Seismic Surveys in Central West Antarctica: Data and Processing Examples from the ANTALITH Field Tests (1994-1995)

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Abstract - During the austral summer of 1994-95, the University of Texas at Austin, in collaboration with the Pennsylvania State University and the British Antarctic Survey, collected a 60 km multichannel seismic reflection profile along with two smaller profiles and two wide-angle profiles over the Byrd subglacial basin in central-west Antarctica. The primary aim of the field season was investigating the requirements of conducting long traverses over the ice sheet as a pre-requisite to any regional traverse that may span continental Antarctica in the future. A secondary aim was obtaining a shallow to mid-crustal section of the lithosphere below the Byrd subglacial basin. Analysis of the multichannel seismic data resulted in an image of the base of ice as well as shallow sub-ice reflections and also revealed intra-ice reflections that (with minor exceptions) conform to the ice-floor topography. The rest of the CMP crustal section is transparent with no major recorded reflections. However, a shorter wide-angle survey conducted using larger charges over part of the same traverse revealed a deep crustal reflection at 4.9 s of two-way traveltime. A one-to-one comparison of the multichannel and wide angle data indicates that the high energy, low frequency seismic energy generated by the larger charges of the wide angle data was more successful in imaging the deep crustal section. This comparison also revealed that the crust in this area is indeed transparent from just below the ice floor to the 4.9 s reflection recorded by the wide angle data. Along the main traverse, the base of ice has significant topographical undulation in both inline and crossline directions with the highest elevations being nearly 750 m above the average depth of the ice-floor. There is ample evidence of faulting at the base of ice and several half grabens and localized basins can be identified. However, if there is sediment beneath the ice in these basins, it is not of significant thickness as indicated by the lack of events in the seismic reflection data. Nevertheless, these findings are in broad agreement with the idea that ice streams generally originate in fault-bounded sedimentary basins (Blankenship et al., 1997).

INTRODUCTION

In Antarctica, which mostly remains buried under a thick ice-cover, geological and tectonic understanding solely based on surface mapping runs into considerable difficulties. However, as an increasing amount of scientific data on Antarctica has accumulated over the years, it has been realized that the evolution of West Antarctica and its relation to East Antarctica have major implications for global plate interactions and paleoclimate, as well as Gondwanaland reconstruction (Dalziel and Elliot, 1982). Unlike the eastern part of Antarctica which is primarily a Precambrian shield, West Antarctica consists of four main crustal blocks i.e. Ellsworth-Whitmore mountains, Marie Byrd Land, Thurstor Island and the Antarctic Peninsula (Dalziel and Elliot, 1982). Each block has had a geological evolution that is largely different from its other neighbors and at various times the blocks have moved relative to each other (Dalziel, 1992). At present, they are separated by fault systems marked by deep ice-filled troughs. However, the crustal blocks in this area have not been clearly demarcated and imaging of the crustal features is necessary for a better understanding of the tectonic history of this region.

The West Antarctic ice sheet is of special importance, being the largest surviving marine ice sheet in the world. Marine ice sheets are characteristically grounded on beds well below sea level and are believed to be inherently unstable and prone to collapse (Van der Veen et al., 1987). Extensive aero-geophysics surveys previously conducted in West Antarctica have resulted in interesting discoveries including sub-ice volcanism (Blankenship et al., 1993) and posed many new scientific problems, one of which is the understanding of lithospheric controls on ice flow. The ANTALITH (Antarctic Lithosphere Studies) field tests were expected to provide important information relevant to the understanding of regional tectonic history and sub-ice geological features that influence the flow of ice.
Acquisition of multichannel seismic data over thick ice poses formidable challenges (Albert, 1978, Blankenship et al., 1986, King et al., 1991, Beaudoin et al., 1992, ten Brink et al., 1993, Stern et al., 1994, King and Bell, 1996, Smith, 1997) and the experience and expertise of conducting over-snow seismic experiments in the remote interior of Antarctica is limited. Apart from the logistic demands of such surveys, snow absorbs a higher proportion of shot energy than any other common shooting medium (King et al., 1991) and results in an overburden that complicates the detection of the underlying geology. The ANTALITH field tests were conceived as a pilot survey to address some of the basic issues that a crew conducting a regional seismic traverse in that region must encounter.

