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Using MASW to map depth to bedrock underneath Dehradun fan deposits in NW Himalaya

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Dun Valley is an intermontane valley located within the Siwalik foreland basin in Garhwal Himalaya. With the evolution of Dun Valley, Dun gravels and post-Siwalik formations were deposited in this valley in the form of fan deposits. Earlier information on the thickness of Dun gravels in the Dehradun fan and bedrock depth level was based on stratigraphy studies and estimated to be 600 m. Later, based on tube-well boring and field observations, the thickness of the Dun gravels has been revised to 100–300 m. In the present communication, shear wave velocity (V_s) field has been calculated using multichannel analysis of surface waves (MASW), surveyed using 4.5 Hz frequency geophones with Elastometer-aided weight drop hammer as a source. This enabled us to map the thickness of the Dun gravels and the depth to bedrock underneath the Dehradun fan deposits as 35 m in the northern flank of the syncline, 140 m in the centre of the broad syncline and 90 m in the southern flank of the syncline below the ground surface. The Middle Siwalik sandstone and Upper Siwalik conglomerates bedrock have been assigned a shear wave velocity of ~750–800 m/s and ~950–1000 m/s respectively, after running a seismic profile directly on the respective bedrock exposed along the river sections. Based on 1D and 2D V_s profiles from north to south, a model of cross-section showing depth of bedrock/thickness of the Dun gravels has been presented. Different litho units of the Dehradun fan defined by earlier researchers have been validated with V_s. Each unit, i.e. units A–C, has been assigned V_s as 700–850, 500–700 and < 500 m/s respectively.

Keywords: Bedrock, fan deposits, multichannel analysis, shear wave velocity, surface waves.

A NUMBER of intermontane broad open synclinal valleys or Dun basins dominate the morphotectonic features of the Sub-Himalaya, e.g. Ropar–Pinjor Dun and Dun Valley in NW Himalaya[1]. These basins are formed on the large-scale synclines of Siwalik strata and are separated from the Lesser Himalaya to the north by the Main Boundary Thrust (MBT) and Mohand Thrust (MFT)[2,3] to the south (Figure 1). A major part of Dun Valley is covered by three fans, from west to east the Donga, Dehradun and Bhogpur fans, deposited by streams following the topography produced by the activity of MBT[4,5]. Due to

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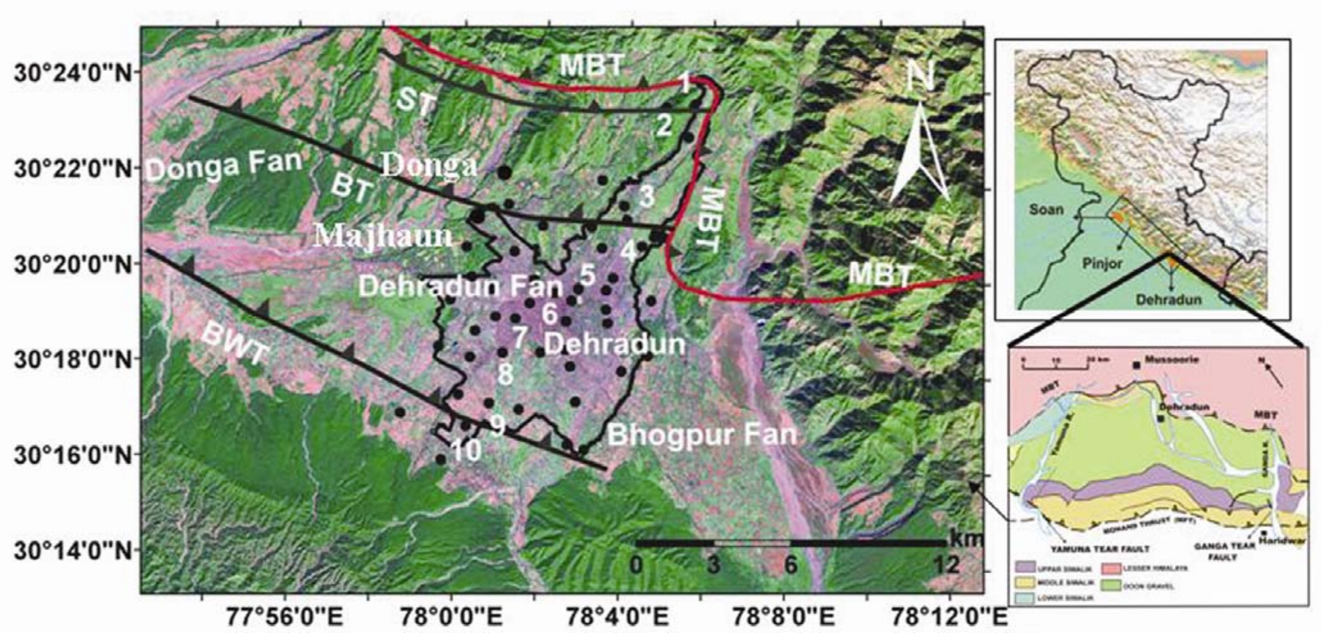

