22 Ramty, J G., Tapster, P. R. and Jakeman, E., *Opt Commun.*, 1987, **62**, 201–203
23 Koashi, M., Kono, K, Hirano, T and Matsuoka, M, *Phys Rev. Lett*, 1993, **71**, 1164–1167.
24. Mandel, L., *Opt Lett.*, 1979, **4**, 205–207.
25. Short, R. and Mandel, L., *Phys. Rev. Lett*, 1983, **51**, 384–387.
26. Lee, C. T, *Phys. Rev*, 1990, **A42**, 1608–1616.
27 Sudarshan, E C. G., *Phys. Rev. Lett.*, 1963, **10**, 277–279, Glauber, R. J, *Phys Rev*, 1963, **131**, 2766–2788.
28 Schleich, W and Wheeler, J. A, *J. Opt. Soc. Am.*, 1987, **B4**, 1715–1720; Schleich, W,, Wheeler, J A. and Walls, D F., *Phys. Rev.*, 1988, **A38**, 1177–1180,
29. Slusher, R E, Grangier, P., La Porta, A, Yurke, B and Potasek, M. J., *Phys Rev. Lett*, 1987, **59**, 2566–2569.

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Post-Gondwana tectonics of the Indian Peninsula

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The concept of plate tectonics implies that the plate boundaries are sites of tectonic activity and that regions within the plate are stable. Exceptions to this rule are known from the Indian Ocean where the oceanic crust is undergoing folding and fracturing. Examples of intraplate deformation within the continental crust are rare. The uplift of landmass in the region of 13°N of the Indian peninsula is one such unusual occurrence.

THE peninsular India, which is a Precambrian shield area, is considered to be a stable landmass. Hence it is generally believed that no major earth movements are possible in this region. This view gains strength from the fact that the Peninsula is an intraplate region bound by passive margins on all sides except in the north. Although this picture is generally true, there is evidence to indicate that certain regions have been active over a considerable period and have left their imprints on the landforms[1,2]. Most of the major geomorphic features owe their genesis to the post-Gondwanaland plate tectonic regime.

The following picture emerges when the history of the Peninsula is traced over the past 150 Ma. It is then that the East Coast emerged due to its separation from Antarctica and Australia. The West Coast came into being much later, due to separation of India from Madagascar. This event can be placed at 93 Ma if the columnar rhyodacitic volcanics of St. Mary islands off Karnataka coast[3,4] represent the rift stage volcanism.

This was followed by the hotspot volcanism which gave rise to Deccan Traps (67 Ma). Due to northerly

