Geological Society of America
Special Paper 328
1999

Search for buckling of the southwest Indian coast related to Himalayan collision

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ABSTRACT

Microseismicity and moderate earthquakes occurring throughout Peninsular India indicate that stresses associated with the Himalayan collision may result in weak deformation of the subcontinent. One geometric response to stress in a thin elastic plate is the creation of buckles, a feature of the oceanic plate south of the Indian continent, but not normally a feature of continental deformation. Geomorphic studies of the Malabar coastline identify erosional and accretional coastlines, and occasionally invoke vertical neotectonics as an underlying cause for their observed distribution. In support of these geological observations are numerous historical accounts that suggest that coastal features have changed in the past 500 yr. We investigated several locations along the southwest coast of India where uplift or subsidence has been reported. We found that evidence for recent vertical motions is ambiguous along much of the coast but geologic, geomorphic, and tide-gauge data near Mangalore (13°N) confirm previous studies that require uplift relative to points to the north and south. Quaternary rates are lower than current rates indicated by tide-gauge data (≈3 mm/yr) and spirit-leveling data (≈6 mm/yr), but both are consistent with recent strain rates observed geodetically in southern India (<10 nanostrain/yr). Although the apparent wavelength of warping (200 km) along the west coast of India is symptomatic of buckling, the known rheological structure of India is not conducive to its development.

INTRODUCTION

The ocean floor south of India is characterized by a series of east-west–oriented buckles (Weissel and Haxby, 1984) having a wavelength of 220 ± 20 km. These have been attributed to northerly or northeasterly compressional stresses in the Indian plate generated by the collision of the Indian plate with southern Tibet (Zuber, 1987). Although these buckles diminish in amplitude northward, we hypothesize that intraplate seismic activity in India may be in part related to the incipient formation of related buckles in the continental crust. Stress orientations on the Indian continent (Gowd et al., 1992) and mantle flow velocities inferred from seismic tomography (Rai et al., 1992) are oriented approximately northeast, parallel to inferred Nuvel 1 plate motions (DeMets et al., 1994) and plate motions observed by global positioning system (GPS) geodesy (Freymuller et al., 1996). The horizontal deformation rate in southern India in the past 130 yr has been measured geodetically to be less than 10 nanostrain/yr (Paul et al., 1995); corresponding tilt rates are 10–20 nrad/yr on approximate east-west axes revealed by spirit leveling (Nagar and Singh, 1991).

This scenario is contrary to the general assumption that plates behave as essentially rigid bodies but, as we have seen elsewhere (Burg et al., 1994; Jin et al., 1994), continental plates are subject to applied stresses close to their elastic strength, and some configurations may produce internal deformation. Buckling usually requires a layered lithosphere. In typical models, a weak subsurface low-velocity layer reduces the effective elastic thickness of the crust allowing it to buckle at stresses less than its fracture strength (Turcotte and Schubert, 1982).

Bendick, R., and Bilham, R., 1999, Search for buckling of the southwest Indian coast related to Himalayan collision, *in* Macfarlane, A., Sorkhabi, R. B., and Quade, J., eds., Himalaya and Tibet: Mountain Roots to Mountain Tops: Boulder, Colorado, Geological Society of America Special Paper 328.

Vertical deformation is invoked in published analyses of coastal and offshore morphology, most notably in arches and subbasins (of ~400 km wavelength) mapped in seismic sections by Biswas (1989), and in interpretations of the Malabar coastline that invoke tectonic explanations for erosion and accretion (Nair, 1987; Ramasamy, 1989). Recent contributions by Subrahmanya (1996) also highlight a region of Quaternary uplift along an axis from Mangalore to Madras. Coastal instability is described in several historical texts and has been inferred from archeological excavations of harbors constructed since the fifteenth century B.C. (Rao, 1989). In the Appendix we give a detailed account suggestive of rapid emergence of parts of the coast in a catastrophic event (cf. Cochin, 1341 A.D.).

We identified 10 sites along the Malabar coast of India which had associated vertical motions described either in the historical or scientific literature (see Appendix). We visited each of these sites to examine evidence for tectonic deformation. In some locations, such as Cochin and Alleppy, historical accounts of emergence or submergence were refuted by local historians or were otherwise interpretable in terms of seashore erosion or accretion. For the majority of the sites, we made qualitative observations regarding the lack of robust sea-level markers such as clear marine terraces or exposed bedrock. The entire Malabar coast was observed to be particularly unsuited to the preservation of tectonic vertical motions because of vast quantities of monsoon-transported sand. We then analyzed tide-gauge data for cities along the Indian coast available for the years 1950 to the present.

RESULTS

Quaternary basins and coastal warping

An intriguing aspect of the western coast of India is the presence of several Quaternary basins that do not extend far inland but that have apparent east-west axes that plunge westward beneath the continental shelf (Fig. 1). The north-south spacing of these basins is of the order of several hundred kilometers and they thus suggest incipient buckling of the form we seek. The crest of one of the east-west anticlines separating these basins is found at Warkallai (Varkala, lat 8°44′N). Most of the Malabar coastline is characterized by straight sandy beaches, southward transport being driven by prevailing currents and winds (Soman, 1980). However, between Quilon and Warkallai (20 km north of Trivandrum), Tertiary sediments rise from below sea level to form a 60-m-high sea cliff capped by laterite that would be actively eroded were it not now protected by a charnockite block seawall. This exposed Tertiary sequence overlies the Precambrian basement farther north, at depths to 250 m in a series of boreholes drilled for aquifer exploration purposes (Fig. 2, Raghava Rao, 1975).