Figure 1. Landsat false colour composite showing morphological (Donga, Dehradun and Bhogpur fans) and tectonic (Main Boundary Thrust (MBT), Bhauwala Thrust (BT) and Bansiwala Thrust (BWT)) features in the study area. Black circles indicate the location of the sites. Site numbers 1–10 have been considered for preparing the Dun gravel thickness model shown.

tectonic reactivation of thrusts/faults as well as modulation by changes in climate and stream flow debouching from hinterland controls the deposition and erosion of fan sediments in such piggyback type of basins[6]. The flat-lying Siwalik strata of synclinal depression are not exposed due to burial underneath a thick pile (~ 600 m) of Dun gravels[7]. These Dun gravels have been classified by Thakur and Pandey[1] into three litho units. Unit A in the Donga fan is mainly composed of sub-angular to sub-rounded granule to pebble-sized clasts set in fine-grained matrix. However, in the Dehradun fan the calcareous conglomerates horizon of variable thickness is inter-layered within unit A. The clasts are mainly composed of quartzite, sandstone and limestone in calcareous cement as a horizontal disposition and are best exposed in the SW part of the Dehradun fan. Unit B is characterized by unconsolidated massive gravels with a predominance of rounded to sub-rounded boulders and pebbles of quartzite with sandy and silty matrix. At the Majhaun site, in the SW part of Dehradun, unit B is dominated by boulder and gravel with clast-supported matrix. Unit C is the youngest gravel constituting the topmost layer of the Dun gravels. It mainly consists of poorly sorted angular to sub-rounded granules and pebbles with 1–2 m discontinuous layers and lenses of sand and silt. All the material has been derived from the Lesser Himalaya and Upper Siwalik rocks. The seismic profile[8,9] across MFT and Dun shows horizontally layered Siwaliks in the synclinal depression of the Dun. Based on tube-well information coupled with field observations, recently, Thakur and Pandey[1] revised the thickness of the Dun gravels over the steeply dipping Siwaliks (in the north) as 100 m, whereas in the central part the thickness of these gravels increases to more than 300 m. The Dehradun fan ranges in elevation from ~ 500 to ~ 1000 m from south to north with thick pile of Dun gravels which can influence the hydrological characterization of the area. The present study aims to determine the thickness of the sediments and depth to bedrock. The shear wave velocity (V_s) bands corroborated with exposed portions along river sections in the northern part of the fan[1] were helped to provide an actual bedrock depth for the central and southern parts, as these are covered with thick deposits of Dun gravel. Thus, applications of multi-channel analysis of surface waves (MASW) using low-frequency geophones (4.5 Hz) with 40 kg Elastometer-aided weight drop hammer (EAWDH) as a source have paved the way for mapping depth to bedrock or thickness of the Dun gravels in the Dehradun fan deposits.

Recent methods make use of spectral analysis of surface waves for near-surface imaging for engineering applications with multiple reflection technology originally developed for petroleum applications[10]. The combination of these uniquely different approaches to acoustic imaging of the subsurface allows delineation of vertical and horizontal variation in near-surface material properties. Applications of MASW method[11,12] have been used to map the near-surface material and depth to bedrock surface. Although the Dehradun fan has been studied in detail in 2007 for subsurface studies, the penetration level was only 50–60 m (refs 13 and 14). The present study focused on the Dehradun fan to evaluate the depth to bedrock level from NE to SW, which could be achieved by changing the field configuration, frequency of geophones and specially shifting the near offset at different distances keeping the receiver spacing as constant in order to get a good dispersion curve.

