Comparison of surface seismic sources at the CO_2SINK site, Ketzin, Germany

Sawasdee Yordkayhun[1*], Alexandra Ivanova[2], Rüdiger Giese[2], Christopher Juhlin[1], and Calin Cosma[3]

[1]Department of Earth Sciences/Geophysics, Uppsala University, Uppsala, Sweden, [2]GeoForschungsZentrum, Section 5.1, Potsdam, Germany, [3]Vibrometric, Vantaa, Finland

(E-mail: sawasdee.yordkayun@geo.uu.se / Fax: +46 18-501110 / Phone: +46 18-471 7161)

ABSTRACT

In 2004 three seismic surface sources (VIBSIST, accelerated weight drop and MiniVib) were tested in a pilot study at the Ketzin test site, a study site for geological storage of CO_2 (EU project CO_2SINK). The main objectives of this pilot study were to (1) evaluate the response of the Ketzin site to reflection seismics, especially at the planned injection depth, (2) test different acquisition parameters and (3) use the results to guide the planning of the 3D survey. The sources were tested along two perpendicular lines of 2.4 km length each. Data were acquired by shooting at all stations (source and receiver spacing of 20 m) on both profiles, allowing CDP stacked sections to be produced. Signal-to-noise ratio, signal penetration and frequency content of the source signals were determined by using single shot gathers and CDP stacked sections. The experiment shows that all three surface sources are suitable for high resolution seismic studies down to a depth of about 1 km and provide enough bandwidth for resolving the geological targets at the site. The CDP stacked sections of the MiniVib source show the highest frequency signals down to about 500 ms TWT (approx. 500 m depth), but the shallowest signal penetration. The VIBSIST source generates signals with the highest signal-to-noise ratio and greatest signal penetration of the tested sources. In particular, reflections below 900 ms (approx. 1 km depth) are best imaged by the VIBSIST source.

Keywords: Seismic source; Seismic acquisition; Signal penetration; CO_2SINK; VIBSIST

INTRODUCTION

Geological storage of CO_2 is probably that technology with the greatest potential for reducing CO_2 emissions into the atmosphere in the near future (Metz *et al.* 2005). An important component of large scale storage will be the monitoring aspect, that is tracking the CO_2 after it is injected into the underground reservoir and detecting any leakage out of the reservoir. The CO_2SINK project (Förster *et al*. 2006) is an European Union funded integrated project that focuses on the application of various monitoring techniques for geological storage of CO_2. It includes both applied and theoretical scientific studies related to the characterization of the sub-surface and to understanding the processes associated with the storage of CO_2. Main objectives are to (1) investigate and advance the understanding of the science and practical processes related to geological storage of CO_2 in a saline aquifer, (2) build confidence towards future European geological storage of CO_2 and (3) provide real case experience that can be used in the development of future regulatory frameworks for geological storage of CO_2.

In order to attain the above objectives a study site located west of Berlin, near the city of Ketzin, Germany (Figure 1) has been selected. The Ketzin site served as a natural gas storage facility up until 2000 and was abandoned in 2004. The existing infra-structure from the natural gas storage facility was an important consideration in choosing the site. Even though the CO_2SINK project involves only injection of CO_2 on a small scale (30,000 tons/year) the methodology is similar to that which will be used on a larger scale. Prior to drilling of the injection borehole, a pre-investigation phase was performed consisting of compilation of available geological information, modeling studies, and evaluation of techniques. An important component in this pre-drilling phase was a 3D baseline seismic survey (Juhlin *et al*. 2006). Construction plans involve the drilling of three boreholes, one injection well and two observation wells, about 50–100 m apart, into the flank of the Ketzin anticline. After drilling and baseline borehole investigations are completed, approximately 100 tons/day of nearly pure CO_2 will be injected at about 650 m depth into a saline sandstone aquifer starting in 2007 and continuing for up to 2 years. During and after injection, extensive monitoring of the distribution of the injected CO_2 will be carried out by using a broad range of geophysical and geochemical techniques, as well as reservoir modeling.

Studies elsewhere (Davis *et al*. 2002, Arts *et al*. 2004, Ziqiu and Takashi 2004) have shown that seismic methods perform well in tracking the movement of CO_2 in the sub-surface using time-lapse techniques. Before carrying out the 3D baseline seismic survey at the Ketzin site a pilot study was performed in 2004 (Figure 1). The main objectives of this pilot study were to (1) evaluate the response of the Ketzin site to reflection seismics, especially at the planned injection depth, (2) test different acquisition parameters, such as surface seismic sources, geophone types and deployment and recording parameters, and (3) use the results to guide the planning of the 3D survey. Vintage seismic data from the 1960s showed that it was possible to obtain good seismic images using several kg of dynamite as a source. However, it was not clear if less costly sources could produce good quality data in the area. Since the 3D seismic survey would require a large number of source points, the time necessary to activate a source was an important factor to consider, as well as the source performance regarding penetration depth and frequency content. Therefore, in this paper we focus on the comparison of the three seismic sources used in the pilot study; VIBSIST, MiniVib and weight drop. First we compare penetration and frequency content of individual source gathers, followed by comparisons of CDP stacked sections along two different test lines. Finally, we comment on the advantages and disadvantages of the three different sources.

