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Characterization of fractured rock in the vicinity of tunnels by the swept impact seismic technique

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Abstract

The diversity of the applications of high-resolution seismics requires investigations in the range of hundreds of meters to be performed in very diverse conditions. We found the swept impact seismic technique (SIST) to be a viable solution for high-resolution surveys in hard rocks. Swept impact seismic technique combines the Vibroseis swept frequency and the Mini-Sosie multi-impact ideas. Several variations of the method have been studied leading to improved resolution and efficiency. The development was partly funded by the Finnish Center for Technical Development (TEKES) and partly by the French National Agency for the Management of Radioactive Waste—ANDRA. A test programme was carried out at the Grimsel test site, operated by NAGRA—the Swiss National Cooperative for the Disposal of Radioactive Waste. Measurements were also carried out with single-pulse sources, but data of acceptable quality could not be obtained. Surface and tunnel-wall, as well as borehole SIST sources have been developed and tested. The ability of the seismic techniques to detect and characterize rock discontinuities was proven by investigating a rock block delimited by two parallel boreholes and a tunnel perpendicular to them, involving source–detector distances of 100–200 m. The characterization included the determination of the 3-D positions and orientations of rock features and the tomographic mapping of seismic velocities. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

High-resolution seismic surveys are carried out for locating features of possible hydraulic significance, for assessing the constructability of rock and earth and for delineating ore bodies with applications like: disposal of hazardous waste, monitoring of excavation works, rock engineering and mining.

The diversity of the applications of high-resolution seismics requires the data collection to be performed in very diverse conditions, e.g. in swamps, shallow water, on soil, gravel, pavement and rock, on tunnel walls and floors; in vertical, horizontal, up-going and down-going boreholes, drilled from the surface and from tunnels. The equipment must be able to operate in confined spaces and boreholes. The acquisition methods must be non-destructive and environmental friendly. The whole apparatus should be compact and mobile in construction and mining site conditions. Speed and ease of use are of essence to make the operation cost effective. These requirements became guidelines in our quest for viable small-scale seismic investigation techniques.

The envisaged range of high-resolution surveys is in the hundreds of meters. The minimum size of the targets is of the order of meters, for localized anomalies, and fractions of a meter for laterally extensive features, e.g. fracture zones. To reach the desired resolution, small-scale seismic data must contain frequencies of 1000 Hz or more, which are usually associated with low-power sources. Conversely, the sources must deliver sufficient energy to carry the high frequencies through, occasionally, highly attenuative media.

The high-frequency and high-energy requirements can be both fulfilled if the signal energy is built-up in time, rather than being emitted as a short burst. The idea of injecting energy over a period of time is common to the Vibroseis [1], the Mini-Sosie [2] and the swept impact seismic technique (SIST) [3] concepts.

The SIST is a combination of the Vibroseis swept frequency and the Mini-Sosie multi-impact ideas. With SIST, a low-power impact source generates a series of seismic pulses, hence the relation to Mini-Sosie. However, instead of a pseudorandom coding of the impact rates, a deterministic, monotonously varying rate is

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used, i.e. a swept impact rate, which makes SIST akin to Vibroseis. Swept impact seismic technique is, reportedly, more time efficient than Mini-Sosie. Compared to Vibroseis, with SIST a firm coupling to the rock or ground is not as critical. This is a clear advantage, as a firm, wide band contact is difficult to achieve in all situations, considering the diversity of the experimental conditions encountered in small-scale surveys. In addition, the SIST apparatus is simpler and more portable than Vibroseis.

The SIST concept has previously been tried with shallow reflection applications, at a comparable scale with the one that we have been concerned with, but with much lower frequencies. We found SIST to be a viable solution for high-resolution surveys in hard rocks, both methodologically and logistically.

The development of the sources based on the SIST concept described in this paper started with the help of the Finnish Center for Technical Development (TEKES). Substantial contribution was offered by the French National Agency for the Management of Radioactive Waste—ANDRA, both directly and as a part of an investigation programme carried out by Vibrometric at the Grimsel test site (GTS) in 1997 and 1998. Grimsel test site is located in the Swiss Alps and is operated by NAGRA—the Swiss National Cooperative for the Disposal of Radioactive Waste.