**ACQUISITION:**
**FIELD PROGRAM AND LOGISTICS**

The study area and survey lines are shown in figure 1 which also shows the details of the different surveys that were conducted during the field program.

The surveys were conducted in three phases: a reconnaissance survey, the drilling of the shot holes and the actual shooting. The reconnaissance was carried out about two weeks before the seismic shooting by a team of surveyors on snowmobiles who surveyed the line using field compasses and steel measuring tapes and marked the shot locations with flags. Drillers took over during the next stage to drill holes in the ice with a pressurized hot water drill. This is a relatively efficient and fast method of drilling in the ice and the drillers were able to drill 30 - 35 holes (each 18-20 m deep) each day with a three member mobile team. After drilling, the shot holes were covered with wooden boards to prevent them from being filled in by fresh snow and the locations were clearly marked on the boards.

A single 60-channel 1.5 km long snow-streamer (Eiken et al., 1989) built by Geco-Fjord Instruments (Norway) was used to record the seismic data. Each active group in the streamer comprised six 14 Hz gimbaled geophones. The recording hut comprised a cabin built on metal skids that was towed along with the streamer by a Tucker Sno-Cat. Offsets up to 10.475 km were shot and this required shooting several shots into the receiving array for each streamer position. Hence, for each location of the recording hut and the streamer, shots were fired at distances of 0 through 9 km from the array at intervals of 1.5 km. Later the data were reorganized into pseudo-common shot gathers of 420 channels with a maximum offset of 10.475 km.

While the main multichannel reflection profile was acquired using PETN (Pentaerythritol-tetranitrate) charges (either as cast cylinders or as cones), the two wide-angle surveys were conducted using ANFO (Ammonium Nitrate and Fuel Oil) pellets and a section of the main profile was also acquired using detonating cord (40 gm/m charge weight). A shorter perpendicular profile was surveyed using detonating cord as a seismic source (see Fig. 1).

For the main survey, the shot holes were drilled to depths between 16 to 20 m and most of them were used several times for detonating charges of varying sizes. A 150 gm charge was first used in each shot hole since experience has shown that this practice (also known as springing) actually improves the signal to noise ratio for subsequent shots. The detonating cord, when used, was buried at a depth of about 1 ft with a specially designed

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*Fig. 1 - Schematic diagram showing general location of survey area and details of survey traverses for the ANTALITH field tests (1994-1995). The long traverse was nearly 60 km while the shorter traverse was 15 km. The wide angle surveys along the main traverse are indicated by regular broken lines and the inline detonating cord survey is indicated by broken lines between the wide angle surveys. Note the scale at the bottom of the schematic diagram.*
plow. This method of burying the detonating cord is very economical and fast compared with drilling holes in the ice and loading them with explosives. As opposed to two teams (having a total of at least four people) working to drill and load dynamite in holes, detonating cord can be laid out by just two persons driving a Sno-Cat and towing the plow and a spool of detonating cord. For each segment (15 - 18 km long) of the survey that was shot using detonating cord, the explosive was laid out in about half a day by a two-member team. In comparison, the rate of coverage for hot water drilling and initial loading was about 7-8 km each day (including drilling multiple shots at selected locations).

For the main survey, there were two shooting groups, each comprising two persons, a snowmobile and a sled. The two groups worked simultaneously to shoot the near and the far offsets respectively. Their shooting schedules were synchronized so that the two groups moved together between consecutive shots, thereby minimizing the time lost during transit. After all the shots for a specific streamer location had been recorded, the recording hut along with the streamer was towed to the next hut location. The distance between consecutive hut locations was 300 m which was also equal to the shot separation. The personnel at the recording hut fired the zero-offset shot. See figure 2 for a schematic representation of the CMP acquisition scheme and figure 3 for the charge sizes used in the main survey.