SITE GEOLOGY

The topography of the Ketzin site is relatively flat, but does contain some isolated highs, consisting mainly of Quaternary sands. Vintage reflection seismic profiles and stratigraphic and lithological information from the many shallow boreholes drilled in the area provide information on the sub-surface geology. The site is located on the eastern part of a salt generated double anticline structure, the Roskow-Ketzin anticline (Figure 2), with an axis striking NNE-SSW and flanks gently dipping at about 15°. Below the Quaternary deposits, Tertiary, Lower Jurassic and Triassic rocks are present, consisting mainly of sandstones, siltstones and mudstones. Within the Triassic rocks, a c. 20 m thick anhydrite layer is present, known as the K2 (Keuper) reflector. This high impedance layer, found between depths of 500 m to 700 m at the Ketzin site, has been clearly imaged on the vintage seismic data and is an important marker horizon for the CO_2SINK project since it lies about 80 m above the top of the Stuttgart Formation, the target formation for the CO_2 injection at Ketzin. The Stuttgart Formation is on average 80 m thick and lithologically heterogeneous. Playa-type rocks of the Weser and Arnstadt formations form an approximately 210 m thick caprock section above the Stuttgart Formation. This section consists mainly of claystone, silty claystone, and the Keuper anhydrite.

The Jurassic sandstones between 250 m and 400 m were used for the industrial storage of natural gas until the year 2000. These sandstones, together with inter-layered mudstone, siltstone, and anhydrite form a multi-aquifer system. A Tertiary clay (the Rupelton), about 80–90 m thick, forms the caprock for this aquifer system. This Tertiary clay acts as a major aquitard separating the saline waters (brines) in the deeper aquifers from the non-saline groundwater in shallow Quaternary aquifers. There is evidence that local erosion of the Rupelton aquitard at some locations (Förster *et al*. 2006) allows saline waters to ascend and mix with fresh water in shallow aquifers.

SEISMIC SOURCES

Explosive sources have been widely used for land seismic surveys for many decades, providing an high-energy high-bandwidth source. However, use of explosives sources is becoming more and more restricted, limiting its use in many areas. In addition, the necessity of drilling shot holes and the speed of operation make it often the most expensive source choice. As an alternative to explosives, vibrators on land and airguns at sea have been used for traditional reflection seismic profiling for petroleum exploration and deep seismic profiling (e.g., Woodward 1994; Steer *et al*. 1996; Staples *et al.* 1999). In the past decade, a large number of land seismic sources have been developed and successfully applied to shallow engineering, groundwater, mining and environmental problems (e.g. Pullan and MacAulay 1987; Jongerius and Helbig 1988; Steeples and Miller 1990; Wright *et al*. 1994). Obviously, there is no single best criterion for choosing a source since the choice depends on the target and the required depth penetration and resolution. Several studies have dealt with source choice and we briefly summarize of the results below.

1) Site dependent and environment conditions

By comparing various sources in different geological settings, Miller *et al*. (1986, 1992, 1994) concluded that the quality of recorded data depends greatly on the depth of the water table and on the near surface geology. Sources which worked well in areas with consolidated surface materials or a shallow water table, such as surface gun type sources, are often no better than simple hammer sources in areas with loose sand at the surface. Moreover, in shallow earth materials, even in consolidated sediments and crystalline rocks, the high frequency components of seismic signals are strongly attenuated (Buhnemann and Holliger 1998), limiting the penetration depth of high frequency signals. A field test of 14 seismic P-waves sources was designed in the Quaternary landscapes of Northern Germany to study the capabilities of seismic sources for shallow sub-surface investigations (Herbst *et al*. 1998). It proved necessary to record up to 120 shots per source in order to get representative results and to compare not only single shots, but stacked sections as well. This was due to local changes in sub-surface conditions showing a strong influence on the recorded data.

2) Energy and frequency content

The energy and frequency content required to record seismic reflections is variable and depends on many factors, including the depth of the target and its thickness (Knapp and Steeples 1986). Since seismic resolution is directly related to the dominant frequency of the signal, it is important to find seismic sources capable of generating adequate high frequency energy. We can quantify the energy of a seismic wave by the energy density (energy per unit volume). Energy density (*E*) is proportional to the square of the amplitude (*A*) within the same medium (Sheriff 1975; Telford *et al*. 1990):

$$E = 2 \cdot \pi \cdot \rho \cdot f^2 \cdot A^2 \qquad (1)$$

where ρ is the density of medium and f is the frequency. Non-geological factors affecting the amplitude include source strength and coupling, geophone sensitivity, instrument balance and scattering in the near surface. Sub-surface (geological) factors include spherical divergence, ray path curvature, transmission losses, multiples, reflection coefficients and absorption. Buhnermann and Holliger (1998) provide more details of amplitude variations versus frequency and sub-surface conditions. In particular, seismic attenuation increases exponentially with increasing frequency (f) of the seismic signal and decreasing quality factor (Q) of the probed medium by:

$$A(\Delta x, f) = A_0(f) \cdot \exp(-\frac{\Delta x \cdot f}{v \cdot Q}) \qquad (2)$$

where v is the seismic velocity, A_0 is the original amplitude, and A is the amplitude at offset Δx. Mayer and Brown (1986), Steer *et al*. (1996) and Juhojuntti and Juhlin (1998) studied the decay of source-generated energy with time along with the corresponding estimated ambient noise levels. From these studies estimates of the depth of signal penetration could be made that aided in interpreting lateral variations of reflectivity in deep seismic sections.

