

Slope-deviatory alignment, stream network and lineament orientation of the Sabarmati River system—Neotectonic activity in the Mid- to Late Quaternary

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The Gujarat alluvial plain located in the semi-arid zone is bounded by the arid Thar region in the north and the coastal/estuarine zone fringing the Arabian Sea in the south. It has been built by the rivers originating in the Aravalli Hills in the northeast. The drainages, with an average length of about 300 km, generally follow the NE-SW regional slope. However, the Sabarmati River shows a flow deviating from the regional slope and follows a N-S to NNE-SSW trend in the alluvial area.

The slope-deviatory trend of the Sabarmati has been investigated with regard to Late Quaternary neotectonics, fluvial-aeolian interaction and sea-level change. Linea-

ment analysis indicates an E-W to WNW-ESE trajectory of maximum principal stress, and that drainage is primarily controlled by geodynamic processes. This is obvious from the correspondence in stress trajectories obtained from the lineament and drainage orientations, respectively.

Sub-surface data indicate pre-Neogene faulting in the basin. It is inferred that these faults have been reactivated in the Mid- to Late Quaternary times. The slope-deviatory drainage of the Sabarmati River is, to a large extent, the result of fluvial adjustment to neotectonic reactivation in the region.

Introduction

THE state of Gujarat in western India consists of four physiographic micro-regions, namely the Rann, the Kachchh peninsula, the peninsular Gujarat, and the Gujarat alluvial plain. The alluvial plain has a network

of drainages, emerging from the N-S to NW-SE trending Aravalli hills. Of these, the Sabarmati (Figure 1) and Mahi are the most important drainages. The Sabarmati River originating in the southern Aravalli follows, for 185 km, a nearly north-south trend up to Navapura ($22^{\circ} 40' 54''$; $72^{\circ} 30' 12''$). The contour map of

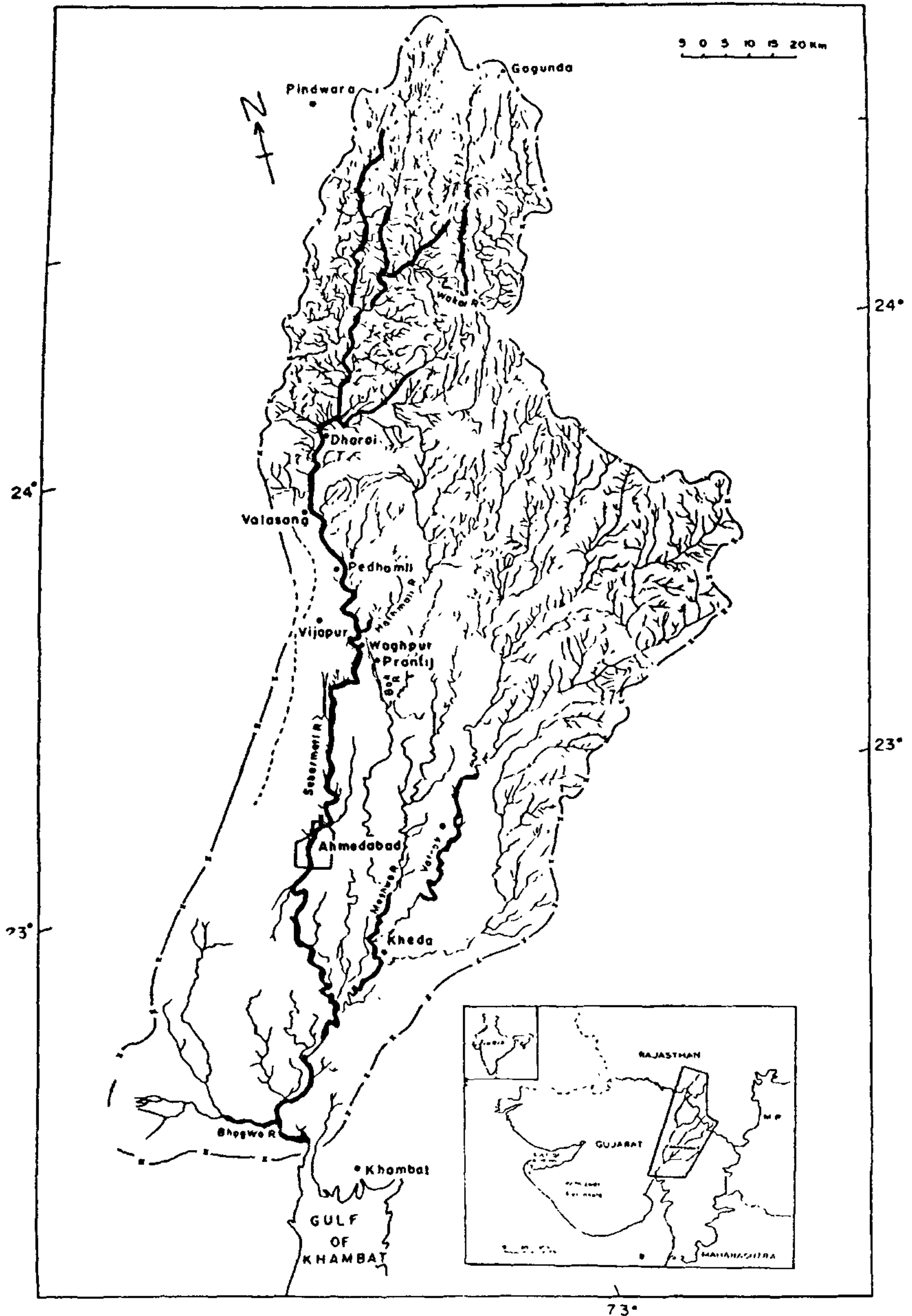


Figure 1. The Sabarmati drainage basin.

the alluvial plains in the alluvial sector between Dharoi and Vijapur shows that there is a maximum deviation of 40° in the flow vector of the Sabarmati from the NE-SW regional slope (Figure 2). The Banas, Saraswati and Rupen rivers to the west of Sabarmati follow the NE-SW regional slope of this alluvial terrain (Figure 3). North Gujarat has been affected by neotectonic activities¹⁻⁵ (also see ref. 10, 11) while the West Coast has had a complex history of sea-level changes. There are three high-level strands corresponding to 6,000; 30,000 and 1,20,000 years B.P.⁶ Evidence for the 30,000 yr high strand is lacking⁷. Recent work on miliolites has provided dates for three episodes of high sea-level strand and these correspond to 50-70; 75-115 and

