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Aspects of modern developments in seismic event recording techniques

Summary

Significant developments in seismic event recording techniques have been reported since 1978, when the Group of Seismic Experts (GSE) was compiling the first report (CCD/558) for the Committee on Disarmament. This paper reviews especially those developments of the last five years which are considered to improve the detection and location capability of a global seismic network. The most advanced model of such a system presented in CCD/558 was named Network III (SRO). This hypothetical system was estimated to be able to detect seismic events of body wave magnitude mb 3.8 to 4.2 in the northern hemisphere and of mb 4.0 to 4.6 in the southern hemisphere with a probability of 90 %. Due to developments in instrumentation, electronics, computer technology and in telecommunications, Network III (SRO) no longer represents a hypothetical concept but a concrete one. With regard to detection capability, the following developments are regarded to be main elements of a future global network:

-- High performance data acquisition systems consisting of broadband seismometers with high resolution and sensitivity combined with powerful 22-bit A/D converters provide all of the information contained in seismic signals without loss of accuracy.

-- Ocean bottom seismometers installed in boreholes on the ocean floor promise to close the gap in the detection capability between the northern and southern hemisphere.

-- Seismic recording systems using "low-power" techniques can be used for optimum configuration of a global network due to the fact that electric power for long-term operation can be taken from batteries or solar panels.

-- Satellite systems have proven to be reliable and efficient for on-line transmission of high-quality digital seismic data from every place on the globe.

-- Detection, location and identification of seismic events within local and regional distances can be improved considerably by deploying small arrays instead of single stations.

-- Costs for digital seismic recording and processing systems have decreased due to microprocessor technology and are now even less expensive than analog systems.

In this context, another aspect is the possibility of improving the detection capability of seismic stations in regions with unfavorable noise conditions by installing the seismometers in boreholes. Initial results gained with a newly established local network of six borehole stations in the northern part of the Federal Republic of Germany -- an area covered with thick alluvial sediments -- reveal that the detection threshold of downhole instruments is as low as that for some stations of the GRF array, which is still the most sensitive network in our country. According to these initial results, the concept of borehole stations in miniarrays as elements of a global network promises efficient monitoring of regional and local events in areas of interest. The technology which this new digital network would use represents the latest stage of development of recording systems for seismological purposes in our country. This technology could also be used for a "black-box" system in a future global network due to the high degree of automation in recording and analysis of seismic data.

Advances in technology of the last five years have improved the quality of recording, transmission, processing and analysis of seismic data. As a consequence of this development, a new, improved concept for a global network should be worked out to demonstrate the efficiency of modern seismological methods for monitoring a future CTB.

1. Introduction

In recent years, an increasing number of countries have reported on improved technical capabilities in seismic instrumentation for the recording of earthquakes. Advances in electronics, computer technology, and in telecommunications have significantly influenced these developments.

A new era of seismology started with the conversion of recorded seismic signals from analog to digital format. This meant that high speed computers could be used for processing and analyzing seismograms. The first time digital techniques were applied on a large scale was in the mid-sixties when the large aperture seismic array (LASA) in Montana, USA, became operational. Since that time, various countries have developed and installed digital systems for recording and analyzing seismological data.

In our country, "digital seismology" dates back to the early seventies when the project of the Graefenberg digital broadband array was initiated. The aim of this concept was to provide an instrument for seismological research which uses the full information content of seismic signals by means of broadband recording in combination with array capabilities. Due to the various requirements with regard to resolution, dynamic range, quality of data and flexibility, it was necessary to use digital components for the system. The installation of 13 array stations with a total of 19 broadband instruments was completed at the beginning of 1980. The performance of the array system could be demonstrated to the GSE at a workshop, held in July 1980 (s. GSE/FRG/7). The high quality data of the GRF array have been used intensively for studying a great variety of seismological problems (SEIDL and BERCKHEMER, 1982; RAEKERS and MOLLER, 1982). Moreover, several investigations have established that broadband array data can be optimally filtered for detection purposes (SEIDL, 1979; STAMMLER, 1981; FERBER, 1983) and have revealed new possibilities for identifying seismic events (HARJES, 1979; HANKA, 1982).

Today, tne Graefenberg system no longer represents the latest technological standard, but due to the quality of recorded seismograms with respect to bandwidth, resolution and dynamic range, it must still be counted among the high performance recording systems presently in operation.

Worldwide, the SRO (Seismic Research Observatories) stations belong to the same category as the GRF system as far as technical standards, data quality and recording capability are concerned. Each of these 13 stations, which are being operated presently in various countries around the globe, is equipped with a 3-component broadband seismometer set. The signals of the sensors are filtered to produce long-period and short-period outputs. The system continuously records the three long-period data channels, sampling them once each second, whereas the short-period data of the vertical component which are digitized 20 times per second, are recorded only when an event is detected.

The SRO seismometers are still the only broadband instruments operated in boreholes. Due to their installation at a depth of approximately 100 m, long-period records are less affected by wind-generated noise than those from conventional seismometers near the surface. As one of the SROs is located only 50 m from a 3-component station of the GRF array, the recording capability of the two systems can be compared directly. It is not surprising that depending on wind conditions, the SRO borehole stations provide a lower noise level in the long-period band, in particular for the horizontal components. On the other hand, it would be desireable for many purposes to record the broadband seismometer output instead of the filtered short- and long-period signals. Both systems can be regarded as being optimal when the different purposes for which they were developed and the technology available at the time they were designed are taken into account.

2. Recent Technical Developments

Four examples of possible global networks for monitoring a CTB were presented in the first report of the GSE (CCD/558), which was submitted to the CD in March 1978. The most advanced system, named Network III (SRO), was assumed to consist of high-quality seismograph stations of the SRO type. In Figure 1 the global distribution of the stations as given in CCD/558 is shown. The capability of this network to detect seismic events at a 90 % probability level was estimated to vary from mb 3.8 to 4.2 in the northern hemisphere and between 4.0 and 4.6 in the southern hemisphere. The station distribution of Network III coincides rather well with existing seismograph stations and is by far not optimal with regard to the detection capability. To achieve further improvements, it would be necessary to

-- increase the number of seismograph stations, especially in the southern hemisphere;

-- install new ocean-bottom borehole seismograph stations;

-- optimize station distribution with regard to detection capability;

-- establish arrays instead of single stations in and around areas of potential interest;

-- install the seismometers of single stations or arrays in boreholes or mines to provide optimum noise conditions.

