

Seismic imaging of glaciomarine sediments of Antarctica: Optimizing the acquisition parameters

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This paper presents some of the significant points on the designing and acquisition parameters for multi-channel seismic reflection survey in the Antarctic waters with an emphasis of imaging Glaciomarine sediments. Due to their importance in unravelling the paleoclimatic clues, we stress on the practical aspects of seismic data acquisition focussed on targeting glaciomarine sediments on the Antarctic margin. We carried out extensive forward modelling exercise assuming sub-surface model parameters from the published literature pertaining to the Eastern Antarctic Margin (EAM). The reason for choosing this area is that the Prydz Bay sector of EAM has been known to have undergone huge glacial sediment accumulation in the past due to its contiguity with the Amery Ice Shelf. In this article we suggest the best suited acquisition parameters for collecting high quality multi-channel seismic data in order to image the Glaciomarine sediments in this region.

[Key words: Antarctic, Glaciomarine sediments, Prydz Bay, Seismic reflection].

Introduction

The Antarctic Ice Sheet and the ocean surrounding it play an important role in the global climate regime from the early Cenozoic. However the precise role of the Antarctic Ice Sheets especially of the East Antarctic Sheet remains a matter of intense academic debate. The primary reasons for this uncertainty are the lack of knowledge of the spatial extent of the ice sheets during the periods of glacial maxima, and high-resolution proxy records from marine sediments. The above parameters can unambiguously be correlated to short-term changes in global ice volume¹. Deposits and landforms on land can provide a detailed history of Antarctic climate. However, their nature is poorly preserved and difficult to correlate². Therefore, it is imperative to look for constraints elsewhere in the geological record.

This study presents discussions on the reflection signature of the glaciomarine sediments of the continental slope and rise off Prydz Bay in east Antarctica in terms of depositional processes. The present study is based on synthetic seismogram modeling using finite difference algorithm. The sub-surface geology of the Prydz Bay continental margin is assumed. The synthetic sections have been generated by varying sub-surface features as well as

the acquisition geometry. This is compared here to understand the best-suited acquisition parameters in such environments.

Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) on the Antarctic continental margin have revealed the presence of glaciomarine sequences in Antarctica. A few studies have concentrated on the slope and rise sequences off Prydz Bay. The extent of glaciomarine sediments remains uncertain because of severe sea bed multiples causing problems with correlating seismic sequences across the outer shelf. Earlier studies have defined³⁻⁵ five sedimentary sequences on the continental slope and rise and interpreted the uppermost sequence as turbidites and hemipelagic sheets of Pliocene and younger age. They interpreted complex stratification of the shallowest sediments to be a result of deposition from down slope turbidity currents interacting with bottom currents. In the past it has been established that the seismic data can be used to image the glaciomarine sediments in the Antarctic waters. The present study is based on synthetic seismogram modeling using finite difference algorithm. Synthetic seismic sections are generated by varying sub-surface features as well as the acquisition geometry.

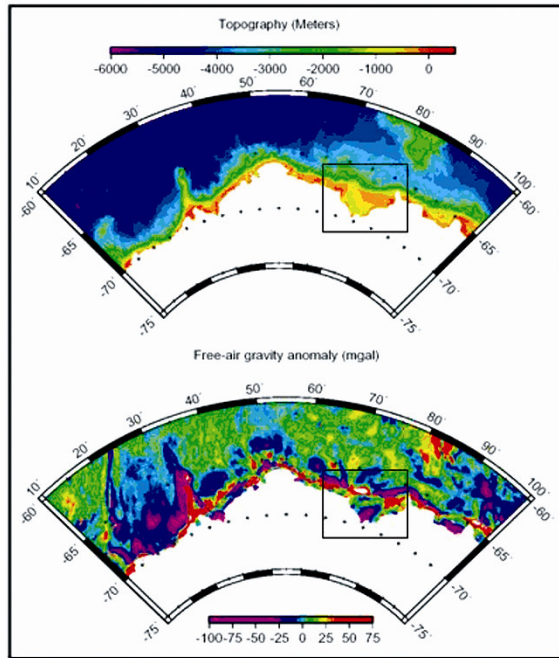


Fig. 1—Location map of Prydz Bay (in box) region, Antarctica. The top map represents the topography whereas the lower map shows the Free-air gravity anomaly map of East Antarctica.

