Terra Antartica
2001, **8**(2), 41-48

TERRA ANTARTICA
AN ANTARCTIC EARTH SCIENCE JOURNAL

The Neumayer Array and Its Impact on Seismological Research in the South Atlantic and Antarctica

T. BÜSSELBERG, C. MÜLLER & A. ECKSTALLER*

Alfred Wegener Institute for Polar and Marine Research, Columbusstraße, D-27568 Bremerhaven - Germany

Received 26 January 2000; *accepted in revised form* 25 September 2000

Abstract - In the austral summer season of 1997, a small-aperture seismological array was installed in the vicinity of the Neumayer German base in western Dronning Maud Land, Antarctica. Small-aperture arrays are important seismological tools for the detection and localisation of weak earthquakes on a local and regional scale. The advantage of seismological arrays over single station recordings is the possibility of directly estimating the slowness vectors of seismic signals. Another advantage is the enhancement of the signal/noise ratios by stacking or beamforming. The array consists of 15 short-period vertical sensors which are arranged in three concentric rings with a maximum diameter of 2 km. The central seismometer is a 3-component broadband sensor. The array design was adopted from existing arrays in the northern hemisphere such as the Norwegian NORESS and ARCESS arrays. In the same season, a standard broadband seismological station (station code SNAA) was installed at the new Sanae IV South African base, and in the beginning of 1998 another seismic station was installed at the Belgrano II Argentinean base (BELO). SNAA and BELO extend the existing Neumayer seismological network to an aperture of 1100 km.
Since deployment of the array, some local events at the passive continental margin of Dronning Maud Land have been identified. The detection of these events shows the excellent capability of the array and will contribute to a better understanding of the tectonic evolution of this region. More than ever before it is now possible to detect seismic events in the South Sandwich region and to locate earthquakes with greater accuracy. Many events observed in this region did not appear in the global catalogues.

INTRODUCTION

The seismogenic regions of the South Sandwich subduction zone, the northern and southern Scotia fracture zones extending to the northern parts of the Antarctic Peninsula, as well as the South Atlantic plate boundaries, including the Bouvet hotspot, are regions in which the detection threshold is very low due to the scarce distribution of stations in the global network. The Scotia Sea and the seismotectonic behaviour of the surrounding plate boundaries are of particular interest, since the tectonic evolution of this region is not yet fully understood (Pelayo & Wiens, 1989). Mechanisms of the intraplate seismicity near the South America-Africa-Antarctica triple junction induced due to internal deformation (Wysession et al., 1995) may be better investigated. Enhanced detection and localisation capabilities in these regions would help better define total seismicity as well as earthquake source parameters and would allow the monitoring of seismicity within the Antarctic continent which appears to be seismically very quiet (Adams & Akoto, 1986).

Neumayer Base, located at 70.66° S and 8.26° W on the Ekström Ice Shelf (Fig. 1) near the Atka Bay coastline, is a snow-buried construction of corrugated steel tubes. The base contains observatories for the study of atmospheric chemistry, meteorology and geophysics. The geophysical observatory is used for geomagnetic and seismological observations. Given the small number of permanently operating geophysical observatories in the southern hemisphere and Antarctica, the observations at Neumayer are essential for providing sufficient geophysical data from this continent.

Through the years the Neumayer seismological network has been systematically extended. The seismological observations started with three S-13 seismometers (station code VNA1, eigenperiod 1 sec) at the Neumayer base and three remote seismographic stations in the wider area around Neumayer Station (Fig. 1), which are located on the ice shelf. Due to the water layer beneath the ice shelf, the observation of S-phases is drastically impaired; seismic stations were therefore installed further south of Neumayer Base. These stations are located 50 km SE of Neumayer on the Halvfar Ryggen (station code VNA2, 3-components, eigenperiod: 20 sec) and 90 km SW on the Søråsen (station code VNA3, 3-components, eigenperiod: 5 sec), both at approximately 350 m and 500 m above sea level. In contrast to the stations on the ice shelf, these stations are located on ice rises. Due to their particular position on grounded ice, these two stations are of great importance for the observation of shear-waves.

Due to weather and ice conditions in Atka Bay, the signal/noise ratio is bad, and the detection capability of the network was therefore very weak. Events with a magnitude below 5.0 and small local events could not be detected.

It was therefore necessary to extend the existing network. The "Neumayer Array" was installed on the Halvfar-Ryggen (February 1997), a seismological station was installed at the Belgrano II Argentinean base (1998,

*Corresponding author (aeckstaller@awi-bremerhaven.de)

