# Applications of two-dimensional seismic tomography for subsurface cavity and dissolution features detection under Doon valley, NW Himalaya

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**The presence of natural voids, cavities and palaeo-channels under the surface hinders the extension of urbanization particularly in the new upcoming cities in the frontal part of the Himalaya. The Doon valley is characterized by such features. In this context, multichannel analysis of surface waves technique is used as a cost-effective solutions for investigating sub-surface cavities, voids, shallow weathered zones and dissolution features in the Doon valley, NW Himalaya. Given the sensitivity of the deduced shear wave velocity to lithology, clast composition, degree of saturation, velocity distribution to a target depth of 40–50 m is a useful guide to demarcate different erosional/ dissolution features, cavities and palaeo-channels. 2D shear wave velocity data sets have been acquired along several profiles in the upcoming region of the Doon valley. Data processing has been carried out at 50 sites and shear wave velocity and profiles were validated taking into account field observations and bore hole data. The subsurface karst features or palaeo-channels are always a matter of concern to engineers before any development starts, because these features could cause subsidence in the region. Anomalies, that include caverns, dissolution features, and erosional channels etched into the Dehradun Fan sediments at shallow depth, have effectively been identified in the 2D shear wave velocity (*Vs*) field from >50 sites. The subsurface architecture further suggests variation in tectono-climatic condition and shifting of provenance during the fan building processes.**

**Keywords:** Caverns and palaeo-channels, Dehradun Fan, dissolution features, multichannel analysis of surface waves, sub-surface investigations.

THE sub-Himalayan morphotectonic belt is marked by a number of intermontane valleys or ‘Duns’ like the Soan, Pinjor and Doon in NW Himalaya (inset in Figure 1). These Duns developed on large synclines of the Siwalik strata and are separated from the Lesser Himalayas to the north by the Main Boundary Thrust (MBT) and from the Indo-Gangetic alluvial plains to the south by the Main Frontal Thrust (MFT) or Mohand Thrust (Figure 1). The deposition and erosion of fan sediments in these piggy-back basins is influenced by reactivation of thrusts/faults and regional changes in climate that can affect stream flow into them. Several intra-basinal faults also govern the sedimentation and geomorphology of these basins[1]. The sedimentologic and geomorphic records of fans within these basins are considered as rich repositories for tracking the climate–tectonic interactions that prevailed during the evolutionary phases of these ‘Duns’[2]. Lateral variations in tectonics, geomorphology and basin architecture have been recognized beneath the frontal Himalayan basins[3,4] and it is well-established that these tectonic and climatic processes interact to shape mountainous landscapes, through a network of tightly coupled drainages and tectonic features[2]. However, the history of their interaction can only be worked out along river sections, which are prone to regular incision due to varied climatic events and flooding.

Based on a detailed account of evolution, geomorphic features and stratigraphic accounts, Dehradun Fan is subdivided into E–W trending geomorphic surfaces, i.e. residual hill surface and piedmont surface[1–8,9]. The residual hill surface consists of thick boulder gravel beds and the renewed tectonic activity along the MBT has raised this surface to the present level, leading to the commencement of the dissection of Doon gravels, named as upper Doon surface (UDS). The piedmont surface is further subdivided into two surfaces, i.e. Middle Doon Surface (MDS) and Lower Doon Surface (LDS). MDS consists of thick gravel beds whereas the LDS is recognized as the alluvial fan of the major tributaries of the Ganga and the Yamuna rivers.

The post Upper Siwalik deformation was followed by erosion of the Himalayan slopes that developed in response to the tectonic activity along the MBT. The erosional phase, resulting in the supply of sediment from the sub-Himalayan slopes, was responsible in the evolution of depositional surfaces[3]. Powered by tectonic reactivation of thrusts/faults as well as modulated by changes in climate, stream flow debouching from hinterland controls the deposition, erosion and thickness of fan sediments in such piggyback type of basins[4].

In earlier studies, stratigraphic reconstructions of Himalayan basins most essentially relied on mapping of limited exposed sections on eroded banks of entrenched streams, generally less than 20 m thick and at most <25 m at the northern junction of the Dehradun and Donga fans[4]. Doon valley was studied in fair detail with respect to lateral variation in the tectonic and palaeo-climatic signatures and response analysis using exposed sections along the river valleys[2,3,6–10]. However, the subsurface information for a large part of the valley, critical for building the evolution model of fan deposits, remains largely unknown. The thickness of Dehradun Fan sediments has also remained a matter of debate for some time and a number of such inferences have been derived from tectonics and surface information which indicate that the