During the wide-angle surveys, shot separation was 600 m and the first shots were fired at shot locations corresponding to the largest offsets, i.e. 12 km in one case and 30 km in the other. At each subsequent shot, the streamer was moved towards the new shot location by 600 m so that the separation between the shot and the first channel of the receiver array decreased by 1.2 km after each move. The final shot for each survey was fired at the zero-offset location, i.e. when the head of the streamer coincided with the shot location (physically, the shot hole was drilled at a laterally offset location to prevent damage to the streamer). This ensured that within each survey, the same subsurface patch was illuminated at each shot but the data were recorded at different offsets. See figure 2 for a schematic representation of the acquisition scheme and figure 3 for the charge sizes used in the wide angle acquisition method.

For the surveys that used detonating cord, 40 m lengths of the cord were buried several days in advance at each shot location. On the day of shooting, detonating caps were attached to each piece of cord by the shooters. This proved to be an efficient process; the burial of the cord a few days prior to shooting allowed it to settle in the snow which resulted in excellent coupling. It is recommended for any future survey using detonating cord that the cord be buried at least a couple of days in advance of the shooting to provide better coupling.

All remnants of capwires, cardboard and plastics were carried back to the camp at the end of each day’s work to...
be stored in waste recovery boxes. On a bad-weather day, it took about an hour to shoot all seven shot locations for just one streamer location while on an average day, it took two hours to shoot all the shots for three successive streamer locations. On a good-weather day, two streamer locations could be covered in an hour. Based on this rate of progress, the rate of traverse coverage can be estimated at 3-5 km per day for modest eight hour working days. At this rate, a 63 km long traverse needs a maximum of eighteen working days (allowing a day or two for inclement weather, mechanical breakdown, etc.).

The data were recorded at 1 ms sample interval on a 24-bit DAS-1 recording system manufactured by OYO Geospace. This system allows QC monitoring of the data before recording on digital tapes. A Global Positioning System (GPS) clock was used to synchronize the source initiation and the start of recording. A custom-made GPS shotbox (built at the Polar Research Center of the University of Wisconsin at Madison) was used to implement the time synchronization.

The ANTALITH field tests used the same streamer and hot water drilling method that were used for the SERIS program (ten Brink et al., 1993, Stern et al., 1994) and similarly comprised conventional multichannel and wide-angle reflection surveys. However, in addition to dynamite charges (used in SERIS), ANFO pellets and detonating cord were also used as seismic sources in the ANTALITH field tests. In addition, a wide range of charge sizes were used (0.45 kg - 7.2 kg) for the multichannel profile, larger shots being fired at greater offsets from the receiver array. In contrast to these tests, earlier experiments on the Rutford ice stream (Smith, 1997) had utilized 40 Hz geophones and 300-800 g charges in 20 m deep holes. During the same season in which the ANTALITH field tests were conducted, a crustal scale seismic experiment was undertaken (using 4.5 Hz seismometers and charges in the 12.5-3200 kg range with a maximum offset of 218 km) near the southern edge of the Byrd subglacial basin (Clarke et al., 1997). Tests conducted during that experiment showed a dramatic increase in charge coupling for hole depths greater than 50 m which was thought to be related to the firm-ice transition point, which for this area was found to lie at about 60 m (Clarke et al., 1997). It should be noted that the shot holes for the ANTALITH field tests were shallower than the estimated firm-ice transition point in the area.

**DISCUSSION OF THE SEISMIC DATA AND ANALYSIS**

Before any processing could be started, a complete reordering of the data files was necessary since the data were acquired in a way that expedited field operations i.e. data recorded for a fixed streamer location but corresponding to different shot locations were recorded to successive files on the data tapes. Thus, for the main CMP survey, all the data files corresponding to a specific shot location had to be extracted from the different tapes and concatenated to construct simulated mega-gathers that represented a 420-channel (maximum offset 10.475 km) recording for each shot location. These large gathers, in theory, are equivalent to data that would have been acquired if each shot had been recorded by a streamer that was seven times as long as the ANTALITH test streamer. Actual deployment of a longer snowstreamer or a group of snowstreamers that resulted in a receiving array of, for example, 10.5 km (compared to the 1.5 km physical array length for this field test) would correspondingly reduce the number of physical shots by a factor of seven and significantly reduce the logistics requirement of the survey.

