Evidence of elastic strength variation across the Central Indian Tectonic Zone: A support to the Proterozoic collisional tectonics

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Isostatic models of the lithosphere generally consider the topographic loads supported in part by stresses within the lithosphere, and in part by forces associated with the deflection of density interfaces. Information on the mechanical properties of the lithosphere is generally derived from the gravity and topography transfer function relationships. In this study, we map for a possible strength variation across the Central Indian Tectonic Zone (CITZ), using coherence method extended to two-dimensional fields. Present estimations yielded relatively higher effective elastic thickness values for the North Indian Block, representing a stronger lithosphere, than the South Indian Block. This strength variation provides significant support to the Proterozoic collisional tectonics across the CITZ.

THE Indian shield characterizes different blocks amalgamated in the Neoarchaean–Palaeoproterozoic period with the imprints of complex tectonothermal history, reflecting its crustal evolution and reworking processes through geologic time. The ENE–WSW trending Central Indian Tectonic Zone (CITZ; Figure 1), characterized by a collage of different litho-tectonic terrains ranging in age from Archaean to Recent, divides the Indian continent into discrete blocks: North Indian Block (NIB) and South Indian Block (SIB). The CITZ is bounded by the Son–Narmada North Fault (SNNF) in the north[1] and the Central Indian Shear Zone (CIS) in the south[2], forming about 120–150 km wide tectonic grain. The near-isothermal, decompressional, clockwise *P–T* paths of the CITZ suggest a tectonothermal process involving initial crustal thickening, subsequent rapid exhumation and cooling, which may record a major phase of collision between the NIB and SIB[3].

The lithospheric strength is usually quantified in terms of the effective elastic thickness (*Te*), which is the thickness of an equivalent elastic plate that produces the same deflection under known tectonic loading structure. *Te* depends on many geophysical parameters like stress acting on the plate, thermal state and composition. The analysis of correlation between topography and gravity data with spectral methods (e.g. coherence analysis) enables the estimation of *Te*. In this communication we made *Te* estimations over identical square data windows in the NIB and SIB to obtain insight into the strength variation between these blocks. A recent study by Stephen *et al.*[4] obtained consistently low values of *Te* (~ 13 ± 2 km) for the South Indian shield, using a 2D multitaper-based coherence analysis[5]. Earlier studies show that *Te* estimation significantly varies with the adopted technique. However, Simons *et al.*[5] discuss the advantages of a multitaper method (MTM) over the earlier averaging techniques (where *Te* values were overestimated), which was further substantiated by Ojeda and Whitman[6]. This study utilizes a 2D MTM for detailed mapping of the Indian shield, and aimed to look for the existence of any significant mechanical strength variations across the CITZ. The results were further compared with the estimation based on a mirrored periodogram method (MPM). The mirroring procedure in an MPM alters the wavelengths of the original signal at its edges, leading to exaggerated plate strength. However, the estimations in identical data windows allow one to map any possible strength variations.

Bouguer gravity and topography coherence analysis were carried out using 2D MTM and MPM-based spectral schemes to invert for acceptable *Te* values. An overall accuracy of 1–2 mGal with a grid interval of about 2–6 km is ensured in the gravity field, by merging various data sets[7–14] to the 10 mGal map of India published by the National Geophysical Research Institute (NGRI), Hyderabad[15]. It has been evidenced that the long-wavelength central Indian Ocean geoidal low causes a large negative bias in the peninsular Indian gravity field. Its source is assumed to be situated deep in the