3) Signal- to- noise ratio (S/N)

Feroci *et al*. (2000) compared different sources in one particular area. They found that even if there are no substantial differences in frequency content, significant S/N ratio differences are observed, suggesting that the source can dramatically influence the S/N ratio. Air blasts, ground roll, and source generated noise can be so large in amplitude that they contaminate all the reflections on near offset traces.

4) Source wavelet (pulse shape)

A recorded seismic trace (x) can be modeled (e.g. Yilmaz 1987; Ziolkowski 1991) as a convolution (*) or time series superposition of the downgoing seismic wavelet (w) with the earth impulse response (e) plus noise (n):

$$x(t) = w(t) * e(t) + n(t) \qquad (3)$$

The wavelet has many components, including source signature, recording filter, surface reflections, and geophone response. The earth impulse response would be recorded if the wavelet were a spike. Such a source would have a flat amplitude spectrum to arbitrarily high frequencies. In general, the shorter the energy pulse, the higher the maximum frequency observed. Knapp and Steeples (1986) pointed out that a flat spectrum over three octaves normally produces excellent seismic reflection data. Wardell (1970) classified land sources into three groups based on the basis of pulse shape. These are wide frequency band pulses (explosive sources), low frequency pulses (surface impact sources) with good low frequency energy due to the coupling effect between the impact pad and the surface, but a relative lack of high frequency energy, and vibratory sources where the shape of the spectrum can be controlled. An important factor affecting resolution is the wavelet phase. In general, the simpler the phase relationship, the narrower the resulting wavelet pulse. Ideally, a zero phase wavelet results in the best resolution compared to minimum phase and complex phase wavelets.

5) Repeatability

Stacking records from multiple inputs of the same energy source at the same shot point is a simple technique to enhance the signal. However, repetition of the energy source requires that input conditions be as similar as possible so that amplitude, phase and spectral content are as constant as possible in the stacked records, otherwise, the source signature will be changed.

6) Portability and economics

Obviously, we want an energy source that provides the required spectrum and energy content at minimum cost. Crews and vehicles needed for operating a source are an important cost factor. In some cases, logistics play an important role. There may be sites where large sources vehicles cannot enter. In these cases, portability is a major issue.

In this paper, we focus our comparison on three seismic sources used in the pilot study at the CO_2SINK Ketzin site, an accelerated weight drop, a MiniVib (vibrator) and a VIBSIST source. The first two are well known within the seismic exploration community. The weight drop is an impact source that utilizes a falling, or accelerating, weight onto a base plate. Momentum at impact, size (mass) of the base plate, and near surface conditions influence the amplitude and frequency content of the signal. The MiniVib uses a swept frequency signal (sweep) that changes frequency at constant amplitude from a low limit f_1 to a high limit f_2 over a period of seconds. After acquisition, the sweep is cross-correlated with a reference signal (pilot sweep). This source generates a highly repeatable signal and the correlation process yields, in theory, a zero phase wavelet. VIBSIST sources have just been developed over the past decade and are based on the Swept Impact Seismic Technique (SIST), a combination of the Vibroseis swept-frequency and the Mini-Sosie multi-impact methods. A few to several hundred impulsive seismic pulses are generated according to a preset monotonic impact sequence in which the impact rate either increases linearly with time (upsweep) or decreases with time (downsweep). The decoding process is a "shift-and-stack" method that is simpler and quicker than cross-correlation. Details of the method can be found in Barbier *et al*. (1976), Park *et al*. (1996) and Vibrometric (Cosma and Enescu 2001). Some characteristics of these sources are listed in Table 1.

DATA ACQUISITION

The pilot reflection seismic data were acquired in September, 2004. Two perpendicular lines, running mostly along two agricultural roads near the target area of the planned 3D survey, were shot (Figure 1). The surface relief along the N-S profile (Line 1) is somewhat higher than that of the E-W profile (Line 2). Surface conditions along the two lines varied. Line 1 was a traditional agricultural road, while Line 2 consisted of a hard soil that had been compressed by heavy military equipment.

Although we focus on the source comparison in this paper, the study consisted of both testing of source and receiver performance. The three different sources were tested along the two lines. The measurements were carried out according to the same scheme for every source. On the first day, tests and parameter tuning were done at five selected locations on or close to the E-W profile. On the following 2-3 days, data were acquired by shooting at all stations (source and receiver spacing of 20 m) on both profiles, allowing CDP stacked sections to be produced. Data were recorded on 240 channels (fixed spread). Sources activated on the E-W profile were also recorded on the N-S profile as were sources activated on the E-W profile recorded on the N-S profile, providing the possibility for a (pseudo) 3D analysis of the survey area. Only a few selected stations were skipped due to the presence of gas lines. The tests also included comparison of 10 Hz and 28 Hz geophones on the E-W line and a comparison of geophones planted on the surface and in holes 30-40 cm deep. Recording conditions were variable due to, at times, heavy rain and wind or traffic on the roads close to the profiles. A summary of the acquisition parameters is provided in Table 2.