Capability studies of models that contain some of these elements have been carried out by HANNON (1983); these studies indicate the degree to which the results of CCD/558 can be improved. Also, the technological requirements for a global network in which all of the mentioned aspects are included have just been fulfilled during the past few years. The following points illustrate the main factors and developments that have to be taken into account in designing a future global network and evaluating its capability.

1. New seismic data acquisition systems especially seismometers and A/D converters have improved resolution and sensitivity. Seismometers like the TG 44000 can be operated at the quitest site, no longer limited in resolution by electronic noise. Combining such an instrument with a new 22-bit A/D converter, which is currently being developed in the United States, will make it possible to record the broadband output with the same accuracy by the presently used multiple-band recording.

2. Significant improvements have been achieved in ocean-bottom seismographs (OBS) since a 3-component broadband system was deployed by the United States in a borehole on the ocean floor. Ambient noise level is reduced considerably when this technology is used. With systems like this, detection capability in coastal regions and island areas, especially in the southern hemisphere can be further improved.

3. New "low-power" microprocessor (CMOS) modules have an extremely low power consumption. Seismic stations built with this technology can be placed nearly anywhere due to the fact that electric power for long-term operation can be taken from batteries or solar panels. The stations of a network of this type can be sited optimally for the tasks the network is designed for.

4. The efficient and reliable use of satellite systems for transmitting high-quality seismic data over several thousand kilometers has been demonstrated by the United States "Regional Seismic Test Network" (RSTN). The integration of microprocessor and telecommunication techniques in this system marks a new stage in the development of seismological recording facilities. This technology can be taken as a standard for a future global system.

5. Encouraging results with regard to detection, identification and location of local and regional events have been obtained from a small-aperture seismic array, a so-called mini-array (NORESS), currently operated by Norway. Systems like this in combination with broadband stations of the RSTN type could become main elements of a Network IV.

6. The cost of digital recording and analysis systems has beeen lowered considerably by microprocessor technology. Even institutions with low budgets will now be able to afford high-quality digital seismograph stations. Low-cost systems are being offered commercially for a variety of applications and consequently there is no longer a need to operate analog stations in a future global system.

3. New Seismic Installations in the Federal Republic of Germany

One aspect to be considered because of its significance for the capability of a global system is related to the improvement of signal-to-noise ratio by installing the seismometers in boreholes at a depth of several hundred meters or, if possible, in abandoned mines. In countries with a high population, industry and traffic density, one of the main difficulties for highly sensitive recording of seismic signals is to find a quiet site for the seismograph station. The problem of high seismic noise is also posed by remote areas covered with thick sediments. In these areas, the borehole concept offers a possibility for improving the detection capability of a seismic station. Initial results from a new, local digital seismic network of borehole stations recently set up in the northern part of Germany (Lower Saxony), a region completely covered with thick alluvial sediments, indicate the extent the expectations can be fulfilled.

This local seismic network was set up in a project started in 1981 as part of a comprehensive geological and geophysical investigation program carried out to establish the suitability of a salt diapir as a depository for high-level radioactive waste. The seismicity of the site area monitored with a local network should provide information on possible active tectonic zones in this region. A main barrier for the recording of small, local earthquakes with a magnitude as low as ML = 0 was the high level of seismic noise. The noise amplitudes measured at the surface were equivalent to an earthquake of local magnitude ML = 3.3 if the epicentral distance is assumed to be 100 km.

To define the decrease of the noise amplitudes as a function of depth in three different boreholes, short-period noise measurements were carried out using a special seismometer sonde. As known from the publications of several authors (DOUZE, 1964; BATH, 1966; TAKANO annd HAGIWARA, 1966; HARWARD, 1970), the behavior of noise as a function of depth follows a general trend. The amplitudes decrease with increasing frequency and depth. The results, however, were found to be inconsistent with each other, probably due to the different geological conditions at the investigated sites.

In the three boreholes used for the measurements, seismic noise samples were recorded between 50 and 400 m in steps of 50 m for about 15 minutes at each level. Simultaneously, the noise was recorded with an instrument installed at the surface. Calculating the power spectra of the recorded samples and comparing the results for the three sites, no significant differences were found between recordings made at the same depth. As expected, the noise amplitudes decreased with increasing depth. At 400 m, the decrease at 10 Hz was found to be -40 dB compared to the surface. More details on the behavior versus depth can be taken from the example given in Figure 2.

The equivalent local magnitude from the noise level at a depth of 300 m corresponds to an earthquake of ML = 1.9 ± 0.5 assuming an epicentral distance of 100 km. The detection threshold can easily be derived from this value by adding 0.3 units, assuming that the signal amplitude is twice as high as the average noise amplitudes. Consequently, at epicenter distances of 200, 300 and 500 km, a 300 m downhole station is expected to detect seismic events of local magnitude 2.7, 3.2 and 3.9, respectively. The corresponding values from a surface station would be about 1.4 magnitude units higher assuming the signal-to-noise ratio increases to the same degree that the noise level is reduced.

In this context it should be added that station detection capabilities are usually estimated in terms of body wave magnitude mb, which is a measure for the strength of a seismic event in the teleseismic range. For local and regional epicentral distances, however, only the local magnitude ML, based on surface waves, is defined. The two scales for magnitude are inconsistent with each other, therefore it is not possible to compare ML and mb directly. NUTTLI (1973), however, reported a modified local magnitude, called m_{bLg}, which can be used to extend the teleseismic mb:Ms relation down to mb = 3.0, if appropriate regional attenuation functions are available.

A concept for a local borehole network was worked out on the basis of the results obtained from the noise measurements. In the final version of this network there are 5 stations at the points of a pentagon with an additional station at the center. These 6 seismometers were installed at a depth of 300 m. The network was planned to cover an area of 20 x 20 km, so that the average distance between stations is on the order of 10 km.