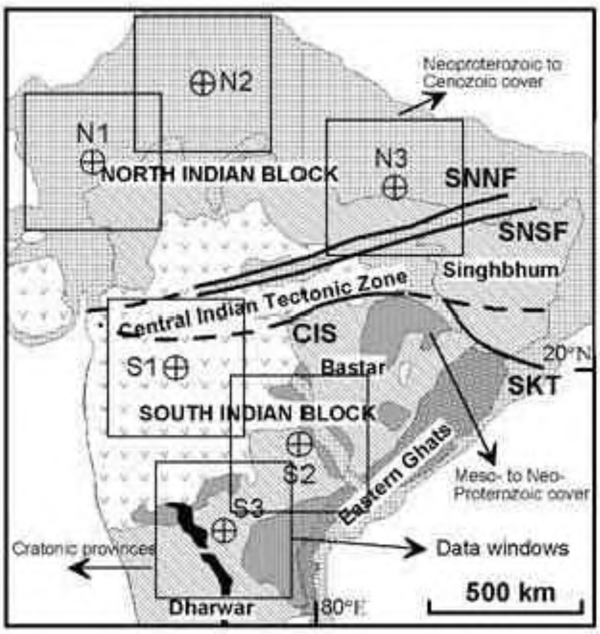

Figure 1. Simplified tectonic map showing NIB and SIB joined along the CITZ (modified after Acharya *et al.*[1] and Zhao *et al.*[3]). SNNF: Son–Narmada north fault, SNSF: Son–Narmada south fault, SKT: Sukinda thrust, CIS: Central Indian shear zone. N1, N2, N3 and S1, S2, S3 are the centres of data windows chosen in NIB and SIB respectively for the analysis.

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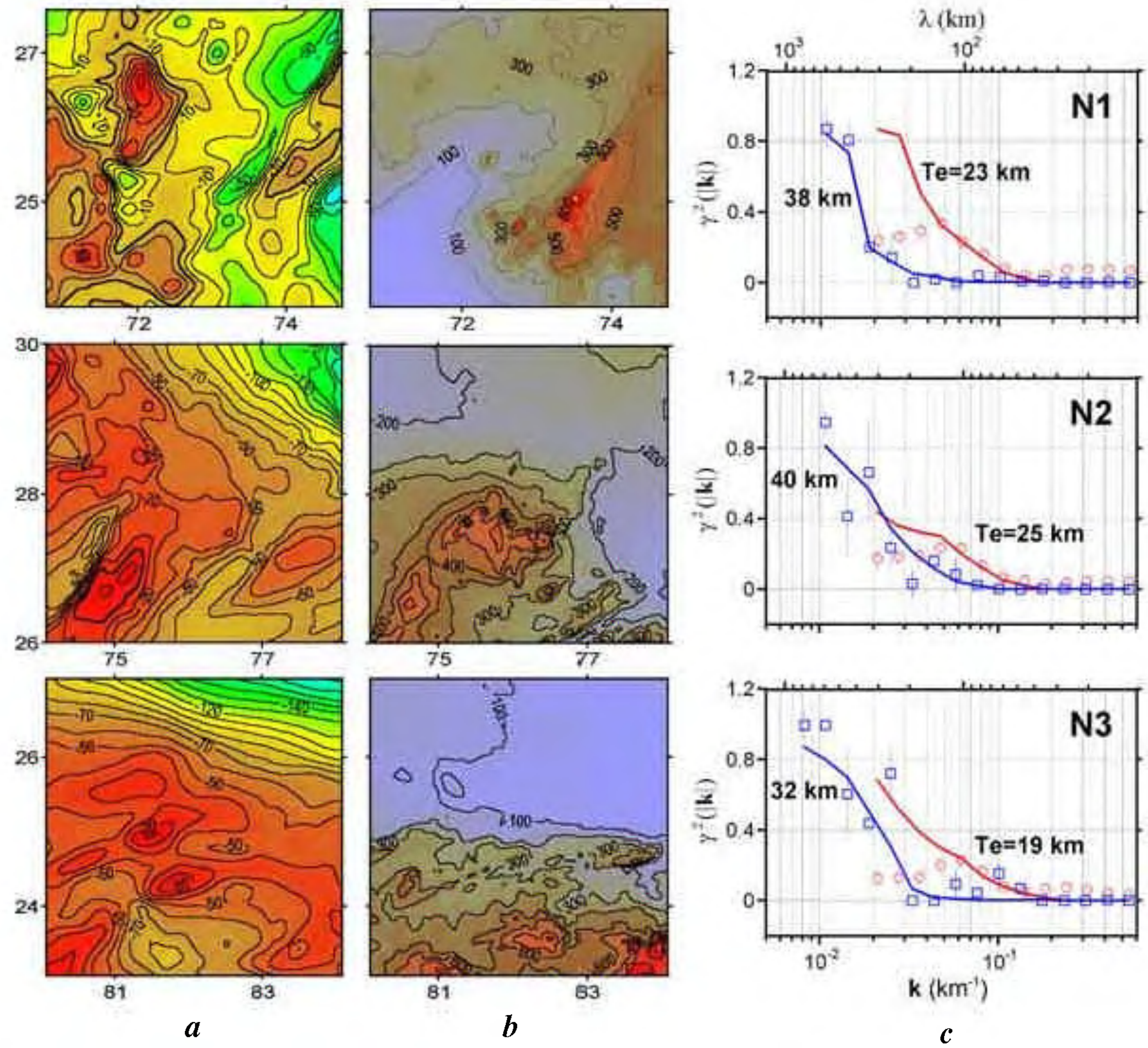