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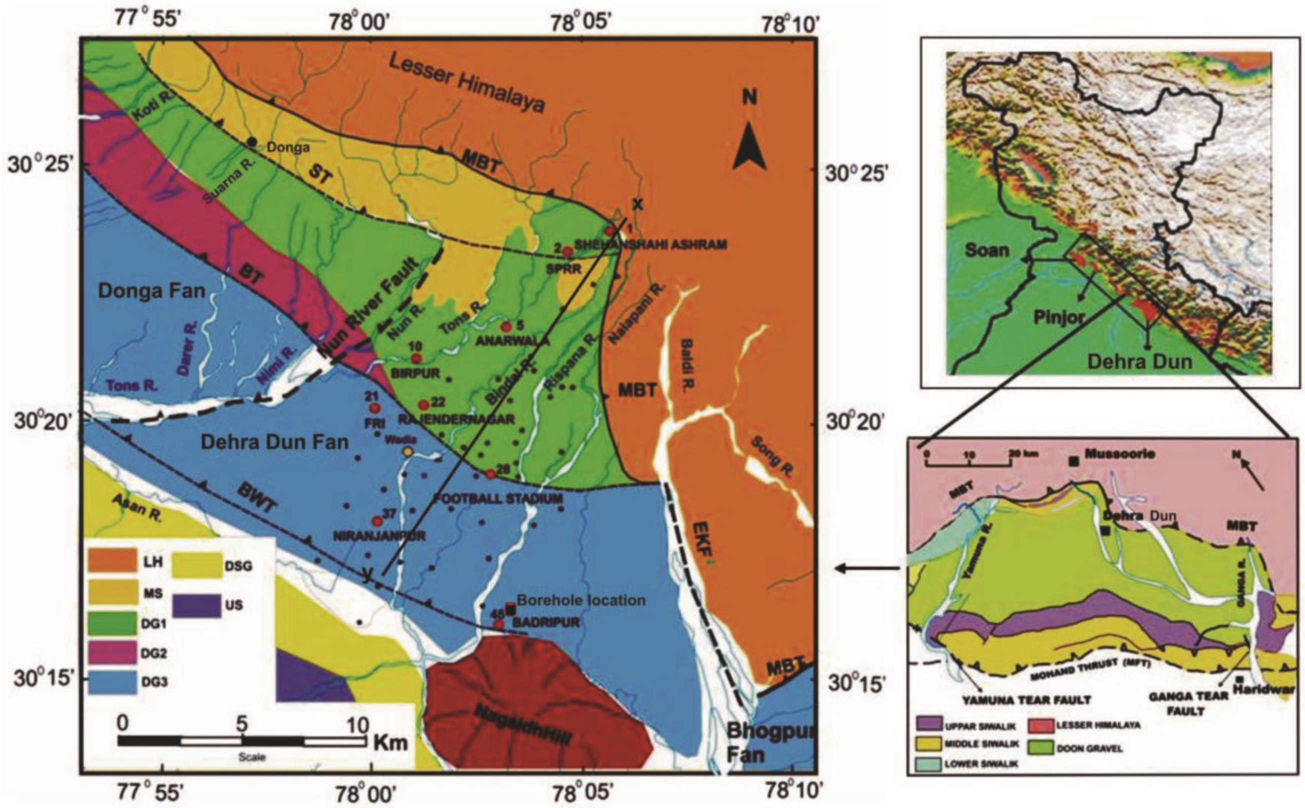


**Figure 1.** Map showing the locations of investigated sites, occupied in the Dehradun Fan for shear wave velocity investigation, using MASW. The sites are shown in the back-drop of geology and tectonic elements of Dehradun Fan and adjoining fans. MBT, Main Boundary Thrust; MFT, Main Frontal Thrust; BT, Bhauwala Thrust; BWT, Bansiwala Thrust; NRF, Nun River Fault; EKF, East Kalinga Fault; LH, Lesser Himalaya; US, Upper Siwalik; MS, Middle Siwalik. The classification of Doon fan gravels is from Thakur and Pandey[1]; DG-1, Doon Gravels unit A, B and C; DG-2, Doon Gravels unit B and C, DG-3: Doon Gravels unit C; DSG, Dip slope gravels, Inset shows the locations of three Duns in NW Himalaya (upper) and regional tectonic map of Doon valley (lower).

maximum thickness of sediments varies from 600 m (ref. 10) to 300 m (ref. 1); however, geophysical studies constraints the depth of the bedrock (~760 m/s) as ~140 m (ref. 11). The focus of the present study is to supplement new information by establishing near-surface shear-wave velocity structure using the proven technique of multichannel analysis of surface waves (MASW)[12–16]. Rooted in the principles of active seismic reflection, MASW enables generation of 2D shear-wave velocity (*Vs*) profiles up to a depth of 40–50 m (refs 13, 14). By validating shear-wave velocity (*Vs*) with exposed litho sections of the Dehradun Fan, the study aims to characterize the lithology and structural configuration to help our understanding of the evolution of the Doon valley.

Ground rolls generated by an impulsive source like a sledge hammer are Rayleigh surface waves that travels along or near the ground surface. Assuming the variation of velocity with depth, each frequency component of a surface wave has a different propagation velocity, called phase velocity, which is a function of elastic properties of the medium trespassed. The technique of MASW uses this dispersion quality of surface waves, i.e. unique phase velocity for each wavelength (particular depth penetrated), to produce shear-wave velocity as a function of depth[14,15]. Given that, the ground rolls are characterized by low frequencies, relatively low velocity and high amplitude[17]. MASW is a well-suited technique for characterization of shallow subsurface (upper few tens of metres) with adequate resolution. The survey was conducted using a 24-channel seismograph along with 14 Hz spike based geophones having geophone interspacing of 2 m (refs 13–15). An 8 kg sledge hammer was applied on a 1 sq. m metal plate for generating seismic energy[13,14]. Multiple shots were gathered using different offset parameters, i.e. near (2 m), middle (26 m) and far offsets (50 m) along a linear survey line. The data was collected using roll-along technique, i.e. by moving both the source and the receiver spread in an incremental manner similar to the common depth point method. To enhance the signal-to-noise ratio, multiple stacks were gathered at each shot location.

