Mapping of the PARASOUND penetration depth in the Pine Island Bay, West Antarctica

Project time: February 10th to April 11th 2006 (Expedition ANT-XXIII/4)
September to November 2006

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Project character, theme, aims, integration

From the 10th of February to the 11th of April 2006, I participated as research student-assistant in the fourth leg of the 23rd Antarctic Expedition of the RV Polarstern. My field of work were the PARASOUND and seismic watch. Pine Island Bay (PIB), which is located in the Amundsen Sea in the South Pacific sector of the Southern Ocean, was the main working-area of ANT-XXIII/4. The area exhibits the most rapid ice thinning and grounding-line retreat of shelf-ice and glaciers in Antarctica. It has been suggested that this area might be the most likely sight for initiation of a collapse of the 2 million km^2 West Antarctic Ice Sheet (WAIS). Such a collapse would cause a melting of the WAIS and result in global sea-level rise of 6 m. Earlier studies have shown that the WAIS has experienced some larger fluctuations and that the ice-sheet might be quite sensitive to climate change. At present, it is not sure whether the current retreat of the WAIS is part of the ongoing recession which started 14 000 years ago or whether it reflects more recent climate changes. The marine record of Quaternary deglatiations in the PIB, coupled with ice-sheet models, can provide important hints for an understanding of climate sensitivity and stability of the WAIS.
Earlier subbottom echosounder data and first results during the Expedition ANT-XXIII/4 have rarely shown penetration of more than five meter and occurrence of layered sediments. Based on these observations the idea for a map showing the maximum penetration of the PARASOUND-system along the ship-track of ANT-XXIII/4 came up. This project should give a first overview of the sediment distribution in the PIB for future sediment sampling and serves as a basis for a more detailed map of sediment distribution in this remote area.

Results of literature research

Introduction

Earlier studies have shown that the West Antarctic Ice Sheet (WAIS) has in recent times experienced rapid variations on short time scales (Shepherd et al., 2001; Payne et al., 2004; Shepherd et al, 2004). Since the WAIS – which is compared to the East Antarctic Ice Sheet relatively instable – contains enough water volume to raise the global sea level by 6 m, past behaviour of the WAIS is getting more and more in scientific focus. The understanding of the behaviour of the WAIS during the last glacial cycle gives important background information to predict future sea-level changes. More than 90% of the mass lost from the WAIS flows through only a small number of about 10 ice streams (Payne et al., 2004). The Pine Island Glacier (PIG) has the largest discharge (66 Gt yr^{-1}) of all WAIS ice streams and together with the adjacent Thwaites Glacier it drains about 40% of the volume of the ice sheet (Payne et al., 2004). Recent studies have shown that the PIG is nowadays retreating and thinning much faster than in previous decades. These processes are assumed to be responses to recent changes in the Amundsen Sea, which cause increased basal melting of PIG (Payne et al., 2004). Shepherd et al (2004) propose ocean water to be about 0.5°C above freezing point as the reason for the thinning of Pine Island Bay (PIB) ice shelves, PIG, Thwaites Glacier and Smith Glacier. They also propose that this thinning reduces lateral traction and the retreat of grounding line reduces basal traction, which leads to accelerated ice flow and thinning further upstream.

Ice shelves of the Amundsen Sea have thinned at rates that are 33 to 100% greater than their equilibrium ice influx since 1992 (Shepherd et al, 2004). This negative trend will be even more accelerated due to faster glacier flow when the ice shelves are removed and glacier retreat proceeds into the deeper part of the glacier basin (Thomas et al., 2004). The strong variability in ice-flow behaviour supports a hypothesis of instability of WAIS (Lowe and Anderson, 2002)

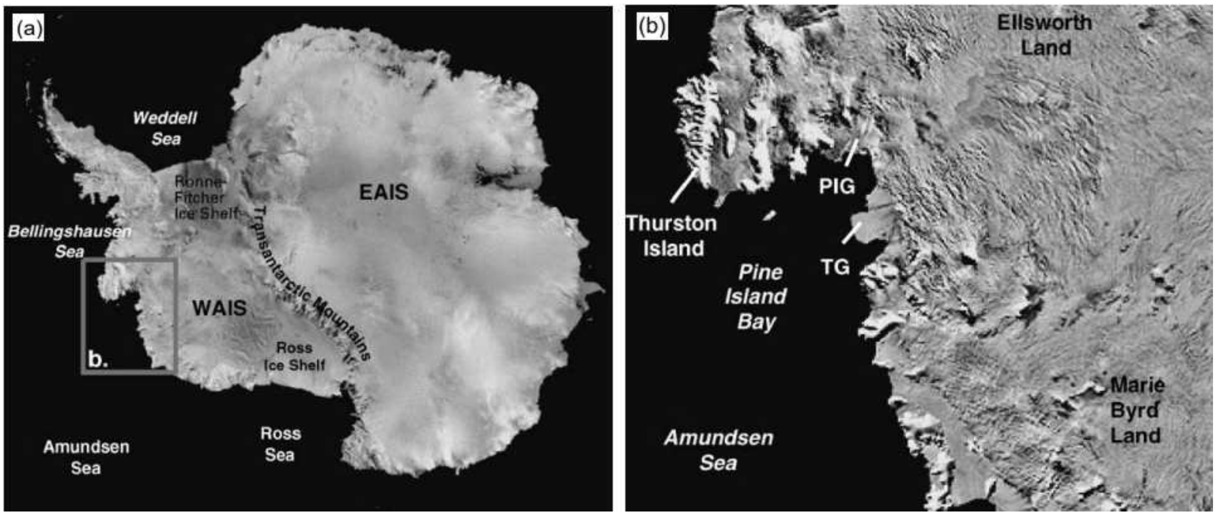

Fig. 1: (a) The satellite image of Antarctica shows the location of Pine Island Bay. Pine Island Bay is located in the east of Amundsen Sea in the South Pacific sector of the Southern Ocean. (b) Magnification of the study area.
(WAIS = West Antarctic Ice Sheet, EAIS = East Antarctic Ice Sheet, PIG = Pine Island Bay Glacier, TG = Thwaites Glacier) (Modified from Lowe and Anderson, 2002)