Figure 2. Bouguer gravity (***a***), topography (***b***) and isotropic *Te* inversion results (***c***) in the NIB. Observed (symbols) and predicted (solid line) azimuthally averaged coherence functions, γ^2 (|**k**|) are plotted against wavenumber, **k** for both multitaper (red) and mirrored periodogram (blue) methods.

mantle and therefore insignificant for any isostatic studies with an areal extent less than its characteristic wavelength. The effect of this bias has been removed from the South Indian gravity field. The topography data[16] were taken from GTOPO-30. Both gravity and topography data were further interpolated to retain a minimum resolvable (Nyquist) wavelength of 8 km. The final Bouguer gravity and topography fields used in each analysed window are shown in Figures 2 and 3.

Average crustal thickness over the Indian shield was mainly constrained on the basis of available deep seismic sounding (DSS) profiles[17–19]. In regions where DSS profiles were not available, average values were taken from teleseismic receiver function analysis[20] and fundamental mode Rayleigh and Love wave studies[21]. Any local perturbations in the Moho depths were considered to be outliers in the present *Te* estimation and therefore neglected.

The spectral relationship between Bouguer gravity and topography anomalies was studied, where the coherence functions are further used to invert for an effective elastic thickness, assuming surface and/or subsurface loading of an elastic plate overlying a fluid substrate. Coherence function is a measure of the consistency of the phase relationship between individual measurements of a particular Fourier component, independent of its magnitude. It is a wavenumber domain analogue of correlation, and suggests a way of synthesizing two fields with known coherence. In this study, we utilize Thomson's multitaper method with discrete prolate spheroidal Slepian sequences as data windows. Spectral parameters, namely the time-bandwidth product (NW), the Shannon number and the number of orthogonal eigentapers were fixed to NW = 4, 2NW = 8 and 2NW-1 = 7 respectively. The use of orthogonal eigentapers of different shapes helps process the input with minimum spectral leakage. A mirrored

