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The 23 September 2003 Varunavat Parvat landslide in Uttarkashi township, Uttaranchal

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Uttarkashi township, located on the right bank of the Bhaghirathi river, is known to have had a history of natural disasters, including the mass movement activities. A disastrous landslide in the area on the slopes of the Varunavat Parvat struck late in the night on 23 September 2003, immediately after the rainy season. The Varunavat landslide has been classified as a classical example of debris slide (debris slide in the crown portion, and rockfall and rockslide in the middle part). Both natural and human-induced factors are responsible for this slide, however, the main triggering factor is the surface and groundwater. The present study lays the foundations for further work to link landslide activity to rainfall – intensity duration trends so that stochastic relationships may be developed to assess high-risk areas around the slide zone.

A landslide is a complex dynamic system. An individual 'landslide' characteristically involves many different processes operating together, often with differing intensity during successive years[1]. A landslide that struck the hill of the Varunavat on 23 September 2003 and endangered the Uttarkashi township is a living example. The Varunavat Parvat is located at long 30°44′N and lat 78°26′E. It is situated on the right bank of Bagirathi river (Figure 1). At the foot of the parvat lies the Uttarkashi township.

The present study emphasizes description based on objective reality, rather than genetic inference. Such findings attempted to interpret the processes responsible for the failure of slope and to infer the environmental conditions for the operation of such processes. However, it has been recognized that there are limitless opportunities to go astray, twist the failure and its interpretation. The site has been investigated for its potential use as a source to build a threshold model for the failure to occur under a given set of conditions.

Uttarkashi and its environs are made up of two main lithotectonic units, viz. the Higher Himalayan Crystallines and the Lesser Himalayan sediments. The Higher Himalayan Crystallines are thrust over the quartzite and volcanics of the Berinag Formation of the Lesser Himalaya along the Main Central Trust (MCT). The Berinag Formation is underlain by the Damta Group which is exposed in the antiformal windows[2]. The area is sandwiched between the Srinager Thrust and the MCT located respectively south and north of the study area (Figure 2). The area has been mapped in detail by Agarwal and Kumar[3].

The rocks constituting the Varunavat Parvat are mainly quartzite and phyllites of Damta Group, dipping into the hill at 30–35°. These are highly shattered, fragmented, fractured and thinly jointed. These are covered with 20–25 m thick slided material.

Four sets of joints along with the foliation have been recorded. The stereo-plot of these joints is depicted in Figure 3. All the joints have openings of about 0.5 to 1 mm. The 60–65° SSE dipping joint coincides with the slip surface. This joint is filled with clayey material of 1–2 mm.

Annual total rainfall in the area is about 1350 mm, with 60% rainfall falling in the months of July–September. During 2003, the number of rainy days for July is 20; August is 27 and until 23 September, the date of initiation

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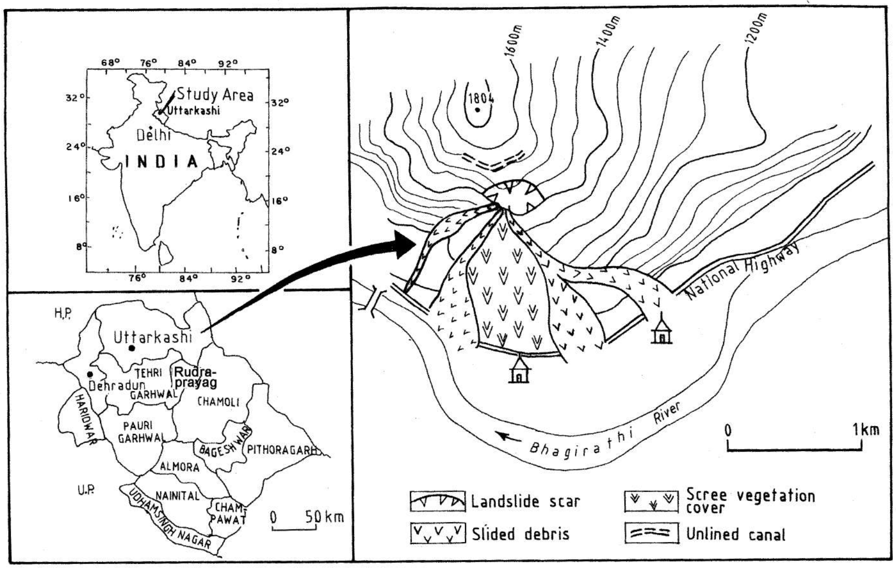