The raw seismic data was configured first with field parameters using SurfSeis 2.0 software developed by Kansas Geological Survey, USA[16]. Each seismic record obtained was used for preliminary processing to assess optimum ranges of phase frequency and phase velocity.

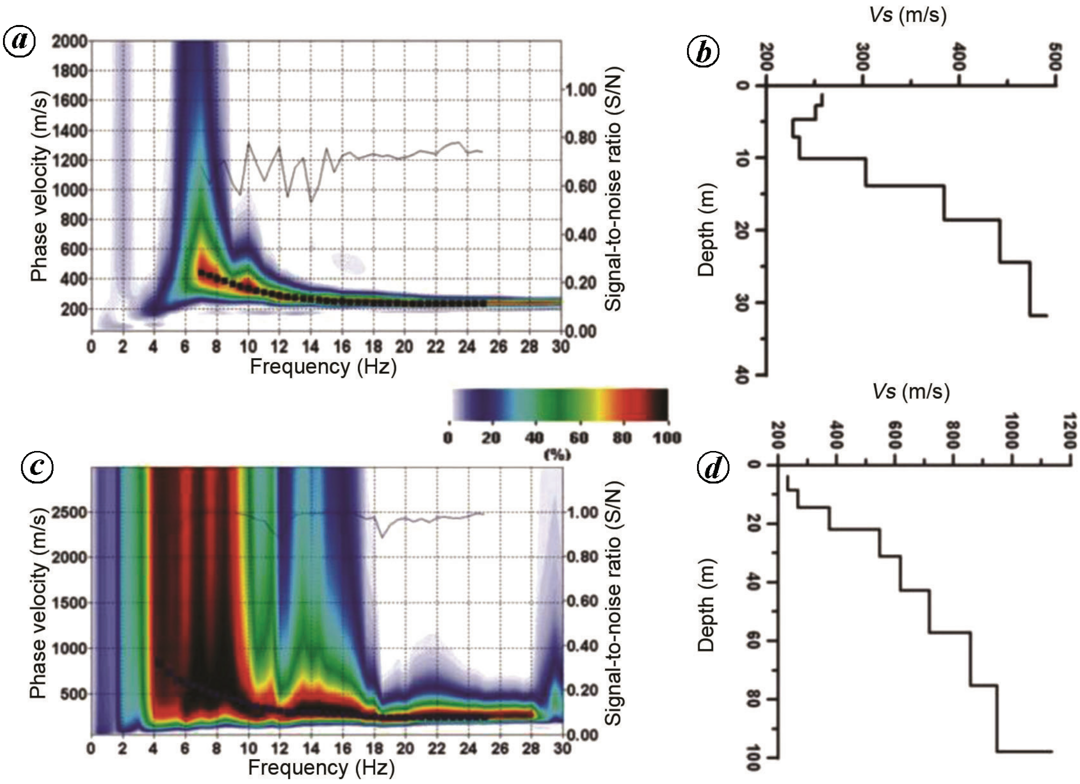


**Figure 2.** Dispersion curves and their corresponding one-dimensional shear wave velocity profiles.

Preliminary processing of each record generated a dispersion image reflecting phase velocity versus phase frequency, which was used to analyse the fundamental mode. After analysing the overtone image (which represents three variables, i.e. phase frequency versus phase velocity while colour represents amplitude of signal), reference phase velocity and phase frequency were assigned for each dispersion analysis. The extracted dispersion curves were inverted to generate one-dimensional (1D) *Vs* profiles, using generalized logarithmic inversion[15]. These 1D profiles appear to be the representative of the material directly below the middle of a geophone spread. A set of 1D velocity profiles were interpolated to invert the data to produce 2D *Vs* profiles of each site[11,13,14]. The depth of penetration is a function of phase frequency versus phase velocity; for e.g. phase velocity of ~400 m/s for the corresponding phase frequency of ~7 Hz, thus restricting the penetration depth to ~30–40 m because the depth ($Z_{max}$) for which *Vs* can be reasonably calculated, is about half the longest wavelength ($\lambda_{max}$) measured (Figure 2 *b*)[17].

Based on the change in shear wave velocity with depth, and validation of shear wave velocity with lithology along the exposed section, we tried to extrapolate the interpretation down to 40 m depth. Although it is a known fact that shear wave velocity is not an analogy to the lithology, the shear wave velocity is dependent on volumetric fracture density, rock fabrics (e.g. shear wave splitting), overburden thickness and water content, therefore it is not uniquely correlative with lithology, but provides stiffness of the soil. Based on geophysical investigations and the information obtained on subsurface features, anomalies and composition of sediments from 2D profiles, the Dehradun Fan can be divided into different zones.