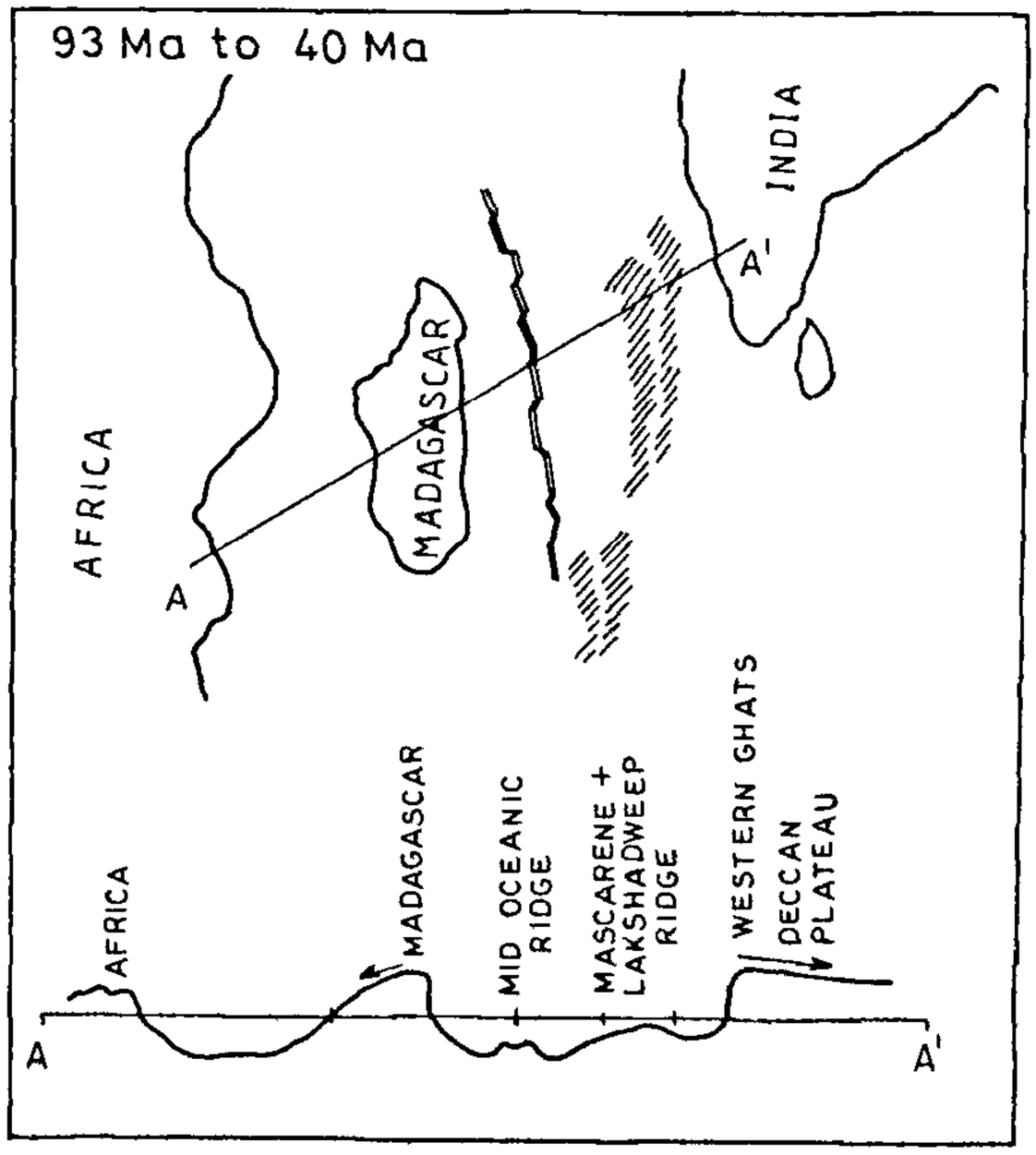

Figure 1. Separation of Madagascar from India along an MOR close to Madagascar (93 Ma). Tilting of blocks and formation of scarps along the Western margin of India (Western Ghats) and the eastern margin of Madagascar. Initiation of easterly drainage in India (indicated by an arrow on the Deccan plateau). Outpouring of large quantity of basaltic lava resulting in Deccan Traps (67 Ma) and a marginal plateau in the Arabian Sea (67 Ma to 40 Ma)

movement of India, the hotspot left its trail as a marginal plateau in the Arabian Sea, which was later split into two, Mascarene Plateau and Laccadive–Chagos ridge due to northerly shift of the spreading axis around 40 Ma. The collision of India with the Asian mainland and continued creation of new crust in the Indian Ocean has tilted the Indian Peninsula in a northerly direction. The continued sea floor spreading has resulted in uplift of the landmass along the Mulki–Pulicat lake axis.

Easterly tilt of the Peninsula

Associated with the origin of the West Coast (passive continental margin)[5] was the development of the Arabian Sea and the genesis of the Western Ghats[6]. The counterpart of the Ghats is seen along the East Coast of Madagascar where a similar scarp faces the Arabian Sea and the landmass has a westerly tilt. The formation of the Western Ghats gave an easterly tilt to the entire Peninsula. As a consequence, a dominant easterly drainage developed (Figure 1). However Cox[7] considers the drainage of the Peninsula as radial and related to dome-flank systems. Radhakrishna[2] while disagreeing with the views of Cox opines that the easterly drainage reflects uplift along a linear belt. The easterly tilt was also responsible for commencement of sedimentation along the East Coast which is now represented by the Cretaceous rocks of Tiruchinapally area[1]. Subsequent to the 93 Ma event which saw the initiation of the Arabian Sea, another event of great significance was the Deccan volcanism (67 Ma)[8] when enormous quantity (about one million cubic kilometers) of lava flowed out as a result of Reunion hotspot activity. The lava which flowed on the already elevated Western Ghats, resulted in giving a variable dip and slope to the region (for example, the Panvel flexure). The open asymmetrical anticline, changes in the direction and intensity of its plunge[9] can all be ascribed to the nature of topography prior to lava flow and the nature of lava flow itself. Viewed this way, the structures seen in Deccan Traps can by and large be considered primary.

