Wave Inversion Technology, Report No. 4, pages 191-203

A High-Frequency Seismic Experiment to Measure Seismic Signatures of Fluid Flow In-situ

A. Goertz, A. Kaselow[1]

keywords: *Hydraulic properties, seismic subsurface measurements*

ABSTRACT

In May 2000, the HIKALISTO experiment was carried out in and around a gallery system in southern Germany. Named for HIgh-frequency CAlibration measurements in the LIndauSTOllen, the survey aimed at measuring fine-scaled variations of hydraulic properties such as porosity, permeability and pore fluid pressure of a well-known hydrothermally overprinted transform fault. Measurements were carried out within and above a 0.7 km long gallery system which crisscrosses the target fault. The structure could be sensed with frequencies of up to 5 kHz over a range of up to 100 m. A large number of sources and receivers ensures a survey geometry similar to a 3D crosshole experiment.

INTRODUCTION

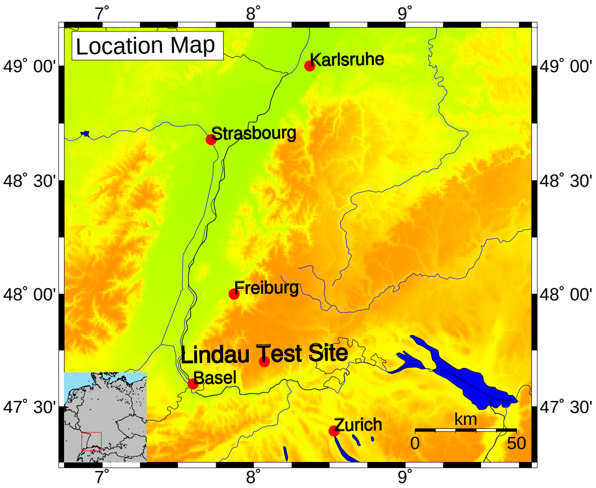
The Lindau Test Site is located within a granite complex of the southern Black Forest, Germany (see fig. 1). The target feature of the experiment is a vertically dipping transform fault, the so-called ore-dyke *Herrmann* which originated in variscan times and consists mainly of quartz and barite. Fluorite minerals originally contained in the ore-dyke have been washed out over time and caused the fault to become a highly porous and permeable layer. In the course of a hydroelectric project the gallery and about 200 shallow boreholes were drilled at the site. As the ore dyke was assumed to lead to leakages below a planned dam, cement was injected into parts of the ore dyke from the gallery system. The project had never been completed which makes the existing infrastructure above and below the surface a unique test site available for research. The location of the ore dyke together with the gallery system and some of the boreholes is shown in fig. 2. The central part of the gallery system consists of a triangular test block (see fig. 5) which makes the ore dyke perfectly accessible for high-resolution in-situ observations. The test site represents a highly controlled environment for seismic measurements which enables us to calibrate techniques to deduce hydraulic

---

[1] **email:** Alexander.Goertz@gpi.uni-karlsruhe.de

properties from the measured seismic signature (e.g. (Batzle and Wang, 1992)). The subsurface structure is known from numerous borehole cores drilled from the surface as well as from the gallery. Furthermore, the hydraulic system of the test site is known from tracer and pumping tests carried out during the last 10 years (e.g. (Himmelsbach, 1993), (Kaselow, 1999)). All boreholes within the gallery system are equipped with pressure gauges which enables us to monitor the fluid pressure during measurements.

Figure 1: Location of the Lindau test site within the crystalline basement of the southern Black Forest, Germany.