Study area

Pine Island Bay (PIB) is located in the Amundsen Sea in the South Pacific sector of the Southern Ocean (Fig. 1) and is one of the remotest areas of coastal Antarctica. It had been relatively unexplored until the late 1980s. The distance from the terminus of the WAIS to the shelf edge is about 450 km. The bay deepens inshore due to isostatic loading and glacial erosion (Lowe and Anderson, 2002). Bathymetry of inner shelf and the eastern region has been determined using multi-beam and swath bathymetry (Lowe and Anderson, 2002). Since the number of available bathymetric data has increased during the last decades, Nitsche et al. (2006) compiled a detailed map of the Amundsen continental shelf, incorporating different methods and data sources including the latest ANT-XXIII/4 and JCR141 multi-beam data. Inner Pine Island Bay is rugged, with water depth of over 1000 m. A deep glacial trough stretches across the inner shelf from PIG NW, fed by narrow and deep tributary from PIG and Thwaites Glacier.

The sea floor of middle and outer shelf of PIB is generally smooth but iceberg scored with water depths between 400 and 500 m. The Antarctic Coastal Current flows along the Amundsen Sea margin (Gordon, 1971) and Circumpolar Deep Water (CDW) reaches PIB via cross-shelf bathymetric troughs (Jacobs et al., 1996).

Previous work in Pine Island Bay

Lowe and Anderson (2002) divide the shelf region of PIB in 4 distinct zones (Fig. 2) on the basis of sea-floor morphology and distribution of glacial landforms. Zone 1 and 2 include meltwater-derived tunnel valleys, channels and cavities, together with drumlins and P-forms formed in crystalline bedrock on the inner shelf; Zone 3 comprised mega-scale glacial lineations developed across sedimentary strata and unconsolidated sediments on the middle shelf; and Zone 4 is located at the outer shelf and comprises iceberg furrows in water depth of less than 700 m. The subglacial bedforms confirm an expansion of a grounded WAIS at least to middle to outer shelf during the Last Glacial Maximum (LGM). More recent results reveal the presence of a major bathymetric trough containing streamlined subglacial bedforms in soft till which extends to the shelf edge (Evans et al. 2006). This suggests that the

WAIS extended to the shelf edge of PIB during LGM and was drained by a grounded, fast-flowing paleo-ice stream through the outer shelf trough (Evans et al. 2006).

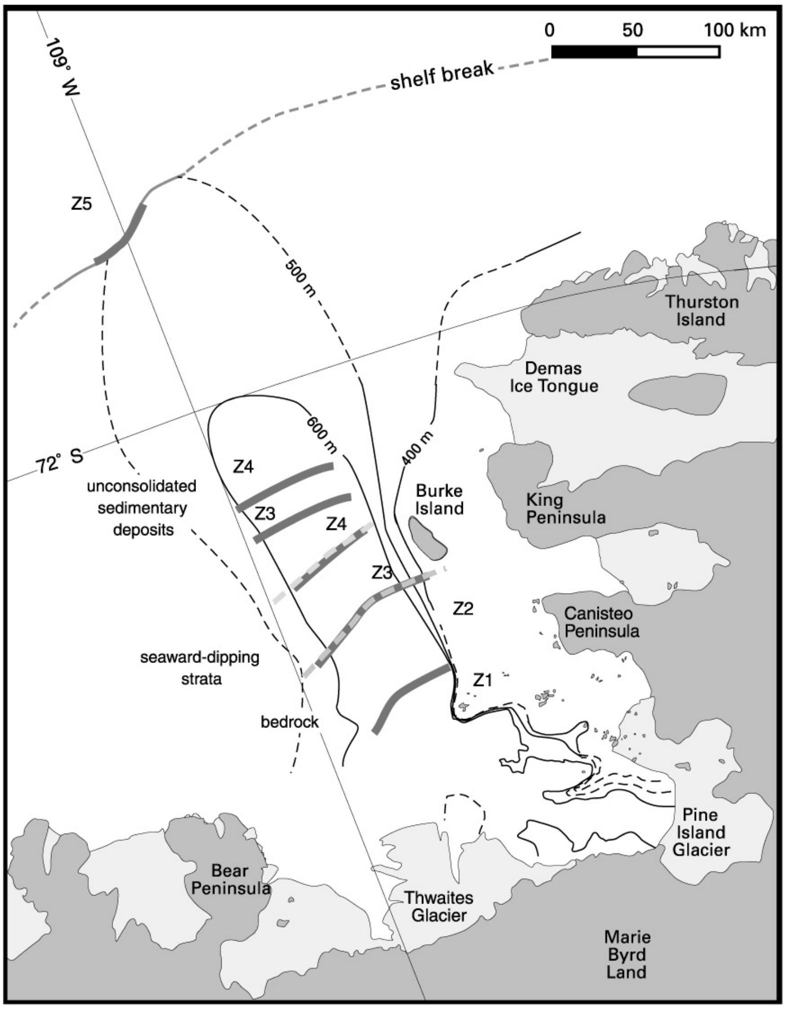

Fig. 2: Map of Pine Island Bay with the five geomorphic zones (Z1 to Z5) identified by Lowe and Anderson (2002). Only zone 1 to 4 are located on the shelf, zone 5 occurs seaward of the shelf break. Heavy grey lines mark boundaries between the zones. Dashed grey lines show where changes in seafloor substrate occur. (Modified from Lowe and Anderson, 2002)