As the northward movement of India progressed due to continued spreading along the Indian Ocean ridge system, the relative southerly movement of the Reunion hotspot left its trail in the form of a marginal plateau of the Arabian Sea. This scenario lasted for a period of 27 Ma between 67 and 40 Ma. Around 40 Ma, the shifting of the spreading ridge from a position close to

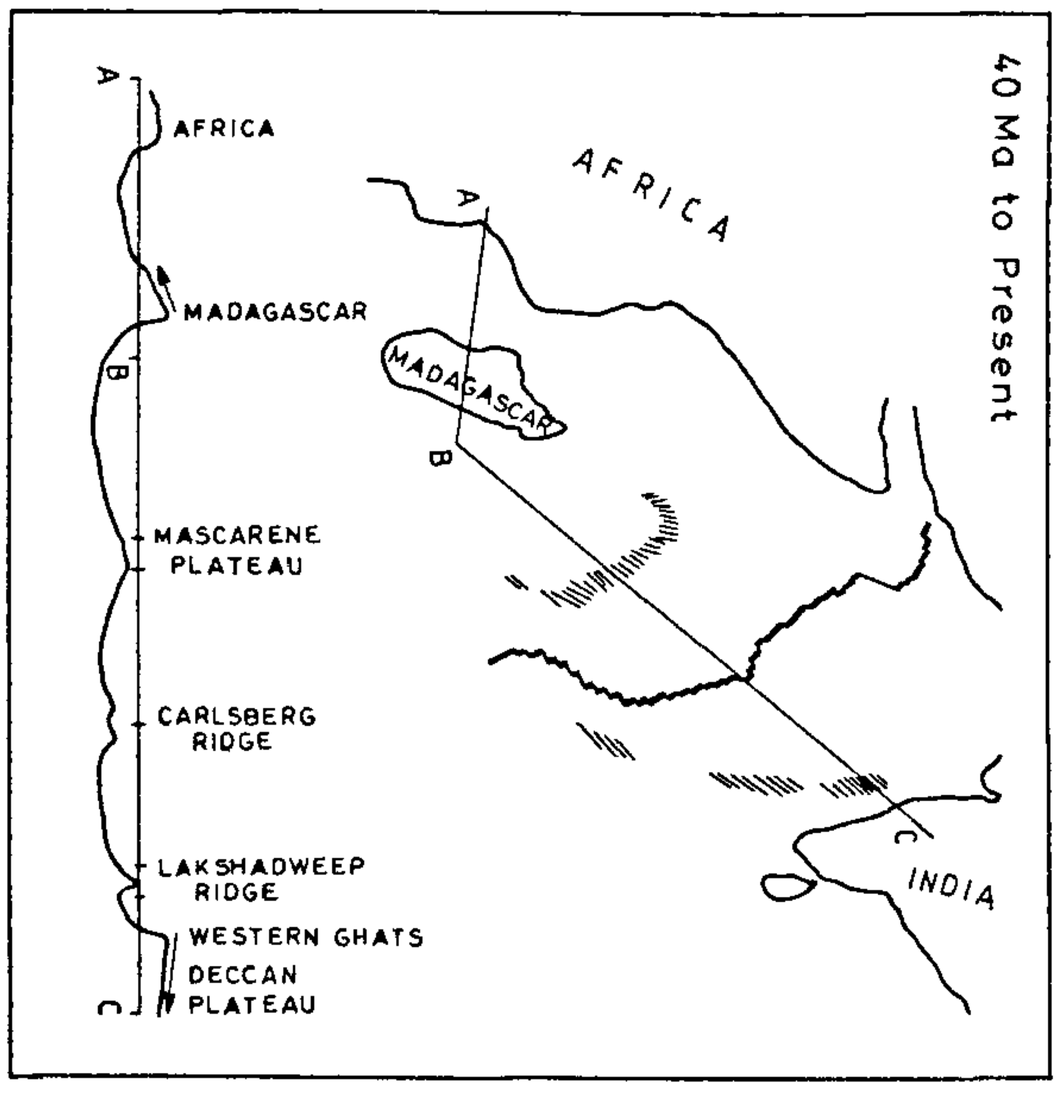

Figure 2. Northerly shift of spreading axis resulting in further uplift of Western Ghats (40 Ma) Separation of Mascarene Plateau from Lakshadweep–Chagos ridge