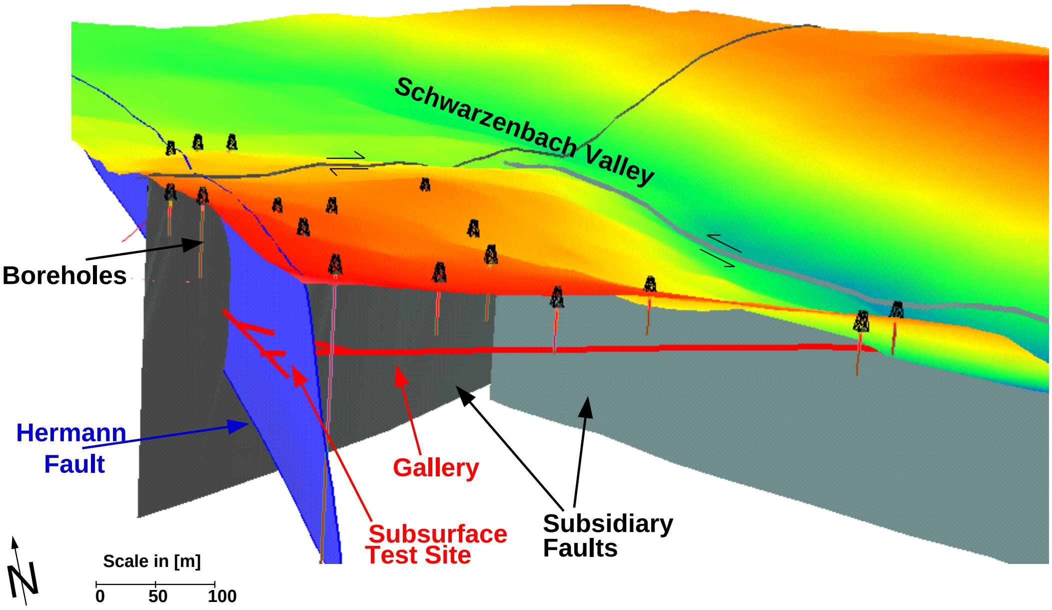


Figure 2: Overview of the Lindau Test Site with the ore dyke and the gallery. Also shown are some of the boreholes which constrain the 3D structure around the test site

SURVEY DESIGN AND RESOLUTION

The dimension and accessibility of the test site as well as the scale of target properties imposed a challenge onto the survey design in order to achieve a sufficient resolution for the anticipated measurements of hydraulic properties.

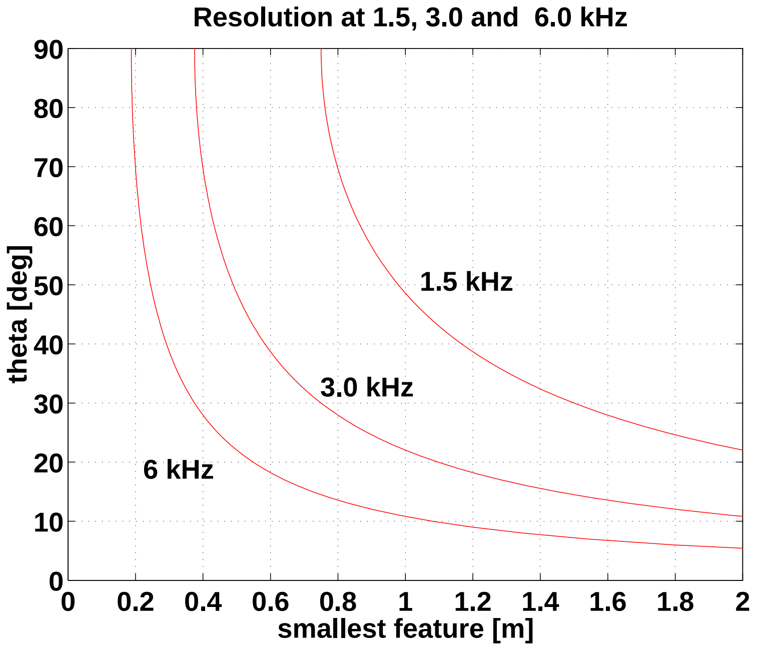


Figure 3: The resolution of a seismic survey is governed by the maximum possible scattering angle and the frequency of the input signal. Curves are plotted for the least (1.5 kHz) and the highest expected signal frequency.