Subrahmanya (1996) identified a region of apparent uplift across the Indian Peninsula at ~13°N that also corresponds to one of the antiforms separating Quaternary basins along the west coast of India. This region of uplift is represented by a major east-west–trending drainage divide, significant microseismicity, and a gravity high. Mapped paleochannels indicate that rivers north of this divide, the Tungabhadra and the Penner, have been migrating northward during the Quaternary. River channels south of the divide, including the Palar, Ponnatyar, Cauvery, Gurupur, and Nethravathi, are moving southward. Ramasamy (1989) reported analogous evidence associated with an axis of upwarping between Cochin and Madurai and claimed that seismicity was concentrated along this as well as the Mangalore-Madras line.

Cocoanut Island, at lat 13°28′N, is the most northerly island of the St. Mary Islands group, and consists of vertical columnar basalt (93 Ma; Subrahmanya, 1996) that has several step-like levels that have been interpreted to represent marine terraces. The central part of the island is an extensive shell bank overlain by a thin soil development that supports shrubs and coconut trees. The terrace levels are nowhere precisely horizontal, suggesting that the erosional surfaces may have exploited cooling joints orthogonal to the vertical columns. Subrahmanya (1996) distinguished levels at 1.5 m, 3 m, 6 m, and 10 m both on the main island and on other islands to the west and south. The ages of these inferred marine terraces are unknown.

The island's western beaches are shelly; the eastern beaches are fine calcareous sands. The highest point of the

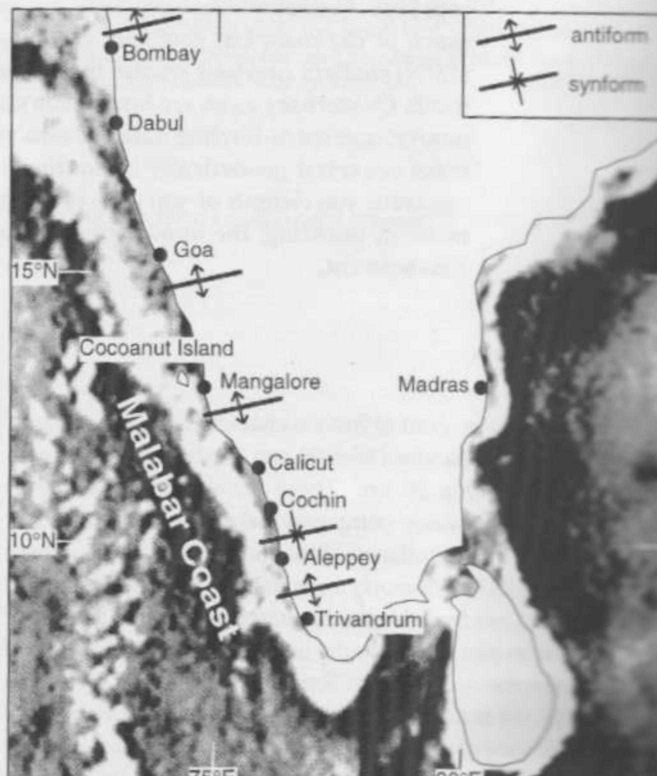


Figure 1. Location map. Quaternary basins along the Malabar coast are mapped with 200–450 km spacing. Geoid swells with ~250 km wavelength (white = high) in the Bengal Fan are faintly visible in SEASAT imagery east and southeast of Madras (13°N).

