

# Lithosphere of Indus Block in the Northwest Indian Subcontinent through Genetic Algorithm Inversion of Surface-Wave Dispersion

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**Abstract** The Indus block in the Northwest Indian subcontinent is a continental area lying between the Chaman fault in the west, the Aravalli range in the east, and the main boundary fault of Himalaya in the north. We evaluate the lithospheric structure of this crustal block through inversion of Love- and Rayleigh-wave group velocities obtained using broadband records at Bhuj from the Kashmir earthquake of 8 October 2005 and its aftershocks; the recording station lies in the southern edge and epicenters lie in the northern edge of this block. The wave paths are mostly in the study area in a direction parallel to the Aravalli trend. The period of the group velocity data ranges from 5.4 to 74.1 sec, and the inversion of these data resolves the structure down to the lithosphere–asthenosphere boundary (LAB). A nonlinear inversion has been carried out through a genetic algorithm with a wide solution space; some new concepts of solution space of a layered structure and of a misfit function are used. The mean and standard deviation of the 50 accepted solutions with low misfit give the structure IB11 for the Indus block; the standard deviation gives the estimation of the uncertainty and the resolution of the corresponding parameter. In IB11, the sedimentary thickness is 5.6 km within two layers. The total thickness of the crust is 44.2 km. The *S*-wave velocity below the crust is 4.393 km/sec, while this velocity is 4.603 km/sec in the Indian region to the east of the Aravalli range. In IB11, the LAB is at a depth of 79 km, which is much shallower than the corresponding depth of 120 km in the Indian region. On the other hand, the *S*-wave velocities below the crust as well as the depth of the LAB are similar to those of the Arabian shield. These similarities support the hypothesis that the Indus block is a detachment of the Arabian–Nubian shield.

## Introduction

The Indian subcontinent (the northern part of the Indian plate) consists of the Gondwana lithosphere containing three main blocks: (1) the south Indian block, (2) the Bundelkhand block in the north, and (3) the trans-Aravalli block in the northwest (Fig. 1). These blocks are geologically unrelated to each other and sutured during different periods of the Earth's history (Qureshy and Iqbaluddin, 1992). Balakrishnan (1997) divided the Indian subcontinent into several crustal blocks based mainly on topography and geology; in the areas covered with alluvium, geophysical maps were the principal guide. He called the trans-Aravalli block, whose major part lies in Pakistan, the Indus block.

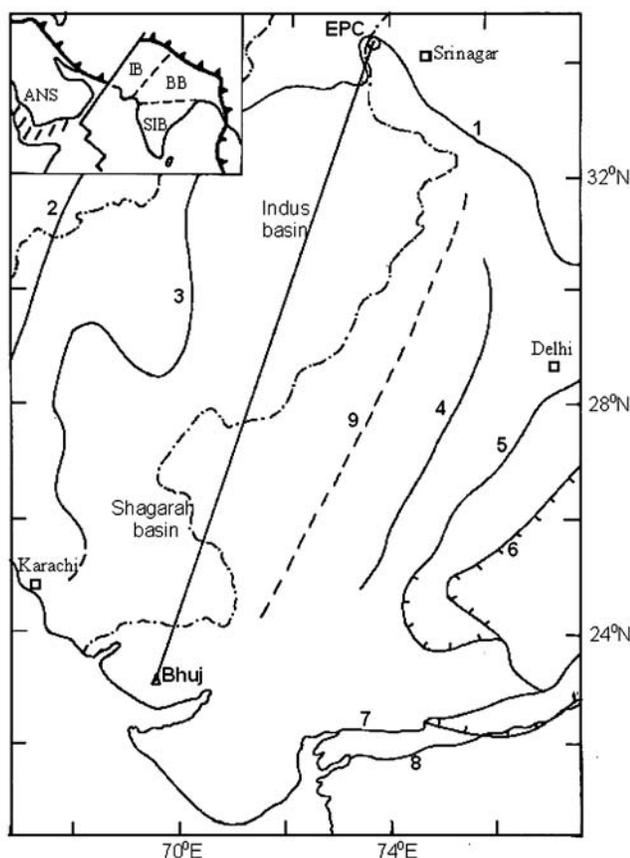
Observed surface wave dispersion data have long been used to evaluate the lithospheric structure of the Indian subcontinent (Bhattacharya, 1981, 1992). The group velocity measurements on regional and global scales are now generating two-dimensional maps of surface wave velocities at dif-

ferent periods that are further used to obtain the three-dimensional structure of the lithosphere. However, Cotte and Laske (2002) tested different sets of such group velocity maps and found a significant difference in group velocities between measurements and predictions from the maps. The surface wave dispersion data for the total wave path give reliable and average lithospheric structure, if the path crosses the same crustal block.

