# Deep probing through ground penetrating radar (GPR) – Case study from Antarctica

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**Abstract**

Ground Penetrating Radar has emerged as an important tool for subsurface investigation in recent years. It is being used in many investigations ranging from Engineering Projects like bridges, tunnels, and dam constructions to detective projects including search for dead bodies. Most of the GPR studies are concerned with shallow depth (near surface to 3 meters) investigation because of its high resolution. But the most serious scientific application of this Ground Penetrating Radar instrument is being done in the field of glaciology. A method developed by the author suggests that the GPR survey can be performed by using multiple low frequency (MLF) antennas with a range of 16 to 80 MHz frequency in continuous mode. This method can be applied by the use of a platform with fixed interchangeable positions for Transmitter and Receivers to be kept at a fixed separation during survey depending upon the depth of penetration. This method was tested in and around Schirmacher Oasis, East Antarctica to delineate the interface between the water column and bedrock in the Polar lakes and between the ice and bedrock below the Polar Ice sheet and deep probing of the Polar ice thickness could be investigated. On the ice track between the Schirmacher Oasis and Wohlthat Mountains, deep probing for bedrock below the Polar ice sheet indicates that the ice thickness is more than 500 meters at most of these places. The data is validated with the information obtained from the Project Bedmap2. With an error of 2 – 8 %, GPR can be used for deep probing in glaciated terrains.

## 1. Introduction:

There are many methods available to detect subsurface materials. Depending upon the requirement of the survey, the depth conditions are categorized into very shallow, shallow, deep and very deep conditions. For Engineering projects, very shallow depths are considered for the depths below 0.3m (1'), shallow conditions are for the depth below 3m, deep conditions are for the depths below 30m and the very deep conditions are for the depths more than 30m (Figure 1).

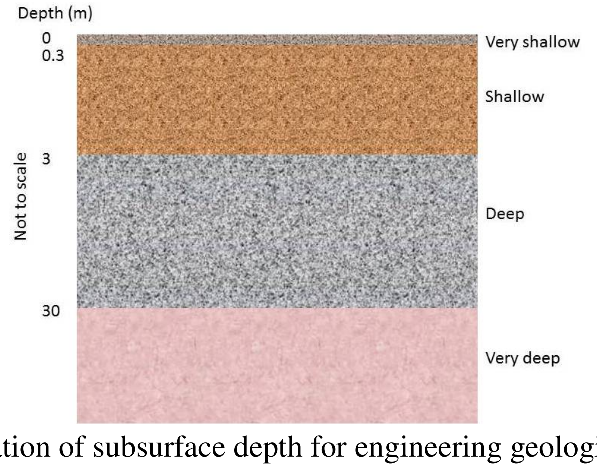


Figure 1 Classification of subsurface depth for engineering geological investigations

There are many resources and methods available for deep probing. These include Airborne geophysical methods and remote sensing technologies, Electromagnetic three-dimensional deep probing technologies and methods, Induced polarization methods, Seismic methods, The joint inversion of gravity, magnetic, electric and seismic methods, 3-dimensional forward and inversion and interpretation technologies, Air drilling, in-situ measurement from boreholes, Ground Penetrating Radar and many other methods. Some of these methods deploy a large quantity of manpower to run the instrument and some others are too expensive to deploy making the survey to have a wide variation in the cost of the operation per km. In a similar way, some instruments involve a fraction of second per km of survey, while some other methods require hours together to complete a km of survey. A comparative study involving the relationship between the cost and the time per km of survey indicates that the Airborne geophysical methods and remote sensing methods takes very less time to conduct the survey, but the cost of the operation is too expensive (Figure 2). In the other hand, Resistivity, Magnetic and seismic methods may be less expensive, but requires more manpower and duration per km of survey (Figure 2). Ground Penetrating Radar (GPR) instruments are comparatively less expensive compared to the former methods and comparable to the cost mentioned in the later methods, but the time required per km of survey is far less than the later ones (Figure 2).

