The case for longer sweeps in vibrator acquisition

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There is growing interest in the oil and gas industry to improve the quality of subsurface imaging and reservoir characterization through improved spatial sampling and wide-azimuth coverage of seismic acquisition designs.

The improvement in subsurface imaging and resolution (temporal and spatial) associated with improved spatial sampling has been reported by a number of authors including Egan et al. (2009), Henley et al. (2009), Long (2004), Meunier et al. (2008) and Lansley et al. (2002). Egan et al. point out that good spatial sampling can be a key factor in producing good temporal resolution in the 3D-migrated image. Further, they advocate point source/point receiver acquisition as a means of improving resolution. A clear message flowing from several of these papers is that reduced source and receiver line intervals in land acquisition are needed.

The referenced papers, and many others, provide good data examples of how improved spatial and temporal resolution and signal-to-noise ratio can result from improved spatial sampling. Improved sampling can help to facilitate stratigraphic interpretation, identification of small-scale faulting, and the unraveling of complex geology.

Improved spatial sampling can be achieved through increased receiver and/or source density and can be cost-effectively implemented using reduced array sizes. State-of-the-art seismic recording systems allow for active channel counts well above 10,000. Small receiver arrays using 3–6 geophones per group or even single sensors allow high productivity in deploying receiver equipment. For vibrator acquisition, source productivity needs to correspondingly increase. Such productivity improvements can be created by spending less time per source point and by utilizing alternative source methodologies such as slip-sweep and simultaneous acquisition.

This paper will focus on improving source productivity through the use of long sweeps at each vibrator point. Long sweeps in association with slip-sweep and simultaneous acquisition methods can be particularly effective as discussed by Meunier et al. (2008) and Krohn et al. (2006). We will review various issues associated with the use of long sweeps and present data examples to support our conclusions.

The primary reason for the use of long sweeps is to allow an increase in vibrator point (VP) density at a reasonable cost by reducing the acquisition time per VP. Since this reduction should not be at the expense of a degraded signal-to-noise ratio, we require that the total sweep length be preserved. The advantage gained through the use of one long sweep replacing N shorter sweeps is the elimination of (N-1) listen times and (N-1) system reset times.

Example

Compare, in Figure 1, the acquisition time per VP using one 48-s sweep and six 8-s sweeps assuming a 5-s listen time and a 2-s system reset time. (Note that in the newest recording systems the system reset time is essentially zero, but we have included it here as there are a significant number of systems still in use where it is applicable.)

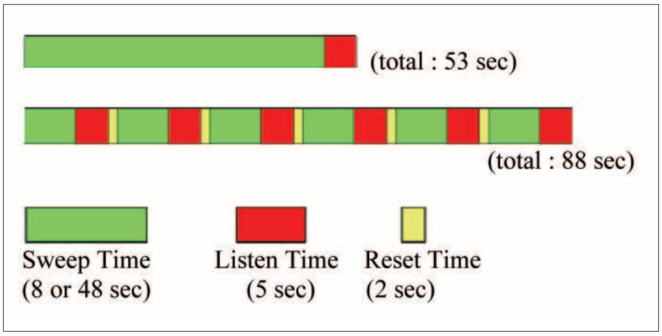

Figure 1. *Example of time saved by a single sweep.*

The savings is 35 s per VP. For conventional acquisition, this savings can translate to an additional 10 VPs/hour and 100 VPs/day assuming 10 hours of pad time per day. Using single long sweeps in association with simultaneous or slip-sweep acquisition methods can produce even more dramatic increases in source productivity.

The increase in source productivity provides an opportunity to increase source density on a project at competitive pricing. Improved imaging realized through increased source density has been reported by Meunier et al. (2008).

Signal-to-noise for vibrator operations

The theoretical improvement in signal to (random) noise ratio for changes in vibrator parameters was given by Lansley (1992).

$$S/N = 20\log_{10}(NVIBS * FGF * \sqrt{NSWPS * SWPLEN})$$

where: NVIBS = the number of vibrators; FGF = fundamental ground force; NSWPS = number of sweeps per VP; SWPLEN = length of sweep in seconds.