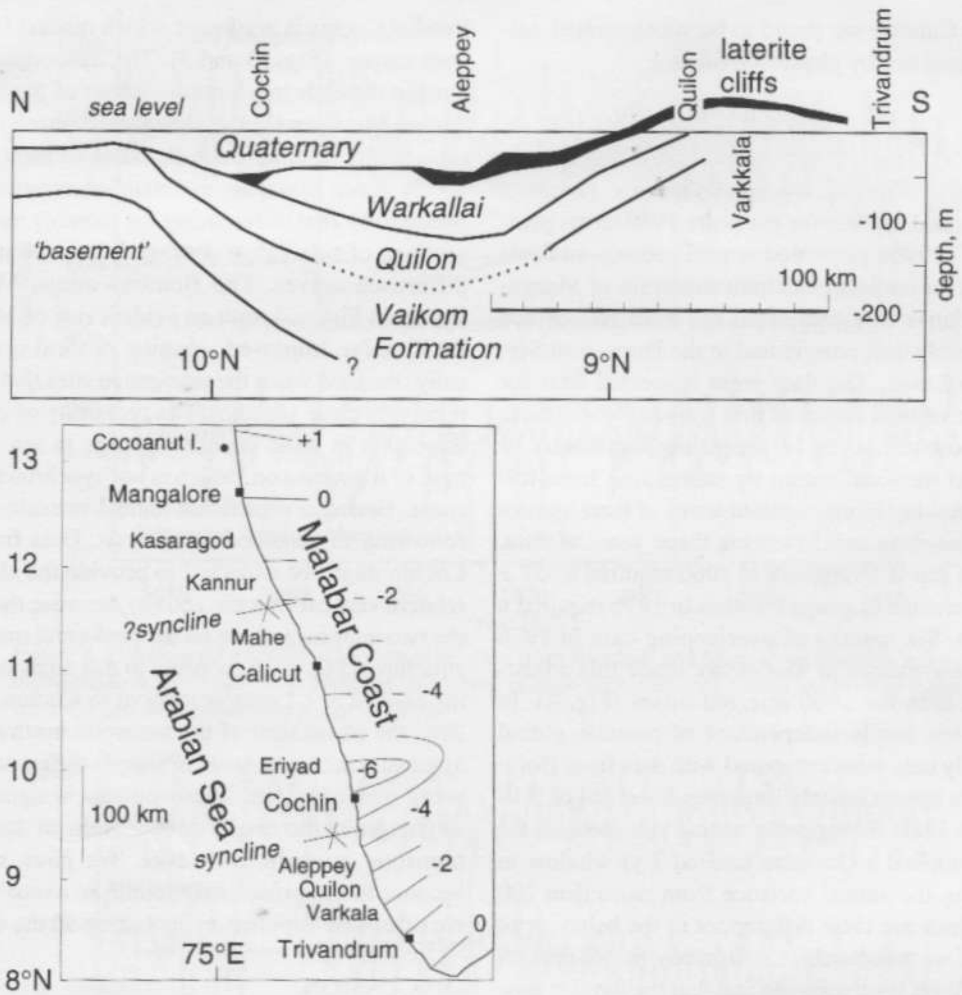


Figure 2. A section through a Quaternary basin along the South Malabar coast from borehole data (after Raghava Rao, 1975; redrawn by Soman, 1980). Laterites (black shading) exposed at Quilon are submerged 50 m below Aleppey. The lower panel shows locations mentioned in text and leveling data from Nagar and Singh (1991). Contours are in millimeters/year. Over a 200 km distance, the vertical uncertainty is approximately 0.1 mm/yr for the 120 yr interval of measurements.

shell deposit approximates the 3 m basalt terrace. We excavated a 2.5 m trench to sea level through the shell deposit ~40 m east of the eroding largest beach, 5 m east of the highest berm. The basal layer, approximately at mean sea level, consisted of basalt cobbles. The shells were fragmented and stratified with textural variations among layers. Upper levels included color changes mixed with occasional thin matrices of mud that may represent former soils. However, numerous mud banks along the coasts are activated in large storms, and these mud layers may be derived from such deposits. Carbon-14 analysis of shelly material yielded ages of 3,150 ± 800 yr (UCL-401) for a sample taken at the base of the trench (0.25 m above sea level) and 2,800 ± 200 yr (UCL-399) for the uppermost sample (2.25 m above sea level). If the age of these materials represents the time of their deposition, we infer an uplift rate of 0.78 ± 0.09 mm/yr.

Historical accounts of emergence and submergence

We reproduce a number of accounts in the Appendix that suggest abrupt coastal events in the past 700 yr: earthquakes, emergence, and subsidence. In particular, several eighteenth and nineteenth century writers discussed the presence of offshore post-sixteenth century ruins at Calicut (11°15′N), and the creation of new land at Cochin (9°59′N) in 1341 A.D. In each of the cases we found no outstanding morphological evidence for vertical motions of the coastline, but found considerable evidence for accretion and erosion. All of the sites that we investigated were characterized by extremely low relief, mainly sandy beaches with few outcrops of bedrock. The new land created at Cochin is representative of many of the sites. It is no more than 1 m above sea level and consists exclusively of sandy soil and debris. Other historical accounts of submerged temples, such as at Calicut, we found to be substantiated neither by local historians nor by physical evidence.

Tide-gauge data

Tide-gauge data (Fig. 3) are available for Bombay, Mangalore, Cochin, and Madras for the years 1950 to the present. Subrahmanya (1996) presented a preliminary analysis using annual means for sea level that indicates uplift of Mangalore and Madras relative to global mean sea level. We extend this analysis to monthly data contributed to the Permanent Service for Mean Sea Level. The data were inspected first for abrupt offsets in the vertical datum of tide gauges. Where these coincided with known changes in operating parameters of gauges, we adjusted the local datum by subtracting from following data, the difference in the constant terms of least squares linear fits to the preceding and following three years of data. For example, a data gap at Mangalore in 1960 required a –37 ± 2 mm offset, and a change in gauge location in 1976 required a +48 ± 1 mm offset. Six months of overlapping data in 1976 from the old and new gauges at Mangalore made this adjustment more certain than the 1960 inferred offset (Fig. 4). In order to examine sea levels independent of eustatic global changes, the monthly data were compared with data from Bombay, which reveal an approximately linear sea-level fall of 0.19 ± 0.02 mm/yr since 1880. To suppress annual variations in the sea-level data, we applied a Gaussian tapered 2 yr window to each series, reducing the annual variance from more than 200 mm to ~20 mm. There are clear differences in the behavior of the selected sites. If we assume that the Bombay record characterizes eustatic sea level for the region and that the longest time series are most representative of secular trends, then Mangalore is rising 2.66 ± 0.13 mm/yr, Madras is stationary (0.04 ± 0.8 mm/yr), and Cochin is sinking at 2.48 ± 0.11 mm/yr. The 40 yr

