Poster-BGP07

# A High-Resolution Seismic Investigation of the Borehole Surrounding with the Seismic Directional SPWD-Method

**Katrin Jaksch & Rüdiger Giese**

## Introduction

In the case of small-layered structures or steeply dipping faults, the resolution of 2D- or 3D-surface seismic methods is often not sufficient to determine there structures for exploration. Borehole seismic methods have been developed, which allow high resolution imaging of this small-scale structures due to signal frequencies up to 100 Hz. Common methods are vertical seismic profiling (VSP) and seismic while drilling (SWD).

A further improvement of the resolution can be reached by the combination of sources and receivers in one borehole device (see figure 1). Such a prototype has been designed, manufactured and tested in the project "(S)PWD- Seismic Prediction While Drilling". The prototype uses a phased array source for emitting focused seismic sweep signals from 300 Hz to 5000 Hz. This allows a structural resolution in the range of 1 m. First tests reveal an exploration range of about 100 m around the borehole.

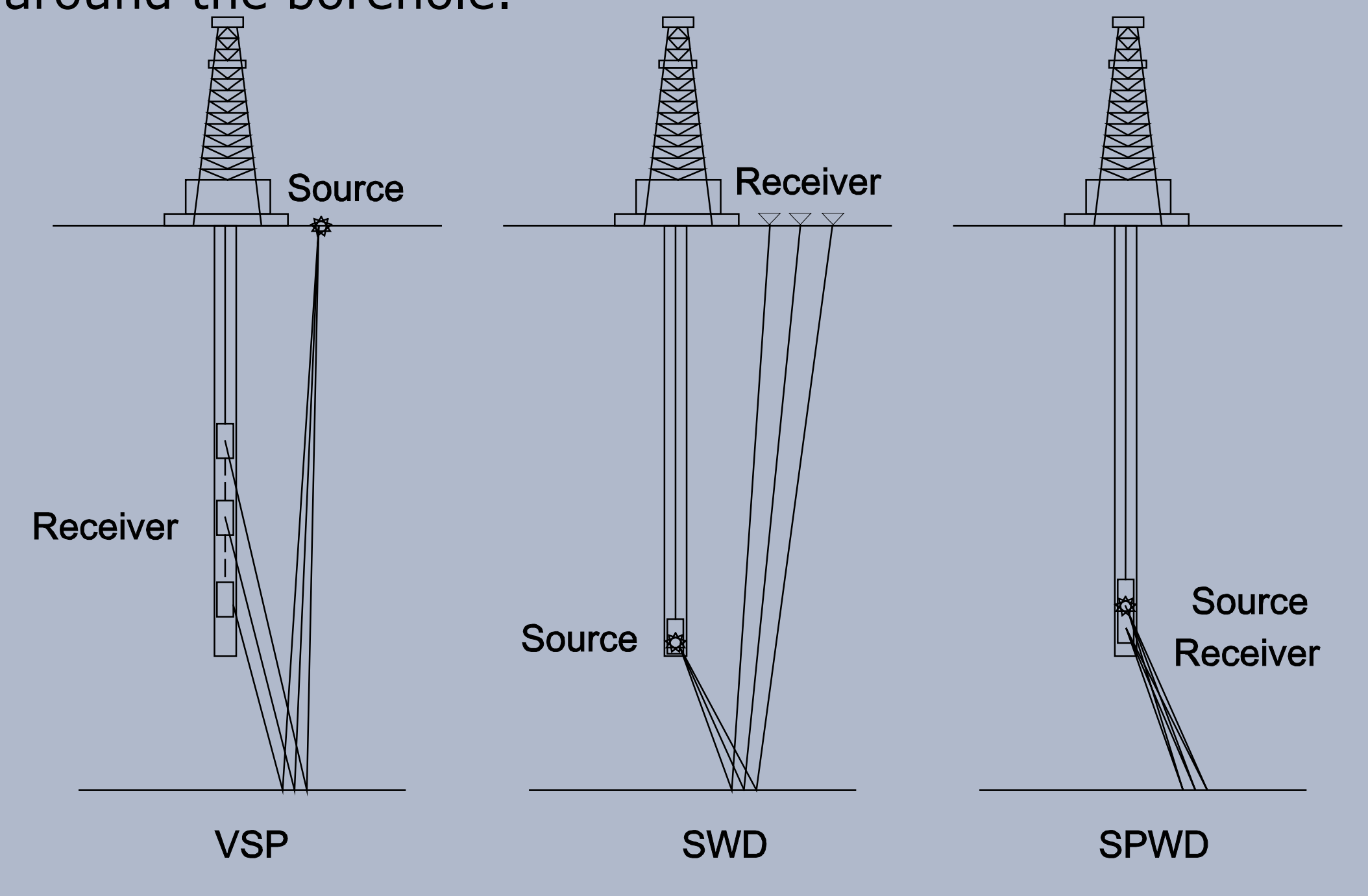

*Fig. 1: VSP and SWD use the surface for sources or receivers . The SPWD-method combines sources and receivers in the borehole.*

## Method

To focus the seismic waves to the desired direction the method of phased array is applied. The main principle of a phased array is to use the phase of several source signals to get a common wave front in the desired direction of exploration (see figure 2 top). To achieve a directional radiation effect it is essential that all aligned seismic sources can be controlled independently of each other. The source signal is controlled in amplitude and phase. Then, the phases for each actuator can be determined in reference to its position within the phased array and depending on the seismic wave velocities of the surrounding rock. Therefor, the distance of the actuators to each other and the frequencies are used.

Two prototypes were designed and manufactured combining source and receiver in a device . The SPWD laboratory prototype is used for tests in horizontal boreholes without borehole fluid and for normal temperatures and pressures (figure 2 bottom). Four seismic actuators (AK1-AK4) as sources and four 3-component geophones (GK1-GK4) as receivers were aligned along the borehole axis. The sources serve as a cascading source to enhance and to focus the applied energy in the borehole surrounding. Sensors are integrated in the stamps which couple the sources to the wall of the borehole. These signals are used to control phases and amplitudes of the sources.

