# Seismic Investigations on the Ice-shelf Near Dakshin Gangotri, Antarctica

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## ABSTRACT

The results of the seismic investigations around the Indian base station in Antarctica have established the efficacy of the seismic reflection methods in delineating sub-shelf structures. The results of the seismic interpretation, in conjunction with those obtained from magnetic studies, have led to the proposition of a structural model describing the thicknesses of ice-shelf and underlying water and glacial sediment layers above the basement. This model explains a number of geomorphological features in the region.

The experience gained in this first-ever seismic studies under the Indian Scientific Research Programme in Antarctica also provides valuable information on the type of explosives and the recording media that should be suitable under Antarctic environs.

## INTRODUCTION

During the Fourth Indian Antarctic Expedition first-ever seismic investigations were carried out near the Dakshin Gangotri permanent station on the ice-shelf. The prime objective of this survey was to examine the efficacy of a shallow reflection (SIE, 12 channel) seismic unit in the delineation of sub-shelf structure including the thickness of the ice-shelf. As we had taken gelatine-based (SGL—80) explosives, commonly employed in seismic surveys in India, it was also necessary for us to test, first of all, the performance of this explosive in Antarctic environs.

Prior to the seismic survey, a long magnetic traverse extending from coast to about 35 km south was taken to identify the geophysically interesting regions where seismic investigations would yield further complementary information.

The seismic records were interpreted in conjunction with the results obtained from the magnetic survey and based on this interpretation a structural model of the ice-shelf around the Indian Permanent Station has been proposed.

## LOCATION OF THE SURVEYED AREA AND DATA COLLECTION

Based on the long magnetic traverse on the ice-shelf taken during the fourth expedition (Verma et a1., 1987) and those taken during the second expedition an area extending from 1 km north of the second expedition Runway Hut (Lat. 70° 02'.32 S, Long. 12°00'.08 E) to about 3 km south of the Indian Permanent Station was selected for the seismic work. This area lies in the vicinity of a valley-like depression in the basement close to the edge of the shelf.

The selection of the site was also constrained by the availability of the proper logistic support such as—availability of Pisten bullys, generator, a shooter from the Indian army etc.

Some of the salient features important from the view-point of effective collection of seismic data are described below:

**Drill-holes**

The most time-consuming aspect of the seismic survey was the drilling of shot point holes in the ice-shelf. The hand augers did not work satisfactorily for drilling holes ranging in depth from 5 m to 10 m. A working alternative to the hand drilling was provided by electrically operating thermal drills. However, it was found to be very slow and to drill a shot-hole of depth 10 m it took about 3 hours. The thermal drilling also required a power-generator on site capable of running continuously for about 10 to 15 hours to drill atleast 3 to 5 points for each location. As the proper logistic support for the seismic surveys was made available only after the second week of February when the weather starts getting rough, at times after drilling all the shot-holes and making the preliminary preparations for the survey, our attempts of shooting the charge and taking the records were frustrated due to changed severe conditions of the weather.

**Explosives and detonators**

We had carried with us the gelatine-based SGL-80 explosive which is commonly used in seismic surveys in India. The explosive-experts of the Indian army, however, informed us that these explosives were not suitable under Antarctic weather conditions. The reason being that the handling of these explosives at sub-zero temperature conditions becomes risky. Also, at sub-zero conditions no moisture is available in the atmosphere due to which the explosives were found to become very brittle increasing the risk factor. It was suggested by the experts from the Indian army that for future seismic surveys in Antarctica, the Plastic Explosives from Kirki (PEK) or the Low Temperature Plastic Explosives developed by ERDL (DRDO) Pune should be used.

The excessive presence of the static electricity was found to be another hazardous-factor in Antarctic environs. Proper precaution must be taken to remove the static charges before connecting the seismic quality (zero-time) electrical detonators to the explosives.

