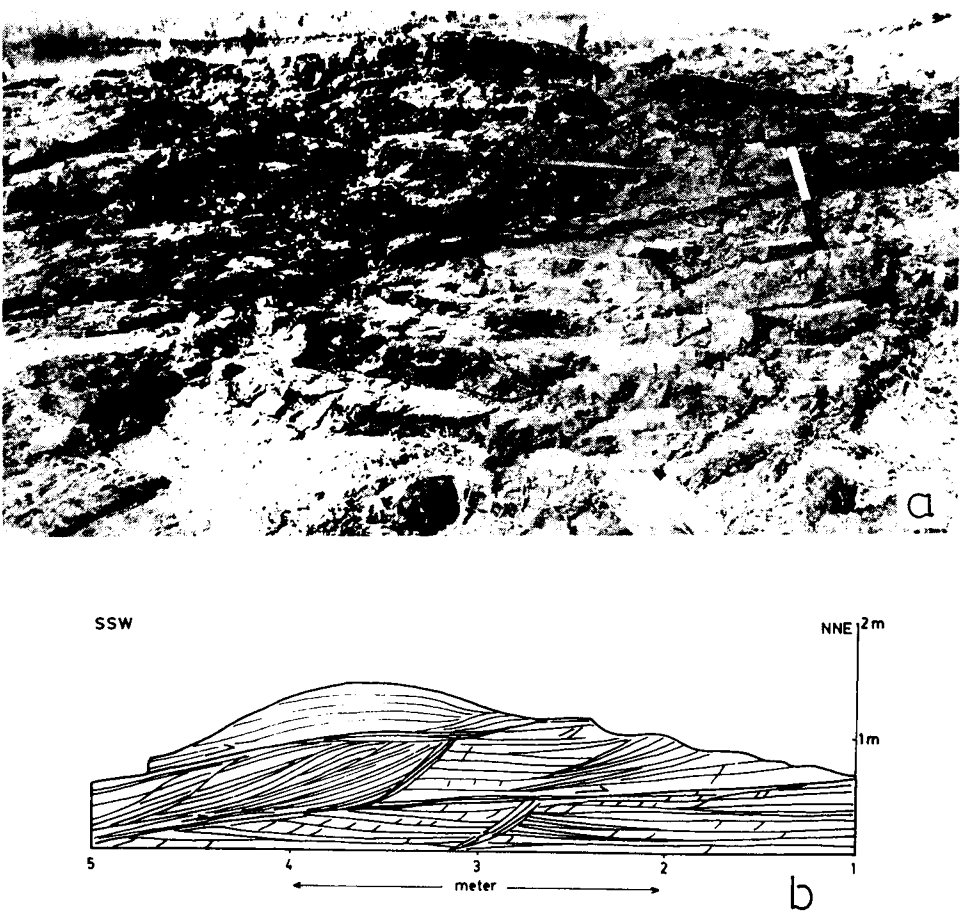

Figure 5. (**a**) A small oblique ramp and branching. Note a spaced cleavage at a high angle to bedding in the footwall (foreground) and cataclastic flow in the hanging wall rocks, Upper Slice. (**b**) Line drawing after (**a**).

limestones (figure 8). An asymptotic curvature upward of the Pedda Gutta Thrust may explain the 'outlier' of the sheet.

A near pervasive upright cleavage transposes bedding lamination. The slice is marked by numerous quartz-carbonate veins which are in general interfoliar or at a small angle to the cleavage (figures 8 and 9). The thickness of such veins varies from less than a millimetre to a few decimetres. Micro- and mesoscopic fold trains are common; one or other limb of the folds may be truncated by small faults (usually vertical or with steep westerly dip). Both oblique slip and thrust sense displacements have been observed. Mesofold and cleavage-bedding intersection lineation have a west-north-westerly azimuth with plunge varying between a few degrees and c. 60° (equal area plot in figure 8). Intensity of cleavage development has a kind of zonality localized either by a distributed fault displacement (cf. shear zone) or an attenuated limb of a fold (figure 9). Coincidentally, a profusion of thin quartz-carbonate veins may occur in such a zone. Displacement transfer from mesoscopic folds to faults is a rule in the Lower Sheet.