Figure 1. Location map of Varunavat Parvat landslide that struck on 23 September 2003 in Uttarkashi District, Uttaranchal.

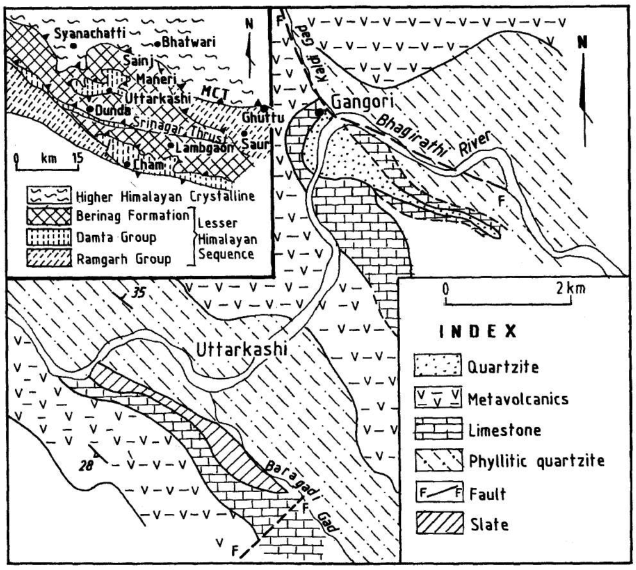

Figure 2. Geological map of the area. Rocks constituting the Varunavat Parvat are mainly quartzite and phyllites belonging to Damta group, dipping into the hill at 30–35°.

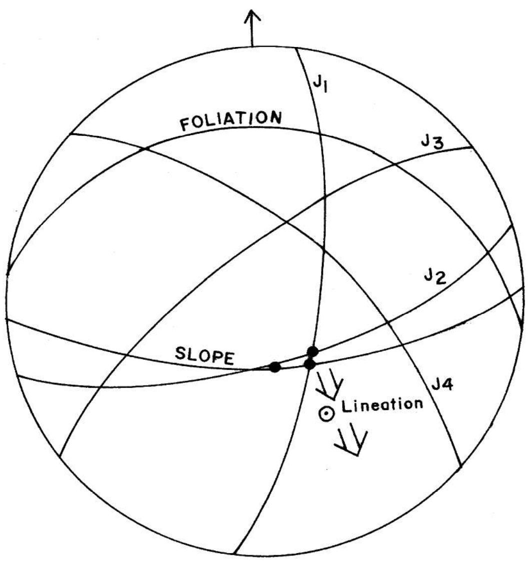

Figure 3. Stereo-plot of four sets of joints along with bedding and slope orientations. Joints J_2 coincides with the failure plane of the landslide.

of the slide, is 13. In terms of intensity, the rain culminating on 6, 25 and 27 July and August 27 is prominent.

Daily rainfall plot for July–September 2003 are shown in Figure 4 *a*, whereas Figure 4 *b* depicts the average annual rainfall for the last 14 years. This clearly shows that the rainfall for the year 2003 is above normal. The slide started on the day that the rainfall ceased, i.e. 23 September 2003.

The rock debris from the hilltop of Varunavat Parvat started falling during the night of 23 September 2003 and continued for the next 15 days. The crown of the landslide is located 1675 m amsl and about 700 m above the Rishikesh–Gangotri National Highway. It is sparsely vegetated with pine (about 30% cover).

The scarp of the active slide is about 30 m long and 150 m wide, which dips at an angle of 55° due S30°E. It is prominent and coincides with a joint plane that is filled with 1–2 mm thick clayey material. The movement of the rock debris has produced sharp slickensides plunging 48° due S25°E, indicating the direction of movement (Figure 3).

