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GEOLOGIC CONSTRAINTS ON DEPTHS OF TECTONIC MOBILITY IN A PROTEROZOIC INTRACRATONIC BASIN

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ABSTRACT

A half-graben model with listric boundary faults and detachments seem to apply for the extensional stage of the Proterozoic Godavari basin. Reactivation of early normal faults during basin inversion is proposed. Stratigraphic, structural, mineral paragenetic and deformation textural data from the basin are analysed to constrain features of the above model. The maximum preserved thickness of the Pakhal Supergroup is of the order of 5-6 km. This implies tectonic subsidence to deeper crustal levels to account for lower greenschist facies mineral paragenesis in the basin-infill material. Deformation textures indicate an ambient temperature of Ca. 300°C for basin infill and of Ca. 800°C for the mylonites derived from basement gneiss protolith. Considering a geothermal gradient of 25-30°C/km the depth to detachment controlling deformation of the basin infill is bracketed at 10 km; the mylonites represent detachment at a depth exceeding 25 km and connected to listric boundary fault adjoining Bhandara craton.

INTRODUCTION

The middle to late Proterozoic records in Indian peninsula testify to the development of a number of basins. Traditionally known as *Purana* basins (T. H. Holland, quoted in Radhakrishna, 1987), these are presumed to be of intracratonic (ensialic) nature. The latter is supported by the general absence of contemporaneous oceanic crust in the Purana records. Some degree of uniformity in the general geologic set-up of these basins have been emphasized by a number of workers (*e.g.*, Radhakrishna, 1987; Hari Narain, 1987). Pending development of a general model of basin evolution consistent with *Purana* records, one needs to find answer to the following questions with respect to a particular basin :

a) What thickness of the crust is involved either at the extensional stage or during closure of the basin ? (As it will be discussed later some of the basinal sequences do show contractional deformation features).
b) Boundary faults seem to play a significant role in the evolution of these basins. To what depths do the faults/fault detachments penetrate ?
c) How does one work out the tectonic subsidence, if any, of the basin infill ?
d) Questions related to thermal evolution of the basin infill and subjacent basement are also pertinent.

With the above queries in mind an analysis of the Proterzoic records of Godavari basin is presented.

GEOLOGIC SET-UP OF GODAVARI BASIN

Proterozoic rocks form two linear belts on either side of an axial outcrop of Gondwana rocks in the Pranhita-Godavari Valley region (Fig. 1). The NW-SE trending basin, referred variously as Godavari Rift, Godavari join, aulacogen, intracratonic orogen, separates the Bhandara craton in the east from East Dharwar craton in the west (Rogers, 1986; Rogers and Callahan, 1987; Saha, 1989). The tectonic mobility in either of the two cratons is supposed to have been ceased by late Archean - early Proterozoic time.

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The general stratigraphic sequence in the western belt of the Godavari basin is given in Table 1. The Albaka Sandstone (Srinivasa Rao *et al.,* 1979), a thick silty quartzite sequence develops in the eastern belt only and is juxtaposed with the gneisses of Bhandara craton along faulted contact. Although supposedly Pakhal equivalent rocks (*sensu stricto* Pakhal subdivision of King, 1881; Pakhal Supergroup of Chaudhuri, 1985) are reported from below Albaka Sandstone from the Albaka belt east of Godavari River, the exact correlation is fraught with difficulties (Saha, 1988). For the present purpose an asymmetry in development of the basinal sequences is important. The noteworthy aspects of this asymmetry are as follows :

a) Unconformable relationship with the basement gneisses are reported from the western Proterozoic belt only.

b) In many areas along the eastern belt, Bhandara craton gneisses are in faulted contact with the sedimentary sequence of the Albaka belt (Albaka sequence including Albaka Sandstone) and the Sullavai Group rocks of Bijur and Ahiri-Allapalli area. Incidentally the Gondwana rocks also exhibit faulted contact with the above Proterozoic sequences.

c) The Penganga Group of rocks are restricted to north of Godavari river in the western belt.

d) The deformed sequence which crop out around the confluence of Indravati and Godavari rivers (Somanpalli area; King's Sironcha country) are unique in the basin in terms of lithostratigraphic attribute and deformation style. (Some similarity in deformation style exist between Somanpalli area and Yellandlapad area (western belt), but the latter is again outstanding by virtue of its higher metamorphic grade).