Although there are more complicated equations for signal/noise (e.g., Bianchi et al., 2002) that include the source and receiver density, number of geophones per group, etc., we have used the above equation because it relates only to variations in the vibrator parameters, assuming that all other factors remain unchanged. Also, this equation relates only to random noise and not source-generated coherent noise such as ground roll which will be discussed later. Theory also predicts that, as long as the vibrator to earth interaction is linear, the downgoing vibrator wavelet will be consistent with different numbers of sweeps of different lengths provided the total sweep time remains constant. Figure 2 compares data from two deep wells with various sweep lengths. The correlated records are averaged over several depth intervals (average depths of wells indicated) and suitably normalized by

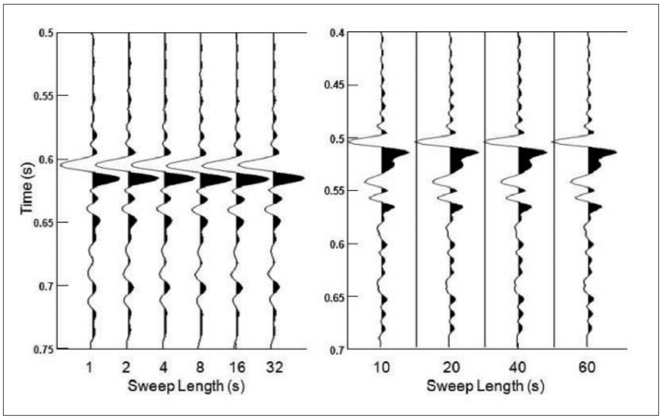

Figure 2. *Correlated, averaged and normalized (by square root of sweep length) wavelets recorded into downhole sensors at ~5200 ft (left) and ~2800 ft (right).*

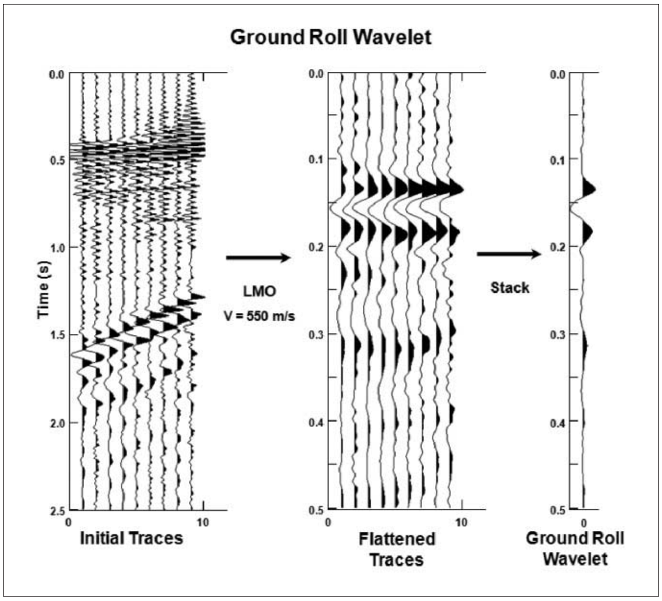

Figure 3. *The process of conditioning ground-roll data for comparing wavelet images (the same process applies for P-wave reflection data). After the data are correlated (input data), aligned and stacked, they are normalized by the square root of sweep length to allow direct amplitude comparisons.*

the square root of the sweep length in order to directly compare amplitudes. The swept frequency band is identical for all sweeps in a given well. Note the consistency of the waveforms for the various sweep lengths.

An additional issue that requires consideration is whether one should try to optimize the signal-to-noise ratio on individual shot records or rather increase the source density and perhaps accept lower signal-to-noise on each record. With some high-productivity vibroseis acquisition techniques currently being used in North Africa and the Middle East, we can see that improved source density is definitely preferred to shot record quality in those regions. Also, with increasing trace densities and, correspondingly, shorter group intervals, ground roll can be better sampled and aliased ground roll can frequently be avoided.

Concerns with the use of long sweeps

A number of concerns about the use of long sweeps have been expressed over the years. The first relates to the supply of hydraulic oil or oil flow required to produce the large reaction mass to baseplate displacements at very low frequencies when using low sweep rates. Typically, this situation has been helped by the use of oil accumulators that supply the additional oil required at the low frequencies for short periods of time at the start of a sweep. For longer sweeps, however, it is necessary to consider the dwell time spent in the low-frequency range of the sweep. Two additional factors are important. The first is that, at frequencies lower than ground resonance, the vibrator baseplate and the reaction mass are actually moving in phase with each other and the volume of oil required is less than predicted by most equations. The second factor is that we are usually sweeping to much higher frequencies today than was typical a few years ago and, even though we may be using longer sweeps, the actual sweep rate may not be unreasonable.