**Recording equipment**

We had taken RM-495 unit alongwith Ru-49R9 digital recorder unit of SIE for the purpose of recording. The unit accommodates upto 12 OPA-9 plug-in seismic amplifiers and permits simultaneous recording of 12 traces of new data and 12 traces of composited data for each shot. This equipment provides analog (photographic) as well as the magnetic tape record of the seismic data. However, the magnetic recording unit was found to be malfunctioning and therefore we had to rely on the photographic records only. The presence of strong ultraviolet rays in the region, however, had an adverse effect on the quality of records despite all the precautions that were taken to shield the recorder. The future seismic investigations in Antarctica should, therefore, be carried out with equipments with reliable facility for magnetic recording in addition to the photographic recording.

**Layout**

Besides the up-hole geophone, twelve more geophones were laid with the closest geophone being 100 m away from the shot point. Subsequent geophones were placed at an interval of 10 m to provide a maximum shotpoint geophone distance of 210 m.

## INTERPRETATION

About 25 to 30 points were shot lor the seismic reflection studies around the Indian station. Prior to this a number of test shots were made to determine the optimum gains for various geophones, charge-quantity shot point depth etc. It was observed that reflections recorded from various layers remained consistent and nearly all the layers were found to be present in records from various locations. One such record is shown in Fig. 1 for the purpose of illustrating the quality of seismic