In the following sections reference to the geology of four areas will be made, namely Mulug area representing the generally undeformed Pakhal Supergroup, the Yellandlapad area with high strain and higher metamorphic grade, the Albaka belt exposing the basement gneisses in faulted contact with the sedimentaries and the Somanpalli area around Godavari-Indravati confluence representing high strain but low metamorphic grade.

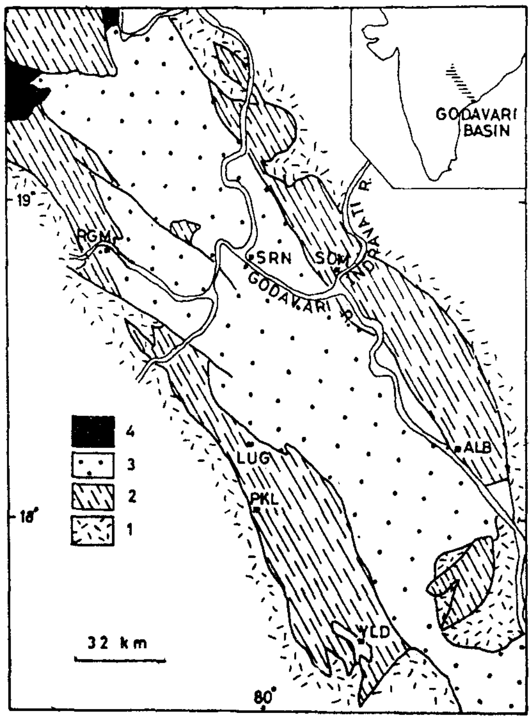


Fig 1 : General geological setting of Godavari Valley Proterozoic rocks (after King, 1881). 1=basement gneiss ; 2=unclassified Proterozoic ; 3=Gondwana rocks ; 4=Deccan Trap. ALB=Albaka, LUG=Mulug, PKL=Pakhal Lake, RGM=Ramgundam, SOM=Somanpalli, SRN=Sironcha, YLD=Yellandlapad.

TABLE 1

MAJOR STRATIGRAPHIC SUBDIVISIONS IN THE GODAVARI VALLEY

MESOZOIC	Gondwana Supergroup
	———unconformity———
MIDDLE TO LATE PROTEROZOIC	Penganga Group
	———unconformity———
	Sullavai Group
	———unconformity———
	Pakhal Supergroup
	———unconformity———
ARCHEAN	Basement Gneiss

IMPLICATION OF STRATIGRAPHIC THICKNESS DATA

To a first approximation the volume of basin infill reflect the subsidence history of the basin. On the other hand the overburden pressure on the basement or oldest of the basin infill strata is determined by the thickness of the basin infill. Thus, estimates regarding basin subsidence/overburden pressure should take into account the following stratigraphic thickness estimates from the basin (Table 2).

METAMORPHIC GRADE IN THE BASIN INFILL AND ADJOINING GNEISSES OF ALBAKA BELT

The Pakhal Supergroup rocks are generally regarded as sedimentary sequences. However, closer scrutiny reveals a low-grade metamorphic imprint (Table 3). The dominant mineral paragenesis in argillaceous rocks from Mulug or the vicinity of Pakhal Lake in the western belt, and Albaka or Somanpalli area in the eastern belt is chlorite-quartz-opaque, a low greenschist facies assemblage indicating an ambient temperature of about 300°C.

The metamorphism of the Pakhal rocks of Yellandlapad area have been worked out in detail by Rammohana Rao (1971). Porphyroblasts of garnet, staurolite and andalusite in phyllite, or those of tremolite and diopside in marble point to a higher metamorphic grade (T 500-600°C). It may be recalled that the maximum preserved thickness of the basin infill is of the order of 6 kms. A geothermal gradient of 35-40°C/km would entail at best anchimetamorphic temperature at the base of Pakhal sequence if the preserved thickness approximates the true thickness. Even assuming 50% loss due to erosion of original depositional pile (corresponding to the Pakhal Supergroup) following uplift, the temperature at the base of the pile would still be lower than that interpreted from metamorphic mineral paragenesis. Thus tectonic subsidence to greater depths and/or enhancement of local thermal gradient needs to be considered.