Instruments and methods

Technical conception of the PARASOUND system

The analyzed data were recorded by the ship-mounted, permanently-installed PARASOUND sediment echosounder system of the RV Polarstern (STN-Atlas Elektronik, Bremen). A hull mounted piezoelectric transducer-array is at the same time generating acoustic signals and receiving of the echo. The system uses a secondary low frequent signal of 2.5 – 5.5 kHz, which is generated by the

superposition of two high frequent signals of 18 kHz and 20.5 to 23.5 kHz. The angle of beam is 4° at a secondary frequency of 4 kHz. The footprint is about 7% of the water depth. Due to its small footprint the system provides a much higher lateral resolution than other low frequent systems, but it is also very sensitive to pitching and rolling motions of the ship and to inclined reflectors. While signals which are reflected from slopes with an inclination of more than 2° do not reach the receiver, are pitch and roll motions are automatically compensated by the system (Spieß, 1993).
The vertical resolution is limited by frequency and sound velocity and is in the range of decimetres. The horizontal resolution depends on the fresnel zone and water depth.
The penetration of the signal is determined by the density and acoustic impedance of the sediment layers. Therefore, the penetration depth and the reflector characteristics of the ocean floor are important information on the physical properties of the sediment and allow a mapping of different acoustic facies (Kuhn and Weber, 1993; Michels et al, 2002). The system provides high-resolution information of the sedimentary layers up to a depth of 200 meters below sea floor. A more detailed description of the system can be found at Spieß (1993) and Bergmann (1996).
In 2004 the hardware of the 1989 installed Parasound DS-1 system was upgraded to the system DS-2 (Fig. 3). The system is now controlled by the program Hydromap Control (ATLAS Hydrographic GmbH). The data are stored digitally on hard disk by the program PARASTORE from ATLAS Hydrographic GmbH as PS3 files. The PS3 format is similar to the SEG-Y format used in seismics. Parastore is also used to show the data online on screen and to print the data (online print). The new system enables a continuous operation and data storage.

PARASOUND-watch-keeping

The system was switched on standby at a few stations only and despite of some failures operated 24 hours a day during our stay in PIB. During operation, the system had to be supervised at all times. Responsibility of the watchkeeper was to make sure that the system was working in the correct depth interval.

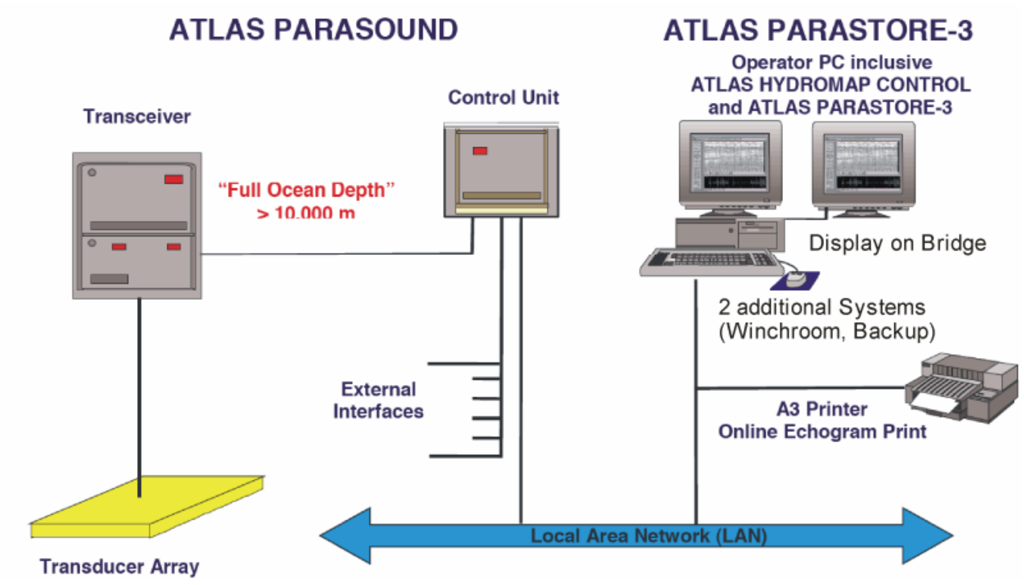

Fig. 3: System architecture of new ATLAS PARASOUND DS2 system with communication over local area network. (G. Kuhn, AWI-Bremerhaven)

Data analysis

The PARASOUND data were band-pass filtered (2 to 6 kHz), the amplitudes were normalized and the noise reduced using the program SENT by Hanno Keil, (University of Bremen, Department of Geosciences, Marine Technology). SENT was also used to plot the data.

The measurement of the maximum penetration of the PARASOUND signal into the seafloor was done by using the depth record of SENT. Correlation to ship position was done by using the time record in SENT. The results were added as new column to an ASCII-file which contained the ship position provided from the ships differential GPS. The ASCII-file contains time and ships position in 10 sec time intervals.

Displaying of the data

All maps were created using the free-available program Generic Mapping Tool (GMT). The used bathymetry is based on a grid provided by Frank Nitsche (Nitsche et al., 2006). This grid was provided as an ASCII-file and had to be edited before it could be read in GMT. Afterwards a new grid for the area 110°W to 98°W and 70.5°S to 75°S was calculated using the GMT program xyz2grd.

In order to show the maximum penetration of PARASOUND along the track a colourscale was calculated and the penetration was plotted with one coloured data point every 10 sec time using the previously prepared ASCII-file (see “data analysis”) as input.

Chronological project narrative

Ship time

On, the 10th of February 2006 the RV Polarstern departed Punta Arena (Chile) to start the fourth leg of the 23rd Antarctic Expedition (Fig. 4). After leaving the Magellan Strait the RV Polarstern set course towards the British research station Rothera (Adelaide Island, Antarctic Peninsula). Leaving the station the ship headed to Peter I Island, a volcanic island in the western Bellingshausen Sea. Finally the RV Polarstern made her way to the main working area the Pine Island Bay (PIB) in the south eastern Amundsen Sea. The RV Polarstern arrived at the outer shelf of PIB on the 23rd of February. Unfortunately, the first attempt to reach the inner PIB failed since the ship was blocked by meter thick sea-ice which was compressed by wind and currents. The ship made only a few meters per hour while breaking the ice and got finally stuck in the ice. Since no way opened into the ice free inner bay, the ship headed towards the western part of Amundsen Sea Embayment after two days of alternative work on the ice free outer shelf. Satellite images had promised better ice conditions for that area. After three weeks of successful work the expedition finally got a chance to enter the inner PIB through a path along the coast of Marie Byrd Land, passing Bear Peninsula, Crosson and Thwaites Ice Shelf.

