Submerged Ancient Indian continent in the Bay of Bengal

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Key points

1. Improved seismic image of the Bay of Bengal and Indian craton using Rayleigh wave group velocity data from ambient noise and earthquakes.

2. An uninterrupted continuation of 140 km thick, high velocity Indian lithosphere from shoreline for about 400-500 km into the Bay of Bengal.

3. We speculate the western Bay of Bengal as the submerged Indian craton, possibly after the India-Australia-Antarctica rifting.
Abstract

We present evidence for an uninterrupted continuation of Indian continental lithosphere into the Bay of Bengal to a distance of 400-500 km away from the passive margin. The inference is based on the shear velocity image of the upper mantle beneath the Bay of Bengal, Bangladesh, and the adjoining Indian craton, computed using ambient noise and earthquake waveform data. The Indian lithospheric mantle is characterized by a progressively increasing shear wave velocity of ~4.5-4.7 km/s, at least up to a depth of 140 km, and continues uninterrupted to about 86° E in the Bay of Bengal. Further east, the thickness of the lithospheric lid decreases to ~90 km and is underlain by reduced shear wave velocity (~4.1-4.3 km/s). We postulate that the Indian craton is embedded in the western Bay of Bengal and the continent-ocean boundary lay around 86° E. The craton possibly submerged soon after the India-Australia-Antractica rifting.
1. Introduction

The Bay of Bengal is generally agreed to have evolved due to the breakup of India from Antarctica and subsequent seafloor spreading (Norton and Sclater, 1979). It is generally accepted that the initial India-Australia-Antarctica rifting created the western Bay of Bengal around 136 Ma (Figure 1). This was followed by the evolution of the eastern Bay of Bengal due to a northward ridge jump at around 118 Ma (Gaina et al., 2007). The boundary between the two is proposed to be around 85-86° E (Talwani et al., 2016). The two linear features in the Bay of Bengal, viz., 85° E and 90° E ridges (Figure 1) are widely considered as the traces of the Crozet and Kerguelen hot spots (Kent et al., 1992).

Based on the analysis of seismic, gravity, and geological data, Johnson and Nur-Alam (1991) proposed an oceanic crust underlying more than 12 km thick sediment beneath Bangladesh. Between Bangladesh and the Indian creation lies the Bengal basin that has developed largely over a remnant ocean basin. The sediment column thickness increases to ~22 km beneath the Bangladesh shelf in the south that progressively reduces to 3-4 km in the southern Bay of Bengal (Curray, 1994). It is proposed that the Bay of Bengal has 5-6 km thick oceanic crust south of 15° N (Curray et al., 1982). Scientific opinion, however, remains divided on the nature of the crust beneath the Bay of Bengal. The controversy initially emerged from the velocity modeling of surface wave group velocity data of Brune and Singh (1986) who argued for a continent like thick crust beneath the Bay of Bengal. Their inferred Moho depth in the northern part of the basin was 5-10 km deeper than the earlier studies (Curray et al., 1982). To resolve this discrepancy, Brune et al. (1992) reanalyzed their surface wave data with constraints from high-frequency Sn wave propagation along several paths across the Bay of Bengal. Their reinterpretation suggests a 22 km thick sedimentary basin under the northern Bay of Bengal with
the lower 6 km layer characterized by Vp ~6.5 km/s. The velocity increase is proposed to be due to the high-pressure metamorphism. This layer was earlier misidentified as oceanic crust and led to the interpretation of an unusually thick crust. The same argument was used by Mitra et al. (2011) to infer the oceanic nature of the crust beneath the Bay of Bengal from their velocity tomography results. The proposition of oceanic crust in the northern Bay of Bengal has been recently questioned by Sibuet et al. (2016) and Rangin and Sibuet (2017) based on several multi-channel seismic data acquired in the region. These studies indicate the presence of a thin (15 km thick) continental crust injected by Mesozoic volcanism, a view that is contradicted by Talwani et al. (2016).