It should also be noted that there have been many improvements in the design of vibrators. Caradec and Buttin (2008) showed that with an increase in the hydraulic supply pressure and a more streamlined hydraulic flow, frequencies as low as 5 Hz can be maintained with significant output force. For modern vibrator designs, long sweeps should no longer be a problem.

Another concern expressed about long sweeps is the lack of noise attenuation during recording. If we record with a single sweep, any short-duration high-amplitude noise will result in a corresponding high-amplitude time-reversed replica of the sweep on the output data after correlation. When four or more sweeps per VP are used, diversity stack is a powerful attenuator of such noises and has been shown to work extremely well in urban environments. Again, we need to consider the potential benefits of recording higher density data with, perhaps, lower signal-to-noise field records, versus recording more poorly sampled data with higher-quality shot records. Diversity stack and other noise-attenuation methods are not limited to field acquisition and can be effectively employed in data processing.

The issue of ground roll

Another issue that has been raised is that “long” sweeps may cause more ground roll than “short” sweeps at the same location. The thought here is that, by dwelling for a longer time at the ground resonant frequency, we may build up the amplitudes and create stronger ground roll. Certainly these effects were observed before the implementation of closed-loop amplitude control of the sweep fundamental. However, since the introduction of fundamental amplitude control, this effect has not been observed by the authors, even though the myth is still being propagated in the industry. Neither downhole measurements nor surface seismic recordings demonstrate any nonlinearity in the amplitudes of ground roll with sweep length.

Figure 3 describes the wavelet analysis technique used to

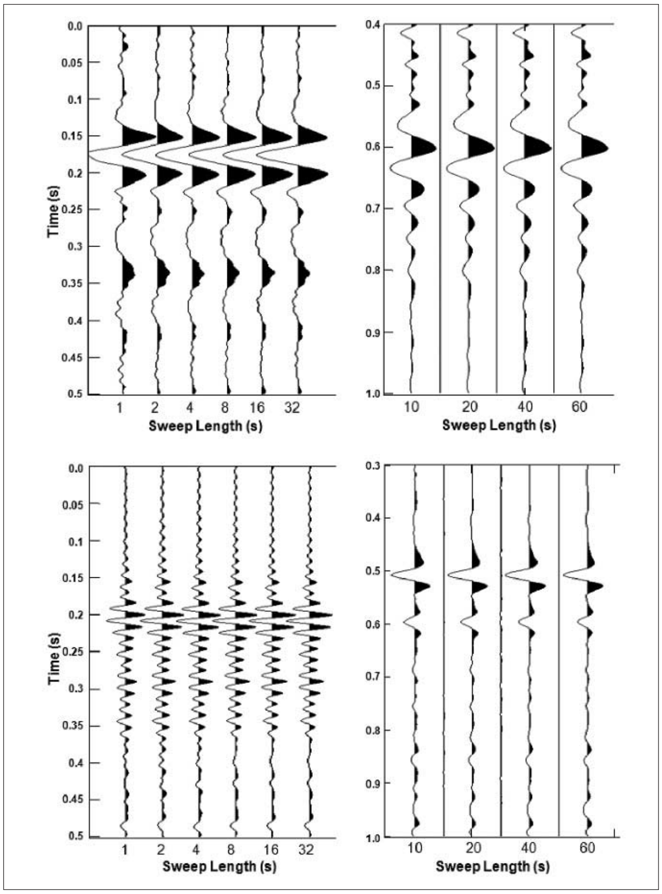

Figure 4. Ground-roll wavelets (top) and P-wave reflection wavelets (bottom) for different sets of sweep lengths for two different project areas. Data for sweeps in acceleration units and thus the higher frequency character