The main objective of the experiment has been to evaluate small-scale survey techniques and their ability to detect and characterize discontinuities in crystalline hectometric rock blocks. The information acquired also contributed to the increase of the knowledge regarding the structure and properties of the rock at GTS.

2. Variants of the SIST technique

A SIST coded record can be written as

$$r_c(t) = y(t) * s(t) * e(t) + n(t), \quad (1)$$

where $\psi(t)$ is the controlled impact sequence, $s(t)$ is the source signature, $e(t)$ is the earth impulse response and $n(t)$ is the noise. The $*$ denotes the convolution operator. Following Park [3], a 'normal' seismic record can be obtained by cross correlating the controlled impact sequence $\psi(t)$ and the coded record $r_c(t)$:

$$\begin{aligned} r_d(t) &= \psi(t) \otimes r_c(t) \\ &= ACF\{\psi(t)\} * s(t) * e(t) + \psi(t) * n(t). \end{aligned} \quad (2)$$

A key assumption in Eq. (2) is that the auto-correlation function $ACF\{\psi(t)\} \cong 0$ everywhere except at zero-lag. In practice, the degree of compliance with this condition will provide a way to evaluate the performance of various coding schemes.

Several time functions were studied and compared with the linear frequency scheme. In particular, an inversely linear frequency (linear period) was found to be effective. A 15–30 Hz, 30 s, 675-pulses linear frequency sweep has been used. It has been noticed during the study that with the linear period scheme the band could be narrowed to 18–30 Hz without an apparent loss of quality. This has been done primarily for practical purposes, as a smaller bandwidth simplifies the mechanical construction of the source. In spite of the narrower band, the linear period sweep leads to a more effective cancellation of the correlation noise, as seen by comparing the diagrams of the two auto-correlation functions from Fig. 1.

A source signature with a frequency band of 800–1800 Hz has been used with modelling, corresponding to the experimentally determined spectrum of several small-scale SIST sources.

In principle, the upper limit of the impact frequency band should be as low as possible to reduce the correlation noise. In practice, there are considerable benefits in increasing the impact frequency as much as possible, provided that the quality of the decoded signal does not decrease noticeably.

Fig. 2 shows the decoded signals for two sweeps, one of 18–30 Hz and the other of 90–150 Hz. The former is 30 s, the latter only 6 s long, which if the signal quality could be maintained would represent a significant improvement of performance. It is important that a tomographic section comprises thousands of measurements, which have to be recorded, inspected for quality assurance and decoded. The time needed for all these operations depends on the sweep length. In Fig. 2, the time-domain signal decoded from the 6 s sweep looks as clean, or arguably cleaner, than the 30 s signal. The characteristics of the noise are the same in both cases.

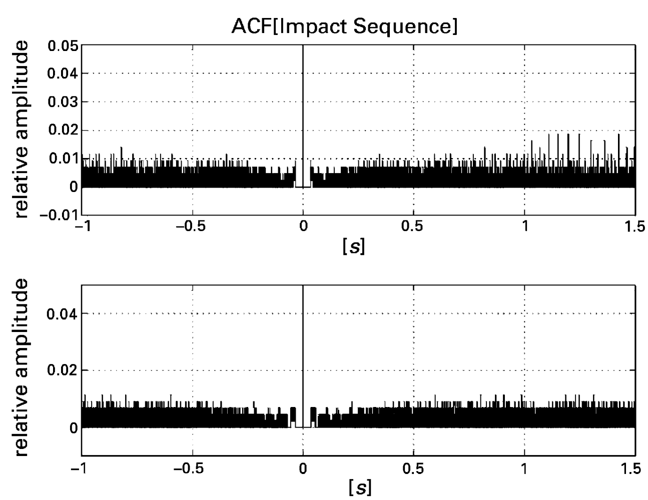

Fig. 1. Auto-correlation functions of the linear frequency (above) and the linear period (below) time coding schemes. The zero-lag peak in both cases is normalized to one and only a part of it is shown. The linear period scheme displays less spurious spikes. The spikier the $ACF(\psi(t))$, in Eq. (2), the more correlation noise in the reconstructed $r_d(t)$.