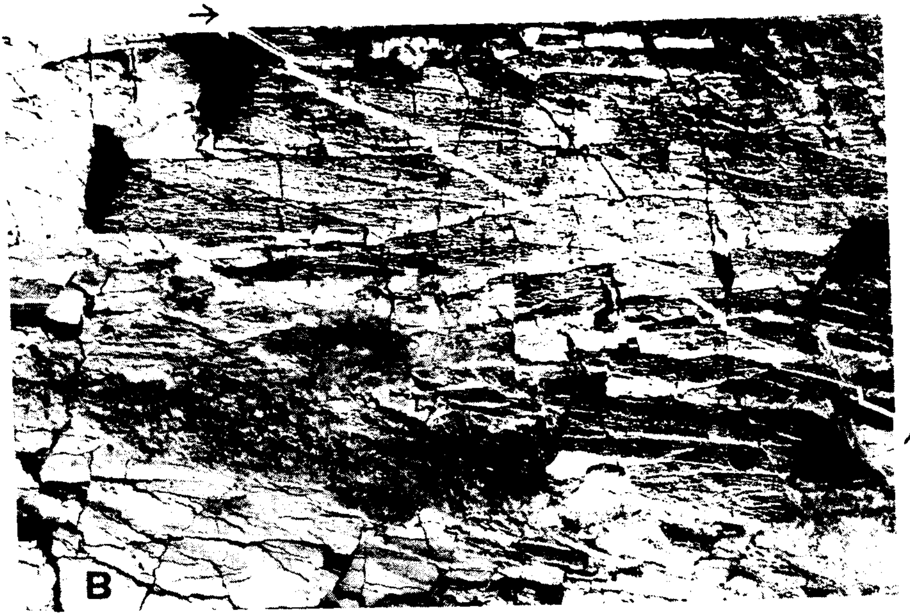

Figure 6. (**a**) Slickencrysts (parallel to the pencil) on a bedding detachment, Upper Slice. Apparently the local slip direction is at a high angle to the strike of microfault array (bottom left). (**b**) Details of the microfault array in (**a**), note the consistent sense of displacement (the steps along the *sawn off* part) on adjacent microfaults.

