Crustal structure of Delhi Fold Belt, India, from seismic reflection data

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The deep seismic reflection profile along the 200 km long Nagaur–Nandsi profile was shot in 1991–92. This profile starts in the Neo-Proterozoic Marwar Basin (MB) in the NW, traverses through the variably metamorphosed palaeo/meso-Proterozoic Delhi Fold Belt (DFB), and ends in the middle/late Archean Sandmata Complex (SC). The studies carried out along this profile[1-8] could successfully decipher the varied reflectivity patterns, suggesting a complex tectonic scenario for the region. However, a crustal velocity model could not be derived as the profile is only a reflection profile, not supplemented by wide-angle reflection/refraction or well input. This communication presents a five-layered P-wave velocity model for the profile. The velocity structure has been derived using interval velocities for the layers using stack velocities as the starting point and forward modelling the same phases observable in the shot gathers. In the absence of the refraction/wide-angle reflection data the model generated a plausible working model. Two major thrust planes are inferred from the presence of crocodiles. The velocity structure clearly demarcates the contrasting structures, notably in the absence of the low-velocity layer and intersecting reflections, etc. The difference is attributed to the contrasting geological history of the two segments.

THE Aravalli–Delhi Fold Belt (ADFB) in northwestern India is a good example of a poly orogenic belt, situated between the late Proterozoic platformal Marwar Basin (MB) in the west and the Vindhyan Basin on the east. These fold belts of northwestern Rajasthan represent a sequential development of ensialic rifting, generation of oceanic crust and its consummation. The evolution of Delhi Fold Belt (DFB) can be explained due to rifting[1]. It is also suggested that the DFB was evolved by the formation of rifts in the north Delhi belt and preceded the ocean opening in the south Delhi belt[9]. The north Delhi rift was abortive, but the south Delhi basin developed into an oceanic trough by 1.3 Ga. This trough was closed by successive subduction with the formation of a trench, accretionary carbonate turbidite, a magmatic arc, a marginal basin and suture zones with ophiolitic assemblages[10].

The deep seismic reflection profile along the 200 km long Nagaur–Nandsi (Figure 1) profile was shot in 1991–92. This profile starts in the Neo-Proterozoic MB in the NW, traverses through the variably metamorphosed palaeo/meso-Proterozoic DFB, and ends in the middle/late

Archean Sandmata Complex (SC). The studies carried out along this profile could successfully decipher the varied reflectivity patterns, suggesting a complex tectonic scenario for the region. However, a crustal velocity–depth model could not be derived from the reflection data due to non-availability of wide-angle reflection/refraction or well input. Hence, the interpretation of the existing anomalies in terms of tectonic evolution of the region has become difficult. Therefore, an attempt has been made to derive the interval velocities for the layers using the stack velocities as the starting point, as discussed by Megallaa[11] and to attempt forward modelling for the phases observed in the shot gathers. The results obtained for a small segment of the profile using the old stack sections were significant[8] and gave ample encouragement to carry out reprocessing and modelling studies for the remaining profile, so as to explain the structural and tectonic patterns from a velocity point of view. This communication presents the crustal velocity picture along the profile and some new reflections obtained as a result of reprocessing, and also discusses them with reference to interval velocities.

The geological history of Northwestern Indian Shield spans the period from Archean to Neoproterozoic. The lithostratigraphy of the region is mostly due to Heron[12]. The oldest cratonic nucleus (3.3 Ma) of the region is the Banded Gneissic Complex (BGC), which has been reclassified into Sandmata and Mangalwar Complexes[10]. The Delhi sediments were deposited over this Archean basement.

The MB, situated to the west of the DFB consists of flat, undeformed clay-evaporate sequences. The MB was earlier referred to as Trans Aravalli Vindhyans and the basement to this sequence consists mostly of Malani igneous suite (~ 750 Ma).

The DFB comprises a system of half grabens and horst, with its axial zone extending all along the Aravalli hill range[9] and constitutes a part of the collisional orogenic belt that developed due to the subduction and accretionary events during the Proterozoic[1,13]. The fold belt consists of highly folded and deformed rocks exhibiting polyphase deformation comprising deep-water to platformal sediments. The profuse basic volcanics and tectonized mafic/ultramafic rocks of this belt include among others, the Phulad ophiolites. Occurrences of the Phulad ophiolites as dismembered bodies[14] has significant bearing on the evolution of the DFB. The Pb model age of the DFB has been constrained to ~ 1100 Ma[15]. Two separate events of rifting were inferred[9] for the Aravalli and Delhi sediments during the Proterozoic. In the first stage of rifting, the Aravallis (located SE of Nandsi, Figure 1) were formed, while in the second stage of rifting, opening of ocean and Delhi sedimentation took place, much similar to the present day Red Sea[7].