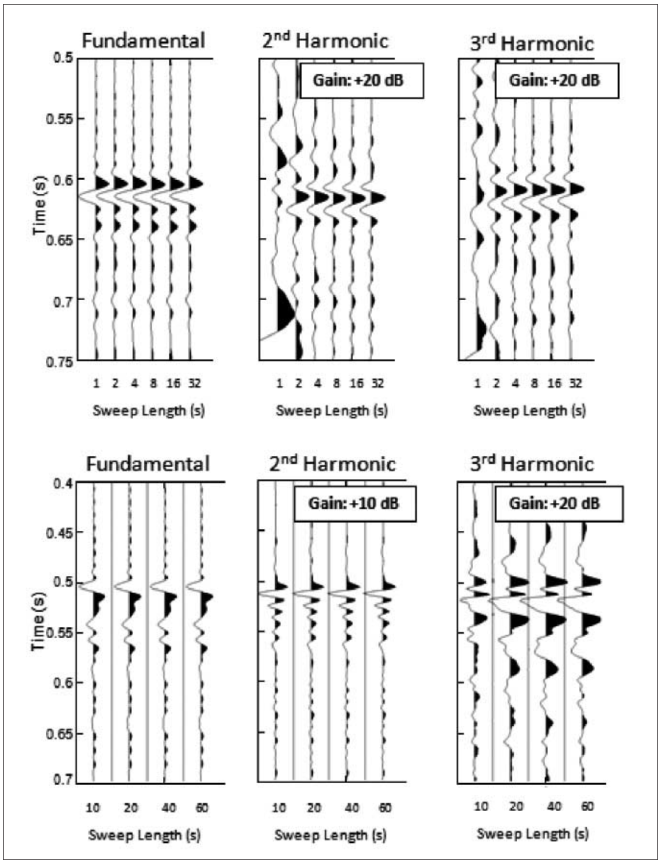

Figure 5. *Correlation of the ground force signal by the fundamental, second, and third harmonics for different sweep lengths. For "short" sweeps (1 or 2 s), the second and third harmonics interfere with the fundamental. (top) Bonnefont test site, France. (bottom) Devine test site, US.*

evaluate borehole direct arrivals and surface reflection data and ground roll for sweeps of various lengths. The methodology for analyzing reflection data is identical to that described for ground roll.

Figure 4 compares ground-roll wavelets (top figure, two different experiments) and P-wave reflection wavelets (bottom figure) for various sweep lengths following the conditioning procedure described in Figure 3. The data for 1- to 32-s sweep lengths are in acceleration units (whereas the other data are in velocity units) and thus the higher frequencies are accentuated. There are no significant amplitude variations with respect to changes in sweep length in either of these. This demonstrates that we should expect comparable amplitudes of both signal and source-generated noise from data acquired using either a single long sweep or multiple short sweeps provided the total sweep time is constant.

Additional benefit from long sweeps

As noted earlier, the most compelling reason to employ long sweeps is to increase source density and hence achieve better data quality through improved crew productivity. Source productivity can be further enhanced using long sweeps in conjunction with simultaneous or slip-sweep recording methods. The slip-sweep method (Rozemond, 1996) is susceptible to harmonic noise contamination but that distortion can be more effectively mitigated with the use of longer sweeps (Meunier and Bianchi, 2002). Figure 5 shows the results from correlating the weighted-sum ground force signal with the fundamental and second and third harmonics for sweeps of various lengths. These results are from two different project areas. One can see the difficulty in obtaining good estimates of the harmonics for the short sweeps owing to the lack of separability from the fundamental. This deterioration in estimating the harmonics for "shorter" sweeps compromises their removal. "Longer" sweeps are less plagued by this problem.

Data examples

Figure 6 shows two 2D seismic lines recorded in West Texas several years ago. In this test, the line was recorded first with a single 20-s sweep per VP (Figure 6a) and then repeated using four sweeps of 5 s (Figure 6b). The start and end tapers on the sweeps were adjusted to give the same amplitude-to-frequency relationship. All other parameters (number of vibrators, sweep frequencies, etc.) remained constant. All data processing parameters were the same for both data sets.