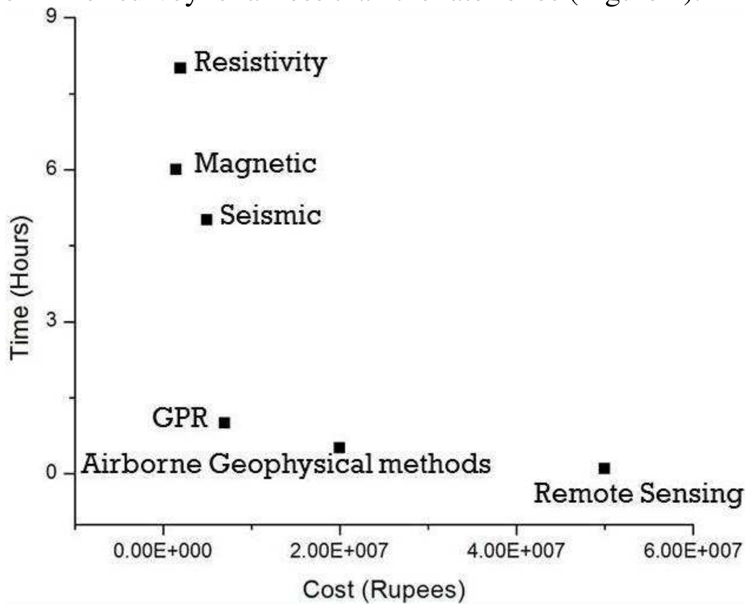


Figure 2 Graph showing the cost versus time required per km of survey shows that the airborne geophysical methods and remote sensing methods are highly expensive, but requires very less time, whereas resistivity, magnetic and seismic methods are less expensive, but requires a longer duration. GPR survey is compared to the later ones for the cost, but requires sufficient less time to conduct the survey per km of survey.

In this regard, the role of GPR is crucial. It has many applications. GPR is being used for numerous military and civil applications, including in ground investigations, normally from the near surface to a depth of several tens of meters including detection of mines, unexploded ordnance, and tunnels. In the recent times GPR systems have become one of the important geophysical tools that are being used for a variety of geological, engineering, environmental and archaeological applications. In environmental remediation, GPR is used to define landfills, contaminant plumes, and other remediation sites, while in archaeology it is used for mapping archaeological features and cemeteries. Engineering applications include non-destructive testing (NDT) of structures and pavements, locating buried structures and utility lines, and studying soils and bedrock.

Ground Penetrating Radar has emerged as an important tool for subsurface investigation in recent years. It is being used in many investigations ranging from Engineering Projects like bridge, tunnel, and dam constructions to detective projects including search for dead bodies (Swain and Shrivastava, 2013). The range of its application varies from detecting Temple foundation (Swain and Thapliyal, 2013) to solving the mystery of cross-border tunnels. Most of the GPR studies are concerned with shallow depth (near surface to 5 meters) investigation because of its high resolution. But the most serious scientific application of this Ground Penetrating Radar instrument is being done in the field of glaciology (Swain, 2018; Swain and Chandra, 2017; Swain and Goswami, 2014; Swain et al., 2018).

Normally most of the glaciological investigations are concerned with high frequency antennas, which can run in continuous mode and deliver high resolution subsurface information. In this regard, the low frequency antennas are deployed for deeper penetration, but yield result in low resolution and the work can be done in point mode of survey. A method developed by the author suggests that the GPR survey can be performed by using multiple low frequency (MLF) antennas with a range of 16 to 80 MHz frequency in continuous mode (Swain and Goswami, 2014). In this paper, the capabilities of GPR towards the estimation of the depths and its validations are discussed.

## 2. Location:

The coldest and driest continent Antarctica is surrounded by Southern Oceans, viz. Southern Pacific, Atlantic and Indian oceans. Around 98% of the total area of Antarctica is covered by ice with average thickness of 2.4 km (source: British Antarctic Survey). It is divided into two by Trans-Antarctic Mountains, viz. west and east Antarctica. East Antarctica lies in the Indian Ocean side and form the largest source of snow and ice with a number of basins, separated by ice drainage divides (Rignotet al., 2008). The Schirmacher Oasis, a small nunatak (ice free area) is situated on Princess Astrid coast in cDML, which is one of the important basins amongst all basins of East Antarctica. It is surrounded by the Polar ice sheet/ East Antarctica ice sheet (EAIS) to its south and the Novolazervaskaya / Nivlisen ice shelf as well as many Epishelf lakes to its north (Figure 3). The Novolazervaskaya / Nivlisen ice shelf lying to the north of the Schirmacher Oasis is an extended portion of the Polar ice sheet that is flowing above the oceans. At least two ice rises are observed in this ice shelf. The erstwhile Indian Antarctic station, Dakshin Gangotri was located on this ice shelf during the time of its operation. The line beyond which the Polar ice sheet crosses the bedrock below it floats above the ocean, but cantilevered to it is called the Grounding Line (Figure 3).