The SC is a part of the BGC, exposed mostly in the western part. The P–T estimates of this complex indicate metamorphic temperatures between 850 and 650°C, but at

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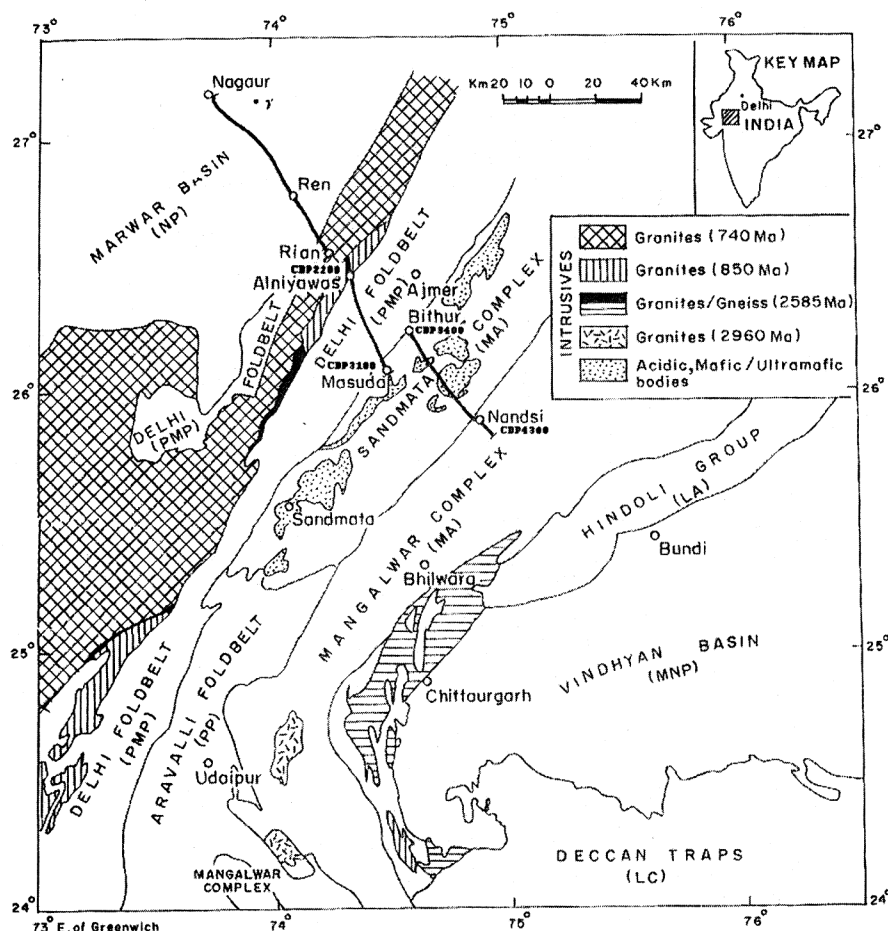
Figure 1. Location of Nagaur–Nandsi sub-profile, Rajasthan and the main geological features (after Tewari *et al.*[2]).

two distinctive pressures of 8–11 and 5 Kb[16], implying its exhumation to the present levels of exposure. The contact between SC and DFB is reported to be a major thrust to the west of Bithur–Masuda region[10].

The deep reflection studies in the ADFB were carried out in 1991–92. The seismic data acquisition along the profile was aimed at 60-fold coverage with shots and geophone groups at every 100 m interval. Due to logistic problems, the profile was divided into three sectors, i.e. Nagaur–Rian, Alniyawas–Masuda and Bithur–Nandsi (Figure 1). A group of six geophones, of 4.5 Hz natural frequency, were planted at each channel and a sampling interval of 4 ms was set for data recording in SEG-B format, thus achieving a wide band of 4.5–64 Hz seismic signals.

The data were processed using the CGG Geomaster software on the CDC CYBER 180/850A mainframe computer. The data were demultiplexed and made available in the trace sequential format. Two 60-channel datasets were merged to generate a single 120-channel dataset. Dead and noisy traces were edited and refracted arrivals muted. In the next stage, the field geometry along with static corrections was applied and a CDP gather was ob-

tained. Velocity analysis was carried out approximately at every 20 km with groups of 24 CDPs using a sweep of 10–15 velocities. The data were finally stacked with a proper velocity after the normal moveout correction. All the earlier interpretations were based on these stacksections.

The reprocessing and modelling was done for the data acquired along the sectors considering each of them as an individual profile. The stack sections prepared earlier[3] were on CGG GEOMASTER (CYBER), while the present reprocessing was done using ProMAX software on the SUN workstation. Velocity analysis is carried out at a spacing of 5 km or 100 CDPs. The reprocessed stack sections were found to be better than the earlier stack sections[3]. Reprocessing has also enabled us to get the stacking velocities at close spacing, as required by Megallaa's program for the calculation of interval velocities.

The data were first edited in the shot domain for removal of cultural, traffic and high levels of ambient noise. True amplitudes were restored using the smooth time variant gain function that varies along the profile. First arrivals were manually inspected and picked from the

shot gathers. The travel-time picks were then used in the trace top mute to remove the first arrivals. A time variant trapezoidal band-pass filter was applied to improve S/N ratio. After CDP sorting, a velocity analysis was performed both interactively and by inspecting the stacked velocity panels to achieve an optimal NMO velocity function along the profile. The data were finally stacked with the appropriate velocity function. The flowchart of the processing flow is shown in Figure 2.

The data pertaining to the first part of the profile, i.e. Nagaur–Rian sector has already been published[8]. In this communication, we deal with the two remaining sectors of the Nagaur–Nandsi profile, i.e. Alniyawas–Masuda and Bithur–Nandsi sectors.