Zone-1 falls in the proximal part and consists of multiple gravel beds, considered as gravity-flow deposits. The thickness of these deposits varies from few metres to ~20 m as per the exposed section in the area and called litho unit B (comprises unconsolidated massive gravels with predominance of rounded to sub-rounded boulders which conformably overlies Upper Siwalik Conglomerates)[1] and also named as Older Doon Gravels/Residual Hill[3]. These gravel deposits are in contact with Middle Siwalik sandstone which are exposed at Malsi Dear Park (MDP), along the roadside. To characterize the litho section of this zone in terms of shear wave velocity, a linear array was designed over the exposed section. Shear wave velocity (*V*s) profile of this section showed a velocity of the order of ~500–600 m/s in the top 20 m soil column, with infill deposits of low shear wave velocity (300–400 m/s; Figure 3 *a*). The velocity further increased to ~750 m/s at ~20 m depth and may represent the velocity of Middle Siwalik sandstone, whereas *Vs* of 500–600 m/s may represent velocity of gravel deposits (Figure 3 *a* and *b*).

Another site surveyed in this zone is located further north on the hill-top surface at Rajpur near Sehanshai Ashram (Figure 3 *b*), where the top 20 m thick layer again shows the shear wave velocity band of ~500–600 m/s in general, which may represent the velocity of older Doon Gravels/litho unit B. Sharp decrease in velocity from 20 m to 45 m depth below station location 114 may mark the erosional surface and probably indicates incision and erosion of Siwalik sandstone, which might have filled with recent deposits (Figure 3 *b*). The low *Vs* enclosures within the high *Vs* layer strata below station locations 118 and 126 may also indicate the presence of dissolution features (site no. 4).

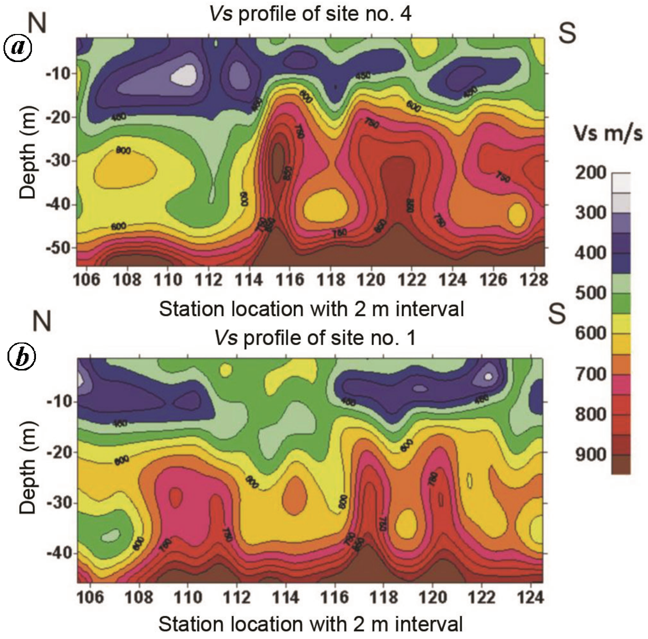


**Figure 3.** ***a***, Shear wave velocity profile of Malsi Dear Park, site 4 (zone-1), showing almost vertical contact between Older Dun Gravels and Middle Siwalik Sandstone at a depth of 20 m below 114 station number. ***b***, Shear wave velocity profiles of Shehnshai Ashram, site 1 (zone-1).

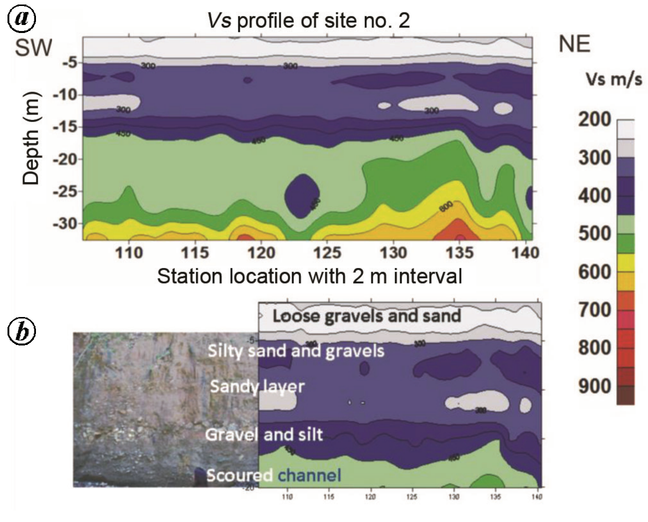


**Figure 4.** ***a***, Shear wave velocity profile at SPRR, site no. 2. Reversal of shear wave velocity is noticed at a depth of about 10 m. ***b***, shows comparison of *Vs* with lithology.

