Lithospheric structure across the western part of the Narmada–Son Lineament from wide-angle seismic data

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Seismic refraction and wide-angle reflection data were acquired in early 1980s in analog form along a 260-km long Sendhwa–Sindad DSS profile over the Deccan Traps-covered area across the Narmada–Son Lineament. The data with 15 Hz high cut filter were later digitized and assembled into record sections which exhibit deep-travelling, identifiable, wide-angle reflected phases by playing with gain. We have derived the lithospheric velocity structure in Central India by kinematic and dynamic modelling of these phases. The result shows two intra-crustal discontinuities, one at a depth of 14.5–16.5 km and the other at 26 km, where velocity jumps from 6.6 to 7.0 km/s. The sub-crustal lithosphere beneath a crust–mantle boundary at 39–41 km consists of two prominent low-velocity (7.0 km/s) zones bounded by high-velocity (8.0–8.2 km/s) layers.

Keywords: Crust–mantle boundary, lithosphere, ray tracing, seismic reflection, wide-angle reflection.

The lithospheric velocity structures can be determined by the earthquake or the explosion seismology data. The crustal and upper mantle structures have been derived in various geological settings of the world using long-range seismic refraction/wide-angle seismic data by several workers. We derive the lithospheric velocity structure by kinematic and dynamic modelling of such wide-angle seismic data iteratively using a ray-tracing software. The velocity structure in different regions of the Indian peninsula is known from travel-time modelling of earthquakes, surface wave dispersion, waves spectra and deep seismic sounding (DSS) studies.

As a continuation of crustal seismic studies, four DSS profiles, each of about 250 km long, were shot across the Narmada–Son Lineament (NSL) in Central India. This lineament is the most conspicuous linear geological feature in India after the Himalaya. It passes through Broach on the west coast of India in NNE–SSW direction cutting across the whole of Central India and has been periodically reactivated since the Precambrian. The crustal velocity models derived from the DSS data acquired along these profiles across the NSL reveal, in general, a high positive velocity gradient up to a depth of about 10 km from the surface. The Moho is found to vary

significantly from 22 km near Billimora along the Mehmadabad–Billimora profile, then subsequently deepen, rise and again deepen to 42 km near Jabalpur along the Hirapur–Mandla profile16.

In the present study, we have analysed the wide-angle reflection data acquired along a 260-km long Sendhwa–Sindad DSS profile (Figure 1) over the exposed Deccan Traps region across the NSL to derive a lithospheric velocity model in Central India.

The seismic refraction/wide-angle reflection data with a total coverage of 2950 line km were recorded in analog form using a POISK 48-channel seismic recording system with geophone groups of 200 m apart and explosives as source at 10 km average intervals. Employing the continuous profiling, data for a total of 26 shot points (SPs) were recorded. Based on the coverage and quality of data, only SP0, SP40, SP190 and SP235 were selected to derive the velocity model. Figure 2 displays the surface coverage for these SPs. Necessary playback records were

Figure 1. Deep seismic sounding profile with shot points (SPs) along with detailed geology in the western part of the Narmada–Son Lineament.

Figure 2. Diagram showing coverage from four SPs executed for the present study.

Figure 3. (a) Observed, (b) synthetic record section and (c) ray diagram showing different sub-crustal phases of SP0.
obtained with desired gain and filter settings with 15 Hz high cut from the data recorded on magnetic tapes. The analog records with very high gain are generally used for picking the first arrivals to derive the shallow velocity model from refraction data. The playback analog records were digitized and assembled into record sections with a reduction velocity of 6 km/s to enhance the visibility and coherency of later arrivals that have been used to derive the deeper velocity model. The first arrival refraction data from respective SPs were superimposed in the trace normalized record sections as dotted points (Figures 3–6). The record sections in the trace-normalized form provide the data to derive the kinematically and dynamically constrained lithospheric velocity model in the study region.

The 2D forward-ray tracing technique is an effective algorithm for computing the synthetic seismograms in laterally inhomogeneous media\textsuperscript{17}. The method is based on zero-order asymptotic ray theory (ART) corresponding to high-frequency approximation, which intends to use both the refraction and reflection data. For modelling, an initial 2D velocity model is required, which is divided into a number of boundaries, each with a velocity and gradient assigned. Amplitudes are determined by generating spreading of spherical wavefronts and energy partitioning at interfaces. Earlier a shallow velocity model revealing the low-velocity Mesozoic sediments between the Narmada and Tapti rivers hidden below the high-velocity Deccan volcanics with basin configuration has been delineated\textsuperscript{18}. Using the refraction and reflection data, a five-layered crustal velocity model for this area has also been derived\textsuperscript{19}. The digitized data have been used to further refine the model and derive the sub-crustal velocity structure in the study region.
The velocity model of the lithosphere has been delineated using the long-distance wide-angle seismic data from the reciprocal shots SP40 and SP235, which are about 200 km apart, and SP0 which was recorded up to a distance of 160 km, SP190 which was recorded up to SP40 on the northern side and up to SP235 in the southern end (Figure 2). The record sections of SP0 (Figure 3), SP40 (Figure 4), SP190 (Figure 5) and SP235 (Figure 6) were interpreted after careful scrutiny of reflection phases and amplitudes of various phases. For SP235, there is nearly 30 km recording gap due to inaccessible hill ranges near Barwani (south of Narmada River). For the present study, a combined model along with some sub-crustal layers has been used as the initial model to delineate the deep velocity structure in the study region. The velocity model is successively refined till a satisfactory match between the computed and observed data both in travel times and amplitudes is achieved. After the $P^{\text{M}}P$ phase, the most striking later events ($P^1$, $P^2$, $P^3$ and $P^4$) in the field records are interpreted as the reflections from the sub-crustal horizons. The data from these identifiable events have been used to derive the velocity model of the lithosphere by both travel-time fit and amplitude modelling.