DATA PROCESSING

Examples of typical unprocessed shot gathers from the three different sources are shown in Figure 3. On the raw shot records, the direct P-wave, ground roll and source-generated noise are clearly seen, as well as reflections. We have focused our data processing and analysis on the upper 1.5 s since the target horizon for the CO_2SINK project is at about 700 m depth and signal strength was expected to have decayed to background levels at later times. Several conventional processing steps were applied in order to enhance the data in the upper 1.5 s (Table 3). Given the different nature of the sources, we decided to process each data set independent of the others when producing CDP stacked sections. However, when analyzing source gathers every attempt was made to treat the data in an equal manner. In the pre-processing phase, the MiniVib data required correlation and the shift and stack process was applied to the VIBSIST data. Due to the topographic relief and rather thick near surface low velocity layers one of the most important processing steps was refraction statics.

For the VIBSIST data, first arrival times were picked and near surface structure were determined. Static corrections were then computed and applied to the data. Deconvolution balanced the spectrum and improved the resolution. Source-generated noise, such as ground roll, is prominent on unfiltered records and contaminated the near offset (0-500 m) traces for all sources. Ground roll (coherent noise) appears within a typical cone, characterized by high-amplitude and low frequency energy which is produced by the near surface geology. Bandpass filtering removed some of the ground roll, but it was still necessary to apply a bottom mute. Based on amplitude spectra, frequency filters of 30-85 Hz were designed to limit the influence of high and low frequency noise. After CDP sorting, careful velocity analysis was performed by picking velocities in constant velocity stacked and/or semblance panels. After stacking, surface consistent residual statics were computed along chosen reflection horizons. By applying residual statics before velocity analysis and stacking, the stacked sections were improved.

Processing flows for the MiniVib and weight drop differed somewhat from the VIBSIST processing. For instance, for the MiniVib data a minimum phase signal transformation was applied before deconvolution. This transformation aims at an improvement of the deconvolution result and for comparison with the minimum phase signals of the impact sources. CDP stacks from the three different sources are shown in Figures 4, 5 and 6. Figure 7 depicts blow-ups of the Line 2 stacked sections between CDP 660 and 720 and TWT of 0.35 s and 0.7 s. The following reflections and layers are marked: (L4) the top Triassic (assumed), (K2) the top reflector of the Weser Formation, (SF) the position of the Stuttgart Formation, (K3) near top of the Grabfeld Formation (Figure 2).

SIGNAL-TO-NOISE RATIOS

Following Staple *et al*. (1999) and Benjumea and Teixido (2001), a direct comparison of the signal-to-noise ratio (S/N) can be made using raw data from the three sources (Figure 3). The apparent signal-to-noise ratio $Q_{S/N}$ is given by:

$$Q_{S/N} = \frac{S_{RMS_{t_0}^{t_0+200ms}}}{N_{RMS_{t_0-200ms}^{t_0}}} \qquad (4)$$

where S_{RMS} is the RMS amplitude measured in a 200 ms window beginning at the first arrival time, N_{RMS} is RMS amplitude measured in a 200 ms window preceding the first arrival time, and t_0 is the first arrival time. The apparent S/N versus offset of the three seismic sources for the offset range 1000-1180 m is shown in Figure 8. This offset range was chosen since the source generated noise is minimal, but first arrivals are still clear. The average apparent S/N ratios of the VIBSIST, weight drop and MiniVib sources is 5.58 ± 1.82, 5.30 ± 1.74 and 4.70 ± 0.98, respectively. These values are consistent with visual inspection of the amplitude decay curves in this offset range (Figure 3).

SIGNAL PENETRATION AND FREQUENCY CONTENT

Lack of deep reflectivity in certain areas may be due to the seismic source generating insufficient energy. As we mentioned earlier, amplitude decay analysis can provide an indication of the source-generated energy and signal penetration depth. A number of studies have been carried out where the amplitude decay with traveltime has been interpreted in terms of signal penetration (e.g. Mayer and Brown 1986; Barnes 1994; Steer *et al*. 1996; Juhojuntti and Juhlin 1998). In these studies, the signal penetration limit is defined as that time where the source-generated energy ceases to decrease temporally and amplitudes are on the same level as the incoherent, time independent background noise. The depth corresponding to this time can be at least a relative indication of the maximum depth of effective signal penetration since amplitudes at later traveltimes are almost entirely dominated by ambient noise. Furthermore, only extremely strong reflections, if any, should be seen on the seismic section at later traveltimes. However, the relationship between true reflection amplitudes and the average value of these decay curves is indirect since the decay curves contain contributions from refractions, surface waves, guided waves, and various forms of backscatter. Consequently, continued amplitude decay beyond a given time is no guarantee of significant vertically reflected energy having been recorded.