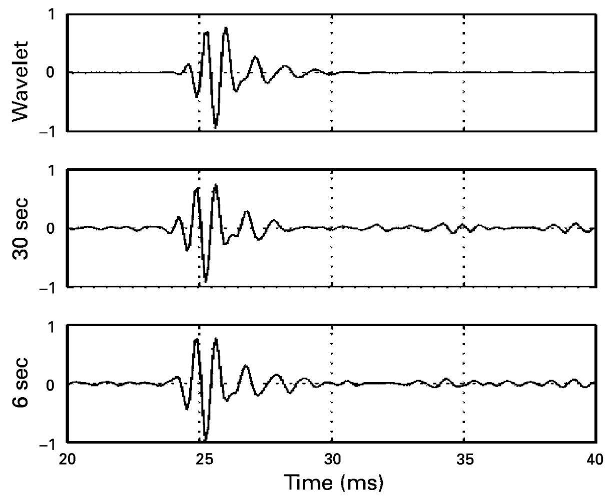

Fig. 2. The synthetic model (above) and the decoded signals corresponding to a 30 s, 18–30 Hz sweep (middle) and to a 6 s, 90–150 Hz sweep (below).

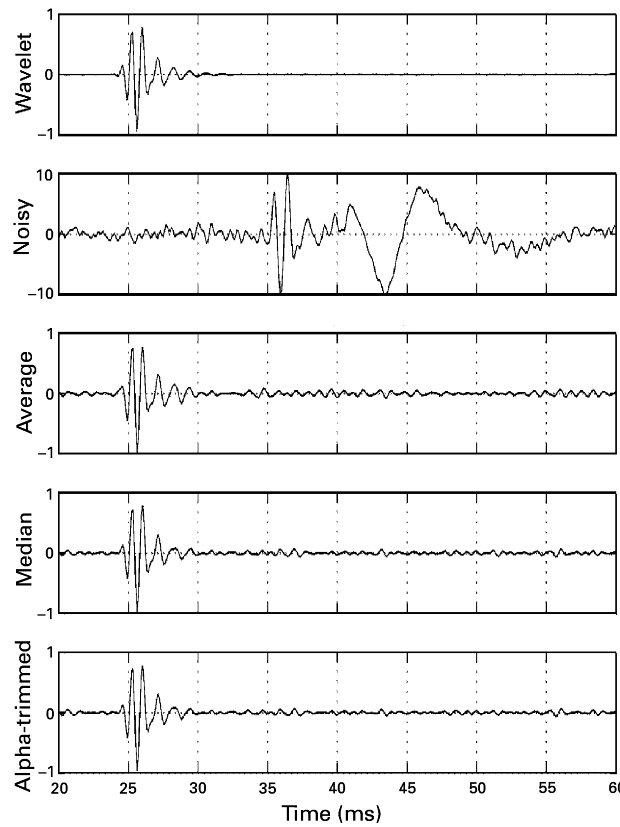

Fig. 3. Different techniques of extracting the useful signal from a noisy coded sequence (denoted "noisy").

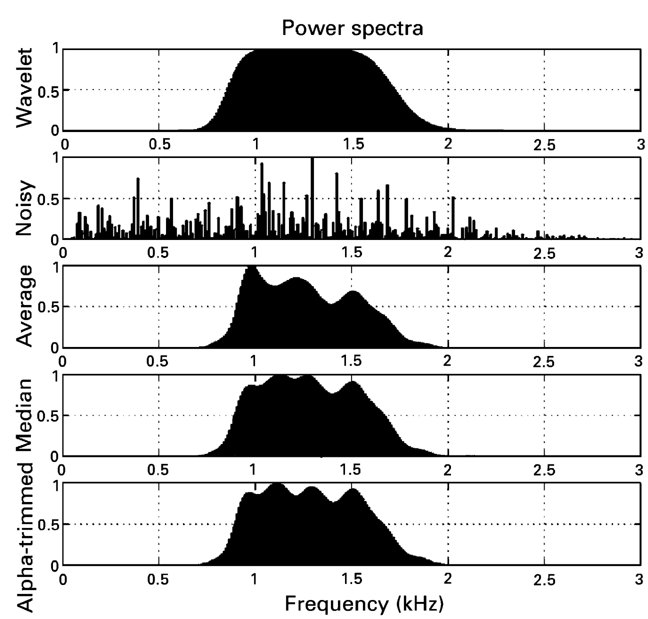

Fig. 4. Power spectra of the corresponding time domain signals of Fig. 3. Clearly, the median techniques are better than the straight sum.