Data were acquired using a 24-channel seismograph (Geometrics Geode) unit with 4.5 Hz spike-based geophones and an EAWDH as the source. A small rectangular (12×12 in) metal plate was used as the strike plate to maximize energy transfer between the hammer and the ground. Multiple number of shot gathers were collected along a linear survey line with optimum offsets according to the sites by moving both the source and the receiver spread in an incremental manner, similar to the common depth point roll-along technique used in conventional seismic reflection survey. For each measurement, several stacks were accumulated to enhance the signal. Data processing was carried out using SurfSeis 2.0 software developed by the Kansas Geological Survey (KGS). The raw seismic data (SEG-2) were first converted into KGS format, combining all shot gathers to be processed into a single file. Field geometry was assigned and acquired data were recompiled into the roll-along mode dataset. Shot gathers from the different optimum offsets of the survey line were configured with field parameters to generate the seismic record for each shot. This consists of incrementing the distance of the seismic source to the geophone spread fixed in the same location; thus a record could be constructed with 12–36 traces. Each seismic record was then used for preliminary processing to assess optimum ranges of frequency and phase velocity. After analysing the overtone image (which represents three variables, i.e. phase frequency versus phase velocity, whereas colour represents amplitude), reference phase velocity and phase frequency were assigned for dispersion analysis. Next, each record was processed to generate a dispersion image to analyse the fundamental mode. Dispersion analysis was carried out by normalization of complex numbers with Fourier-transformed seismic traces[15]. Dispersion analysis results in the generation of a dispersion curve (frequency versus phase velocity) for each geophone station. Once all necessary dispersion curves had been extracted, they were inverted to generate 1D V_s profile using the Inversion algorithm[12–14]. These 1D profiles appear to be most representative of the material directly below the middle of a geophone spread. Multiple 1D plots of V_s versus depth were generated using a source and receiver roll-along a survey line as discussed earlier. A set of 1D plots of V_s profiles have been interpolated to produce 2D V_s profile at each site.

Ten sites have been considered in this study from NE to SW to represent variation in thickness of the Dun gravels/depth to bedrock. However, before characterizing the bedrock V_s, two sites have been selected where the bedrock was found exposed along the stream-cutting for validation of the V_s vis-a-vis lithology by running direct V_s profiles on the top of the exposed topography. For validation purpose, the first site was surveyed using MASW at Donga village where the Dun gravels (unit C) unconformably lie over the horizontally disposed Middle Siwalik sandstone[1] along the Suarna river section (Figure 2). The second site was along the Nimmi river section in the Donga fan where the Dun gravels (unit A) unconformably overlie the boulder conglomerate bed of the Upper Siwaliks[1] (Figure 3) and unit B of the Dun gravels overlies unit A. Similar experiments have also been carried out in other sites along the exposed section in the Dehradun fan and Donga fan deposits for validation of different litho units. The V_s profiles taken from each site were validated from field observations by measuring the exact thickness of the sediments up to the surface of the bedrock. The V_s of Middle Siwalik sandstone and Upper Siwalik conglomerate derived from these sites has been taken into consideration while defining the thickness of the Dun gravels in the Dehradun fan along the NE–SW section. Although V_s is not an analogy to the lithology, it depends on the stiffness parameters. After validation of V_s with the exposed sections, we have assigned the V_s band and marked the boundary of bedrock level. Two-dimensional V_s profiles shown along northeast–southwest section indicate the variation in the thickness of the Dun gravels from north to south and depth of the bedrock level according to the validation carried out at the two above-mentioned sites (Figure 4). Simultaneously, 1D plots of different sites are shown in Figure 5, indicating V_s with depth. The thickness of the Dun gravels based on V_s profiles across the Dehradun fan in the NE–SW section is shown in Figure 6 (upper portion) based on 1D plots. Units A–C show V_s of the order of 700–850, 500–700 and < 500 m/s respectively. In case of the representative Majhaun site, units A and B show different velocity bands due to compositional variations from the Donga fan to Dehradun fan deposits. High V_s bands of ~750–800 m/s and ~950–1000 m/s noticed in the V_s profiles of Donga village along the Suarna River and Majhaun site along the Nimmi River were used as bedrock velocity (i.e. representing Middle Siwalik Sandstone and Upper Siwalik conglomerate respectively) after due validation of V_s profiles with the exposed sections (Figure 1).