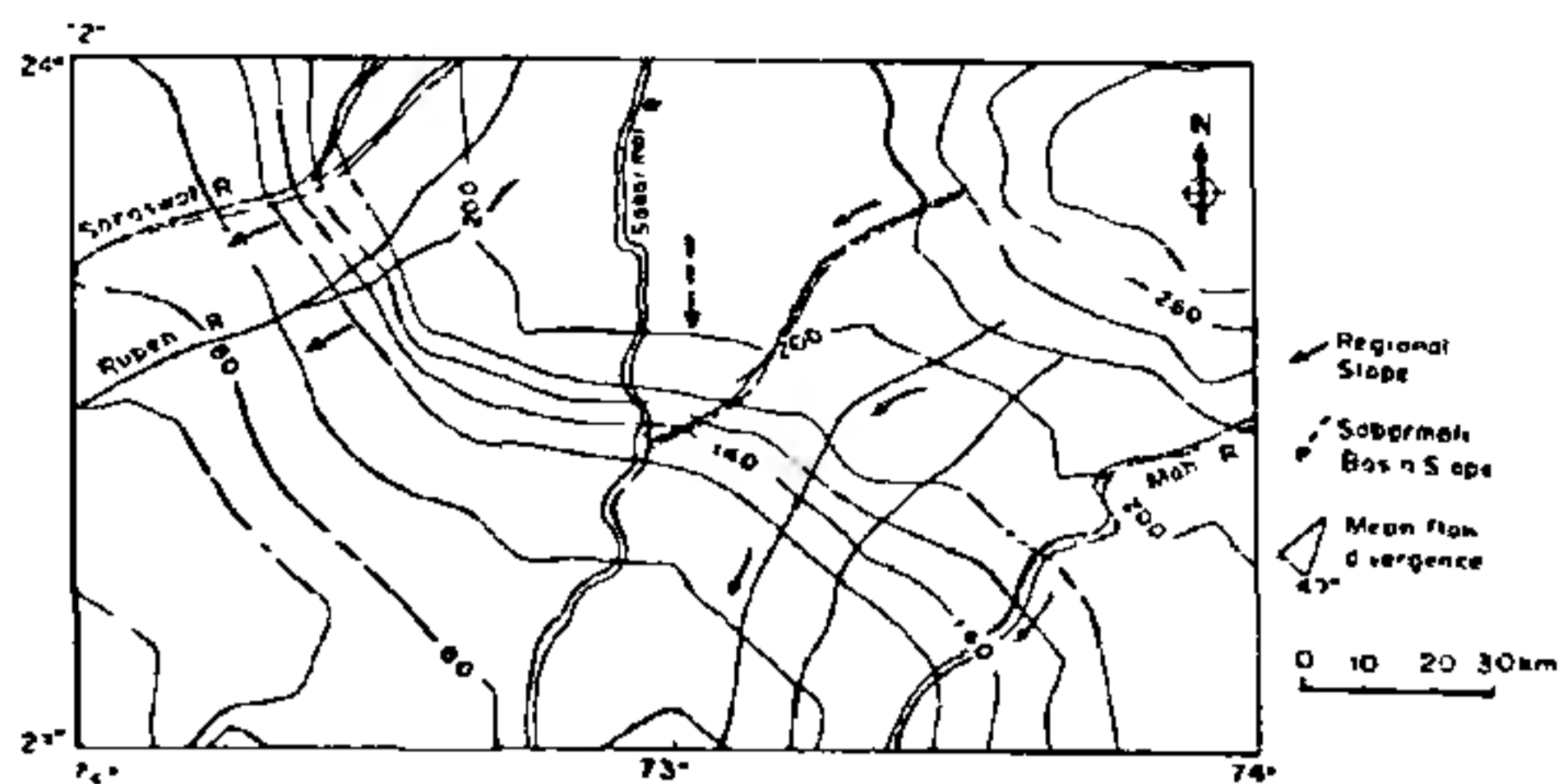


Figure 2. Generalized contour map prepared by a computer using the contour and spot elevation data of 1:2,50,000 scale degree sheets. Note the divergence of flow of the Sabarmati River with respect to other slope parallel rivers of the region.



Figure 3. Satellite imagery covering the Sabarmati River and other important rivers in the region.

140–210 thousand years⁸. A factor of importance is the increase of aridity in north Gujarat. The SE-NW trending dune fields are developed on both sides of the Sabarmati basin and within the interfluvies of the tributaries of the river basin. The dune complexes on the western side of the Sabarmati river are stabilized and are dated to 20,000 to 5,000 yr⁹.

The primary objective of this study is to examine the development of the Sabarmati drainage system in relation to neotectonic activity. The anomalous flow of the main Sabarmati channel reflected by a deviation of 40° from the regional slope and lack of development of flow lines on the eastern flank of the river is also investigated for recognition of possible causal factors. Studies carried out on various aspects of neotectonic activity in the surrounding areas of Thar desert¹⁰, Southern Aravalli⁵, Cambay¹¹ and Saurashtra¹ indicate reactivation of pre-Quaternary faults in the region. Several earthquakes have also been recorded in recent years^{12,13}. However, information about the alluvial terrain comprising the Gujarat plains is meagre⁴.

Sabarmati basin

The Sabarmati basin is a narrow oblong basin which has a wide eastern flank and a narrow western flank (Figure 1). The basin has three broad sub-divisions: (1) the upper reaches, where left and right bank tributaries flow on greater slopes and act as erosive channels

debouching on to the alluvial plains; (2) the middle reaches, where all the tributaries join the main channel from the wider eastern side of the basin; and (3) the lower reaches, where all the tributaries of the Sabarmati converge into one main channel. This area is also influenced by estuarine tidal processes from the Gulf where the river meets the sea.

The basin margin on the eastern side is marked by a sharp break in slope-forming escarpments whereas the western basin margin marks a piedmont zone. Southwards, from lat. 24° 15' N to 24° N, the river basin margin tends to become wider as the characteristic linear trend of ridges spreads into low, diffused masses of hills and dissected granitic country with occasional granite tors. Further southwards, from lat. 24° N to lat. 23° N, the river basin becomes widest (115 km) as the river cuts through a flat alluvial plain. The main channel flows nearly N-S and closer to sharp, and linear western margin of the basin. The wider eastern margin is gradational. All the tributaries from the eastern side of the River flow in the NE-SW direction. No river tributaries join from the west.

From lat. 23° 30' N to 23° N, southwards the River maintains a N-S to NNE-SSW trend. The basin width is reduced to about 90 km and the main channel closely follows the western margin. From lat. 23° N to lat. 22° 30' N southwards the River enters the estuarine zone and the main channel occupies the centre of the basin, which is only 60 km wide. South of lat. 22° 30' to

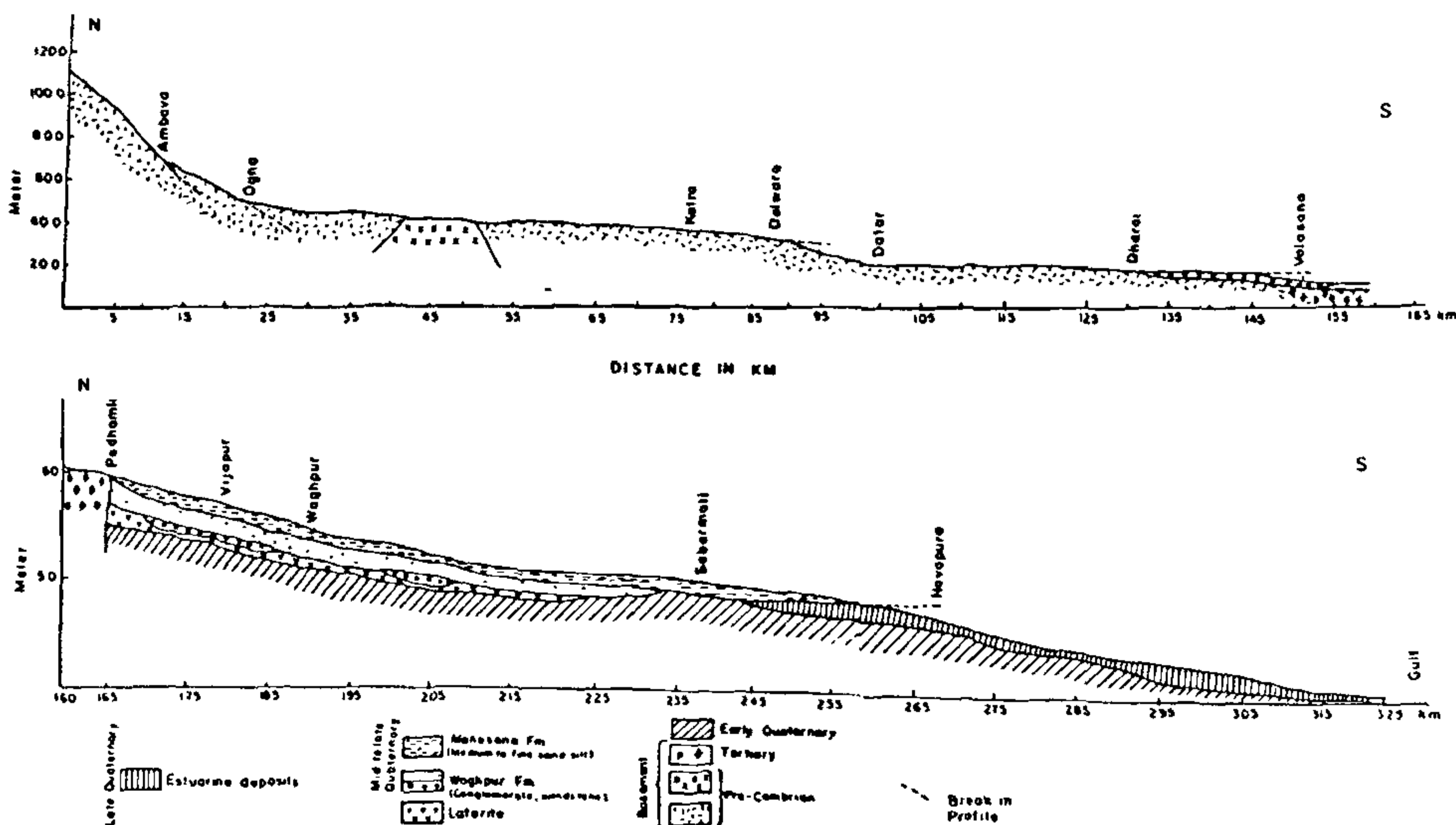


Figure 4. Longitudinal profile of the Sabarmati River in the Aravalli and alluvial areas.

lat. 22° 15' the river flows along the eastern basin margin. A tributary joins the river from Saurashtra uplands from the western side and in contrast the eastern basin margin becomes narrow (Figure 4). In general, the Sabarmati valley profile (Figure 4, Table 1) is smooth with only a few visible breaks. There are six breaks in the river profile of which three are observed in the higher reaches in the hilly terrain, two in the middle reaches of the river in alluvial area and one break in the alluvial/estuarine interaction zone.