The sweeps have been contaminated with 60–2000 Hz uniform random noise and noise bursts with bands of 50–200 and 600–1350 Hz. The random noise has twice the amplitude of the source signals. The burst amplitudes are 10 times higher and the mean rate is 6 and 10/s, respectively. These noise levels, however extreme they may seem, represent realistic conditions, such as in a production area of a mine.

As in Eq. (2) $\psi(t) = 1$ at the moments of impact and $\psi(t) = 0$ at any other time, the cross correlation can be replaced by simple 'shift-and-stack'. For purely random noise, the S/N of the sum signal will decrease by the square root of the number of impacts. However, in real life, the straight sum may not be the most efficient way to increase the S/N ratio. As it will be shown further on, SIST techniques based on more elaborate estimators than the shift-and-stack average, posses an even higher capability to suppress noise.

Fig. 3 displays three techniques of estimating the source signal: average, median and alpha-trimmed median. The noise is the same combination of uniform random and bursts as described above. Note that the noisy coded sequence is plotted with a 10-fold scale. The signal is literally invisible in the coded sweep. The time-domain signals obtained by all techniques resemble closely the synthetic wavelet. Differences appear when looking at the corresponding power spectra presented in Fig. 4. Clearly, the median techniques are better than the straight sum.

3. Investigations at GTS

The rocks at the GTS are Paleozoic granite and granodiorite that have been heavily deformed and altered during the Alpine orogeny. Consequently, the seismic transparency of the rock at GTS is very low, corresponding to a Q factor of 10–20. The NAGRA has earlier performed comprehensive studies regarding the performance of various seismic sources [4]. Apparently, a suitable combination of high frequency and high energy could be reached only by explosive sources. The fact that explosives are able to produce both high energy and frequency in a burst is because the high-energy results from the high speed of the particles during the detonation rather than from the movement of a large mass. However, this does not make explosives more user friendly, or more environmental friendly, or more time efficient in routine use, which, in accordance with the requirements outlined at beginning of this paper, did not make them a preferred option in our case. We eventually overcome the low seismic transparency of the GTS rocks by using the SIST concept. Measurements were performed in a rock block positioned between two gently down-going boreholes (i.e. BOUS 85.003 and ADUS 96.001), 120 m apart, 150 and 190 m deep and the WT tunnel, perpendicular to the boreholes [5]. The measurements performed included tunnel-to-hole and crosshole. The maximum source–receiver distance has been around 200 m.

A first measuring campaign was carried out with single-pulse sources. Three-component accelerometers were clamped in one of the holes and the sources were fired in the other hole and in the tunnel. A piezoelectric and an electromechanical source, both single pulse, were used. The conclusion of this campaign has been that single-pulse sources are not suitable for high-resolution surveys because, on one hand, increasing the source power to increase S/N ratio narrows the frequency band of the seismic pulse, and on the other hand, increasing the total energy by online stacking takes too long time for routine operations.

The first attempt of using standard construction site equipment to build a SIST source was done with a modified 1 kW electric hammer drill. A 20–80 Hz impact frequency band was generated by varying the input voltage, as shown in Fig. 5. It is important to note that the amplitude of the pulse does not depend on the input voltage and that the impact frequency varies linearly with the voltage. These characteristics make electromechanical sources computer controllable, by adjusting the voltage as a function of time. Various impact frequency codes can thus be generated.

To date, several models of surface and tunnel-wall electromechanical SIST sources have been taken into routine use. The hand-held 1.5 kW hammer from Fig. 6 (SIST20) delivers 20 J/impact, at a mean impact rate of 25/s. The energy delivered in a 20 s sweep is 10 kJ, which compares with a midsize drop weight. The signal frequency, though, goes well beyond 1 kHz, while a drop weight of comparable energy, used in similar conditions, remains in the low hundreds of Hz [4].