In the beginning of the field season, there were apprehensions about the possible effect of surface statics. This was not found to be a problem in the subsequent data processing stages. The concatenated mega-gathers indicated excellent continuity in the direct arrival event from one subsection to another, each corresponding to different receiver locations. Also, in general, the coupling between the gimballed geophones and the snow was excellent. Although the coupling might have been improved by burying the geophones in the snow, it would have required significant amounts of additional time and labor, thereby slowing down the daily progress of the seismic survey.

An observation made during the survey was the occasional occurrence of static bursts of energy (with no moveout or change of arrival time with receiver location) that appeared across the seismic records. The occurrence and duration of these events were unpredictable. However, during their occurrence on any given day, these events were aperiodic. This noise is believed to have resulted from ionospheric phenomena and could be removed by a simple filter during subsequent data processing.

After the data were reorganized and labeled with the proper geometry information, different tests were performed to evaluate the frequency content of the data. These tests included visual inspection of raw shot gathers, filter panels and frequency spectrum analysis (see Fig. 4 and Fig. 5). Figure 4 shows a comparison of the scaled energy spectra of the different types of charges at small and medium offsets (i.e., less than 1.775 km). These energies are expressed in terms of charge size and type.

![Fig. 4 - Comparison of scaled energy spectra for various charges. The Fourier transforms were computed from the stacked autocorrelation traces of each gather. The near channel offsets were between 0 and 300 m and the farthest offsets were between 1475 and 1775 m. The maximum of each spectrum was set to 0 db.](image_url)
Spectra include both noise and signal and are good indicators of the distribution of energy among various events on the seismic records. Note the concentration of energy in the higher frequencies for the detonating cord.

The different surveys that were conducted during the ANTALITH field test required different processing strategies and some of the problems that were encountered were specific to the individual surveys. The processing techniques applied to the data from the different surveys are summarized in figure 6.

**MAIN REFLECTION SURVEY**

The primary purpose of the main survey was to evaluate the efficacy of conducting a seismic traverse with a snowstreamer and buried explosives and to optimize the performance of a small but properly trained crew.

The data for the main part of the reflection survey were shot using PETN cast charges (see Fig. 3) and the signal-to-noise ratio at the reflection from the base of the ice layer was good (as expected). The multiple reflections from the base of the ice and surface were also strong. However, penetration to greater depths was not consistently good and for most parts of the line the records are noisy beyond the first two sets of multiples.

Figure 5 shows the variation of energy spectra with streamer offset (and charge size) for a fixed shot location. The fixed shot location implies that the physical and geological conditions in the vicinity of the source are the same in every case. Note the similarities in the spectra obtained for the three cases where the distance between the source and the first recording channel is 3 km, 6 km, 7.5 km and 9 km respectively. The spectra for two cases where the first channel is at 1.5 km and 4.5 km from the source are also shown.

**Figure 5** - Comparison of scaled energy spectra for cast-cylinder PETN charges used at different near-channel offsets for a fixed source position in the main reflection survey. In figure captions, offset refers to near channel offset.

Field records
Geometry in headers
Sorting / mega-gathers
Frequency analysis
Filter design
CDP sorting
NMO & stacking
Migration

Field records
Updating trace headers
Frequency analysis
f-k filtering
CDP binning
NMO correction/ stacking
Migration

Field records
Geometry in headers
Binning / Stacking
Frequency analysis
Filter design
Amplitude balancing
Curve fitting / velocity estimation

Fig. 6 - Processing sequences for (A) main CDP survey, (B) detonating cord survey and (C) wide-angle surveys conducted during the ANTALITH field tests.
source, are contaminated by noise in the records. The spectrum for the zero-offset shot is heavily influenced by geophone resonance resulting from the strong direct arrival. It is important to note that the trends observed in these spectra have been influenced by changes in both charge size and offsets since larger charges were used at greater offsets. The general similarity of the normalized spectra indicate that the different charge size vs. offset combinations result in remarkably similar energy distribution among the different frequency bands.