The signal penetration of the VIBSIST, weight drop and MiniVib sources were compared in a quantitative manner by studying the amplitude decay curves. Absolute values of seismic traces in the offset interval 1000-1200 m were used for estimating the amplitude decay. As seen in the raw shot gathers (Figure 3), this offset range was selected for analysis to ensure that the receivers were sufficiently far enough from the source to avoid contamination from the high amplitude air wave, ground roll and source-generated noise. These traces were then summed to a single trace for each shot. Stacked traces from five adjacent shots were then averaged and average amplitudes were calculated for 100 ms time windows from 0 to 1.5 s. Given that the first arrival is at about 500 ms in this offset range, the amplitude values from the first to the fifth time window represent background (ambient) noise levels. In order to compare peak amplitudes of the three seismic sources, amplitudes relative to background levels versus traveltime were plotted (Figure 9). Since amplitudes remain above background levels down 1.5 s, signal penetration appears to be at least depths corresponding to this time for the three sources. For explosive sources, Juhojuntti and Juhlin (1998) found that peak amplitude in the first arrival time window increases with the size of the charge, in agreement with source generated energy increasing with charge size. In our case, the MiniVib data show the highest peak amplitude in the first arrival time window, whereas the amplitudes of the VIBSIST data and the weight drop data are lower, suggesting that the MiniVib is putting the largest amount of energy into the ground. However, if amplitude is normalized to peak amplitude for each source (Figure 9b), the amplitude decay curves differ after the 700 ms time window. Normalized amplitude decreases more slowly for the VIBSIST data, suggesting that this source has the greatest penetration.

Amplitude spectra for each source in the same offset windows as shown in Figure 3 are shown in Figure 10. All three sources have dominant signal frequencies of around 30-120 Hz (> 2 octave), providing enough bandwidth for resolving the geological target. The high frequency portions of the amplitude spectra differ for the three sources. The amplitude spectrum of the MiniVib is controlled by the frequencies put into the ground, 30-150 Hz. Amplitude outside the 30-150 Hz range for the MiniVib should be regarded as noise. No upper limit exists for the frequencies put into the ground by the VIBSIST source, however, the VIBSIST data are normally wide-band filtered before the shift stack method is applied. The falloff in amplitudes at high frequencies reflects this preprocessing step. No filtering or preprocessing, aside from vertical stacking, was applied to the weight drop data, suggesting that the flat spectrum from 150 Hz to 250 Hz represents mainly noise. Low amplitudes in the frequency range 100 Hz to 150 Hz indicate that the weight drop data contain little useful energy above 100 Hz.

Praeg (2003) demonstrated that resolution naturally decreases with depth due to earth filtering of higher frequencies. Normally, seismic waves are attenuated by the frequency response of the geophones and by absorption in the earth as the waves propagate from source to receiver. The low frequency end of the spectrum is attenuated primarily by the frequency response of the geophone and recording electronics, while the decrease at the high end of the spectrum is mainly due to propagation through the earth. Therefore, a comparison of relative amplitude decay curves from the three sources in different frequency bands may give an indication of which frequency band gives the best penetration for a given source (Figure 11). In general, the three sources show similar patterns of amplitude decay in the different frequency bands, the higher the frequency band the greater the attenuation or amplitude decay. However, the amplitude decay of the various frequency bands for the VIBSIST data is less rapid than for the other two sources, again suggesting that the VIBSIST source has greatest penetration.

COMPARISON OF SEISMIC SECTIONS

For our comparison we consider the following reflection horizons (according to Reinhardt 1993): 1) the T1 horizon, i.e. the transgression phase of the Cenezoic (soft-hard rock reflection); 2) the assumed L4 horizon at the base of the Hettangian (=near Top Triassic), 3) the K2 horizon, i.e. the top of the Heldburg-gypsum at the top of the Weser Formation; and 4) the K3 horizon, i.e. the top of the 'Oberer Hauptgips', a gypsum or anhydrite at the top of the Grabfeld Formation, close to the base of the Stuttgart Formation (Figure 2, 6 and 7). The two most well constrained seismic reflection horizons are the near Base Tertiary (T1) and the Top Weser reflection (K2).

The stratigraphic correlation of the seismic horizons is based on available borehole data from the area, as well as from interpretations of older, available regional seismic data. Stratigraphic borehole information mainly comes from the Ktzi 163/69 well (Figure1), as this well is the only deep one in the area. Although the seismic data is of good quality, proper well control is hampered by the lack of borehole seismic data.

Correlation of several stratigraphic units to particular reflection seismic events is, therefore, associated with some uncertainty (Förster *et al*. 2006).

The sections from all three sources (Figure 4, 5 and 6) generally show the same reflections. In contrast to the sections of Line 2, Line 1 is characterized by an overall lower signal to noise ratio. In particular, the northern part of Line 1 up to CDP 1100 is of low signal quality. In this area the weathering layer consists of a thick Quaternary sand layer (30 m) which significantly attenuates the seismic waves. Whereas the VIBISIST and the weight drop sources show clear reflections below the K2 horizon (0.45 s to 0.5 s TWT, 450 m to 500 m depth) the MinVib section (Figure 5a) shows only some discontinuous reflections. The sections from the two impact sources show the same events down to a weak reflection at a TWT of 1.3 s to 1.4 s (approx. 1400 m - 1500 m depth).