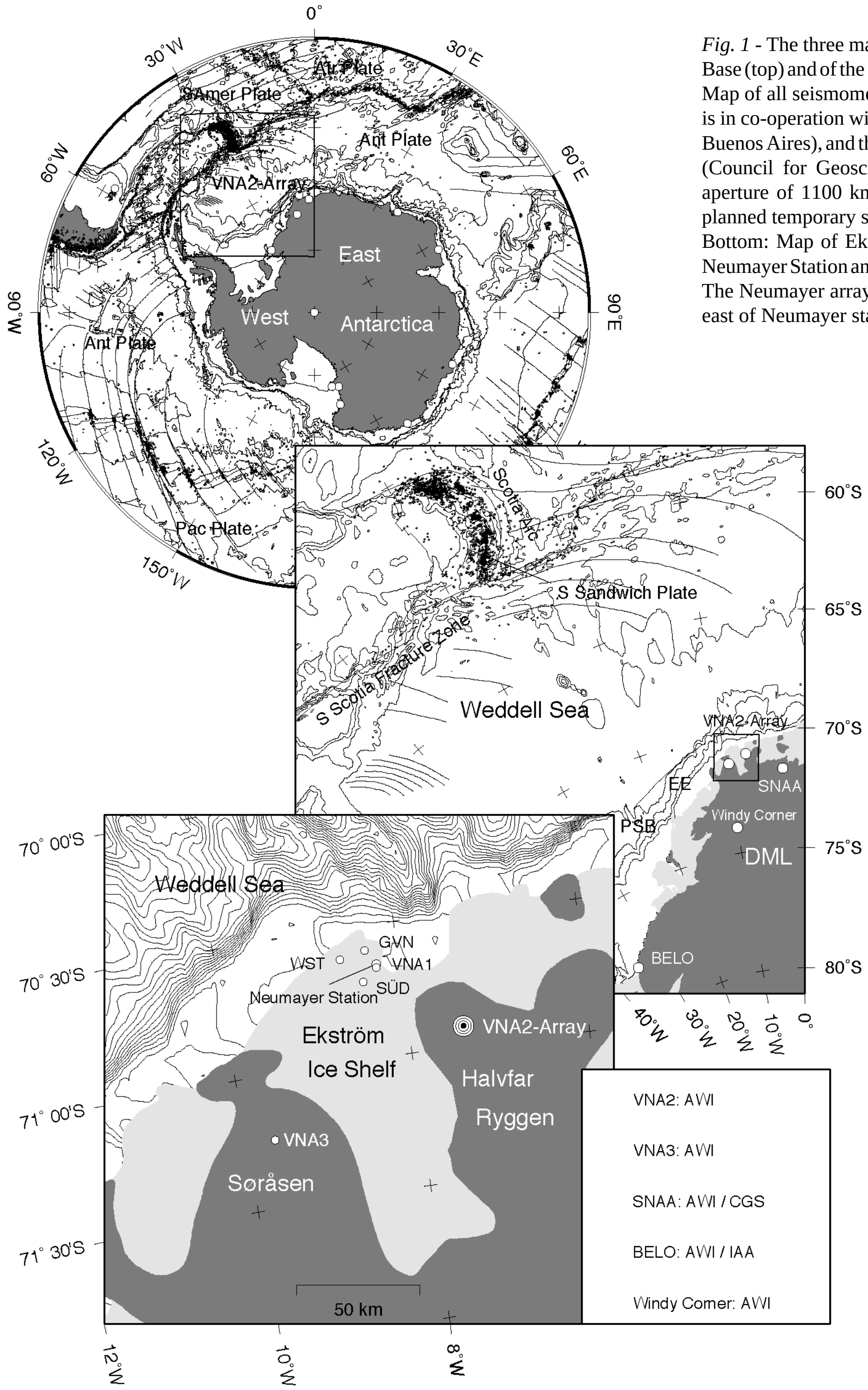


Fig. 1 - The three maps illustrate the location of the Neumayer Base (top) and of the seismic sites (middle and bottom). Middle: Map of all seismometer stations. The station at Belgrano Base is in co-operation with the IAA (Instituto Antartico Argentino, Buenos Aires), and the station at the SANAE Base with the CGS (Council for Geoscience, Pretoria). This network yields an aperture of 1100 km. "Windy Corner" is the location of the planned temporary station in the 1999/2000 southern summer. Bottom: Map of Ekström Ice Shelf showing the locations of Neumayer Station and the stations of the seismological network. The Neumayer array is located on the Halvfar Ryggen, south-east of Neumayer station

eigenperiod: 20 sec) and a broadband station (station code SNAA) was set up at the new Sanae IV South African base (1997). Figure 1 illustrates the location of these stations. As a result, a complete network of 24 stations and a total network aperture of 1100 km was established.

Another important point that can be focused on using array recordings is the detailed examination of azimuth and slowness anomalies beyond the passive continental margin of Dronning Maud Land (DML). Azimuthal dependent traveltime anomalies were reported by Eckstaller (1992) and are associated with large scale lateral heterogenities and seismic anisotropy. Appropriate array recordings may contribute to explain these anomalies in more detail.

In the first years the acquisition system of the Neumayer network (PCM5800) worked in a trigger mode with a tape recording system. The remote stations on the ice shelf are equipped with 1 Hz seismometers (LENNARTZ Le-3D / 1sec) and only the vertical component is transmitted. The stations transmit the amplified FM-modulated signals and the dynamic range is therefore limited to 60 dB. The stations on the Halvfar Ryggen and Søråsen are equipped with autonomously running PCM-systems. They operate in a gain-ranging mode which enables a dynamic range of nearly 120 dB. In the geophysical laboratory, the transmitted digital code is added to the central PCM-mixer unit, which also evaluates the transmitted trigger-status. Since 1998 the whole network around Neumayer base works in a continuous mode with a sample rate of 62.5 Hz.

First arrival times and other phase readings of recorded events are sent to NEIC and ISC on a regular basis.

NEUMAYER ARRAY

The installation of the array had four scientific objectives:

1. Continuous monitoring of regional seismic activity at distances up to 30°. Normally, the magnitude of local and regional events at these distances, *e.g.* the South Sandwich Islands, the Scotia Sea, South Atlantic Ridge or the Antarctic Peninsula, are too small to be recorded by stations outside Antarctica. The array can help to find a better and new understanding of seismicity and tectonics in this region.