The Polar ice sheet lying to the south of the Schirmacher Oasis is very important location due to its vast expanse till the Wohlthat Mountains. A small part of the Polar ice sheet lying adjacent to the Schirmacher Oasis has low elevation, but a large part of it lying close to the Wohlthat Mountains towards the Schirmacher Oasis shows a gentle but gradual slope. A narrow zone lying in between these two areas show moderate slope (Figure 4). Detailed study to estimate the depth of the Polar ice sheet was not undertaken till recently, for which the work was initiated during 2016. Before the starting of the work, a route was planned to be undertaken by satellite imagery studies (as marked by continuous red line in Fig. 4). But, due to the movement of the Polar ice sheet crevasses were found to have opened up along some part of the proposed route. In this regard, a new route was taken for the survey (marked by continuous yellow line in Figure 4), part of which coincides with the route undertaken by the first South Pole Expedition (Swain and Chandra, 2017).

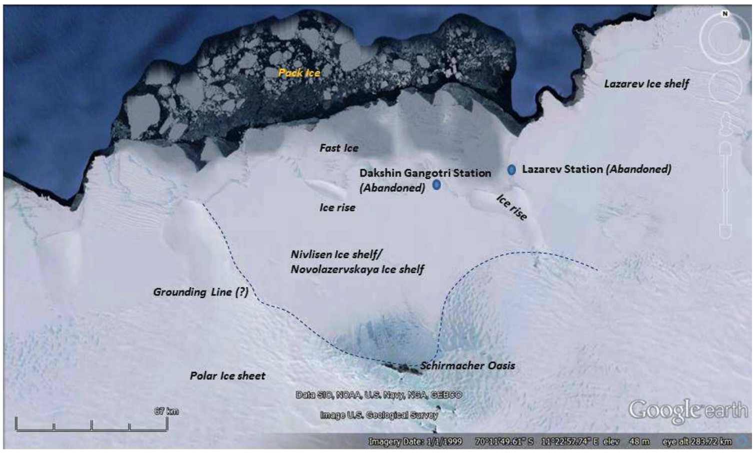


Figure 3 The Google imagery showing the expanse of the area around Schirmacher Oasis

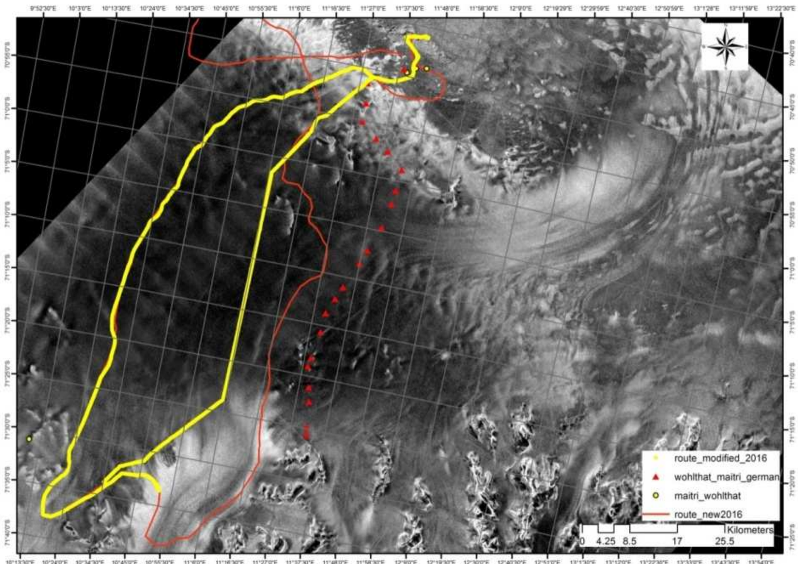


Figure 4 The proposed and the executed ice track between the Schirmacher Oasis and Wohlthat Mountains undertaken by the author for estimating Polar ice thickness.

