Application of supergrouping to enhance 3D prestack seismic data from a desert environment

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Abstract

Fit-for-purpose enhancement remains a critical task for processing land seismic data, especially with the increasing popularity of high-channel-count and single-sensor data. We describe here a flexible scheme called smart supergrouping that performs summation of traces from neighboring shots and receivers. Supergrouping enhances desired reflection signals while suppressing ground roll and other noise. It also delivers prestack data of significantly high quality, critical for deriving velocities, deconvolution operators, scalars, and statics, as well as for improved imaging. While similar in concept to field source/receiver array forming, supergrouping may be applied to data already acquired with field arrays. Unlike field arrays, supergrouped data have kinematic corrections applied with overlapping apertures. We also have the ability to compensate for intra-array statics and wavelet variations. We demonstrate the signal-enhancing abilities of such generalized supergroups with normal-moveout corrections on challenging land and ocean-bottom-cable seismic data from Saudi Arabia. Applications of supergrouped data cover various steps of land seismic processing from first-break picking to deconvolution to statics to full-waveform inversion and imaging.

Introduction

Land seismic data from desert regions are known to have low signal-to-noise ratio (S/N) (Robinson and Al-Husseini, 1982). Modern seismic acquisition is trending toward recording a higher number of channels to increase spatial sampling. For economic reasons, high channel counts come at the expense of using smaller receiver arrays or single sensors. Likewise, a similar tradeoff applies on the source side where increased spatial sampling is also accompanied by reduced size of field source arrays. In areas with a complex near surface such as Saudi Arabia, this means acquiring data of higher density but significantly lower prestack quality. Naturally, every processing step that relies on prestack signal becomes challenging to execute. Signal processing can help but only if the signal present on each trace is above a certain minimum useful threshold. Unfortunately, a lot of acquired data remains below such a threshold. In this case, collecting signal from neighboring traces becomes perhaps the only practical option.

It is well established that source and receiver arrays in the field are capable of greatly improving S/N, and they are still widely used. Since there is no practical way to introduce any kinematic corrections in the field, such arrays require fine spatial sampling. The use of field arrays in acquisition has been greatly reduced following the rise in popularity of single-sensor acquisition. The spatial sampling of modern high-channel-count or single-sensor data remains significantly larger than what is required for conventional group forming. This creates a challenge for seismic processing that can no longer rely on field arrays or digital group forming because of large spatial sampling.

In this study, we propose a method of enhancing the quality of conventional 3D land prestack data using a supergrouping technique (Bakulin et al., 2016) that combines elements of grouping and stacking. With increased emphasis on low frequencies and proliferation of hierarchical techniques (applied from progressively low to high frequencies) from statics to velocity model building, we expect that adaptive supergrouping may fill the missing gap for different frequency bands. Supergrouping builds on group forming but goes beyond that to deal with large source/receiver intervals, using simple assumptions and smart summation techniques proven to work well for field data with low S/N from a variety of different terrains. In this paper, we briefly describe the methodology and show applications using various seismic data sets from Saudi Arabia.

Method

Algorithm. Supergrouping is typically applied to input data that have already been recorded with source/receiver arrays, hence the use of the prefix "super." It is similar to conventional group forming in that traces are summed within the group, but there are significant differences. Most importantly, in contrast to field arrays, in processing we can apply additional moveout and amplitude/phase corrections before summation. In addition, supergrouping is designed to operate on 3D field data and handle irregular geometries. For these reasons, preconditioning of the data is not trivial, as it may require individual adjustments for every supergroup as well as some regularization. Supergroups can be implemented in the source domain, receiver domain, cross-spread domain, or any combination, with the most general supergroup being four-dimensional. In all examples presented here, the output geometry is identical to the input, although regular coarser geometry may also be acceptable for many processing steps. Therefore, this could be thought of as a sliding spatial window in which an enhanced trace is output at the "central" location of the supergroup aperture (Figure 1). We use a simple naming convention for such supergroups as number of shots inline × number of shots crossline × number of receivers inline × number of receivers crossline. For instance, the group in Figure 1 comprises summation of 3 by 3 shots for each receiver and 3 by 3 receivers for each shot, thus it is referred to as a 3 × 3 × 3 × 3 supergroup. Likewise, as shown in Figure 1, the area of the supergroup is defined by multiplying by the grid size in each dimension. There is half a grid size perimeter zone around sources and receivers similar to that used for classical group forming.