Geology of Prydz Bay Area

Prydz Bay (Fig. 1) is situated on the Antarctic continental margin adjacent to the Southern Indian Ocean between 66°E and 79°E. The Prydz Bay region constitutes a dominantly north–south structural depression. This arose as an aulacogen within the triple junction formed due to rifting between India and Antarctica in the Late Palaeozoic and Early Mesozoic^{3,4}. Prydz Bay marks the seaward end of the Lambert Graben, a major structural feature, which allows access of marine waters into the East Antarctic interior, particularly during periods of reduced ice-sheet volume. The Lambert Graben–Prydz Bay basin is about 900 km long and progressively narrows (from 1000 to 50 km) and deepens (from 200 to 1600 m below sea-level) farther inland^{6–8}. The glaciomarine sediments in this region have been reported to rest unconformably on Proterozoic metamorphic basement⁴. Permian and Mesozoic continental deposits initially accumulated on this surface within a rift basin. The region is heavily glaciated, the Lambert Graben being fully covered by the Amery Ice Shelf⁹ north of a grounding line at *c.* 73°40'S. This ice shelf is fed by the Lambert Glacier and numerous tributary glaciers, which together drain

13% (by surface area) of the EAIS, the largest catchment area in East Antarctica.

It has been suggested that the glaciomarine sediments in Prydz Bay were deposited mainly during glacial periods. Glaciation in Prydz Bay probably commenced at ~40 Ma, when Antarctica changed from being essentially ice-free to having a large ice sheet. Many a times the seismic reflection profiles over such regions do not have sufficient resolution to distinguish the seismic stratigraphy of glacial and inter-glacial periods. The sediments above top most reflectors on the continental rise in Prydz Bay have a maximum thickness of 2100–2200 m, which exceeds the same in the Weddell sea by almost a factor of two. However, as the Lambert glacier has the larger drainage area, a higher sediment input is reasonable in the Prydz Bay area. Seismic reflection data does not allow any definitive statements about the orientation of the deposits, but if the observed sediment ridges correlate they are elongated oblique to the continental margin. The orientation of the large sediment ridge in a particular study area can be explained by its close association to the shelf margin of a large channel. In the Prydz bay area, this channel can be followed from the shelf edge to the continental rise. The combination of well-developed levees and contourite like deposits on the margins, may suggest that bottom currents have been active in the area.

Depositional units within Antarctic waters have been identified from seismic data^{3,4,10–14}. The seismic reflection pattern on the Antarctic shelf is characterized by a seaward prograding sequence overlain by an upper unit up to 300 m thick consisting of chaotic and sometimes continuous flat lying reflectors. The depositional units often comprise of several facies such as:

- a) Well-stratified reflectors showing cut-and-fill features, interpreted as channel levee systems.
- b) Large scale mounded stratified facies are also observed which form large scale sediment ridges and is characterized by internal well-stratified gently to steeply dipping reflectors.
- c) Well known contourite drifts, resulting from current influenced sedimentation.

Most of these different sequences can be mapped using seismic reflection data depending upon the thickness and the impedance contrasts among different depositional environments.

Materials and Methods:

The present study takes a holistic approach to work out the desired acquisition parameters for any such seismic data acquisition. The results of synthetic modelling presented in this article have been carried out using various different methods. For modelling the source acquisition parameters, publicly available software *SEISAC* was used. The synthetic seismograms have been computed using the finite difference modeling algorithm of standard seismic data processing software *ProMAX*. Most of the computing has been done in CDP domain. Some of the key parameters that decide the data acquisition are:

The source parameters

Following are the important consideration for the source configuration before the survey:

- Source depth, which is a parameter for the airgun source at sea.
- Source power, which governs the frequency of the signal
- Source signature

Receiver parameters

The parameters related with the signal detection have effect on the temporal as well as the spatial character of the measurement. The first choice is obviously on the detector type. The response of the receiver at low frequencies is important. Hydrophones have a resonance frequency and below resonance the response decays at about 12 dB/octave. High-frequency phones are used in shallow seismic survey in order to boost the recording of high frequencies.