The Alniyawas–Masuda sector starts in the DFB and ends in the SC covering the major thrust zones and the entire Delhi orogenic sequence. The seismic section (Figure 3) clearly depicts the upliftment of the entire mid and lower crustal columns. At approximately 10 km (CDP2401), the near-horizontal reflectivity is interrupted by a steeply east-dipping, convex upward-reflective sequence that coincides with the Delhi Thrust on the surface. A prominent fault zone (F2) is thereby imaged from this reflection sequence. This strong, high-amplitude, high-reflectivity band in the midcrust (7–8 s, CDP 2401-CDP3001) is considered to infer the presence of crustal fault (F2) and the subsequent updoming of the entire midcrust as a result of collisional tectonics. From around 5–7 s to about 12 s two-way time (TWT) interlayers of continuous, sub-horizontal, high-amplitude reflectivity and bands of discontinuous, lower-amplitude reflections are interpreted to image a thick pile of Delhi sediments. A set of prominent, discontinuous, high-amplitude reflections below this major boundary allow us to infer that the upwelling is present at all levels below F2.
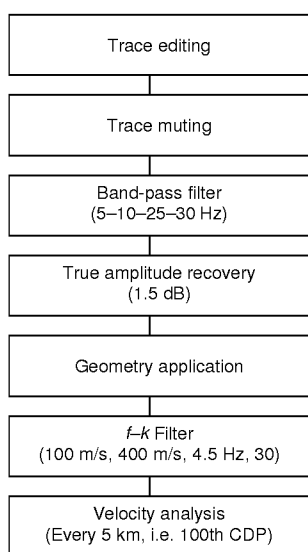
Also, a set of oppositely dipping reflections is identified at an offset of about 15 km. These reflections (A, B, C, occurring at about 4.8, 8 and 10.2 s respectively) may indicate the collision between the MB and the DFB.
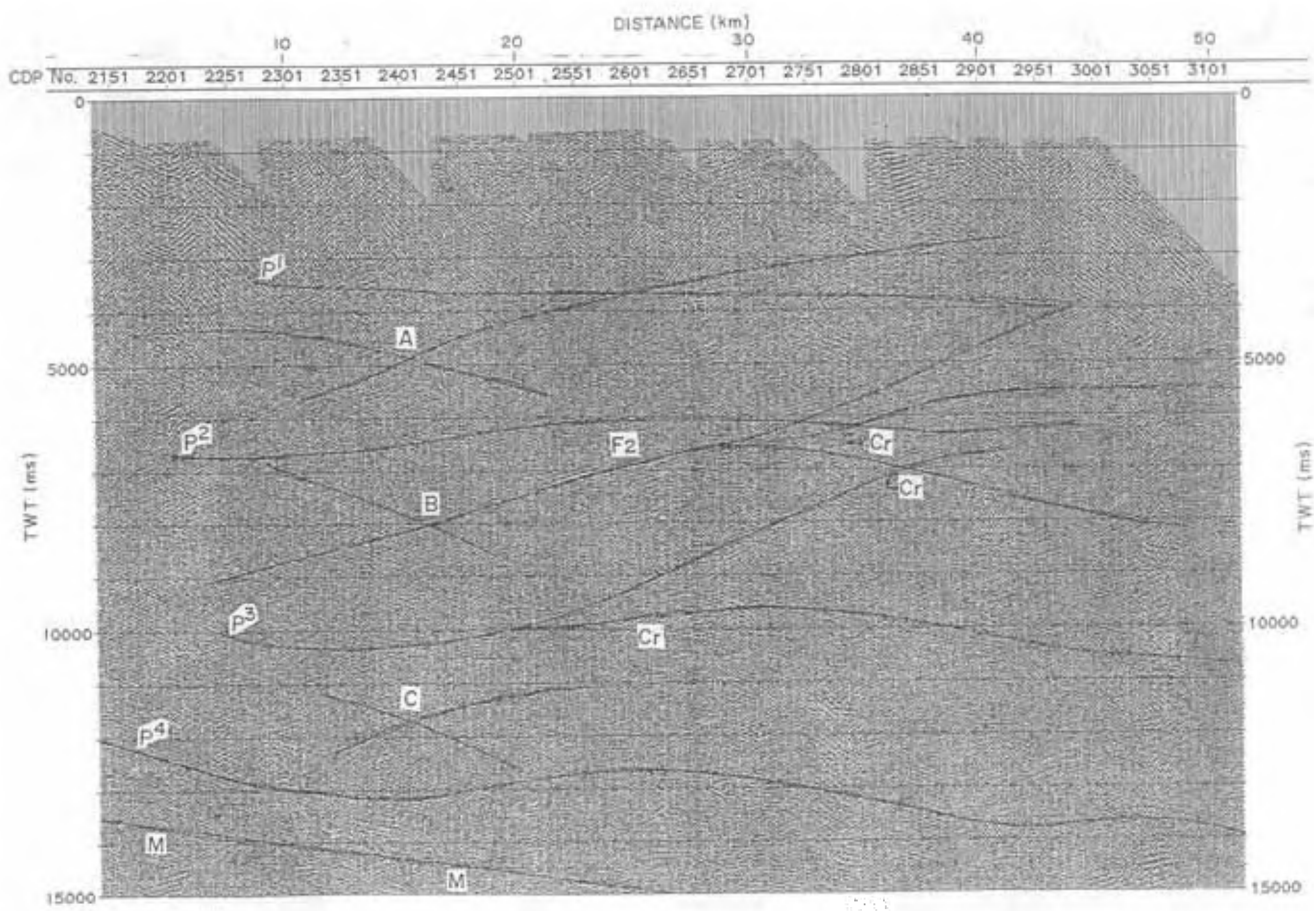
The lower crust seems to be nearly horizontal, except for a slight undulation below the DFB. Moho is identified as a band of short, discontinuous reflections beyond 13 s TWT. It is also interesting to note that the Moho reflections are notably down-dipping, in sharp contrast to all the superseding ones. The depth of Moho could not be imaged in the present seismic section and the significant down-dipping trend could be an indication of deeper Moho, under DFB. The section presented here seems to be comparable to the line drawing (~ 30 km in depth) inferred for the URSEIS experiment[17].