## 3. Methodology:

GPR technique is based on the use of high frequency radio signals (EM waves),which are artificially produced by a device which are sent down into the ground by antennas (transmitters) and the reflected signals are captured through a device known as receiver. This technique uses electromagnetic radiation in the microwave band (UHF/VHF frequencies) of the radio spectrum. Time taken by a pulse to travel to and from the target indicates its depth and location. The quality of the GPR depends upon the electrical properties of Geological Media (Table 1).

Table 1
Electrical properties of geological media for GPR survey.

| Material | Dielectric constant | Conductivity (mS/m) | Velocity (m/ns) | Attenuation (dB/m) |
|---|---|---|---|---|
| Air | 1 | 0 | 0.3 | 0 |
| Distilled water | 80 | 0.01 | 0.033 | 0.002 |
| Fresh water | 80 | 0.5 | 0.033 | 0.1 |
| Sea water | 80 | 30,000 | 0.01 | 1000 |
| Dry sand | 3.5 | 0.01 | 0.15 | 0.01 |
| Saturated sand | 20-30 | 0.1-1.0 | 0.06 | 0.03-0.3 |
| Limestone | 4-8 | 0.5-2 | 0.12 | 0.4-1 |
| Granite | 4-6 | 0.01-1 | 0.13 | 0.01-1 |

The depths to which the GPR instruments normally penetrate are based on the Antenna frequency. The application of the GPR also requires the choice of antennas for the required survey (Table 2).

Table 2
The choice of antenna with its appropriate application and the approximate depth range

| **Appropriate Application** | **Primary Antenna Choice** | **Secondary Antenna Choice** | **Depth Range (Approximate)** |
|---|---|---|---|
| Structural Concrete, Roadways, Bridge Decks | 2600 MHz | 1600 MHz | 0-0.3 m (0-1.0 ft) |
| Structural Concrete, Roadways, Bridge Decks | 1600 MHz | 1000 MHz | 0-0.45 m (0-1.5 ft) |
| Structural Concrete, Roadways, Bridge Decks | 1000 MHz | 900 MHz | 0-0.6 m (0-2.0 ft) |
| Concrete, Shallow Soils, Archaeology | 900 MHz | 400 MHz | 0-1 m (0-3 ft) |
| Shallow Geology, Utilities, UST's, Archaeology | 400 MHz | 270 MHz | 0-4 m (0-12 ft) |
| Geology, Environmental, Utility, Archaeology | 270 MHz | 200 MHz | 0-5.5 m (0-18 ft) |
| Geology, Environmental, Utility, Archaeology | 200 MHz | 100 MHz | 0-9 m (0-25 ft) |
| Geologic Profiling | 100 MHz | MLF (16-80 MHz) | 0-30 m (0-90 ft) |
| Geologic Profiling | MLF (16-80 MHz) | None | 30 m (90 ft) |

The higher antenna frequency of the GPR instruments shows a good resolution, but the depth of the investigation is less. It is applied for the works as mentioned in Table 2. In Antarctica, the GPR profile obtained by using 200 MHz shows good resolution, which can be utilized to undertake the survey for estimating the lake depths of the Polar Lakes (Figure 5). When the GPR antenna frequency is lowered, the depth of investigation increases, but the resolution is getting poorer. The lower frequency range in between 16 to 80 MHz penetrates to a deeper level, but the data used to be taken in point-mode. The continuous profiling was not possible earlier. Slightly deeper penetration was possible by using 100 MHz antenna frequency in bi-static mode (Figure 6). For deeper penetration, a method developed by the author suggests that the GPR survey can be performed by using multiple low frequency (MLF) antennas with a range of 16 to 80 MHz frequency in continuous mode (Swain and Goswami, 2014). This method can be applied by the use of a platform with fixed interchangeable positions for Transmitter and Receivers to be kept at a fixed separation during survey depending upon the depth of penetration (Figures 7a,7b, 7c, 7d). Another technique involves fixing the Transmitter and Receiver at a fixed position at the front and rear side of the snow vehicles and survey wheel attached to the unit for keeping track of the distance, which was exclusively used during first Indian Scientific Expedition to South Pole by the author(Figure 8) (Swain, 2010).