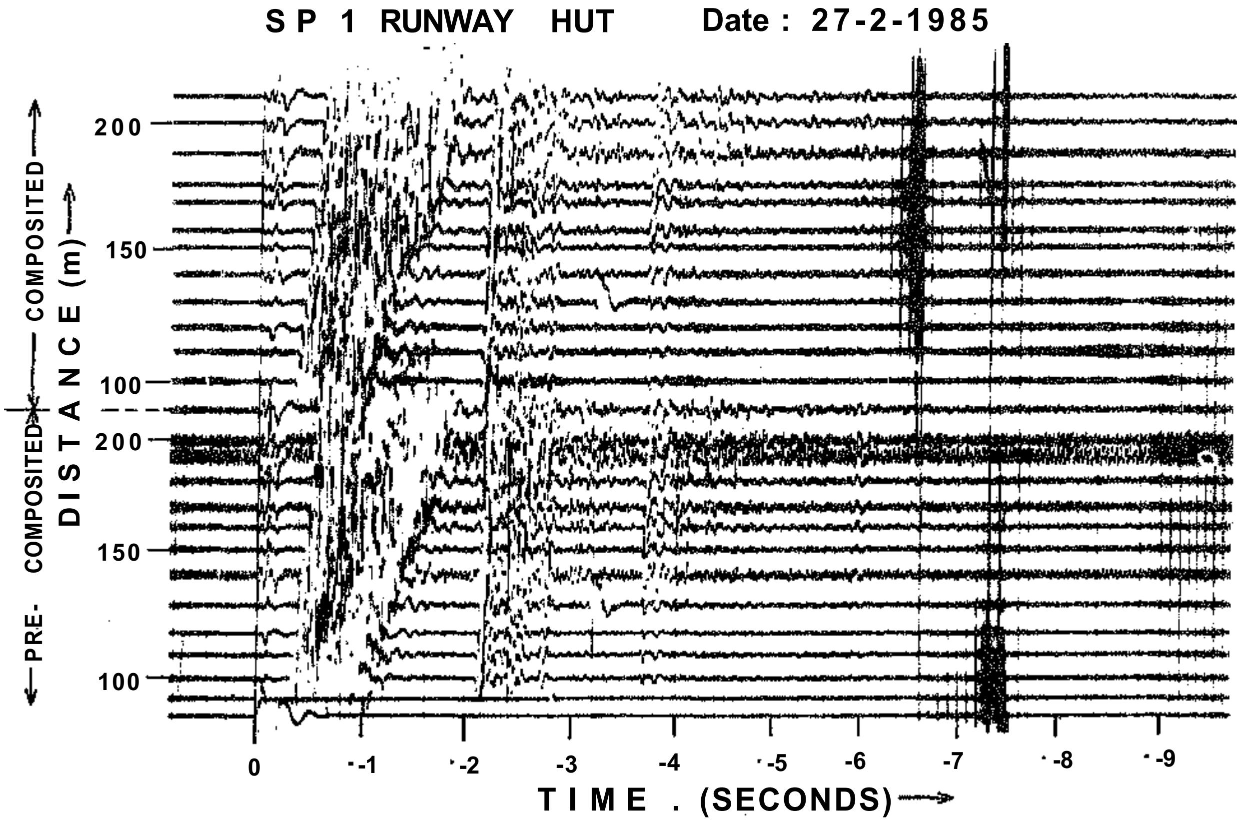



*Fig. 1.* Record of seismic reflection obtained near the Dakshin Gangotri Station.

records. This record was obtained near the Second Expedition Runway Hut. In the following section an interpretation to the record shown in Fig. 1, is presented. The interpreted results for other records from nearby shot-points showed similar structure. The seismic records obtained at other locations were not found to be of good quality. Though attempts were made to interpret these records the details of the ensuing interpretations are not presented here.

## Refracted signals

To interpret the seismic record, first of all the first arrival delay-times were plotted against the geophone distance to get the time-distance curve for the refracted waves (Fig. 2). In Fig. 2. it can be easily seen that there are two clear-cut velocity segments. The velocities of 3,220 m/sec and 4337.3 m/sec appear to be those of ice layer forming the shelf. The difference in the velocity arises due to compaction of ice giving rise to higher density that finally results in an increase in the velocity. The velocities of this order in ice have been reported by a number of workers like Bentley and Cheng (1971), Beitzel (1971) and Bentley (1971 a & b). The standard formula given by equation (1) below can be used to calculate the thickness of the layer with velocity 3,220 m/sec

$$h = \frac{T_i}{2} \frac{V_0 V_1}{\sqrt{(V_1^2 - V_0^2)}} \qquad ...(1)$$

where $h$ is the thickness of the first layer, $T_i$ is the intercept time given by (OB-OA) in Fig. 2, $V_0$ is the velocity in the top layer and $V_1$ is that in the second layer. As the value of $T_i$ was found to be 9 m from Fig. 2, the thickness *h* is given by:

$$h = \frac{.009}{2} \frac{4337 \times 3220}{\sqrt{(4337)^2-(3220)^2}} \quad ...(2)$$

Thus, the thickness of the top layer with velocity 3220 m/sec is found to be 21.63 m. After this depth the ice becomes compact enough to yield a much higher velocity.

**Reflection analysis**

The interpretation of reflection data needs precise knowledge of the velocities of various layers causing the reflections. As the logistic constraints did not permit us to complete a detailed seismic reflection survey, it was found to be rather difficult to determine the velocities of various layers precisely. An attempt, nevertheless, has been made to interpret the reflections from various layers by considering realistic models of the region and assuming the velocities of various layers in these models. We have considered two models. Various layers and the velocities assumed in these models are given below:

*Model A:* Ice layers (3320 and 4337 m/sec), Water layer (1487 m/sec), Glaciated sediments (2000 to 2500 m/sec), Basement (6000 m/sec).

*Model B:* Ice layers (3320 and 4337 m/sec), Water layer (1487 m/sec), Basement (6000 m/sec).

The results of 1-D numerical modelling of the seismic reflection data are shown in Figs. 3 and 4. As the first layer with velocity 3220 m/sec does not give zero intercept time, a thin top layer consisting of porous ice (density about 0.35 gm per cc and velocity 1350 m/sec) was included in the forward computations. The thickness of various layers obtained for the two models are shown below:

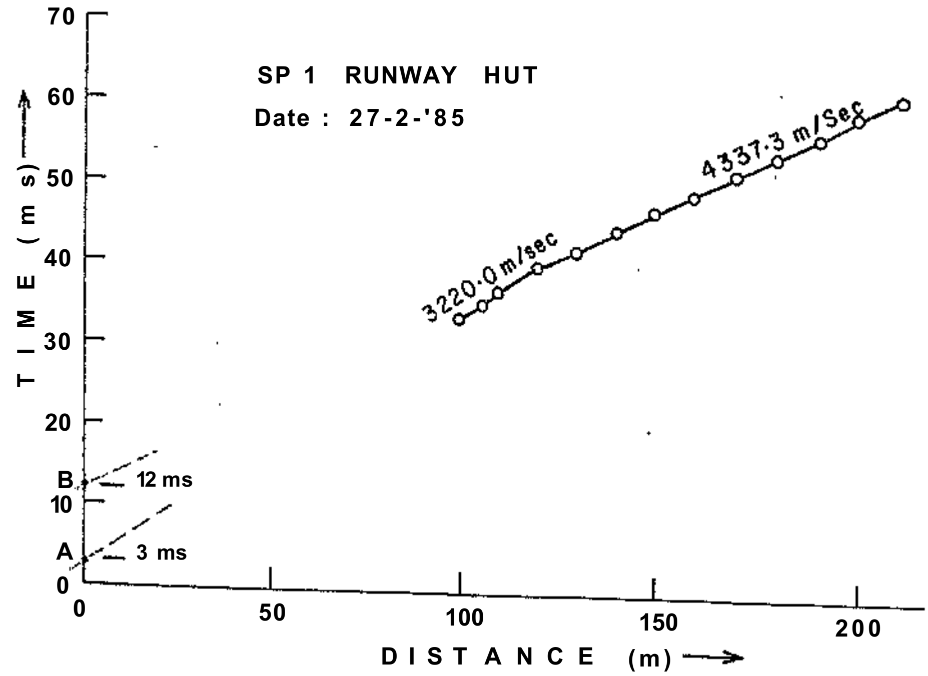



*Fig. 2.* Plot of delay time against the geophone distance.

**Model A**

| | | |
|---|---|---|
| Top porous ice layer | : | 1 m (velocity 1350 m/sec) |
| Unconsolidated ice layer | : | 19 m (velocity varying from 3100 to 3600 m/sec) |
| Consolidated ice layer | : | 395 m (velocity varying from 3600 to 4350 m/sec) |
| Water layer | : | 120 m (velocity 1485 m/sec) |
| Glacial sediments | : | 285 m (velocity varying from 2000 to 2500 m/sec) |

*Depth to the basement : 820 m*

**Model B**

| | | |
|---|---|---|
| Top porous ice layer | : | 1 m |
| Unconsolidated ice layer | : | 19 m |
| Consolidated ice layer | : | 395 m |
| Water layer | : | 285 m |

*Depth to the basement : 700 m*

(Note: Velocities of various layers in the two models are same).