The Bithur–Nandsi sector covers a part of the DFB and the SC, terminating in the same complex. The midcrustal domal feature that had originated in the Alniyawas–Masuda sector seems to extend to this sector also. This domal feature takes an anticlinal shape in the easterly direction and finally merges with a prominent, sub-horizontal reflective boundary in the middle crust (~ 4 s TWT).

A set of diverging reflective patterns (D, E, F, G, H; Figure 4) demonstrating the complexity of the region, appear at the upper, middle and lower crustal levels, which might represent the contact between the DFB and the SC. A band of short, discontinuous reflection marks the starting of the lower crust. The extension of this reflection beyond the thrust zone, i.e. F3 (Figure 4) is predominantly strong and highly laminated. The continuity of the reflection sequences increases tremendously in this part of the sector and may be indicative of more or less undisturbed lower crust. However, the reflections within the DFB, i.e. about 20 km from Bithur are relatively dispersed in nature, indicating tectonic disturbances in the region.

Moho is not seen in the region covering the DFB for this sector, but in the SC region it appears as a strong band. We can also see a double Moho in the SC, adjacent to the DFB, with the lower branch dipping downwards, to the west. This, in turn, indicates that Moho gets deeper below the DFB. The track of Moho could not possibly be traced in the record section, which is only for 15 s TWT. The presence of double Moho on either side of the DFB with highly reflective lower branch is assertive of collisional tectonics being the cause of orogeny.

Travel-time and amplitude modelling (Figure 5 a and b) were undertaken for the shot gathers of the two sectors, spaced at every 10 km. The TWTs of the reflections that appear prominently on the stack section are noted down and then phases are picked on the corresponding shot gathers about the same TWT. The reflectors that are strong and horizontal only are considered for the purpose of velocity determination. The reflections that are considered for the purpose of velocity determination are indicated as P^x ($x = 1, 2, 3$ and so on) in the stack sections

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│        Trace editing         │
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│      Band-pass filter        │
│     (5–10–25–30 Hz)          │
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│    True amplitude recovery   │
│          (1.5 dB)            │
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│         f–k Filter           │
│ (100 m/s, 400 m/s, 4.5 Hz, 30)│
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│      Velocity analysis       │
│  (Every 5 km, i.e. 100th CDP)│
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Figure 2. The reprocessing flow.

Figure 3. Crustal seismic stack section (two-way time in seconds) along Alniyawas–Masuda sector. Reflectors used in the velocity determination are marked as P^1, P^2, P^3, P^4; crocodiles by Cr; diverging reflection patterns as A, B, C and Moho by M. F2 denotes the crustal fault that caused the Delhi uplift.

(Figures 3 and 4). Reflectors with strong dips (A, B, C for sector II and D, E, F, G, H for sector III) are not considered in the velocity determination as the program for interval velocity conversion is not applicable in the case of strong dip. The primary criterion for identification of the phases on the shot gather is the correlatability of the TWT of the picked phase with the TWT of strong reflection on the stack section. The phases that appear on the stack section are stronger compared to the ones on the shot gathers as a result of stacking of 30–40-fold data. The phases that are reasonably good and identifiable on the shot gathers are selected for amplitude and travel-time modelling. (Figure 5 *a* and *b*).

The initial velocity depth model that is required for forward modelling is derived using the algorithm of Megallaa[11]. The idea of dip-corrected interval velocities has been used here, so that it provides us with a more realistic model. Velocity–depth models were modified iteratively using RAYAMP[18], until an optimal adjustment between the observed and model-derived travel-times and amplitudes is achieved. Synthetic seismograms are also calculated using RAYAMP. The model that allows for the best fit between observed and calculated phases and

travel-times is considered final for the shot point. The 2D-velocity–depth models are prepared by iterative modelling for each shot gather and a final depth section along each sector is delineated by simple interpolation of boundaries.

The depth section along the Nagaur–Nandsi sub-profile is made by combining the velocity–depth sections obtained for the three sectors, viz. Nagaur–Rian, Alniyawas–Masuda and Bithur–Nandsi. The final interval velocity–depth section is shown in Figure 6. The section clearly demonstrates the two collision boundaries, the first one at Alniyawas (F1; Figure 6) and the other one (F2; deduced from the crocodiles C1, C2, C3) at Masuda. Similar to the varied reflectivity patterns the velocity structure of the Marwar Craton/Basin (Nagaur–Rian sector), is quite different from adjacent blocks in the reflective nature, horizontality of the reflectors, velocity structure and the presence of a prominent low-velocity layer (LVL).