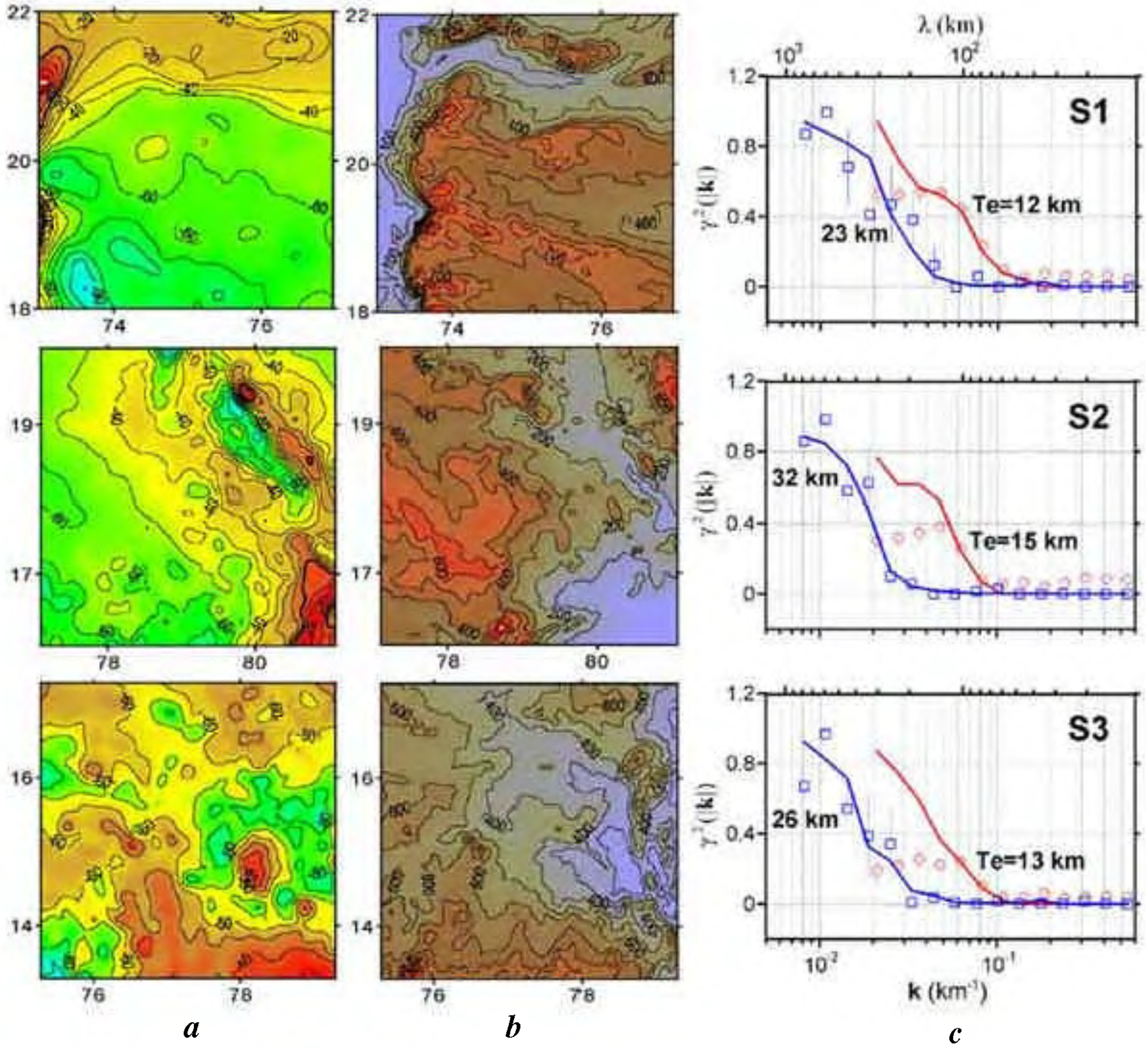

Figure 3. Bouguer gravity (***a***), topography (***b***) and isotropic *Te* inversion results (***c***) in the SIB. (descriptions same as in Figure 2).

periodogram method is also used to obtain *Te* values in the present study. It has been generally understood that MPM yields exaggerated plate strength, compared to MTM. Earlier studies provide detailed discussions on MTM technique and its advantages over other traditional mirrored or windowed periodogram methods[5]. However, we show the results from MPM here, since the use of identical windows could provide an opportunity to study any relative strength variation between different blocks. A high coherence is obtained for long-wavelength topography and statistically independent subsurface loading, while the short-wavelength loads are generally supported by intra-plate stresses, giving no coherence. Information on the flexural strength of the plate is obtained from the transitional wavelength of compensated to uncompensated loading response.