The RV Polarstern crossed 110°W – the western boundary of the area for this study – on the early afternoon of the 11th of April. Since new sea-ice was forming due to the low temperatures, there were only a few days time for research before the ship would have been enclosed in the sea ice. During this time geological sampling took place as well as seismic-, hydrosweep- and parasound-surveying. The RV Polarstern started its way out of the bay on the 16th of March. Due to heavy sea ice condition it took until the early morning of 19th of March until the open ocean was reached and the shelf of PIB was left. The expedition continued its research program in the deep sea of Amundsen Sea and at the Marie Byrd Seamounts. After finishing scientific work there, the RV Polarstern headed towards the Argentinean research station

Jubany (King George Island, Antarctic Peninsula) stopping again at Peter I Island and Rothera Station. From Jubany the ship set direct course back to Punta Arenas where the expedition ended after eight weeks on the 11th of April 2006.

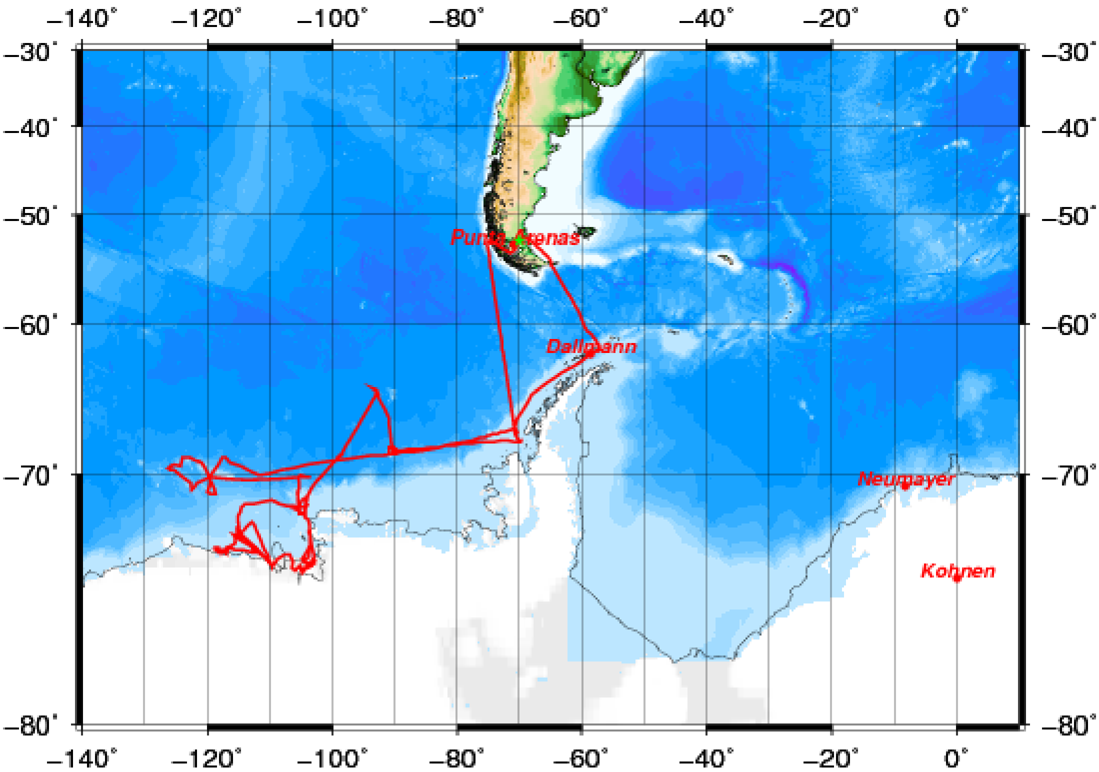

Fig. 4: Ship track of the expedition ANT-XXIII/4 of the RV Polarstern.
(Alfred Wegener Institute for Polar and Marine Research, Bremerhaven)

Project work

During the cruise with the RV Polarstern first discussions were held with Dr. Claus-Dieter Hillenbrand (British Antarctic Survey, Cambridge) and Dr. Gerhard Kuhn (Alfred Wegener Institute for Polar and Marine Research, Bremerhaven) concerning a project using the data of the expedition ANT-XXIII/4. The idea came up to map the maximum penetration of the PARASOUND-system within the PIB to give a base for a sediment distribution map of PIB for future work.

At end of June 2006 another meeting with Claus-Dieter Hillenbrand and Gerhard Kuhn took place in Bremerhaven, where more details of character, content and realisation of the project were discussed.

On the 4th and 5th of September talks about further proceedings of the project with Claus-Dieter Hillenbrand and Gerhard Kuhn were held in Bremerhaven. Among other things it was discussed which data would be required for this work. On these two days the copying of the required data also took place in Bremerhaven and Prof. Dr. Rüdiger Stein (Alfred Wegener Institute for Polar and Marine Research, Bremerhaven) could be enlisted as supervisor for the project.

The time from the 6th to the 15th of September was used for investigation of literature and to get familiarised with the data and software. The time was also used to find further data such as the bathymetric data of the study area.

The work was continued on the 9th of October and the time period until the 3rd of November was spent working on the data. During this period, the PARASOUND penetration was determined and the first maps where created. The provided bathymetric grid was edited to a format which could be read by GMT. The file being very large and containing more than 2.5 million rows caused some problems so the editing took an unexpectedly long time.

During the last one and a half week (the 9th to the 15th of November), most of the writing for the project report and the creation of the final figures and maps were done.