Looking further afield, bulk of the gneisses adjoining the Albaka Sandstone in the Albaka belt are of amphibolite facies. Migmatisation is a common feature here. An assemblage of amphibole-garnet plagioclase/quartz or brown biotite-garnet plagioclase in the mafic bands indicates upper greenschist- to amphibolite-facies temperatures (650°C-800°C). However, relict assemblages of orthopyroxene-clinopyroxene-garnet indicate low granulite-facies protoliths.

TABLE 2

STRATIGRAPHIC THICKNESS IN DIFFERENT PARTS OF PROTEROZOIC GODAVARI BASIN

sequence / area	works referred	thickness (km)
PAKHAL SUBDIVISION western Proterozoic belt	King (1881)	1.6
PAKHAL SUPERGROUP and SULLAVAI GROUP Ramgundam area	Chaudhuri (1985)	1.7-2.1
PAKHAL GROUP Mulug-Pakhal lake area	Basumallick (1967)	5.9
ALBAKA SUBDIVISION and SULLAVAI GROUP Albaka belt	Srinivasa Rao *et al.* (1979)	5.3

TABLE 3

METAMORPHIC MINERAL PARAGENESIS IN DIFFERENT PROTEROZOIC FORMATIONS OF GODAVARI VALLEY

Horizon / area	Paragenesis	Metamorphic facies	T°C
MULUG SHALE Mulug	CHLORITE + MUSCOVITE	LOW GREENSCHIST[1]	300
TIPPAPURAM SHALE Albaka	CHLORITE + MUSCOVITE	LOW GREENSCHIST[1]	300
SOMNUR Fm Godavari-Indravati confluence	CHLORITE + MUSCOVITE + QUARTZ	LOW GREENSCHIST[1]	300
PAKHAL GROUP Yellandalapad	CHLORITE + CHLORITOID + QUARTZ BIOTITE + STAUROLITE + GARNET BIOTITE + GARNET + ANDALUSITE	ALMANDINE [1, 2] AMPHIBOLITE	525-670 (2 kb)
	CALCITE + TREMOLITE + DIOPSIDE	HORNBLENDE HORNFELS[2]	550-700 (1-3 kb)
BASEMENT GNEISS Albaka belt	BROWN BIOT + GT + QTZ + PLAG BROWN HBL + GT + HYPERSTHENE BROWN HBL + PLAG + QTZ + OPQ GREEN / BROWN HBL + PLAG	UPPER AMPHIBOLITE[1]	500-700
	OPX + CPX + GT	LOW GRANULITE[1]	850
[1] THIS STUDY	[2] RAMMOHANA RAO (1971)		

The question remains whether these high-grade gneisses could be regarded as representative of the basement subjacent to the basin infill referred to above. To this end geometric models of external basin evolution is considered below.

GEOMETRY OF EXTENSIONAL BASIN MARGIN AND FAULT REACTIVATION

One mode of extension of the upper continental crust is rifting. Traditional models of rift basins assume symmetric structure with planar boundary faults on either side. The growing volume of seismic data on both recently developed and ancient rifts worldwide (for example, East Africa and the North Sea) allows a glimpse beneath the surface and consequently, a reappraisal of the rift structure. The new model of rift structure is dominated by a controlling boundary fault and a number of synthetic faults or antithetic faults producing an asymmetric half-graben (Rosendahl *et al.,* 1986).