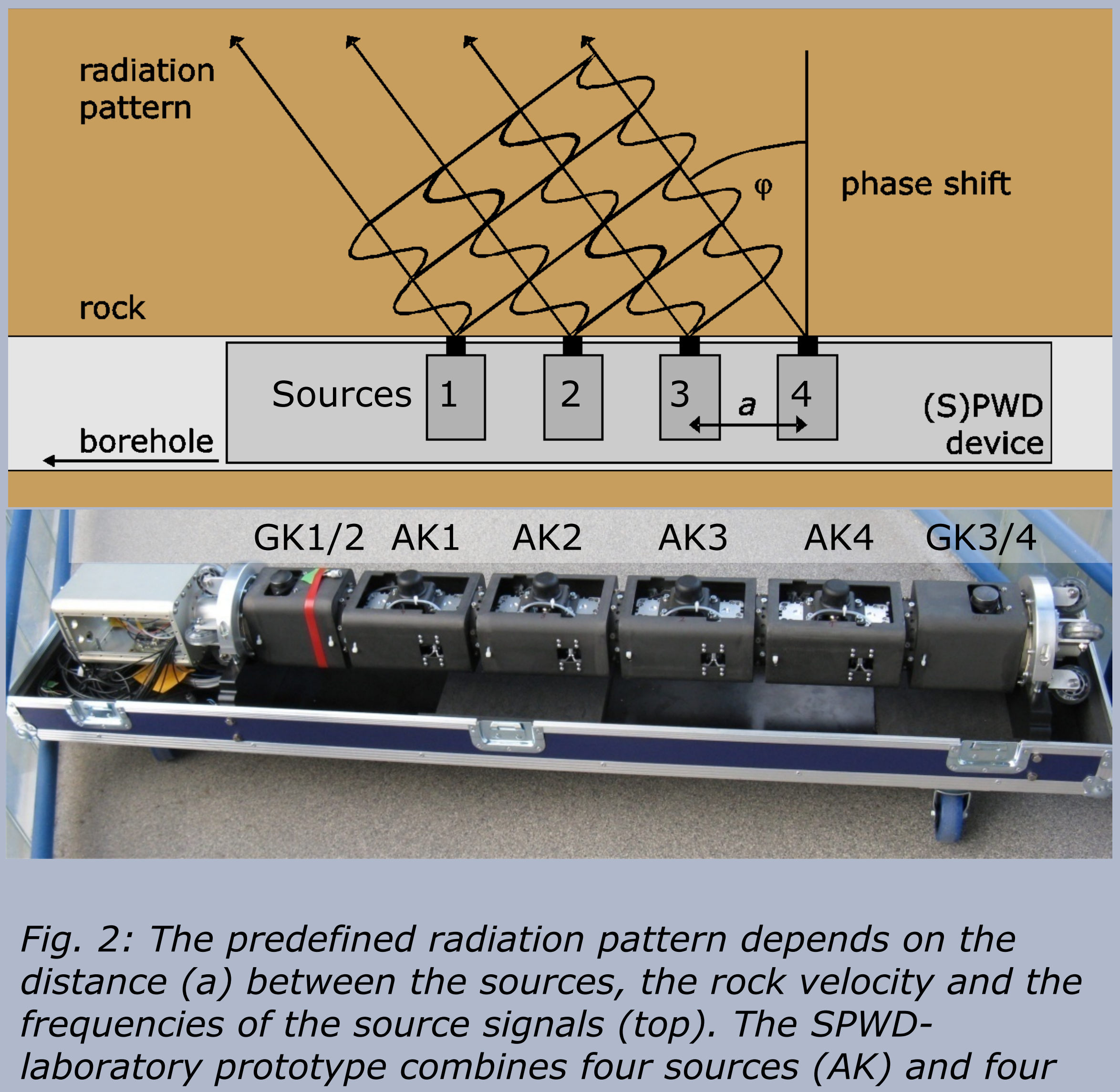

*Fig. 2: The predefined radiation pattern depends on the distance (a) between the sources, the rock velocity and the frequencies of the source signals (top). The SPWD-laboratory prototype combines four sources (AK) and four 3-component receivers (GK) for dry horizontal borehole application. The length of the prototype is 1.8 m and the spacing between the receivers and adjacent sources is about 0.24 m (bottom).*

## SPWD wireline prototype

Technical Parameter:

Length: 6 m
Weight: 750 kg
Diameter: 6 ¼"
Max. depth: 2000 m
Max. temperature: 85 °C
Contact pressure: up to 2000 N
Number of seismic sources: 4
Number of seismic 3C-receivers: 2