Results of surface wave dispersion in the Indian region have been reviewed by Bhattacharya (1992). The mainland has two types of lithospheres: the model IP11 for the Indian Peninsula and the model IG11 for the Indo-Gangetic basin (Fig. 2). Further, Bhattacharya (1991) found that IP11 also satisfies the dispersion data along wave paths just east of the Aravalli range. The subcrustal region of IG11 is the same as that of IP11 supporting the penetration of the Indian lithosphere below the Gangetic basin. However, much less is known about the lithospheric structure for the Indus block.

Here we evaluate the lithospheric structure of the Indus block through inversion of group velocities of fundamental

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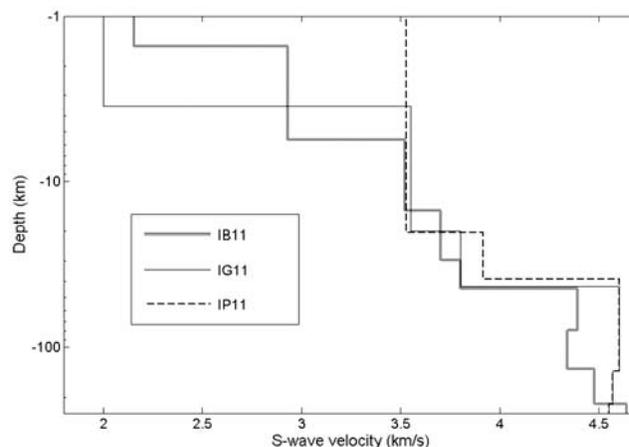


**Figure 1.** Inset shows the location of the Indus block (IB) or trans-Aravalli block on a sketch map (based on Qureshy and Iqbaluddin, 1992); Bundelkhand block, BB; South Indian block, SIB; and Arabian–Nubian shield, ANS. IB is bounded by the Chaman fault in the west and by the Aravalli frontal suture in the east. The main figure shows the major tectonic elements of IB and its neighborhood (based on Balakrishnan [1997]). The epicenter (EPC) of the main earthquake of 8 October 2005 is shown along with the location of the Bhuj observatory. Surface wave paths are joining epicenters of the main earthquake (EPC) and its aftershocks to Bhuj. The important faults are (1) the main boundary fault, (2) the Chaman fault, (3) the Suleiman fault, (4) the West Aravali fault, (5) the East Aravalli fault, (6) the Great boundary fault, (7) the South Bundelkhand fault, and (8) the Narmada fault. The western limit of the Aravalli trend is shown by a dashed line (9).

mode Love and Rayleigh waves using a genetic algorithm; the surface wave paths are mostly in the Indus block (Fig. 1). The structure obtained is compared with lithospheric structures of the Indian region and the Arabian shield to investigate the postulate of Qureshy and Iqbaluddin (1992) that the Indus block is a detachment of the Arabian–Nubian shield.

### Tectonic and Crustal Features

The Indus or trans-Aravalli block is a continental region bounded by the Aravalli frontal suture in the east, the Chaman transform fault in the west, and the main boundary fault in the north (Fig. 1). The Indus block represents a younger crustal block (<1400 Ma) than the Bundelkhand



**Figure 2.** Comparison of  $S$ -wave velocities in the models IB11 (for the Indus block), IG11 (for the Indo-Gangetic basin), and IP11 (for the Indian Peninsula). The depth is in a logarithm scale to show the details of the lithosphere. For each model, the velocity at 1 km depth continues up to the surface.

block (Gupta *et al.*, 1980). Qureshy and Iqbaluddin (1992) showed that the gravity anomaly, magnetic characteristics of the crust, and other geophysical parameters of the Indus block are similar to the Arabian shield from 1200–560 Ma and postulated that the Indus block, along with rest of the Indian plate, apparently separated from the Arabian–Nubian shield during the mid-Tertiary (Miocene) and moved northward along the Owen fracture zone–Chaman fault system, finally colliding with the Eurasian plate.