Zone 2 covers the banks of the Tons River, which runs in the northwest part of the Dehradun Fan (Figure 1) and mainly consists of dissected Dun gravels, named as Upper Dun surface (UDS)[3]. In this zone, Tons River developed a number of terraces and preserved anomalous features underneath. Seismic profiling was started from the terraces developed in the north, with the objective of validating the exposed litho units on the head-ward side of the terrace. The examination of the exposed section shows the presence of unconsolidated gravels and sand followed by silty sand and gravels up to ~15 m depth and the shear wave velocity of this part also shows *Vs* of the order of 200–300 m/s; however it increased to 400–600 m/s at 25 m depth (Figure 4 *a*). A reversal in shear wave velocity observed below stations 109 and 135, may be attributed to the pounding effect[18] as the site is close to the stream. Below 17 m depth, ~10 m soil column deposits are compact and thick layers of silt, sand and gravel have been noticed (field observation) showing a shear wave velocity of the order of 500 m/s (Figure 4 *a*). However, below ~30 m depth, the shear wave velocity increases to more than 700 m/s reflecting very stiff material and the exposed litho-section shows poorly sorted brecciated gravels that may indicate tectonic episodes (Figure 4 *b*).

Further downstream, the top 20 m soil column comprises rounded to sub-rounded boulders of unconsolidated massive gravels such as limestone, quartzite sandstone and phyllites. Below 20 m depth, anomalous curvilinear features were detected below station location number 112 (Figure 5), which were attributed to the presence of a palaeo-channel as also observed in the field[19]. To trace the continuity of palaeo-channels, three parallel profiles across the possible palaeo-channel were taken. All the channels showed almost similar features below location numbers 112, 116 and 124 (Figure 5 *b* top), 112, 116–125, 132–136 (Figure 5 *b* middle) and 112, 119, 122–127 (Figure 5 *b* bottom) respectively. However, the width of curvilinear features varied from one side to another, which may indicate the direction of flow of the palaeo-channel (Figure 5 *b*). The same feature was verified by electrical methods[19].

Further downstream, the gravel deposits were found to be calcified at a depth of 10 m below the surface. The calcification of these gravels resulted in caverns and karst topography thus increasing the shear wave velocity of sediments (Figure 6). The main idea for selecting this site was to trace the subsurface dissolution features (cavern), incidentally exposed on the southern face of the ground along the river section enabling us to compare subsurface and surface features. The top 8 m thick layer of this site (site no. 10) showed enclosures of loosely packed gravel beds with silt and sandy clay (Figure 6*a* and *b*) with a shear wave velocity of 500 m/s. Further increase in calcification with depth increases the shear wave velocity to ~800–900 m/s at ~25 m depth. The presence of low velocity enclosures below station location number 108–111, 116, 128 and 136 may indicate lateral variability in sediments cementation (Figure 6*a*).

The field photograph of a 16 m thick exposed section near Tapkeshwar temple (right above) lying below the ground where the profile was taken, was used to validate the *Vs* profile as shown in Figure 6*b*. Further, at ~25 m depth, the velocity changes to ~800 m/s, representing compact calcified gravel beds with presence of caverns. Therefore, the shear wave velocity of these deposits rises from ~500–600 m/s to ~800–900 m/s and interpreted to be the presence of calcite deposits in boulder beds. Similar observations were reported from Las Vegas valley where calcite cementation of alluvium (Caliche) raises

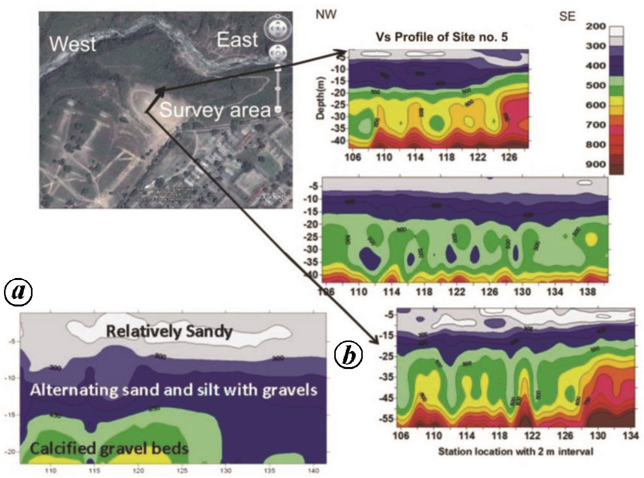


**Figure 5.** ***a***, Correlation of upper 20 m soil column of Anarwala site with the field investigations for characterization of lithounits. ***b***, The shear wave velocity profiles of Anarwala, site no. 5 along three parallel west to east running profiles to represent the alignment of palaeo-channels. The Google photograph (upper left) shows the location of the ground covered under the study and arrow represents the direction of palaeo-channel.

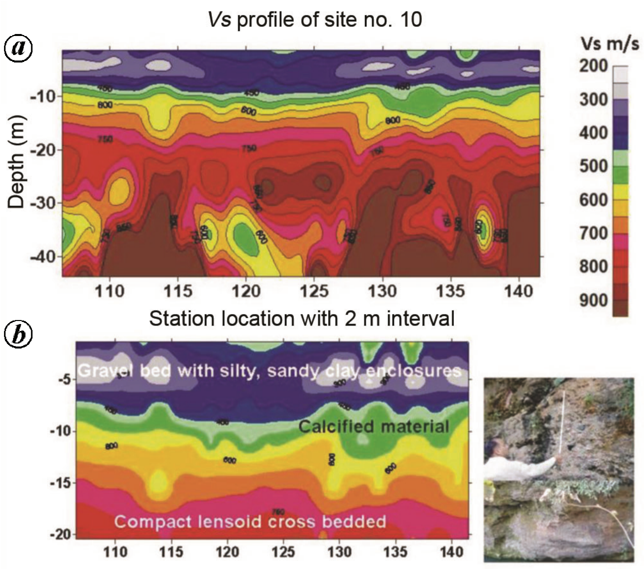


**Figure 6.** ***a***, Shear wave velocity profile of Birpur site no. 10 (zone 2), which shows a low shear wave zones beneath station location 109–110 and 118–124. ***b***, A blow up of top 20 m soil column, which has been measured and correlated with the field investigation.