Lineament studies and analysis of stress fields

Lineament studies in and around Sabarmati basin were carried out on LANDSAT false colour composite (FCC) covering bands 2, 3 and 4 of 1:250,000 scale. The multispectral scanner (MSS); thematic mapper (TM) and Indian Remote Sensing Satellite (IRS-IA) data were analysed (Figure 5).

Assuming that all the lineaments are traces of shear

lines or vertical fracture surfaces of a tectonic stress field, maximum and minimum stress directions have been determined^{14,15}.

Alluvial area

The 185 lineaments demarcated in the alluvial area (Figure 5a) fall into two groups of preferred orientations, one trending ENE-WSW to E-W and the other trending NW-SE. The two maxima are calculated to be 68° and 138° with an acute intermediate angle of 70°, giving maximum (P) direction as 103° and minimum (T) direction as 13° (Figure 6, Table 2).

Using enhanced seismic techniques, several NW-SE to NNW-SSE trending subsurface faults have been recorded in the Mahesana-Ahmedabad sector, east of Sabarmati River¹⁶. This information is corroborated by data from a number of exploratory wells. Obviously, the lineament orientations are related to the subsurface faults and folds and thus suggestive of reactivation of the pre-Quaternary faults.

Table 1. Channel characteristics: Sabarmati River

S.No.	Segment		Length (km)	Altitude (m)			Confluence/tributary Rt/Lt Bank	Distance from source
	From	To		From	To	Fall		
1	Khakhdi	Ambava	14.55 (12.5)	1123	700	423)		
2	Ambava	Ogna	22.63 (18.5)	700	500	200)		
3	Ogna	Nayagaon	20.87 (17.5)	500	416	84)	Wakal	
4	Nayagaon	Manpur	13.93 (12.5)	416	390	29)	River	
5	Manpur	Kotra	21.04 (16.75)	390	350	40)		
6	Kotra	Delwada	7.98 (7)	350	325	25	Sabarmati (Rt. Bank)	
7	Pipla	Merpur	7.25 (5.25)	698	600	98		7.25
8	Merpur	D. mata	25.78 (23.0)	600	400	200		33.03
9	D. mata	Delwada	15.11 (12.5)	400	325	75	Wakal (Lt. Bank)	48.14
10	Delwada	Datar	16.95 (11.75)	325	300	24	Sei river (Rt. bank)	65.09
11	Datar	Champa	4.87 (4.25)	300	250	50		69.96
12	Champa	Bhanpur	6.18 (5.5)	200	200	50		76.14
13	Bhanpur	Thalvara	5.61 (5)	200	190	10		81.75
14	Thalwara	Vijlasan	17.77 (15)	190	180	10	Marnar (Lt. Bank)	99.52
15	Vijlasan	Dharoi	7.24 (5)	180	168	12		106.76
16	Dharoi	Valasana	25.82 (20)	168	155	13		132.58
17	Valasana	Pedhamli	19.25 (17.5)	155	110	45		
18	Pedhamli	Vijapur	14.5 (11.25)	110	90	20		166.33
19	Vijapur	Waghpur	17.52 (11.75)	90	78	12	Hathmati (Lt. bank)	183.85
20	Waghpur	Varsoda	13.86 (10)	78	70	8		197.71
21	Varsoda	Sadra	11.77 (8.75)	70	63	7		209.48
22	Sadra	Pethapur	8.92 (8.0)	63	55	8		218.40
23	Pethapur	Sabarmati	29.33 (22)	55	48	7		247.73
24	Sabarmati	Navapura	36.55 (28.75)	48	40	8		284.28
25	Navapura	Virpur	30.06 (21.25)	40	20	20	Vatrak (Lt. bank)	317.34
26	Virpur	Rinjha	20.23 (16.25)	20	12	8		337.57
27	Rinjha	MotiBoru	17.52 (13.25)	12	52	7	Bhogwa (Rt. bank)	355.09
28	Moti Boru	Gulf	13.36 (10.5)	5	0	5		368.45
29	High water line	Low water line	13.14					381.59

* Figures in parentheses indicate direct length.