In the crown region, many upslope tilted trees have been noticed, which indicate the rotational movement of the slide mass. Based on the geometry (Figure 5) of the exposed scarp and the raised benches at about 1525 m, the depth

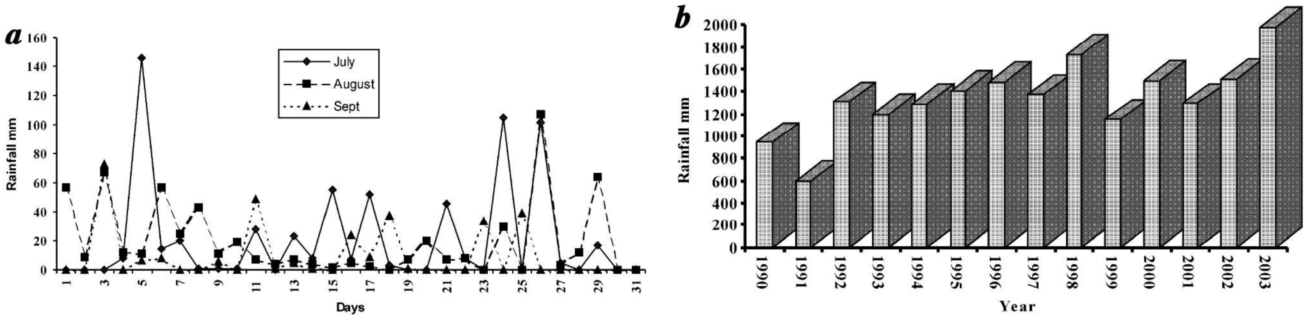

Figure 4. ***a***, Line diagram of daily rainfall plot for July–September 2003. ***b***, Average annual rainfall totals for the years 1990–2003. Data are collected from the district administration of Uttarkashi.