Using formulae given in (Yilmaz, 1987) and revisited by (Margrave, 1997), the size of the smallest resolvable length δx on a reflector can be approximated by

$$\delta x = \frac{\alpha v}{4 f \sin(\theta)} \tag{1}$$

where α is a proportionality factor near unity, f is the maximum frequency of the probing signal, v the velocity at target depth and θ the maximum scattering angle recordable with the installed array. The scattering angle itself will depend on the aperture of the seismic array, the record length and the overburden structure. The receiver spacing is a crucial parameter as it restricts the maximum resolvable dips (and therefore scattering angles) due to spatial or operator aliasing caused by a spatial sampling which is too coarse. Fig. 3 shows the smallest discernible feature depending on the scattering angle θ and the frequency according to equation. 1. A more detailed discussion of these problems can be found in (Traub, 1999).

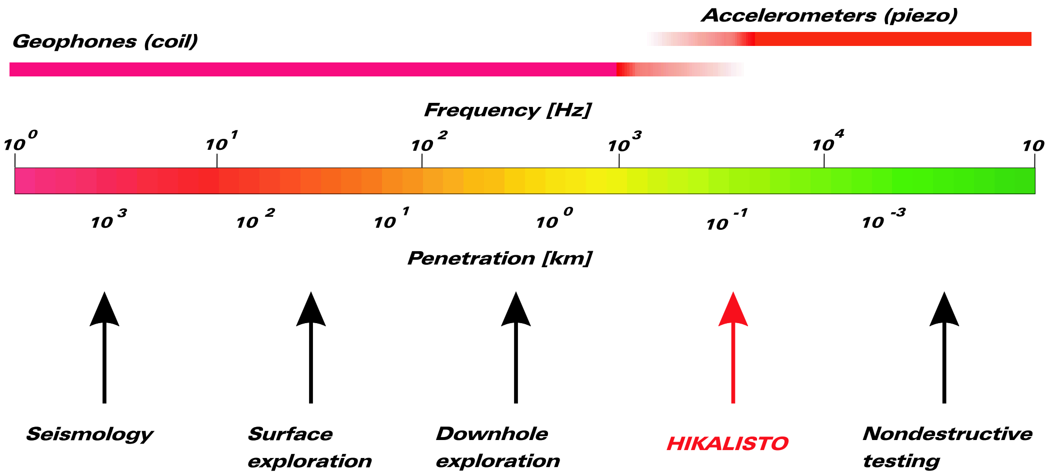


Figure 4: Frequency and transmission range of typical survey configurations used in seismic exploration and non-destructive testing as compared to the anticipated scale of measurements in the HIKALISTO experiment.

Considering a mean thickness of the ore dyke of about 2 meters, a resolution of less than 1 meter within a granitic environment of about 5 km/s had to be reached. This implied high scattering angles as well as frequencies well above 1 kHz. In this frequency range, limitations are imposed not only by the possible sources and signal transmission, but also by the recording characteristics of available receivers. This situation is depicted in fig. 4, where the scale and frequency range of our experiment is compared with other survey configurations frequently used in exploration and non-destructive testing. Available recording equipment shows a gap in the range between 1 and 10 kHz.

Survey Layout

The seismic measurements consisted of two parts: firstly, a low-frequency ($\approx$ 100 Hz) survey at the surface above the gallery involving groups of 6 geophones with an eigenfrequency of 14 Hz and an airgun-type source. Secondly, a high-frequency survey (up to 5 kHz) within the gallery, mainly concentrating on the testblock shown in fig. 5. In order to resolve the ore dyke with a thickness of about 1 - 3 meters within a granitic host rock, frequencies of up to 5 kHz had to be reached within the gallery. This could be achieved by a combination of high-frequency receivers including geophones with an eigenfrequency of 100 Hz and piezo-accelerometers. The geophones are able to record frequencies up to 3 kHz, whereas the accelerometers are recording in a frequency range of about 1 kHz to 10 kHz. As sources, detonator caps and a HILTI bolt gun were used.