Contra these studies, our knowledge of the state of sub-crustal lithosphere mantle beneath the Bay of Bengal is limited. Lithosphere, representing the plate, is characterized by high-velocity lid overlying the low-velocity zone corresponding to the asthenosphere (Eaton, 2009). The concept of the lid and the low-velocity zone have evolved in the past from different processes like partial melting (Gutenberg, 1959; Kawakatsu et al., 2009), mineral physics considerations (Anderson and Sammis, 1969), chemical changes (Regan and Anderson, 1984), and the presence of hydrated phases (Karato, 2012). The lithosphere-asthenosphere boundary (LAB) is classically associated with the depth of the 1300°C isotherm (Artemieva, 2006) and can be related to the V$_{SV}$ parameter at the top of the low-velocity zone. The velocity drop varies from 5 to 10% depending on the age of the ocean. The effect of increasing lithospheric age is to shift the low-velocity zone to deeper depths and increase the value of minimum velocity. Considering an ambient shear velocity of 4.7 km/s, for a 100 Ma oceanic lithosphere, the minimum shear velocity is expected to be around 4.3 km/s (Stixrude and Lithgow-Bertelloni, 2005). The thickness of most of the oceanic lithosphere increases with the square root of its age, until ~100
km (Doin and Fleitout, 1996). In the northwestern Pacific ocean with seafloor age of 150-160 Ma, Nishimura and Forsyth (1989) inferred lithospheric thickness of about 90 km, using Rayleigh wave phase velocity data. Their results indicate high shear velocity of 4.7 km/s ± 0.07 km/s in the upper lithosphere that extends to ~65 km depth, followed by a negative velocity gradient with a minimum of 4.30 ± 0.09 km/s at 150 km depth. For 100-130 Ma old oceans, Kawakatsu et al. (2009) and Kumar and Kawakatsu (2011) suggest LAB at ~70 km. In the framework of above results and considering 136-118 Ma age of the Bay of Bengal, the lithospheric thickness is expected to about 100 km.

We briefly discuss the state of lithosphere beneath the Bay of Bengal. Based on the efficient propagation of Sn wave along a few paths, Brune et al. (1992) argued for cold uppermost mantle beneath the Bay of Bengal. Bhattacharya et al. (2013), inverted five surface wave inter-station phase velocity data to show that the path-averaged lithosphere-asthenosphere boundary at a depth of about 110 km. Similar thickness of high velocity mantle is inferred from the global tomographic map computed using group velocity maps (Shapiro et al., 2008). The studies discussed previously, are either spot values limited in extent or averaged over the region. Lateral variability of the structure of the lithosphere, therefore, remains speculative.

In this research paper, we present a detailed 3-D shear wave velocity image of the lithospheric mantle to a depth of 140 km beneath the Bay of Bengal and Bengal basin/Bangladesh and compare them with the adjacent Indian craton. The velocity image is used to understand the seismic character of the lithospheric mantle beneath the Bay of Bengal and to place a constraint on the continent/oceanic lithosphere dichotomy. We use here surface wave tomography approach to generate the velocity image of the region. The method and its application in different geological environments has been reviewed in Thurber and Ritsema
We use Rayleigh wave group velocity data retrieved primarily from cross-correlation of ambient noise recorded over 683 seismic stations covering south Asia and adjoining north Indian ocean (Figure 2a). To improve lateral resolution we have supplemented the ambient noise data with earthquake surface waveform data from 417 earthquakes (M>5.5, depth 10-95 km) between 10° S to 50° N and 31° E to 130° E, recorded by 209 seismic stations over India (Figure 2b).

2. Surface wave dispersion maps

The data processing of ambient noise to extract Rayleigh wave group velocity is accomplished, following the techniques of Bensen et al. (2007). All the vertical component waveforms data recorded on 683 seismographs are decimated to one sample/s and cross-correlated among the stations operated during the same time interval. The cross-correlated functions (CCF) are averaged to generate a symmetric signal, which is further stacked for the entire duration of operation to increase the signal to noise ratio (SNR). In subsequent analysis, we use the waveforms with S/N>15 and the source-receiver distance more than three times the wavelength (Bensen et al., 2007). We compute the fundamental mode Rayleigh wave group velocity from CCFs and also the earthquakes waveforms recorded over seismic stations using the multiple filter taper analysis approach (Herrmann and Ammon, 2004). The combined ray coverage using ambient noise and earthquake data for every 1° × 1° grid is presented in Figure S1 for selected time periods. The Rayleigh wave travel times along multiple paths are then converted into group velocity maps at different time periods following Barmine et al. (2001).