Geometric considerations alone show that a set of normal faults (domino faults) with constant dip is associated with space problem at the detachment; a large extension is also necessary for any appreciable thinning of the crust. An extensional basin model with listric form geometry for the boundary faults, which overcomes the above problems associated with domino faults, have been proposed for the North Sea (Gibbs, 1984). Here, geometric considerations are supplemented by seismic sections and actual well control. In essence, there is similarity in geometry of listric fan along a rift margin and imbricate fan of a linked thrust system. Recycling of once-formed structure is possible in basins where an extensional regime is followed by a contractional regime and vice-versa. Old fault zones are mechanically favoured for renewed movement, although field recognition of such reactivation may be difficult (Etheridge, 1986; White *et al.,* 1986). Fault reactivation and *moulding of folds* against extensional regime faults have been proposed for the deformation in the ensialic Labrador trough *geosyncline* (Dimroth, 1981). An example of thrust sense movement on normal fault during basin inversion has been described from Australia (Etheridge, 1986). Interpretation of the MOIST profile across the Scottish Caledonides favour repeated fault movements across some of the crustal-scale faults (Smythe *et al.,* 1982).

In the eastern Proterozoic belt of the Godavari Valley the gneisses of the Bhandara craton are in faulted contact with the Proterozoic sedimentary sequences of Somanpalli and Albaka belt (Saha, 1988). Over a strike length of about 100 kms in the Somanpalli-Albaka terrane, tectonic dislocations which are steep at current erosion level separate strikingly dissimilar lithofacies association (Saha and Ghosh, 1987, 1988; Saha 1989). Rapid sedimentary facies change controlled by faults is a common feature in East African Rift basins (Frostick *et al.,* 1986) and in passive continental margin undergoing extension as for example in SE Aegean (Harbury and Hall, 1988). It is proposed that west-dipping listric faults associated with a half-graben structure opened up a trough which acted as a repository for the Proterozoic sequence adjoining Bhandara craton (Fig. 2).

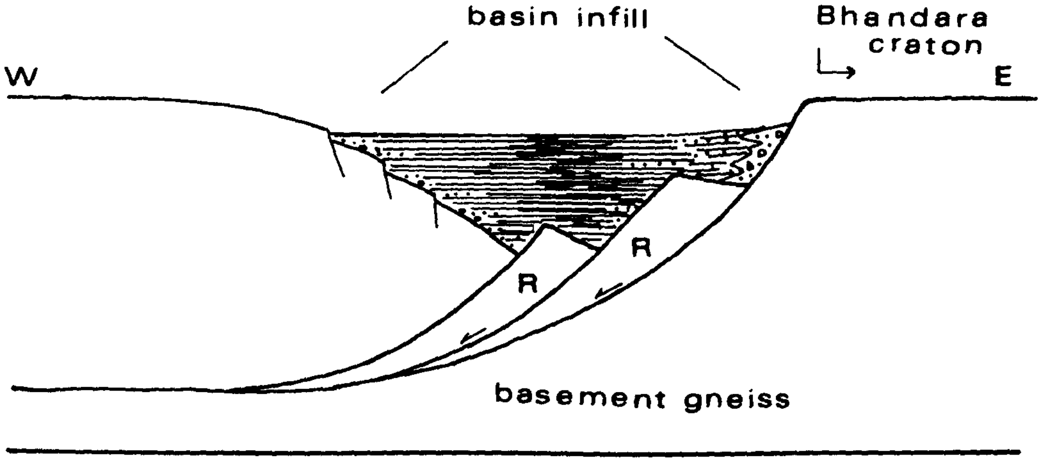


Fig 2 : Cartoon section (not to scale) showing a half-graben listric fan model for the extensional stage of the Godavari Valley Proterozoic basin adjoining Bhandara craton. Some of the riders (R) may push up along the listric boundary fault during basin inversion.

Small- and large-scale structures representing shortening across basin strike are well-documented from the Proterozoic rocks of Somanpalli and adjoining areas (Saha and Ghosh, 1987; Saha, 1990). Here, tectonic dislocations extending for a few tens of kilometres are interpreted to be associated with fold-thrust movement affecting the basin infill. Following the listric geometry of the bordering faults inherited from extensional regime some of the basement slices originally forming the floor of the sedimentaries are likely to be pushed up by thrust-sense movement. The coexistence of cataclasite as well as strongly mylonitic rocks in a 2-3-km wide-belt of gneissic rocks immediately adjoining the sedimentaries is highly suggestive of juxtaposition of rocks of different crustal levels.