Stacking itself can be achieved with a multitude of methods including straight summation (a simple stack), diversity stacking, and weighted stacking. A simple stack denotes summing traces from the supergroup ensemble typically with moveout corrections

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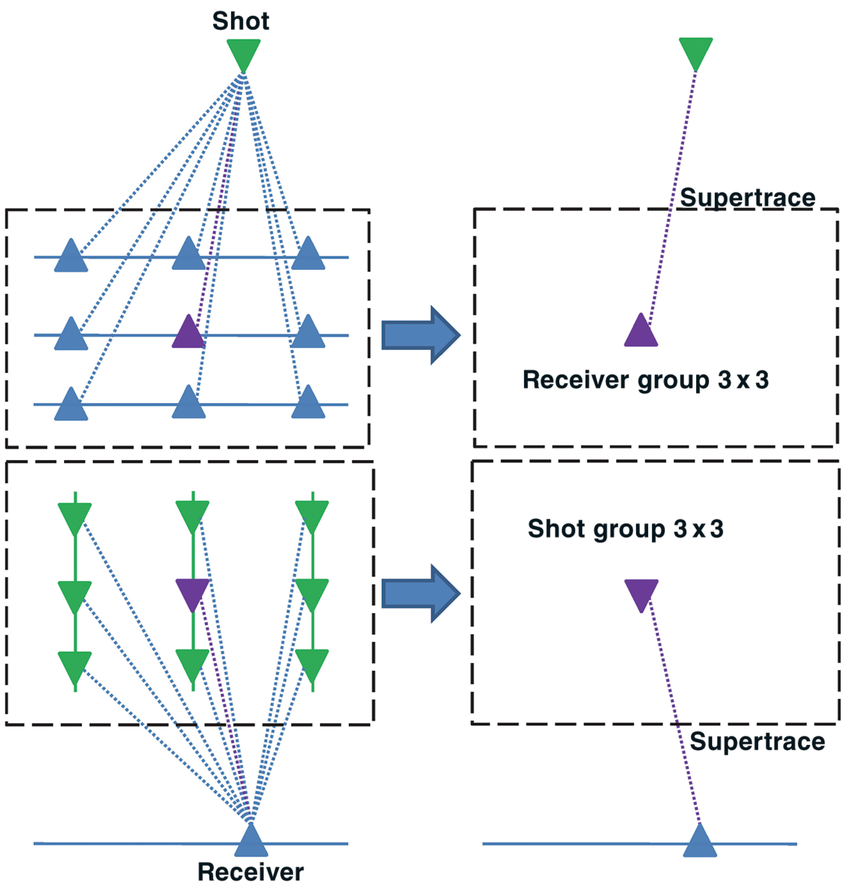

Figure 1. A schematic showing four-dimensional supergrouping. In terms of station numbers, each supergroup has dimensions: SX inline stations, SY crossline stations for sources, RX inline stations, and RY crossline stations for receivers. Similar notation is used for absolute distances with half a grid size perimeter zone. Here dx_s, dy_s, dx_r, and dy_r are inline and crossline spacings for sources and receivers, respectively.

as explained later. Diversity stacking (Martinez et al., 1993) weights each trace by its smoothed envelope before summation and then normalizes the output by the sum of the weights. This helps to reduce the effect of high-amplitude noise bursts and improve S/N of supergrouped data that includes such input traces. The weighted stack (Neklyudov et al., 2015) applies special amplitude and phase corrections for each frequency component of the gathers used in forming a supergroup. Stacking is done in the temporal frequency domain. These amplitude and phase corrections help to prevent smearing at near offsets that may occur with a simple stack, although it does carry a higher computational cost.

Supergrouping after NMO correction. In the field, array forming is limited by logistics and cost; however, during seismic processing there are a great number of options. In most cases, supergrouping is applied after normal-moveout (NMO) correction. Preliminary velocity information is almost always available, so it makes perfect sense to use this a priori information in time processing. Clearly, reflections after NMO will be better aligned, therefore making signal summation more straightforward irrespective of the spatial sampling. What would be the noise-reduction properties of such arrays? Let us examine this in detail.

Figures 2a and 2b show the moveout of a reflection event and ground roll as well as their apparent velocities with offset. Based on moveout differences, conventional group forming with a five-point array and 50 m spacing between elements will effectively suppress ground roll starting from 3 Hz, although it will damage signals above 15 Hz due to the large sampling interval (Figure 2c). If we apply NMO, moveout and the event apparent velocities will be transformed as shown in Figures 2d and 2e. A linear noise event with constant velocity becomes curved with an apparent velocity varying between 1000 and 1200 m/s after NMO correction is applied, whereas a reflected signal acquires an infinite apparent velocity. Simulating the array response for moved-out data, we observe that not only is signal preserved over the entire frequency band, but also ground roll remains similarly filtered (Figure 2f). We conclude that arrays after NMO correction are excellent at preserving signal while maintaining similar efficiency in suppressing noise.