Results

First of all, it is outstanding that the depth of penetration is less than 5 m in most areas, which is caused amongst others by the rugged relief. Since in most of the study area penetration is less than 5 m, only penetration of more than 5 m will be mentioned in the following chapter. High penetration is found only in deep troughs and significant depressions. The Pine Island Bay (PIB) was split into the three parts West, South and North (Fig. 5). For the purpose of better description the three parts were divided in subparts. The order of description of the areas and order of numbering of subparts is based on the chronology of the expedition.

PIB-West (106°W to 110°W, 73.5°S to 75°S)

In the centre of the most western part of the study area a bathymetric high separates two troughs: one in front of Crosson Ice Shelf stretching in northwest direction, and the other from Thwaites Ice Shelf in northern direction (Fig. 6). While crossing this area, the ship had to break through thick sea ice; the inconstant speed and ramming, has reduced the data quality. In areas of a white coloured track, the disturbance of the PARASOUND-signal was such strong that the seafloor could not be determined.

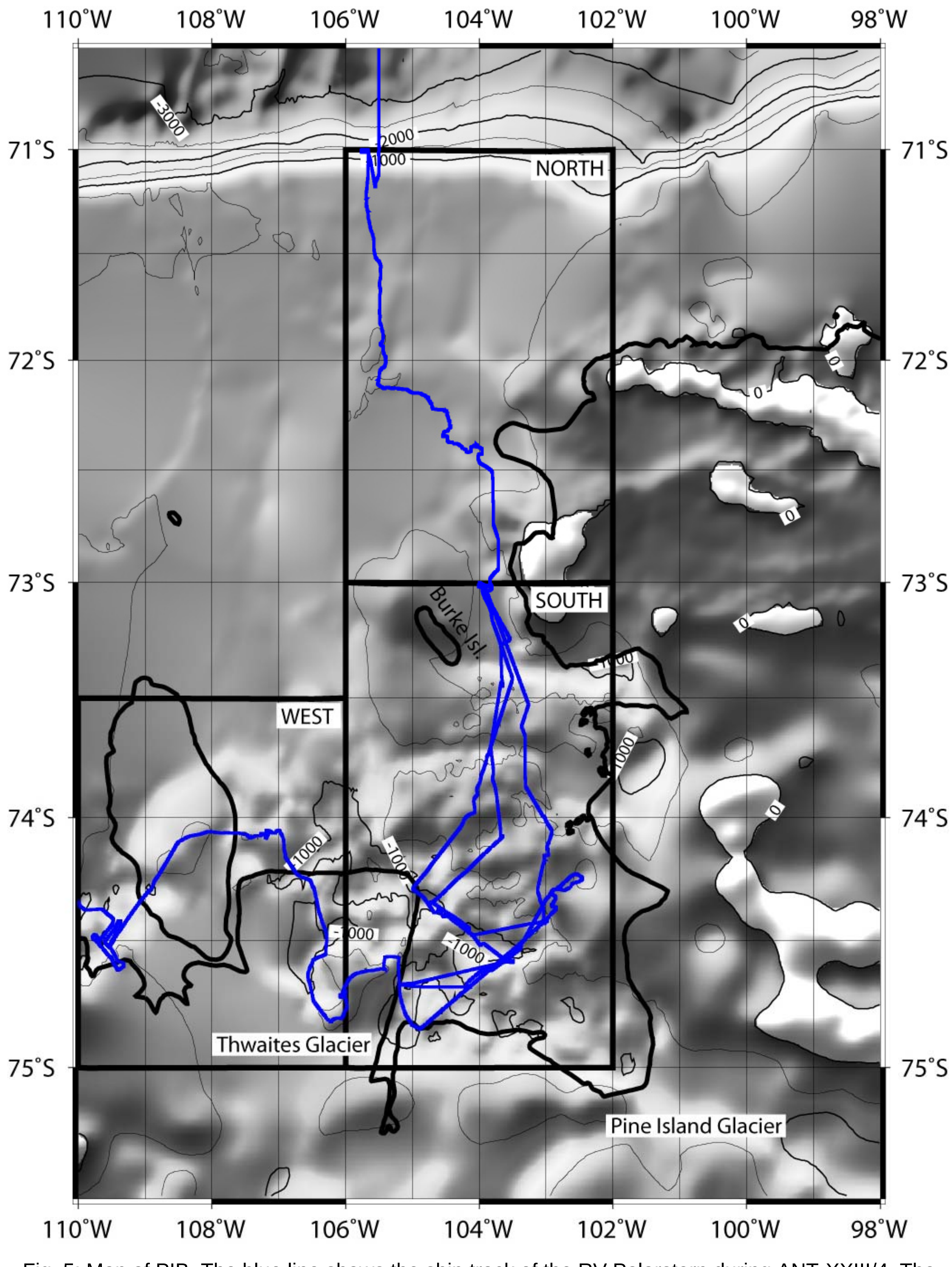

Fig. 5: Map of PIB. The blue line shows the ship track of the RV Polarstern during ANT-XXIII/4. The ship entered the study area in the southwest and left PIB in the north. The black boxes show the positions of the more detailed maps Fig. 6 (west), Fig. 7 (south), Fig. 8 (north). The thick black line shows the coastlines provided by GMT, these coastlines do not necessarily match up with the real coastlines, but they are shown for purpose of better orientation. Contour lines are plotted in intervals of 500 m.

This area was divided into two subparts (W1 to W2) (Fig. 6):

W1

W1 is located west of the bathymetric high at the western border of the study area. The five small patches of 15 and 30 m penetration depth found are all located in smaller depressions in water depth of 600 to 800 m.

W2

W2 is located on the western boundary of the area, where the bathymetry deeps to the trough in front of Thwaites Glacier and Pine Island Bay Glacier.
There is a larger area of up to 10 m penetration depth in a depression of water depth of 1000 m in the north of W2. To the south the penetration rises up to 15 and 20 m. Further to the south the relief is getting more rugged and penetration depths of 10, 15, and 20 m can be found in depressions.