All sections of Line 2 (Figure 4b, 5b and 6b) show clear reflections down to 1400 ms TWT. In Figure 4b the deepest reflection (1.3 s to 1.4 s) is characterized by a pronounced continuity in its phase along all CDPs, showing the higher signal energy transmitted by the VIBSIST source. A more detailed signal analyses with respect to the target horizons is shown in Figure 7. In this time segment (0.35 s to 0.7 s) the reflection signals of the MiniVib data (Figure 7c) show higher frequencies (higher resolution) than the signals of the VIBSIST (Figure 7a) and of the weight drop source (Figure 7b). The transmitted signal energy of the three sources is high enough to image the reflections from the L4 to K2 reflectors at all CDPs. Below the K2 reflection the MiniVib data show less continuity of the reflections (e.g. K3 reflector, CDP 660 to 685) than the two impact sources.

DISCUSSION AND CONCLUSIONS

We characterize the three seismic surface sources with respect to their signal-to-noise ratios, signal penetration and frequency content by analysis of single shot gathers and by examination of CDP stacked sections along two lines within the planed 3D seismic area at the Ketzin site. In comparison to explosive sources there are some particularities of the surface sources which have to be taken into account. Compacting effects at the source point have a strong influence on the data quality. The stability of the source signal waveform is of critical importance with respect to the improvement of the signal-to-noise ratio by vertical stacking of pulse sequences at each source point. One of the main shortcomings of surface sources is the presence of strong noise waves (e.g. surface and air-coupled waves). Near surface conditions strongly influence the signal bandwidth (resolution) and signal energy. For example, at the Ketzin site the high variability of the near surface conditions is expressed by the difference in reflectivity of the two CDP lines (Figure 4, 5 and 6). All these factors need to be taken into account when choosing a surface seismic source.

The three sources image the upper 500 ms with approximately the same clarity. The MinVib data show the highest resolution (Figure 7) for this part of the time section, but the signal reflection energy below about 500 ms TWT is lower than for the two impact sources. The lack of deeper reflectivity in certain portions of the lines may be due to the seismic sources generating insufficient energy. The VIBSIST source gives a better image below 900 ms than the weight drop source and the MiniVib. This is in agreement with the analysis of single shot gathers, where clear evidence is found for a higher signal-to-noise ratio of the seismic signals and greater signal penetration for the VIBSIST source compared to the other tested sources. This is indicated by the high apparent signal-to-noise ratio in the offset range of 1000 m to 1180 m and the slowly decreasing normalized amplitude beyond 700 ms traveltime in Figure 9b. There is an overall tendency that the content of higher frequency signals decreases with increasing source power, consistent with other field observations (Herbst *et al*. 1998).

The Ketzin pilot study shows that the VIBSIST, weight drop and MiniVib are suitable sources for high resolution seismic surveys down to a depth of about 1 km. The average amplitude spectra show that all three sources provide enough bandwidth for resolving the geological target (e.g. the Weser and Stuttgart Formations). The CDP sections of the MiniVib source show the highest frequency signals to about 500 ms TWT (approx. 500 m depth), but the shallowest signal penetration. The VIBSIST source generates signals with the highest signal-to-noise ratio and greatest signal penetration of the tested sources. In particular, the reflections below 900 ms (approx. 1 km depth) are best imaged by the VIBSIST source.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge M. Stiller (Section 2.2, GFZ Potsdam) for support in preparation and conduction of the field work. We wish to thank the Geophysik-GGD (Leipzig), GGA-institute (Hanover) and Vibrometric Oy (Helsinki) source crews for good cooperation in the field. We also thank A. Sippel and J. Mlynek for their support while conducting the experiment. We acknowledge the Geophysical Instrument Pool Potsdam (GIPP) for its technical support. The European Commission is gratefully acknowledged for their funding of the "CO_2SINK - CO2 Storage by Injection into a Natural Storage at Ketzin", Project No. 502599.

REFERENCES

Arts R., Eiken O., Chadwick A., Zweigel P., van der Meer L. and Zinszner B. 2004. Monitoring of CO_2 injected at Sleipner using time-lapse seismic data, *Energy* **29**, 1383-1392.

Barbier M.G., Bondon P., Mellinger R. and Viallix J.R. 1976. MiniSOSIE for shallow land seismology. *Geophysical Prospecting* **24**, 518-527.

Barnes A.E. 1994. Moho reflectivity and seismic signal penetration. *Tectonophysics* **232**, 299-307.

Benjumea B. and Teixido T. 2001. Seismic reflection constraints on the glacial dynamics of Johnsons Glacier, Antarctica. *Journal of Applied Geophysics* **46**, 31-44.

Buhnemann J. and Holliger K. 1998. Comparison of high-frequency seismic sources at the Grimsel test site, central Alps, Switzerland. *Geophysics* **63**, 1363-1370.

Cosma C. and Enescu N. 2001. Characterization of fractured rock in the vicinity of tunnels by the swept impact seismic technique. *International Journal of Rock Mechanics and Mining Sciences* **38**, 815-821.

Davis T.L., Terrell M.J., Benson R.D. and Kendall R.R. 2002. Seismic Monitoring of the CO_2 Flood at Weyburn Field, Saskatchewan, Canada. EAGE 64th Conference & Exhibition, Florence Italy.