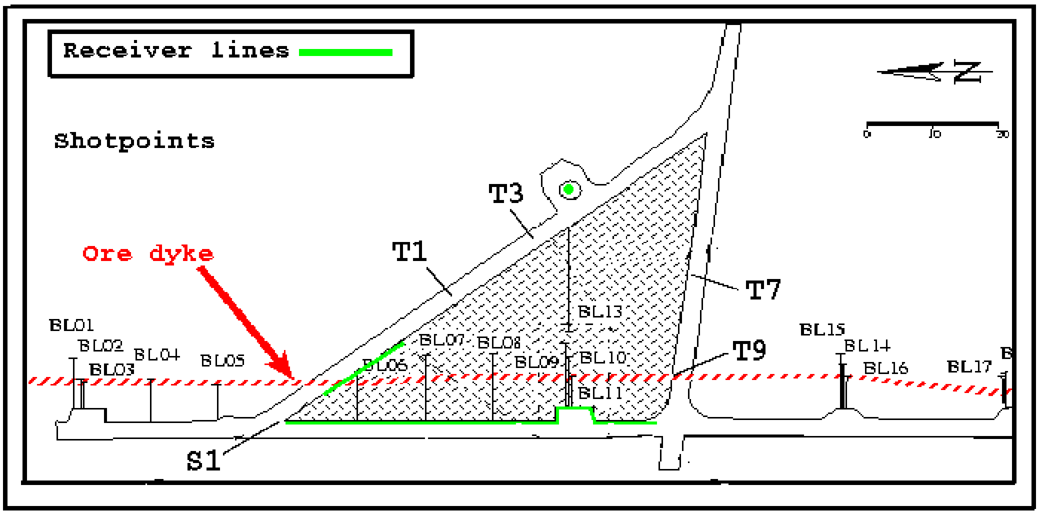


Figure 5: The central part of the test site where the gallery system excises a triangular test block of about 50 m length.

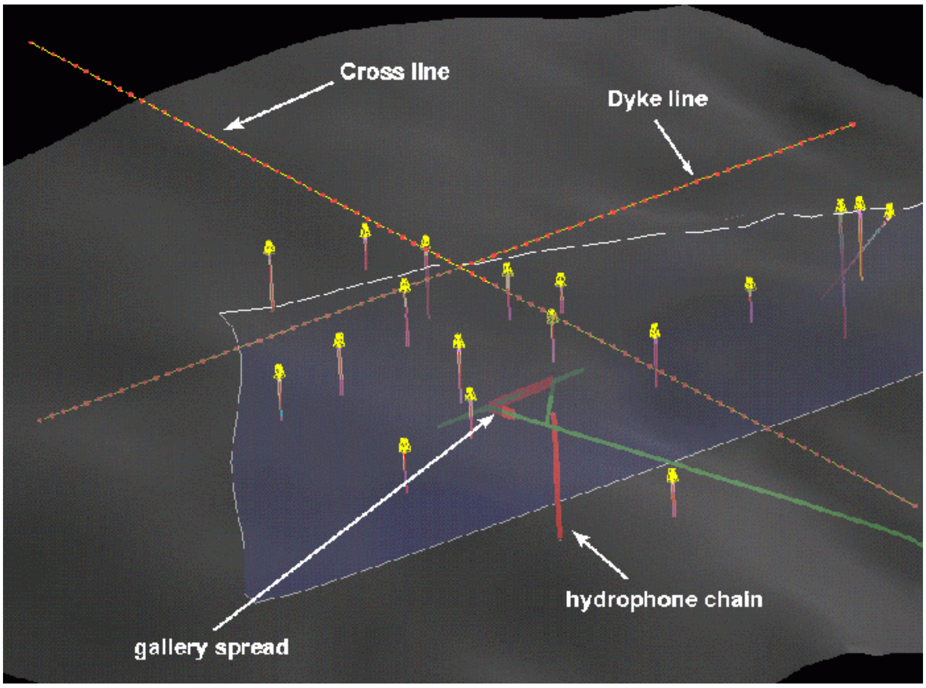


Figure 6: Overview of the Test site showing the geometry of the geophone spread. Through installation of receivers at the surface and within the gallery, a threedimensional array of receivers could be realized.