PIB South (106°W to 102°W, 73°S to 75°S)

This part of the study area includes the centre and inner part of PIB. The density of data in this area is much higher than in the north and in the west. It includes the deepest parts of the study area with water depth of more than 1400 m (Fig. 5). The maximum penetration of PARASOUND varies between less than 5 and less than 45 m. The central part of this area is also characterized by a rugged bathymetry.
The area was divided into six parts (S1 to S6) (Fig. 7):

S1

S1 is located next to the western margin of the trough in a depth of more than 1400 m. To the west there is a steep rise in the bathymetry to less than 600 m water depth. The area shows a maximum penetration of up to 35 m which is thinning and instantly fading out to the north to less than 5 m penetration depth, while thinning out to the south on a longer distance with a penetration depth of up to 15 m.

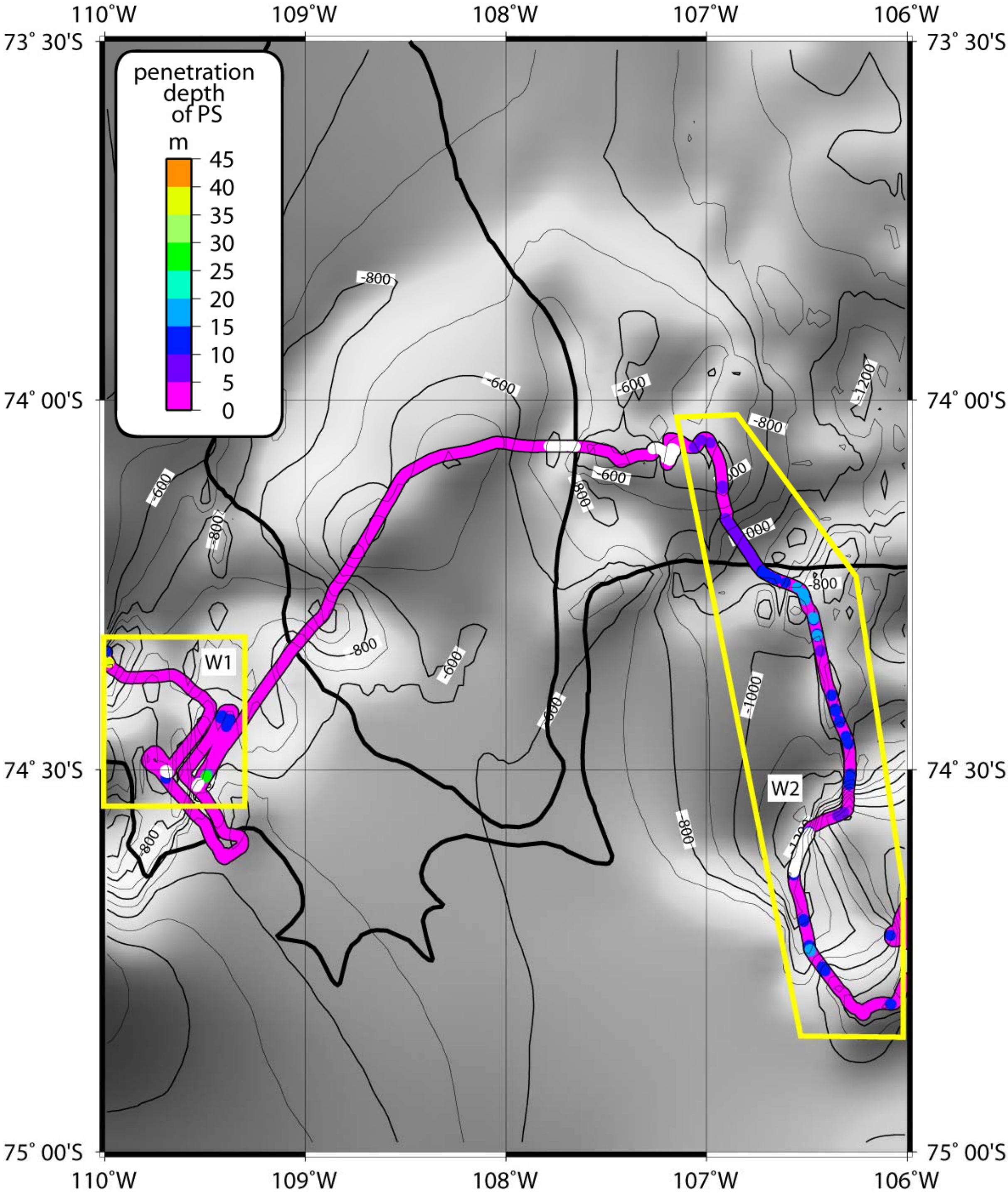

Fig. 6: PIB West. The ship track shows colour coded the maximum acoustic penetration depth of the PARASOUND-system (PS); white coloured parts mark areas where data quality was to bad to determine a penetration. The yellow boxes mark the subparts which are explained in more detail in the text. The thick black line shows the coastlines provided by GMT, these coastlines do not necessarily match up with the real coastlines, but they are shown for purpose of better orientation. Contour lines are plotted in intervals of 100 m.

S2

S2 includes only two small patches of higher penetration depth located on the periphery of a small depression with water depth of more than 1400 m. The patches show a penetration of up to 35 and 45 m. The latter is the deepest penetration of the study area.

S3

S3 crosses the central part of the trough and shows sporadic patches of penetration depths from 20 to 30 m but as well as some spots with less penetrations (5, 10 and 15 m). The deepest part of the trough – more than 1200 m – shows an accumulation of higher penetration depth (10 and 15 m).

S4

S4 stretches along the centre of the trough in northeastern direction. It shows a larger area of penetration depth of up to 15 m, which is thinning out to the northeast to penetration of less than 10 m.

S5

S5 follows the trough further northeast. It is located in a narrow depression with steep slopes of more than 1300 m water depth. The PARASOUND signal penetrates up to 40 m into the seafloor in the centre of the depression, while the penetration is getting less (up to 30 m) towards the steep slopes of depression.