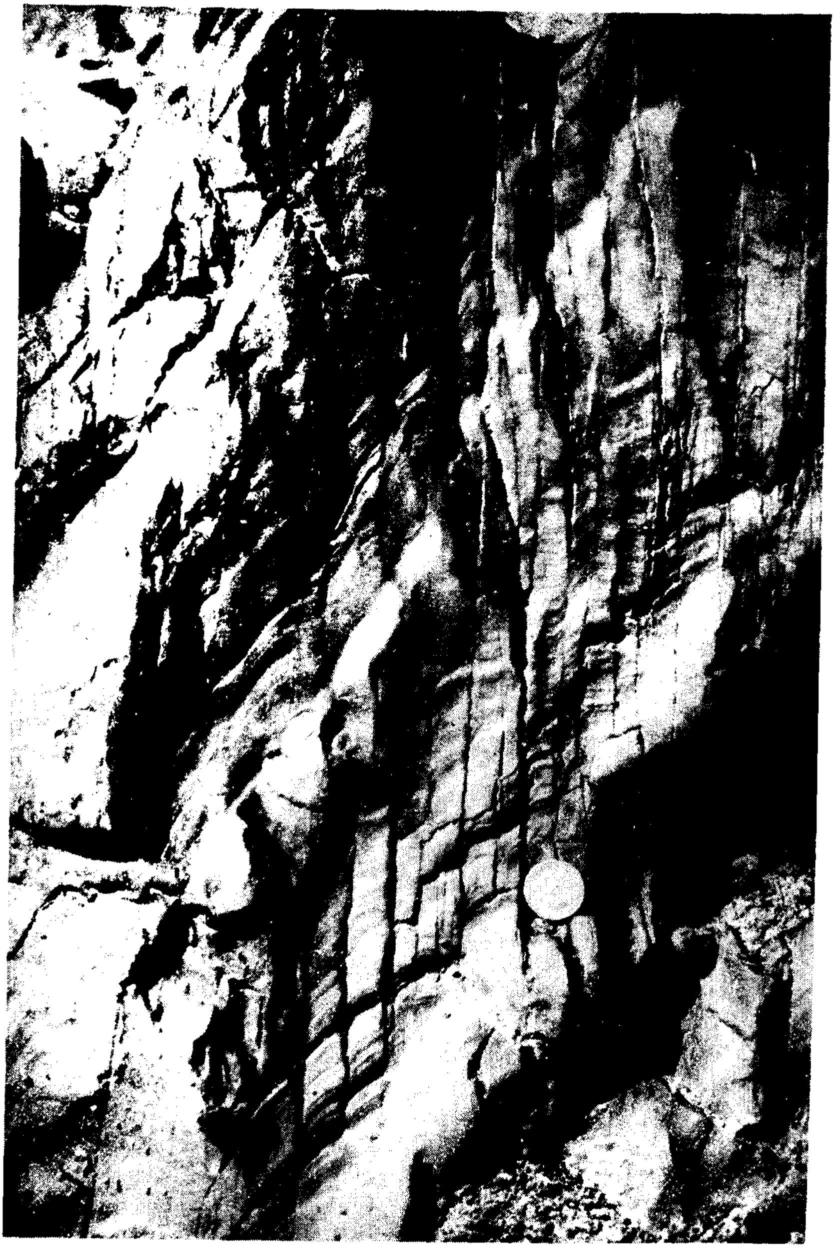

Figure 7. Crenulation cleavage in the phyllonite belt, near lower bounding thrust of the Middle Slice.

3. The limestone horse

Wedge-shaped outcrop of the limestone unit (Somnur Formation) south of the branch point *B* on figure 8 is considered to be a *horse* here, enclosed between a splay separating the quartzite from the limestone and the Pedda Gutta Thrust proper. The asymptotic curvature upward of the Pedda Gutta thrust is indicated by the 'outlier' of