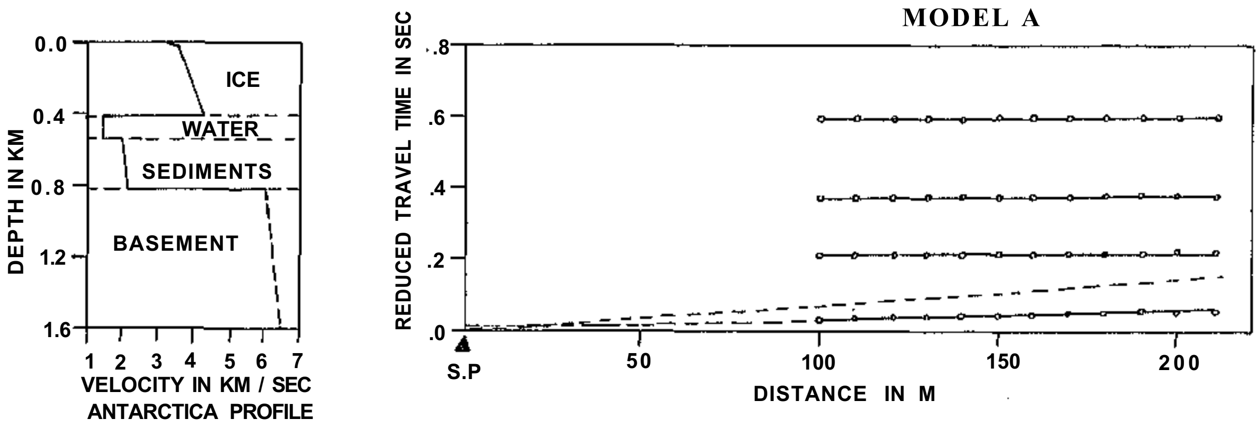



*Fig. 3.* Results of I-D numerical modelling of the seismic reflection data.

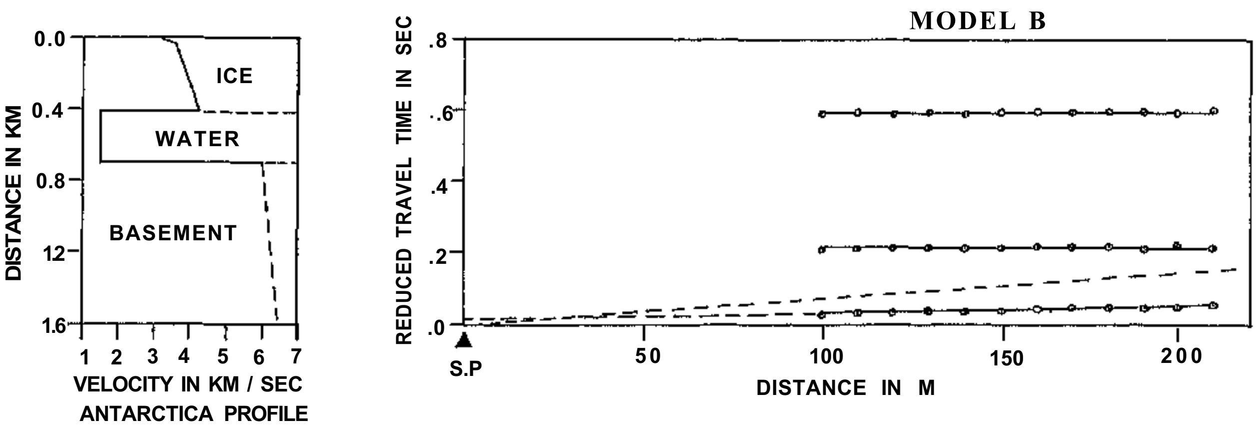



*Fig. 4.* Results of I-D numerical modelling of the seismic reflection data.

From the above tables it is clear that the ice in the shelf becomes compact enough to yield a high velocity at a relatively shallow depth of about 20 m. This conclusion is also supported by the time-distance curve obtained for the refracted signals.

The thicknesses obtained for total ice-layer (i.e., 415 m) and that for water layer (120 m for Model A and 285 m for Model B) also seem to be realistic as they are well supported by the results of the drilling on the ice-shelf in the adjoining region (Korotkevich, 1978). The results of the study by Korotkevich (1978) alongwith those obtained in the present study are shown in Fig. 5. The total thickness of the ice-shelf at the drilling site No. 1 (70°22'08"S, 12°21'04"E), No. 2 (70°13'02"S, 11°53'03"E) andNo. 3 (70°23'06"S, 11°39'06"E) were found to be 374 m, 357 m and 447 m respectively. While the water layer was absent at site No. 1, the thicknesses of the water layer at site Nos. 2 and 3 were found to be 203 m and 40 m respectively.