The map in Figure 3 shows the location of the seismometer sites. The center station contains a three-component set, whereas the remaining stations are equipped with vertical instruments. Short-period MARK L4 instruments with a natural frequency of 1 Hz are installed at all stations. Modern microprocessor modules are used for the network recording system.

The block diagram of Figure 4 shows the elements of the data acquisition system for a borehole station. The seismometer output is sampled at a rate of 120 Hz. The 12-bit A/D converter has a resolution of 66 dB. Gain-ranging provides a dynamic range of 120 dB. By use of "low-power" modules, a station can be operated with batteries for approximately 4 months. The digital data from each station are transmitted continuously via commercial telephone lines at 2400 Baud to a recording center near the center station of the network.

The main purpose of this central recording system is to control and synchronize the network, to collect the data from the borehole stations, to detect and store seismic events temporarily on magnetic disk. A block diagram of this newly developed multi-microprocessor system is shown in Figure 5. Once a day or, if needed, on request, the recorded data are sent via a 4800-Baud data line (DATEX-P) to the seismic data analysis center of the BGR (Federal Institute for Geosciences and Natural Resources) in Hannover. In principle the system could broadcast the recorded events via these telecommunication channels all over the globe. The capacity of modern satellite systems like INTELSAT would even allow on-line transmission.

On the whole, this network documents the latest technological stage in the development of recording systems for seismological purposes in our country.

Immediately after the system was set in operation, an experiment was carried out to determine the increase in the signal-to-noise ratio obtained from downhole instruments compared with surface stations. An additional vertical seismometer was installed for this purpose near the surface at the center borehole station. Figure 6 shows typical recordings of the instruments, both presented with identical magnification. The seismic signal, found only on the record of the downhole seismometer (lower trace), was generated by a chemical explosion of 0.002 t (2 kg) TNT fired 10 km from the location of the instruments.

More evidence for the good performance of downhole seismometers in areas of high noise is given in Figure 7. The signals were recorded from a teleseismic event of magnitude mb 5.2 (GRF) in the Kurile Islands. The upper two traces are simulated short-period WWSSN records obtained by appropriate filtering of the broadband seismometer output of two GRF array stations. The selected channels represent the best and worst records from the array with respect to the signal-to-noise ratio. Additionally, the figure contains low-pass filtered outputs of the surface and downhole seismometers resampled to 20 Hz. As in the previous example, the signal in the record of the surface seismometer cannot be separated from the noise, neither in the time nor in the frequency domain. During the experiment, unfortunately, there were no teleseismic or regional events that were strong enough to quantitatively determine the improvement in the signal-to-noise ratio between the surface and downhole channels. A comparison with the GRF records, however, reveals that the detection threshold of the seismometer in the borehole is as low as that for some stations of the GRF array. This is a promising result as the array is still the most sensitive seismic recording instrument in our country.

The only signals observed during the test measurements on both channels were from local shocks. In the example given in Figure 8, the ratio between the scaling factors applied to the output of the downhole and surface instrument is five. Taking the different magnifications into account, the signal recorded in the borehole has lower amplitudes, however, the first onset is not covered by noise as on the surface trace. The improvement in the signal-to-noise ratio for the downhole channel turns out to be 0.5 units in magnitude when time intervals of 0.5 s are analyzed before and after the onset of the signal.

The results gained in this first phase of network operation indicate that detection capability in areas of unfavorable seismic noise conditions can be improved by installing the seismometers in boreholes. To complete the project, the studies will be continued to obtain more information on the threshold magnitude of this network, especially with regard to local and regional seismic signals.

The integration of the borehole concept in a future advanced model for a global network is certainly one important point to be taken into account, in addition to the elements provided by recent technological developments in seismological recording facilities. As far as the technology of the described network is concerned, the system, designed for unmanned operation and automated analysis, could be used as a "black box", controlled by international data centers. Access to the data could be provided via modern telecommunication channels. As interference by human interaction is only necessary for maintainance or repair, it is possible to eliminate subjective factors in the extraction of seismic parameters. This could be done at international data centers according to agreed procedures. This is one of the main perspective which is offered by modern technology with respect to the operation of a future global network.

4. Conclusions

When the GSE was compiling its first report, CCD/558 in 1978, detection and location capabilities of two different types of global networks were estimated quantitatively. The first system, called Network I, consisted of existing seismograph stations, whereas the second one, Network III (SRO), defined a hypothetical digital network which consisted of stations for which the SRO standard was assumed. Meanwhile, the compilation of the third report is finished. It contains important information on the achievements of many countries in the field of seismograph stations and networks.

According to the developments of the last 5 years, Network III (SRO) has partially changed from a hypothetical system to an operating one. New perspectives for a future network, however, have not yet been elaborated by the GSE, although the technical elements of such an advanced network are already available, as pointed out in this paper. We feel that it is necessary to develop a new model for a global system as soon as possible for which the present stage of technology is taken as a standard, and moreover, to estimate quantitatively the detection and location capability of this network to be able to document the efficiency of monitoring a future CTB with seismological methods of today.