By synthetic seismogram modelling, we could generate the amplitudes of $P^{\text{M}}P$ and reflection from the lower crustal boundary, which are comparable to recorded amplitudes. The amplitudes of deeper reflections are quite low compared to the observed ones. To increase the amplitudes of these phases to match with the observed data, it is necessary to increase the velocity contrast for sub-crustal layers. This is not possible by increasing the velocity to fit the observed data, as it requires velocity beyond the acceptable limit. On the other hand, the Moho is assumed as a first-order jump at a depth of 39–41 km with two alternating low-velocity layers of ~5 km thickness sandwiched between two high velocity layers, one at a depth of about 50 km and the other at 58 km.

The trial and error procedure has been adopted until the best fit between the synthetic and observed record sections is obtained by adjusting velocity contrast in order to satisfy the observed amplitudes for all identifiable phases. The final velocity model (Figure 7) consists of Moho at 39–41 km depth underlain by ~5 km thick two alternating low-velocity layers (LVZs), with a velocity of 7.0 km/s in each at an average depth of about 50 and 58 km with intermittent high-velocity (8.0–8.2 km/s) layers. The reversed reflection travel-time data recorded from the reciprocal SP235, which is at a distance of about 200 km from SP40, is also interpreted to derive the lithospheric velocity model of the region. A satisfactory fit to the observed $P^{\text{M}}P$ phase as well as the deeper phases has been obtained for both SP40 and SP235 by two-dimensional kinematic and dynamic modelling.

The reinterpretation of another DSS profile, about 300 km south of the present area, over the Deccan Traps in the Koyna region revealed similar feature of alternating LVZs (7.4–7.6 km/s) intervened by a thin, high-velocity layer in the sub-crustal lithosphere. It is interesting to note the striking similarity between the lithospheric velocity–depth functions inferred in the Koyna region and the Sendhwa–Sindad region across the NSL. There are many evidences in the recent past emphasizing the lateral heterogeneity not only in the crust, but also in the uppermost mantle. A sequence of high- and low-velocity layers in the sub-crustal lithosphere is basically accepted by many authors. The seismic refraction experiments on long-range profiles suggest that the offset of travel-time branches is indicative of the existence of a sequence of low and high-velocity layers in the sub-crustal lithosphere and asthenosphere. Unless we introduce LVZs below Moho in the final velocity model, we cannot produce amplitudes comparable with the observed data. Although there is an inherent difficulty to derive
independently the thickness and velocity drop in the LVZs, the joint interpretation of travel-times and amplitudes has reduced the ambiguity to a greater extent. The delineation of LVZs is important from the geodynamic point of view, as low velocity could be associated with lower viscosity and higher mobility of the mantle material. For instance, the existence of the topmost LVZ is due to the partial dehydration of the pyrolitic mantle. In the sub-crustal lithosphere, the lower velocities could be produced either by the absence of a preferred orientation or by a decreased concentration of olivine.


Frontal recession of Gangotri Glacier, Garhwal Himalayas, from 1965 to 2006, measured through high-resolution remote sensing data

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We report in this communication the length fluctuation and frontal area changes at the snout of Gangotri Glacier based on high-resolution satellite data from 1965 to 2006. Glacial outlines were mapped from declassified imageries from Corona (1965, 1968), Hexagon (1980) and Indian satellites IRS PAN (2001) and Cartosat-1 (2006). The results show that Gangotri Glacier exhibited retreat up to 819 ± 14 m and lost 0.41 ± 0.03 sq. km (~ 0.01 sq. km year−1) at its front from 1965 to 2006. The retreat rates are lower than those previously reported using coarse-resolution remote sensing data and the Survey of India topography map. The results of the present study are supported by in-situ field survey conducted by the Geological Survey of India.

Keywords: Gangotri Glacier, remote sensing, retreat, satellite data.

GANGOTRI Glacier is the largest glacier (length ~ 30 km) in the Garhwal Himalayas. The Bhagirathi River originates from the snout (Gaumukh; ~ 3950 m asl) of Gangotri Glacier, which is the main source stream of Ganga River (Figure 1). Gangotri Glacier originates from the Chaukhamba group of peaks (~ 6853–7138 m asl) and flows northwest towards Gaumukh. About 29% of its total area is covered by debris1. Gangotri Glacier is one of the well-documented and monitored glaciers in the Indian Himalayas as regards to its snout position. Auden2 first systematically mapped the snout and geomorphic features of Gangotri Glacier in 1935 using a plane-table survey at a scale of 1 : 4800. Several scientists from GSI have resurveyed Gangotri Glacier and marked the position of the snout on Auden’s plane-table map and measured its length in terms of retreat3–6. Length records though are not the most significant parameter for glacier

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