The next important parameter is the receiver spacing. This parameter is determined by the spatial-aliasing concept. Spatial aliasing occurs when the distance traveled by the wave to reach from one receiver to the next is more than half the smallest wavelength. There are some parameters in this description: the angle with which the wave impinges on the surface; the smallest wavelength, which depends on the highest frequency and the velocity. The highest frequency is determined by the sampling rate and the angle of incidence and the velocity are to be determined either from earlier surveys in that area, or from areas with the same circumstances. The receiver spacing is determined by the maximum wave

number in the data. A typical marine seismic data acquisition diagram is shown in Fig. 2:

Defining the sub-surface model

The following sub-surface model based on the data collected from the published literatures around Antarctic waters has been utilised for the modelling. It consists two Glaciomarine sedimentary layers (as labelled GS1 and GS2 below) beneath the seafloor in order to observe the effect of acquisition parameters in the seismic data.

The basic hypothesis while choosing the above model is that the seismic survey should be designed in such a way to produce a good quality image of the two Glaciomarine sequences (comprising of a mixture of turbidites and bottom current influenced sediment deposits) having different physical properties. Most of the commonly used parameters have been taken from¹⁵ demonstrate a good use of the seismic data from Antarctic waters.

The first and the top most layer in the model comprises of sea-water with 500-800 m deep seafloor. The velocity of sound in water has been taken as 1500m/s. Below the sea-floor, two glaciomarine sedimentary deposits GS1 and GS2 have been assumed with the respective thickness ranging from 400-600 m and 100-200 m, with velocity varying from 1700-2100 m/s and 2300-2600 m/s. The sedimentary layers in the model have been underlain by a basement with velocity of 3000 m/s. The source and streamer both are floating in the water throughout the modelling. .

Modelling steps

Modelling has been divided into following main parts comprising:

- Source parameter modelling
- Estimation of ghost arrivals
- Frequency and offset of recording

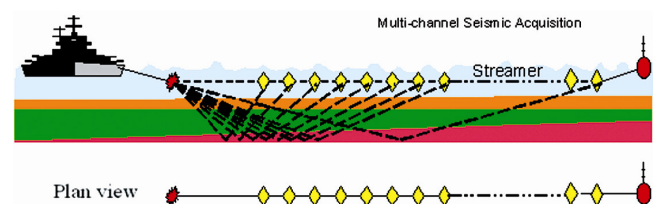


Fig.2—A typical multi-channel seismic acquisition setup where sources and receivers are towed behind the ship.

Source parameter modelling

Specifying the energy source is a major part of planning a seismic survey. The proper selection of source directly affects both the data quality and the survey costs. In general, larger sources (airguns in this case) produce more usable energy (but lower frequencies) than smaller sources.

The signal from a single airgun has typically a length of few hundred milliseconds. Mostly the target of the seismic surveys is creating a short seismic signature, preferably close to a band-limited delta pulse. This is the main reason why arrays are used. Airguns of different sizes and at different distances from each other are used such that the first pressure peaks coincide but the other peaks cancel, i.e., destructive interference for the other peaks. The quality of source is measured in terms of two commonly used terminologies: Peak-to-Peak (PTP) strength and Primary-to-Bubble (P/B) ratio. PTP is the distance between the two major external of a signature, whereas the ratio between the first peak and the second-largest peak is referred as P/B. Effect of gun depth are depicted in Figs 3 & 4.

The bubble period emerging from an airgun T can be quantified as:

$$T=K (P_{in}^{1/3} V_{in}^{1/3})/P_H^{5/6}$$

where P_{in} denotes the pressure inside the airgun before firing, V_{in} is the volume of the chamber, P_H is the hydrostatic pressure and K is some constant. This formula implies that the airgun bubble period scales as the 1/3 power of the pressure or the volume, in general and as the 1/3 power of the released energy. Keeping this in mind one can easily work out the desired gun array for the shallow Antarctica waters of Prydz Bay region.

Recommendations

The bubble period should be modelled in respect of the shooting interval so as to avoid the destructive interference between the bubbles.