Gravity and magnetic studies carried out for the region indicate a prominent gravity high, which coincides with the domal shaped body of the lower crust delineated by the seismic reflection crust[19]. The velocity–depth section presented here also shows a prominent upwarp of all
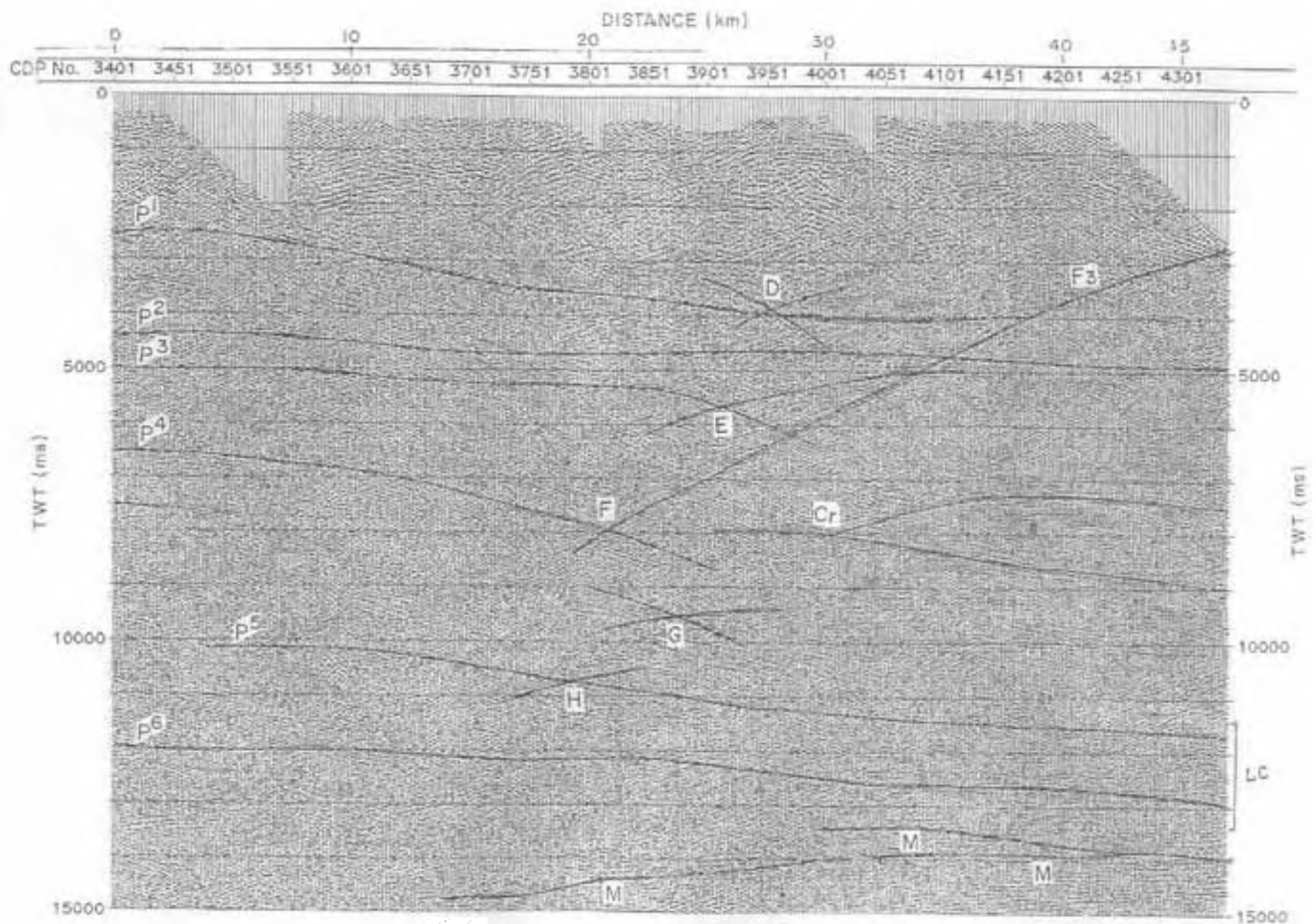
Figure 4. Crustal seismic stack section (two-way time in seconds) along Alniyawas–Masuda sector. Reflectors used in the velocity determination are marked as P^1, P^2, P^3, P^4, P^5; crocodiles by Cr; diverging reflection patterns as D, E, F, G, H, and Moho by M. F3 denotes the crustal fault beyond which there is a relatively undeformed crust.

the layers, right from the upper crust to the lower crust. The sharp high shown in the gravity picture (Figure 7) corresponds to the fault F2, which has been delineated in the present study (Figure 6).

The gravity picture shows a high density (3.04 g/cc) for this domal structure. The calculated velocity for this density at depth of 40–45 km turns out to be 7.1–7.3 km/s. It may be noted here that the gravity picture is drawn based on the earlier seismic reflection studies, which do not have the velocity input. The present study gives the much needed velocity information and it shows a clear upwarping of all the layers at all levels. The sharp increase in reflectivity forming the convex side of the domal shape can now be interpreted as a mid-crustal fault in that area. Presence of the intrusion cannot be ruled out as such, since it is one of the causes that might have triggered collision. However, the present velocity information derived from the amplitude modelling of the phases does not support such a huge intrusive body and in turn depicts an updoming of the entire crustal column.

A major part of the gravity high is attributed to the presence of the Gneissic complex in the area, whose densities are in the range 2.72–2.77 g/cc[19]. The corresponding velocities give by Christensen and Mooney[20] at depth of 10 km turn out to be in the range 5.8–6.0 km/s, which is quite close to the values determined in the present exercise. The gravity low west of the DFB is attributed to the presence of Erinpura granite whose density is of the order of 2.9 g/cc. And the corresponding velocity of 5.5 km/s can be observed in the velocity–depth section also.