The GTS tunnel-to-hole surveys resumed with SIST sources [5]. The tunnel-wall source from Fig. 6 and an array of down-the-hole accelerometers produced the spectra presented in Fig. 7. The frequencies above 1 kHz tend to be lost in steps, corresponding to zones of fractured and altered rock crossed by the seismic signal. However, frequencies of up to 2 kHz can be observed all the way to a depth of 110 m, which corresponds to a source–receiver distance of approximately 140 m. The frequency content at the receiver end has been higher than obtained in the previous campaign, with single-pulse sources. It is also higher than reported by earlier seismic investigation programmes carried out at the same site [4]. In support of this observation, one can see Fig. 8, which displays axial component receiver gathers obtained with a single-pulse source (PH52) by online stacking and the SIST20 source. Both profiles were measured at GTS from the WT tunnel to a down-hole 3-component accelerometer in BOUS 85.003. Fig. 9 also shows a dramatic increase of resolution of the SIST profile vs. the single-pulse profile, both due to a wider

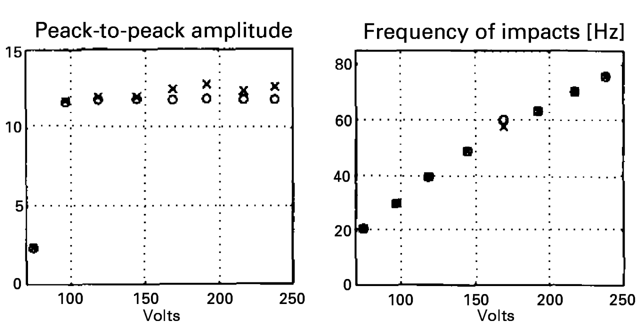

Fig. 5. Variation of the peak-to-peak amplitude and impact frequency with the input voltage, determined experimentally for an electric hammer drill.

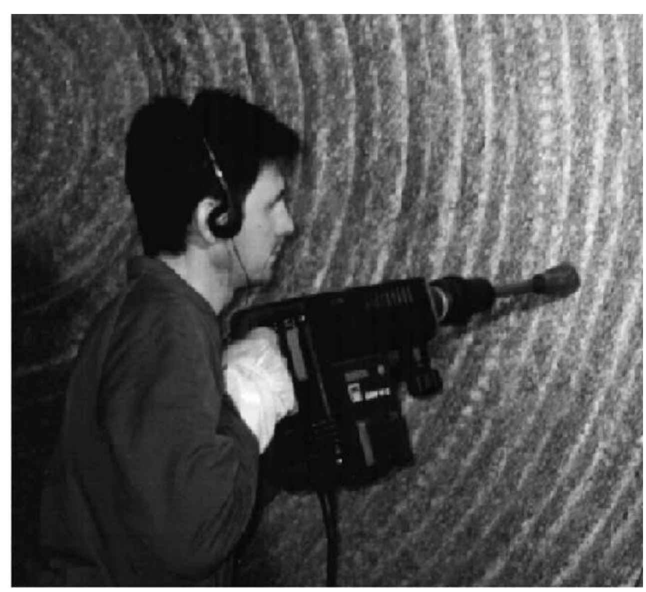

Fig. 6. SIST tunnel-wall source built starting from an electric demolition hammer.