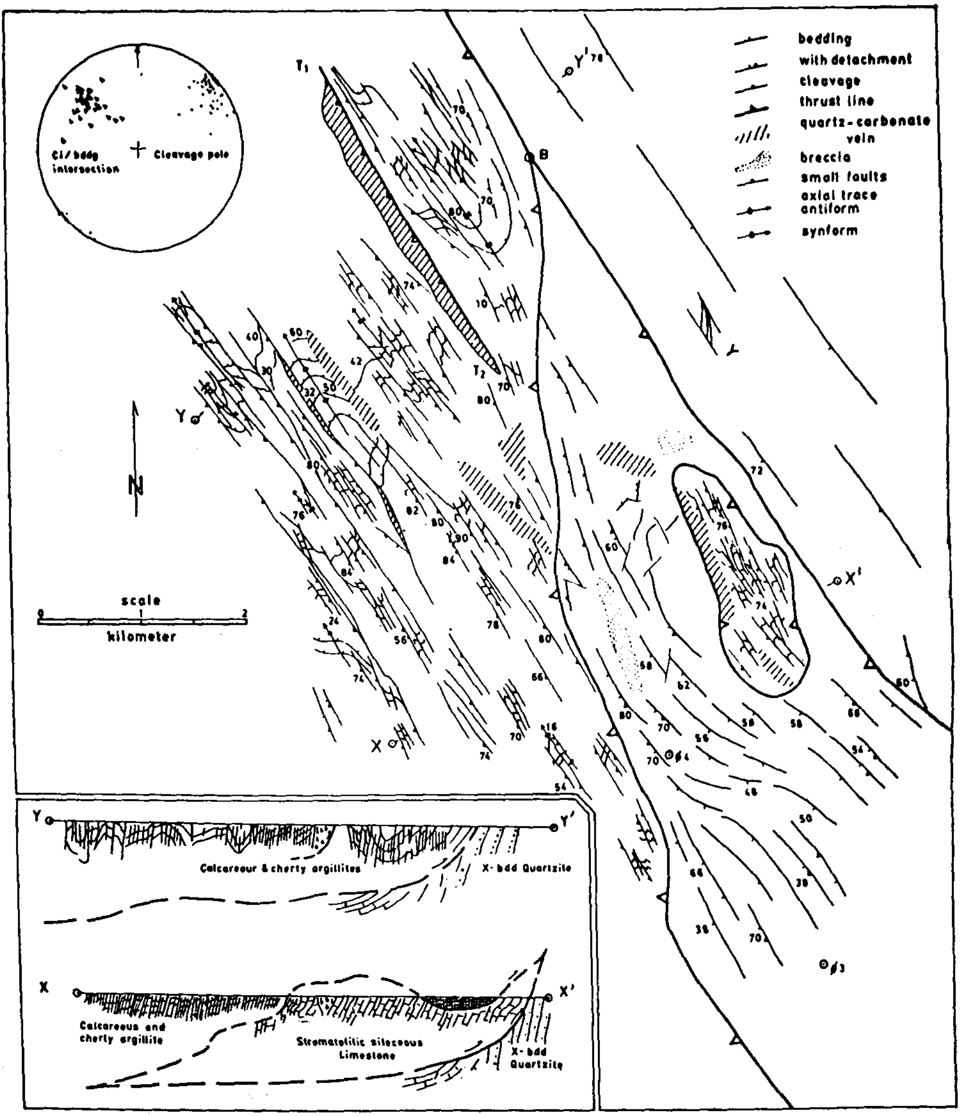

Figure 8. Structural details in the Lower Slice, for location see figure 2. Cleavage is of near vertical orientation; mesofold hinges and cleavage-bedding intersection lineation shows considerable spread (equal area plot, top left), consistent with displacement transfer from small fault (fault zones) to folds, the former having an orientation close to the cleavage. Schematic sections along *XX'* and *YY'* (bottom left) bringing out upward asymptotic curvature and branching of the Pedda Gutta Thrust.

the Pedda Gutta sheet as indicated earlier. Internal deformation within the horse is restricted to brittle faults, shallow folds of kink geometry and local breccia patches.

4. Thrust linkage and sequence of development

The bounding thrusts at the eastern margin of the three slices of the Pedda Gutta thrust sheet are steep at current erosion level. Stratigraphic arguments have already