The shallow crust, i.e. up to the basement has been delineated for Alniyawas–Masuda and Bithur–Nandsi sectors, using the first arrival refraction data. The reprocessing of the data collected for these two sectors allowed for delineation of a better velocity picture. The reprocessing for the Nagaur–Rian sector (sector I) was not carried out owing to data-retrieval problems and the weaker first arrivals owing to which the delineation of shallow structure for the sector was not possible. A shallow sediment layer
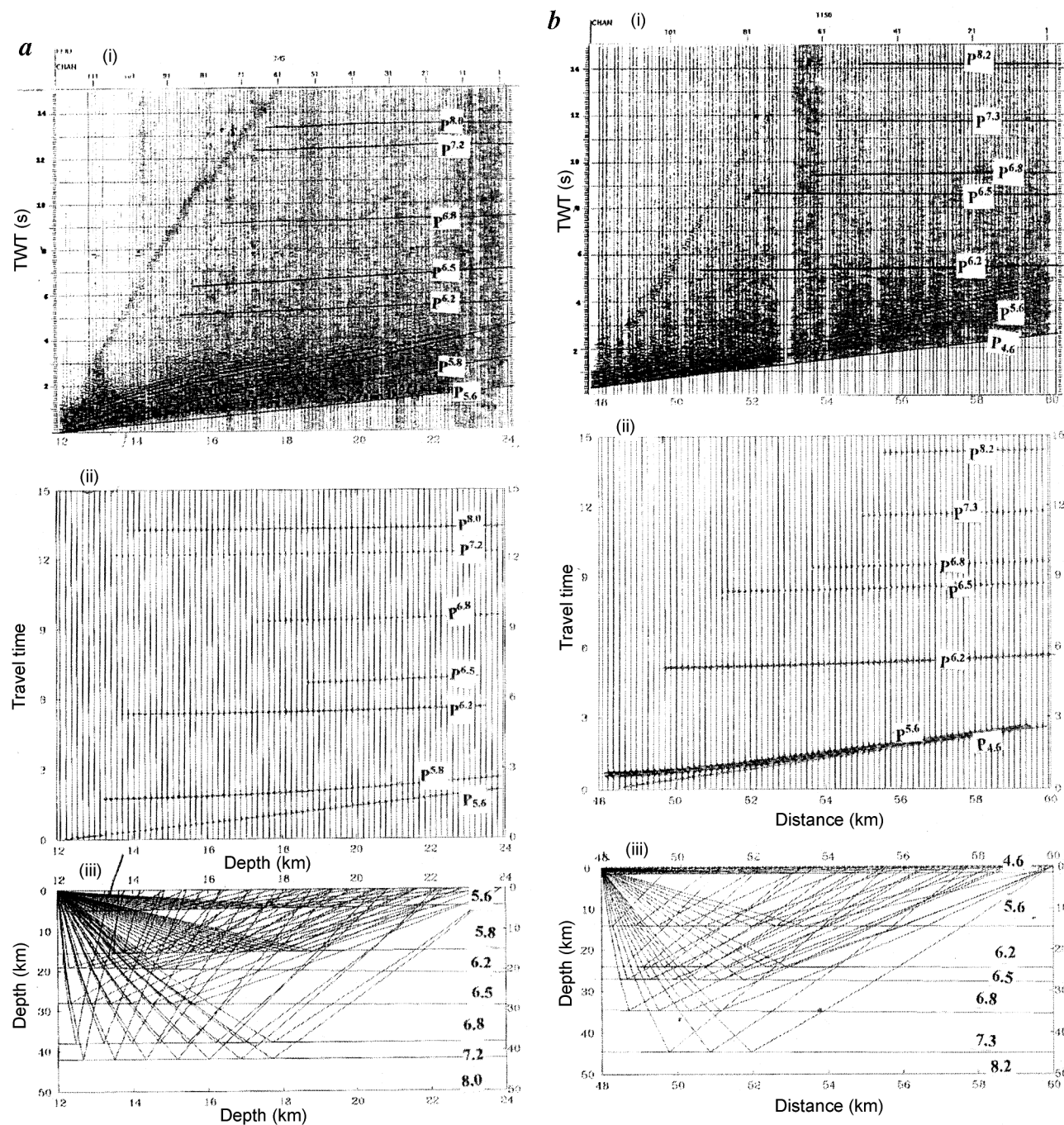
Figure 5. *a*, Observed seismogram (i), synthetic seismogram (ii) and ray-diagram (iii) of the synthetic seismogram (ii) for SP 745 (CDP2300). *b*, Observed seismogram (i), synthetic seismogram (ii) and ray-diagram (iii) of the synthetic seismogram (ii) for SP 1152 (CDP3801). Shot point is indicated by solid triangle. Refraction velocities are marked as P_v, and reflection velocities are marked as P^v, where v is the velocity in km/s.

with velocity of 4.6 km/s, extending to depths of about 2 km is, however noticed in the Bithur–Nandsi sector. This layer is modelled using the first arrivals and can be correlated with the velocity of the metasediments reported in this region[2]. The basement having a velocity of 5.6 km/s has been clearly demarcated around a depth of 5–6 km in the Alniyawas–Masuda sector, while further southeast in the Bithur–Nandsi sector, the basement

(5.6 km/s) is found around 8–9 km, which can be attributed to the variations in the thickness of both the supracrustal layer and the upper crust as can be expected in the scenario of upthrusting or exhumation of the lower crust.