The Indus block is dominated by Mesozoic and Paleozoic sediments, which outcrop in the Salt Range, in the Jaisalmer area, and in Kutch. Raja *et al.* (1989) and Kadri (1995) noted that the average thickness of the Indus basin is 4.8 km. In the Indus basin, sedimentary rocks have a marine origin and age from late Precambrian to Quaternary. Bouguer gravity anomaly is higher in the Indus block than in the Vindyan and Peninsular blocks even with continental deposits in the latter two blocks; Balakrishnan (1997) inferred that the Indus block has been a scenario of substantial transgressions, and it is overlain with thick marine deposits.

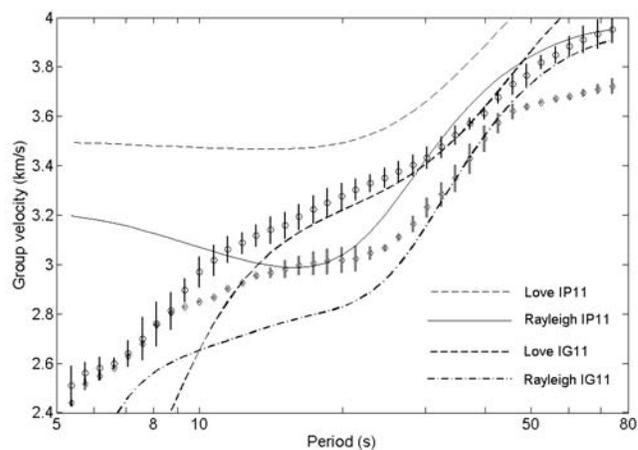
Crustal studies through regional surface waves are rare for the Indus block. Chun (1986) considered east–west paths from two earthquakes in central Pakistan to Delhi, India; a large portion of these paths are along the Aravalli region. He obtained a crustal thickness of 40 km with 4 km of unconsolidated sediments ( $V_S = 2.34$  km/sec, where  $V_S$  is  $S$ -wave velocity) and 6 km of consolidated sediments ( $V_S = 3.06$  km/sec); further,  $V_S = 4.52$  km/sec in the region below the crust. Mandal *et al.* (2007) considered the Kashmir earthquake of 8 October 2005 and its five aftershocks and used records of observatories located in the Kutch region as well as in the southern Indian Peninsula. The stacked group velocities were obtained for periods between 7 and 35 sec for Love waves and between 7 and 38 sec for Rayleigh waves for wave paths along both the Indus block and the Indian Peninsula, and the average crust of

the two regions was obtained. A linear inversion showed that the upper crust is 13.8-km thick with  $V_S = 3.2$  km/sec, and the lower crust is 24.8-km thick with  $V_S = 3.7$  km/sec; in the region below the crust  $V_S = 4.65$  km/sec as noted for the Indian Peninsula by Singh *et al.* (1999). To improve the regional seismic-event location an initial three-dimensional  $P$ -wave velocity model for the region was obtained using regional  $P$ -wave arrival times from well located events (Reiter *et al.*, 2005); the mantle lid  $P$ -wave velocity for the Indus block was found around 8.1 km/sec.

### Data

An earthquake of magnitude ( $M_w$ ) 7.6 occurred close to Muzaffarabad in Kashmir on the western syntax of the main boundary fault on 8 October 2005 (Fig. 1). It was followed by several aftershocks of  $M_w$  5 and above. These epicenters are located just north of the Indus block. Surface waves were recorded by broadband seismographs at Bhuj (23.254° N, 69.654° E) in Kutch at the southern edge of this block. Thus, the paths remain in the study area and are nearly parallel to the Aravalli trend (Fig. 1); the paths cross the upper Indus basin in the north and the Shagarah basin in the south (Biswas, 1987). The seismograph at Bhuj consists of a three-component seismometer STS2 connected to a Quanterra recorder Q680LVG (Bhattacharya and Dattatrayam, 2000). The velocity response curve is nearly flat up to the period 120 sec. The list of earthquakes used here is given in Table 1. The average epicentral distance from Bhuj is 1335 km.