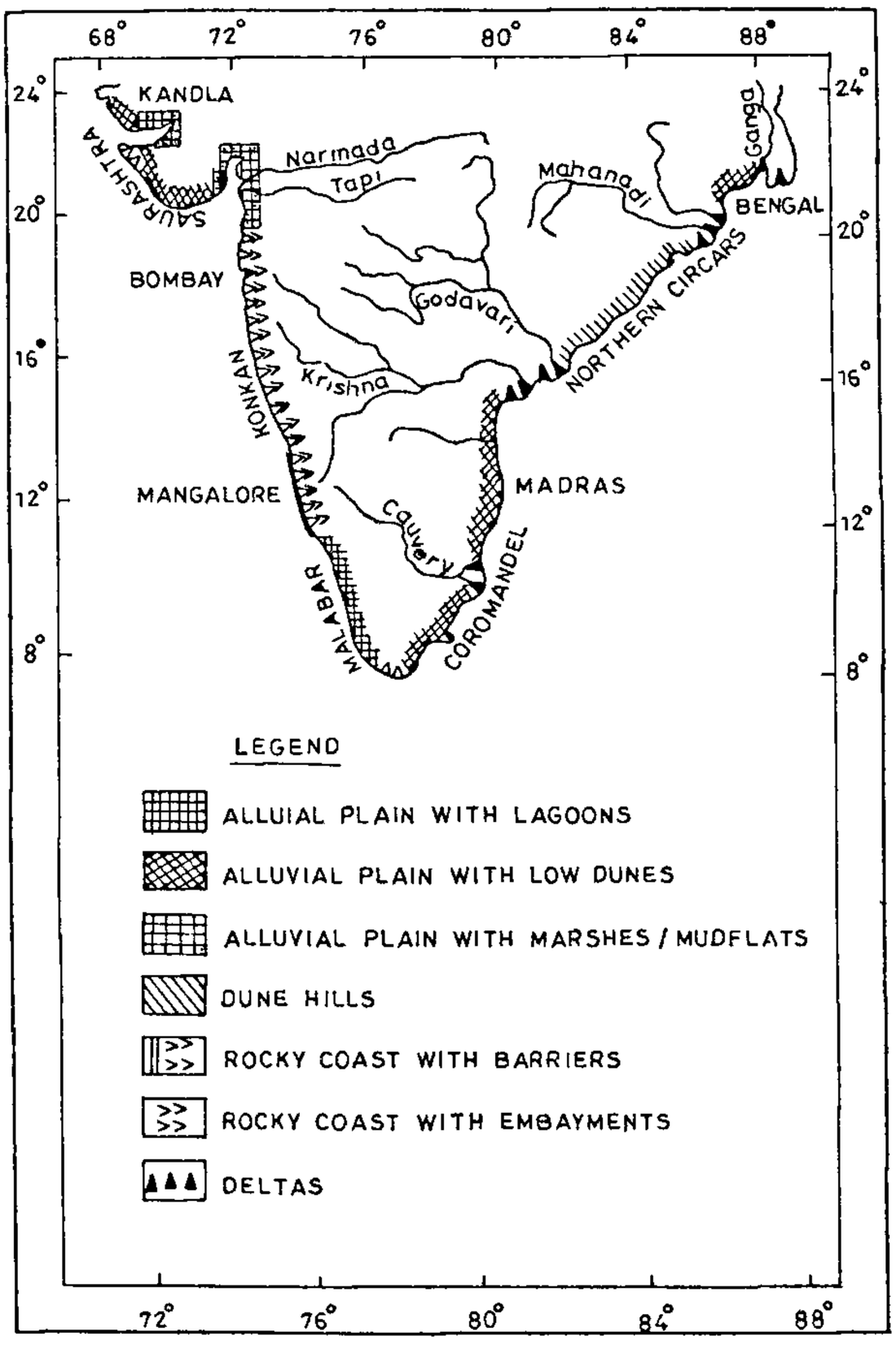

Figure 3. Nature of coastline in different parts of India (Adapted from the Map 'Coastal Landforms of India', GSI, 1972). Submergent (cliffed) coast in the north (Konkan) and emergent (alluvial plains) coast in the south (Malabar) with transitional coast in between.