According to the seismic cross-sections, Middle Siwalik is exposed only in the northern part of the Dehradun fan and overlain by boulder conglomerate of Upper Siwalik toward south due to tectonic disposition[9]. Thakur[7] while studying the evolution of the Dun Valley gave the stratigraphic section of this valley and assigned the thickness of gravel as 600 m. Later, Thakur and Pandey[1] revised their estimates to ~100 m in the north to ~300 m in the centre of the city based on tube-well information. However, the present study based on seismic method (MASW method) indicates that the thickness of the Dun gravels varies from 35 m in the northern flank of the syncline, to

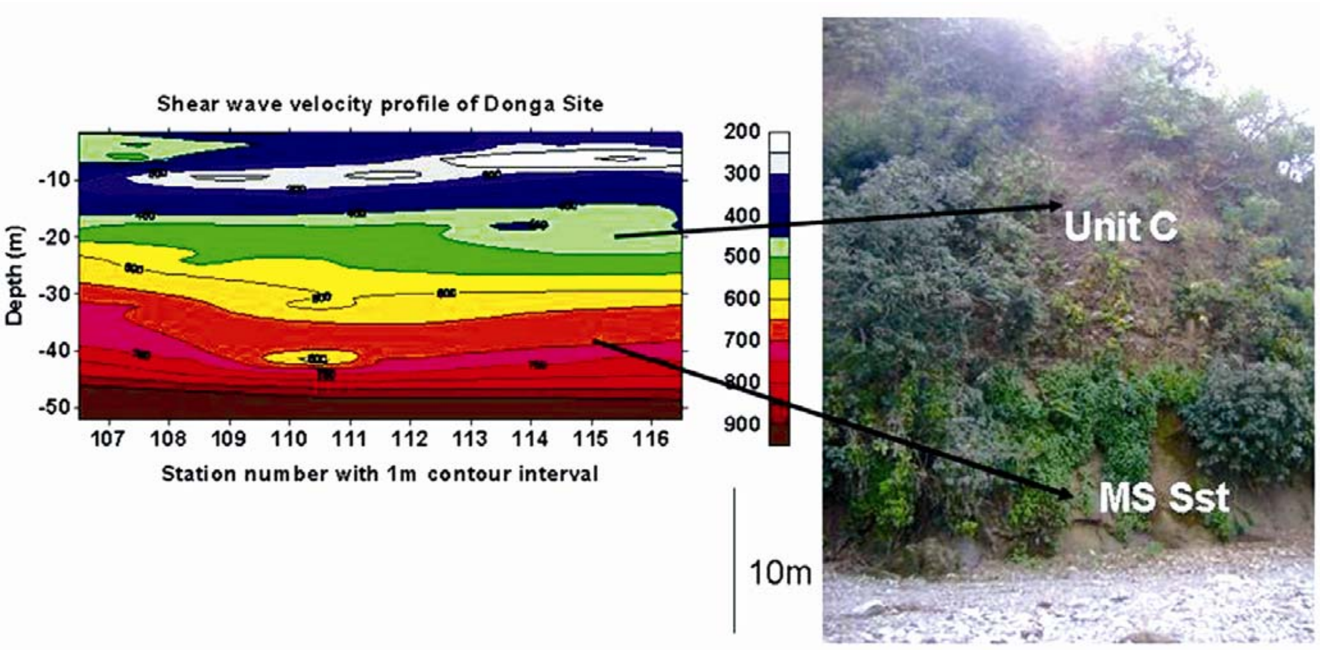

Figure 2. Units C of Dun gravels underlain by horizontally disposed Middle Siwalik sandstone (MS Sst). Unit C is a discontinuous layer of horizontally disposed silt and sand within the gravel (after Thakur and Pandey[1]).