Using a seismograph response, the digital data are converted to ground displacements that are further converted to vertical, radial, and transverse components with a known back azimuth of the epicenter. Group velocities are obtained through frequency-time analysis (FTAN) following Bhattacharya (1981, 1983). Both the vertical and radial components are used to obtain the fundamental mode Rayleigh-wave group velocity, and the transverse component is used to obtain the fundamental mode Love-wave group velocity



**Figure 3.** Observed group velocity data of the Love wave (open circles) and the Rayleigh wave (open diamonds) from epicenters to Bhuj; the vertical lines across data show corresponding standard deviations. The theoretical dispersion curves for the models IG11 and IP11 (Fig. 2) are also shown.

(Fig. 3). The observed group velocities have been compared with the theoretical dispersion curves corresponding to the structures obtained for the Indian Peninsula (IP11; Bhattacharya, 1981, 1992) and the Indo-Gangetic plain (IG11; Bhattacharya, 1992). The comparison shows that the structure of the Indus block is different than either IP11 or IG11 (Fig. 2). However, the observed data are closer to the dispersion curves for IG11 than those for IP11 (Fig. 3).

### Inversion and Lithospheric Structure

A surface wave dispersion curve is a nonlinear function of medium parameters, and thus, the inversion of observed surface wave dispersion data is a nonlinear inverse problem. In a linear approach, the higher order terms in the Taylor series are neglected (Herrmann and Ammon, 2002). The method based on this approach requires adequate knowledge of the starting model and evaluates a single solution inher-

Table 1

List of Earthquakes Used for Evaluation of Group Velocity

Number	Date (mm/dd/yyyy)	O-Time hr:min:sec (UTC)	Epicenter		Depth (km)	Magnitude	Epicentral Distance from Bhuj (km)
			Latitude (°N)	Longitude (°E)			
1.	10/08/2005	03:50:28.9	34.90	72.63	10.4	7.6 ( $M_w$ )	1322
2.	10/08/2005	04:02:20.7	35.13	72.69	33.0	5.5 ( $M_L$ )	1378
3.	10/09/2005	04:58:52.8	35.10	72.93	33.0	5.5 ( $m_b$ )	1351
4.	10/09/2005	07:09:14.7	34.95	72.73	20.0	5.6 ( $m_b$ )	1333
5.	10/09/2005	08:30:02.0	34.75	72.89	33.0	5.6 ( $m_b$ )	1316
6.	10/12/2005	20:23:33.2	35.26	72.90	10.0	5.6 ( $m_b$ )	1366
7.	10/17/2005	10:43:21.0	34.13	73.30	33.0	5.5 ( $m_b$ )	1256
8.	10/23/2005	15:04:18.5	34.94	72.77	12.0	6.5 ( $m_b$ )	1333
9.	10/24/2005	13:14:15.9	35.08	73.59	33.0	5.6 ( $m_b$ )	1364
10.	10/26/2005	01:42:37.5	34.63	73.83	10.0	5.6 ( $m_b$ )	1324
11.	10/28/2005	21:34:16.0	34.65	73.24	33.0	5.9 ( $m_b$ )	1310
12.	11/21/2005	08:26:11.6	35.09	73.12	30.0	5.7 ( $m_b$ )	1354
13.	12/25/2005	08:02:03.1	35.04	72.81	33.0	5.8 ( $m_b$ )	1344
14.	03/20/2006	17:40:42.4	34.71	74.09	62.2	5.5 ( $m_b$ )	1340

ently depending on the assumed starting model; on many occasions such a starting model is difficult to ascertain. Here we choose a genetic algorithm (GA) to invert the dispersion data because it gives a fully nonlinear solution in a large model space (Lomax and Sneider, 1995). The GA does not improve a solution, but it works on a population of possible solutions. Search techniques such as the Monte Carlo technique also allow a large model space to be explored to produce solutions (Bhattacharya, 1981). However, the GA is an iterative directed search operating on a population of trial solutions within a user defined search space to find new solutions with lower misfit in each generation; the misfit is obtained from the difference between observed data and theoretical values based on a solution.