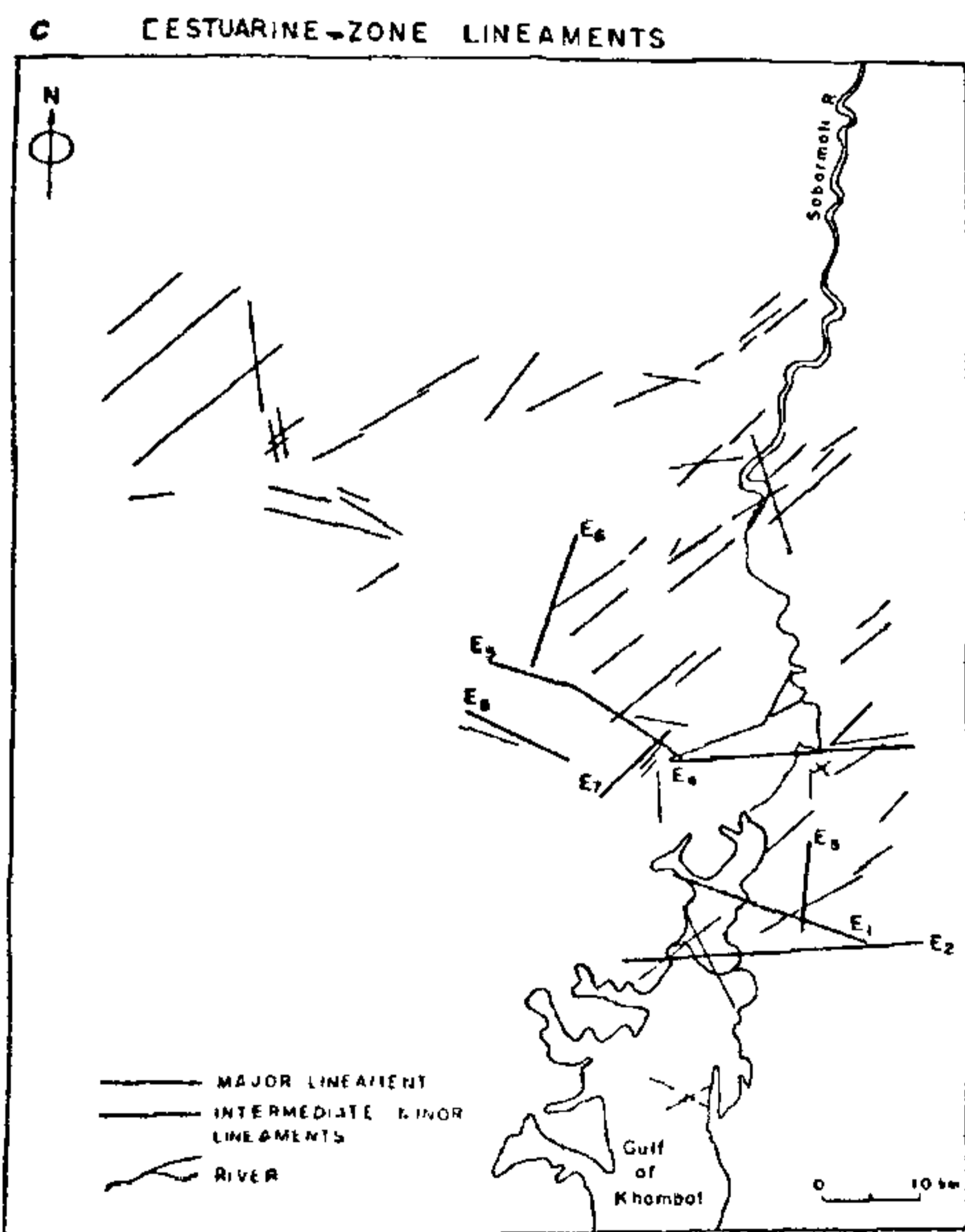
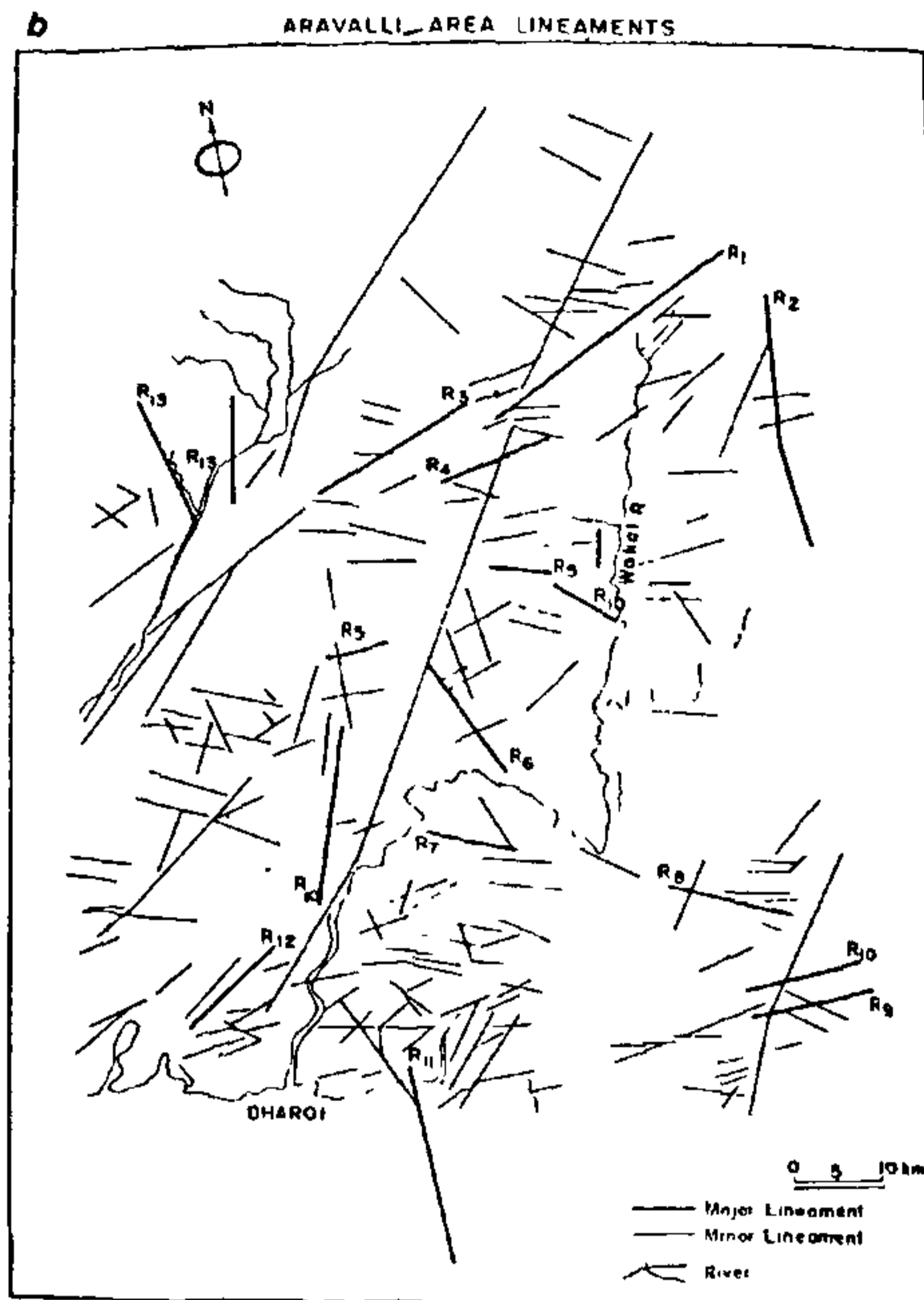
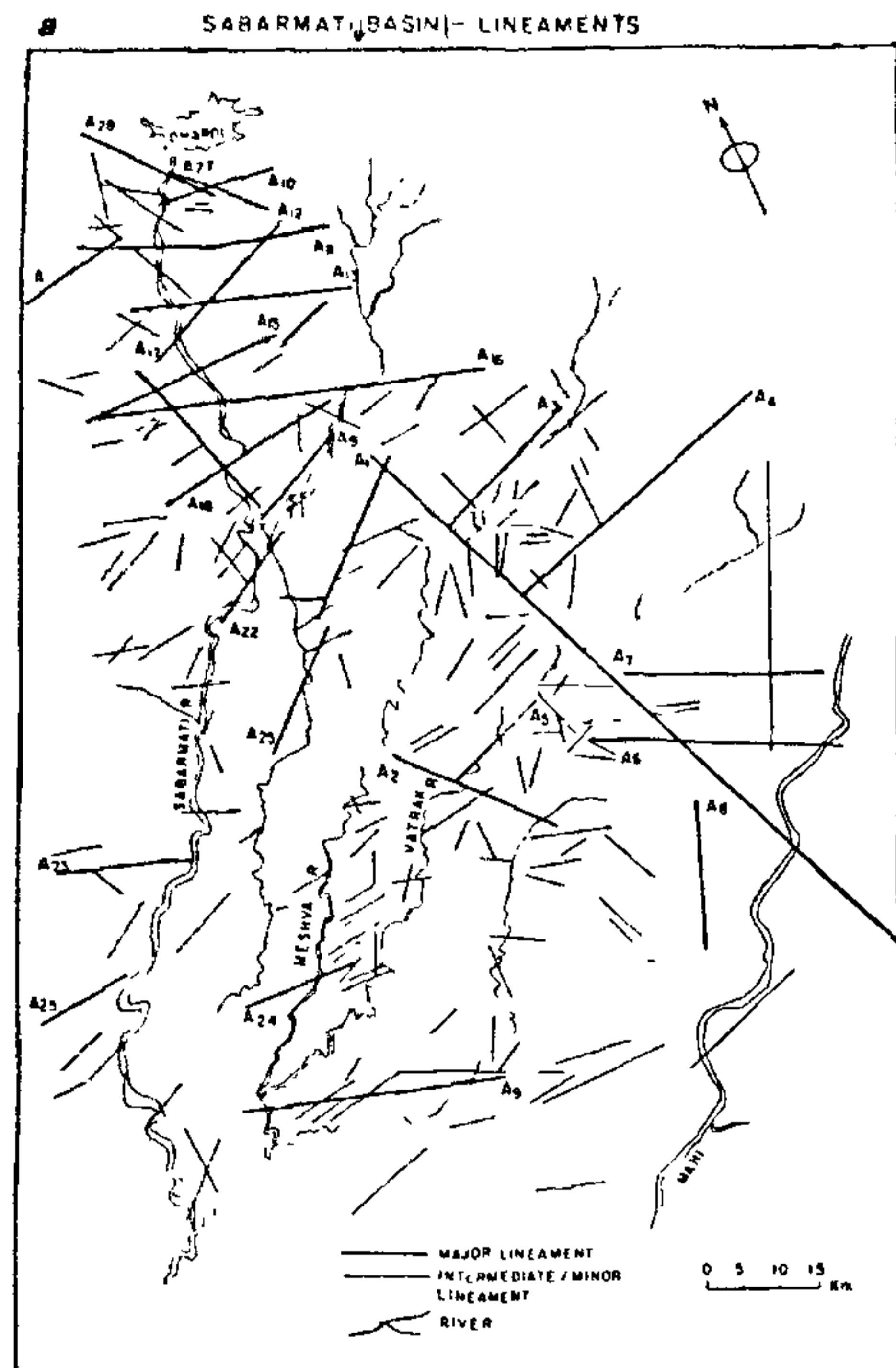


Figure 5. Lineament maps of the Sabarmati Basin (based on Satellite FCC data): (a) Alluvial area. (b) Aravalli area, (c) Estuarine area.