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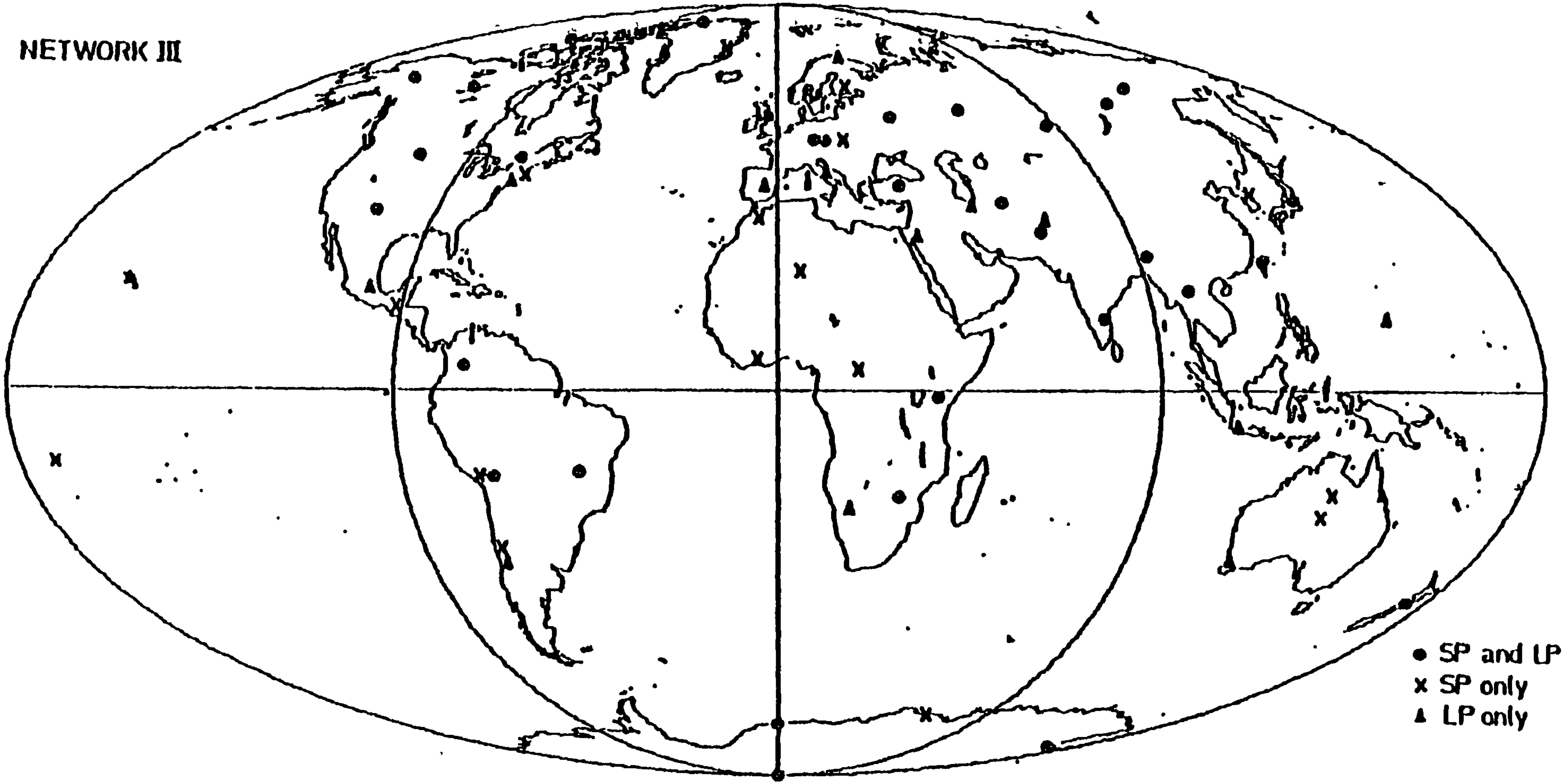

Fig. 1 : Map showing the location of stations in Network III and Network III (SRO) (CCD/558)

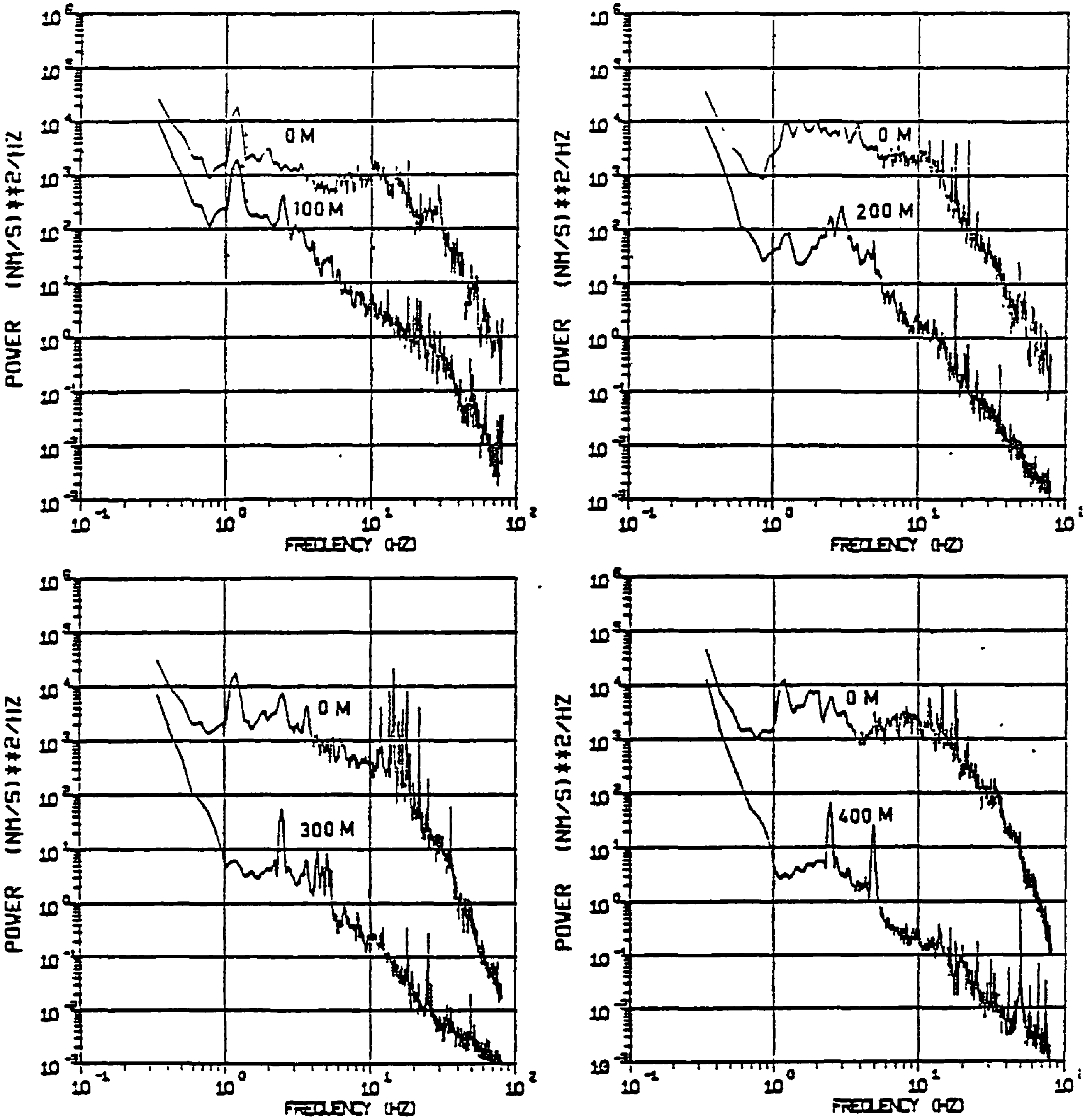

Fig. 2: Power density spectra of seismic noise recorded on the surface and in a borehole at a depth of 100, 200, 300 and 400 m