In order to produce an informative geological section representing the shallow and middle crust, conventional CMP gathering, velocity analysis and stacking were performed on the data. One of the most interesting features that can be seen in the stacked image is a series of intra-ice reflectors whose presence can be detected along almost the entire line (see Figs. 7-9). At most places, these reflectors follow the structural trend of the ice-floor. These reflectors can be detected best in the filter pass-band of 55-70-340-350 Hz. On the field records of the CMP survey, these reflections were detectable only at the near offsets. Interestingly, these intra-ice reflectors have not been detected in ground penetrating radar data collected in the same area.

Below the ice floor and the shallowest sub-ice reflections, the signal to noise ratio is generally poor. In investigating the resulting poor quality of the images at these greater depths, it should be noted that the actual signal strengths vary among the different constituent
gathers that were concatenated to generate each mega-gather. Each piece of a mega-gather was acquired from a different physical explosion and recorded at different offsets with larger explosives for the farthest offsets. Without explicitly taking into account variations in charge size, coupling effects or attenuation, there are large variations in the signal amplitudes among the different constituents of a mega-gather. To remove these disparities, the trace amplitudes were equalized by comparing and averaging within groups of adjacent traces. (However, this data processing technique eliminates the use of the modified data for studies where amplitude variations with offset are of interest.) The problem can be avoided in the future by using a longer snowstreamer or several snowstreamers deployed end to end so that a longer receiving array records each shot. Also, since fewer shots will be required, the shot size can be increased to improve penetration and maintained constant for recording at all offsets.

Secondly, we must consider the fold of the CMP survey. CMP fold is determined by the number of recording channels and shot spacing and is a measure of the redundancy in the CMP gathers. The greater the fold, the greater the improvement in the signal-to-noise ratio after adding all the normal moveout (NMO) corrected traces in a CMP gather. Fold can be increased by increasing the number of channels in the survey and/or by decreasing the shot spacing. In our case, for each mega-gather on the main multichannel line, only the first 120 recorded channels were ultimately used to construct each CMP gather.

processed in this study. The other channels (i.e. channels 121-420) were not considered because of their poor signal to noise ratio. With a 300 m. shot interval, the nominal fold was reduced to 5, i.e. each CMP gather consisted of only 5 traces that were later stacked. We could combine CMP bins so that the CMP spacing was 25 or 50 m thereby increasing the fold from 5 to 10 or 20 but only at the cost of decreasing the along-line resolution. The theoretical improvement in signal-to-noise ratio after stacking is proportional to the square root of the fold, assuming normally distributed errors in the data. Thus for a fixed bin size, the signal gain associated with a shot spacing of 12.5 m is approximately 5 times that achieved from stacking for 300 m shot spacing.

THE WIDE-ANGLE SURVEYS

Two wide-angle surveys were added to the main program of the field test to augment the main survey (see Fig. 1). These surveys were conducted through expanding spreads where the source and receiver locations are symmetrically located about a single midpoint (see Fig. 2). Beginning with a specific source-streamer separation, the source and the first channel of the streamer were moved by equal distances towards each other until they were coincident. In practice, a safe crossline distance is always maintained at the zero-offset point between the source and the streamer to avoid physical damage to the receivers. The spreads acquired for the wide-angle surveys during the field test had 20% overlap, i.e. 12 out of 60 recording channel positions were repeated for successive shots. This created a redundancy that was used to check data quality and enhance the signal-to-noise ratio by stacking the overlapping traces during processing. Expanding profiles are wide angle CMPs, i.e. common midpoint profiles which repeatedly illuminate a restricted part of the subsurface geology. This enhances the data quality since multiple estimates of a restricted region are sampled and the CMP geometry makes an idealized 1-D earth model a viable approximation.