For inversion through GA, we have chosen ranges of parameters of a layered structure (Table 2). We consider a nine-layered structure out of which the top five layers form the crust; the subcrustal region down to 220 km has three layers, and the region below 220 km is a half-space with the same velocities and density as in the preliminary reference Earth model (PREM; Dziewonski and Anderson, 1981). In layers 1–8, we have considered not only the solution ranges of  $V_S$  ( $S$ -wave velocity) but also the ranges of the  $V_P/V_S$  ratio, where  $V_P$  is the  $P$ -wave velocity. The density in each layer has been kept constant because it has the least effect on the dispersion curve. We have also considered ranges of thicknesses for layers 1–4, 6, and 7; for the fifth layer, being the lowest layer of the crust, we considered the range of depth of the bottom of this layer, and this range corresponds to that of the crustal thickness. Thus,

$$\begin{aligned} &\text{the thickness of the fifth layer} = \text{crustal thickness} \\ &\quad - \text{sum of the thicknesses of the top four layers.} \quad (1) \end{aligned}$$

In total, we have considered a solution space with 23 variable parameters of the structure (Table 2). The bottom of the eighth layer is fixed at a depth of 220 km. Hence,

$$\begin{aligned} &\text{the thickness of the eighth layer} = 220 \text{ km} \\ &\quad - \text{sum of the thicknesses of the top seven layers.} \quad (2) \end{aligned}$$

For inversion of the observed group velocity data, we use the GA and direct search tool box of MATLAB. The misfit function is considered as

$$\text{misfit} = \max \left[ \frac{1}{NL} \sum_{i=1}^{NL} \frac{|U_o^{(L)}(T_i) - U_c^{(L)}(T_i)|}{\sigma^{(L)}(T_i)}, \frac{1}{NR} \sum_{j=1}^{NR} \frac{|U_o^{(R)}(T_j) - U_c^{(R)}(T_j)|}{\sigma^{(R)}(T_j)} \right], \quad (3)$$

where  $NL$  and  $NR$  are the numbers of observations for Love and Rayleigh waves, respectively;  $U_o^{(L)}(T_i)$  and  $\sigma^{(L)}(T_i)$  are the observed group velocity and its standard deviation of the Love wave for period  $T_i$  ( $i = 1, 2, \dots, NL$ ), respectively; and  $U_c^{(L)}(T_i)$  is the theoretical group velocity of the Love wave at period  $T_i$  based on the solution. The theoretical group velocities are obtained using the programs of Bhattacharya (1986).  $U_o^{(R)}(T_j)$ ,  $\sigma^{(R)}(T_j)$ , and  $U_c^{(R)}(T_j)$  are the corresponding values for Rayleigh waves at period  $T_j$  ( $j = 1, 2, \dots, NR$ ). Equation (3) shows that the misfit function is a maximum of two separate misfits, one for the Love wave and other for the Rayleigh wave; this has been done to avoid giving too much importance to either the Love wave or the Rayleigh wave. The inversion with the misfit function considering the mean of the Love and Rayleigh waves together includes solutions whose dispersion curves are too good for one of the waves but not so good for the other; we have avoided such solutions defining the misfit function as in equation (3).

The GA begins with a random initial population of  $K$  models within solution limits (Table 2). We consider population size  $K = 60$  at each generation, where we create a new population with two elite members, 46 members through crossover, and 12 members by mutation; the elite members replace the worst models in the current generation with the best individuals of the previous generation, so that the best individuals are not lost (Yamanaka and Ishida, 1996). We have considered 300 generations; however, if the misfit value does not decrease for 50 generations, the operation stops. Such large population sizes of 60 in each generation and 300 such generations are required because of the large number (i.e., 23) of variable parameters in the structure. The best

Table 2  
Nine-Layered Structure with Search Space of the Solutions

Layer Number	Thickness (km)	Depth of the Bottom (km)	Density (gm/cm <sup>3</sup> )	$V_S$ (km/sec)	$V_P/V_S$
1	1–2	—	2.00	1.80–2.30	1.70–1.82
2	3–5	—	2.30	2.40–3.20	1.70–1.82
3	8–12	—	2.65	3.30–3.60	1.70–1.82
4	13–17	—	2.90	3.60–3.90	1.70–1.82
5	—	36–48	3.05	3.70–4.00	1.70–1.82
6	30–40	—	3.37	4.30–4.62	1.70–1.82
7	50–60	—	3.36	4.30–4.62	1.70–1.82
8	—	220	3.35	4.30–4.62	1.70–1.82
9	$\infty$	—	3.44	4.64	1.8448