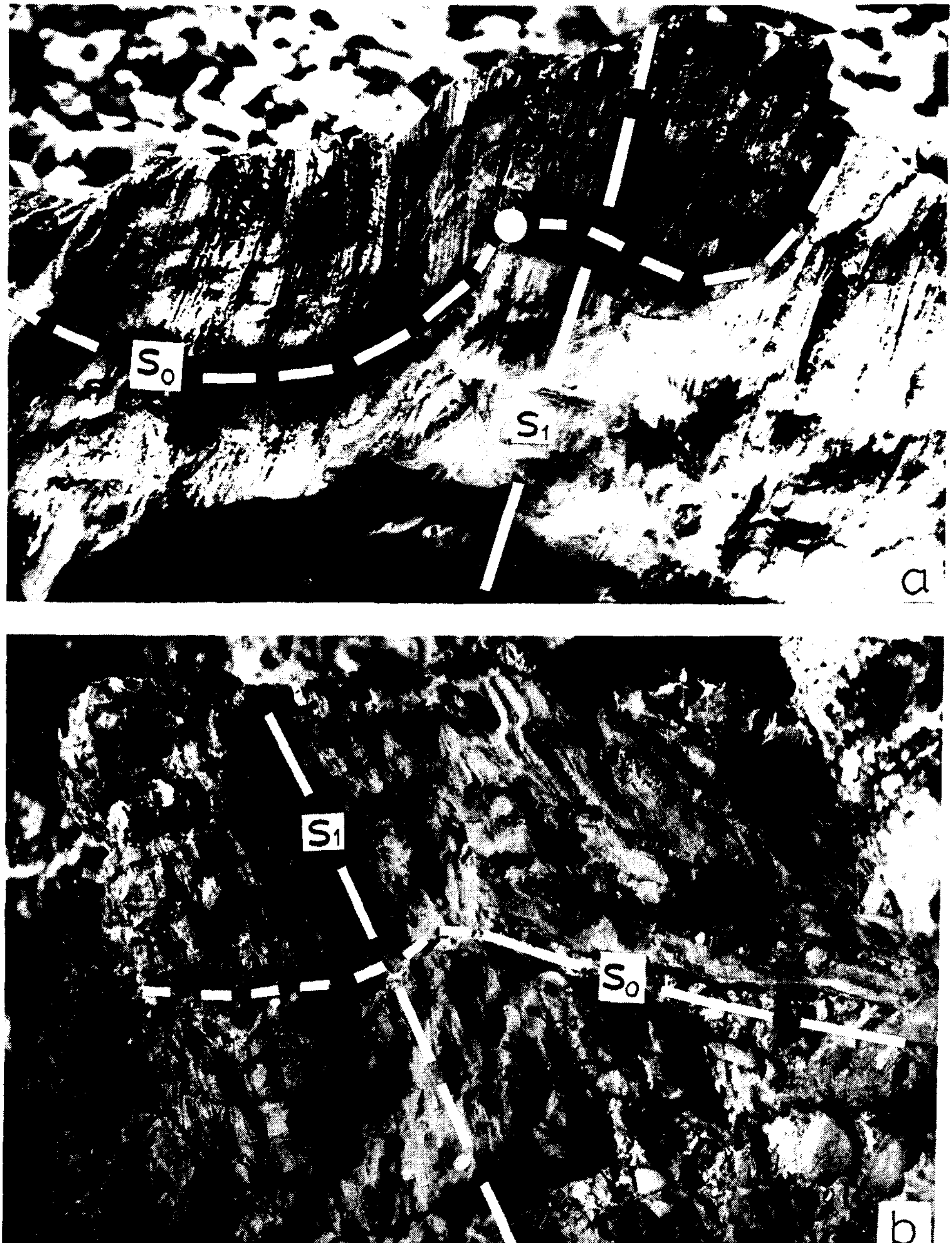

Figure 9. (a) Cleavage (S_1) associated with mesofold hinges and interfoliar quartz-carbonate veins. (b) Variation in the intensity of development of cleavage and interfoliar quartz carbonate veins within the domain of a small fold; transposition of bedding (S_0) is more marked on the left of the photograph, section looking south.

been put forward to indicate that the Pedda Gutta Chert Formation is allochthonous, brought to its present position by a horizontal translation on the Pedda Gutta Thrust. Albeit the obvious structural heterogeneity across the western boundary of the Somnur Formation, the metamorphic grade remains unchanged, scricite and chlorite delimiting the metamorphic threshold. There seems to be little doubt that on both sides of the dislocation, structures represent shallow crustal deformation. In the absence of any suitable stratigraphic marker horizon across the dislocation, the estimation of thrust shortening across the belt is only a hazardous guess. Taking the small Mesozoic basin of the southern Tethyan continental margin in the SE Aegean (Harbury and Hall 1988) as a reference point, the transition from a tidal flat carbonate facies through slope carbonates to basinal sediments may involve horizontal traverse of a few tens to one hundred kilometers. Even taking the basinal dimensions of the Proterozoic belt under discussion an order of magnitude lower, the horizontal translation involved in the juxtaposition of Pedda Gutta Chert Formation and Somnur Formation would be of the order of a few kilometres. If the dip of the Pedda Gutta Thrust at current erosion level (c. 70° west) remains constant at depth, horizontal displacement of a few kilometres may necessiate even a larger vertical component of slip. Obviously then one would have expected more marked metamorphic distinction across the dislocation, which it is not at the present case. Thus asymptotically curved downward listric form seems to be a reasonable proposition for the bounding thrusts.