A second 2D data comparison from the northern United States is shown in Figure 7. In this example, a 48-s sweep is

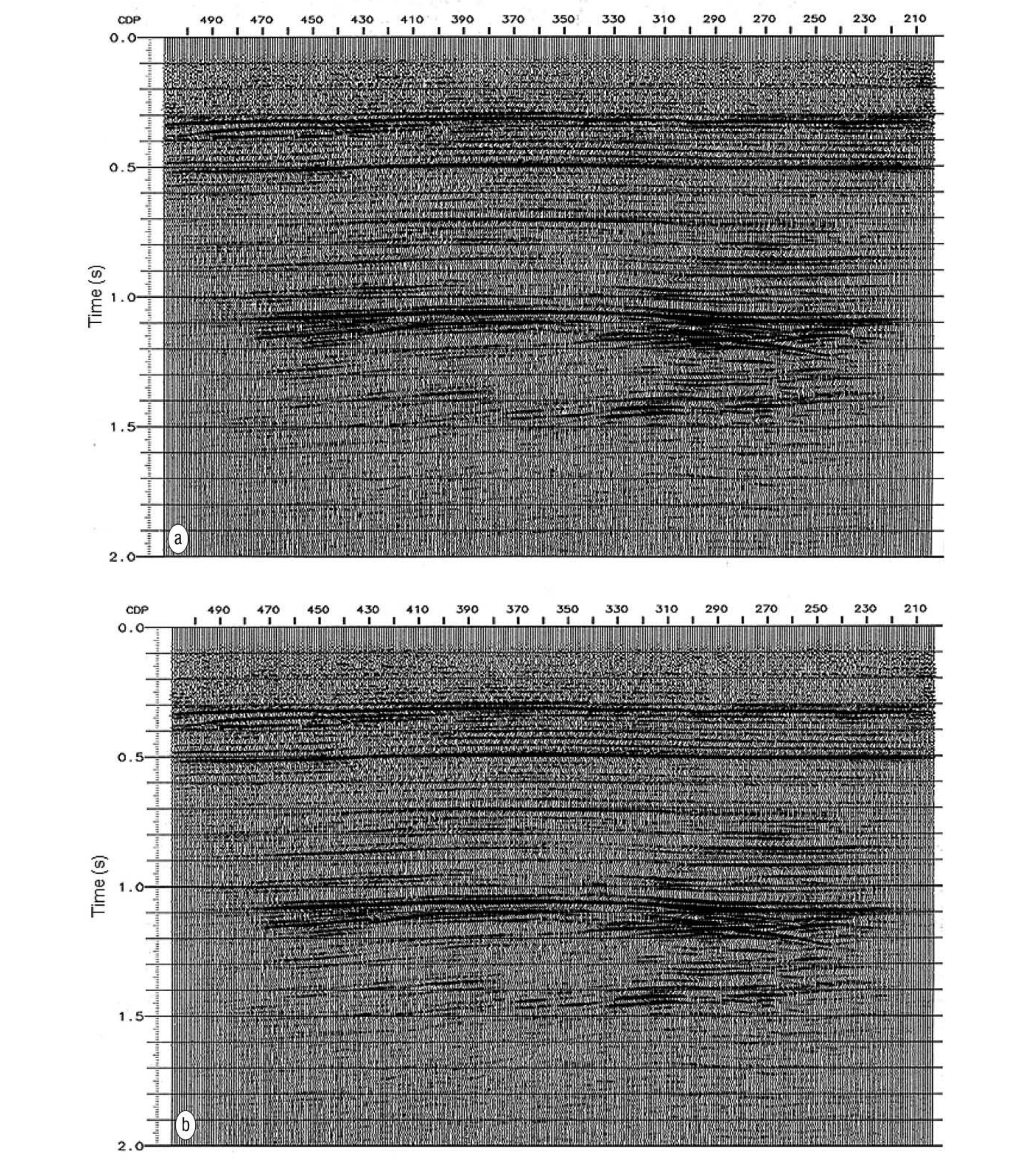

Figure 6. *(a) West Texas 2D line recorded using a single 20-s sweep per VP. (b) The same West Texas 2D line recorded using four 5-s sweeps per VP.*

compared with six 8-s sweeps per VP. Taper definitions are as noted for Figure 6 and, again, processing parameters are identical for this comparison.

As can be seen, the data sets for comparison in Figure 6 and Figure 7 are essentially identical, although the recording time for single sweep per VP acquisition is reduced approximately 35–40% relative to multiple sweeps per VP.