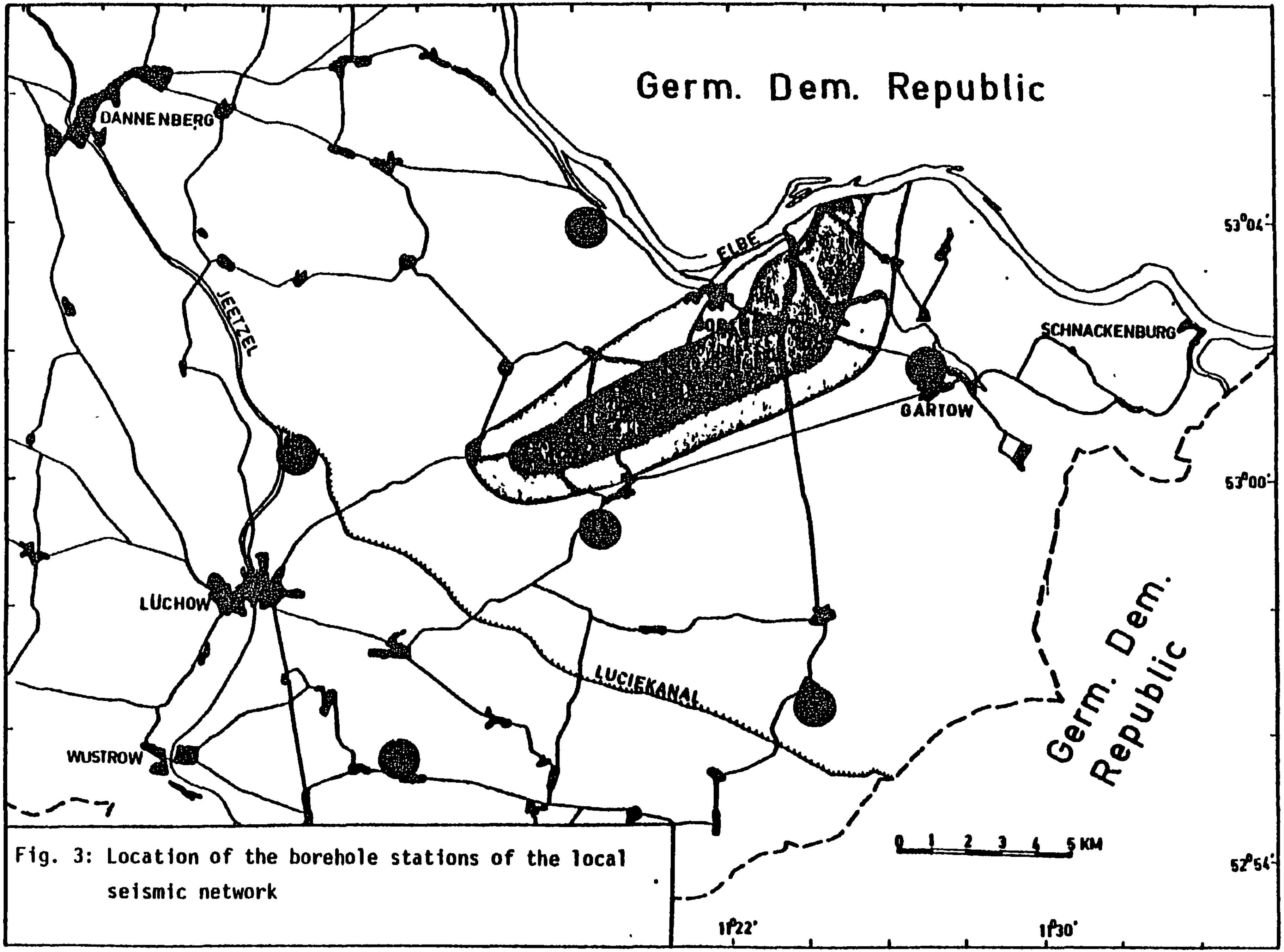

Fig. 3: Location of the borehole stations of the local seismic network

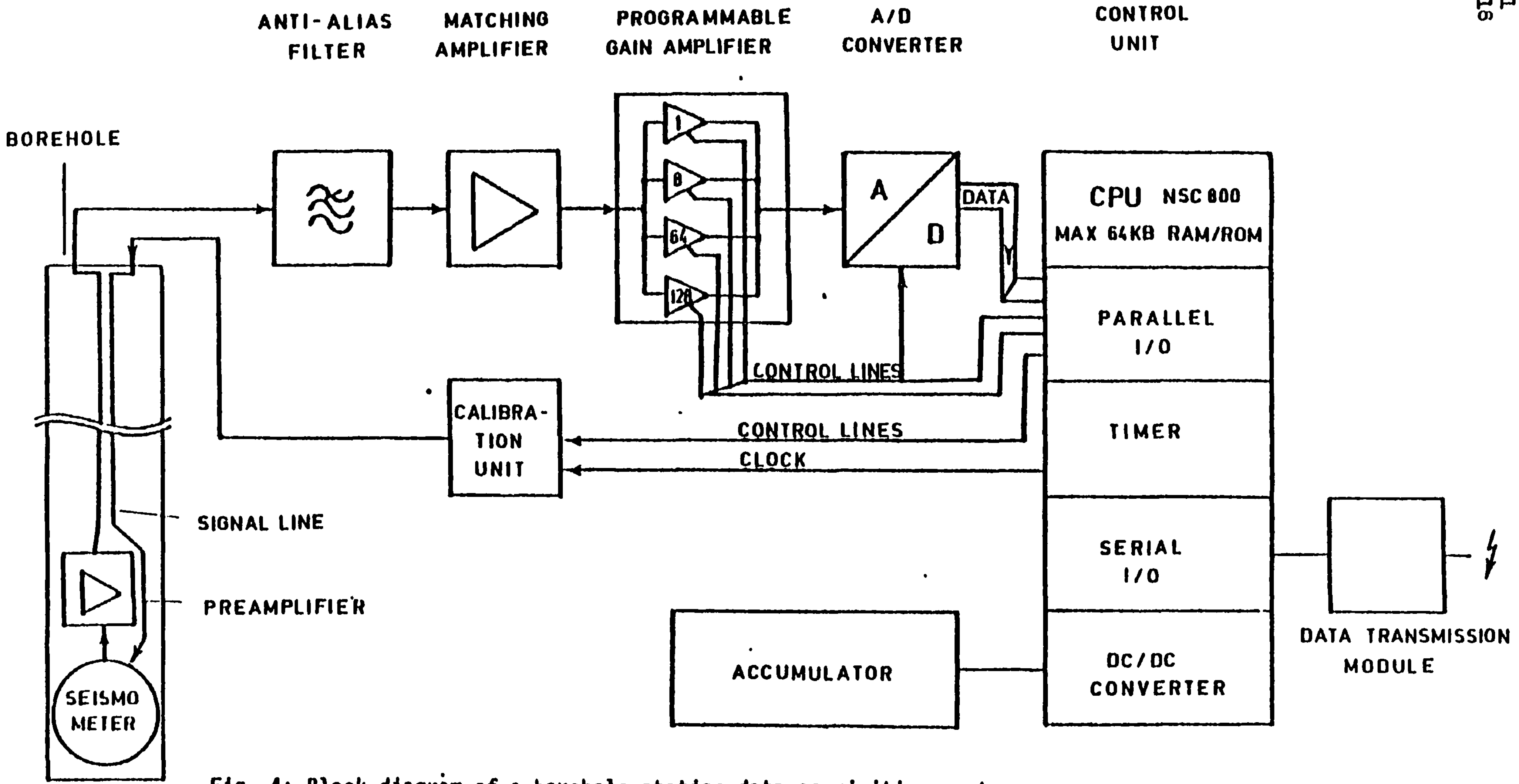

Fig. 4: Block diagram of a