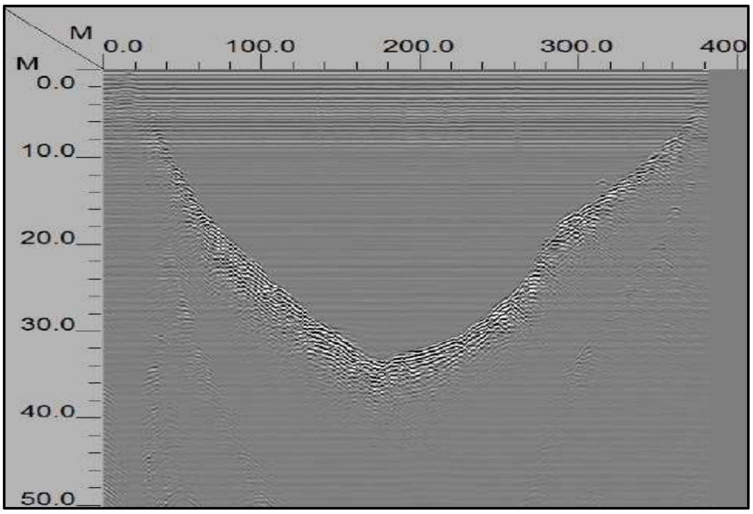


Figure 5 A GPR Profile with 200 MHz frequency

Figure 6 100 MHz antenna has facility for using it as transmitter and receiver separately or as trans-receiver type

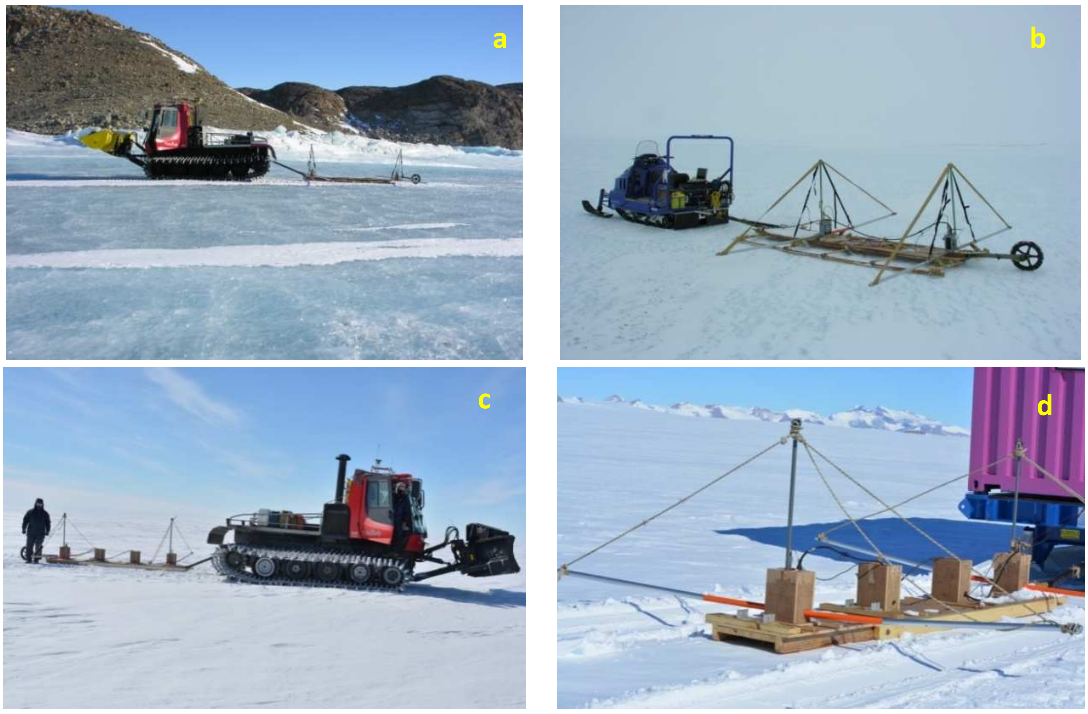


Figure 7a Testing of the methodology and the antenna arrangement over a Polar lake in Schirmacher oasis, East Antarctica to delineate the interface between the water column and bedrock. Figure7b Testing of the methodology and the antenna arrangement over the Polar ice sheet near Schirmacher oasis, East Antarctica to delineate the interface between the ice and bedrock. Figure 7c Method developed by the author for the use of a platform with fixed interchangeable positions for Transmitter and Receivers during GPR survey using snow mobiles over the Polar ice sheet in East Antarctica. Figure 7d Method developed by the author for the use of a platform with fixed interchangeable positions for Transmitter and Receivers during GPR survey depending upon the depth of penetration.