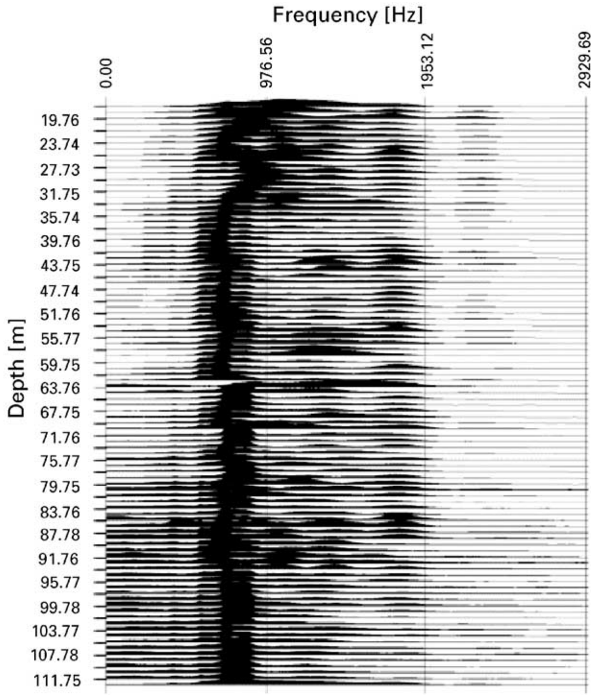

Fig. 7. Amplitude spectra of a Z-component VSP profile at GTS. A part of this profile is shown in time domain in Fig. 9(b). The signature of the SIST source from Fig. 6, used to survey this profile, extends from 500 Hz to beyond 2 kHz. The highly attenuative rockmass at GTS absorb most of the frequencies above 1 kHz.

frequency band and a higher S/N ratio. The improvement was realized in spite of the fact that a quadruple amount of time was spent for acquiring a single-pulse record.

4. Borehole SIST sources

Piezoelectric SIST sources for investigation depths up to 1 km and for borehole diameters from 46 to 100 mm have been built based on an existing single-pulse model (PH52). The seismic signals are produced by applying controlled sequences of high-voltage pulses to a stack of piezoelectric ceramics. The frequency band is 500–2500 Hz and can be changed with a variation of the design. The source is clamped by a motor-driven wedge mechanism. Recently, a variation of coupling of the source through the borehole water has been developed and successfully tested. So far, the clamping has been a factor limiting the overall operational speed and increasing the impact frequency, following the discussion from Section 2, was more of a theoretical interest. The fluid coupling allows the source to be run in a more or less continuous mode, which can take full advantage of the increase of the impact frequency.

Fig. 9 displays two profiles obtained with a fluid coupled PH70 piezoelectric source at distances of