The wide-angle data were acquired with 50, 75 and 100 kg shots (see Figs. 2 and 3). At equivalent source-receiver offsets, the penetration of energy into the subsurface is significantly better than in the corresponding CMP data shot with smaller charges e.g., 0.450 kg - 7.2 kg. However, it appears that the shallow and mid crust are largely non-reflective for most parts of the main survey line. This is indicated by the general absence of significant reflection events on the wide-angle gathers except for one event at 4.9 sec in the data acquired along the last quarter of the main line (see Fig. 10). This event is hardly detectable in the data acquired over the same area during the main CMP survey. This implies that by using larger charges, this deeper event could have been imaged in the CMP survey. Also, the large non-rigid charges like the ANFO pellets used in the wide-angle survey send out more low frequency energy which is able to penetrate to greater depths. Direct comparison of the wide-angle profile and CMP data at equivalent positions and offsets leads us to conclude that the CMP line was undershot in

Fig. 10 - The stacked and migrated CMP section from the vicinity of the wideangle survey centered at the 48 km location on the main traverse (left) is compared with the wide-angle gather (right). The event at 4.9 sec on the wide-angle gather can be hardly detected in the CMP section. Refer to figure 1 for detailed location of surveys.
terms of charge sizes (see Fig. 10). However, since only a single crustal reflection at 4.9 sec is observed in the wide-angle survey with its larger charge sizes, we can conclude that between the shallowest sub-ice reflections and this event, the crust in the survey area is mostly non-reflective. We can also conclude that even larger charges (e.g. 25 - 50 kg) are required to generate deeper reflections.

Several steps were required to enhance the weak reflection event at 4900 ms. Each of the wide-angle surveys was shot (see Fig. 2 and Fig. 3) with 50 kg of explosives for the short offsets (0.0 km to 14.0 km), 75 kg for the middle offsets (14.0 km to 26.0 km) and 100 kg for the far offsets (26.0 km to 30.0 km) and the differences in the signal level in these three subsets of data were considerable. Hence amplitude balancing was performed prior to processing of the data. The data were sorted so that traces with the same source-receiver offsets could be stacked and averaged. The data were then analyzed and the velocity to the deep reflection event was estimated to be ~6 km/s.

Fig. 11 - Results of f-k filtering on a shot gather recorded from detonating cord buried at a depth of 1 ft. The plot on upper left shows the raw data with strong ground roll (indicated by arrow). The plot on upper right shows the f-k spectra of the raw data. The plot on bottom right shows the filtered data corresponding to the spectra on bottom left. On the spectral plots, the frequency axis ranges from 0 to 100 Hz and the wavenumber axis ranges from -20 to 20 1/km. Red and yellow represent higher amplitudes on the spectra compared to blue and green.
THE DETONATING CORD SURVEYS

For the detonating cord data, the signal-to-noise ratio was low because of ground roll. This guided wave phenomenon often masked even the strong ice-floor reflection in these records. A substantial part of the energy also dissipated as an air wave. This was primarily because these charges were buried at very shallow depths (~1’ in a furrow) and hence a significant amount of energy was airborne. The removal of this noise is both straightforward and simple using f-k filtering (see Fig. 11). However, energy penetration beyond the ice-floor is poor. The comparative spectra indicate (see Fig. 4) that much of the energy from the detonating cord is concentrated at the higher frequencies which also tend to decay faster in an attenuating medium. The same factor however contributes to a very sharp image of the ice-floor and the stacked and migrated images of the inline and crossline surveys using detonating cord display a clear and coherent picture of the ice-floor but record nothing of significant interest below it (see Fig. 12). Consequently, even though using the detonating cord was very efficient during the acquisition phase, it can only be recommended for studies of the shallow sub-ice section.