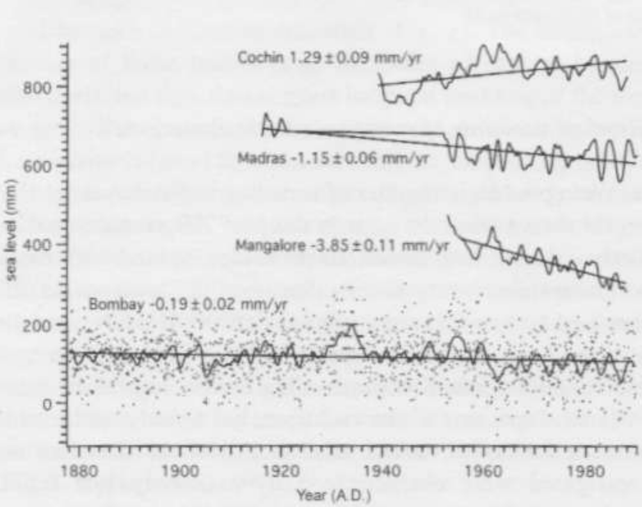


Figure 3. Smoothed sea-level data and least-squares trends in sea level from four tide gauges on the coast of India. The monthly mean data for Bombay shown as dots are illustrative of typical annual variance at all of the gauges. Cochin data are not well represented by a linear trend.

trend at Cochin is nonlinear, which renders linear trend analysis here suspect (Figs. 3 and 5). The least-squares linear trend for Cochin depends much on the subset of the time series selected for analysis, and subsidence of 3 mm/yr prior to 1961 is replaced by an emergence signal of ≈2 mm/yr since then.

A more accurate estimate of relative motion may be obtained by first differencing the monthly values of overlapping sections of tide-gauge data, and then estimating trends in the difference curves. The Bombay minus Mangalore series is shown in Figure 4 with an evident rise of Mangalore of 1.95 ± 0.13 mm/yr. Improved rejection of local oceanic noise is typically obtained when the tide-gauge sites that are differenced are relatively close together. The proximity of gauges is especially important in India because a surge in sea level occurs at the time of the monsoon, which is not synchronous along the Indian coast. Hence, a significant annual oceanic origin may remain following this method of analysis. Data from Mangalore and Cochin might be expected to provide the clearest evidence for relative vertical tectonic activity, because they are the closest of the two gauges, and are on the peaks and troughs of Quaternary structures (Fig. 5). According to this analysis, Mangalore is rising at 3.22 ± 1.1 mm/yr relative to Cochin, yet even for these data, the phase shift of the monsoon northward is sufficient to aggravate the noise level in simple differences. In theory, were we to seek additional improvements in signal to noise ratio, we might ignore the two to three months of data during which the monsoon perturbs sea level. We have not attempted this because this approach may mimic an annual thermal signal that we otherwise suppress by including all the data.

DISCUSSION

Quaternary basins and coastal warping

The borehole data from the two structural basins mapped on the Malabar coast do not permit an unequivocal interpretation of the structural development of the coastal basin, but it would appear that the Miocene Vaikom beds (>100 m of gravels, clays, and thin lignite beds) that overly the basement were folded after deposition. The same may be true of the overlying Quilon formation, which has a maximum thickness of 70 m. The Pliocene Warkallai formation is 60 m thick and consists of lignites, clays, sands, and laterite, interpreted by Soman (1980) as shallow-water littoral deposits of upper Miocene age. These beds have a laterite cap of varying thickness and are unconformably overlain by Quaternary sediments.

If we assume that deformation of the 120 m amplitude basin (assuming north-south symmetry) started at the beginning of the Quaternary (1.8 Ma), the minimum rate of basin growth is ~0.07 mm/yr and the wavelength is ~180 km along the coast. If this is interpreted as a buckle associated with Himalayan collision, this represents an almost negligible shear strain rate (≈0.7 nanostrain/yr). Had the deformation between Eriyad and Quilon started in the late Pleistocene, the