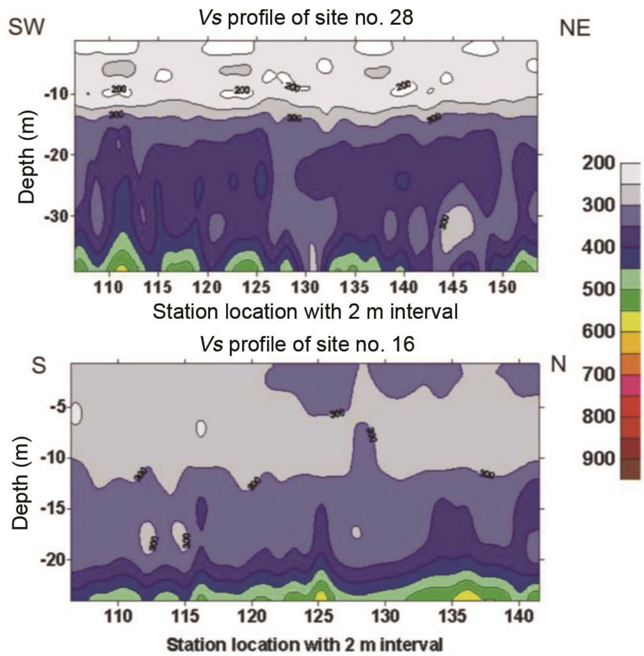


**Figure 7.** Shear wave velocity profiles of site nos. 28 and 16 (zone 3) showing the depth of low shear wave velocity sediments (~300 m/s).

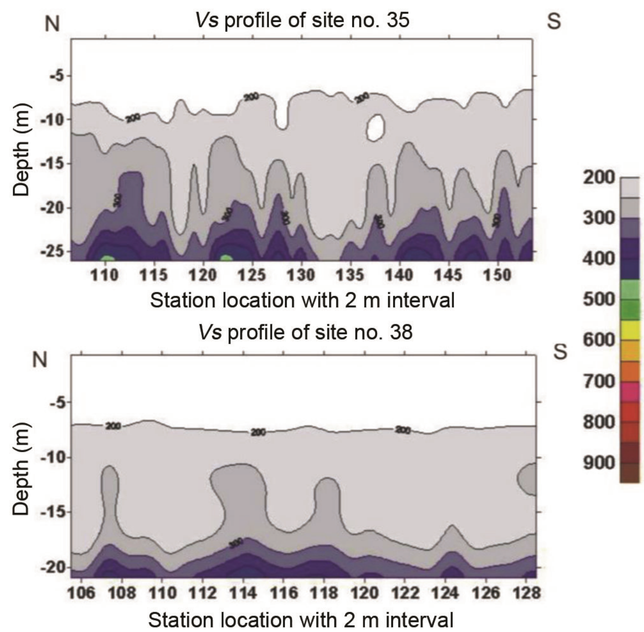


**Figure 8.** Shear wave velocity profiles of site nos. 35 and 38 (zone 4), showing the thickness of low clay deposits (~200 m/s).

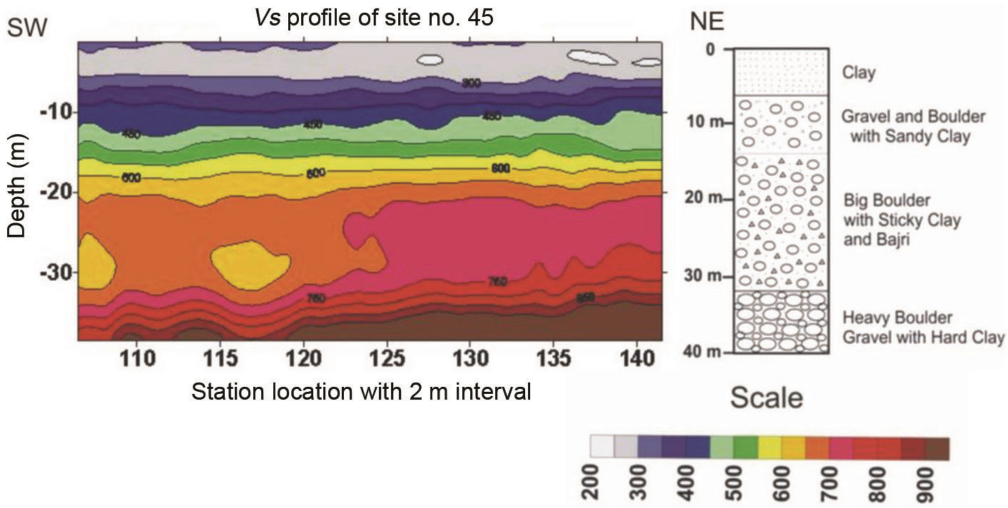


**Figure 9.** Shear wave velocity profile of Badripur site no. 46 (zone 5) showing different shear wave velocity bands (*Vs*) with corresponding tube well log.

the *Vs* values from 300 m/s to 500–600 m/s (ref. 20). The abundance of limestone in the depocentre of fan deposits complements the fact that streams feeding the proximal zone emerged from lime-rich rocks in the hinterland.