GEOLOGICAL INTERPRETATION

The ice sheet is 1.4 km - 2.2 km thick along the main traverse and is characterized by a nearly continuous series of intra-ice reflectors that mostly follow the trend of the ice-floor. These features have not been detected in radar data collected over the same area and they are probably signatures of seismic anisotropy in the ice resulting from the selective alignment of crystal axes in the ice. Preferential orientation of the ice crystals may arise from stresses developed due to the interaction between flowing ice and the underlying bedrock. However, these intra-ice reflections do not exist close to the base of the ice where partial melting and possible re-crystallization occurs. Seismic velocities are markedly affected by anisotropy resulting from preferentially oriented ice crystals whereas electromagnetic wave velocities are not. Hence seismic investigations are more likely to detect these features than radar studies.

Analysis of the data reveals that the crust in this area has poor reflectivity from just below the ice floor to at least the 4.9 s reflection detected in the wide angle data. The topography at the base of ice is severely undulated in both inline and crossline directions and the most significant elevations are nearly 750 m above the average depth of the ice-bedrock interface. Faulting at the base of ice has created half grabens and localized basins that can be observed on the migrated seismic sections. Obvious reflection signatures of sediment in these basins were not observed in the data but the presence of sediment cannot be ruled out completely. Anandakrishnan et al (1998) have presented evidence in favor of such a possibility. Aerogeophysical surveys have indicated gravity lows and magnetic highs over some of these basins near the north-west end of the main survey (Bell et al., 1998) that agrees well with the presence of sediments in these fault-bounded

Fig. 12 - 18 km migrated in-line section (top) and 15 km migrated cross-line section (bottom) from detonating cord surveys. Both figures show details of the ice-bedrock interface in a window between two-way traveltimes of 600 ms and 1400 ms. Refer to figure 1 for details on locations of surveys.
basins. Considering the proximity of ice-streams to the survey area, these findings are in broad agreement with the idea that ice streams generally originate in fault-bounded sedimentary basins.

The crust is at least 15 km thick in this area and may be significantly thicker. The data from our surveys did not record the base of the crust. The velocity in the crust is in the range of 5.8 km/s - 6 km/s between the base of the ice layer and the 4.9 s reflection in the wide-angle data. This agrees well with established global velocity ranges for the upper crust (Christensen and Mooney, 1995). Results from deep crustal seismic refraction and wide-angle reflection measurements conducted alongside the ANTALITH field tests have revealed a reflective lower crust and overall crustal thicknesses that are typical of extended continental crust (Clarke, 1996, Clarke, 1997).

SURVEY ANALYSIS AND RECOMMENDATIONS

Analysis of the seismic data clearly indicates that the largest charge (7.2 kg) used in the CMP survey was insufficient to generate detectable signal corresponding to the 4.9 s event observed in the wide-angle data. Any future survey in this area must use charges that are at least large enough to generate signal strengths comparable to that of the wide-angle data and are capable of generating sufficient signal to noise ratio that may be further enhanced by conventional processing techniques to elicit deeper reflections.

Signal-to-noise ratio in seismic data is enhanced in different ways. The use of larger charges releases more energy into the subsurface and usually generates more low frequency energy that penetrates to greater depths than the energy typically released by smaller charges. Alternatively, recorded data from multiple shots and multiple receivers are sorted into common midpoint gathers and stacked at the processing stage so that random noise cancels out and the coherent information is enhanced. To minimize operating costs, an optimum strategy must be devised that combines the advantages of using larger (and hence more expensive) charges with appropriate processing techniques (e.g. stacking) that can enhance the signal to noise ratio in the data after acquisition. While the dependence of signal strength on charge size depends on a scaling law, the enhancement obtained from stacking is proportional to the square-root of the fold.

According to Ziolkowski (1980), far-field signal strength scales as the cube root of the charge size. If there were no frequency dependent losses in the subsurface, a decrease in source size could be compensated by an increase in fold. Thus the 7.2 kg charge used in the CMP data could be recorded with a fold of 4 or more and stacking could enhance the signal to noise to the level of the 50 kg wide angle shots.