Feroci M., Orlando L., Balia R., Bosman C., Cardarelli E., and Deidda G. 2000. Some considerations on shallow seismic reflection surveys, *Journal of Applied Geophysics* **45**, 127-139.

Förster A., Norden B., Zinck-Jørgensen K., Frykman P., Kulenkampff J., Spangenberg E., Erzinger J., Zimmer M., Kopp J., Borm G., Juhlin C., Cosma C. and Hurter S. 2006. Baseline characterization of the CO_2SINK geological storage site at Ketzin, Germany, *Environmental Geosciences* **13**, 145-161.

Herbst R., Kapp I., Krummel H. and Luck E. 1998. Seismic sources for shallow investigations: A field comparison from Northern Germany. *Journal of Applied Geophysics* **38**, 301-317.

Juhojuntti N. and Juhlin C. 1998. Seismic lower crustal reflectivity and signal penetration in the Siljan Ring area, Central Sweden. *Tectonophysics* **288**, 17-30.

Juhlin C., Cosma C. Förster, A., Giese, R., Juhojuntti, N., Kazemeini H., Norden B. and Zinck-Jørgensen K. 2006. Baseline 3D seismic imaging for the CO2SINK project in the Ketzin area, Germany. Proceedings of the 8th Greenhouse Gas Technology Conference, Trondheim, Norway.

Jongerius P. and Helbig K. 1988. On-shore high-resolution seismic profiling applied to sedimentology. *Geophysics* **53**, 1276-1283.

Knapp R.W. and Steeples D.W. 1986. High-resolution common depth-point reflection profiling: Field acquisition parameter design. *Geophysics* **51**, 283–294.

Mayer J.R. and Brown L.D. 1986. Signal penetration in the COCORP Basin and Range-Colorado plateau survey. *Geophysics* **51**, 1050–1055.

Metz B., Davidson O., de Coninck H., Loos M. and Meyer L. 2005. Carbon Dioxide Capture and Storage: IPCC Special Report, Cambridge University Press, UK and New York.

Miller R.D., Pullan S.E., Steeples D.W. and Hunter J.A. 1992. Field comparison of shallow seismic sources near Chino, California. *Geophysics* **57**, 693-709.

Miller R.D., Pullan S.E., Steeples D.W. and Hunter J.A. 1994. Field comparison of shallow P-wave seismic sources near Houston, Texas. *Geophysics* **59**, 1713–1728.

Miller R.D., Pullan S.E., Waldner J.S. and Haeni F.P. 1986. Field comparison of shallow seismic sources. *Geophysics* **51**, 2067–2092.

Park C.B., Miller R.D., Steeples D.W. and Black R.A. 1996. Swept impact seismic technique (SIST). *Geophysics* **61**, 1789-1803.

Praeg D. 2003. Seismic imaging of mid-Pleistocene tunnel-valleys in the North Sea Basin—high resolution from low frequencies. *Journal of Applied Geophysics* **53**, 273-298.

Pullan S.E. and MacAulay H.A. 1987. An in-hole shotgun source for engineering seismic surveys. *Geophysics* **52**, 985-996.

Reinhardt H.G. 1993. Regionales Kartenwerk der Reflexionsseismik. VEB Geophysik Leipzig.

Sheriff R.E. 1975, Factors Affecting Seismic Amplitudes. *Geophysical Prospecting* **23**, 125-138.

Staples R.K., Hobbs R.W. and White R.S. 1999. A comparison between airguns and explosives as wide-angle seismic sources. *Geophysical Prospecting* **47**, 313-339.

Steeples D.W. and Miller R.D. 1990. Seismic reflection methods applied to engineering, environmental, and groundwater problems. In: *Geotechnical and environmental geophysics, I: Review and tutorial,* Vol. 1 (Ward, S. H., Ed.), pp. 1-30, Soc. Explor. Geophys.

Steer D.N., Brown L.D., Knapp J.H. and Baird D.J. 1996. Comparison of explosive and vibroseis source energy penetration during COCORP deep seismic reflection profiling in the Williston Basin. *Geophysics* **61**, 211-221.

Telford W.M., Geldart L.P. and Sheriff R.E. 1990. *Applied Geophysics*. Cambridge University press, 770 pps.

Wardell J. 1970. A comparison of land seismic sources. *Geoexploration* **8**, 205-229.

Woodward D. 1994. Contributions to a shallow aquifer study by reprocessed seismic sections from petroleum exploration surveys, eastern Abu Dhabi, United Arab Emirates. *Journal of Applied Geophysics* **31**, 271-289.

Wright C., Wright J.A. and Hall, J. 1994. Seismic reflection techniques for base metal exploration in eastern Canada: examples from Buchans, Newfoundland. *Journal of Applied Geophysics* **32**, 105-116.

Yilmaz O. 1987. *Seismic data processing, Investigations in Geophysics*. vol. 2, Society of Exploration Geophysicists, Tulsa, 526 pps.

Ziolkowski A. 1991. Why don't we measure seismic signatures?. *Geophysics* **56**, 190-201.