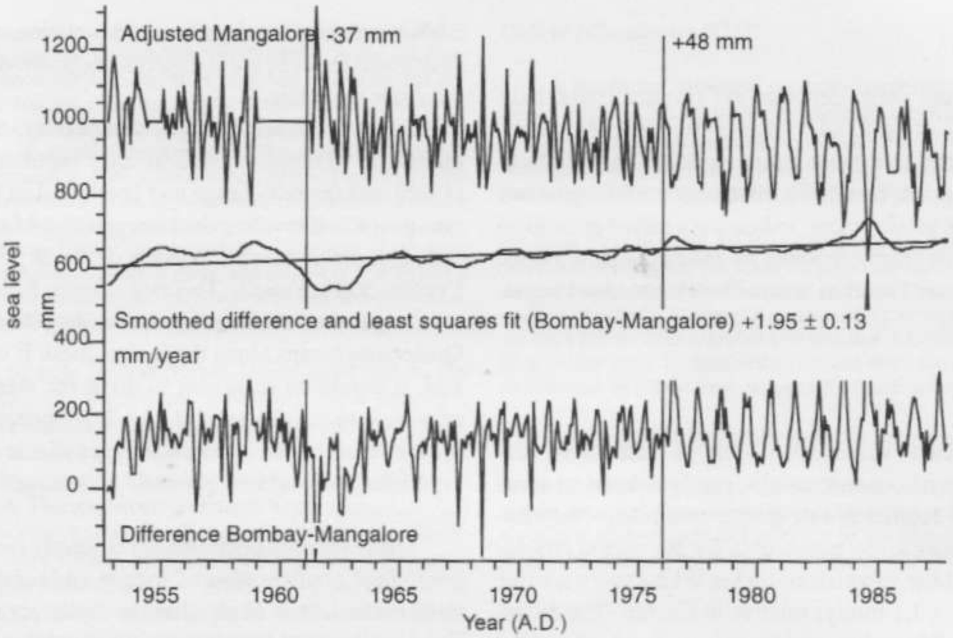


Figure 4. Differenced monthly mean sea-level data from Bombay and Mangalore showing adjustments made in 1960 and 1976. Note the substantial change in character of annual sea level obtained from the new Mangalore tide gauge in 1976.

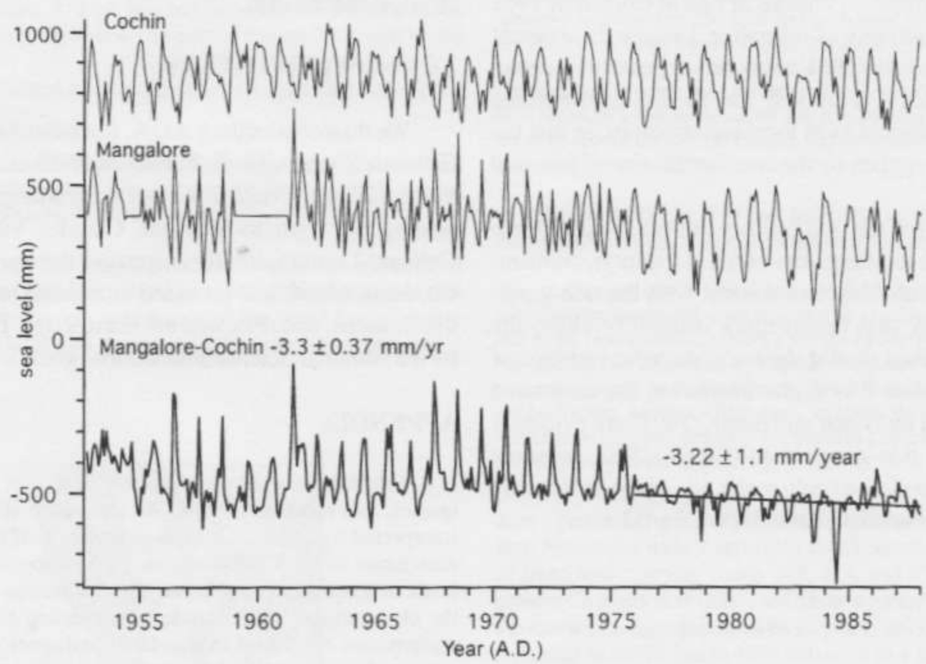


Figure 5. Differences in sea-level data between Mangalore and Cochin from 1953 to 1988 reveal residual annual spikes caused by the phase lag of the annual monsoon. The mean fit to all the data differs little from the mean trend obtained from improved post-1976 data.

strain rate would be roughly an order of magnitude larger. In contrast, Prabhakara Rao (1968) estimated a sedimentation rate in the Warkalli formation of ≈4 mm/yr, requiring a Tertiary subsidence rate almost two orders of magnitude larger. Vertical deformation data for the period 1860–1980 (Fig. 2) indicate that the Cochin region subsided 6 ± 0.1 mm/yr relative both to Mangalore and the southern tip of India (Nagar and Singh, 1991). Paulose and Narayanaswamy (1968) claimed that a second basin of deposition hosts Tertiary sediments between Kannur (Cannanore) and Kasargod, although this apparently is not associated with significant recent vertical deformation.

Uplift at 13°N

Dates derived from shelly deposits on Cocoanut Island indicate a maximum rate of uplift of 0.78 ± 0.09 mm/yr. However, we consider it doubtful that these dates represent the emplacement of the island deposit. The shelly mixture contains organisms from several different provenances, indicating a mixed ecological assemblage typical of storm deposits of historical time (Ellis, 1924). Thin mud layers found at several levels are also characteristic of storm wash.

Tide-gauge data

The residual secular variations evident in differenced sea-level data are partly of oceanic origin, partly related to local tectonics, and partly related to tide-gauge instability. Notwithstanding these limitations, the gauge data for the period considered are consistent: Mangalore rises 1.95 ± 0.13 mm/yr relative to Bombay and 3.22 ± 1.1 mm/yr relative to Cochin. The difference in rate between Mangalore and Cochin is clearly above the oceanic noise level on the Malabar coast, although we are unable exclude the possibility that the tide gauge at Cochin is sinking relative to the region inland. A change in rate at Cochin in 1961 may signify vertical instability of the gauge. Despite its apparent emergence after a gap in 1961 with an exponential decay between 1961 and 1963, it is unlikely that the Bangalore gauge continues to rise with respect to its local surroundings, in that the same emergence rate applies to the two installations (pre- and post-1976).