In reality, frequency dependent attenuation does occur in the subglacial media and causes most of the energy released from the small charges to be absorbed before it penetrates to deep crustal depths. To overcome this problem, the initial explosion must generate sufficient energy in the proper frequency band to survive attenuation in the media. The resulting reflections will then be strong enough to be recorded and a statistical enhancement by stacking will further increase the reflection signal strength.

To account for attenuation, we recommend a charge size of 25 kg which is greater than 7.2 kg (the largest charge size used in the CMP survey) but less than 50 kg (which was sufficient to generate good signal to noise ratio in the single fold wide-angle data). The 50 kg charges used in the wide angle acquisition were more efficient generators of useful seismic energy, i.e. a larger fraction of the initial available energy was converted into elastic radiation (O’Brien, 1969) in the required frequency band. A 25 kg charge, according to the scaling law, generates as much as 80% of the energy released by a 50 kg charge and we still expect it to generate sufficient seismic energy at low frequencies to ensure penetration to deep targets. In figure 13, the solid circle at 12 Hz represents the estimated strength of the reflected signal corresponding to the 4.9 s deep reflection that would be recorded for a 25 kg charge. This estimate was made using the energy spectra of wide angle data recorded at 6000 m - 7475 m from a 50 kg charge as a basis and the scaling law (Ziolkowski, 1980).

Figure 13 also shows that in the frequency window corresponding to the reflection event at 4.9 s on the wide-angle data, the recorded energy from the 2.4 kg charge of the MCS survey was almost 40 dB less than that from the 50 kg charge of the wide-angle experiment. This ratio is significantly greater than predictions from the scaling law in the absence of frequency dependent attenuation in the media and the difference may be attributed to the Q-related loss in the ice and shallow crust.

Assuming that the charges in a future survey are large enough and generate the required lower frequencies, the fold of the data can be increased by either decreasing the shot spacing or increasing the CMP bin size. The MCS data from the field test were acquired with 300 m shot spacing and processed with 25 m bin size and hence had a resultant fold of 10. Reducing the shot spacing would increase the number of shot holes needed to cover the same length of a traverse and require a significantly higher drilling expenditure. Hence that approach is not recommended.

Retaining the 300 m shot spacing used in this survey, an alternative scenario can be proposed where a composite streamer three times as long as that in the ANTALITH field test may be used to record each shot over offsets of 0 - 4.5 km. A three fold increase in the effective streamer length is technically and economically feasible. For such a streamer, only two physical shots will be required at each streamer position for recording up to 9 km, whereas during the ANTALITH field tests, seven shots were fired for each streamer position to acquire the same range of offsets. In order to maintain uniformity in the source spectral content, both charges fired for each streamer position could be 25 kg. Use of a longer receiver array will not only require fewer physical shots and fewer streamer moves to cover the same distance but will also eliminate the necessity of repetitive shooting in the same hole. The rate of acquisition
will improve significantly and more traces recorded for each shot will have good signal to noise ratio (owing to larger charge sizes) and will eventually contribute to a greater CMP fold compared to the ANTALITH field tests.

**CONCLUSIONS**

The ANTALITH field tests succeeded in estimating the requirements for future multichannel seismic traverses in the Byrd Subglacial Basin and provided insights into the structure of the ice sheet and upper crust.

Localized zones were detected within the ice sheet where the crystal axes probably have preferential alignments that result in seismic anisotropy. These features were manifested as a series of intra-ice reflectors on the seismic data that followed the general trend of the base of the ice layer. Along the main traverse, the base of the ice was characterized by strong topographical variations, faulting and fault bounded basins while the upper crust in the area of the survey appeared generally non-reflective.

The charge sizes for future surveys must be significantly larger than those used for the ANTALITH field tests and the charges must be buried in deeper holes. A longer composite streamer will reduce the number of physical shots, allow for the planning of deeper holes, improve the rate of acquisition and ultimately enable the recording of high fold seismic data of good signal quality.

Finally, we sincerely thank Dr. Edward King and an anonymous reviewer for their valuable suggestions that helped improve shortcomings of the original draft.

**REFERENCES**


efficient tool in seismic acquisition. *First Break*, 7(9), 374-378.