The question naturally arises: how are the bounding thrusts of the different slices linked with each other? The eastern bounding thrusts of the Upper Slice and Middle Slice are also envisaged to be listric in form. The lithostratigraphic changeover across these bounding thrusts is gradational: from calcareous and cherty argillites through cherty argillite to cherty argillites and cherts. Therefore, the displacements across these individual bounding thrusts do not seem to be as large as on the Pedda Gutta Thrust, which, in my opinion, is comparable to a sole thrust in a hinterland dipping imbricate fan (cartoon section along *AB* on figure 2). Higher detachments breaking to the erosion surface through small ramps are common on all the slices (*e.g.* tip line $T_1 T_2$ on figure 8, section along YY' on figure 8; $T' T''$ on figure 3).

The wedge of limestone south of the branch point *B* (figure 8) is a horse bounded by an asymptotic curvature upward of the Pedda Gutta Thrust (section along XX', figure 8). The horse provides a glimpse of the footwall stratigraphy with respect to the sole thrust. Apart from beds rotating to an overall steepness, relatively lesser intensity of penetrative deformation within the horse suggests that this may be a late stage accretion in the progressive thrust movement towards the foreland (cf. Piggyback sequence, Butler 1982, 1985). Noticeably, nonplane noncylindrical fold forms are more common in the Middle and Upper slices as compared to the Lower Slice. One way of interpreting this is to consider folding of the higher thrusts as the sole thrust cuts through more of footwall ramps and consequent "intraplate" deformation. The folding rotation of an oblique cleavage near the western boundary of the Middle Slice is a case in point (figure 10). However, one must bear in mind that as compared to the classical examples of thrust systems (*e.g.* the Canadian Rockies or the Moine Thrust system) we are dealing with structures of a much smaller scale, possibly comparable in scale of cleavage dupluxes (examples given by Nickelsen 1986 are only 2–60 m thick); the depth to the sole thrust from the present erosion level for the Pedda Gutta thrust sheet is envisaged to be at best 50 metres.