borehole station data acquisition system

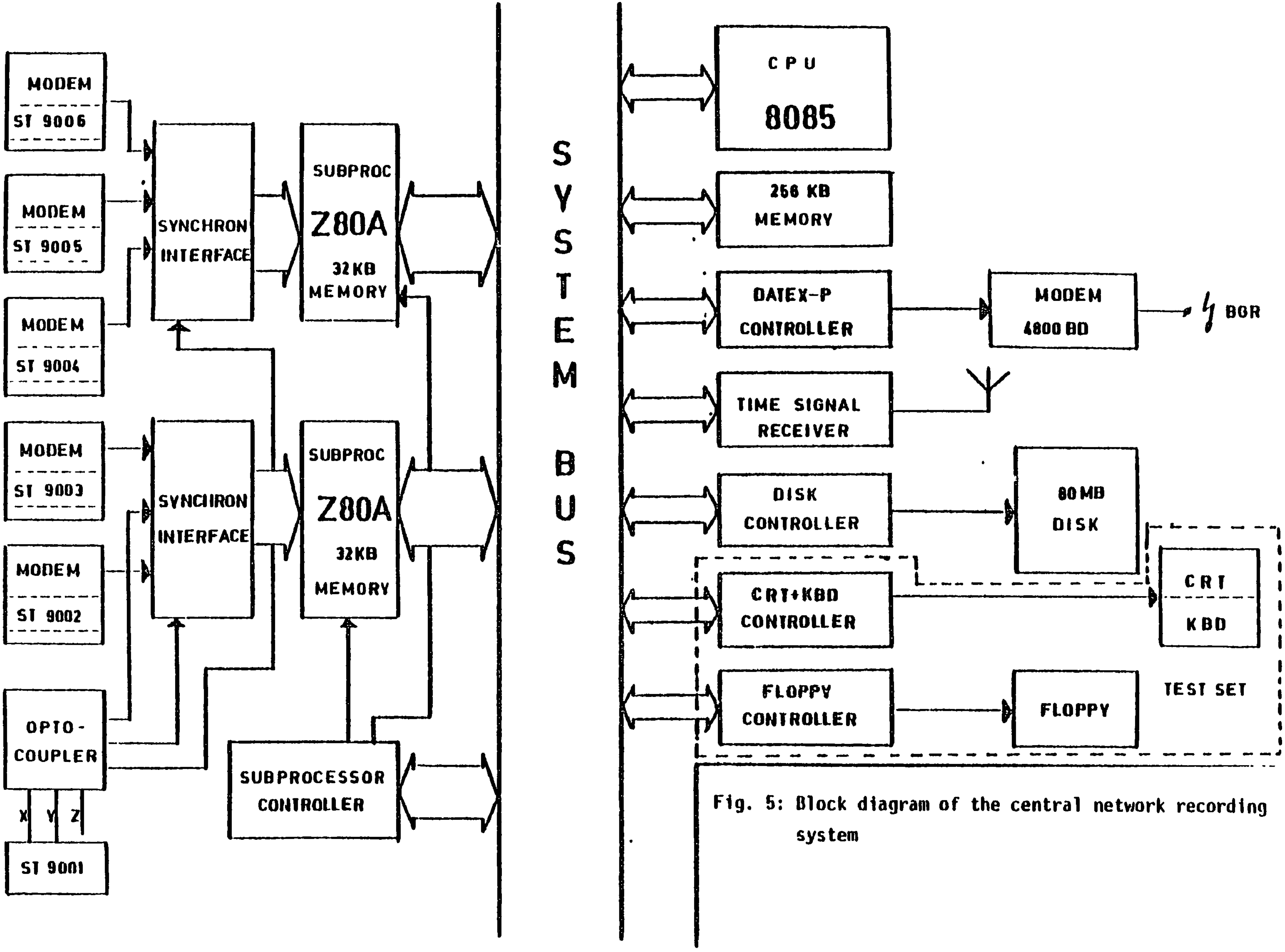

Fig. 5: Block diagram of the central network recording system

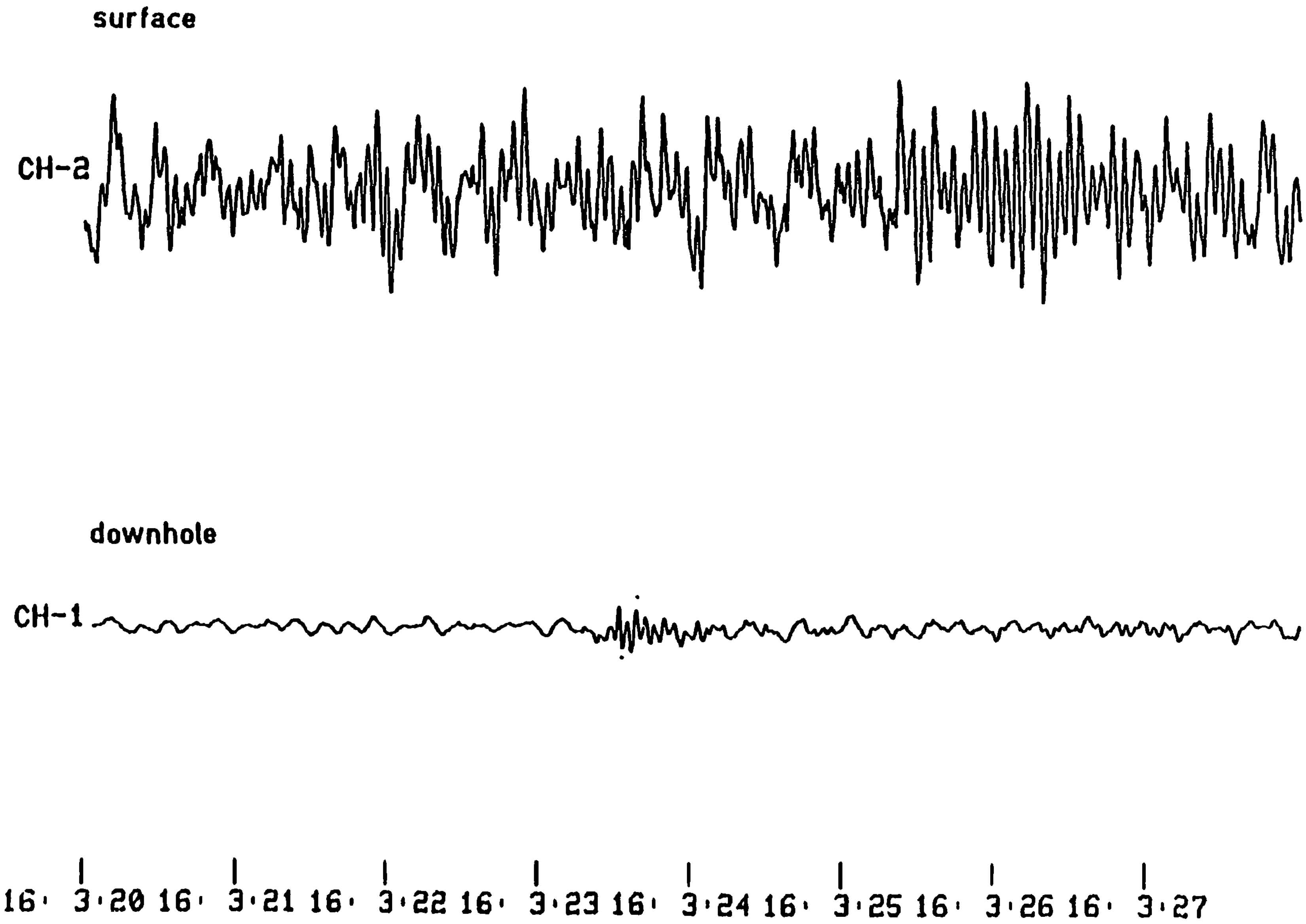

Fig. 6: Seismograms of a 2 kg explosion 10 km from the center borehole station of the local network recorded with MARK L4 vertical seismometers installed downhole and at the surface