The above line of reasoning leads to the consideration that some of the gneisses scooped up along the boundary fault represent deeper crustal material originally occurring subjacent to the basin infill. An analysis of the deformation microstructure (texture) in the gneisses straddling the boundaıy fault and those in the basin infill material as detailed below will justify the proposition made above. A brief review of deformation texture as an indicator of ambient temperature is given first.

DEFORMATION TEXTURE AS (P, T) INDICATOR

The major controlling factors in deformation of crustal material are temperature (T), confining pressure (P), strain rate and fluid pressure. Theoretical consideration, analysis of results of experimental deformation and observation on naturally-deformed mineral aggregates form the basis of some general conclusions on the relationship between deformation texture and controlling factors. Deformation textures induced in common rock-forming minerals like quartz, feldspar, calcite, dolomite, mica, hornblende and pyroxene are known to be temperature-sensitive (Table 4).

TABLE 4

DEFORMATION TEXTURAL INDICATORS OF AMBIENT TEMPERATURE (THE MAJOR WORKS PERTAINING TO EXPERIMENTAL OR NATURAL DEFORMATION IN COMMON ROCK-FORMING MINERALS ARE QUOTED)

Authors	Indicator	T
Griggs *et al.*, 1960	experimental deformation / Yule marble sharp, planar twins extending from edge to edge, calcite e twin	500°C
Higgs and Handin, 1959	experimental deformation, dolomite single crystal f twin	400-500°C
Schmid, 1982	theory, coexistence of calcite e twin and dynamic recrystallisation *cf.* Lochseiten mylonite, Glarus	0.5 T/T_m
Groshong, 1988	grain-scale fracture, P.S., crystal plasticity in qtz + calcite, polygonisation,	0.3 T/T_m upper limit
Olsen and Kohlsted, 1985	deformation twins of intermediate plagioclase in amphibolite	low granulite facies 750-900°C
Boudier *et al.*, 1988	Zabargad Island gneiss, acid granulite and gabbros recrystallised An_{25}-An_{45} and hornblende	gt-cpx• geotherm 900-1000°C - 10.8 kb
Tullis and Yund, 1985	experimentall-deformed synthetic aggregate Ab_{98} dynamicrecrystallisation	900-1000°C 15 kb 10^{-5}-10^{-6}/s
Etheridge and Hobbs, 1974	annealing of experimentally-deformed phlogopite biotite	1050°C 10kb Ca. breakdown T

[T_m = Liquidus Temperature ; P. S. = Pressure Solution ;
•Garnet (gt) – Clinopyroxene (cp_x) geothermometer is after Ellis and green (1979)].

Only optically-recognisable deformation texture is considered here. Whereas cataclasis is a near-surface (0-3 kms) phenomenon (Wu, 1989), ductile behaviour of feldspar represents deformation at higher temperature and pressure (Boudier *et al.*, 1988 ; Tullis and Yund, 1985). Pressure solution in quartz, calcite and feldspar is restricted to low-temperature deformation regime (Rutter, 1983).

DEFORMATION TEXTURE IN BASIN INFILL AND ADJOINING GNEISSES

Grain-scale penetrative deformation is recorded from within the Proterozoic sequence of Somanpalli-Albaka terrane in the eastern belt and Yellandlapad area of the western belt. Thin sections of rocks showing obvious mesoscale L-S fabric were examined for optically-recognisable deformation texture in different mineral phases. In order to exclude the possibility that strain intensity may have some influence on the texture induced by dominance of a particular deformation mechanism, the specimens were so selected as to represent a spectrum of low to high strain.

Quartz grains in the basin-infill material with well-developed cleavage show pressure solution, undulose extinction and dynamic recrystallisation, the latter more common in high-strain zones. In contrast, both alkali and plagioclase feldspars deform dominantly by microfracturing (Fig. 3). Only in highly-strained arkoses overlying gneisses in the Yellandlapad area, a few grains of feldspar show undulose extinction. The deformation texture in different mineral phases including calcite, dolomite, chlorite, muscovite, biotite, hornblende, pyroxene, garnet representing the basin infill and/or basement gneiss are summarised in Table 5.