STRUCTURAL MODEL BELOW THE ICE-SHELF AROUND DAKSHIN GANGOTRI

The results of the long magnetic traverse taken on the ice-shelf (Verma, et al., 1987) have already revealed the presence of a 1850 m deep submarine valley (northern end of profile 8 in Fig. 11

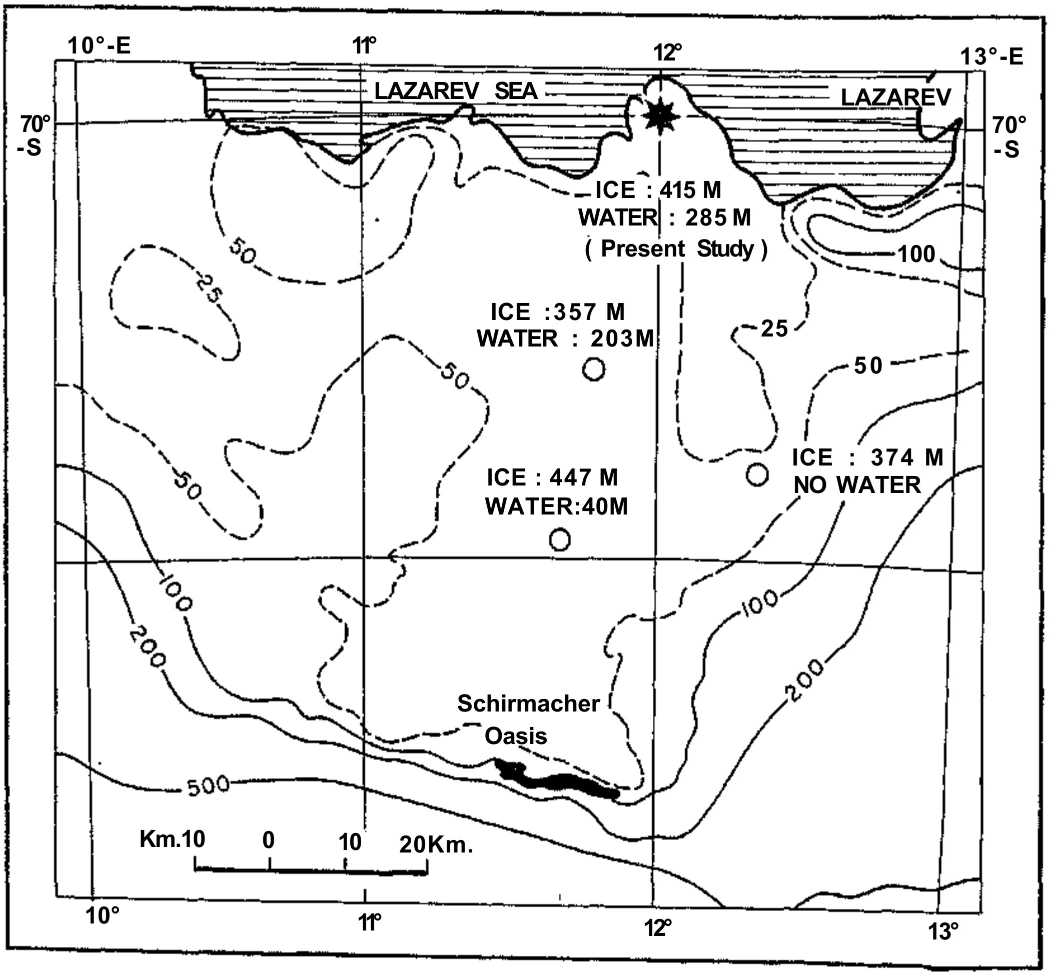



*Fig. 5.* Results of the drilling or various locations on the ice shelf alongwith the results of seismic interpretation obtained for Model B (present analysis).

of Verma, et al., 1987). An examination of the Fig. 11 (In Verma et al., 1987) immediately reveals that the Runway Hut, from where the seismic reflection record presented in this study was obtained, lies on the northern flank of the submarine valley. The depth of 820 m obtained for the top of the basement (for Model A) or 700 m (for Model B) seems to be reasonable enough for the flank of the valley.