Ziqiu X. and Takashi O. 2004. Time-lapse crosswell seismic tomography and well logging to monitor the injected CO_2 in an onshore aquifer, Nagaoka, Japan. IEA Monitoring and Verification Workshop, Santa Cruz.

FIGURE CAPTIONS

Figure 1 Map of the Ketzin pilot study area close to Potsdam, Germany. The two CDP profiles are marked in blue as Line 1 (N-S profile) and Line 2 (E-W profile). Borehole Ktzi 163/69 is indicated in by the black circle. The area marked by the polygon approximately encloses the area for the main 3D survey. The expected injection site is also indicated.

Figure 2 Geological structures of the site inferred from a local borehole (163/69) in Ketzin and adjacent boreholes (http://www.co2sink.org/techinfo/geology1.htm).

Figure 3 A raw shot gather (left) and average amplitude versus traveltime (right) of (a) VIBSIST, (b) Weight drop and (c) MiniVib. Red windows marked the offset range of amplitude analysis.

Figure 4 VIBSIST stacked section of (a) Line 1 and (b) Line 2. T1= near base Tertiary, L4 = top Triassic (assumed), K2 = top Weser Formation, K3 = near top of Grabfeld Formation.

Figure 5 MiniVib stacked section of (a) Line 1 and (b) Line 2.

Figure 6 Weight drop stacked section of (a) Line 1 and (b) Line 2.

Figure 7 Blow-ups of the Line 2 stacked sections from (a) VIBSIST (b) Weight drop and (c) MiniVib sources. L4 = top Triassic (assumed), K2 = top Weser Formation, SF = Stuttgart Formation, K3 = near top of Grabfeld Formation.

Figure 8 Apparent signal-to-noise ratio of different source at selected offset from Figure 3.

Figure 9 Signal penetration of three seismic sources by comparison of (a) amplitude relative to background versus traveltime plot and (b) normalized amplitude versus traveltime plot.

Figure 10 Average amplitude spectra of three seismic sources calculated from traces in offset between 1000-1200 m as shown in Figure 3.

Figure 11 Amplitude relative to background versus travetime of different sources at different frequency bands.

TABLE CAPTIONS

Table 1 Some parameters for the sources used in the Ketzin pilot study.

Table 2 Acquisition parameters.

Table 3 Processing flow.

Table 1

Characteristic	VIBSIST	MiniVib	Weight drop
Type	Swept impact, VIBSIST 1000	Vibrator MHV 2.7	Impact EWG III
Contractor	Vibrometric, Helsinki	GGA[1] institut, Hanover	Geophysik GGD[2], Leipzig
Specification	Energy ≈ 2000 kJ up to1000 J per Impulse	Baseplate mass: 138 kg Reaction mass: 181 kg Peak force: 27600 N Freq. range: 16-500 Hz	≈ 250 kg Energy ≈ 9.5 kJ
Spectrum	Variable (controllable)	Variable (controllable)	Variable (depend on weight)
Repeatability	Yes	Yes	Yes
Field record	Need stack and shift	Need stack and correlation	Need stack
Operation	Complex	Fairly complex	Fairly complex
Field equipment	Heavy	Moderate to heavy	Moderate to heavy
Approximate production rate	4 min/shot	5 min/shot	3 min/shot

[1] Leibniz Institute for Applied Geosciences
[2] Gesellschaft für Geowissenschaftliche Dienste m.b.H.

Table 2

Parameter	Detail
Sources	Weight drop, VIBSIST and MiniVib
Profile	
Length	2.4 km
Number of stations/line	120 stations
Number of shots/line	113-115 (Weight drop), 107-114 (VIBSIST) and 71-117 (MiniVib)
Shots per station	5-8 (Weight drop), 3 (VIBSIST) and 5 (MiniVib)
Receivers	
Natural geophone frequency	10 Hz and 28 Hz (single)
Spacing	20 m
Recording	
Recording system	SERCEL 408 system
Record length	3 s (Weight drop), 30 s (VIBSIST) and 18.5 s (MiniVib)
Sweep length	27 s (VIBSIST) and 16 s (MiniVib)
Sampling interval	1 ms

Table 3

Processing step	Description
1. Data import	Correlation (MiniVib data) and/or stack of shot gathers, shift (VIBSIST data)
2. Geometry	Assign input source and receiver locations into header.
3. Trace editing	Kill bad traces and fix polarity reversals.
4. True amplitude recovery	Compensate for geometrical spreading by scaling by t^2.
5. Deconvolution	Minimum phase predictive deconvolution with a design gate limited to the time range of clear reflections.
6. Bandpass Filter	15-30-85-135 Hz.
7. AGC	Adjust amplitudes using 300 ms window.
8. Refraction statics	Model near-surface structure and calculate static corrections.
9. Top mute / bottom mute	Zero all data amplitude before and including first arrivals / Zero all cone of ground roll.
10. Sort to CDP Domain	Reorder data by common midpoint number.
11. Velocity analysis -Pass 1	Integrate analysis of stacked velocity panels and semblance plots.
12. Residual Statics	Surface-consistent, based on maximum stack power.
13. Velocity analysis -Pass 2	
14. NMO	Apply stacking velocities.
15. Stack	