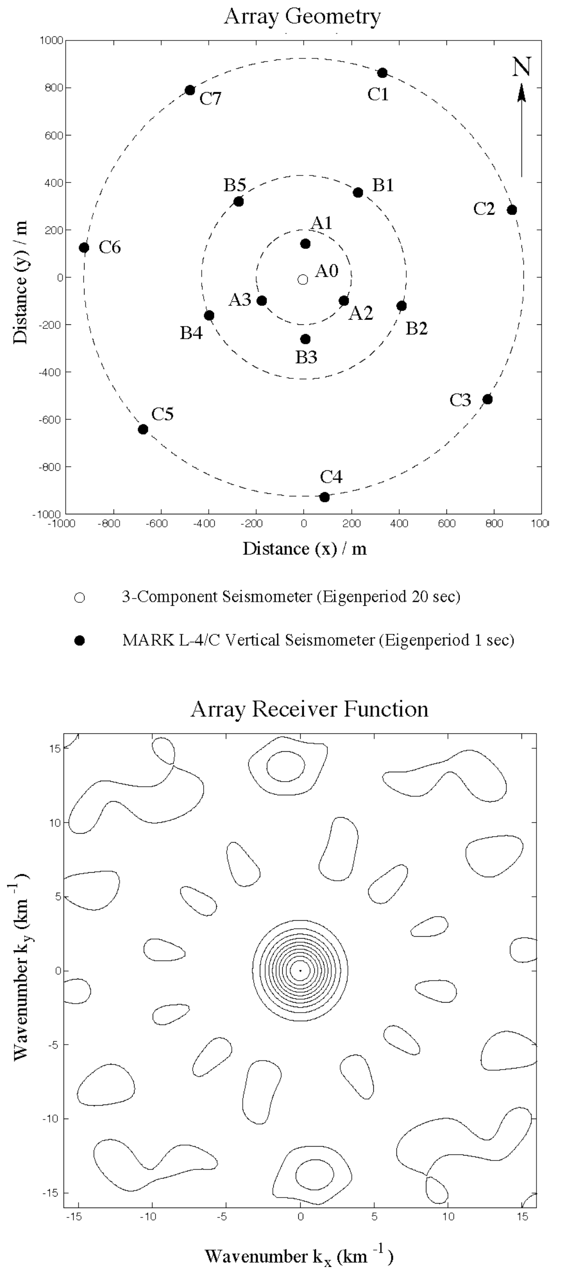


Fig. 2 - Above: The geometry of the Neumayer array. The seismometers are located on three concentric circles with three, five, and seven vertical sensors. The central seismometer is a 3-component broadband sensor. Bottom: The corresponding array response function in wave-number space. The concentric contour of the maximum represents that wave-number domain which can be resolved by the array. Aliasing effects may occur at the weaker maxima representing longer wave-lengths. Each contour line corresponds to 10% of the maximum energy, the highest density of contour line indicates the maximum of energy.

2. The analysis of slowness and azimuth anomalies. In some cases the differences between theoretical and observed backazimuths are large and seem to be systematic. Similar differences can be observed for the apparent velocity or the slowness vectors. The array allows the analysis of the structure of the earth's crust and upper mantle in the area of the Neumayer station.
3. Data from the seismological network and the array may provide missing data for current investigations of the earth's crust. This may help better understand the structure of the crust in this region of the earth.
4. To continue the analysis of teleseismic travel time residuals (Eckstaller & Miller, 1992) with enhanced resolution.

The design of the Neumayer array is very similar to that of the NORESS and ACRESS arrays in Scandinavia or the GERESS array in Germany. The basic concept for the design of these arrays was published and described several times (Followill & Harris, 1983; Mykkeltveit, 1985; Harjes, 1990). It is configured in three concentric rings around the central stations with 3, 5, and 7 elements in each ring. Each of these 15 elements are 1 Hz vertical short-period instruments (LENNARTZ Mark L4). Only the central instrument is a 3-component station with an eigenperiod of 20 sec. The radii of the concentric rings follow the equation:

$$R = Rmin\ 2.15^{n-1},\ n = 1,2,3$$

The Rmin radius is 200 meter, the largest radius is 925 meter. Figure 2 (top) shows the geometry of the array. This configuration results in a large number of different distances between the seismometers. This is necessary for a homogeneous sampling of the complete wavefield and to reduce the effects of spatial aliasing in the wavenumber domain. The distribution also guarantees that detection is independent of the arrival direction of a wave. This configuration comprises subsets of sensors with very different intersensor separations, implying that both high-frequency and low-frequency regional phases can be well enhanced by appropriate subsets of the array (Kværna, 1989).

The design of the array is based on the assumption that intersensor spacings have a maximum correlation with the signal and a minimum correlation with noise. Seismic signal and noise characteristics are not only influenced by the geological structures of array sites, but also by the type and strength of sources and their locations with respect to the array (Harjes, 1990).

Figure 2 (bottom) shows the array response function, the Fourier transform in the frequency-wavenumber domain. The concentric shape of the maximum in the middle represents the wave number range that can be resolved by the array. There are only very weak secondary maxima at larger wave numbers for which one might expect some aliasing effects.

In contrast to initial plans, some of the sensors were not installed directly on the rings. This was necessary to reduce aliasing effects when recording high frequency regional earthquakes. These corrections resulted in a reduction of the sidelobes of the array response function.