Figure 8 Method developed by the author for fixing the Transmitter and Receiver at a fixed position at the front and rear side of the snow vehicles and survey wheel attached to the unit for keeping track of the distance, which was exclusively used during first Indian Scientific Expedition to South Pole.

## 4. Results and Discussions:

Though the resolution is poor by using MLF antenna ranging from 16 to 80 MHz frequency, but it can be able to penetrate to a deeper level. The Polar ice sheet thickness estimation survey during 2016-17 shows an ice thickness of more than 420 to 580m (Figure 9a). Wherever the thickness was more than 580m, the interface between ice-bedrock could not be obtained as it has reached the optimum level in that condition. During a recent 6.4 km long survey using MLF antenna with 35 MHz frequency, antiform and synform features are observed in the snow layers up to 40 m (Figure 9b).

To validate the data, the area was compared with the data obtained through Bedmap2 project. Thickness map of ice cover generated using Bedmap2 data indicates that the thickness is maximum of the order of 1200 m to 1700m in central part of the of the study area whereas the northern part shows thin ice cover of the ice sheet that range up to a maximum of 722m (Figure 9c). The range of the depth estimated by Bedmap2 project is shown by double arrow line, and the average is by a filled square in Fig. 10a. Both of the depth estimations are comparable with the errors ranging from 2.8 to 8 %. The lower the depths, the error percentage is less and vice versa (Figure 10b).