The effective elastic thickness inversions were carried out for six data windows, each of $4° \times 4°$ size centred over the NIB (N1, N2, N3) and SIB (S1, S2, S3), as shown in Figure 1. These $4° \times 4°$ (~ 440×440 km^2) identical square windows were chosen for all the six analyses to obtain the unbiased *Te* variation of the shield, and to retain the uniformity in both the *x* and *y* coordinates for the analysis of 2D windows, and hence to allow a comparative study. The ability of this window size to capture elastic behaviour of the Indian lithosphere has been earlier studied by Stephen *et al.*[4]. The elastic parameters such as Poisson ratio (σ), Young's modulus (E), average crustal density (ρ_c) and mantle density (ρ_m) were chosen to be 0.25, 10^{11} N/m^2, 2700 kg/m^3, and 3300 kg/m^3 respectively. In all the inversions, topographic loading and one interface of subsurface loading (at Moho) were considered.

The multitaper and mirrored periodogram *Te* inversion results for NIB and SIB are shown in Figures 2 and 3 respectively. A lowered *Te* throughout the Indian shield is evidenced, compared to other shield regions of the world obtained using the same methods (e.g. the Australian *Te* given by Simons *et al.*[5]). Again, within the shield, the northern and southern blocks characterize distinct strength, with the

NIB being relatively stronger than the SIB. Three estimations each over SIB and NIB yielded *Te* variations in the range 12–15 km and 19–25 km respectively, using MTM-based techniques. Whereas MPM analysis yielded *Te* values in the range 23–32 km and 32–40 km for SIB and NIB respectively. It has been found that though MPM gives relatively wider range of *Te* estimates, both MPM and MTM results evidence a strength variation across the CITZ, suggesting a clear division between SIB and NIB.

It has been evidenced that in the oceanic region, *Te* is relatively low and its variation appears to be more or less simple compared to the continental regions. Oceanic *Te* is mainly influenced by its reduced crustal thickness, and coincides roughly with the 300–600°C isotherms. In the continental regions, however, it do not follow any regular rules and appears to be much complicated with varying nature from place to place, even in identical geological settings. We found that *Te* estimates for the continental interiors of India are generally in agreement with those obtained earlier for its continental margins[22,23].

For the western continental margin of India, the lithospheric *Te* obtained through cross-spectral analysis of gravity and bathymetry data[23] were in the range 8–15 km. A composite nature is observed in the eastern continental margin, with the southern region (below 16°N) yielding relatively lower *Te* values (even < 5 km) compared to that of the northern region (10–25 km)[22].

The low *Te* for the southern segment of this margin (especially in the Cauvery basin) is attributed to its shear–rift tectonic setting[24]. Whereas for the Krishna–Godavari basin in the north, Radhakrishna *et al.*[25] obtained a much higher *Te* of up to 30 km. One could expect a relation between this large northward increase in *Te* of margin with that obtained for the continental interiors in the present study. The possible influence of India–Madagascar and India–Antarctica rifting processes in lowering the SIB *Te* values should be further studied.

The higher *Te* values obtained for NIB in our present study show a clear separation of this block from the southern block along the CITZ, which has been already acclaimed as the major tectonic divide in the Indian shield. Many hypotheses have been postulated on this tectonic zone. Earlier, possible magmatic underplating, which could result from collisional tectonics, has been suggested on the basis of high velocity structures identified in the CITZ, at a depth of about 10 km (6.9 km/s) and above the Moho (7.3 km/s)[26]. The Himalayan collisional tectonics and crustal thickening to the northern-most parts also could have greatly influenced the elastic strength. Earlier studies evidenced much higher *Te* (up to 35 km) for the Himalayan region[27].

Compared to other shield regions of the world, the Indian shield comprises an overall normal crust, averaging a thickness of about 35 km, with few exceptions. The Proterozoic regions in the shield exhibit a different crustal structure, more representative of tectonically reactivated provinces. Mohan *et al.*[28] obtained contrasting velocity structures for Archaean and Proterozoic terrains. For the South Indian Archaean regions, they obtained high lower-crustal velocities (3.9–4.1 km/s) and low upper-mantle velocities (4.4–4.6 km/s) compared to other shield regions. But significantly lower velocities were obtained in the Proterozoic belts, with 3.7–4.0 km/s for the lower crust and 4.0–4.2 km/s for the upper mantle. The shear wave velocities are found to be slower in the upper mantle beneath the Indian shield[29]. In the lower-Himalaya and Indo-Gangetic plain, low velocities, attributed to the crustal thickening, are obtained.