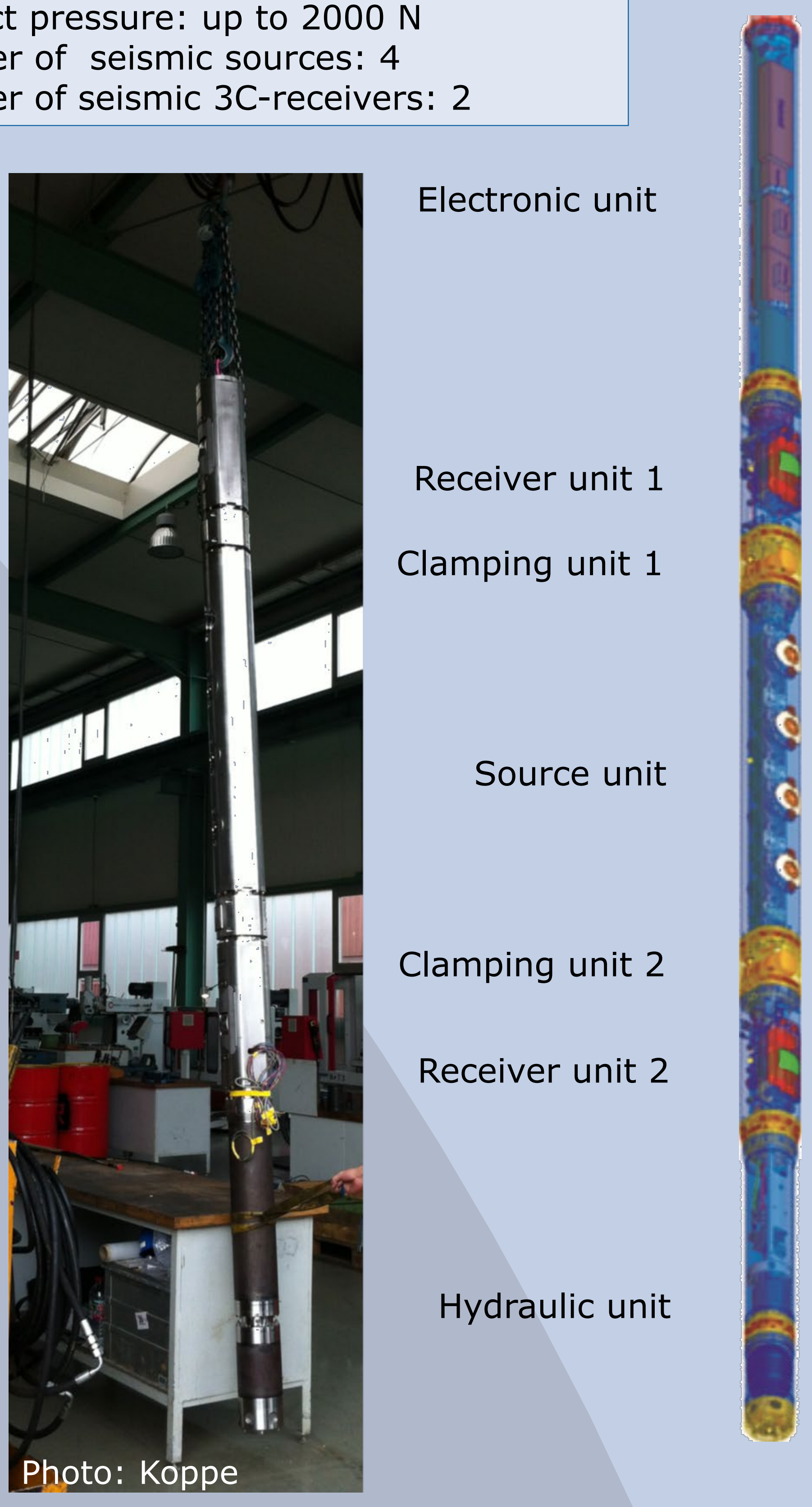

*Fig. 3: The SPWD wireline prototype and its constituents, during manufacturing (left) and technical sketch (right) (patent no.: PCT/EP2009/003334)*

The SPWD wireline prototype (figure 3) was constructed for tests in vertical boreholes up to 2000 meters depth. Preliminary measurements to test the pressure tightness and hydraulic circuit of the device will be carried out at the KTB-test site soon. Afterwards, 3D-seismic borehole measurements to calibrate the SPWD wireline prototype will be performed at the GFZ-Underground-Lab and at a test site in Italy in sedimentary rocks.