The ability to detect small earthquakes based on the

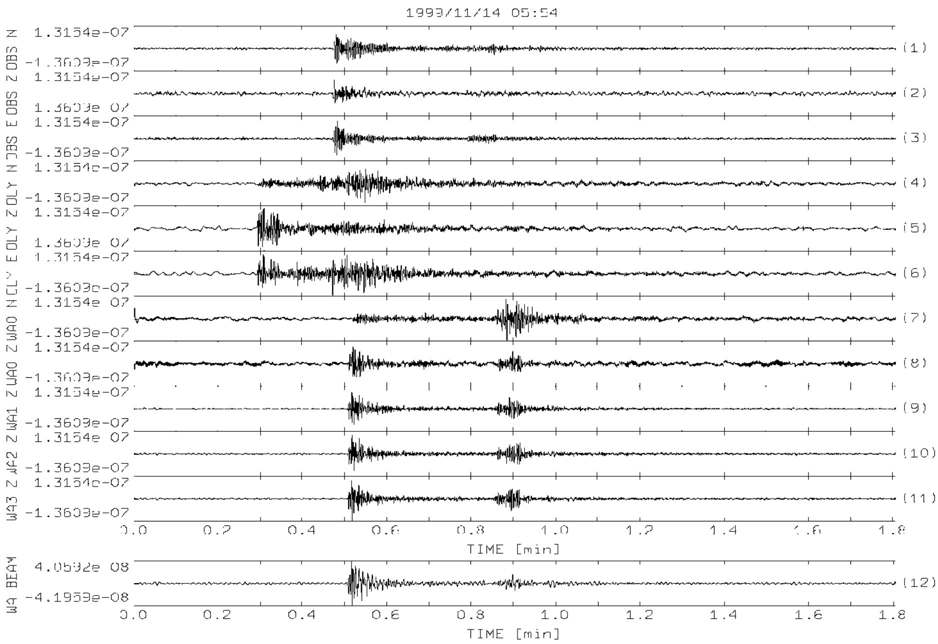


Fig. 3 - Recording of a local event, located 120 km east of Neumayer station, from 99/11/14. The recordings of the 3-components (VNA1, VNA2, VNA3) and that of the Neumayer array beam are shown.

coherence of waveform depends on distances between instruments. The largest wavelength (smallest wavenumber) is given by the largest distance between the seismometer and the shortest distance corresponding to the smallest determinable wavelength (largest wavenumber). The main lobe of the array response (Fig. 2, bottom) clearly shows, that the Neumayer array can resolve wavenumbers between approx. 0.4 and 2.0 km^{-1}. This corresponds to an epicentral distance up to 30° (*e.g.* South Sandwich Islands).

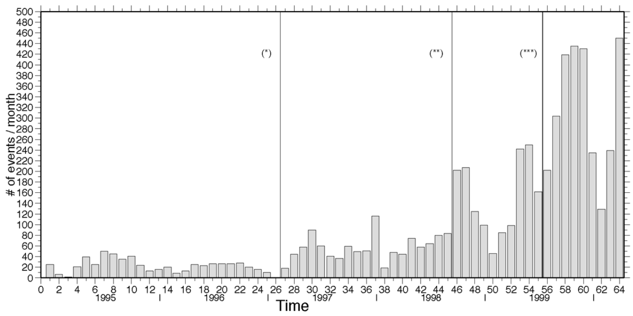
For this distance range it is possible to improve the signal/noise ratio through a numerical procedure like beamforming. For the Neumayer array this results in a significantly better signal/noise ratio. Moving frequency-wavenumber analysis (fk-analysis) of array data allows high resolution analysis of azimuth and slowness anomalies. Both methods help identify the phase type of the waves. This additional information makes it possible to locate the earthquake by using a global or local earth model.

Based on these advantages of an array, one of our major aims was to improve the detection rate and to decrease the detection level. In addition, the stations at Belgrano II and Sanae IV can confirm the observation of local and regional events and may help locate these events with good accuracy. The earthquake illustrated in figure 3 is located 120 km east of the Neumayer Array; it is an example of an earthquake, which occurred within the Antarctic continent but was not detected in any of the global networks.

FIRST RESULTS

One of the aims was to lower the earthquake detection limit. Figure 4 shows the statistics of the detection rate in the last 5 years. Two significant increases are observed: the first when the array was installed (February 1997), the second when a new acquisition software and a trigger algorithm were installed (September 1998). The figure illustrates a strong increase in the number of detected events due to the installation of the array. One can observe a seasonal effect. In the southern summer the number of detected events is low due to noise conditions in Atka Bay. Normally the sea is ice-free in the summer and generates strong noise with a high grade of signal coherence. As a result, the trigger and detection algorithm can not distinguish between noise and signal. This problem could be solved if the array were deployed much farther south and at greater distances from the coast. Unfortunately, this is not possible for logistic reasons and for the adopted data transfer technique.

Another aim of a long term observatory is the contribution of event data to data centres like ISC or NEIC. Figure 5 shows the distribution of earthquakes that are observed on the Neumayer network. The location of these events, a subset of the actually observed ones, are taken from NEIC. Each year more than 300 events are not registered in the NEIC or ISC bulletins. Most of these events are small or local events which are not observed by a large number of stations. Especially in the area of the South Sandwich Islands, twice as many events were



(*) - Deployment of the array
(**) - Continuous registration and automatic analysis of PCM Triggerbits
(***) - First month of automatic triggering/analysis with NORSAR-Software

Fig. 4 - Frequency distribution of detected events at the Neumayer seismological network from 12/1995 until 3/2000. After deployment of the array, there is a clear increase in the number of detected events and further improvements by the use of better detection algorithms.