The leveling data for the past century indicate a subsidence rate for Cochin relative to Mangalore of 6 ± 0.1 mm/yr, confirming a broad region of subsidence consistent with the tide-gauge results. The possibility that bench-mark instability along the 400 km line Malabar coast should show a systematic variation of the form shown in Figure 2 is slight. Moreover, the contoured leveling data presented by Nagar and Singh (1991) are evidently unconstrained by the tide-gauge data (Singh, 1997, personal communication), and are linked only to the tide gauge at Bombay which, according to the leveling data, rises at 5 ± 0.1 mm/yr relative to Mangalore.

CONCLUSIONS

Geomorphological evidence for buckling of the Indian continent along the Malabar coast is limited and ambiguous. Portions of the Malabar Coast have advanced and retreated, but its dynamic morphology may be as easily attributed to coastal processes of erosion and deposition as to vertical motions. Specific historical accounts of subsidence and uplift are attributed to littoral processes causing coastal advance and retreat. The shallow slope of the coastal zone, the scarcity of bedrock, and the difficulty in dating laterite exposures provides few opportunities to find clear geologic indicators of recent vertical motion along the coast. Reported terrace levels in columnar joints on offshore islands permit an ambiguous interpretation, and associated constructional terraces are interpreted as storm deposits of reworked sea-floor materials.

Some evidence remains compelling: the drainage divide along the Mangalore-Madras axis reported by Subrahmanya (1996) and the tide-gauge and leveling data presented here. The tide-gauge and leveling data suggest that Mangalore, for the past few decades at least, has been rising at >3 mm/yr relative to Cochin, 300 km south. This rate is more than an order of magnitude larger than onshore rates prevailing during the formation of Quaternary basins along the Indian coast. If the observed uplift is real, it would be sufficient to drive the weak but concentrated microseismicity observed at 13 ± 1°N. Independent confirmation of localized uplift is potentially available through the future application of modern geodetic techniques (GPS and absolute gravimetry).

Observational uncertainties currently prevent the conclusive geological confirmation of long-wavelength active continental deformation. It is likely that the Indian craton, lacking a pronounced low-velocity layer, is too thick to buckle under the stresses imposed by collision. Hence, the presence of localized uplift at 13°N, and subsidence at 10°N may have an alternative physical mechanism.

ACKNOWLEDGMENTS

We thank our colleagues, A. Radhakrishna, K. Subrahmanya, Gyanesh Sharma, G. C. Suresh, John Paul, V. K. Gaur, and Dr. Valdiya and Dr. Cochhar in Bangalore, Mangalore, and Calicut for hosting our visit to Malabar. Claudio Vita-Finzi, University College, London, kindly estimated the ages of materials from Cocoanut Island, and provided thoughtful interpretations of their implications, and reviewed the manuscript. The study was funded by the National Science Foundation, grant INT-94 23240.

APPENDIX

The Malabar coast abounds with legends of sunken temples, earthquakes, and submarine ruins. We reproduce accounts that have been interpreted by some authors as subsidence of the Calicut region and emergence of the Cochin region. Field inspection of these two areas leads us to conclude that erosion and accretion could equally explain the observations. We conclude by appending a summary of historical earthquakes not found in standard catalogues of Indian events. The magnitudes of most of these events are unknown, except perhaps for the 1881 Bay of Bengal earthquake. The most intriguing of these accounts is the Dabul tsunami of September 1524, experienced in deep water on the continental shelf between Goa and Bombay by the fleet of Vasco da Gama.

Cochin 9°59′50″

Historical accounts indicate the emergence of part of the coast of the island of Vaipin, north of Cochin, in 1341 A.D. Commemorative plaques near the Portuguese fort record the 1341 event as a storm, although on what authority it is not clear. Newbold (1846) wrote the following about Cochin.

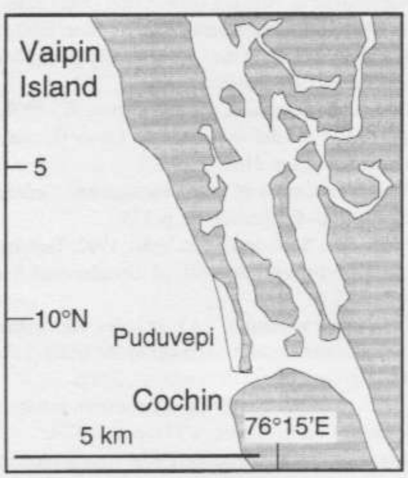
The most remarkable changes are to be found in the vicinity of Cochin. On its northern side we find the island of Vaypi, which was thrown up by the sea about the year 1341. The soil upon this new formation resembles that of the flat districts of Malabar, which consists of sea-sand and calcareous matter combined with clay, said to be washed down from the Ghauts. The production of this island had so strong an effect on the minds of the Hindus, that they marked the geological phenomenon by commencing from it the new era, termed Puduvepa (New Introduction). Contemporaneous with the appearance of the island of Vaypi, the waters which during the rainy season are discharged from the Ghauts, broke through the banks of the river Cochin, and overwhelmed a village of the same name, with such impetuosity as to sweep it away, and formed in that district a river, a lake, and a harbour so spacious that very large ships can now lie in security on the north-east side of Cochin, where the river runs into the sea.