The horizontal resolution of the tomographic maps is investigated using the checkerboard resolution test in which the input synthetic model comprises an alternating pattern of higher and
lower wave velocity (Rawlinson and Spakman, 2016). Using the observed ray-path geometry, we compute the synthetic group velocity travel time at different time periods and invert them to reconstruct the input velocity map. Here we use a discrete spike test involving a sparse distribution of spikes, rather than the conventional tightly-spaced checkerboard. We used cells of size 0.5°, 1°, and 2° blocks with alternate ±6% velocity perturbation. The test is performed for Rayleigh wave group velocity at selected time periods from 10s to 70s. The minimum cell size of 1° could be resolved for the study region. Figure S2 shows the recovered velocity for every 1° × 1° horizontal grid. For most part of the study region the input model is well recovered for the ray paths used.

Figure 3 shows surface wave velocity maps at time periods from 10s to 70s over the Bay of Bengal, Bengal basin/Bangladesh and the adjoining Indian craton. Since the group velocity inversion at any period is performed from independent travel time data sets, continuity of features in imaged velocity maps at subsequent time periods suggests that the anomalies represent accurately the structural features. To establish a correspondence between the group velocity at any time-period and depth of investigation in the Earth, we present the group velocity sensitivity kernel for different time periods assuming a layered Earth model (Figure S3). The group velocity map at the time-period of 10-15s is an average for the velocity in the approximate depth range of 4-15 km with a peak sensitivity at a depth of ~8-10 km. In this depth range, we observe strong variation in the morphotectonic features of the Earth differentiating crystalline upper crust, sedimentary basins, fold belts, oceanic crust, etc. (Pasyanos, 2005). The Indian craton, at the time period of 10-15s, has a group velocity of ~3.2-3.3 km/s representing crystalline crust. Progressively, the velocity reduces near the craton boundary to ~2.8-3.0 km/s in the Bengal basin/Bangladesh and the Bay of Bengal. Bangladesh is characterized by progressive
lowering of velocity from the west to the east which could be a consequence of variation in sediment thickness of 3-5 km in the west to 10-12 km in the east (Lindsay et al., 1991).

The group velocity at the 20s period has an average group velocity of 3.1 km/s in the continental region, decreasing progressively to 2.8 km/s beneath the Bengal basin/Bangladesh. The Bay of Bengal has a group velocity of 3.2 to 3.4 km/s. The depth sensitivity for 20s period Rayleigh wave is between 10 km and 35 km corresponding to uppermost mantle beneath the ocean in contrast with lower crust in the continent. Usually, the 20s period group velocity response shows strong discrimination between the continent and the ocean because of the difference in their crustal thickness (~35 km vs ~10 km). Presence of similar group velocity in Indian continent and the adjoining Bay of Bengal suggests a thicker crust beneath the oceanic region.

At a higher time-period of the 30s, the Indian continent and the Bay of Bengal have distinct group velocity of 3.2-3.4 and 3.6-3.8 km/s respectively. The response at the 30s corresponds to a velocity structure at a depth of 15-50 km with the maximum resolution at 30-35 km depth. It is possible that due to the presence of thicker crust beneath the Bay of Bengal, the distinction between the continent and the ocean is delayed to the 30s group velocity data. With a further increase in the time-period to 50s, corresponding to the velocity response in the depth of 40-90 km, the average group velocity varies between 4.0 and 4.2 km/s. These features continue even at the deeper time-period of the 70s. A noteworthy observation is the presence of a high velocity (>4.2 km/s) region covering most of the adjacent Indian craton (Singhbhum, Bastar and eastern Dharwar) representing their cold upper mantle.

3. Shear Velocity Structure
To quantify the depth variation of shear velocity, we extract the Rayleigh wave group velocity dispersion data from 10 to 70s for each grid node of $1^\circ \times 1^\circ$ and invert them for shear wave velocity as a function of depth using the linearized least squares inversion (Herrmann and Ammon, 2004). The starting model for the velocity inversion consists of a stack of isotropic layers with constant shear wave velocity of 4.5 km/s. The layer thickness is one km up to 10 km depth, followed by two km thick layers from 10 to 50 km depth, and finally, layers with five km thickness extending from 50 to 140 km depth. During the inversion, constant velocity and density are assumed in each layer. The density is calculated using the relation $\rho = 0.32V_p + 0.77$ (Nafe and Drake, 1963). We have performed inversion with other initial velocity models like AK135 and PREM and found an insignificant change in the result. In case of data from the oceanic region appropriate thickness of water column was considered. We repeat the inversion 20 times to compute the final shear wave velocity-depth model at each node. The 1-D velocity-depth is generated at every 0.5° interval and stitched to get a 2-D velocity-depth section and velocity maps at different depths.