Madagascar to one closer to India (the Carlsberg ridge) resulted in the splitting of the marginal plateau into two—the Mascarene plateau and the Lakshadweep–Chagos ridge[10] (Figure 2). This must be the time when the Western Ghats experienced a further major uplift. Subsequent to this, there may have been several episodes of minor uplift as indicated by the planation surfaces[11] at altitudes of about 50, 200, 800, 1100 and 1400 m, noticed to the west of Western Ghats. As the Indian subcontinent is anchored to the Asian mainland, spreading along the Carlsberg ridge can be accommodated mainly by underplating of mantle material. This may explain the minor uplifts along the Western margin of India.

Northerly tilt of the Peninsula

The coastal geomorphology of India[12] (Figure 3) indicates that the West Coast can be roughly demarcated into two regions: the northern having a submergent character (the Konkan coast) and the southern having an emergent nature (the Malabar coast). The plausible explanation for this situation is that the Indian plate tilted northward due to subduction, collision, and continued spreading in the Indian Ocean. This tilt caused the submergence of the coastal plains of the Konkan, making the Ghats come closer to the sea, thus giving it a cliffed character. The same process has lifted up the Malabar region, thus exposing part of the continental shelf resulting in a wide coastal plain. The hinge line separating the two distinct coasts is situated to the south of Karwar. Similar features along the East Coast cannot be identified as they are masked by deltas of major rivers.

East-West trending upwarp

The Indian plate is a zone of compression and the compressive forces are not being fully accommodated at the collision boundary. This has resulted in the intraplate deformation in the equatorial region of the Central Indian Ocean[13, 14]. The same forces are acting on the landmass too. The rheological pattern being different in oceanic and continental crust, the manifestations are to be distinct. The nature of drainage pattern around 13°N (Mulki–Pulicat lake axis, Figure 4) indicates the presence of a major water divide separating the