Estimating the Ghost arrival

The primary arrival is followed closely by the large negative peak which represents the free surface reflected or the “ghost” arrival. The time delay between the primary and the ghost signals depends on the depth of the source and the hydrophone position. One can model the timing of arrival of the ghost as

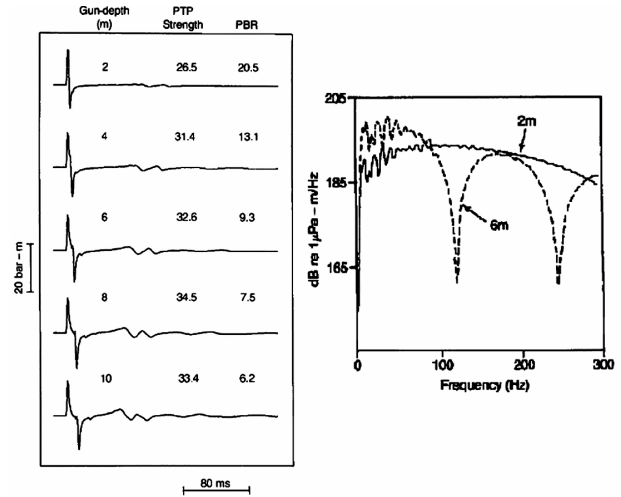


Fig. 3—Effect of gun depth on the source signature (left); and Amplitude spectra of the source signature for the arrays at shallow (2 m) and standard (6 m) depth. Shallow arrays are weaker source.

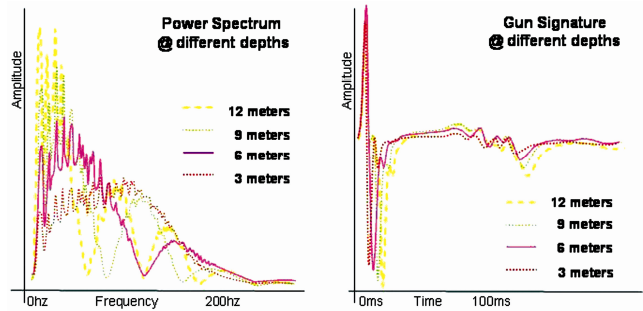


Fig. 4—Effects of gun depth on power spectrum and the gun signature.

well as the first non-zero frequency at which ghost occurs using the following relationship¹⁶:

$$f=V/2d (1+x^2/D^2)^{1/2}$$

Where d is the depth to the source, V is the speed of sound in water, D is the hydrophone depth and x is the lateral offset between the centre of an array and the hydrophone position. When $x=0$, the equation becomes,

$$f=V/2d$$

Therefore in this case for sea water $V=1500$ m/s, $d=6$ m, $f=125$ Hz.

Recommendation

- Gun depth: 6m
- Streamer depth: 10 m

Frequency and recording offset considerations

Figs. 5 and 6 show the stacked and migrated seismic sections at different dominant frequencies (20 and 40 Hz. respectively). Seismograms have been computed using the point source fired 6 m below the sea surface. The CDP spacings have been kept as 25 m and the receiver spacing as 50 m. Smearing effect at the lower frequencies can be clearly seen on the seismograms. Based on our exercise performed with several frequencies, we report a reasonably good quality data if the dominant frequency lies between 40-50 Hz.

Example Stack section at different frequencies:

Further, a ray tracing algorithm had been used to see that given a subsurface model as presented above (Table 1), where do the different phases appear at the streamer’s level. The purpose of this exercise is to know the acquisition parameters to accommodate the maximum offset recorded; which could in turn be

correlated with the length of the streamer. It is observed that the reflections and refractions from both of the Glaciomarine sediments appear within 3.2 Km offset (Fig. 7). For example: the refracted arrivals from the GS1 for the mentioned model appears to start at 1.83 km and maximum offset for this arrival is 3.14 km. Therefore the length of the streamer should be chosen in such a way that the maximum information could be gathered at one stretch.

Table 1—Model parameters of the assumed sub-surface geometry in the Antarctica.