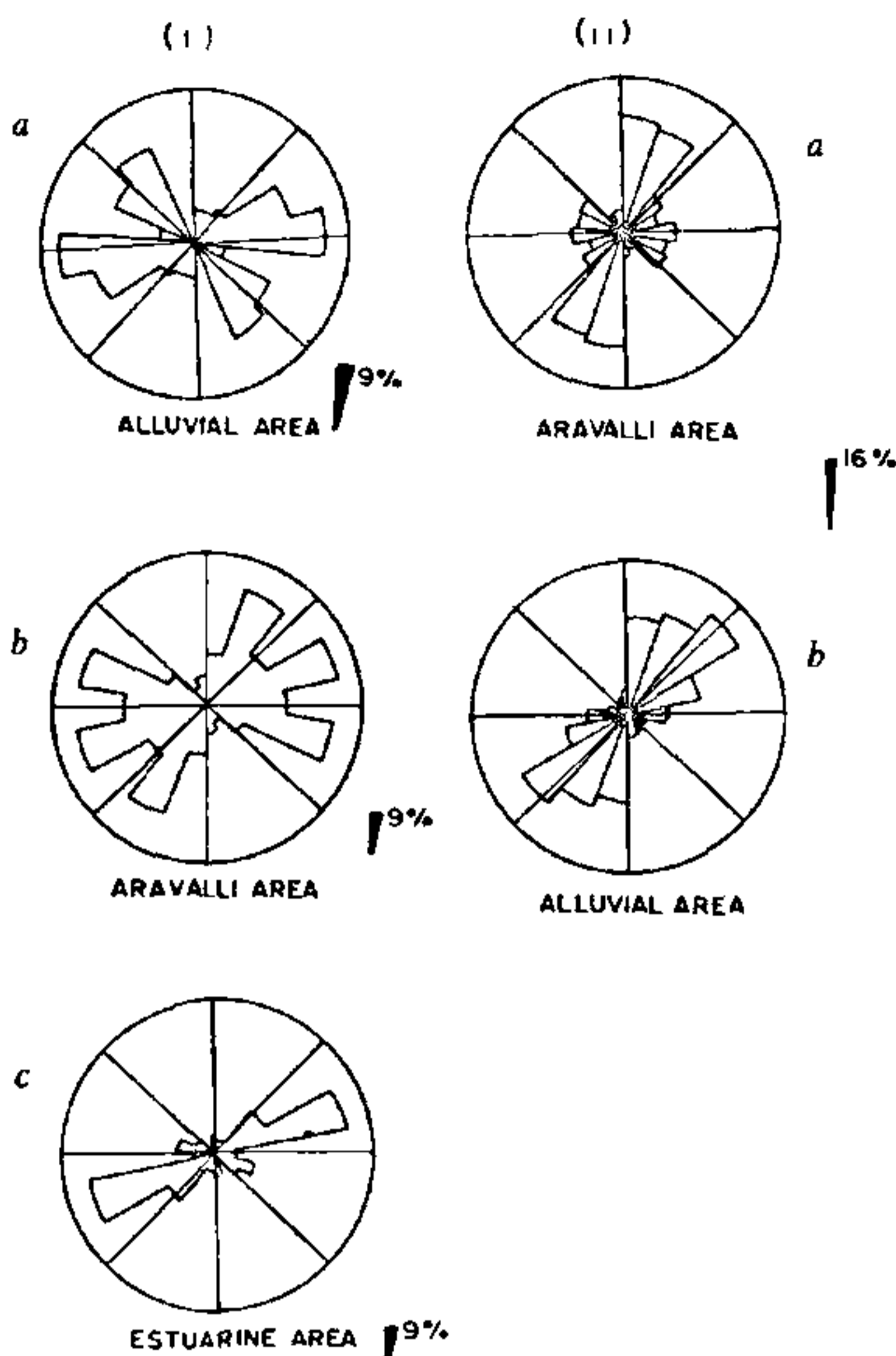


Figure 6. (i) Circular histograms of weighted average lineament azimuths: (a) Alluvial area; (b) Aravalli area; (c) Estuarine area. (ii) Circular histogram showing weighted average rectified link length azimuths in Sabarmati basin. (a) Aravalli area; (b) Alluvial area.

Aravalli area

The southern Aravalli ranges bounding the Sabarmati basin (Figure 6) show strong WNW-ESE; NE-SW and ENE-WSW trends. Geomorphological studies showed that the Aravalli region has been tectonically reactivated along the Precambrian regional faults⁵. Multispectral LANDSAT images of the Precambrian shield of Rajasthan also indicate later rejuvenation of Precambrian lineaments⁴. However, the involvement of NE-SW trending Aravalli lineaments¹⁷ during Quaternary reactivation is doubtful for this trend is not reflected in the analysis of the Quaternary alluvial area. The

WNW- ESE and ENE-WSW trends represent possible reactivation of earlier tectonic trends as indicated by geomorphic studies⁵. These two conjugate sets have been considered for calculation of stress direction. This conjugate pair has an angle of 71° and 119° with maximum principal stress (P) directed towards 95° and minimum principal stress (T) towards 5° (Figure 6). Stress analysis for entire Aravalli reveals a maximum principal stress (P) of N 110° and minimum principal stress of N 25°¹⁸.

Estuarine zone

In the estuarine zone, recognition of the lineament features is difficult owing to extensive sediment cover. There are two strong trends—the ENE-WSW trend and a minor NW-SE trend. The two maxima calculated by taking weighted averages are 61° and 118° with an intermediate angle of 57°. The direction of maximum principal stress (P) is calculated to be 90° and the minimum stress (T) to be 360° (Figure 7).

Analysis of valley trends

Orientation of river valley trends of Sabarmati River has also been carried out by applying the techniques of Scheidegger^{14,19-21}. There are two prominent preferred trends—the NNE-SSW trend and NE-SW trend. The regularity of the trends is assumed to be a result of neotectonic phenomenon with little lithological influence²².

The rectified drainage map (Figure 8) of Sabarmati basin, characterized by linear drainages is studied in conjunction with analysis of circular histograms (Figure 6) of lengths and azimuths of drainage lines and the statistical distribution of link orientation. Applying the Scheidegger technique^{21,23}, the following deductions have been made.

Aravalli area

There are two trends—the strong but scattered NS to NE-SW trend and the weaker EW to ENE-WSW trend

Table 2. Maximum and minimum stress directions

Area	No. of observations	Angle			P	T
		Max. 1	Max. 2	Max. 3 (2,3)		
(1) Lineament trends						
Aravalli Hills	214	38	71	119	48	95
Alluvial Plain	29	-	68	138	70	103
Estuarine Zone	68	-	61	118	57	360
(2) Rectified drainage (Valley trends)						
Aravalli Hills	116		28	120	92	74
Alluvial Plain	192		36	128	92	81