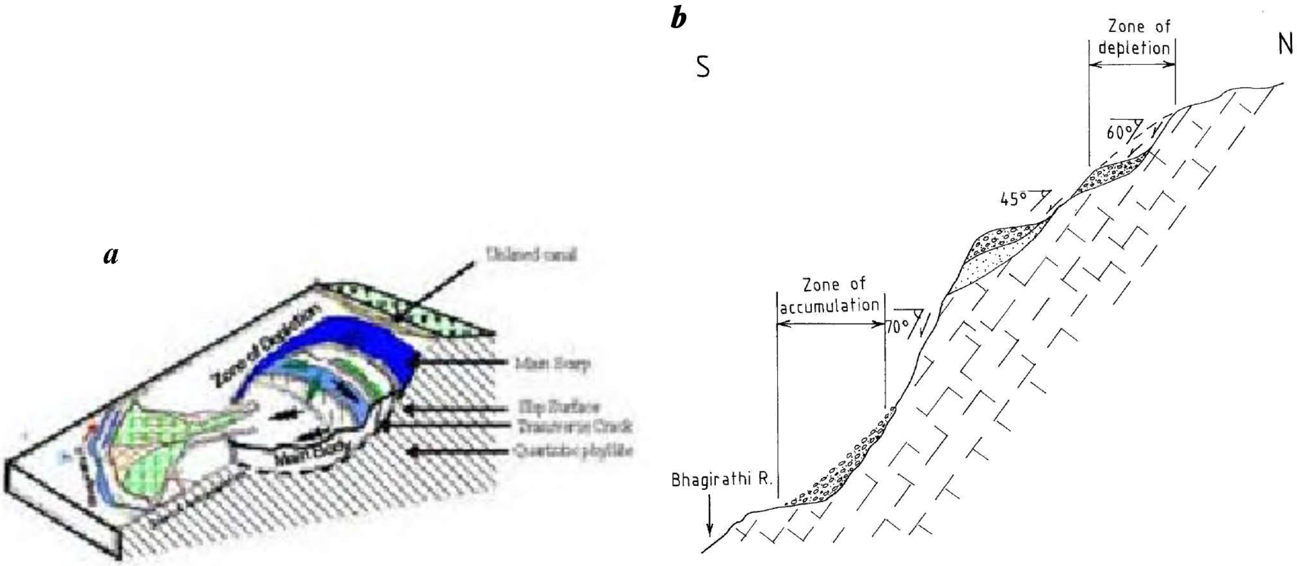

Figure 5. ***a***, Schematic block diagram of Varunavat Parvat landslide. ***b***, Cross-section of Varunavat Parvat slide along the Ramlila ground slide track as on 10 October 2003 (not to scale).

Figure 6. A crack in the slide mass remaining along NE–SW and extending for about tens of metre.

of the slip surface is estimated to be 20–25 m. The zone of displaced mass is about 200 m long, 250 m wide and 20 m deep. The topographic cross-section of the slide as observed on 10 October is hummocky, with two raised, horizontal benches. A number of cracks trending NE–SW and E–W have been observed in this zone (Figure 6) and are traceable for tens of metre. Some of the cracks are about 3 m deep. The slide zone has been regularly monitored by the authors many times after 10 October to visualize and monitor the slide zone and cracks. Though no extension of slide has been observed in the upslope direction, new cracks have been noticed on the left flank of the slide. One horizontal bench located along the slide tract at 1525 mm has been washed away, giving an angle of repose of about 30–35°. Though the slide is stabilized, the loose material is still resting on the slopes and may move down in the near future.