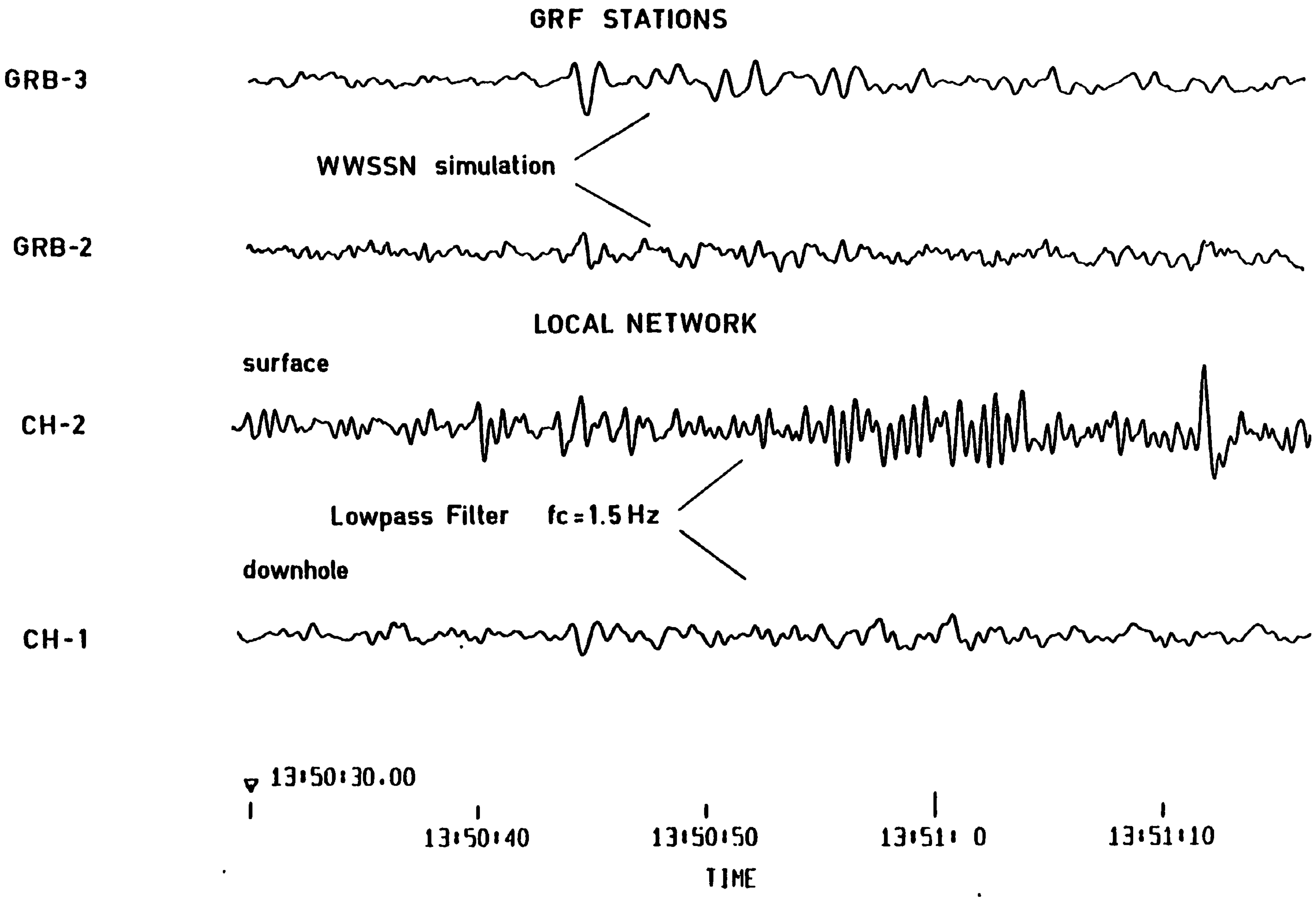

Fig. 7: Seismograms of a Kurile Islands event (mb = 5.2) recorded at two stations of the GRF array and at the center station of the local network with seismometers installed downhole and at the surface

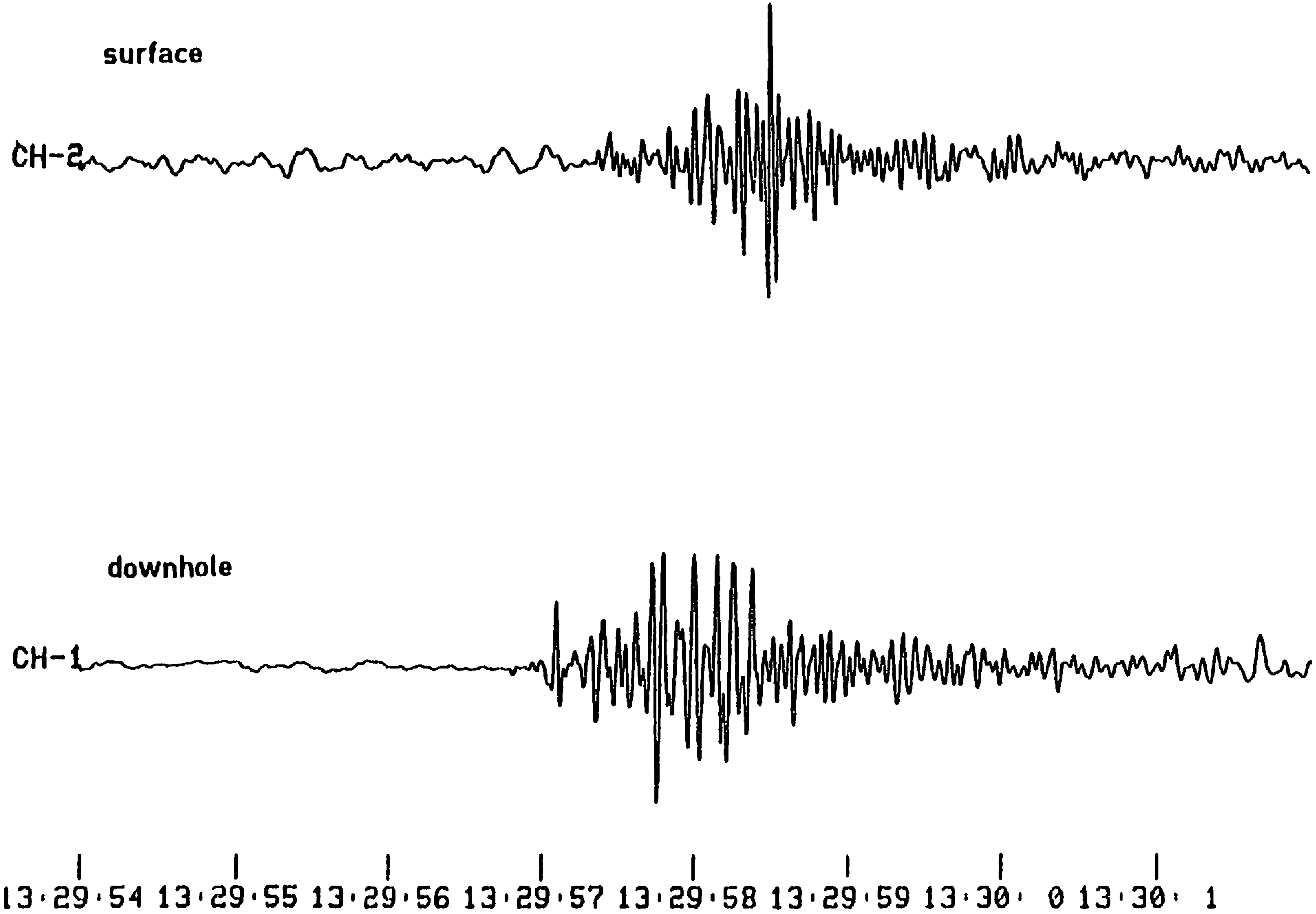

Fig. 8: Local shock recorded at the center station of the local network with seismometers installed downhole and at the surface