## Test Site

We operate an underground laboratory to develop and to test seismic sources and receivers as well as data imaging techniques for high resolution exploration in tunnels and boreholes. The GFZ-Underground-Lab is situated 150 m below surface on the first level in the education and research mine "Reiche Zeche" of the Technical University Bergakademie Freiberg. Surrounded by three galleries the measuring site comprises a block of homogeneous high grade gneiss of almost 50 m width and 100 m length, ensuring constant conditions. Along the galleries over thirty 3-component geophone anchors are installed with a distance of 4-9 m from each other. In 2009 two horizontal 8 ½" boreholes (BH 1 and BH 2) of 30 and 20 m were drilled (see figure 3). In 2011 and 2012 the GFZ-Underground-Lab has been extended by a 40° inclined ramp and chamber (BC) 10 m above the galleries. From there a 70 m 8 ½" vertical borehole (BH3) has been drilled downwards through the gneiss block.

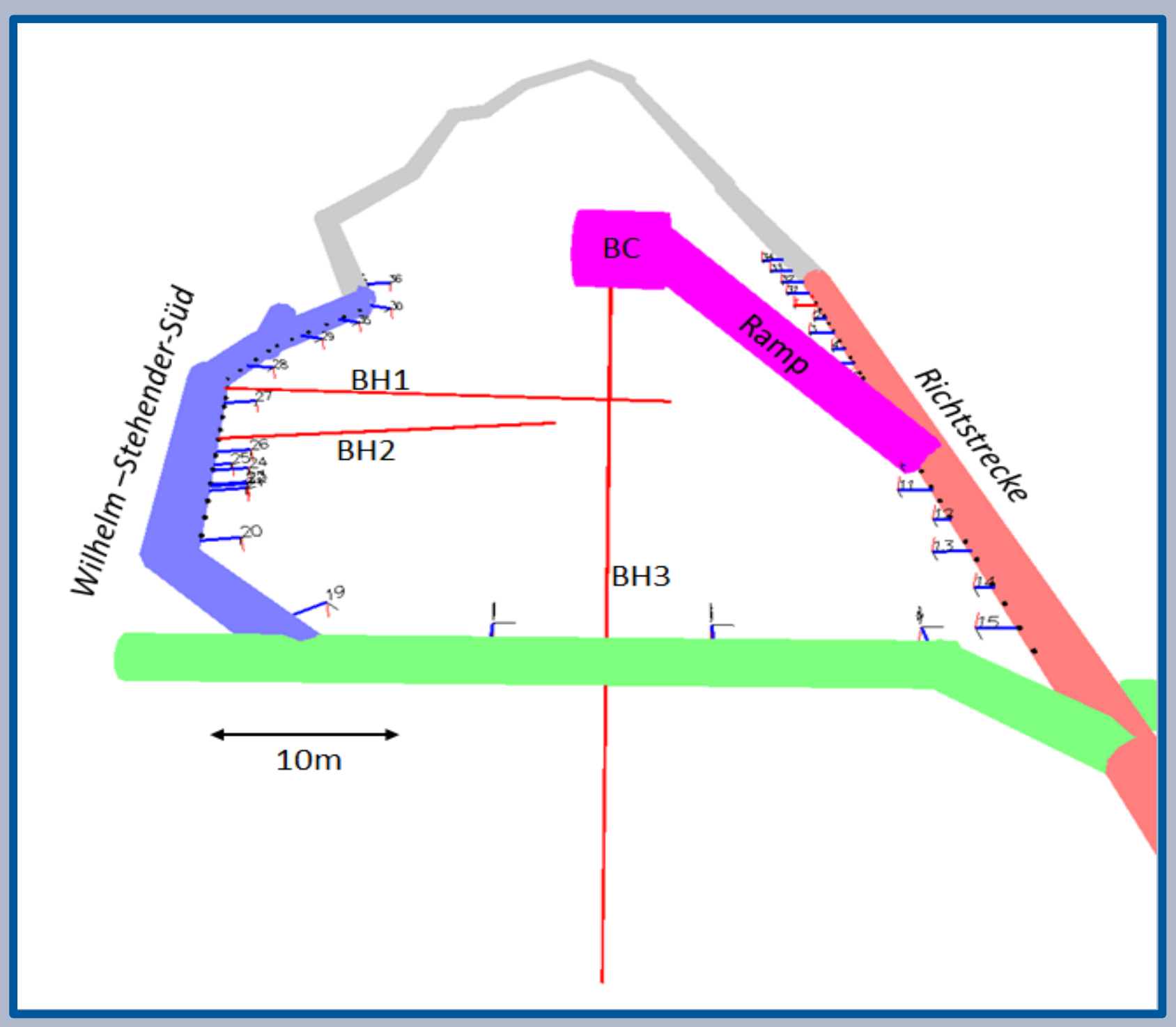

*Fig. 4: Side view of the GFZ-Underground-Lab with ramp, boreholes (BH) and borehole chamber (BC) 10 m above the galleries*

## Measurements

The main objective of the measurements is to test the controlled seismic sources with respect to their capability to focus seismic waves of predefined amplitude and frequency content. The source signals are linear sweeps. Typical signal frequencies excited by the magnestostrictive vibrators are 500 to 5000 Hz.

Figure 5 (right) shows a radiation pattern example for different amplification directions of the direct S-waves in the frequency range between 500 and 2000 Hz. The phased array borehole source was situated in BH1 and the emitted wave field was recorded by the receiver array mounted along the galleries (see figure 4). Three different amplification directions have been applied. The green colour (90°) marks the data values for amplification in perpendicular direction to the boreholes axis, whereas the red (0°) and the blue (180°) colour marks data values for the amplification in both directions of the borehole axis. Further evaluation of the source radiation patterns reveals large differences of the emitted wave field with respect to the type of waves (P or S, see figure 5 left). S-waves energy is about five times higher than P-wave energy for all frequencies and directions.