To study the variation of velocity from the continent to the ocean, we plot the shear wave velocity-depth section along the longitude at different latitudes from 14° N to 25° N (Figure 4A-F). We also present the map view of the shear wave velocity of the proposed 3-D model at different depths (Figure 5) for detailed analysis. Beneath the Indian craton, we observe high velocity (upto 4.7 km/s) continuing to a depth of 140 km with no sign of velocity reversal. This signature continues horizontally beneath the Bay of Bengal until 86° E beyond which, we observe velocity reversal with depth representing thinned lithosphere of about 90 km. Beneath Bangladesh, the velocity reversal is observed at a depth of ~110 km. In summary, the velocity-depth sections and maps suggest two distinct patterns: a layered lithosphere mantle similar to the
Indian craton beneath the region west of 86° E (western Bay of Bengal) and a thin (<90 km) lithospheric mantle to the east of 86° E in the region widely known as eastern Bay of Bengal. The thinned lithosphere is also underlain by low velocity (<4.2 km/s) mantle. The underlying asthenosphere shear wave velocity beneath the Bengal basin and Bangladesh (Figure 4 section F and G) is marginally higher (4.3-4.4 km/s) than that beneath the eastern Bay of Bengal (Vs ~4.1-4.3 km/s) (Figure 4 section A to E). This feature is well reflected in velocity map of 80, 100 and 120 km depth (Figure 5).

4. Geological interpretation of velocity-depth sections

Theoretical considerations and other observations suggest a lithospheric thickness of about 90-100 km for oceans of age over 90 Ma. Beneath the Indian craton, we observed a two-layer lithospheric mantle with a maximum shear wave velocity of 4.7 km/s, extending at least up to 140 km beyond which we do not have depth resolution. With these constraints, we examine the boundary of the Indian continent vs oceanic lithosphere. We observe the signature of Indian continental lithosphere continuing beyond the shoreline and uninterrupted traceable up to ~86° E beneath the Bay of Bengal. This seismically imaged thick and old lithosphere beyond the coastline up to over 400-500 km into the Bay of Bengal suggests that the northern Indian ocean is a mix of continent and ocean. Similar high-velocity thick lithosphere beneath the ocean basins has been mapped elsewhere (King and Ritsema, 2000; Deen et al., 2006; Begg et al., 2009; Kaban et al., 2016). The phenomena responsible for the presence of thick continental cratonic lithosphere found beneath the oceans remain unresolved. It is argued that either the cratonic mantle lithosphere is not permanently attached to the drifting continental lithosphere and could detach during the process of continental movement (Wang et al., 2017) or it has shifted due to basal drag induced by mantle flow (Kaban et al., 2016).
Along most of the profiles, we observe more than 140 km thick high-velocity lid continuing until about 86° E and then progressively decreasing to 75-90 km further east. This is in contrast to a mono-phase rifting model of McKenzie (1978) where the breakup is instantaneously resulting in the juxtaposition of continental and oceanic crust. The contact between these two types of crusts is often assumed to be sharp and marked by a magnetic anomaly. This classical model is significantly revised to show that breakup is gradational rather than a sharp event as evident along the Iberia-Newfoundland conjugate margins (Pe’ron-Pinvidic et al., 2007). A more detailed analysis by Huismans and Beaumont (2011) suggested that Iberia-Newfoundland type observations could be explained by depth dependent extension in which crust and lithosphere are firmly bonded. Here, the crust breaks first while the lithospheric mantle is still necking and progressively thins with time. This would lead to progressive thinning of continental lithosphere away from the continent, a signature also observed east of 85° E in the Bay of Bengal.

Another interesting feature of the Bay of Bengal emerges from an examination of the distribution of minimum Vs in the depth section. We observe that the western Bay of Bengal has velocity signature of a stratified lithosphere akin to the adjoining Indian Archean cratons. In contrast, the eastern Bay of Bengal has a significantly lower Vs of 4.1 to 4.3 km/s in the depth of 90-120 km. The contact between the western and eastern Bay of Bengal happens to be around 86° E. Talwani et al. (2016) proposed that the eastern basin is younger than 118 Ma. They, however, could not place lower bound on the age of the eastern ocean basin. Beneath the Bengal basin/Bangladesh, the sub-lithospheric low-velocity is 4.3-4.4 km/s while it is 4.1-4.3 km/s in the eastern Bay of Bengal. As discussed above, the effect of decreasing lithospheric age is to decrease the value of minimum velocity. The local minimum velocity is related to the age of the
lithosphere by \( V_{sm\text{in}} = V_{s0} - \frac{1}{\left(1.63 + 0.16\epsilon^2\right)^{\frac{1}{2}}} \), where \( V_{s0} = 4.77 \text{ km/s} \) and \( t \) is in Ma (Stixrude and Lithgow-Bertelloni, 2005). For a 100 Ma ocean, the Vs minimum varies from 4.2 to 4.3 km/s similar to the observation in the eastern Bay of Bengal. The inferred lithosphere thickness of about 90 km beneath the eastern Bay of Bengal, based on the inversion of shear velocity with depth is similar to the expected cooling of a \( \sim 100 \) Ma plate.