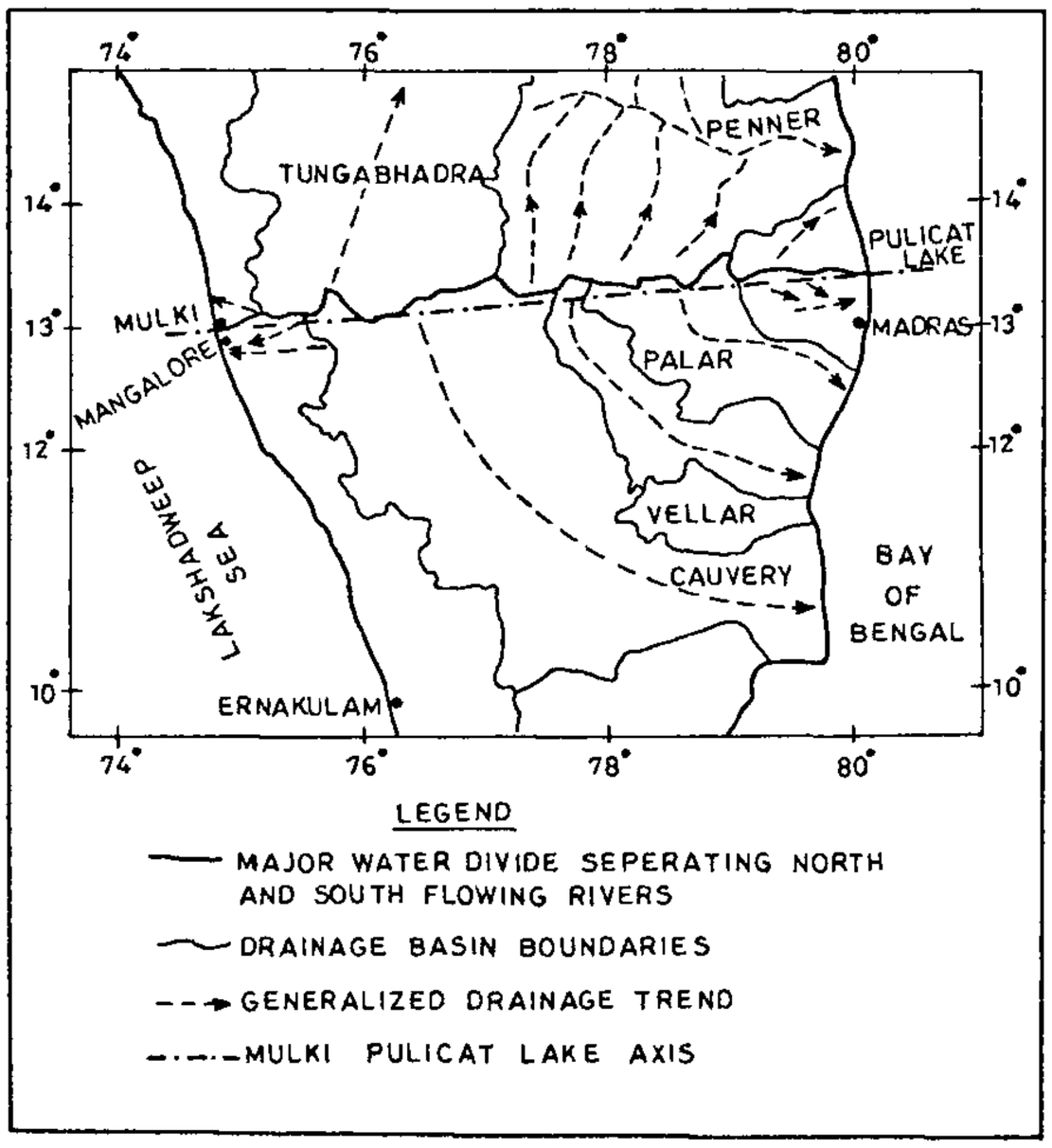

Figure 4. Generalized drainage map of Southern Peninsula A major water divide along Mulki–Pulicat lake axis separates the north and south flowing rivers The water divide is an active zone of uplift causing migration of river channels. The region has anomalous gravity field