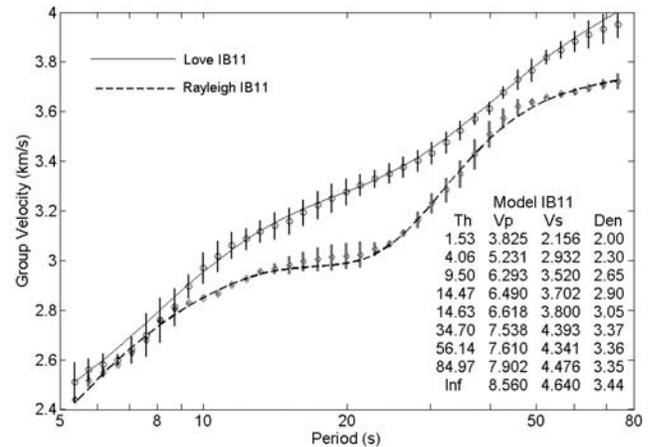
model in the last generation is accepted if the misfit value  $< 1$ , and as per equation (3) this limit of misfit value indicates that on an average the difference of the observed and theoretical group velocities is within a corresponding standard deviation of the observed data. Such an operation is made a number of times, and a list of 50 acceptable solutions is prepared; the misfit value of these models lies between 0.75 and 1.0.

The mean and standard deviation (S.D.) of each of the varying parameters of all the 50 accepted solutions are obtained (Table 3). For each solution, the thicknesses of the fifth and eighth layers are evaluated by equations (1) and (2), and the mean as well as the S.D. of each of these thicknesses is obtained. Similarly for each solution,  $V_P$  is obtained from  $V_S$  and  $V_P/V_S$ ; the mean and S.D. of  $V_P$  are obtained (Table 3). The thickness of the crust is  $44.19 \pm 1.34$  km. The model with mean value is accepted, and it is named IB11, which gives misfit 0.36 and 0.98 for Love and Rayleigh waves, respectively (Fig. 4). In general, the S.D. of the observed Rayleigh wave is lower than that of the observed Love wave; this has caused a higher misfit value for the Rayleigh wave because the S.D. is appearing in the denominator of the misfit function given in equation (3).

### Discussion

Table 3 gives the accepted structure IB11 for the Indus block. An S.D. gives an estimation of the uncertainty and a resolution of the corresponding parameter. The S.D. of thickness is increasing in downward layers. The S.D. of  $V_S$  is relatively high in the top two layers (sediments). In general, the S.D. of  $V_P$  is relatively higher than that of  $V_S$  showing a lower resolution for  $V_P$ , which can be inverted by Rayleigh wave data only.

In IB11, the top layer with  $V_S = 2.156$  km/sec corresponds to young, unconsolidated sediments. This is underlain by a layer of consolidated sediments with  $V_S = 2.932$  km/sec. The total thickness of these two sedimentary layers is 5.59 km. As indicated in the section Tectonic and Crustal Features, large sedimentary cover in the Indus block is well known. In Figure 2, we compare  $S$ -wave velocities of IB11 with those of IG11 and IP11 of the Indian region. Many features of the crust in IB11 are similar to those of IG11.



**Figure 4.** The observed group velocity data of the Love wave (open circles) and the Rayleigh wave (open diamonds) are compared with theoretical dispersion curves for the model IB11, which is also shown in tabular form: thickness (in kilometers), Th;  $P$ -wave velocity (in km/sec),  $V_P$ ;  $S$ -wave velocity (in km/sec),  $V_S$ ; and density (in  $g/cm^3$ ), Den.

Excluding the sedimentary layers, the upper crust and lower crust of IB11 have nearly the same  $S$ -wave velocities as in the corresponding layers of IG11. However, the IB11 contains an additional layer between the upper and lower crust. The crustal thicknesses of IB11 and IG11 are also close. However, a significant difference between IB11 and IG11 exists in the subcrustal region (Fig. 2).