The upper crustal layer with a velocity of 5.6 km/s at the top and a gradient of 0.01 km/s/km can be noticed in the MB (Nagaur–Rian sector), extending to a depth 8–10 km. This layer shows a prominent southeast dip and is
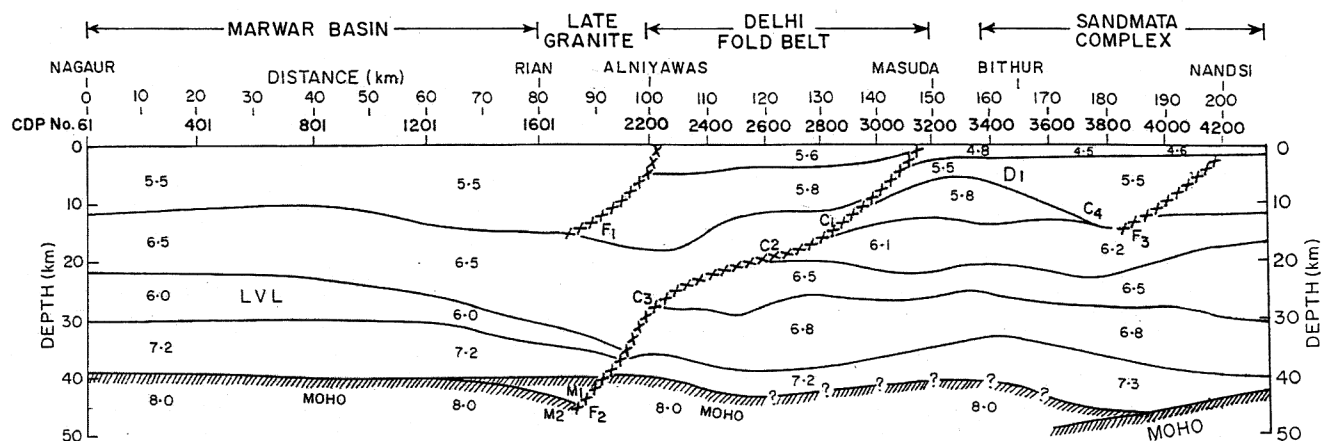
Figure 6. Comprehensive velocity–depth section along the Nagaur–Nandsi sub-profile, India derived using reflection data.
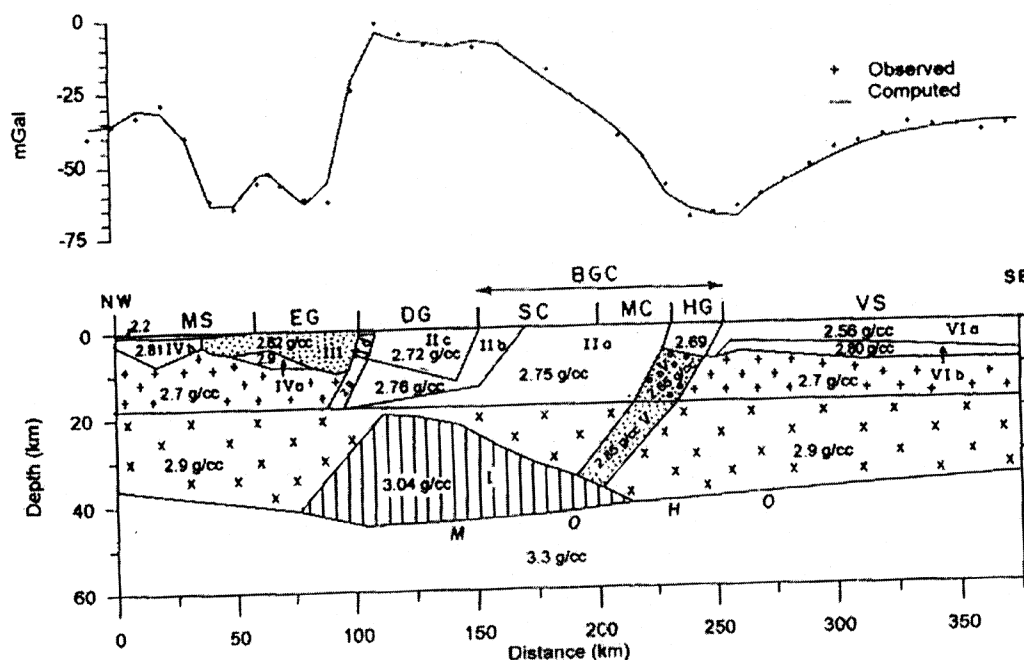

Figure 7. Observed Bouguer anomaly along the Nagaur–Nandsi sub-profile and the crustal section thus derived showing a thick crust and a high-density body in the lower crust (modified after Mishra et al.[19]).

replaced with a layer of velocity 5.8 km/s after Alniyawas. This replacement could be a denser basement than the Delhi super group and consequence of the Delhi orogeny and the subsequent origin of the fault F2. The upper crust for Alniyawas–Masuda and Bithur–Nandsi sectors can be modelled with a velocity of 5.8 km/s and is displaced to deeper depths by the fault F2. A significant vertical displacement in the upper, middle and lower crustal layers is due to the presence of the crustal scale fault F2. The upper crustal (5.8 km/s) layer shows a clear domal structure (D1) adjacent to fault F2 and merges with the underlying layer.

The velocities of the upper crust delineated for the entire sub-profile from the present study are in the range

5.8 km/s, at average depths of 15–20 km. It has been observed earlier[19] that most of the Precambrian shields/ orogens have a velocity of 6.06 ± 0.39 to 6.1 ± 0.40 km/s at a depth of 15–20 km. The lower limit of this range, i.e. 5.67–5.7 km/s, correlates well with the value of 5.8 km/s determined in the present study.

The middle crust in the DFB is comprised of layers with velocities of 6.2, 6.5 and 6.8 km/s. The velocities are continuously increasing, in sharp contrast to the decreasing velocities (6.5 and 6.0 km/s) observed in the MB. This fact may be taken to support the hypothesis of Vijaya Rao et al.[7] that Marwar Craton and the BGC represent two different regimes and that the DFB has originated as a result of a collision between them. However,

the extensional plume-related tectonics[21,22] associated with the late Proterozoic evolution of the Marwar Craton and the associated bi-modal magmatism could generate a compression in the DFB that may account for some of the deformation.