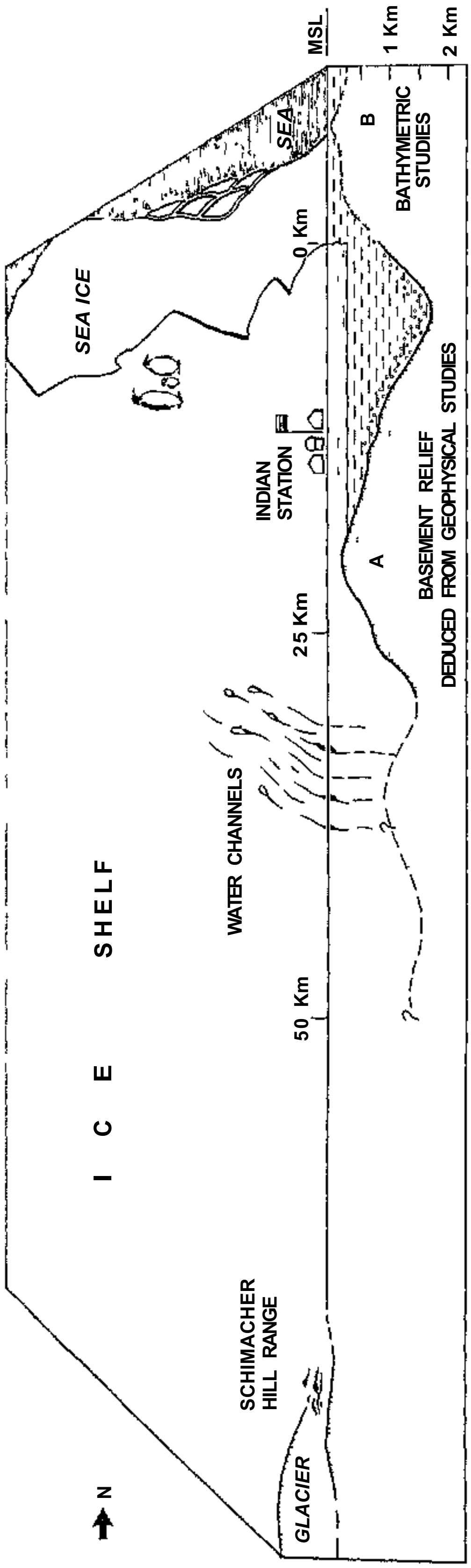
The ice-shelf of an average thickness of 400 m (Korotkevich, 1978 and the present study-Fig. 5), on which the Indian station Dakshin Gangotri is located, is virtually floating over the submarine valley. About 30 km south of the ice-coast, this sheet is found to be resting on the peak of a subsurface hill A that rises as close as 300 m from the surface of the ice-shelf. On the northern side (*i.e.* towards the sea) the sheet forming the ice-shelf extends almost to the bathymetric high associated with the submarine ridge B that rises to within 100 m from the sea surface and runs approximately E-W, parallel to the ice-coast in the region. This model, showing the thickness of the shelf and the structure below the shelf, is shown in Fig. 6.

The structural model depicted in Fig. 6 provides a clue to the presence of water channels occurring at about 35 km south of the ice-coast. As the floating ice-sheet is pivoted against the basement hill A in the south and is open to the sea in the north, sufficiently strong vertical movements are produced in it by the large rolling waves (swell) caused by typical Antarctic weather disturbances. These movements create enough stress in the ice further south of the hill causing deep cracks. A sudden depression in the basement south of the hill is perhaps also associated with the fault system running E-W (Kogan, 1972) in the region. The presence of this fault system could play sympathetic tectonic role in creating the cracks in the ice-shelf. During Antarctic summer, these cracks melt to form lakes and water channels (almost like rivers, 50 to 100 m wide at places, with flowing crystal clear unpolluted water) in the region. Some of these water channels are quite deep and might be connected even with the sea water occurring at a depth of about 450 m. These water channels make a direct access to Schirmacher Hills from the Indian station on ice almost impossible during the summer season.