No.	Geology	Thickness (m)	Velocity (m/s)
1	Sea-water	500-800	1500
2	GS1	400-600	1700-2100
3	GS2	100-200	2300-2600
4	Basement		3000

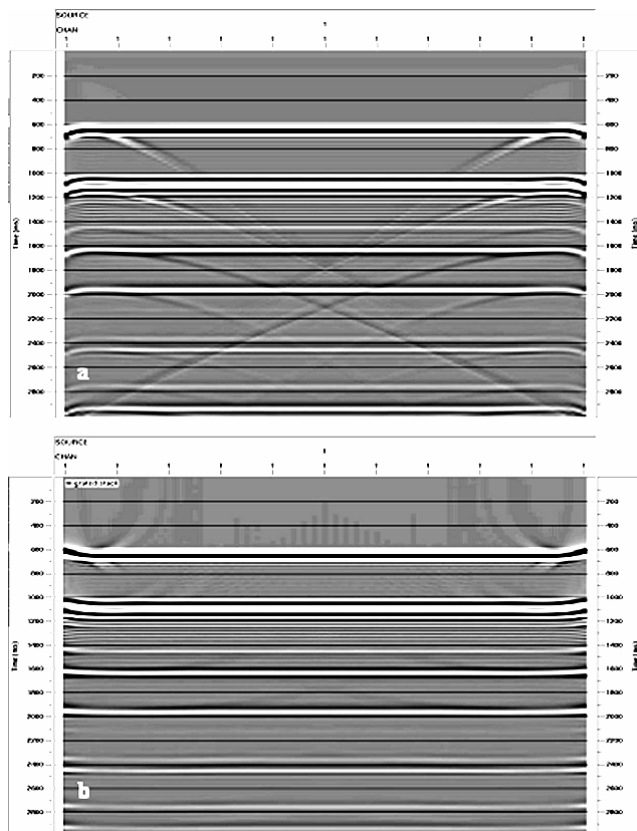


Fig. 5—A typical stacked (a) and F-K migrated (b) stack section at dominant frequency of acquisition of 20 Hz. The seafloor arrival appears to be at around 600 ms. The next two consecutive arrivals represent the reflections from the GS1 and GS2. The severe multiples can be noticed below 1600 ms.

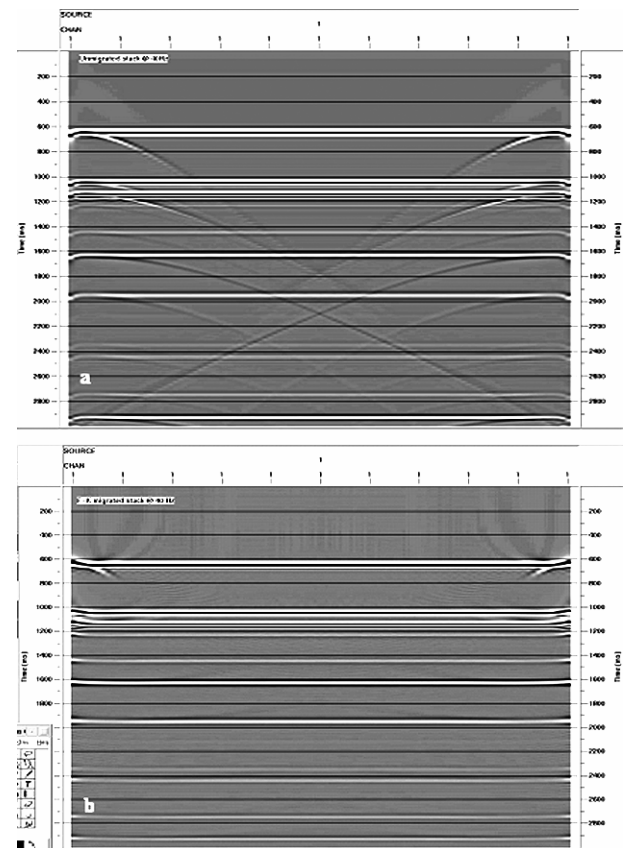


Fig. 6—A typical stacked (a) and migrated (b) stack section at dominant frequency of 40 Hz. The seafloor arrival appears to be at around 600 ms. The next two consecutive arrivals represent the reflections from the GS1 and GS2. The severe multiples can be noticed below 1600 ms. The better quality data can be seen at 40 Hz as compared to 20 Hz signal.