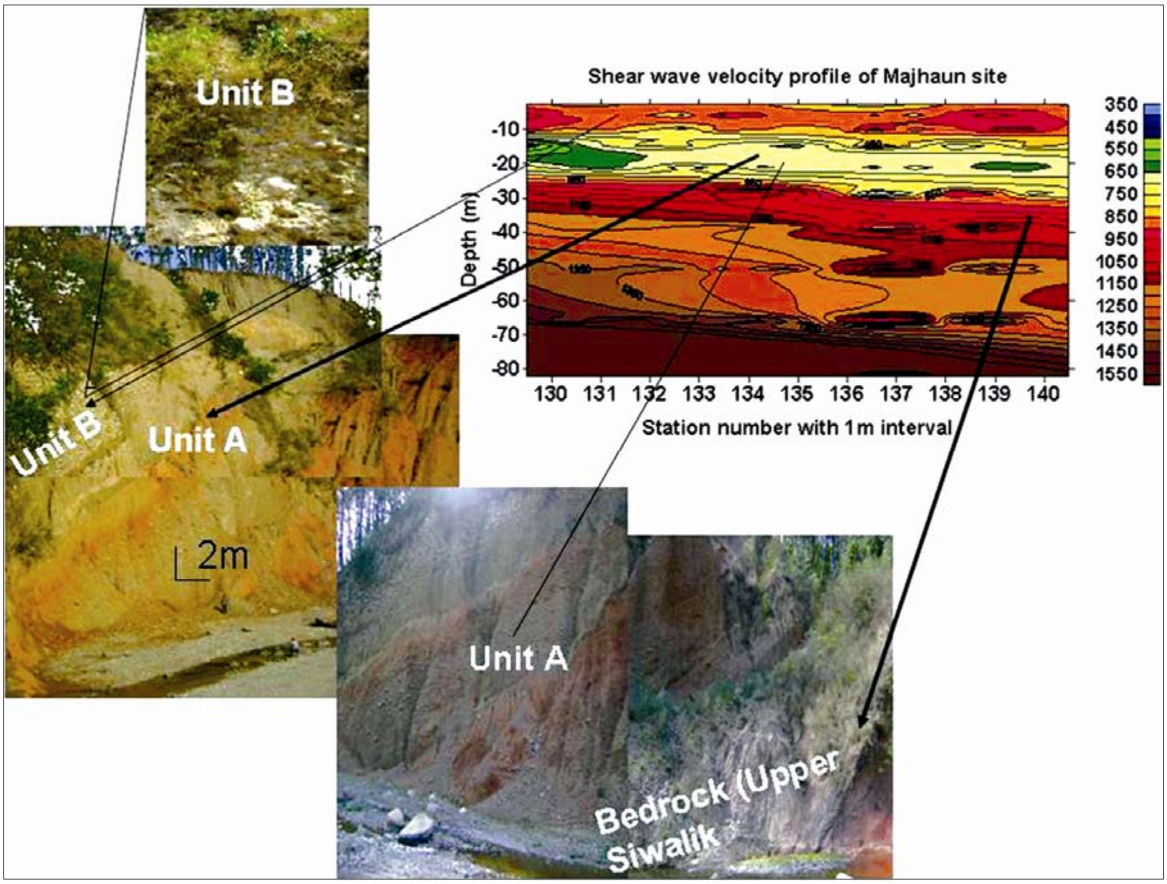

Figure 3. Different units of Dun gravels according to the classification of Thakur and Pandey[1] with base of Upper Siwalik boulder conglomerates. (Right) Two-dimensional V_s profile of the sites validating V_s of different units.

140 m in the centre of the broad syncline and 90 m in the southern flank of the syncline below the ground surface of the Dehradun fan deposits.

The above results may help the geologist in future to understand the evolution history of Dun in a better way. The valley has been the focus of attention since the 1905 Kangra earthquake it had caused damage of intensity VIII (MM Scale) in Dehradun. Further, variation in intensity level from the north (high intensity) to the centre of the city (comparatively low intensity) during the 1991 Uttarkashi earthquake[16] indicated variation in thickness of sediments and the role of impedance contrast in site amplification[14].