As indicated earlier, cataclasite bands do occur within the gneisses adjoining the sediments of Somanpalli-Albaka terrane. In these bands, a dominance of grain-scale microfracturing irrespective of mineral phase overprints the older metamorphic recrystallisation. The texture in mineral phases listed in the right-hand column of Table 5 refer to mylonite bands affecting the basement protoliths. Noticeably, the plagioclase grains here show common deformation twins, extreme grain elongation without fracturing and even recrystallisation (Fig. 4). Kinking and polygonisation are common in large perthite grains. The effect on mafic minerals like biotite, hernblende and pyroxene are also indicative of deformation at a much higher temperature compared to the basin-infill material.

DISCUSSION

A half-graben model with listric boundary fault is proposed for the Proterozoic basin development in the Somanpalli-Albaka terrane. Reactivation of the extensional stage fault zones during later shortening across the basin strike is consistent with geologic observations detailed in the preceding section. The influence of detachment horizons in the fold-thrust development of the basin infill has been demonstrated elsewhere (Saha, 1990). The question of depth to these detachments is addressed below :

The metamorphic mineral paragenesis in the basin infill (Table 3) suggests that the highest temperature attained, except for the Yellandlapad sequence is of the order of 300°C. Metamorphic minerals in the Yellandlapad area represent temperatures of the order of 500-600°C. The area probably was one of anomalous geothermal gradient. An estimate of 300°C for ambient temperature is obtained from consideration of dominant deformation texture in quartz, calcite, dolomite and feldspar, the principal rock-forming minerals in the basin infill.

Conversion of temperature estimate to corresponding depth value is possible by invoking an appropriate geothermal gradient. The geothermal gradient in the earth's crust varies both in time and space (Thompson, 1984 ; Watson, 1984 ; Weber, 1984). The geothermal gradient in the Basin and Range Province in the United States is of the order of 25-30°C/km (Weber, 1984). This figure is taken as a representative of Proterozoic Godavari basin on two counts. The Godavari Rift basin is in an ensialic set-up as is the Basin

TABLE 5

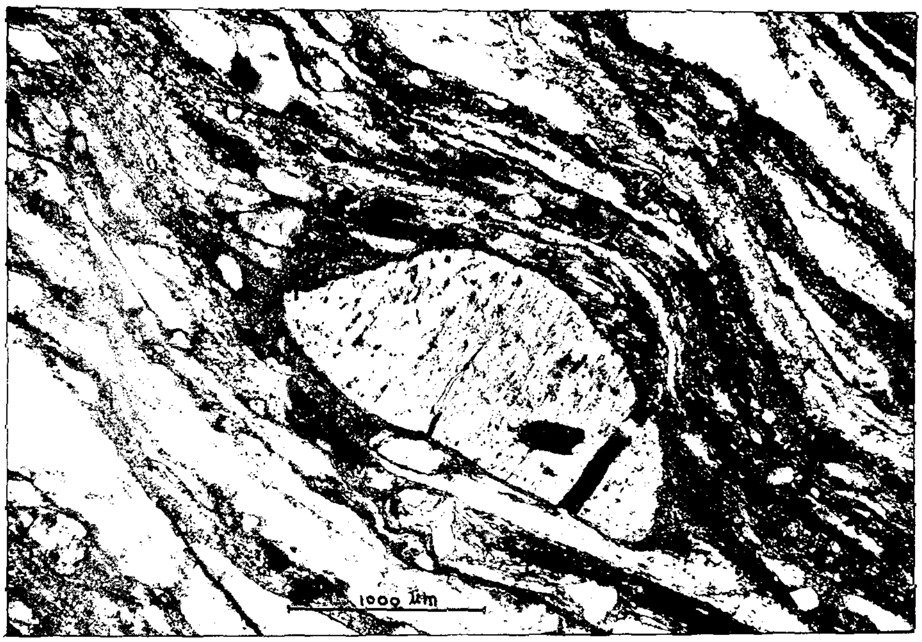
OBSERVED DEFORMATION TEXTURE IN MINERALS OCCURRING IN BASIN INFILL AND BASEMENT GNEISSES OF GODAVARI BASIN