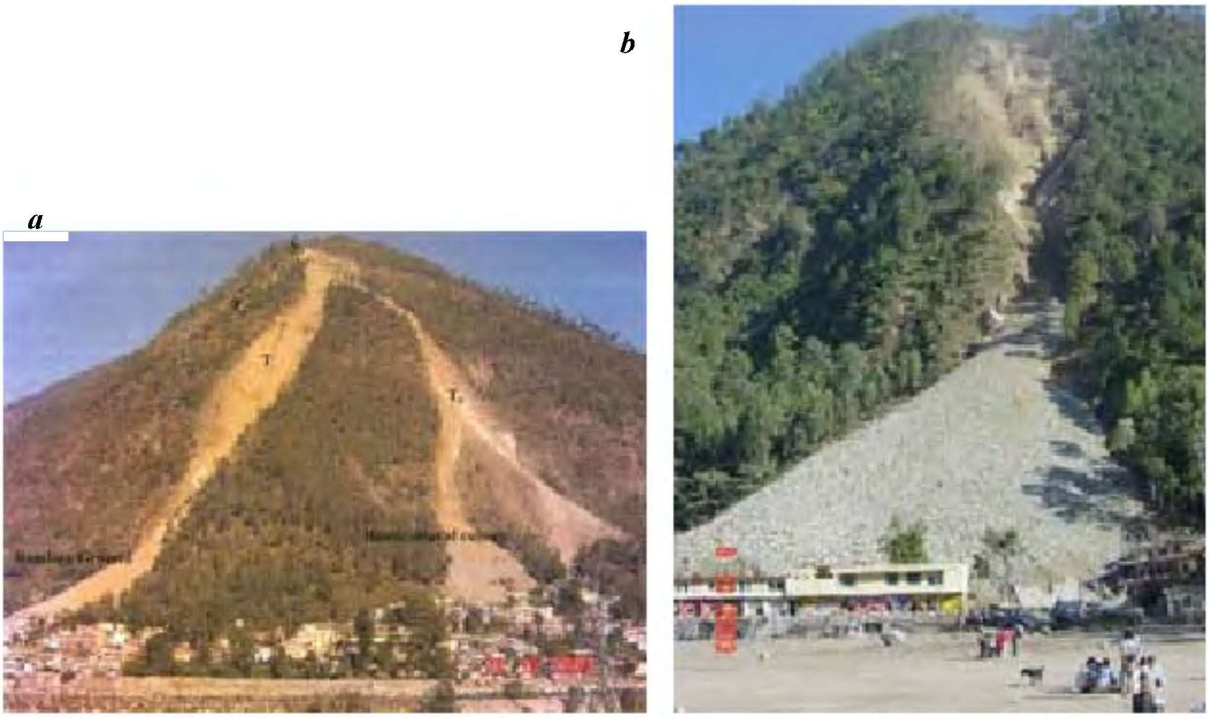

Figure 7. ***a***, Panoramic view of Varunavat Parvat slide. S_1 is the location of main Varunavat Parvat landslide. T_1, T_2 and T_3 are the three different transportation zones. Ramlila ground and horticultural colony accumulation zones are also visible. ***b***, View of Ramlila ground accumulation zone. An estimated volume of about 25,000–30,000 m^3 debris has been accumulated in this zone. This debris buried many residential and commercial establishments and also caused huge damage to the infrastructure.

Using volume calculation formula, based on the ellipsoidal geometry of the landslide mass, i.e. $1/6\partial L_r W_r D_r$ (where L_r is the length of surface of rupture, W_r is the width of surface of rupture and D_r is the depth of surface of rupture)[4], an estimated 50,000–60,000 m^3 volume of material has been displaced, which has rolled down the slope of Varunavat Parvat along three transportation tracts and accumulated in three different accumulation zones respectively (Figure 7 *a*). These zones are locally named as Tambakhani zone, Ramlila ground zone and Horticultural and Jal Nigam zone. Out of these three accumulation zones, the Ramlila ground zone is the most prominent (Figure 7 *b*). Characteristic features of each accumulation zone are briefly described here.

The Tambakhani zone, which is an old landslide zone, has developed along S10°W of Varunavat Parvat. This slide often caused damage to the Rishikesh–Gangotri National Highway. In the present scenario, the scarp of this landslide has merged with the main Varunavat landslide, thus forming a part of the main Varunavat Parvat landslide.

The Tambakhani slide track has a total length of about 650 m and has maximum width of about 100 m in the middle portion of the slope. The toe portion of this track is narrow and of the order of about 5–10 m. Most of the fallen boulders from the crown portion stop in the middle of the slide zone (altitude 1400–1500 m), forming a bench-like structure, with a slope angle of about 10–15°. However, few boulders find their way to the valley bottom on the national highway. Overall, the shape of this slide track is in the form of a funnel.

The Ramlila ground accumulation zone has developed along S30°E (Figure 7 *b*). This zone constitutes a major slide segment among the three accumulation zones in the area. Total width of this zone is 125 m. The accumulated material at the base forms a cone-shaped structure about 100 m long, 125 m wide and with a slope angle of about 40°. Approximately 25,000 to 30,000 m^3 of material has accumulated at the base burying 125 m stretch of road and destroying three multistoried hotels, one workshop and Nagar Palika buildings, including electric poles, telephone lines and sewerage lines. The maximum diameter of the boulders observed at the base is 20 m. However, most of the boulders break into smaller pieces when they roll down the hill, and thus the dominant size of the boulders present downhill is 0.5–1 m diameter.

Masjid Mohalla accumulation zone is the secondmost favourable direction for the boulders to accumulate. The rolling boulders further take two prominent directions, viz. S80°E and S60°E (Figure 7 *a*). This zone has affected residential houses at Jal Nigam and Horticultural colonies, and Masjid Mohalla. Approximately 10,000 m^3 of material has rolled down and is lying loose on the slope, posing a serious threat to the Government offices lying along the lower slopes. The dominant size of the falling boulders is 0.5–1 m.

The Varunavat Parvat is a typical example of 'debris slide' with rockfall and rockslide in the middle of the slope. The slide occurred in two distinct phases. The first phase involved rotational sliding of about 20–25 m thick slab of Quaternary material on 23 September 2003 along a prominent joint plane, while the second phase involved the toppling of blocks that disintegrated and initiated a rockfall and rockslide in the middle portion of the slope. The slide incorporates the old slided materials and fragments of quartzite and phyllites. Though distress was noted in June 2003 (Disaster Mitigation and Management Centre, Uttarkashi, Unpublished Tech. Report, 2003), the mass was mobilized by continuous increase in pore water pressure over months due to heavy monsoonal rainfall.