Altogether, close to 260 shotpoints were covered, recorded by about 220 live channels. Fig. 6 depicts the location of the threedimensional recording array at the surface as well as within the gallery.

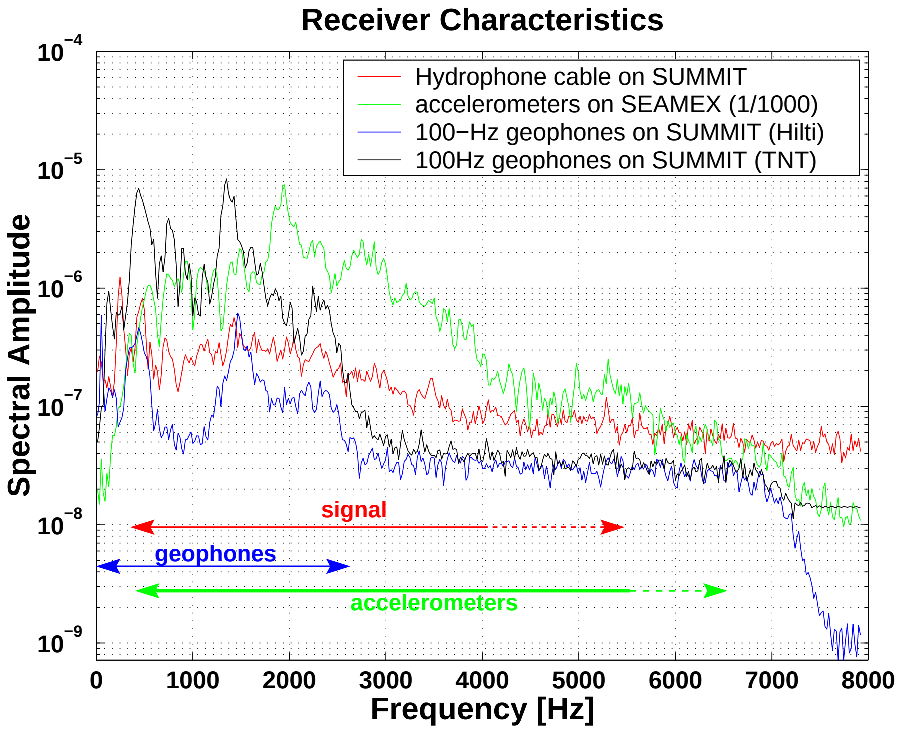
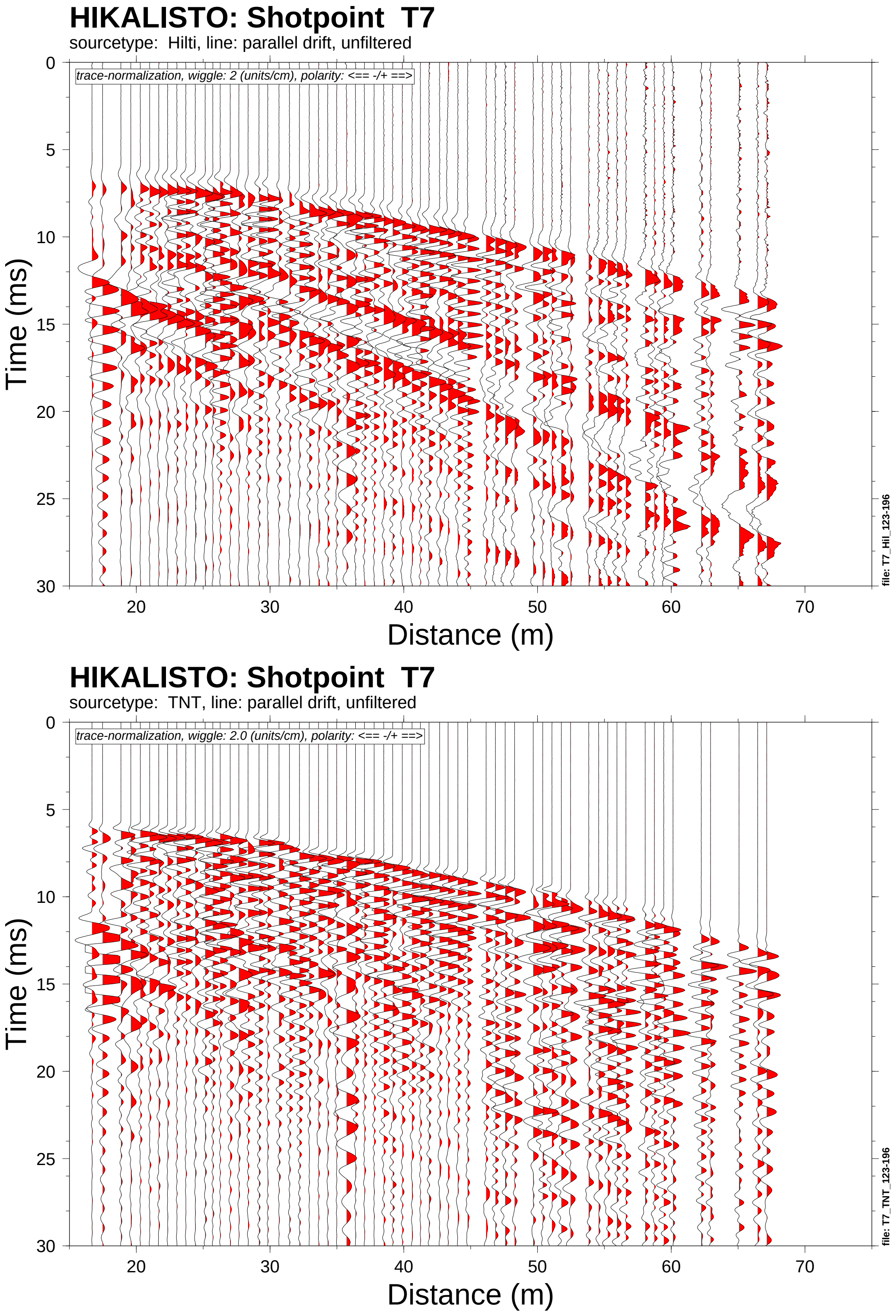