On the basis of the low power of uncompensated topography to characterize the peninsular Indian and Siberian shields, Watts[30] suggests that the contribution of buried loading is also significant. This subsurface loading might have also acted as an important factor in providing low *Te* in the shield regions. Earlier studies supported that shield regions in the world are normally characterized by high *Te* values. It is widely accepted that the thickness and mean velocity of the continental crust increase with its age[31], at least, on scale lengths larger than about 1000 km. Given enough residence time, the crust underplated by basaltic magmas may evolve to a new, deeper Moho[32], and the transformation of mantle materials during crustal cooling also results in crustal thickening[33]. However, the seismic velocity–depth function in Precambrian provinces shows that most of the Archaean crust is significantly thinner than the Proterozoic crust and lacks a high velocity basal layer[34]. A clear distinction between thinner Archaean and thicker Proterozoic crust in the Indian shield has been shown using tele-seismic receiver function analysis[20]. The present low *Te* values obtained for Archaean terrains in the SIB, agree with the recent views that the older cratons may not be thicker and mechanically stronger[35].

Earlier studies have investigated a possible correlation of heat flow in the continental interiors and the effective elastic thickness; the hotter lithosphere being mechanically weak with lowered *Te*[36]. However, the Indian shield provides a complicated picture, where the heat flow (Q) measurements show a large scatter, mainly attributed to the varied crustal radioelemental heat production. Relatively high heat flow is associated with the CITZ, which has undergone reactivation since the Proterozoic. Distinct radioelemental abundances and heat production of the Proterozoic granites and gneisses have been observed[37]. It is noticed that generally heat flow in the Indian Shield represents local excursions rather than regional tectonics[38]. Varying crustal heat production contributes to the heat flow measurements in the Indian shield, and therefore, we find it difficult to have a good correlation of Q and *Te*. Moreover, the observed *Te* variation in the Indian shield, either that of NIB or SIB, is insufficient to make any significant correlation. In both the northern and southern blocks, we obtain *Te* values in consistently uniform ranges. Thus, we imagine that the compositional discrepancies of the lithosphere mainly contribute to the observed *Te* variations in the Indian shield, rather than the thermal gradients.

The present study clearly shows a substantial strength variation between the NIB and SIB joined along the CITZ, though values of *Te* estimated vary in both MPM and MTM. Taking into account the efficiency of the multitaper in spectral estimation, it is noticed that the entire Indian shield characterizes low lithospheric strength with respect to any other shield regions of the world. Within the plate itself, two distinct strength patterns are observed; the NIB characterizing relatively higher *Te* (19–25 km) than the SIB (12–15 km). Here we suggest that the distinct *Te* obtained on either sides of the CITZ supports the Proterozoic collisional tectonics between the northern and the southern blocks. Stephen and Singh[39] have recently reported a possible correlation of these elastic thickness values with the average focal depths of the major earthquakes in the Indian shield. The highly varying radio-elemental heat production in the shield makes it difficult for its direct correlation with *Te*. The present results support the earlier suggestion that the older cratons may not be thicker and mechanically stronger.

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ACKNOWLEDGEMENTS. We thank Dr V. P. Dimri, Director, NGRI for permission and encouragement to publish this work. We also thank Dr U. Raval for useful discussions.

Received 13 August 2004; revised accepted 17 February 2005

Ecological impact of tsunami on Nicobar Islands (Camorta, Katchal, Nancowry and Trinkat)

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Assessment of tsunami-inflicted damage to island ecosystems assumes great importance owing to the life-sustaining and livelihood support abilities of the ecosystems. Apart from damages caused to life and property, significant damages were caused to ecosystems, which will have long-lasting effects. The tsunami-induced damage to coastal ecosystems was studied in four Nicobar Islands, viz. Camorta, Katchal, Nancowry and Trinkat. The extent of damages assessed ranged from 51 to 100% for mangrove ecosystems, 41 to 100% for coral reef ecosystems and 6.5 to 27% for forest ecosystems. The severity of damages and their consequences suggest the need for a definite restoration ecology programme.