MINERAL PHASE	DEFORMATION TEXTURES	
	Basin Infill Protolith	Basement Gneiss Protolith
Plagioclase	relict growth twins rare deformation twins in high-strain mylonites	* abundant mechanical twins (Albite & Pericline laws) bent twin lamellae, undulose ** dynamic rextln ** globular grains with rextln. trails, LPO
Chlorite	kink, patchy extinction, recrystallisation	
Muscovite	kink	kink
Biotite	kink	kink, dynamic rextln
Hornblende	——	undulose, marginal rextln in high-strain necking of grains
Hypersthene	——	undulose, kink
Garnet	——	fracture
Dolomite	* P.S., mechanical twins dynamic rextln. at high strain, LPO, g.b.a	
Quartz	P.S., undulose extinction * deformation lamellae * (subbasal & basal) deformation band, subgrain ribbon grains, dynamic rextln. LPO in high-strain foam texture in recrystallised chert	ribbon grains, undulose subgrain, dynamic rextln * prism Fairbairn lamellae * LPO in migmatitic quartz
K-feldspar	microboudins at high strain, fractures, rare marginal rextln	patchy extinction, polygonisation, subgrain "deformation lamellae", healed microcrack, rextln. trail with porphyroclasts, LPO
Perthite	fracture	subgrain, kink

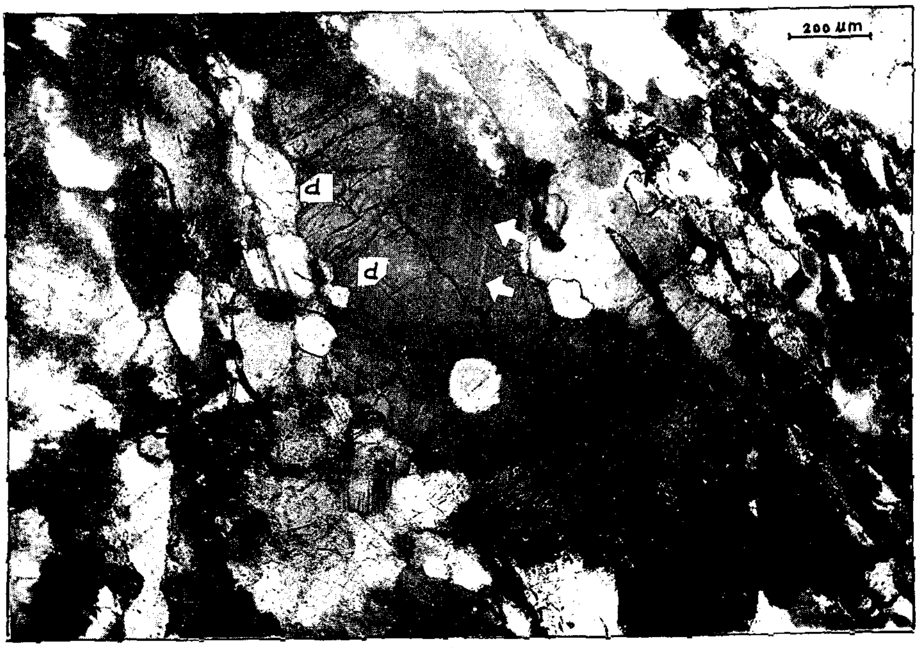
[Rextln = Recrystallisation, g.b.a = Grain boundary alignment, P.S. = Pressure solution., LPO = Lattice preferred orientation]

and Range Province. The latter is known to be an area of active normal faulting (extensional structures ranging in age from Oligocene to Holocene; Hamilton, 1987). A similar value for the geothermal gradient has also been proposed for the Proterozoic continental crust from a general consideration of metamorphic assemblages (Watson, 1984).