Figure 7: Comparison of different receiver characteristics for the type of receivers used in the experiment. The full frequency range of the input signal can be estimated from the accelerometer recordings.

FIRST RESULTS

In this section, we will show some data examples from the triangular test block within the gallery (see fig. 5). Here, all shots were recorded with three arrays: first, a spread along the parallel drift, consisting of 74 100-Hz-geophones spaced 0.7 m apart, then a 48-channel hydrophone cable with 0.5 m spacing which was installed in a 80 m deep water-filled shaft depicted in fig. 5. Shotpoints were shot several times in order to cover the whole shaft with the borehole cable. A high-frequency array consisting of 20 accelerometers was installed in the oblique drift where it crosses the ore dyke. Fig. 5 also depicts the location of some of the shotpoints that are shown in the example shotgathers below.



HIKALISTO: Shotpoint T7

sourcetype: Hilti, line: parallel drift, unfiltered

HIKALISTO: Shotpoint T7

sourcetype: TNT, line: parallel drift, unfiltered

Figure 8: Comparison between bolt gun (upper) and detonator cap (lower) as sources, recorded by an array of 100-Hz geophones along the parallel drift. The HILTI bolt gun produces considerable S-wave energy in contrast to the explosive (detonator cap) source.

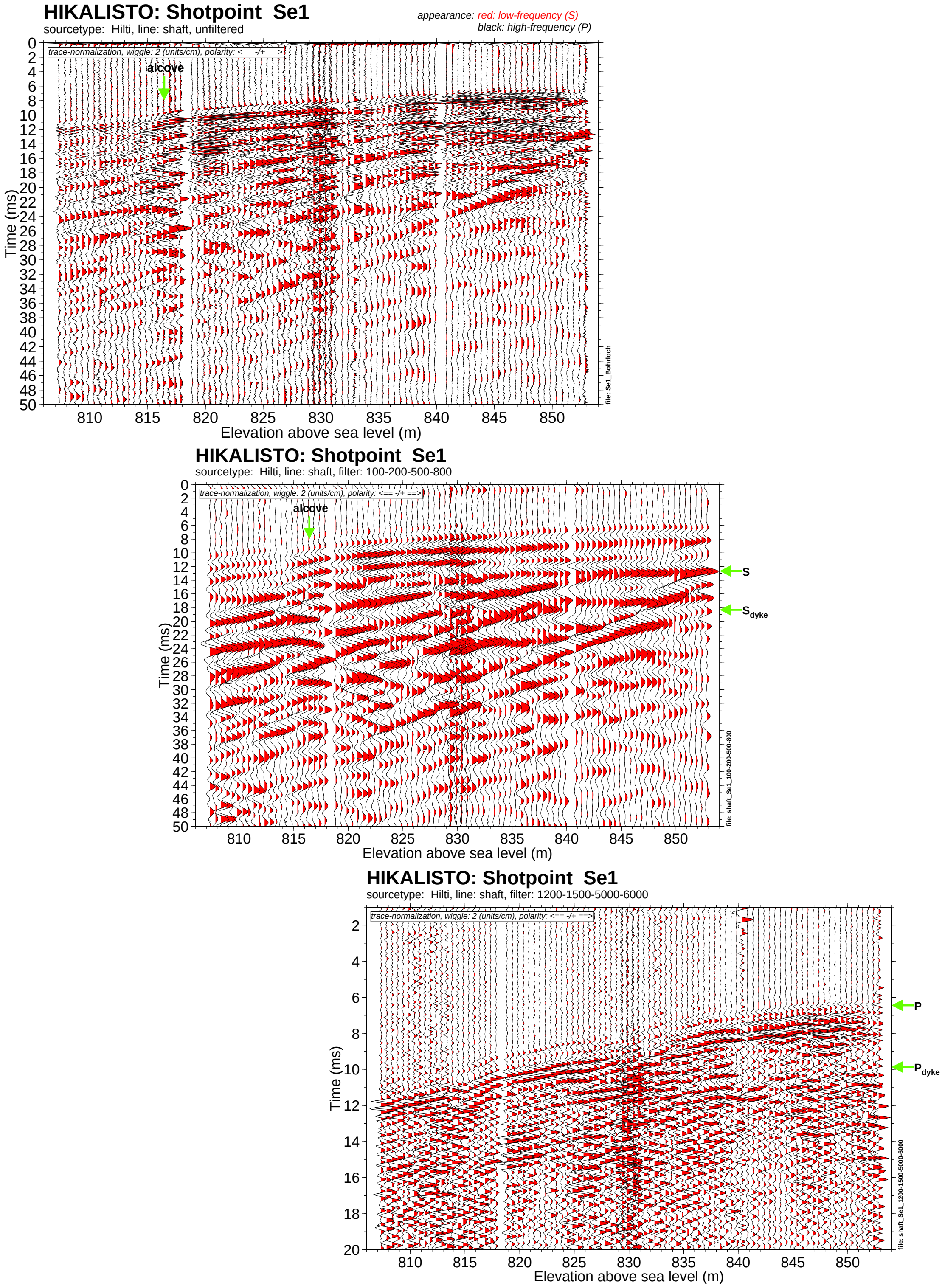


Figure 9: Comparison of different filters for a shot recorded by the hydrophone cable within the shaft. The unfiltered data (upper figure) show both P- and S-wave energy. Lowpass filtering (middle figure) enhances S-wave energy, whereas S-wave energy can be removed by highpass filtering the data (lower figure).

Differences between the different source types used can be seen in fig. 8. The HILTI bolt gun (upper figure) produced a considerable amount of shear wave energy which can be seen between 12 and 25 ms in the shotgather. The recording of the detonator cap (lower figure) shows predominantly P-wave energy. Thus, by comparing the two source types, we are able to distinguish converted wave energy from S-wave energy created at the source. Both sources produce roughly the same frequency range (dominant frequency above 2 kHz).