TSUNAMIS are water waves generated by the disturbance associated with seismic activity, explosive volcanism, submarine landslide, meteorite impact with the ocean, or in some cases meteorological phenomena. These waves can be generated in oceans, bays, lakes or reservoirs. The term 'tsunami' in Japanese means harbour (*tsun*) wave (*ami*)[1]. The earthquake on 26 December 2004 with its epicentre at Sumatra, Indonesia triggered a tsunami which had a major impact on the Andaman and Nicobar Islands. The massive tsunami swept through the Indian Ocean region to become arguably the largest natural disaster in living memory. Initial reports indicate that natural ecological systems such as coral reefs, mangroves and wetlands have suffered extensive damages. This calamity highlights the key protective role of coral reefs, mangroves and the importance of CRZ (Coastal Regulation Zone) Notification. Physical damages might impact the structure and function of coastal ecosystems and their ability to sustain marine life and support livelihood of coastal communities. The extent of damage caused to coastal ecosystems and communities in Camorta, Katchal, Nancowry and Trinkat Islands is studied using remote sensing and GIS tools. Ecological impacts of tsunami are not available from previous scientific literature. This communication reports first-hand assessment of ecological damages caused by the December 2004 tsunami in some Nicobar Islands.

The Nicobar Islands are situated southeast of the Bay of Bengal. There are altogether 22 large and small islands, out of which only twelve have inhabitants. The latitudes and longitudes of the four islands under study are as follows: Camorta 7°59′12″–8°14′43″N, 93°25′49″–93°34′36″E, Katchal 7°51′50″–8°01′56″N, 93°17′41″–93°28′47″E, Nancowry 7°55′04″–8°01′57″N, 93°29′23″–93°35′01″E, and Trinkat 8°01′45″–8°08′48″N, 93°37′04″–93°37′30″E. Nancowry and Camorta have a hilly terrain covered with grass, forming undulating meadows. In Camorta, Empress Peak is the highest peak, about 1.420 ft high. Katchal is one of the largest islands in the central group. It is about 61 sq miles in area. It is slightly hilly at the centre, but otherwise it is remarkably flat. Trinkat is another small flat is-

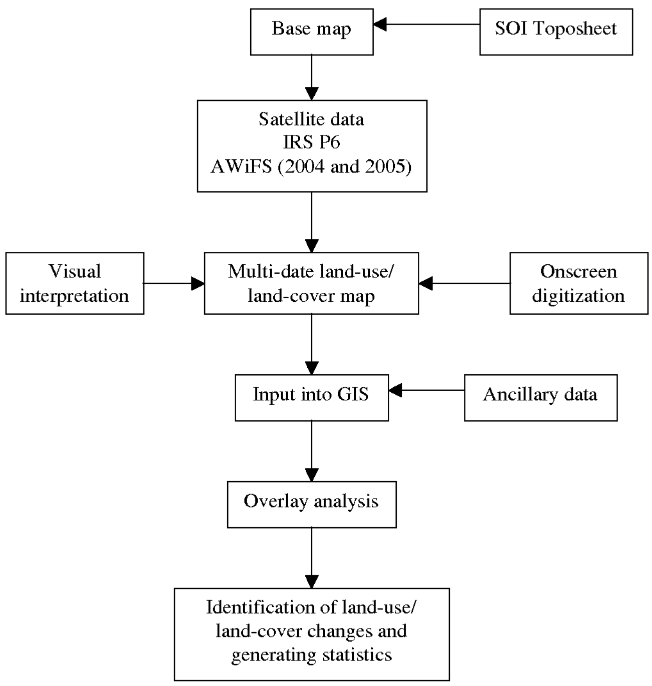

Figure 1. Methodology for land-use/land-cover mapping.

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