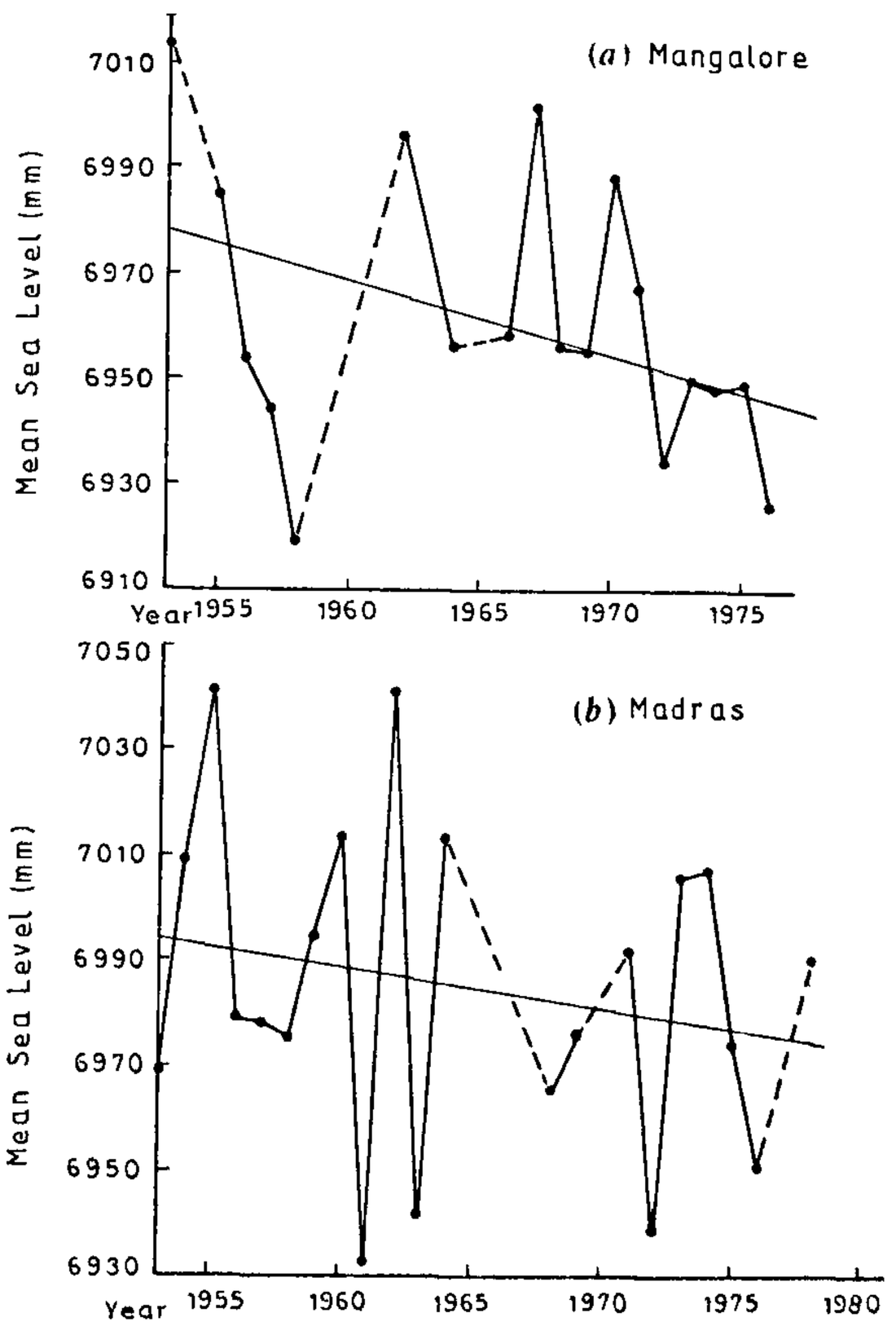

Figure 5. Tide gauge data for Mangalore (*a*) and Madras (*b*) indicating relative fall in sea level

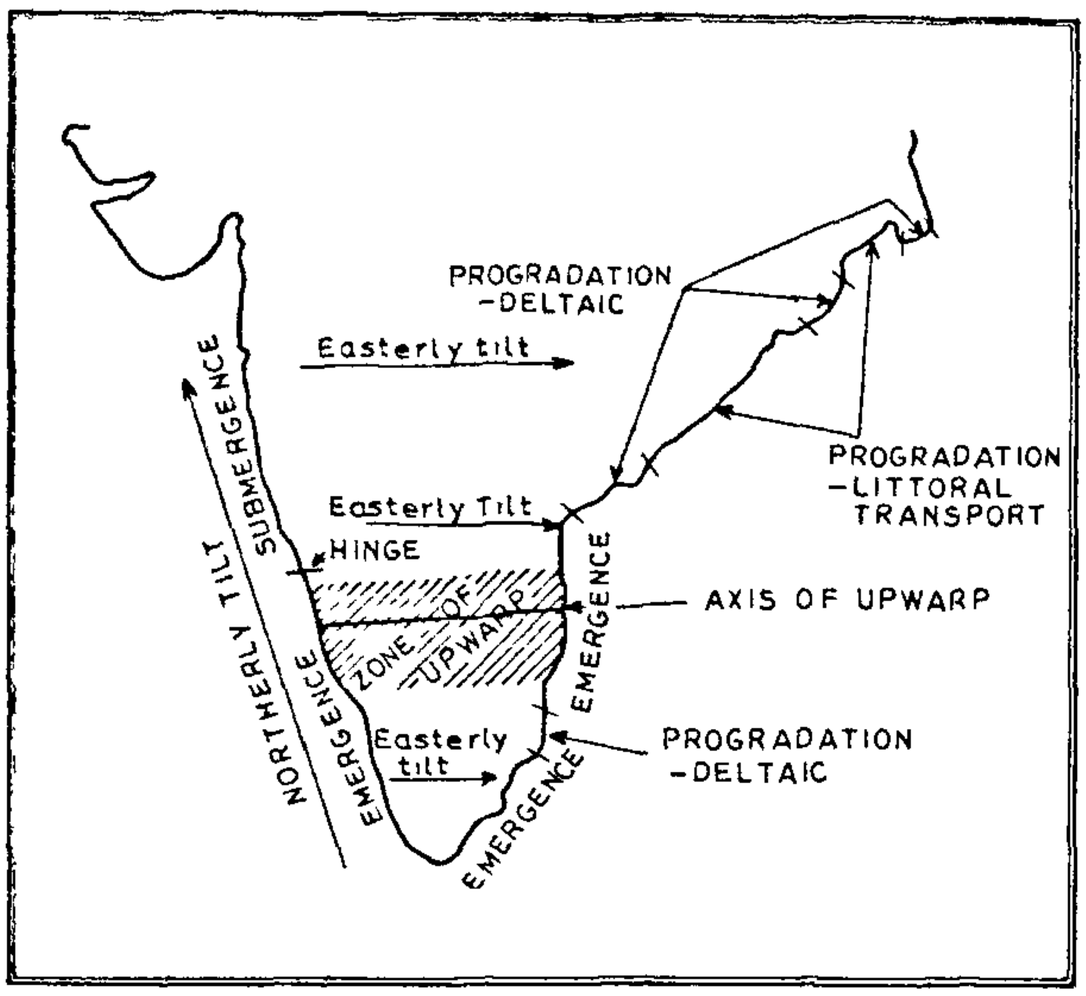

Figure 6. Map of the Peninsula indicating Easterly tilt (93 Ma & 40 Ma), Northerly tilt (post collision) and upwarp along Mulki–Pulicat lake axis (post-collision to Recent).