The emergence of new land at Vaipin Island gave rise to the Hindu Era "Puduvepa" or "Putuveppa" (meaning "new deposit"; Logan, 1887, p. 158). The era is associated with the sudden appearance of a coastal tract and the impounding of waters behind the coastal bar. This lends itself to a possible interpretation of coastal uplift, or of storm-related accretion. The southwest portion of Vaypin Island, which we visited in 1995, is now known by the name of Puduvepa. Three coastal beach ridges were visible in front of the western-facing seawall, at ≈50 m intervals with <50 cm of relief above the mud-filled swales between them. The ridges appear as storm beaches of sand near the present shore (no or few shells); a covering of trees and bushes IS inland. A remarkable feature of the island elsewhere is its absence of relief. Numerous channels and ponds are found inland and ancient beach ridges that have been mapped throughout the island show no tendency to form terraces. At high tide in December we found that sea level was less than 1 m (3 ft) below any part of the southern part of the island.

Hamilton (1727) hinted that the marine coast at Cochin had eroded many kilometers by 1703.

The first Europeans that settled at Cochin were the Portugeze, and there they built a fine City on the River's Side, about 3 leagues from the Sea: but the Sea gaining on the Land yearly, it is not now 100 Paces from it.

The absence of marine terraces indicates to us the absence of continued uplift, and evidence for erosion and accretion suggests that the "Puduvepa" event was not emergence of the coast but accretion of additional land to the island during the 1341 storm (see Appendix Figure 1).



Appendix Figure 1. Map of the southern half of Vaipin Island, accessible by ferry from Cochin. The southwest corner of the island is known as Puduvepi.

Calicut (Khozikode) 11°15′

A number of historical accounts suggest that part of the old Portuguese city of Calicut may be currently submerged. Hamilton (1727, p. 177) wrote the following (note that Chess-trees were two pieces of wood projecting on each side of the ship to confine the lower corners of the mainsail. His ship was the *Albermarle*).

On Anno 1703 about the Middle of February, I called at *Calecut* in my Way to *Surat*, and standing into the Road, I chanced to strike on some of the Ruins of the sunken Town built by the *Portugeze* in former Times. Whether that Town was swallowed up by an Earthquake as some affirm, or whether it was undermined by the sea, I will not determine; but so it was, that in 6 Fathoms at the main Mast, my Ship, which drew 21 Foot water, sat fast afore the Chess-tree. The Sea was smooth, and, in a short Time, we got off without damage.

Stanhope (1785, p. 109) wrote the following in his memoirs.

Calicutt, which is now an inconsiderable village, was formerly a magnificent city, and the residence of a powerful Prince. According to the tradition of the natives, it was overwhelmed near 200 years ago by a sudden rising of the sea, and all its inhabitants perished. We anchored on the spot where the ancient city stood and as we went ashore at low water, the foundations of the buildings were discernible to the naked eye.

Newbold (1846, p. 252) repeated oral legends and invoked eustatic sea-level rise, or a storm surge, as a possible mechanism.

In some places, as on the Coromandel coast, tracts formerly inhabited have disappeared under the sea. The bank on which stood the old city of Calicut (the landing place of Albuquerque) a little to the south of the present site, is now buried under the sea, but it does not appear at all clear whether in this, or other cases of submergence, the cause was a sinking of the land, or a change in the configuration of the coast by a sudden rise of the sea. It is said that the remains of an old factory are to be seen in the surf off Pukaad, and those of Pagodas in the surf at Tricanapulyon on the coast of Travancore.

Logan (1887, p. 75) had difficulty in reconciling the nineteenth century anchorages with the location of the city.

The entrance and exit to and from the anchorages (2–3 miles offshore), particularly from the southward, is encumbered by a reef known as the Coote Reef, from one of the Honourable Company's vessels having grounded on it. This is probably also the reef alluded to by Captain Alexander Hamilton as "The ruins of a sunken town built by the Portuguese." That the sea has encroached at Calicut cannot be doubted, but that a Portuguese fort once stood where the Coote Reef now is cannot be believed, although the tradition alluded to by Captain Hamilton has great currency on the coast.

The shoreline near Cochin is straight, sandy, and essentially featureless. Numerous widely separated shoals are mapped offshore on Survey of India hydrographic charts 218, 219, and 259 (scale 1:300,000). The present Customs Port Office at Calicut appears to be located at the end of the screw pile jetty described by Logan (1887), which is currently in disrepair (as in 1881), but in 1887 extended to 4 m of water. It is not known whether tidal records were obtained on this jetty at any time. The Port Officer was unable to confirm rumors of offshore ruins, although he did mention that vague reports had been related to him about submarine structures 15 km to the north beyond Kappad beach. On following this lead we found that this beach is interrupted by scattered rock outcrops that show possible wave-cut terraces at ≈1 m and perhaps 3–5 m. Local villagers expressed no knowledge of submarine ruins. A historical marker at Kappad beach commemorating the landing of Vasco de Gama in 1498 has been relocated inland twice, according to local villagers, suggesting that the coast has retreated. Logan (1887) also offered evidence for the erosion of the coast near Calicut in the marine exhumation of the grave of Shaikh Mammu Koya, but cautions that the erosion could have been minor and followed by annual coastal accretion.