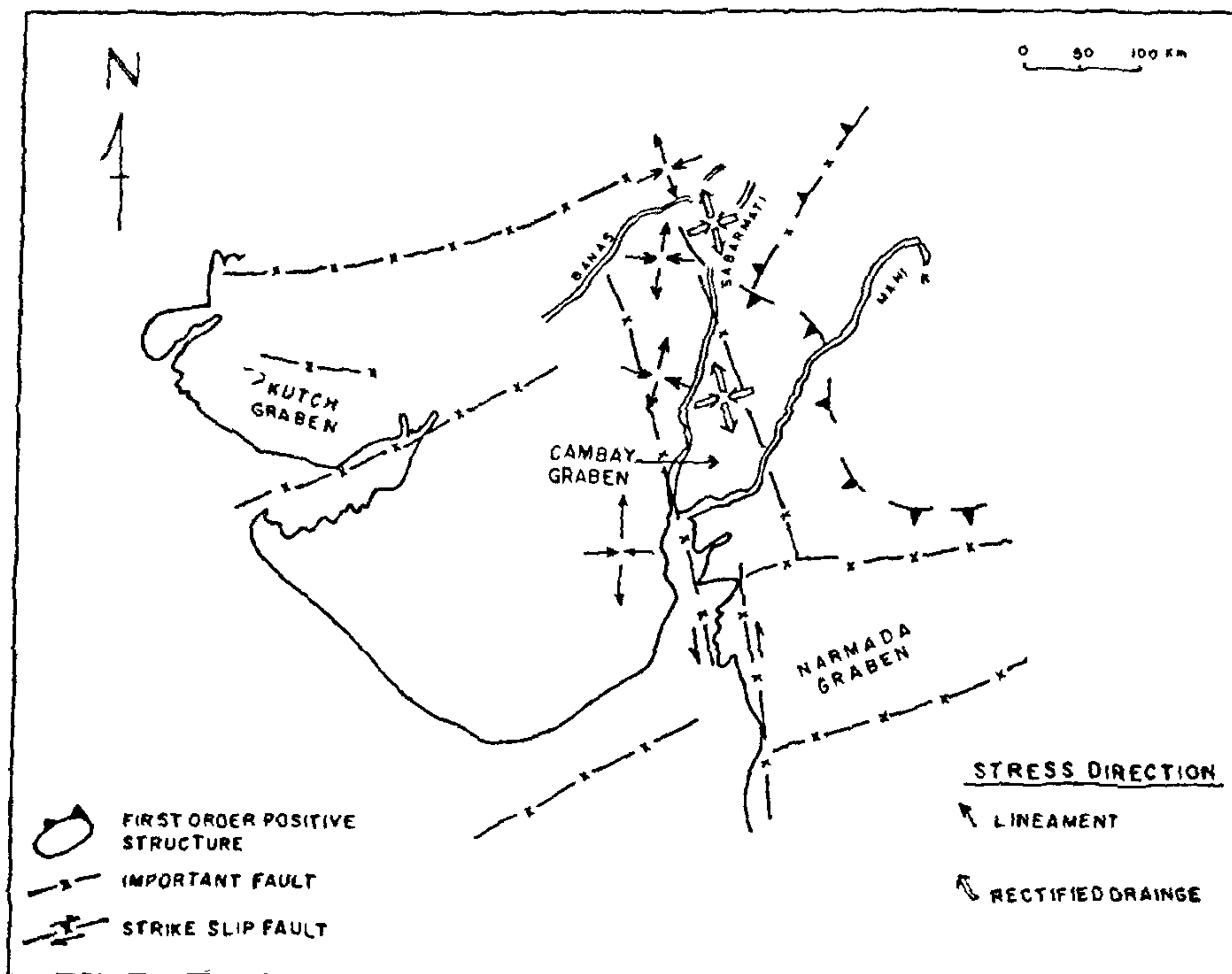


Figure 7. Stress direction in various sectors of the Sabarmati valley as revealed by lineament and valley trends. Corresponding regional faults are also shown.

(Figure 6). Two maxima are obtained by dividing these two sub-populations and calculating their mean orientations. Max. 1 and Max. 2 are obtained as 28° and 120° respectively. It may be noted that the angle between the two conjugate pairs is close to 90° . The two principal stress directions obtained are 74° and 344° (Figure 7). However, identification as to which of the two stresses represent maximas (P and T) is uncertain as the conjugate pairs are formed at nearly 90° angle.

Alluvial area

There are preferred valley trends—the prominent but scattered N-S to NE-SW trend and the weak E-W to NW-SE trend (Figure 6b). The mean of these two distributions is calculated to be 36° and 128° respectively. The control in this case is due to NE-SW regional slope for smaller drainages. The N-S to NNE-

SSW oriented main Sabarmati drainage may be influenced by the fault structures of the Cambay graben. However, as only two maximas are present in the case of rectified drainages, these are assumed to be a conjugate pair developed by a single tectonic episode, the stress directions of which are calculated to be 81° and 351° (Figure 6). As in the case of Aravalli area, determination of maximum (P) and minimum (T) is not possible as both the conjugate pairs are developed at nearly 90° .

The origin of the lineament patterns of the Aravalli and alluvial areas is different—the former represents reactivation along Pre-Cambrian faults⁵ and the latter along Tertiary faults². Significantly, the parametric statistical analysis does not reveal any significant difference in valley orientation trends and stress trajectories developed in the Aravalli and the alluvial areas. They correspond more or less with each other. In the analysis of valley orientations, it has not been possible to ascertain P and T due to the development of

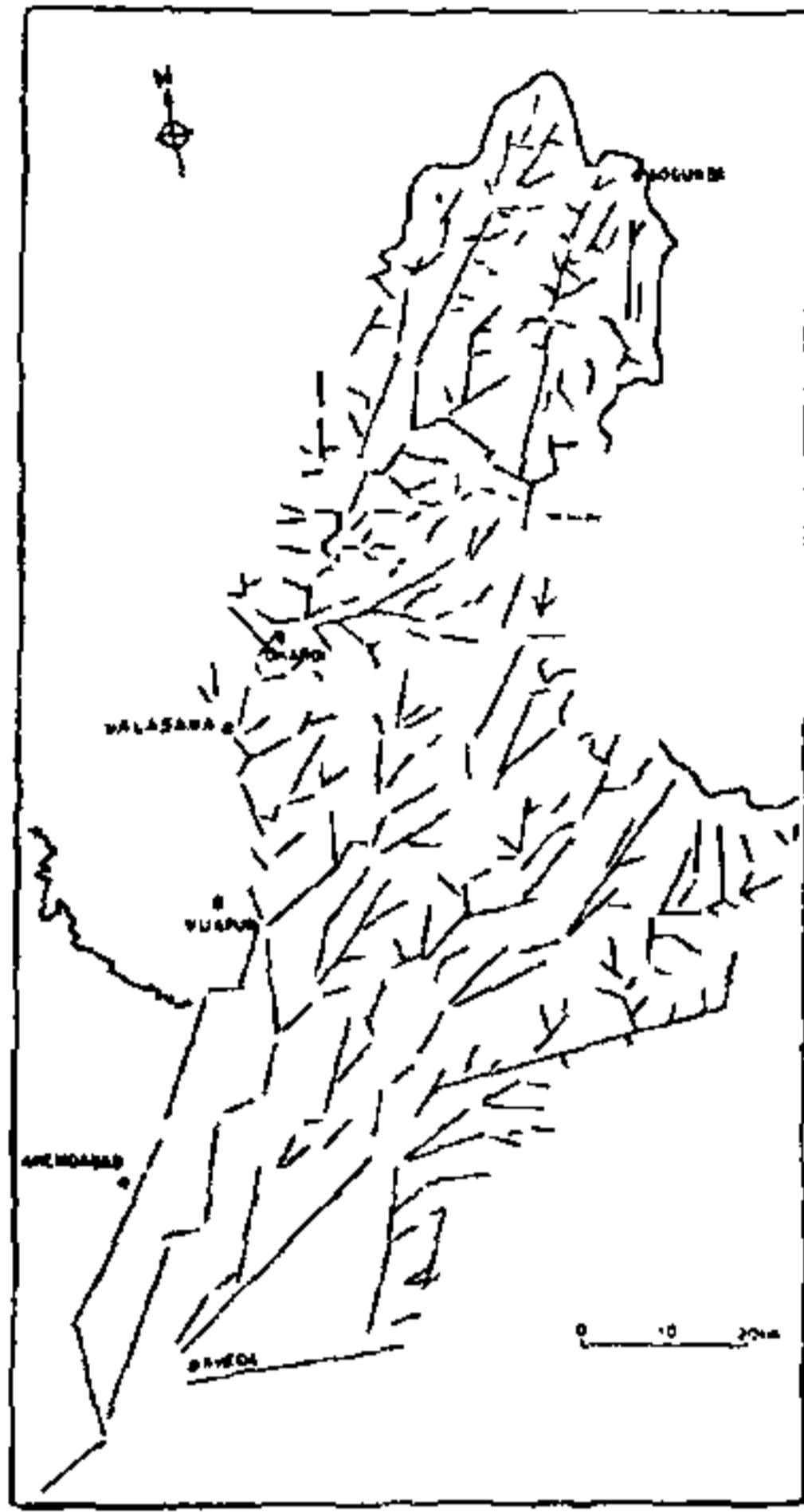


Figure 8. Rectified map of the Sabarmati and its tributaries. Only higher order drainages have been rectified.

the *normal* conjugate pair. However, a comparison with lineament azimuth of the two areas suggests that the maximum principal stress (P) developed nearly E-W and minimum principal stress (T) nearly N-S direction.

Discussion and conclusion

In the stretch from Gogunda to Dharoi (Aravalli area), the river alignment follows, mainly, two prominent trends—the main lines of drainages follow the NE-SW Aravalli-Delhi structural trend which incidentally is also the regional slope trend and the network drainages follow a joint-controlled E-W trend. The Sabarmati main drainage shows a marked change to N-S direction in the alluvial area in the Dharoi-Vijapur sector and to the NNE-SSW direction in the Vijapur-Ahmedabad sector. The network drainages in the alluvial area show a greater NE-SW slope controlled pattern with a subordinate E-W to WNW-ESE lineament controlled pattern.