In addition to rainfall, several factors probably contributed to slope failure.

(i) Geological structures like shattered, fragmented and highly jointed rocks and topography like steep slopes, interacted to provide the geometry conducive to sliding. This is clearly visible in Figure 3, where the intersection of J_1 and J_2 with one another and J_1 and J_2 with slope made the area highly unstable[5]. Also the plot of the lineation features produced by landslide movement in the area indicates that it is the orientation of J_1 and J_2 that controls the direction of the landslide.

(ii) The landslide occurred at the end of the rainy season, which normally is towards the end of September and the groundwater was probably near its highest seasonal level. Rainfall from 17 to May 23 was 72 mm and the week after, the total rainfall was about 73 mm. October and November, no rainfall had been recorded. This marks the near end of the rainy season. Short-duration rainfall certainly could not have produced abnormally high antecedent groundwater levels. It is the collective rainfall of many months that has caused the pore water pressure to rise.

(iii) An unlined canal extended across the crown of the slide. Unsubstantiated reports suggest that the water may have percolated for several months before the slide, which could have significantly raised the groundwater level in the hillside and thus reduced the shear resistance. Infiltration from this canal, along with the copious rainfall, probably also led to further failure of the hill mass.

(iv) Steep-cut slopes for roads, pathways and residential and commercial buildings near the base of the slope may have further destabilized the slope by removing the basal support.

There have been a variety of natural hazards, including occasional mass movements of destructive impact in the Uttarkashi and the adjoining regions in the past[6]. The year 1978 witnessed widespread flooding and landslide activity due to cloud bursts and flash floods in the region. Land sliding in June 1980 had taken a toll of 24 human lives in Uttarkashi District. The disastrous landslide of 23 September 2000 in the area caused widespread damage. All these make it necessary to properly evaluate the potential hazards and suggest appropriate counter measures for future development of steep mountain sides and narrow valleys. Based on remote sensing data, this particular stretch of area has been classified as potential landslide hazard zone[7]. However, on the spot field investigations are necessary to pinpoint the exact areas susceptible to failure under a given set of conditions.

The landslide triggered at the end of the monsoon season indicates that the groundwater pressure might have progressively increased during the previous rainy months. The rainfall in the year 1998 was also above normal, i.e. 1733 mm and there is no report of any mass movement. Thus it is concluded that the threshold for the slope to fail in the area is above 1733 mm. Since duration and intensity of one particular event play a major role, the threshold of rainfall for a particular event or for the rainy season is important, rather than for a year. In the present case, the total rainfall for July–September is 1545 mm, with total of 60 rainy days out of 75.

Also in the present case, the infiltration of water from the unlined canal located at 1700 m a msl and about 100 m above the landslide scarp, played a major role in the increase of pore water pressure. It is the combination of clay and water that has caused the slope to fail on the Varunavat Parvat. Thus in the similar topographic setting, the combination of 1500 mm of rainfall in the monsoonal months along with the clayey filled joints (Figure 3) can be seen as potential threat and thus the threshold rainfall limits can be set along with the given set of geological conditions.

The observations discussed here set limits on the causes of the Varunavat landslide. Precise on-the-spot geotechnical tests are needed and laboratory tests may be helpful to determine the conditions that triggered the slide. Wadia Institute of Himalayan Geology, Dehra Dun has chosen the Varunavat slide as a pilot site for in-depth investigation of rocks and soils and also for continuous monitoring of slope. The study presented here points towards short-term mitigation measures. In the present scenario, the material is lying loose on the slopes of the Varunavat Parvat. It is advisable to remove it manually, and the slide should be allowed to take its natural path. For long-term stabilization measures, detailed in-depth geotechnical characterization of soils and rocks involved in the sliding is needed.