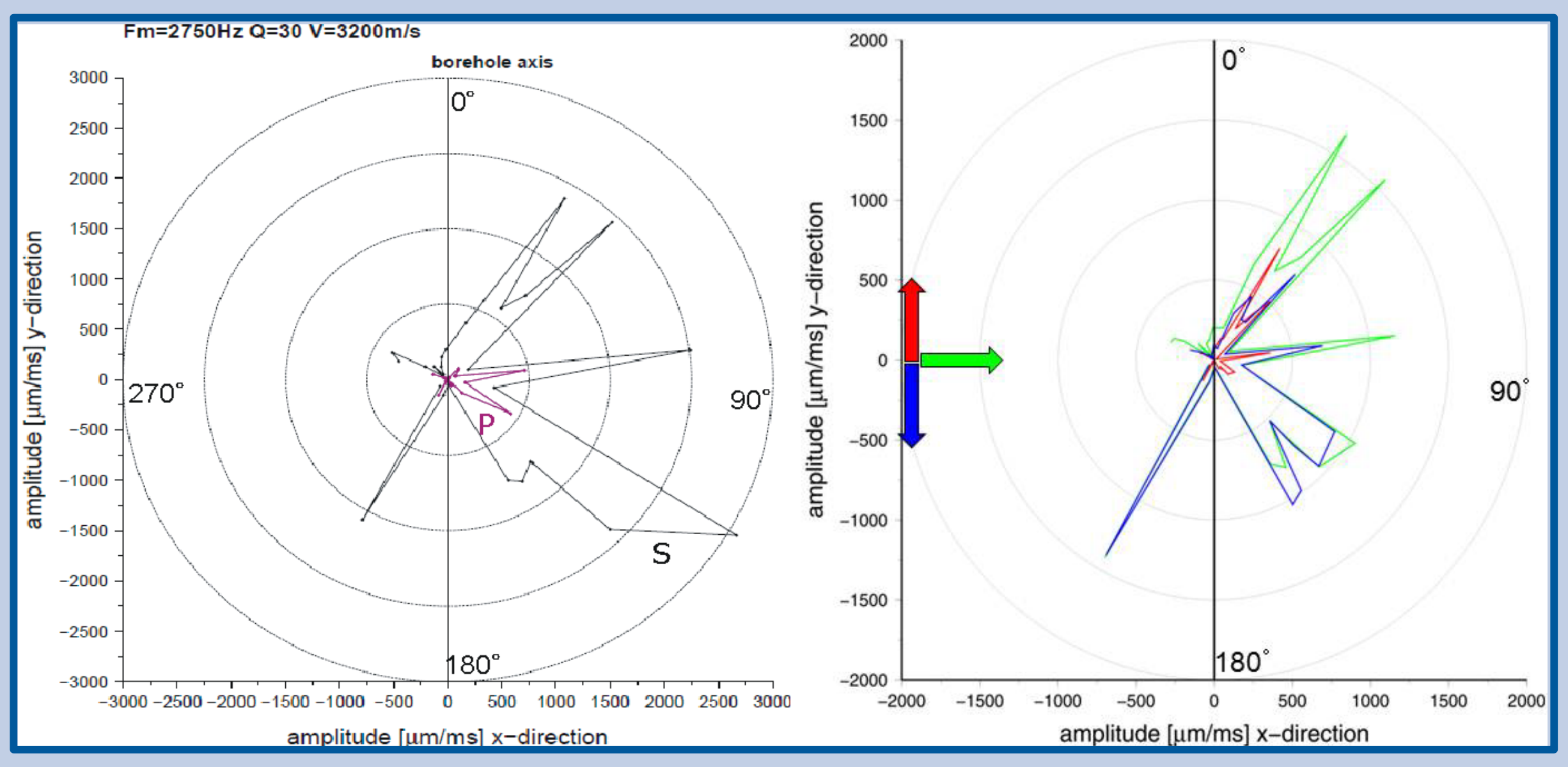

Fig. 5: 2D-Radiation pattern for separated direct P- and S-waves of the shot in figure 6 (left) and radiation pattern of the directed S-waves combined for different amplification directions of the phased array borehole source (right).