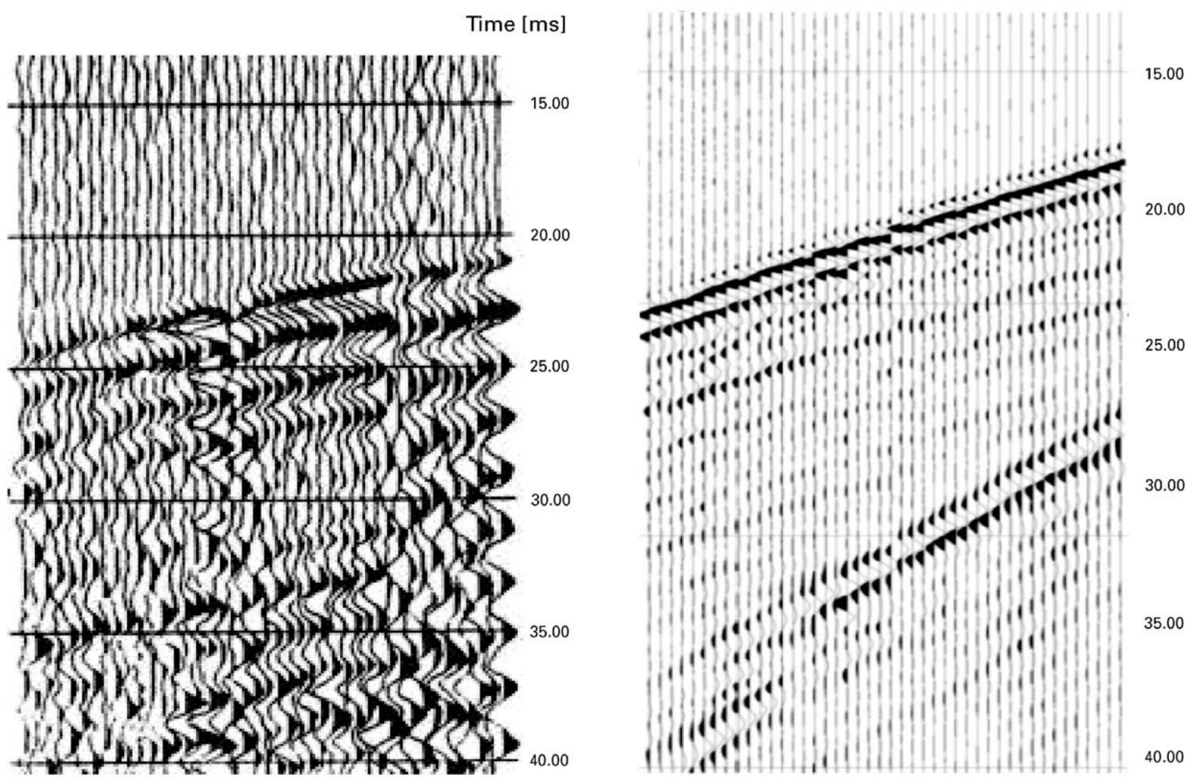

Fig. 8. Axial component receiver gathers obtained at GTS from a single-pulse source (PH52) (a) and the SIST20 source (b) (18–30 Hz, 20 s sweep, 500 impacts).

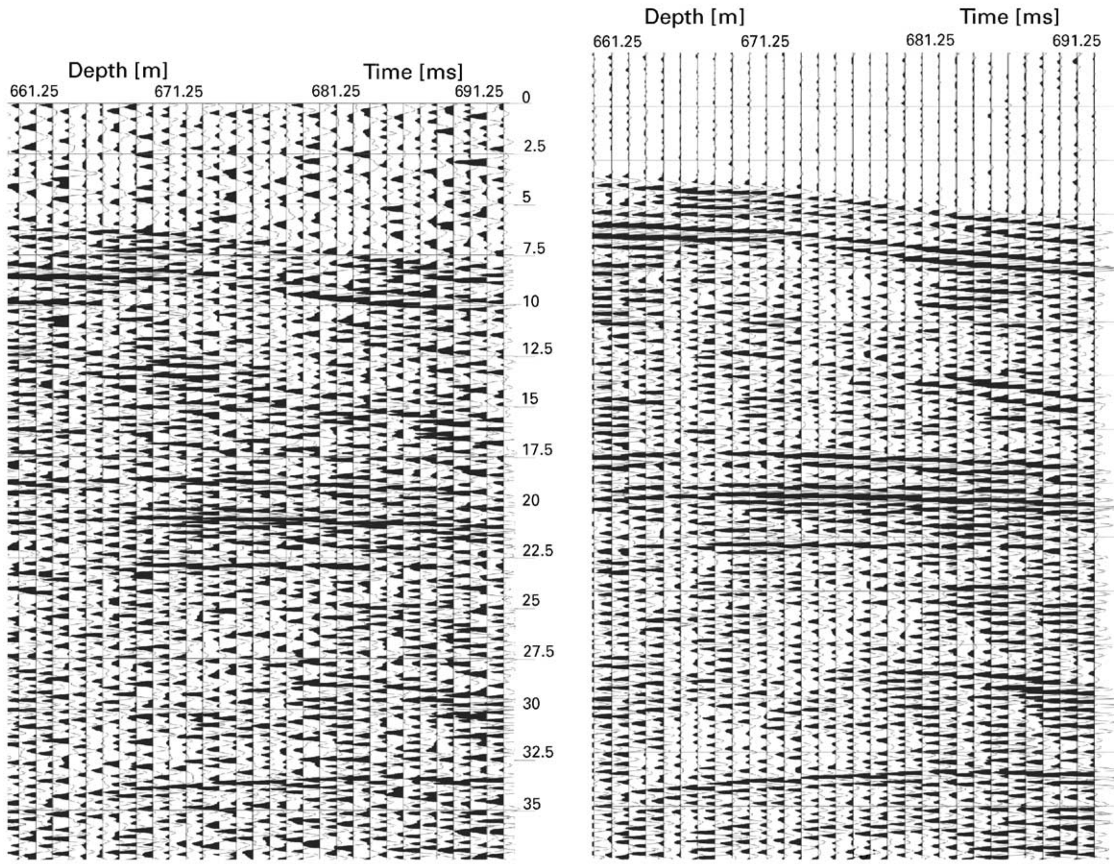

Fig. 9. Source gather measured with the PH70 SIST piezoelectric source. (a) Portion of the long SIST sequence. (b) Decoded profile (5–40 Hz, 10 s sweep, 200 impacts).