The lithosphere–asthenosphere boundary (LAB) is marked by a depth at which the  $S$ -wave velocity starts decreasing downward in the uppermost mantle. Under the Indus block (IB11) the LAB is at a depth of 79 km; the low-velocity zone (the seventh layer) is noted for  $V_S$  but not for  $V_P$ . However, in the Indian region (east of Aravalli) the LAB is at a depth of 120 km (IG11 or IP11). Below the crust of IB11,  $V_S = 4.385$  km/sec, which is much lower than that found in IG11 or IP11 ( $V_S = 4.603$  km/sec). On the other hand, in the Arabian shield, inversion of surface wave group velocity and receiver function showed that  $V_S$  below the crust varies between 4.3 and 4.6 km/sec with LAB between 50 and 70 km (Julià *et al.*, 2003; Tkalčić *et al.*, 2006). Thus, the lithosphere of the Indus block has a similarity with that of

**Table 3**  
Structural Parameters (IB11) of the Indus Block with Standard Deviations

Layer Number	Thickness (km)	Density ( $gm/cm^3$ )	$V_S$ (km/sec)	$V_P/V_S$	$V_P$ (km/sec)
1	$1.53 \pm 0.30$	2.00	$2.156 \pm 0.099$	$1.7739 \pm 0.0231$	$3.825 \pm 0.179$
2	$4.06 \pm 0.37$	2.30	$2.932 \pm 0.122$	$1.7841 \pm 0.0174$	$5.231 \pm 0.234$
3	$9.50 \pm 1.01$	2.65	$3.520 \pm 0.023$	$1.7879 \pm 0.0129$	$6.293 \pm 0.064$
4	$14.47 \pm 1.28$	2.90	$3.702 \pm 0.040$	$1.7530 \pm 0.0281$	$6.490 \pm 0.121$
5	$14.63 \pm 2.03$	3.05	$3.800 \pm 0.058$	$1.7415 \pm 0.0277$	$6.618 \pm 0.152$
6	$34.70 \pm 3.00$	3.37	$4.393 \pm 0.035$	$1.7159 \pm 0.0178$	$7.538 \pm 0.097$
7	$56.14 \pm 3.11$	3.36	$4.341 \pm 0.024$	$1.7530 \pm 0.0270$	$7.610 \pm 0.129$
8	$84.97 \pm 5.01$	3.35	$4.476 \pm 0.086$	$1.7655 \pm 0.0261$	$7.902 \pm 0.213$
9	$\infty$	3.44	4.64	1.8448	8.56

the Arabian shield not only with regard to velocity below the crust but also with regard to lithospheric thickness. Rodgers *et al.* (1999) noted that the  $V_S$  of the upper and lower crust in the Arabian shield are 3.58 and 3.93 km/sec, respectively; the slight difference of these crustal velocities from those of IB11 may be due to crustal processes in these two regions. A comparable difference in crustal velocities also exists between IG11 and IP11 (Fig. 2). The aforementioned similarities of the lower lithosphere between the Indus block and the Arabian shield support the hypothesis of Qureshy and Iqbaluddin (1992) that the Indus block was separated from the Arabian–Nubian shield.

### Conclusions

We have obtained the lithospheric structure of the Indus block inverting surface wave group velocity data through a GA where a few new concepts for solution space in a layered structure are used. The misfit function has been formulated to avoid disproportionate importance to either the Love or Rayleigh wave. The structure IB11 evaluated for the Indus block shows that the sedimentary section is of thickness 5.59 km and consists of two layers. The total thickness of the crust is 44.19 km with three layers below the sedimentary section. The crust of the Indus block shows a similarity with that of Indo-Gangetic basin (IG11). The thickness of the lithosphere in the Indian region (east of the Aravalli range) was noted earlier as 120 km, while in the Indus block it is 79 km. The  $S$ -wave velocity below the crust as well as the lithospheric thickness in the Indus block are different from those of the Indian region (IG11 or IP11) and are similar to those of the Arabian shield. The similarities of the lower lithosphere and the Arabian shield support the hypothesis that the Indus block is a detachment of the Arabian–Nubian shield.

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