The above model also explains the exceptionally slow drift rate of the ice-shelf around the Indian station. The Antarctic glacier about 2 km in thickness, stretches 4000 km across, covers more than 95% of the continent, and flows outward to the ocean. The rate at which this glacier is moving outward has been found to be as high as 2 to 2.5 km per year at some places. Compared to this, the ice-shelf around the Indian station is very stable with a drift rate of only 40 to 50 m per year (Sharma, 1986). This slow rate could be ascribed to the presence of the Schirmacher Hill range, which bears the main thrust of the southerly glacier. The movement of the ice-shelf north of the Schirmacher Hills is further retarded due to the submarine hill delineated by the geophysical studies. On the northern side, the submarine ridge B running parallel and very close to the ice-coast, not only halts the further northward movement of the ice-shelf but also provides a barrier to the icebergs that separate from the shelf and try to move north in the open sea. This is well reflected by the two high mounds of grounded ice that lie on eastern (Leningradkollen height 120 m above m.s.l.) and western (Kuvkiaken, height 80 m above m.s.l.) sides of the Indian station and by a number of E-W aligned large icebergs close to the ice-coast.

## CONCLUDING REMARKS

The first-ever seismic study under the Indian Antarctic research programme in conjunction with the results of the magnetic surveys has successfully yielded the structure below the ice-shelf on which the Indian station, Dakshin Gangotri is located. The experience gained in respect of the type and the quality of the explosives, performance of recording media etc., will be valuable from the point of view of future seismic investigations in Antarctica.




Ag. & Structural model around the Indian permanent station on the ice-shelf in Antarctica.

An attempt has been made to evolve a model that yields not only the structure below the ice-shelf but also explains certain other geomorphological features in the region. It must be emphasised here, though, that the conclusions arrived at in this study are based on certain assumptions to provide a meaningful interpretation to the seismic reflection data. Alternative assumptions can always be made to provide a different interpretation and as such the results presented in the paper are not unique. The objective of the seismic investigations during the Fourth Indian expedition was to examine the feasibility and efficacy of seismic reflection surveys in studying the structure of the ice-shelf. The results of the present study show that such studies are very useful and can provide valuable structural information.

## ACKNOWLEDGEMENTS

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## REFERENCES

Beitzel, J.E. 1971. Geophysical exploration in Queen Maud Land, Antarctica. In:*Antarctic Snow and Ice Studies II,* edited by A.P. Crary, published by AGU, p. 39-88.

Bentley, C.R., 1971a.Seismic evidence for moraine within the basal Antarctic ice-sheet. IN:*Antarctic Snow and Ice Studies II,* edited by A.P. Crary, published by AGU, p. 89-130.

Bentley, C.R., 1971b. Seismic anisotropy in the West Antarctic ice sheet. In:*Antarctic Snow and Ice Studies II,* edited by A.P. Crary, published by AGU, p. 131-178.

Bentley, C.R. and F.K. Cheng, 1971. Geophysical investigation in Mary Byrd Land, Antarctica. In: *Antarctic Snow and Ice Studies II,* edited by A.P. Crary, published by AGU, p. 1-38.

Kogan, A.L., 1972. Results of deep seismic soundings of the earth's crust in east Antarctica. In: *Antarctic Snow and Ice Physics,* Universitetsforlaget, Oslo, p. 485-489.

Korotkevich, V.S., 1978. Drilling through the ice-shelf in the vicinity of Novolazarevskaya. *Annual Scientific Reportion Antarctic Studies of USSR,* p. 50.

Sharma, S.S.,1986. A study of Dakshin Gangotri ice-shelf. *Scientific Report on the Third Indian Scientific Expedition to Antarc tica,* Department of Ocean Development, New Delhi, India, p. 243-248.

Verma, S.K., G.S. Mital, H.V. Rambabu, M. Venkatarayudu and K.N. Srinathareddy, 1987. Magnetic survey over the ice-shelf around the Indian permanent station in Antarctica (In this Report).