The limitation of using high frequency geophones of 14 Hz with 8 kg sledge hammers as a source over Dehradun fan sediments while carrying out seismic microzonation study of the area was that it could not permit us to penetrate deeper than 40–50 m (ref. 13). However, repeat survey using 4.5 Hz geophones with 40 kg high energy sources, i.e. EAWDH enabled us to penetrate deeper than 150 m at some places. At the same time the use of EAWDH with 14 Hz geophones also helped us to penetrate deeper than 50 m. Thus, applications of MASW using low-frequency geophones (4.5 Hz) with 40 kg weight drop hammer have paved the way for mapping depth to bedrock.

Variation in the thickness of the sediments of the synclinal basin could be the important parameter to unfold the tectonic history of a particular region and will also be

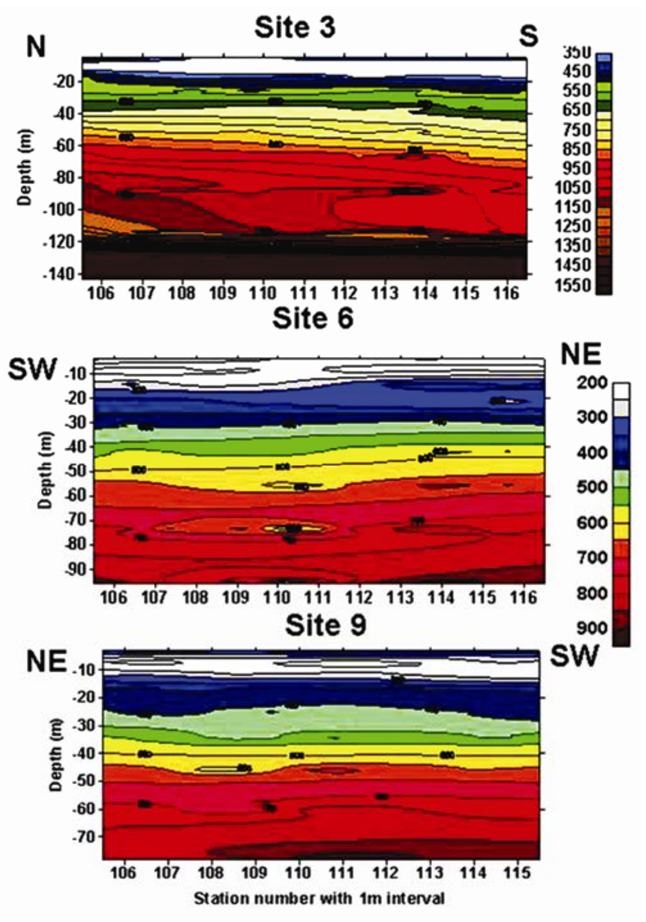

Figure 4. Two-dimensional velocity model of different sites from north to south depicting shear wave velocity.

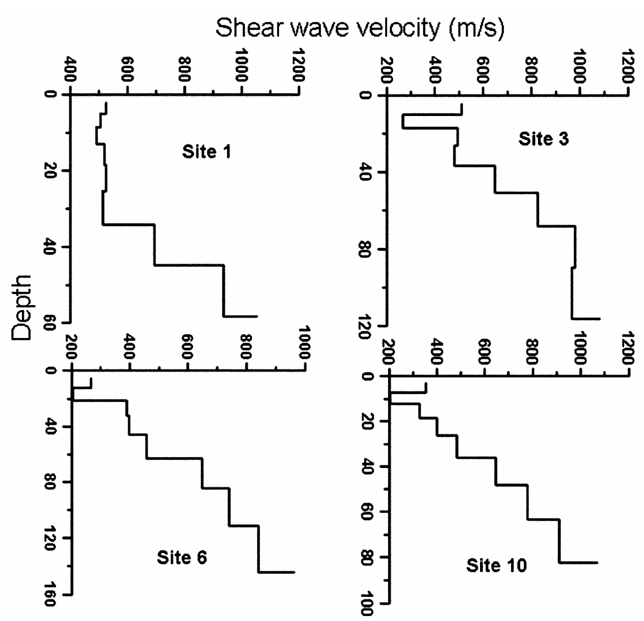

Figure 5. One-dimensional shear wave velocity with depth at different sites of the Dehradun fan.