Zone 3 lies in the middle part of the Dehradun Fan, represents the lower Dun surface and is dominated by mudflow deposits[3,8]. The *Vs* profiles taken from 20 different sites show *Vs* of the order of ~200–350 m/s, to the top 10–15 m and may represent the velocity of gravel with sand, silt and muddy matrix deposits. Increase in *Vs* to ~300–450 m/s below 20 m depth may mark the onset of stiffer material (coarse sand and gravels beds; Figure 7).

Zone 4 part of the fans is mainly composed of poorly sorted angular to sub-rounded gravel with silty, sandy and muddy matrix, overlain by thick deposits of clay layer, named as lower Dun surface[6] (Figure 8). The shear wave velocity profiles of this zone show *Vs* of the order of 150–180 m/s, indicating the presence of clay layer at the top (8 m) followed by increase in velocity, which may indicate the presence of pebbles with sand, silt and muddy matrix.

Zone 5 represents the absence of palaeo-channels and erosional features. Shear wave velocity profile of this zone shows the horizontal and vertical distribution of *Vs*, indicating the layered structure. Borehole data from a nearby site (site no 45, defence colony) helped to corroborate the material composition with the observed *Vs* profile of this zone (Figure 9). The top layer (7 m) has average *Vs* of about 250 m/s, representing the clay deposits, whereas the velocity increases 300–500 m/s below 7 m and may indicate the presence of gravel and boulder intermixed with sandy clay. The *Vs* of ~500–750 m/s below 10 m depth may indicate the presence of big boulder with sticky clay and coarse sand. Further, increase in *Vs* to >750 m/s below 33 m depth may represent the emergence of bedrock (Figure 9). This may be seen as an extension of Nagsidh hills, which are exposed southeast of the site and are considered to be a part of the Siwalik ranges[21]. This zone is mainly used for agricultural activities.

Based on the subsurface variation and local geological investigation mainly along stream cuttings of Dehradun Fan deposits, the city could be divided mainly into five different zones (Figure 10). The north-western and northern parts of the city are mainly marked by the existence of palaeo-channels and caverns, which resulted in karst topography in the region. The centre part of the city is underlain by thick (~140 m) braided stream deposits of fan showing evidences of erosion and aggradations, representing change in sedimentation from time to time. The south-western parts of the city located at the distal end of the Dehradun Fan, have thick clay deposits. The eastern most part of the city shows stratified layer and has shallow bedrock due to presence of Nagsidh hill[21]. As dissolution features can have a high impact on engineering design specifications, their effectiveness can be enhanced if designed with a drilling programme. The subsurface architecture, thickness of sediments and subsurface material properties may indicate the influence of tectonics and climate in the development of Dehradun Fan deposits and reveal that Dehradun Fan is not a single fan deposit but a product of multiple fans. The variation in thickness of sediments, their depositional characteristics and subsurface architecture also reflects variation in provenance and tectonics. The most prominent feature of the zones 1 and 2, bordering the MBT to the south, is a stratigraphic sequence marked by bi-variant velocity distribution in the deeper section of the fan deposit (30–40 m), i.e. modest (400–550 m/s; Figures 4 and 5) to high