The further reduced Vs of 4.1 km/s beneath the eastern Bay of Bengal (Figure 5, depth 100, 120 km map) suggests significant high viscosity and hence, a higher degree of melting in the asthenosphere. Presently we do not have a clear idea of what led to such heating of the basin. It may be noted that in the northernmost part of Bangladesh, lies the Rajmahal and Sylhet traps that possibly originated from a Kerguelen hotspot (Curray and Munasinghe, 1991; Kent et al., 2002). As India moved northward, the trail of this hotspot is seen as 90°E ridge. Interaction of this hotspot could have led to reheating of the eastern basin.

5. Conclusion

This is the first study to resolve the presence of two distinct lithospheric features in the Bay of Bengal: the western basin (west of 86°E), a thick and high velocity layered lithosphere (>140 km, Vs ~4.5-4.7 km/s) similar to the Archean Indian craton; and a thinner lithosphere (~90 km) underlain by a low-velocity layer (Vs~4.1-4.3 km/s) possibly representing asthenosphere to the east of 86°E representing the eastern Bay of Bengal. Given the uninterrupted continuation of Indian lithosphere velocity signature up to 86°E, we speculate the possibility of continuation of the Archean craton beneath the western Bay of Bengal and the continent-ocean boundary at 86°E. The western Bay of Bengal possibly represent the submerged Indian craton. This could have happened after the India-Antarctica-Australia rifting at 136 Ma. The eastern Bay of Bengal was
subjected to multi-phase depth dependent rifting which also evidenced in its distinct lithospheric structure. The reliability of the hypothesis proposed here could be tested through petrological analysis of mantle rock samples and improved seismic imaging using broadband ocean bottom seismographs.

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**Figure 1:** (a) Geological map of the study region depicting individual terrains. Interpreted continent-ocean boundary and other geological features based on the shear wave velocity model from Figure 4 and 5 is also shown.
Figure 2: (a) Map shows the distribution of 683 seismic stations from India and the neighboring countries used to compute cross-correlation function from the vertical component ambient noise recording. This contributed to more than 21600 ray paths. (b) Additional group velocity data were generated using 417 earthquakes (red star) and the corresponding 209 seismic stations (black reverse triangles).
Figure 3: Fundamental mode Rayleigh wave group velocity maps at periods of the 10s, 15s, 20s, 30s, 50s, and 70s. Group velocity is contoured at an interval of 0.2 km/s.
Figure 4: Shear wave velocity-depth section along west to east from Indian craton to the Bay of Bengal/Bangladesh. Velocity sections are generated at different latitudes from 12° N to 25° N (marked as profile from A to G). Shear wave velocity is contoured at an interval of 0.2 km/s. Major geological domains and tectonic boundaries, faults are marked on top of individual figures.
Figure 5: Map view of the shear wave velocity of the 3-D model at different depth. The depth for each map is marked in the upper-left corner of each panel. Shear wave velocity is contoured at an interval of 0.2 km/s.
Supporting Information

Submerged Ancient Indian continent in the Bay of Bengal

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Figure S1: Ray path density distribution for combined noise and earthquake data computed for 1° × 1° grid cells at periods of the 15s 30s, 50s, and 70s.
Figure S2: Checkerboard resolution tests for 15s, 30s and 70s Rayleigh wave group velocity maps with cells $1^\circ \times 1^\circ$. The input model is alternately $\pm 6\%$ velocity variations in the blocks. Corresponding recovery maps are produced by inverting synthetic travel times through the checkerboard model for the same paths as those used in the tomographic inversion of real data.
Figure S3: The depth sensitivity kernel of fundamental mode Rayleigh wave group velocities at time periods 10s, 15s, 20s, 30s, 50s, and 70s.