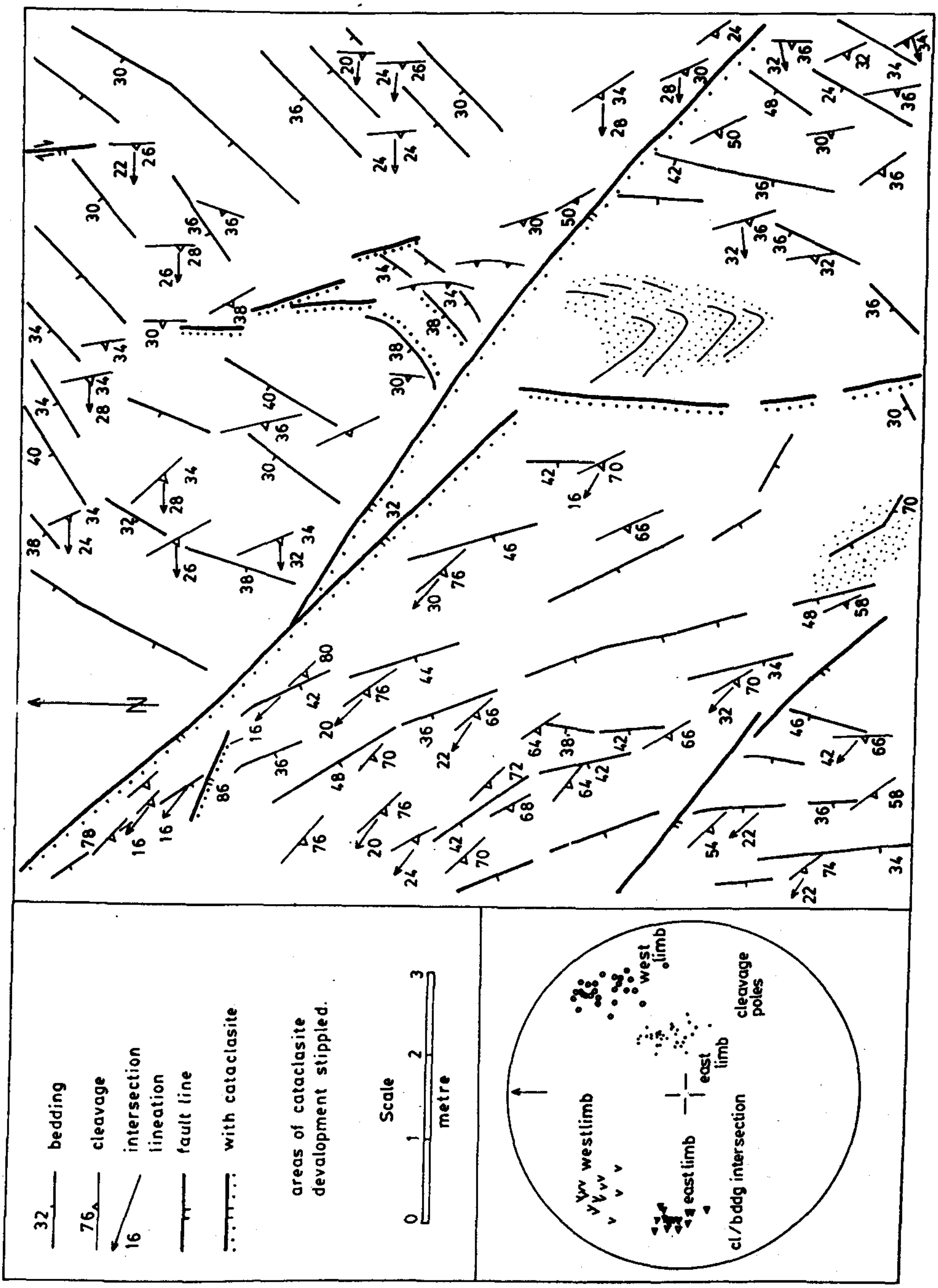

Figure 10. Rotation of the oblique cleavage around an angular fold subsequently disrupted by brittle faults, Middle Slice. For location with respect to the lower bounding thrust of the Middle Slice see figure 3.

5. Conclusion

A small thrust sheet, a few tens of metres thick, as exemplified by the rocks of the Pedda Gutta Chert Formation may exhibit a spectrum of mesoscopic structures, the spatial distribution of which may be linked up with certain bounding thrusts. Mesofolds in this sheet are in general non-cylindrical; folds with rounded hinges and to a certain extent periodic, occur in the Lower Slice, the most frontal part of the sheet; aperiodic folds of kink geometry prevail in the Middle Slice (higher up from the sole thrust); aperiodic folds with complex three-dimensional from (cf. those of sheath-like geometry) occur in the Upper Slice and/or where bedding detachments form a network through ramps in various directions in a small volume of rock. Cleavage is upright in the most frontal part of the sheet where there is a coincidental profusion of fluid mobility as indicated by syntectonic quartz-carbonate veins. Cleavage is moderately inclined and at an acute angle to bedding in the Middle Slice. In the Upper Slice, a spaced cleavage transecting bedding parallel parting develops in the vicinity of ramps which may connect displacement transfer from one flat to another (bedding parallel detachments); otherwise mylonitic foliation at a very low angle to bedding develop in thin zones along bedding detachments.

Displacement transfers from faults, either brittle or cataclastic flow zones (Rutter 1982), to folds is a common feature throughout the thrust sheet. In spite of the spatial relationship, conclusive proof of all folds nucleating at the tip or lateral terminations of faults and subsequently amplifying to their present form is not forthcoming from the structures of the Pedda Gutta thrust sheet (cf. Laubscher 1977 on the origin of Jura folds; House and Gray 1982).

In spite of the scale difference, the whole of the exposed part of the Pedda Gutta thrust sheet is comparable to the classical external zone of a Mountain belt in terms of structural style; qualitatively speaking, bulk shortening across the belt is accommodated as much by thrust displacements as by homogeneous shortening (the oblique cleavage without any obvious relationship with mesofold structures) or through periodic or aperiodic folding within the volume of the thrust sheet. If the geometry and style of mesoscopic structures are any indication, the strain distribution is extremely heterogeneous across even smaller bounding thrusts and emphasizes the necessity of detailed small scale structural studies before any large scale strain integration is attempted in fold-thrust belts.

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