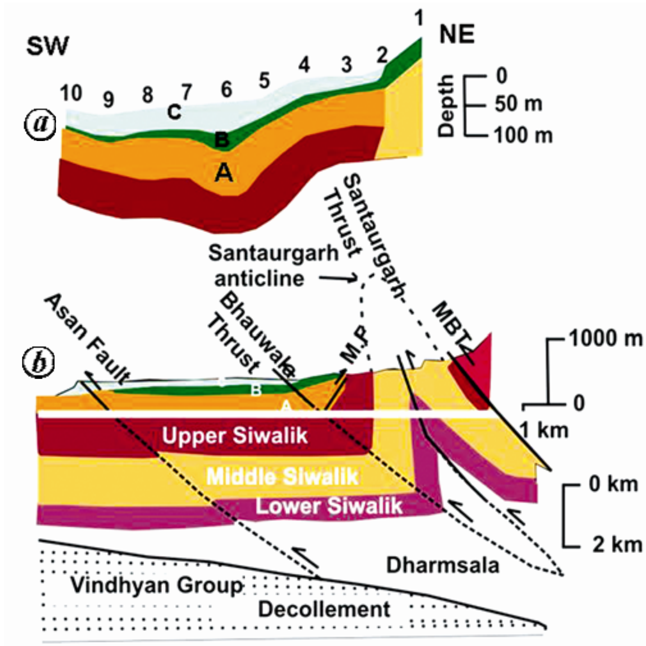

Figure 6. ***a***, One-dimensional velocity model using shear wave velocity of the Dun gravels (different units) underlain by V_s of MS Sst and Upper Siwalik conglomerates. ***b***, Subsurface structure (below white strip) based on seismic reflection profile of Dun Valley by the Oil and Natural Gas Corporation Ltd, India adapted after Power *et al*.[9]. The vertical scales are given separately, although they are the same as the horizontal scale. The portion above the white strip is vertically exaggerated for better depiction of structural disposition of post-Siwalik Dun gravel (units A–C, after Thakur and Pandey[1]). Colours of the upper and lower sections represent the same lithology.

helpful to comprehend the seismic behaviour of the basin during an earthquake. Since the Dun Valley has been interpreted as a synclinal basin which is characterized by the Santaurgarh anticline to the NE and Mohand anticline to the SW[7], the present study was aimed at mapping the thickness of sediments/depth to bedrock in terms of V_s after validating the lithosections with V_s exposed along river-cuttings for the Dehradun fan, which is a part of the Dun Valley. In this study, we have considered the V_s with depth of 10 representative sites along a NE–SW section across the Dehradun fan to map the thickness of sediments/depth to bedrock. The sediments of the Dehradun fan have been described as Dun gravels due to the preponderance of gravels as a compositional material. Further, the Dun gravels have been divided into three lithological subunits, i.e. units A–C. These subunits have been assigned by V_s bands after validation with the exposed lithosections. Unit A shows a V_s band of 700–850 m/s, whereas units B and C represent 500–700 and < 500 m/s respectively. The V_s bands for the Upper and Middle Siwaliks have been derived after running the direct V_s profile at the top of the exposed section at Donga and Majhaun sites, where the Middle Siwalik sandstone and Upper Siwalik conglomerate were exposed along the river sections respectively. The Middle Siwalik sandstone represents the V_s band of > 750 m/s whereas the Upper Siwalik boulder conglomerate is characterized by V_s band of > 950 m/s. The corresponding V_s of the Dehradun fan will help earthquake engineers to characterize the seismic behaviour of the waves from the actual bedrock to the surface instead of doing the analysis on the basis of mean V_s of upper 30 m soil column.

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A decision tree analysis for predicting the occurrence of the pest, *Helicoverpa armigera* and its natural enemies on cotton based on economic threshold level

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The cotton bollworm, *Helicoverpa armigera* (Hübner) is one of the most important pests affecting crop production globally. The data-mining technique, for predicting pest incidence using biotic and abiotic factors has not been developed so far. To identify the biotic

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