From a comparison of the neotectonic stress fields obtained from lineament analysis and the valley orientations, the stress trajectory angles show a difference of 22° in the Quaternary alluvial areas of the Sabarmati basin. The control of the main Sabarmati channel by the Aravalli structural trend becomes obscure in this stretch. The computed compressional stress (P, max., σ_1) is confined to a regional E-W trend and extensional stress (T, min., σ_3) to N-S trend, respectively (Figure 9). It is also interesting to record that in the alluvial area, the River flows in the Cambay

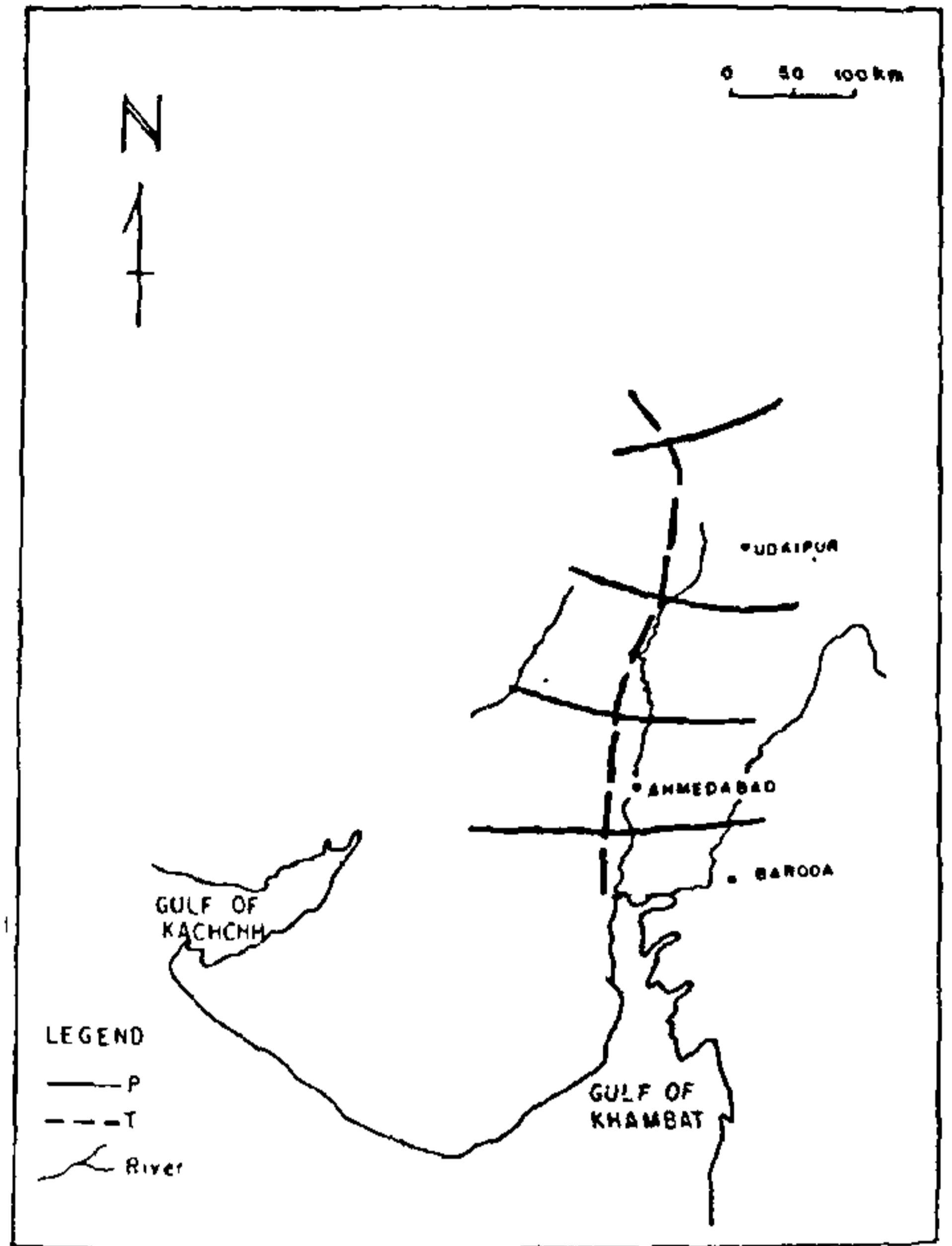


Figure 9. Horizontal stress trajectories (σ_1 and σ_3) causing development of lineaments.

graben. Figure 10 shows the position of the Cambay graben which occurs in the form of a long and narrow depression trending N-S in southern Cambay and NNW-SSE in the northern part. The southern part of the Cambay graben is downthrown by a N30E-S30W trending fault²⁴. The Sabarmati River follows this trend

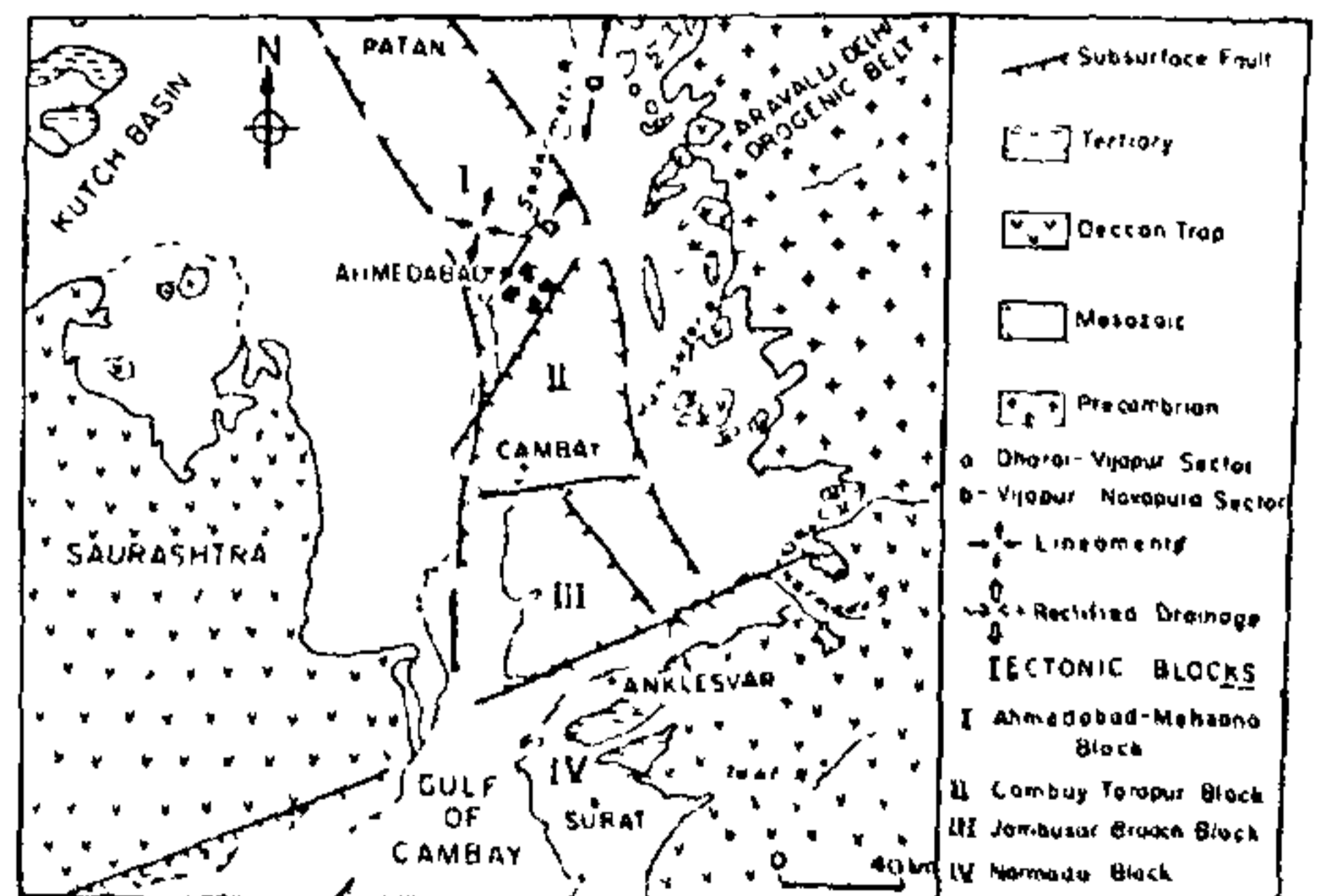


Figure 10. Pre-Neogene position of the Cambay graben and associated structures (modified after Biswas²)