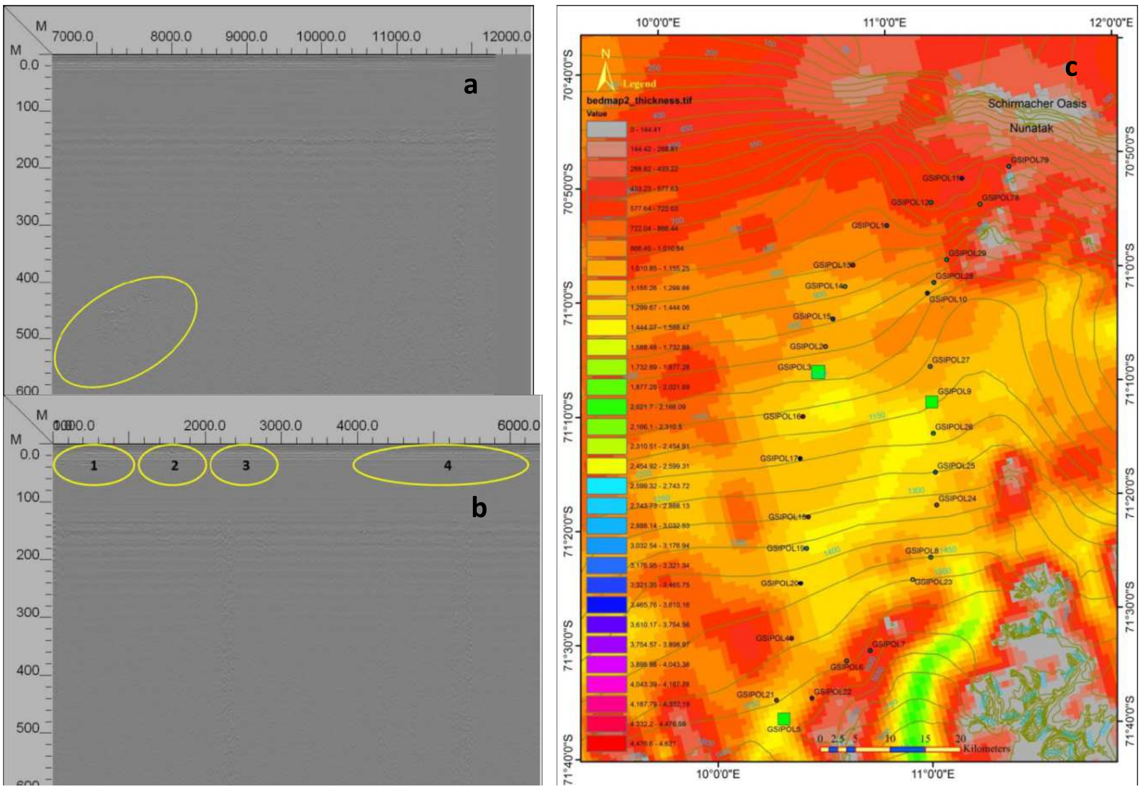


Figure 9a A 6 km long GPR profile using MLF (35 MHz) antenna showing the bedrock at the depth of 420-580 m. Figure 9b A 6.4 km long GPR profile using MLF (35 MHz) antenna showing snow layers up to 40 m depth forming an antiform and synform features. Figure 9c Ice sheet thickness map of entire area with superimposed contour map of the study area derived from Bedmap-2 data.

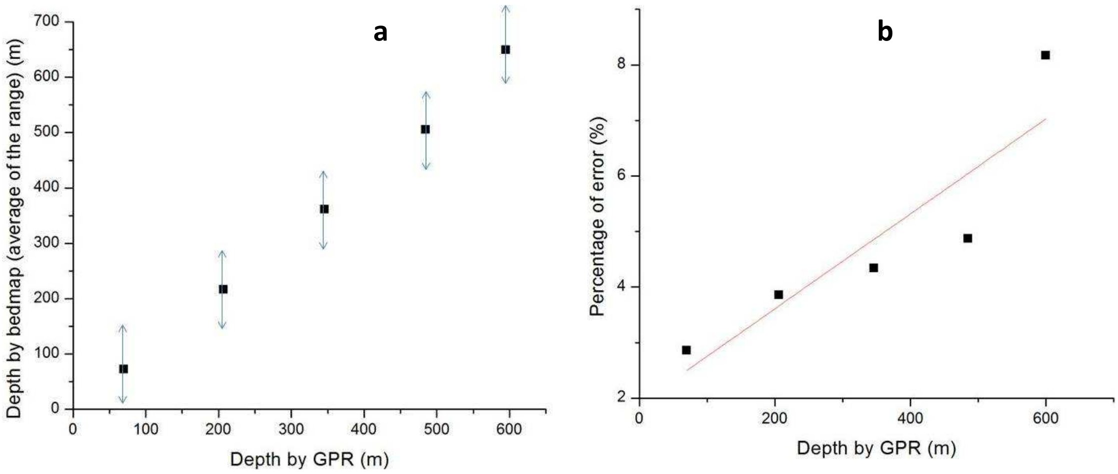


Figure 10a Graph showing the comparison of the depth estimated by GPR and the depth estimated by Bedmap2 project. The range of the depth estimated by Bedmap2 project is shown by double arrow line, and the average is by a filled square. Figure 10b Graph showing the depth estimation by GPR versus the percentage of error as compared to the depth estimated by the Bedmap2 project.

## 5. Conclusions:

There are many limitations in GPR methods. Some of these limitations include its dependence upon the dielectric contrast between the mediums, Presence of en-glacial boulders resulting in the ambiguities in interpretation of data, Presence of en-glacial channels within the glacier, Presence of high-conductivity materials such as clay soils and contaminated soils, especially for geological investigations, Signal scattering in heterogeneous conditions, the radio signal contamination due to other signals including transmission lines, mobile towers etc. But in spite of these, this method of GPR investigation is cost and time effective as compared to the other methods which are either very expensive or it takes longer duration per km of survey. Higher GPR antenna frequency provides good resolution. But the lower antenna frequency in the range of 16 to 80 MHz described by the method of Swain and Goswami (2014) can be used to help in deeper penetration with a comparable resolution to estimate the subsurface interface. When the depth of the interface is more, the error is higher as observed by an error up to 8% up to a depth of 600m. But the lower depths reduce the error considerably. From these points, it can be concluded that GPR method can be used for deep probing of any Engineering geological investigations.

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