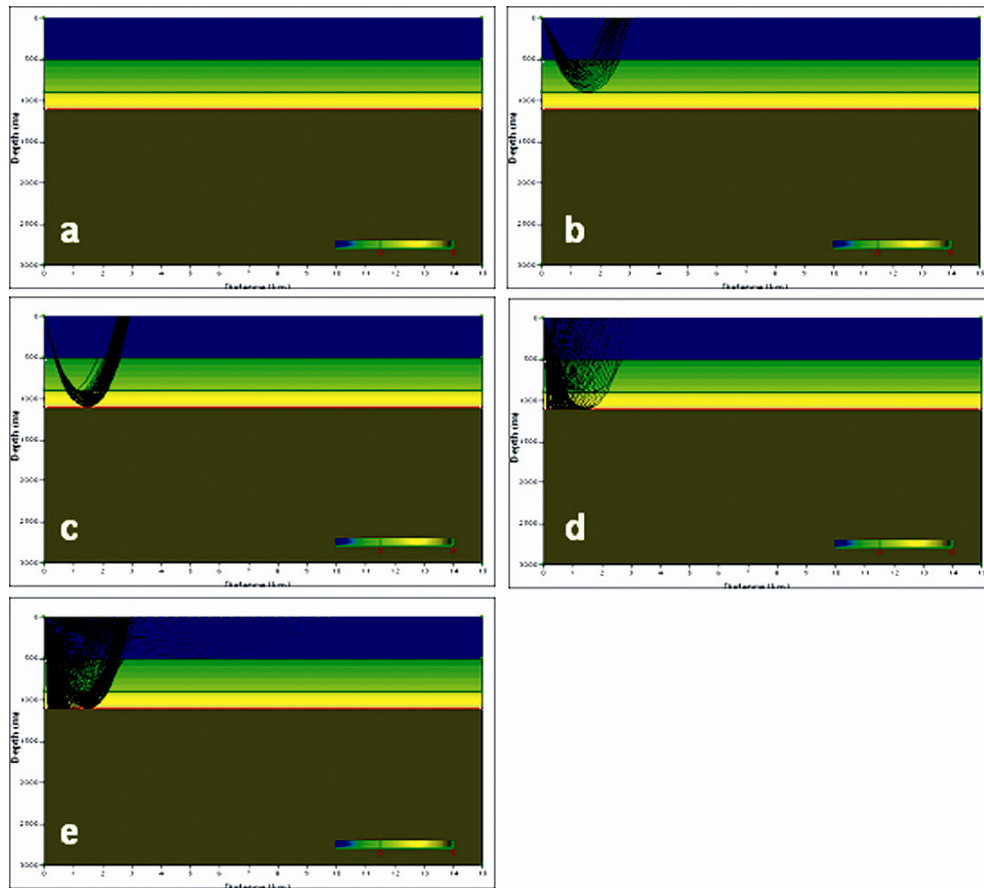


Fig. 7—Offset dependence for the acquisition of MCS data. The different layer from the top represent the sea-water, Glaciomarine sedimentary layers GS1, GS2 and the Basement respectively. The velocity colour map is shown at the bottom of each diagram (a) The assumed model, (b) refracted arrivals through GS1 (c) refracted arrivals through GS2, (d) reflected arrivals from the base of GS1 and GS2, (e) Arrivals above the basement.

Changing just the group positions in a streamer would result in the aliasing phenomenon. A series of exercises had been performed to see that what could be the effect of perturbation in the sub-surface model onto the minimum and maximum offset. The group configuration had been kept unchanged while making alterations to increase the maximum offset. In the plot shown below we compare three different maximum offset to show what offset to choose to image the deepest targets of interest.

Recommendations

Frequency: 40 Hz

Streamer length: a typical 24 channel streamer with 50 m group interval would provide a good quality data. However, to record the refractions through the GS1 and GS2 in the regions of thicker

glaciomarine sedimentary layers, longer streamer such as 6 Km is highly recommended.

Conclusions

Based on the modelling exercise attempt had been made to describe the best suited important acquisition parameters to acquire seismic reflection data in Antarctic waters in this paper. The modelled parameters include the gun volume, gun depth, dominant frequency, minimum and maximum offset etc. The information presented in this paper would be particularly useful in view of the envisaged seismic acquisitions in the Antarctic waters in near future. It should also be noted that the modelling exercise presented in this paper is totally based on the sub-surface data available through various published sources. Therefore, the actual field records are

usually learnt to have been affected due to several others parameters which are beyond the scope of this article such as, sea conditions etc.

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