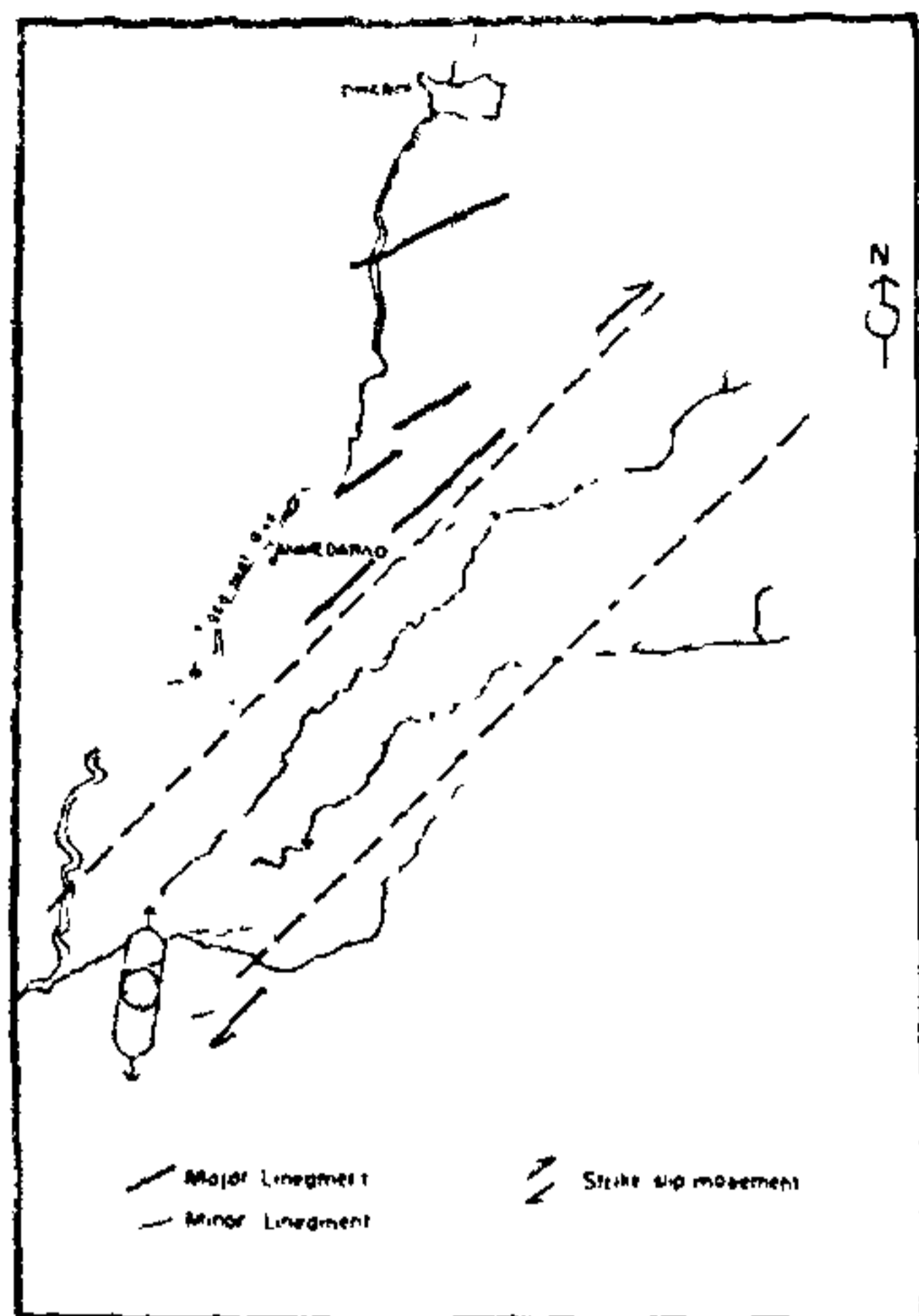


Figure 11. Zone of development of en-echelon lineaments and resultant strain ellipsoid.

in the Vijapur-Navagam area. In the estuarine zone, the river follows the N-S trend along the Cambay fault. Clearly, the E-W lineaments recorded in the alluvial area have not exercised a major control on the development of the Sabarmati main drainage as a minimal tendency of shifting of the river along the E-W axis is observed. The area east of the Sabarmati main channel (shown by dashed lines, Figure 11) is a zone of development of en-echelon lineaments corresponding to a zone of shear and a dextral strike slip movement along NNE-SSW direction. The western margin of the Sabarmati main channel is, therefore, a morphostructural feature and is a positive area forming N-S uplift axis along the western margin. The N-S to NNE-SSW trend of the Sabarmati river in the alluvial area appears to have developed in response to the complex neotectonic stress field originating through reactivation of the pre-Quaternary faults.

Development of river bends, knick points, river deviations and linear fractures are some of the indirect evidence of faulting involving loose sediments. Several such features are observed in the Sabarmati basin.

The Sabarmati drainage basin anomaly is to a large extent the result of fluvial adjustment to neotectonic activity. The lowermost Waghpur Formation (preliminary TL age ~ 300 k.y.) is dissected by the N-S flowing Sabarmati channel²⁵. The palaeoflow directions in the Waghpur Formation indicate the presence of palaeo-

drainages flowing along the NE-SW regional palaeoslope. Hence, this neotectonic activity causing the N-S alignment of the Sabarmati is younger than ~ 300 k.y. and can be dated Mid- to Late Quaternary.

The study of the mutual relationship of the drainage orientation structure, lineament patterns and trends, supported by the study of alluvial deposits in the basin has allowed for the interpretation that the regional slope deviatory trend of the Sabarmati basin represents a fluvial adjustment to neotectonics in the Late Quaternary.

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Gravity and seismicity of Jaisalmer region, Rajasthan

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An attempt is made to explain the causes of the earthquake which occurred on 8 November 1991 in the Jaisalmer region on the basis of the Bouguer gravity anomaly map. The gravity data indicate a thickness of about 4 km for the sediments of the Sheo (Barmer) Basin. The gravity highs encountered in the region cannot be explained as mere reflections of basement ridges. A considerable part of the gravity highs seems to be caused by uplift of dense lower crustal (or upper mantle) rocks. It is suggested that the seismicity reported in this region is due to the reactivation of the zones of weakness created presumably by the emplacement at shallow depths of denser lower crustal or upper mantle material.

Introduction

An earthquake of magnitude 6.3 on the Richter scale, with its epicentre located in the sparsely populated desert area of Jaisalmer occurred on 8th November 1991. This earthquake is of special significance, for there has been no recorded seismic event in the Jaisalmer region so far (Table 1). As the gravity maps are useful in understanding the geological structure, and faults are possibly responsible for seismicity¹, the present work deals with an analysis of the Bouguer gravity anomaly map of the Jaisalmer area (Figure 1) in order to infer the existence of active faults (Figure 2) and to suggest the probable crustal structure (Figure 3) in that region.

Geological setting

The extensive arid plain of Rajasthan lying west of Jodhpur forms the great Thar desert. A summary of the geological evolution and hydrocarbon prospects of Rajasthan Basin (based mostly on the work by the

ONGC) has been published by Datta² together with a small scale gravity map of that region. The basement is made up of mostly the Malani suite of rhyolites and granites, the Aravalli metamorphics and the Jalor/Siwana granites. The total sedimentary thickness of the Shahgarh Depression is likely to be of the order of 10,000 m or more. There are eight sedimentary cycles from the Upper Proterozoic sediments to Indus Alluvium of the Quaternary age in the evolution of the Jaisalmer Basin². The final phase of uplift of the axial belt is believed to have started during the Oligocene times.

There are four phases of Malani igneous activity in Sankara, Jaisalmer³. The first phase is represented by rhyolites and rhyolite porphyry flows, the second phase comprises coarse-grained biotite-granite intruding into the Jalore-type granites, the third phase includes both extrusives and intrusive rocks of acid and intermediate composition, and the fourth phase is represented by the intrusive basic rocks. The emplacement of ultramafic rocks and gabbro-diorite in the axial zone of the Delhi fold belt, and the acid effusives in the Trans-Aravalli region (Malani rhyolites) are the manifestations of the extensive anorogenic magmatism resulting from abortive rifting around 850 m.y. ago⁴. The mafic and alkaline rocks of the Malani volcanic province belong to two younger magmatic events⁵ (a) a Mesozoic event (ca. 125 m.y.) related to opening of several sedimentary basins in western Rajasthan, and (b) a Paleocene event related to collision of Indian plate with the Asian. In the early Jurassic, epeirogenic movements led to subsidence and formation of Kachchh and Sanchor Basins in the south and the Jaisalmer Basin in the central part⁵. These movements continued till the Upper Cretaceous when subsidence and attendant fracturing transformed the Barmer Basin into a graben. The intermediate alkaline rocks of Tavidar (in the eastern margin of Sanchor

Table 1. Seismicity in the Jaisalmer area^a

Date	Latitude (deg)	Longitude (deg)	Place	Magnitude	Source
25.7 1907	26.0	72.0	Malani	VI	Historical
26.5 1959	27.2	70.2	Feyzabad	—	International Seismological Summary, UK
8.11 1991	26.28	70.58	Jaisalmer	5.6	(22 km) USGS 5.7

ISS: International Seismological Summary, UK; USGS: United States Geological Survey, USA