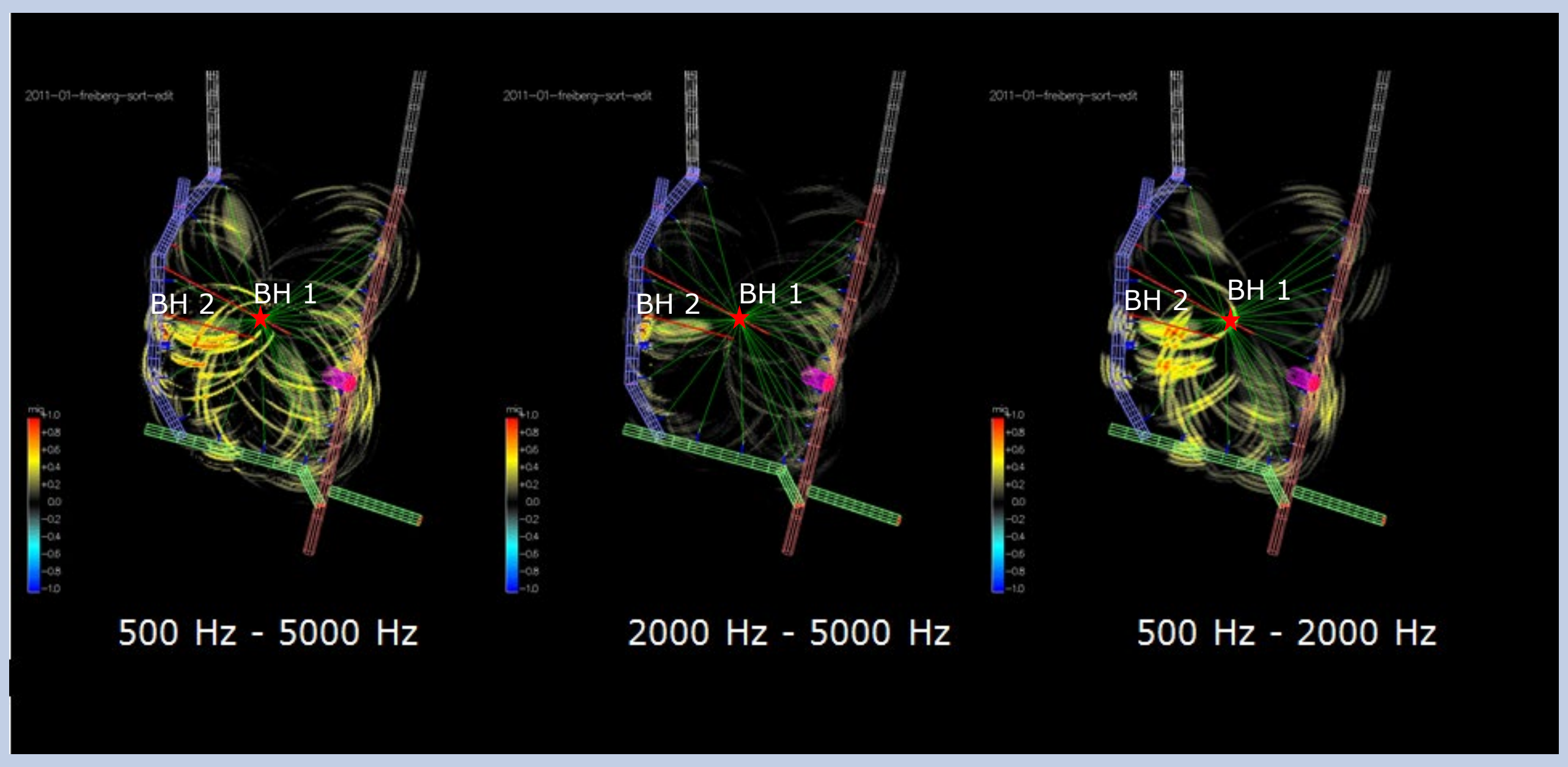

*Fig. 6: 3-component Fresnel-Volume-Migration for P-waves with different signal frequencies, full spectrum (left), high frequencies (middle) and lower frequencies (right). High signal frequencies resp. short wave lengths are focused in borehole axial direction whereas lower signal frequencies are focused perpendicular to the borehole axis. The source amplification direction was perpendicular to the borehole axis.*

The frequency dependency of the P-wave radiation pattern can be confirmed by a Fresnel-Volume-Migration of the reflected wave field (see figure 6). The dependence of the reflected P-wave field amplitudes to the signal spectrum was clearly observed. For the high frequency range of 2000 Hz to 5000 Hz the reflected waves are imaged in the direction of the borehole axis (see figure 5 middle). In contrast, the lower signal frequencies (<2000 Hz) show their maximum in borehole perpendicular direction (see figure 6 right).

## Conclusion

The application of a phased array borehole source allows the amplification of the emitted wave field in predefined directions. An appropriate choice of the source signal frequency range, with respect to wave type and desired direction of exploration can further improve the result of the wave amplification. The frequency dependence of the radiation pattern can be explained with the existence of an excavation damage zone around the borehole which leads small wave lengths along the boreholes axis. The application of innovative imaging techniques which take advantage of 3-component recordings, such as the Fresnel-Volume-Migration, can further improve the spatial resolution of seismic borehole measurements.

The project (S)PWD- Seismic Prediction While Drilling) is funded by the German Federal Environment Ministry, BMU. The project partners are Bergakademie Freiberg, GeoThermal Engineering GmbH and Herrenknecht Vertical GmbH.

Dr. Katrin Jaksch; Dr. Rüdiger Giese, Scientific Drilling, Telegrafenberg, 14473 Potsdam
Tel.: 0049/331 288 1518/1575, email: kawi@gfz-potsdam.de; rudi@gfz-potsdam.de