S6

S6 is a large area with relatively flat bathymetry and water depth of 500 to 600 m, which shows a continuous penetration depth of 10 m. It is the largest area in the PIB of a continuous penetration of more than 5 m, but it also shows three separate patches of more than 10 m penetration depth.

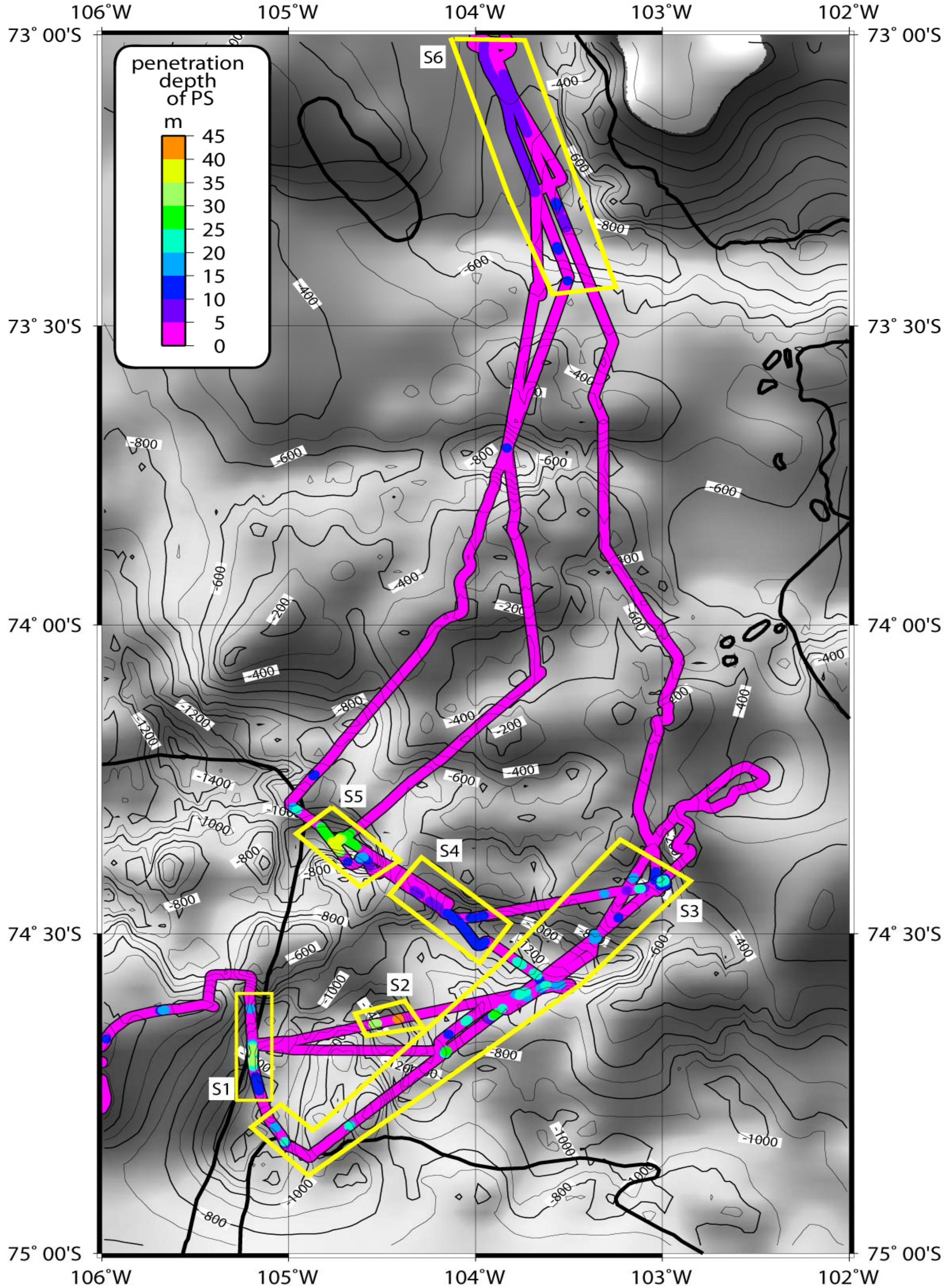

Fig. 7: PIB South. The ship track shows colour coded the maximum acoustic penetration depth of the PARASOUND-system (PS); yellow boxes mark the subparts which are explained in more detail in the text. The thick black line shows the coastlines provided by GMT, these coastlines do not necessarily match up with the real coastlines, but they are shown for purpose of better orientation. Contour lines are plotted in intervals of 100 m.