The outcome of this work has two major implications. First, with the continuous increasing development activities in the region, the risk posed by natural hazard must also be evaluated. This is well-exemplified by a series of natural hazards in the region. With this case study, further research aims to link landslide activity to rainfall-intensity duration trends so that stochastic relationships may be developed to assess high-risk areas. Secondly, if a successful relationship between rainfall and landslide activity can be established for the Himalayan region, analysis of palaeo-landslides may provide important new information on past variation in rainfall patterns. Equally, such relationships may predict changes in mass movement activities in the Himalayan regions based on modelled regional impacts of global change.

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Analysis of interval velocity vs amplitude blanking in a gas hydrate province

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Seismic reflection profiles across many continental margins have imaged bottom-simulating seismic reflectors (BSRs), which have been interpreted as being formed at the base of a methane hydrate zone. These reflectors might arise from an impedance contrast between high velocity layers, partially hydrated sediments overlying gas/water-saturated sediment. Our study was aimed at amplitude analysis and its relation with velocity on one of the profiles on the western continental margin of India. In our data BSR is found to be discontinuous in the profile and amplitude blanking is seen above the BSR. To get an idea about amplitude in the region with and without BSR, we have performed both amplitude and velocity analysis. The relation between amplitude variation and velocity variation is utilized to estimate range of velocity in the blanked zone.

GAS hydrates are ice-like crystalline solids that are formed when a cage of water molecule surrounds a guest gas molecule (mainly methane). Evidence for their existence has come from recognizing a bottom-simulating reflector (BSR) on the seismic profile that marks the base of the zone of occurrence of gas hydrates. No attempt has been made to quantify them through velocity analysis. This aspect of velocity value distribution would serve as good indicator for the presence of gas hydrates and its resource estimate.

Gas hydrates are known to increase interval velocity of sediments[1–4] by an amount that is proportional to the amount of hydrate[5]. These relations have been used by researchers to explain the velocity variation of 1.6 to 1.9 km/s as a result of variation in saturated hydrated sediments[2–4].

Another indicator of gas hydrates is amplitude reduction[6] or blanking typically observed above the BSR in reflection profile from regions of known hydrates. It has been proposed that the marked decrease in amplitude above the BSR to a reduction in impedance contrast across sedimentary interfaces is caused by the presence of hydrates[7].

Amplitude blanking, also observed over true-amplitude seismic sections, has been ascribed to hydrate formation[8]. These studies imply that amplitude information can be used as an indicator of hydrate concentration. Here, we have demonstrated the lateral variation of zone of blanking with continuity/discontinuity of BSR. We have also shown the relation between reflectance and average interval velocity estimated from the zone above and below the BSR.

The location of multichannel seismic profile used for investigation is shown in Figure 1. It was recorded in the early 2000s using tuned air-gun arrays of 2000 p.s.i. minimum pressure and 4000 in^3 volume. The data were recorded using 240 channels (short interval 50m and group interval 25 m) through IBM-3590 media with SEG-D format in the interval of 2 ms. These profiles provide 60-fold coverage with 6000 m stream length. We performed a 2D velocity analysis along the line shown in Figure 1. Prior to velocity analysis, the data were pre-processed. We first applied a time-varying spherical divergence correction. Subsequently, predictive deconvolution with operator length of 80 ms and prediction distance of 240 ms was performed to suppress a ringing in the data caused by air-gun bubbles. The deconvolved data were then band-pass filtered to their original bandwidth to remove spurious, deconvolutional, high-frequency noise. A final stacked section in near offset range is shown in Figure 2.

Detailed velocity measurements were made via stacking analysis at every 30 CDPs. It is difficult to draw an inference about amplitude blanking on the basis of interval velocities because reflections are weak and laterally discontinuous. Consequently, in this area, interval velocities, calculated from stacking velocities, are not consistently representative of the same geologic interval.

Our amplitude analysis was done in the interval of 400 ms thick section immediately overlying the BSR. The amplitude variation near the BSR can be examined using plots similar to those shown in Figure 3. In these plots, each dot represents the amplitude in an 8 ms window for six CDPs.

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