Conclusions

Improved source and receiver spatial sampling of seismic acquisition designs can produce clear benefits in improving seismic image quality. Channel count increases for land acquisition have improved receiver sampling and promoted more wide-azimuth designs but somewhat less attention has been paid to improving source density, particularly for the

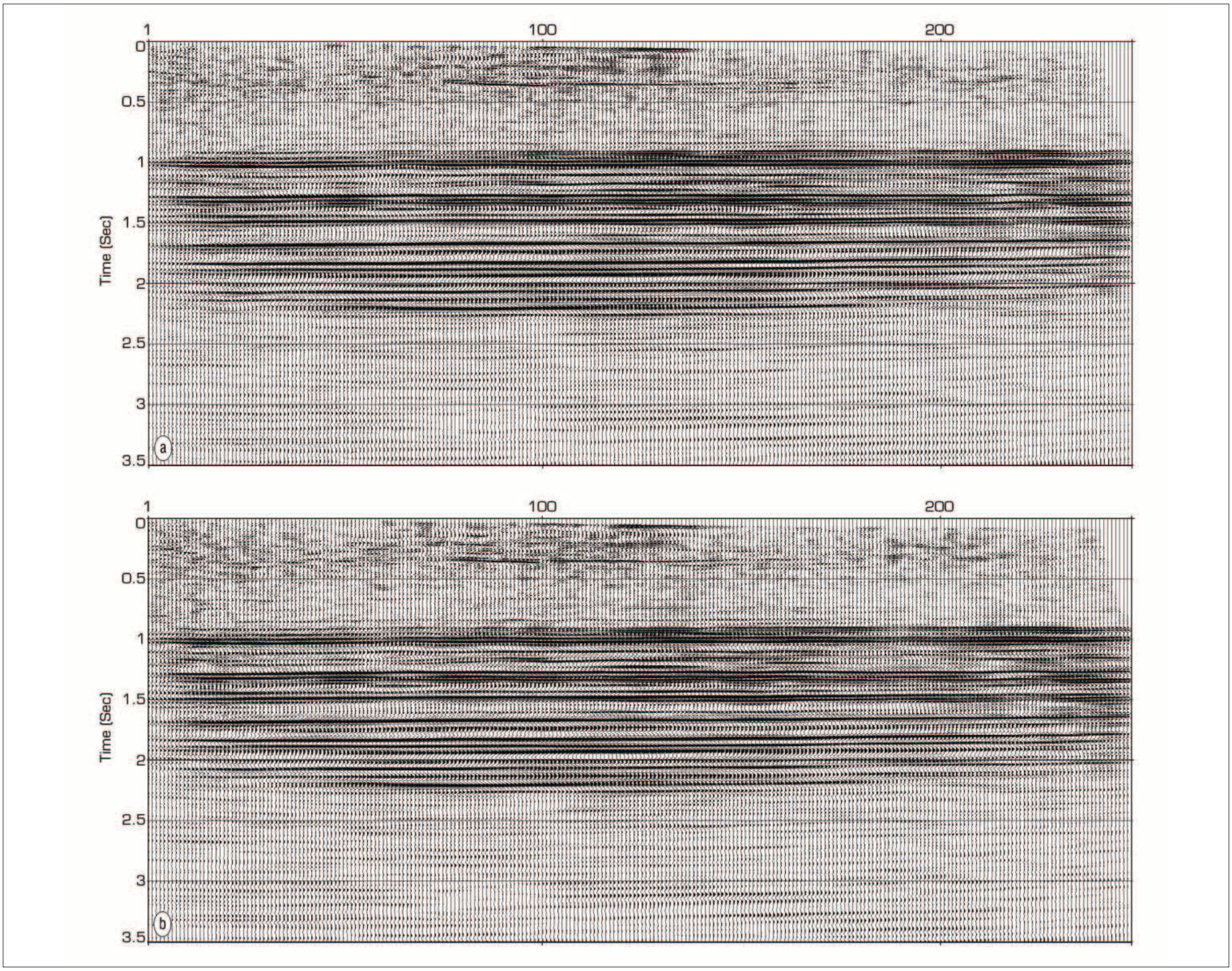

Figure 7. *(a) Northern US 2D line recorded using a single 48-s sweep per VP. (b) Northern US 2D line recorded using six 8-s sweeps per VP.*

vibrator source. One means of improving source density is through the use of longer sweeps.

Advances in vibrator acquisition and in processing methods for noise rejection have made the use of long sweeps much more attractive. Analysis of surface and borehole data clearly confirms that data acquired using both long and short sweeps are equivalent given that the total sweep length is preserved. Single long sweeps at each vibrator point can significantly improve source productivity and thus help to create the cost-effective, better spatially-sampled designs currently being sought in the industry. TLE

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