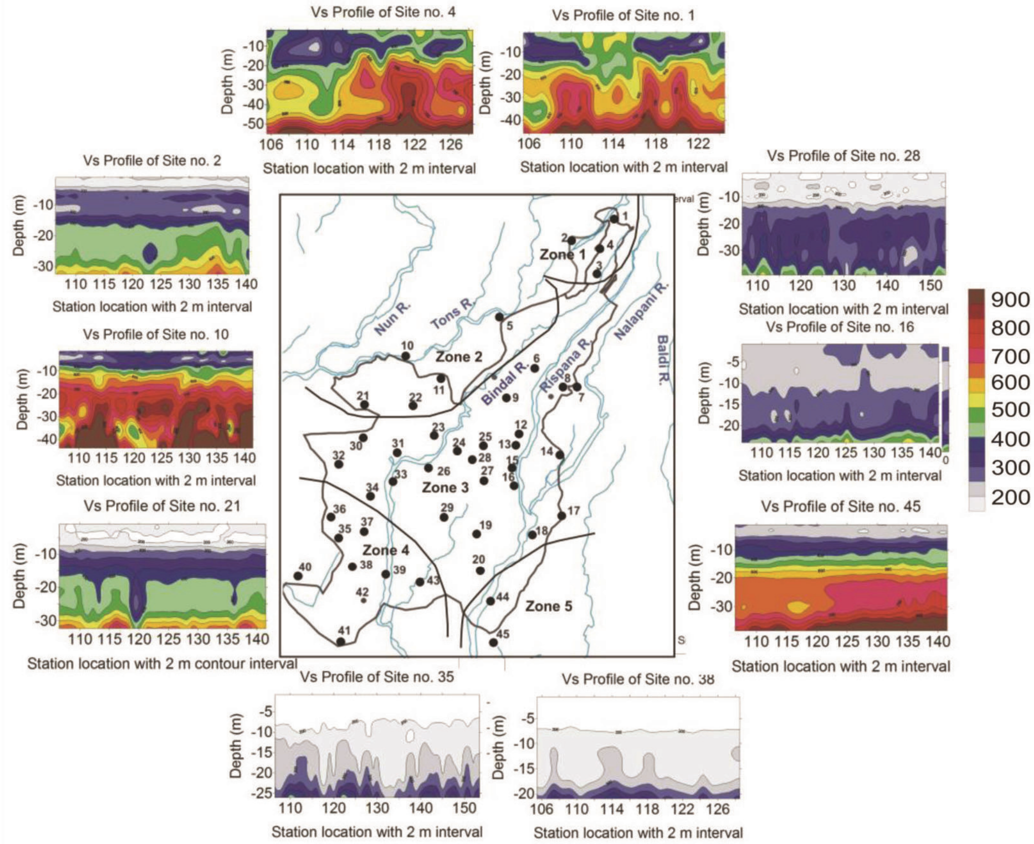


**Figure 10.** Classification of Dehradun Fan sediments in different zones based on shear wave velocity information of the subsurface up to 40–50 m depth.

velocity (>550–700 m/s) horizon (Figures 4–6). This bi-variant distribution of velocity relates to the spatial variation in the degree of calcite cementation in the gravel sequence in deeper depth sections of the fan deposits. The entire middle zone is homogenously characterized by 30–40 m thick sequence associated with velocities of >250–450 m/s which is related to compact gravels with high fraction of sand and silt in matrix. This stratigraphic transition from proximal zone (zones 1 and 2) to middle zone (zone 3) may signify change in degree and extent of entrenchment of streams as well as mode of sedimentation from high-energy gravity-flow to more regularized mudflow and finally into braided streams deposits.

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# Study of a snow avalanche accident along Chowkibal–Tangdhar road in Kupwara district, Jammu and Kashmir, India

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**An avalanche accident was occurred on 5 January 2018 on Chowkibal–Tangdhar road in Kupwara district, Jammu and Kashmir about 6 km from Chowkibal village. One light passenger vehicle was swept away in the avalanche and 10 persons lost their lives. In this communication, we study the cause of avalanche accident and simulate the snow avalanche flow using Rapid Mass MovementS model. Total snow depth recorded at the nearest observation location from the accident site was 31 cm and fresh snow of the storm was 24 cm. Avalanche condition on slope was building up and the Snow and Avalanche Study Establishment issued an avalanche warning of 'Low Danger' for the Chokibal–Tangdhar road axis. Maximum thickness of avalanche debris on road was observed to be 3.0 m. Flow simulation showed maximum velocity of avalanche to be ~25 ms$^{-1}$, maximum impact pressure ~9.39 × 10$^4$ kg m$^{-1}$ s$^{-2}$ and maximum height of avalanche flow ~3.0 m.**

**Keywords:** Avalanche accident, mountainous terrain, snow storm.

SNOW avalanche is the sudden downward motion of a huge mass of snow from a mountain top to the valley bottom, which is hazardous when people or property come in the way[1]. Snow avalanches are a common phenomenon in snow-bound mountainous regions. Generally, avalanches flow over an open channel or close gullies in a mountainous terrain. McClung[2] provided statistics of avalanche fatalities during 1895–2014 in the high mountains of Asia, i.e. Himalaya, Karakoram, Pamir, Hindu Kush, Tien Shan and Dazu Shan covering snow-bound regions of India, China, Pakistan, Nepal, etc. He observed that about three-quarters of the deaths resulted from improper camp placements and failure to forecast snow avalanches. Ganju *et al.*[3] studied the characteristics of avalanche accidents in the Western Himalayan region, i.e. snow-bound areas of Jammu and Kashmir (J&K), Himachal Pradesh and Uttarakhand, India and reported that a considerable proportion (~62%) of the total fatalities occurred when people were in movement and majority of the accidents took place during snowfall or immediately after cessation of snow storm. This study provides scientific insight regarding an avalanche accident in the Pir Panjal range of the Himalaya.

An avalanche accident occurred in J&K, on 5 January 2018. The accident took place on the Chowkibal–Tangdhar (C–T) road, about 6 km from Chowkibal village towards Tangdhar. One vehicle was swept away by the avalanche and buried under the debris. A total of 12 persons were caught in the avalanche – 2 were rescued alive and 10 persons were recovered dead. On the same day, an another avalanche accident took place on the same road axis, in which one Border Road Organization (BRO) official was buried in the debris and found dead. The C–T road axis is one of the roads in Tangdhar region of J&K, which is most vulnerable to snow avalanches. Other regions which are vulnerable to avalanches around Kashmir valley are Drass, Gurej, Keran, Machhal,

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