The mid-crustal layer found in the Nagaur–Rian sector sharply dips in the southeast direction and attains a maximum thickness under Rian. This layer seems to be replaced with a velocity of 6.1 km/s in the DFB region, and shows a significant uplift and thinning on encountering fault F2. All the layers at the mid-crustal level are disturbed due to prominent faulting and assume a domal shape owing to compressional tectonic pattern resulting from the extensional setting in the MB and the emplacement of large volumes of acid and basic magmas that could have triggered the Delhi orogeny.

Presence of a mid-crustal LVL in the Nagaur–Rian sector and its conspicuous absence in the remaining two sectors is an interesting observation. This LVL significantly tapers towards the end of the sector, closer to the DFB and can be considered as an intrusion, which might have occurred due to DFB-related orogenic activity and rift-related collisional processes[8]. This seems relevant as the rift-related intrusions can also be seen in the interpretative sections[1], though they are confined only to the last 20–30 km of the sector. The presence of LVL may also be the consequence of the large-scale alkaline/granitic volcanic component of bi-modal volcanism in the Marwar region.

The average thickness of the middle crust along the entire profile is around 18–22 km and is in accordance with the global average of 11.5 + 8.4 km for the Proterozoic regions[23,24].

The other significant reflection fabrics noticed in the seismic section are the oppositely dipping features, dominantly in the middle crust and to a lesser extent, in the lower crust. This kind of indentation and interfingering is found in most of the young and old mountain belts[25,26]. In some cases, the crust seems to be dominated by inclined reflectors, occasionally with geometries of duplexes and ramps and flats or the interwedging patterns, which can be referred to as 'crocodiles'. These crocodiles are commonly associated with the shallow thrust sheets and nappes[25]. These may be correlated to the fault zones at the surface, which often assume a sub-horizontal orientation in mid-crustal levels, as in the case of F2 here. Crocodiles are formed due to crustal thickening and shortening that takes place during the continental collision and can be a clear indication of compressional tectonics. These can be identified by their strong reflectivity patterns that are due to the presence of strong density and velocity contrasts along a layer inside the fault zone. Occurrence of divergent reflection fabrics along with the crocodiles is not so uncommon for the compressional regimes and the present case may be inferred to be one such case. These crocodiles have been examined thoroughly and then considered

while delineating the faults in upper and middle crust, which play an important role in the process of compression and post-orogenic adjustments. All major displacements and detachments take place along these faults and this particular aspect is evidenced in the present case, by distinct offsets in velocity layering brought about by the faults F1, F2, and F3.

The lower crust with a high velocity of 7.2 km/s can be explained in different ways. The presence of the 7.2 km/s layer under the Nagaur–Rian sector can be explained as a result of mafic and ultramafic intrusions. These intrusions are common to extensional terranes of the Proterozoic area and the lower crust is highly reflective with strongly laminated appearance[25]. These strong laminations are also observed in areas where intense folding has taken place, like those of the metamorphic core complexes[24]. Presence of strong laminations and good reflectivity in both such cases allows us to infer that the velocity of 7.2 km/s is not so uncommon for the MB, which witnessed a hot-spot bi-modal basalt-rhyolite magmatism in late Proterozoic[21,22]. The velocity of 7.2 km/s for the lower crust in the SC, may represent a denser lower crust made up of predominance of the basic components of the high-grade granulite belt. The thickness of this layer is around 8–12 km, which is well in accordance with the value of 15.7 + 8.5 km given earlier[23].

A double Moho for the Nagaur–Rian sector has been reported before[3,8], while a double Moho for Bithur–Nandsi sector has been inferred in the present study. The most plausible explanation for the presence of double Moho is that the reflections are from the doubled crust representing remnants of older crust formed as a result of collisional processes[2]. Page et al.[27] have demonstrated that the double Moho is observed mostly in the tectonically disturbed zones, thus allowing us to infer the double crust, though the intervening LVLs are non-delineable. As such the possibility of having two different reflections in a transitional Moho zone is also not ruled out, but earlier studies also indicate the Moho as a double Moho. Moho is not clearly observed in the Alniyawas–Masuda sector covering the DFB. The lower limbs of the Moho adjacent to the DFB approach each other, and their convergence point may be at deeper depths (> 15 s TWT) and not imaged in the present section. This allows us to infer greater depth for Moho under the Delhi orogenic feature.

Meissner[25] observed that the depth to Moho increases during collision and decreases after the onset of the post-orogenic extension, until finally the crustal root disappears completely together with the erosion of the mountains. Going by these indications, it may be inferred that the DFB has also undergone post-orogenic extension.

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How effective is an extended Kalman filter for continuous yeast cultures affected by both inflow and measurement noise?

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The usefulness of the extended Kalman filter (EKF) as an on-line estimator of process variables is known for monotonic laboratory-scale fermentations. However, this has not been tested for oscillating cultures under non-ideal conditions representative of large bioreactors. So, in this study an EKF was applied for on-line filtering of simulated data of an oscillating continuous *Saccharomyces cerevisiae* culture with inflow and measurement noise. For better accuracy, the tuning of the EKF was updated over successive time slices such that deviations between the noise-affected and noise-free profiles were minimized during each interval. As shown by the concentrations of biomass and ethanol, noise

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