Using the above figure for geothermal gradient the upper limit of depth corresponding to a temperature of 300°C is about 10 km. Hence, the basin-infill material in the Godavari basin sufferred tectonism above this depth. The intrabasinal listric faults moulding the fold-thrust movement within the basin infill should flatten out at a depth of ten kilometres. On the other hand, deformation texture in the mylonites derived from gneissic protoliths indicate an ambient temperature of about 800°C. The latter corresponds to a depth



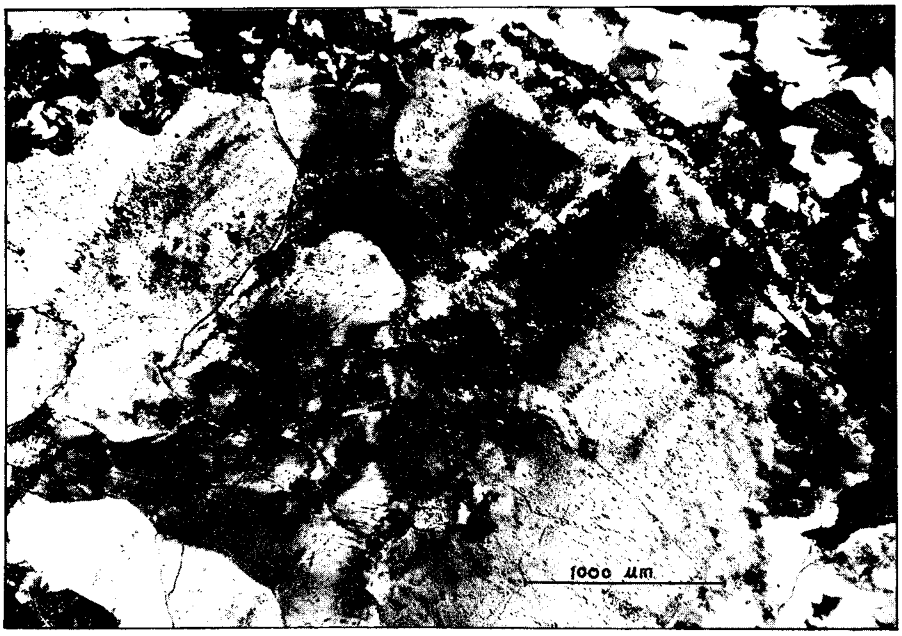
a



b

Fig 3 : Contrasting deformation texture in feldspar from the basin infill(a) and basement gneiss(b). Quartz shows ribbon grain and dynamic recrystallisation in both. (a) Deformed subarkoses overlying gneisses, Yellandlapad ; feldspar shows brittle microcracks at a high angle to mylonite foliation. (b) Plagioclase grain running diagonally across the width of the photograph has an aspect ratio of 5:1 ; note deformation twins (arrow) and naturally-decorated tangled dislocation(d), deformed amphibolite gneisses, boundary fault zone, Albaka belt. The axial crack is a preparation damage.

a



b

Fig 4 : Ductile deformation texture in plagioclase and perthite. (a) Deformation twins in plagioclase, amphibolite gneiss, boundary fault zone, Albaka belt. Note tapering twin lamellae and combined Albite and Pericline law twins (bottom right). (b) Kinking and polygonisation of large perthite grain, migmatite band, Albaka belt.

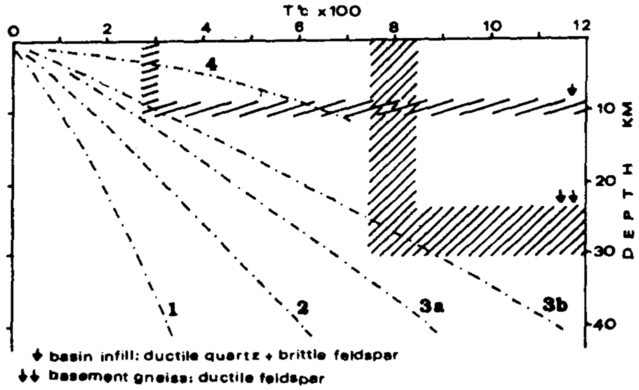


Fig 5 : Geothermal gradient in the earth's crust and conversion of ambient temperature estimate to an estimate for depth of tectonic mobility for basin infill (single arrow) and basement gneiss (double arrow). Geotherms after Weber (1984); 1=Sierra Nevada, 2=stable crust, 3a-b=Basin and Range Province, 4=Rheinesche Schifergebirge.

of about 25-30 km using the same geothermal gradient (Fig. 5). If indeed these gneisses are brought up to the surface during thrust movement on listric boundary fault as suggested earlier, the depth to detachment for the boundary fault would be about twentyfive kilometres.

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