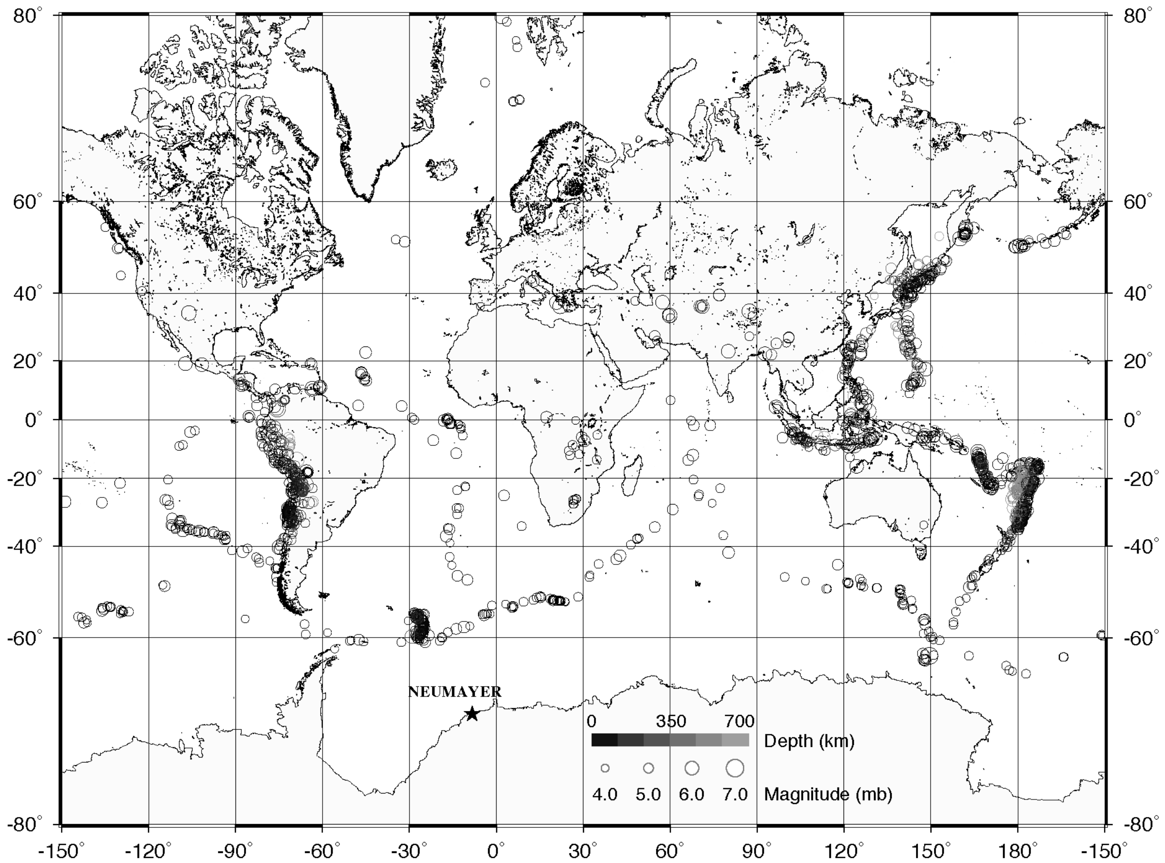


Fig. 5 - The distribution of earthquakes observed by the Neumayer network in 1997/1998. The locations of these events are taken from NEIC. Subglacial topography from Steinhage et al. (1999).

detected than appear in these global catalogues. As described above, before the installation of the array, local earthquakes were never observed. Figure 6 shows the

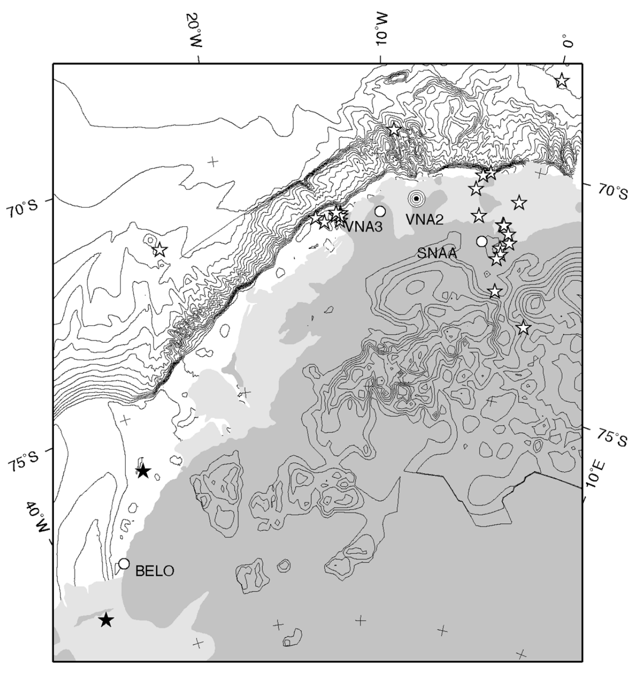


Fig. 6 - Map showing local events which occured since deployment of the array (white stars). Note the clusters at Kapp Norvegia, west of VNA3, and a NS elongating line east of SNAA, the Jutul-Penck-Graben. The two events around BELO (black stars) were only detected in the BELO recordings and localised from S-P travel time differences and P wave polarisation analysis.

location of local earthquakes that have been detected and localised since the deployment of the array. The locations of these events were calculated by the new Hyposat software (Schweitzer, 1997).

This software uses all station-to-event azimuth (backazimuth), travel-time data (*e.g.* for phases included in ak135-type tables (Kennett et al., 1995)), and ray parameter values to locate events. The initial source time is derived from all S-P travel-time differences after Wadati (1933) or derived from the earliest onset time at the closest station. The linearized system of normal equations is solved by an iterative inversion with the Gernalized-Matrix-Inversion (GMI) technique (*e.g.* Menke, 1989) using Single-Value-Decomposition algorithm (SVD). All partial derivatives are calculated during the inversion process and the Jacobi matrix is recalculated for each iteration. The iteration process stops, if the change between two different solutions falls below a predefined limit.

The observed local events are located along the passive continental margin of Dronning Maud Land. The region east of the base Sanae IV and an area west of Neumayer (Kapp Norvegia) is of special interest. Events are located in areas of old fault systems along the Jutul-Penck-Graben (Paech et al., 1991) and off Kapp Norvegia (Kaul, 1991). About 29 earthquakes were triggered in the surrounding area of the Neumayer network. Only the largest event (1997/12/25 22:13:02.00, -71.0966S, -24.2318W, mb=3.9) can be found in the Bulletin of the ISC.