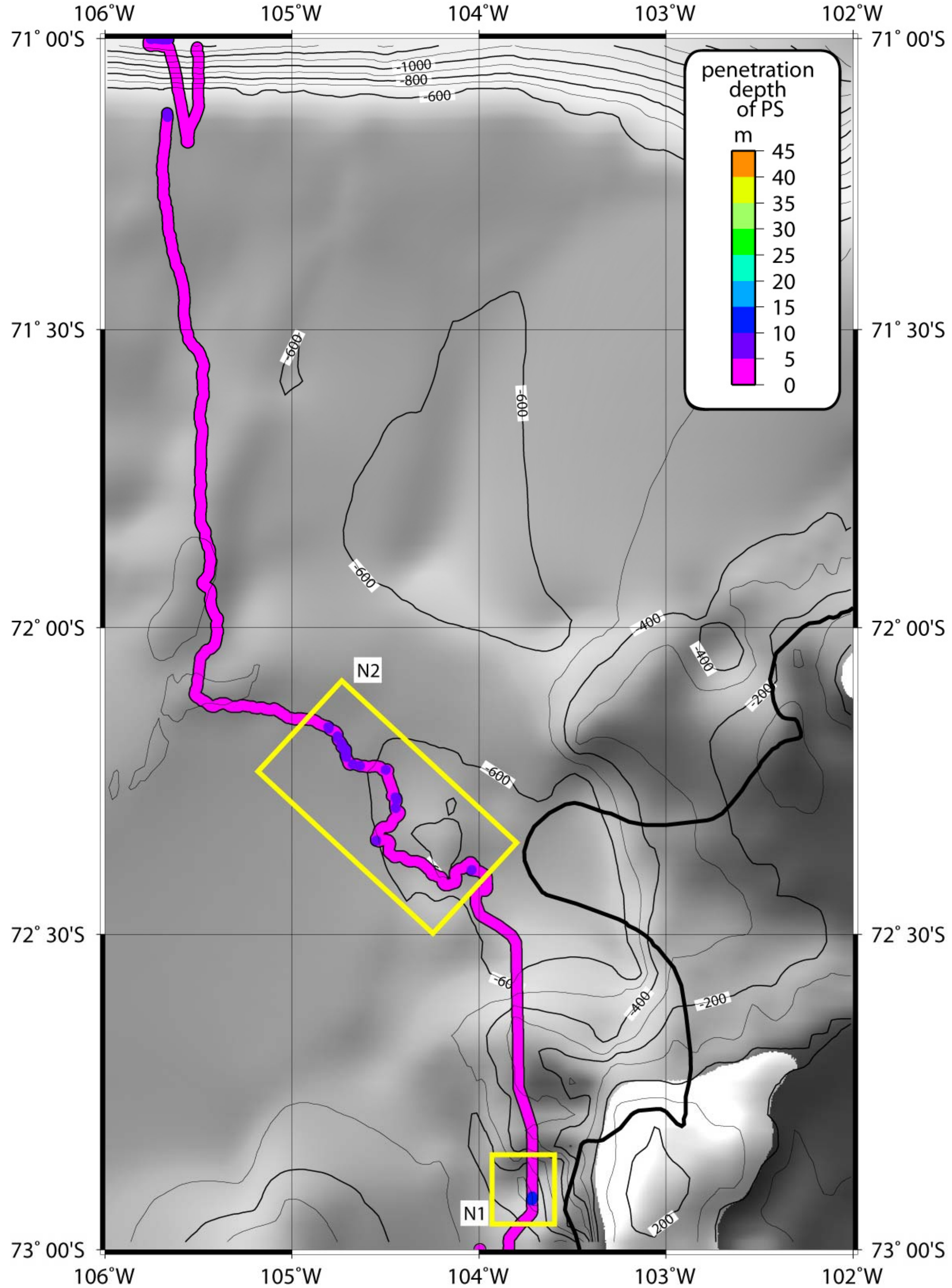

Fig. 8: PIB North. The ship track shows colour coded the maximum acoustic penetration depth of the PARASOUND-system (PS); yellow boxes mark the subparts which are explained in more detail in the text. The thick black line shows the coastlines provided by GMT, these coastlines do not necessarily match up with the real coastlines, but they are shown for purpose of better orientation. Contour lines are plotted in intervals of 100 m.

PIB North (106°W to 102°W, 71°S to 73°S)

The northern part of the study area is located on the middle and outer shelf with a relative shallow water depth of about 500 m compared to the deep trough of the southern study area (Fig. 5). The penetration-data north of 72.5°N are based on very low data quality since the ship had to break through thick ice.
The area was divided into two parts (N1 and N2) (Fig. 8):

N1
The small area of N1 is located in the centre of a depression in about 600 m water depth. The penetration depth is here about 15 m.

N2
N2 is an area of relative plane bathymetry and a water depth of 500 to 600 m. The area shows a significant number of discontinues patches of a penetration depth between 5 and 10 m. The ice in this area was very thick and the ship had tremendous problems to break through the ice by ramming. For that reason, the data quality was very low and as it was sometimes difficult to determine the maximum penetration depth of the PARASOUND some errors might have occurred.

Summary and outlook

Summary

The PARASOUND-data of the study area show all a relative small penetration depth. The acoustic penetration is between 0 and 45 m, but in most parts of the area less than 5 m. The maximum of 45 m occurs only at one point. The bathymetry is very rugged in most parts of the study area. Due to the sensibility of the PARASOUND-system to a dipping seafloor the wide low penetration depth is not only an effect of the physical properties of the seafloor, but also of the relief. Data quality in western and northern parts of the study area was strongly influenced by sea ice conditions, due to inconstant speed, ramming and the ice itself. In some parts of PIB West disturbances during measurements were so strong that the seafloor could not be located. While PIB North has almost no penetration of more than 5 m, PIB West has some parts of deeper penetration in troughs and depressions. High penetration was almost exclusively found in the deep troughs – especially in depressions within the troughs. Since PIB South includes the deepest troughs, it is the area where one can find the penetration at its largest; here the high penetration is most frequently. This part has also the highest density of data, the largest continuous area of penetration larger than 5 m and the deepest penetration depth (45 m).

Outlook

In face of a future map of PARASOUND-penetration for PIB it is important to improve the density of the data points. Therefore it would be interesting to add subbottom-profiler data of other expeditions to this work. Taking sediment samples and seismic data into account would allow to create a high resolution sediment facies map and would give important information for sediment distribution in PIB.

Critical self-evaluation of the project

I underestimated the time I needed to become acquainted with the used programs. Especially I underestimated the time I needed to program the GMT scripts. I thought after a few GMT lectures in university I would easily be able to write a GMT script which satisfies my demands. Since we usually got a prepared script during lectures it was quite a challenge to write my own. I had also some problems to edit the provided bathymetric grid to make it readable for GTM. It cost a lot of time to find a proper way to edit the grid. Finally I solved all problems by myself and improved my organizational skills, my time management and my knowledge of the programs GMT and SENT

Acknowledgments

I would like to thank Claus-Dieter Hillenbrand and Gerhard Kuhn for providing me with the data and also for the assistance they send to me from a small island and the end of the world. I also would like to thank Frank Nitsche for providing me with the bathymetry, Rüdiger Stein for undertaking the task of marking, Anna Trampe for all the feedback and Siri Rackebrandt for continuously improving my English.

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