70–90 m. Profile (a) is a single-pulse record, profile (b) has been obtained by SIST. The acquisition time was 10 s with a bandwidth of 5–40 Hz and comprised 200 pulses. This leaves ample possibilities for S/N improvement, as discussed above. After the optimization of the impact frequency band, the time needed to acquire a single pulse as in Fig. 9a and a SIST sequence as in Fig. 9b becomes, for all practical purposes, equal.

Several reflectors are already visible in the single-pulse record of Fig. 9a, which illustrates the efficiency of the fluid coupling system recently developed. The fact that such single-pulse data is indeed processable is a promising step towards the acquisition of spatially quasi-continuous data profiles, which would likely lead to a breakthrough in multi-dimensional and directional data processing.

5. Discussion and conclusions

The proof of the ability of high-resolution seismic techniques to detect and characterize rock discontinuities was made by characterizing a rock block delimited by two parallel, gently dipping boreholes and a tunnel perpendicular to them, as shown in Fig. 10 [5].

The rockmass characterization included the determination of the 3-D positions and orientations of rock features by multi-offset VSP and crosshole imaging and the tomographic mapping of seismic velocities. The structural model was constructed by joint analysis of reflection and transmission data.

The main groups of reflectors were located and their existence and position were confirmed in borehole and tunnel profiles. One of the main sets strikes roughly perpendicularly to the tunnel dipping approximately 60°. This set is abundantly represented in the tunnel as lamprophyre dykes. Another set dipping 60° strikes nearly parallel to the tunnel and consists of zones of intense fracturing. This set is confirmed by observations in the tunnel and boreholes. The third main orientation is sub-horizontal and has been confirmed mainly by borehole observations. Besides the reflectors following these main orientations, some isolated features were associated with a high-velocity feature found by tomographic analysis.

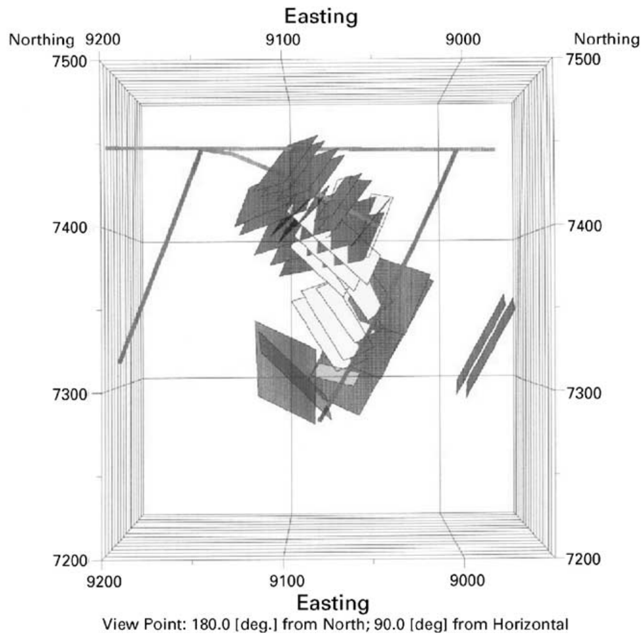

Fig. 10. Structural model of the investigation site at GTS as inferred from the SIST tunnel-to-hole and crosshole investigations.

Abundant fracturing and extensive lamprophyre dykes brought the average Q factor of the rock to values as low as 10. In spite of this, the acquisition system including SIST sources provided the level of detail needed for tomography and migration.

Data of acceptable quality could not be obtained with single-pulse sources.

Regarding the methodology, the multi-offset VSP methods based on the Image Point transform [6] formed the core of the processing/interpretation scheme for determining the 3-D position and local orientation of the reflectors. With the high operational speed and resolving power offered by the SIST techniques in hard rock, as shown in this paper, it becomes possible to acquire at a reasonable cost the large volume of data needed to integrate 3-D imaging procedures with the existing multi-offset VSP technique. The capability of the method will be thus greatly extended towards imaging folded and local discontinuities with greater accuracy.

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