The detection of these events shows the excellent capabilities of the array and will contribute to a better

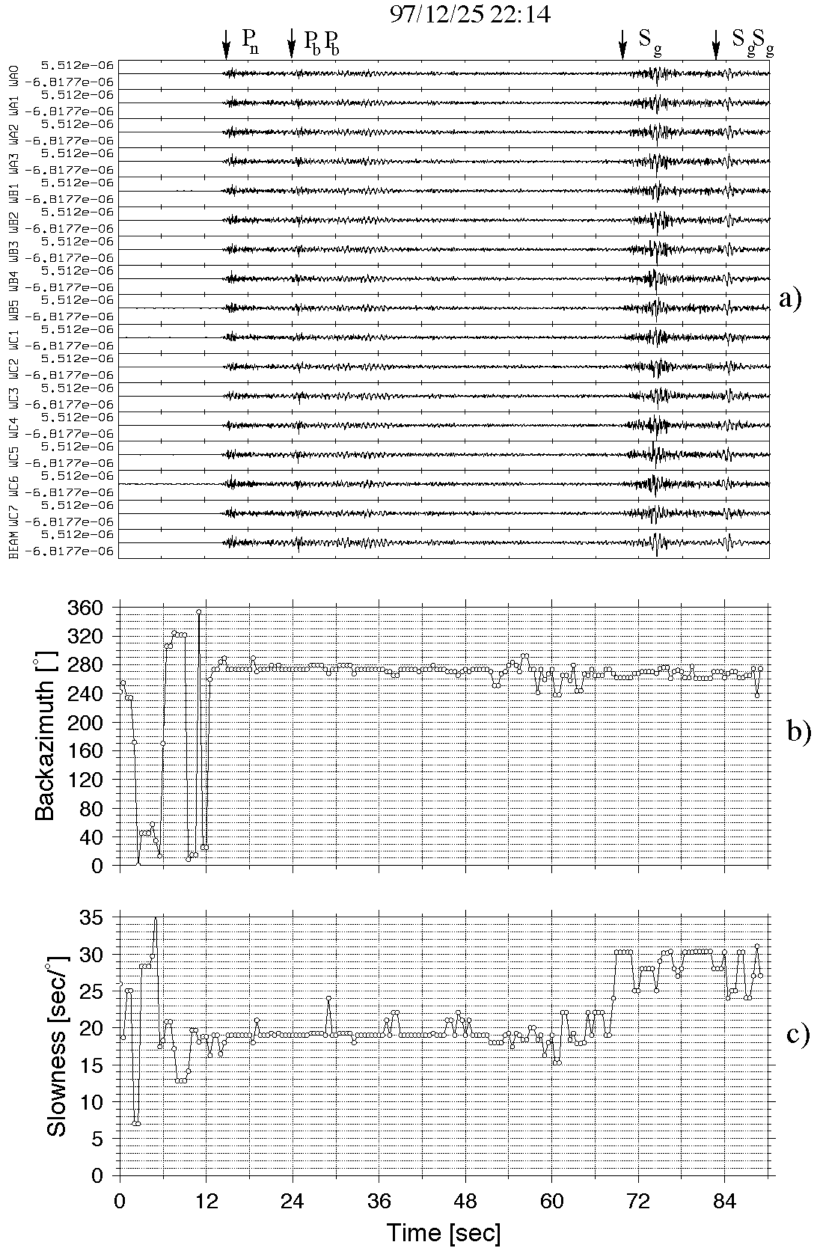


Fig. 7 - Example of an earthquake registration with hypocenter in the eastern Weddell Sea (a), corresponding lower diagrams show the result of a moving window frequency-wavenumber analysis: backazimuth (b) and slowness (c). The points mark the results of the analysis of a 1sec-window which moved in 0.5 sec steps along the seismogram.

understanding of tectonic processes in this region. There are two important array techniques for earthquake detection and localisation. One is the frequency-wave number analysis, which searches for the direction and velocity of the energy in the wavefield. The other is the beamforming technique, which also investigates the direction and velocity of earthquakes, but works in the time domain by rotation and stacking the traces of the array.

Figure 7 shows the result of a moving frequency-wavenumber analysis (fk-analysis) on a local earthquake which occurred in the western Weddell Sea 120 km from the Neumayer base. At top we see the recorded traces of the event.

The two plots below show the results of the moving fk-analysis. This demonstrates the stability of this analysis for determining backazimuth and slowness. Only the slowness of the S-wave appears to have some uncertainties, which depend on the effects of wave scattering along the ray path. The quality of this slowness estimate allows the determination of the type of phase. This is useful for localising the event.

Figure 8 (top) shows a plot of a typical 30 minute record from the Neumayer network. Due to the bad signal/noise ratio it is very difficult to analyse the local event inside this reord.

A selection of 4 traces (Fig. 8, bottom), here the 3-components of the central station and one trace of the array, illustrates the noise situation. The signal/noise ratio is very low in these unfiltered traces. Trace 5 shows the trace after the beamforming procedure and the improvement of the signal/noise ratio.

For the interpretation of tectonic processes, *e.g.* in the South Sandwich Island subduction zone, based on earthquake data, the location and ray path of these events is important. Figure 9 shows an example of different localisations for one earthquake. As the location depends strongly on the number and distribution of stations, extreme differences in the location are observed. Localisations based on Neumayer array data alone are offset with respect to other localisations; this difference can be caused by local or regional differences in the ray path. Only when the complete Neumayer network data set and the Belgrano II and Sanae IV arrival times are considered the locations agree with those of NEIC or PIDC.

FURTHER DEVELOPMENT AND STUDIES

The location of local earthquakes observed since installation of the array is shown in figure 6. Given that no earthquakes were observed in the continental area south of Neumayer base, a temporary station will be installed