The data show also that the S-wave energy recorded is of considerable lower frequency than the P-wave data. This seems to be a source effect of the HILTI bolt gun, but can be used to easily separate the two wavefields. This is demonstrated for a record of the hydrophone cable in fig. 9. The unfilterd data (upper part) show both P- and S-wave energy, whereas the S-wavefield can be enhanced by lowpass filtering the data (middle). When high-pass filtering the same record (lower part), the S-wavefield can be eliminated. Arrows on the side point to P- and S-wave reflections of the ore dyke. Note that the shot (Se1, see fig. 5) was not inline with the cable. Diffraction patterns that can be seen in the left half of the shot records are produced by a drilling alcove within the water-filled shaft. Figure 7 illustrates the range of recorded frequencies of the different types of receivers used in the experiment. 100-Hz-geophones are not able to record more than 2500 Hz which is a limit imposed by their construction (induction coil). However, the sources (HILTI bolt gun as well as detonator caps) produce much higher frequencies as can be seen in the spectra of the hydrophones (red) and the accelerometers (green). We assume a flat response for the accelerometers up to 10 kHz (factory specifications). However, when comparing their spectra, one has to take into account that they were driven by a different recording system with different gain.

OUTLOOK

Preliminary data examples of this experiment show that the anticipated goals of this experiment could be achieved within a challenging frequency range. Data will be used for inversion of rock-physical parameters within the well-known ore dyke. We will test ideas and approaches to invert for hydraulic target properties. This includes seismic tomography, attenuation studies, detailed AVO studies in the depth domain and comparison of crack statistics with measures of possible anisotropy within the ore dyke. Such studies are feasible because the structure and geometry of the target feature is already well known. Structural uncertainties can thus be ruled out as a cause for biases in the data. Furthermore, the existing database allows us to test a variety of effective media approaches over a wide range of frequencies. The amount of detailed information is unique and enables us to study rock physical properties relevant for 4D seismic monitoring. In addition, the equipment of the gallery enables us to perform experiments under controlled transient hydraulic conditions by injection or extraction of groundwater.

ACKNOWLEDGEMENTS

We thank the following people who enabled this experiment with their strong support: Michael Nutto and Eva Richter of the Geodetic Institute, Karlsruhe University; Robert Krämer and Christof Gelbke of DMT, Essen; Thomas Dickmann of Amberg Measuring Technique, Switzerland; Jens Bribach of GFZ Potsdam, Axel Fabritius of GTC Kappelmeyer GmbH; Gundo Klebsattel and Mr. Senn of Schluchseewerke AG (Freiburg).

REFERENCES

Batzle, M., and Wang, Z., 1992, Seismic properties of pore fluids: Geophysics, **57**, 1396–1408.

Himmelsbach, T., 1993, Untersuchungen zum Wasser- und Stofftransportverhalten von Störungszonen im Grundgebirge (Albtalgranit, Südschwarzwald): Ph.D. thesis, Applied Geology Karlsruhe.

Kaselow, A., Goertz, A., Sule, R., Hofmann, S., and Wagner, D., 2000, Investigating Pore Fluids with Seismic Probing: Examples from Steeply Dipping Faults: AGU Fall Meeting, San Francisco.

Kaselow, A., 1999, Analytische und numerische Modellierung von Stofftransport in einer Störungszone im Grundgebirge: Master's thesis, Univ. Karlsruhe.

Margrave, G. F., 1997, Seismic acquisition parameter considerations for a linear velocity medium: 67th Annual International Meeting, Soc. Expl. Geophys., Expanded Abstracts, 47–50.

Traub, B., 1999, Seismic wave field modelling in 3D structures by means of recursive cell ray tracing: Master's thesis, Karlsruhe University.

Yilmaz, O., 1987, Seismic Data Processing: Soc. Expl. Geophys., Tulsa, OK.

PUBLICATIONS

Parts of the results were published by (Kaselow et al., 2000).