According to Logan (1887, p. 319–320) the Portuguese fort at Calicut, "square in form with bastions at the corners facing the sea," was constructed in 1513 by an engineer named Thomas Fernandez with assistance from the local Zamorin "south of the city on the northern bank of the Kalayi River at the southern extremity of Calicut . . . flanked on two sides by water." The fort was abandoned during hostilities in 1525 (Logan, 1887, p.326), but its subsequent history remains unknown. If the fort had been constructed on an estuarine sand bar it could easily have collapsed during an erosional phase of the river or the sea, and its ruins might now be covered by subsequent accretion. If these were the submerged ruins that Hamilton and Stanhope encountered, the anchorage they would have used would have been much different from that used today.

The coastal region inland from Calicut is flat and close to sea level. Significant subsidence in this region (e.g., more than 1 m) would thus bring a large region close to marine flooding. Had an earlier tract of Calicut been submerged, it would have had to have been constructed on a coastal terrace below the present coastal plain. In that we find no evidence for multiple terrace levels above the present level, a lower marine terrace is unlikely, but not impossible. We are unable to bring further evidence to bear on the existence or nonexistence of a submerged offshore ruin, but geomorphic evidence for the coast at Calicut to be subsiding is decidedly weaker than evidence for shoreline structures being undermined and submerged by repeated accretion and erosion.

Earthquakes

The following Malabar earthquakes were encountered in our search through colonial materials. Except for the 1881 earthquake, the events were not listed in Mallet (1853), Gangopadhay (1988), or Dunbar et al., (1992).

Dabul: September 1524. Two apparently independent descriptions of a tsunami, related either to a major earthquake on the Arabian Sea, Bay of Cambay, or Macran coast, or to an offshore submarine slump, afflicted Vasco Da Gama's fleet three weeks before his death as the newly appointed Viceroy of India. In the fifteenth century, the town of Dabul at 17°34′ was a major trading port near Ratnagari roughly midway between Goa and Bombay (Yule and Burnell, 1903). Logan (1887, p. 322) wrote about the event.

On 11th (or 21st) Sept 1524 Vasco da Gama as Viceroy of India arrived at Goa with 3000 men in 14 ships. On reaching the land at Dabul and with the wind becalmed during the watch at daybreak, the sea trembled in such a manner, giving such great buffets to the ships, that all thought they were on shoals, and struck sails, and lowered boats into the sea with great shouts, and cries and discharge of cannon. On sounding they found no bottom, and they cried to God for mercy, because the ships pitched so violently that the men could not stand upright and the chests were sent from one end of the ship to the other. The trembling came, died away, and was renewed each time during the space of a Credo. The subterranean disturbance lasted about an hour, in which the water made a great boiling up, one sea struggling with another. When daylight was fully come, they saw the land. Da Gama maintained his presence of mind during this, and reassured his men by telling them that even the sea trembled at the presence of the Portugese.

The recitation of the Latin Credo (fast) has a duration of fewer than three min. If the sea waves resulted from an earthquake its moment release must have been considerable, similar perhaps to the 1819 Rann of Cutch event. An independent account of the same event indicating that Vasco da Gama recognized the tsunami as the effects of an earthquake can be found in Kerr (1824), who cited (Astl. I, 54. b.) as his source.

While in the Gulf of Cambaya, in a dead calm, the ships were tossed about in so violent a manner that all on board believed themselves in imminent danger of perishing, and began to consider how they might escape. One man leapt overboard, thinking to escape by swimming, but was drowned; and such as lay sick of fevers were cured by the fright. The viceroy, who perceived that the commotion was occasioned by the effects of an earthquake called aloud to his people, "courage my friends, for the sea trembles from the fear of you who are on it."

Cochin 1784. Newbold (1846) wrote, "In 1784 a strong concussion was felt."

Calicut 1881–1882. Logan (1887, p. 34) wrote the following.

Calicut 30 Dec 1881 midnight Bay of Bengal (R.D. Oldham, Rec. Geol. Suv. India, 17, 47-53, 1884). Felt throughout India (Arracan and Malabar Coasts, Nicobar Islands, Kathmandu) but very weakly in Calicut. The tsunami was recorded around the Bay of Bengal.
Calicut 31 Dec 1881 7:10 AM Madras Time Felt by persons at rest.
Calicut 28 Feb 1882 6:16 Madras time Furniture, roof tiles and window frames shook audibly for a second. Total duration 4–5 secs felt at Telichery and Nilgiri.

Allatur. Logan (1887, p. 34) wrote, "14 Oct 1882 14:00 near Palghat 'tables and boxes rattled audibly for about 1 sec.'"

Trivandrum 1823–1856. Logan, 1887, p. 34) listed the following.

Trivandrum Feb 1823
Trivandrum Sept 12 1841
Trivandrum Nov 20 1845
Trivandrum March 17 1856
Trivandrum Aug 11 1856 5:51:25
Trivandrum Aug 22 1856 16:25:10
Trivandrum 1 Sept 1856 12:15:00

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MANUSCRIPT ACCEPTED BY THE SOCIETY FEBRUARY 3, 1998

Printed in U.S.A.