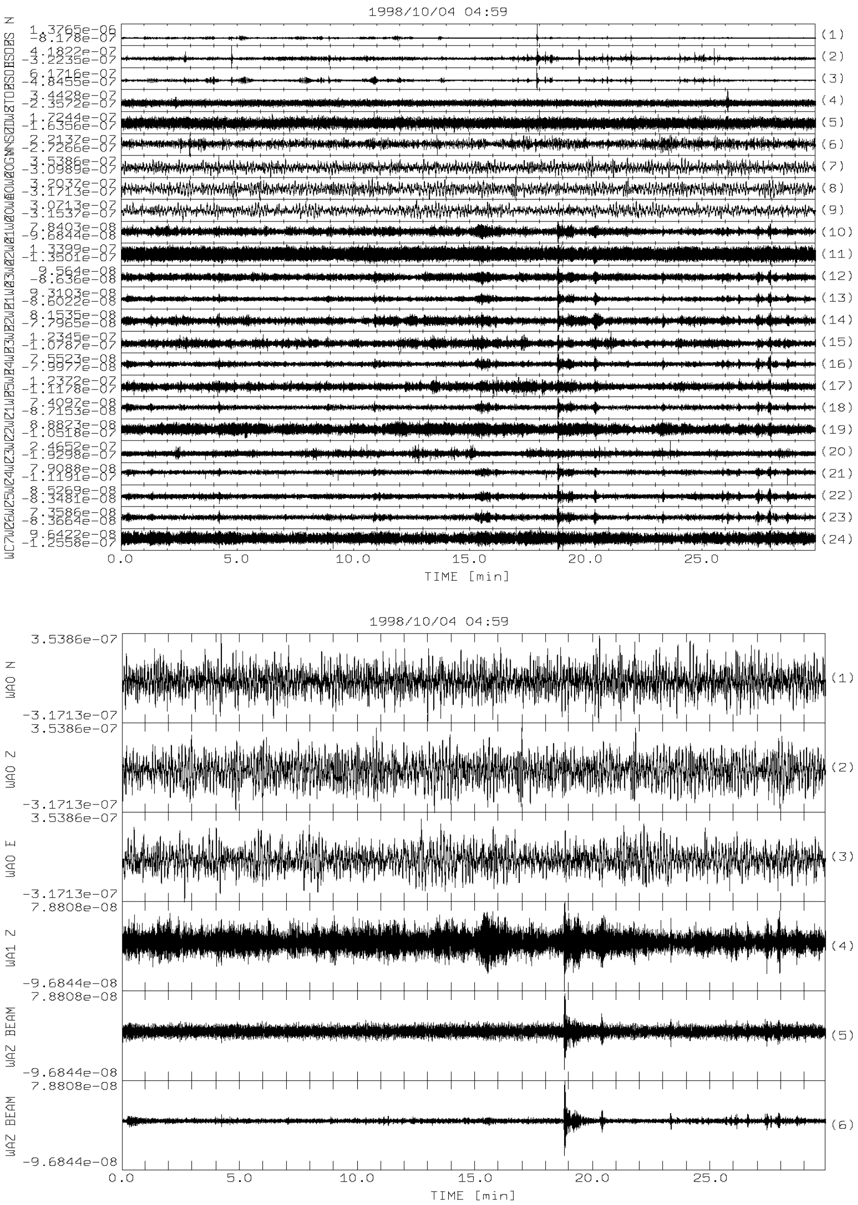


Fig. 8 - Top: Example of a typical 30 minute data block of the Neumayer network. This figure illustrates the noise situation. Without any beamforming procedure (Fig. 9) it is not possible to analyse the local event inside this record. Bottom: Recording of a local event and the result of the beam-forming procedure. The top three traces are from the central 3-component station, the fourth trace is from one station of the array. The fifth trace is the result of beam-forming, and the trace on the bottom is the filtered beamtrace.

400 km south of Neumayer (Fig. 1). This station should be operating for three months in the next southern summer.

Aims include improved automatic analysis of the continuous data and automatic reporting of earthquakes to international data centres.

In the future parameters and waveform data will be available via permanent satellite links. A data bank with location and parameters of observed earthquakes will be established.

In addition to the investigation of local and regional events, the main topics of research are (Eckstaller et al., 1997):

1. calculating and modelling receiver functions using selected seismograms recorded with seismometers of intermediate eigenperiods;
2. analysing slowness and azimuth anomalies utilising almost all usable network data;
3. continuation of the analysis of teleseismic travel time residuals, including more data from other stations in Antarctica;
4. investigations on shear wave splitting.

CONCLUSIONS

The Neumayer array is the first permanent array in Antarctica. It is a sensitive antenna for local and regional seismicity. In the first years of operation it has been possible to detect and locate events in Antarctica, a region where earthquakes had never been previously observed. The number of detected earthquakes in the region of the South Sandwich Islands is greater than the number of earthquakes localised by international agencies, and shows that seismic activity of this region is significantly higher than previously believed. Most of these events are not localised by NEIC or ISC because their magnitudes are too small to be recorded at other stations outside Antarctica. The seismological recordings of the Neumayer network are very valuable for a detailed mapping of seismic activity in these regions.

Only in very few cases can Neumayer network data be successfully used to approximately determine hypocenters. On a regional scale, these data combined with recordings from other Antarctic stations the mislocation errors are reduced to a reasonable degree. Due to the sparse distribution of seismic stations in this region, the Neumayer network, combined with the seismological stations at Belgrano II and Sanae IV, is a powerful and important tool for detection, localisation and observation of earthquakes in this part of the world. This network of stations has the possibility to change or improve our knowledge about the seismic activity and neotectonic situation in the Scotia Sea and the region of the South Sandwich Islands.