north flowing rivers from the south flowing. It is possible to interpret this as an ancient arch. However, even if it is a Precambrian basement feature, there are evidences to indicate that this ridge is active now. One of the evidences is that the drainage developed on the Quaternary landforms along the east and west coasts also have an east-west water divide. Even the drainage in the older surfaces is migrating away from the arch[15]. In addition, the protrusion of landmass near Mangalore along the West Coast and near Madras along the East Coast[16], more precisely at the extremities of the Mulki–Pulicat lake axis, is a further proof of uplift. The offshore bathymetry in the Mangalore region, when compared with earlier records indicates shifting of the contours away from the land indicating shallowing of the sea. The picture is different in the adjacent areas, which points out that this feature is not related to sedimentation. The progradation and uplift is substantiated by the tide gauge records of Mangalore and Madras which indicate a relative fall in sea level (Figure 5). Accretion along beaches[17], presence of beach ridges[18], occurrence of dead oyster colony a few centimeters above the highest high water line near Mangalore, highly dissected nature of the lateritic plateau in the southern Karnataka coast are ample evidences to show that the uplift has been active during Holocene. The Bouger and Free-Air anomaly maps[19] show gravity highs approximately coinciding with this upwarp. The complimentary troughs that are to be associated with the ridge are seen to the south and north, but they are not prominent.

From the foregoing, it is evident that the Indian Peninsula is not as stable as it is believed to be (Figure 6). The youthful topography of the Western Ghats, the submergent and emergent nature of coasts, the behaviour of drainage along Mulki–Pulicat lake axis are all pointers in this direction.

1 Radhakrishna, B P., Proceedings of the Seminar on Geomorphological Studies in India, Sagar, 1965, pp. 4–14
2. Radhakrishna, B. P., *Curr. Sci.*, 1991, **61**, 641–647.
3 Naganna, C., *J. Geol. Soc India*, 1966, **7**, 110–117.
4. Valsangkar, A B, Radhakrishnamurthy, C., Subbarao, K. V. and Beckinsale, R. D., in *Deccan Volcanism and Related Basalt Provinces in Other Parts of the World* (eds. Subbarao, K. V. and Sukheswala, R N), Geol. Soc. India Mem 3, 1981, pp. 265–276
5 Curray, J R., *Philos Trans R. Soc. London*, 1980, **A294**, 17–33.
6. Subrahmanya, K R, *J Geol. Soc. India*, 1987, **29**, 446–449
7. Cox, K. G, *Nature*, 1989, **342**, 873–877.
8 Duncan, R A and Pyle, D. G., in *Deccan Flood Basalts* (ed. Subbarao, K V.), Geol. Soc. India Mem. 10, 1988, pp. 1–10.
9. Beane, J E, Turner, C. A., Hooper, P. R., Subbarao, K. V. and Walsh, J N., *Bull Volcanol.*, 1986, **48**, 61–83.
10. Royer, J-Y., Sclater, J. G. and Sandwell, D. T., *Proc. Indian Acad. Sci (Earth Planet. Sci)*, 1989, **98**, 7–24.
11. Gangadhara Bhat, H, Ph D Thesis (unpubl), Mangalore University, 1993.
12. *Coastal Landforms of India*, Geological Survey of India, 1972 (map published by the Govt. of India).
13. Bull, J. M. and Scrutton, R. A., *Nature*, 1990, **344**, 855–858
14. Murthy, K. S R., Neprochnov, Yu. P, Levchenko, O V., Rao, T C. S, Milanovsky, V. E. and Lakshminarayana, S, *Mar. Geol.*, 1993, **144**, 185–193.
15. Narasimhan, T. N., *J. Geol Soc. India*, 1990, **36**, 471–474.
16 Ramasamy, Sm, Geol. Survey India Spl. Publ. 24, 1989, pp 333–339
17. Jayappa, K. S. and Subrahmanya, K. R, Geol. Survey India Spl. Publ 24, 1989, pp 299–306.
18 Gangadhara Bhat, H. and Subrahmanya, K. R., *Int. J. Remote Sensing*, 1993, **14**, 3311–3316.
19 Free-Air and Bouger anomaly maps of India, National Geophysical Research Institute, Hyderabad, 1976

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