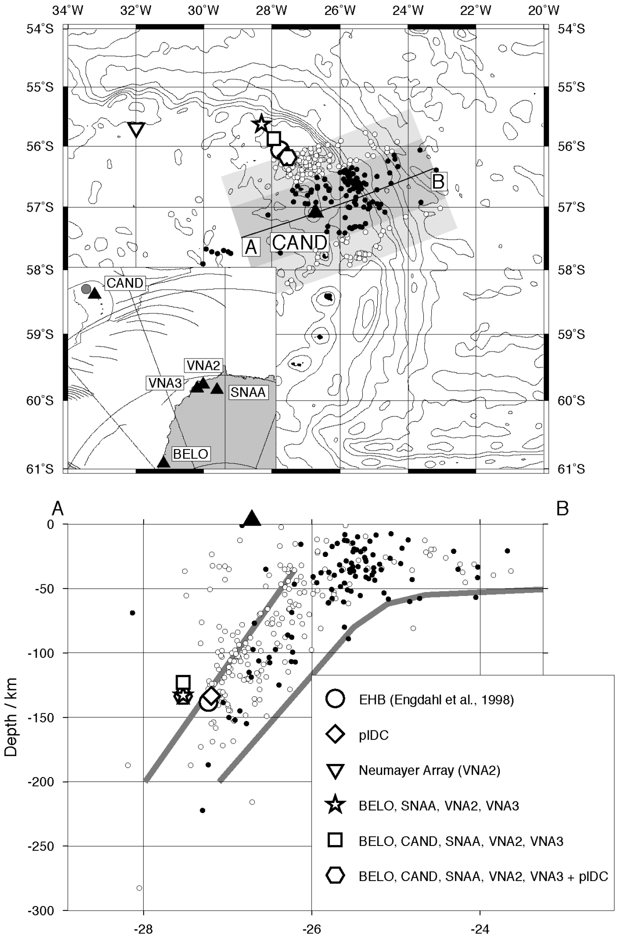


Fig. 9 - Localisation capabilities including a variable number of stations for a magnitude 5.5 (mb) South Sandwich Islands event which occured at 98/02/06. AWI stations are shown in the small inlet of the top figure. Station CAND was a temporary AWI station during two months in the beginning of 1998. To get a simple model of the subducting plate the profile (A-B) shown in the figure below, was constructed from the relocalised EHB (Engdahl, van der Hilst & Buland, 1998) earthquake catalog. The used hypocenters were taken from a 100 km wide stripe around CAND and along A-B (black hypocenters). Also shown are hypocenters from a 200 km wide stripe (white hypocenters). Contour lines show the 1000 km depth intervals of the seafloor topography in the top figure. See text for interpretations.

ACKNOWLEDGMENTS - The authors wish to thank the overwintering teams at Neumayer Base, especially Stefan Krull and Udo Neumann, for their help during field work and in various stages of data evaluation. Maps were produced using GMT by Wessel and Smith (1995).
Johannes Schweitzer made his software (Hyposat and Onset) for locating earthquakes available for this study, and he is gratefully acknowledged.
The manuscript benefited significantly from the thoughtful comments by one anonymous reviewer and Dario Slejko.

REFERENCES

Adams, R.D. & Akoto A.M., 1986. Earthquakes in continental Antarctica, *J. of Geodynamics*, **6**, 263-270.

Eckstaller A. & Miller H., 1992. Seismological Research at Georg-von-Neumayer Base, Antarctica, Part II: The Analysis of Travel Time Residuals. *Polarforschung*, **62**(1), 39-50.

Eckstaller A., Müller Ch., Nixdorf U. & Rogenhagen J., 1997. The Geophysical Observatory at Neumayer Station, Antarctica. In: Ricci C.A. (ed.), *The Antarctic Region: Geological Evolution and Processes*, Terra Antarctica Publication, Siena, 1039-1048.

Followill F. & Harris D., 1983. Comments on small aperture designs, *Internal Report*, *Lawrence Livermore National Laboratory, Livermore California.*

Harjes H.-P., 1990. Design and siting of a new regional array in central Europe. *Bull. Seism. Soc. Am.*, **90**, 1801-1817.

Kaul N.E., 1991. Detaillierte seismische Untersuchung am östlichen Kontinentalrand des Weddell Meeres von Kapp Norvegia, Antarktis. *Reports on Polar Research*, **89**.

Kennet B.L.N., Engdahl E.R. & Buland R., 1995. Constraints on seismic velocities in the Earth from traveltime. *Geophys. J. Int.*, **122**, 108-124.

Engdahl E.R., Van der Hilst R.D. & Buland R.P., 1998. Global teleseismic earthquake relocation with improved travel times and procedures for depth determination. *Bull. Seism. Soc. Amer.*, **88**(3), 722-753.

Kværna T., 1989. On exploitation of small aperture array NORESS type arrays for enhanced P-Wave detectionability. *Bull. Seism. Soc. Am.*, **73**, 173-186.

Menke W., 1989. Geophysical data analysis: discrete inverse theory-revised edition, *International Geophysics series*, **45**, Academic Press.

Mykkeltveit S., 1985. A new regional array in Norway: design work and result from analysis of data from a provisional installation, *The VELA Program: A twenty-Five Year Review of Basic Research, A. U. Kerr, Editor, Defense Advanced Research Projects Agency*.

Paech H.J., Laiba A. A., Shulyatin O. G., Aleksashin N.D. & Traube V. V., 1991. Contribution to the Geology of Western Dronning Maud Land: Present Knowledge, Latest Results and Unsolved Problems, *Z. geol. Wiss.*, **19**, 127-143.

Pelayo A.M. & Wiens D.A., 1989. Seismotectonics and relative plate motions in the Scotia Sea region, *J. Geophys. Res.*, **94**, 7293-7320.

Schweitzer J., 1997. HYPOSAT - A new routine to locate seismic events. *NORSAR Sci. Rep.*, 1-97/98:94-102.

Steinhage D., Nixdorf U., Meyer U. & Miller H., 1999. New maps of the ice thickness and subglacial topography in Dronning Maud Land, Antarctica, determined by means of airborne radio echo sounding, *Ann. Glacial.*, in press.

Wadati K., 1933. On the travel time of earthquake waves. *Part II. Geophys. Mag.* (Tokyo), 7, 101-111.

Wessel P. & Smith H.F., 1995. New version of the Generic Mapping Toll released, *EOS*, **76**, 329.

Wysession M.E., Wilson J., Bartkó L. & Sakata R., 1995. Intraplate Seismicity in the Atlantic Ocean Basin: a Teleseismic Catalog. *Bull. Seism. Soc. Am.*, **85**, 755-774.