Field applications

Processing of land seismic data remains a tedious and time-consuming business because all sorts of prestack corrections are required to fully harvest the power of the stack for imaging (Figure 3). Algorithms in existence today largely demand that good prestack signal be present on the majority of the traces, which is exactly the luxury that is escaping us with modern data acquired with smaller arrays and single sensors. For instance, surface-consistent deconvolution analyzes prestack events within an appropriate time window and assumes they represent pure reflected signal. Likewise, surface-consistent scaling looks at prestack amplitude variations, also assuming they represent only reflections. If these assumptions are violated, then parameters for scaling, deconvolution, statics, and velocity analysis can result in severe artifacts and distortions and poor imaging (Cary and Nagarajappa, 2013). We propose to use smart supergrouping as an efficient way to achieve desirable S/N for optimal parameter selection for each prestack processing step. Each step, however, may demand different levels of enhancement. Smart supergrouping provides the noise-suppression power of source and receiver arrays and allows task-specific flexibility. The processor has full control over the specifications of essentially a very simple and efficient four-dimensional filter and can tune it for each task. Let us examine how smart supergrouping can help at various stages of seismic data processing.

Automatic first-break picking. It may be surprising, but the minimum required S/N might not be present on the raw field data, even for the strongest arrivals such as refracted waves used for near-surface model building. Figure 4 shows examples of near and far cables from recently acquired high-channel-count land seismic data with nine geophones per group and two vibrators

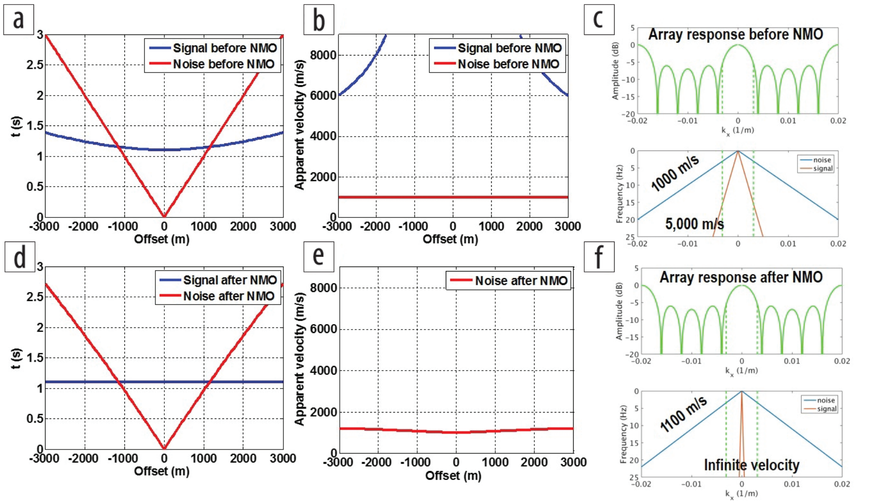

Figure 2. Traveltime curves, apparent velocities, and array responses (a–c) before and (d–f) after applying NMO corrections. Signal is the blue reflected event (V_{nmo} = 3600 m/s, t_0 = 1.2 s) and ground roll is the red linear event with V = 1000 m/s. Without NMO correction, a five-element inline array with 50 m spacing between elements filters noise from 3.1 Hz and passes signal below 15 Hz. When NMO correction is applied to the data (d, e), signal is passed at all frequencies, whereas ground roll is filtered above 3.5 Hz (f).

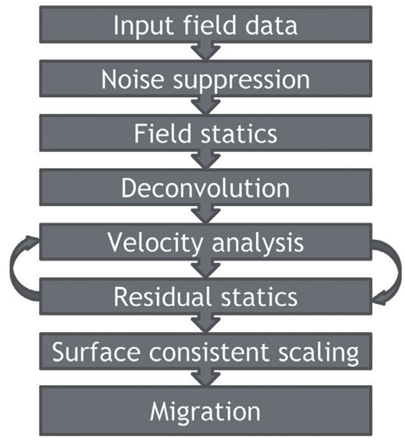

Figure 3. A generalized land seismic data processing flow.

per source array. While these data have denser spatial sampling (sources on a 100 by 25 m grid and receivers on a 25 by 150 m grid), clearly prestack data quality becomes extremely challenging when recorded with small field arrays. Vast volumes of data can be handled by automatic picking algorithms, yet they can fail when the S/N is insufficient (red dots on Figures 4a and 4b). Standard ways of data preconditioning can help, but low S/N still leads to many inconsistent time picks (Figures 4c and 4d). As a consequence, tomographic inversion and resulting statics will have a high degree of error, and this is just the initial challenge for data with smaller field arrays. When we apply 3 × 5 × 1 × 1 supergrouping in addition to conventional preprocessing, we obtain results shown in Figures 4e and 4f. There is a clear improvement in problem areas for both near- and far-offset regions. While we may lose some high-frequency details, those can be recovered by residual-statics algorithms. Most importantly however, we obtain more reliable traveltimes for refraction tomography that constrain long-wavelength statics critical for proper delineation of subtle low-relief structures.

Surface-consistent processing: 2D point-source point-receiver land data. Point-source, point-receiver data, if they are of high density, are often assumed to

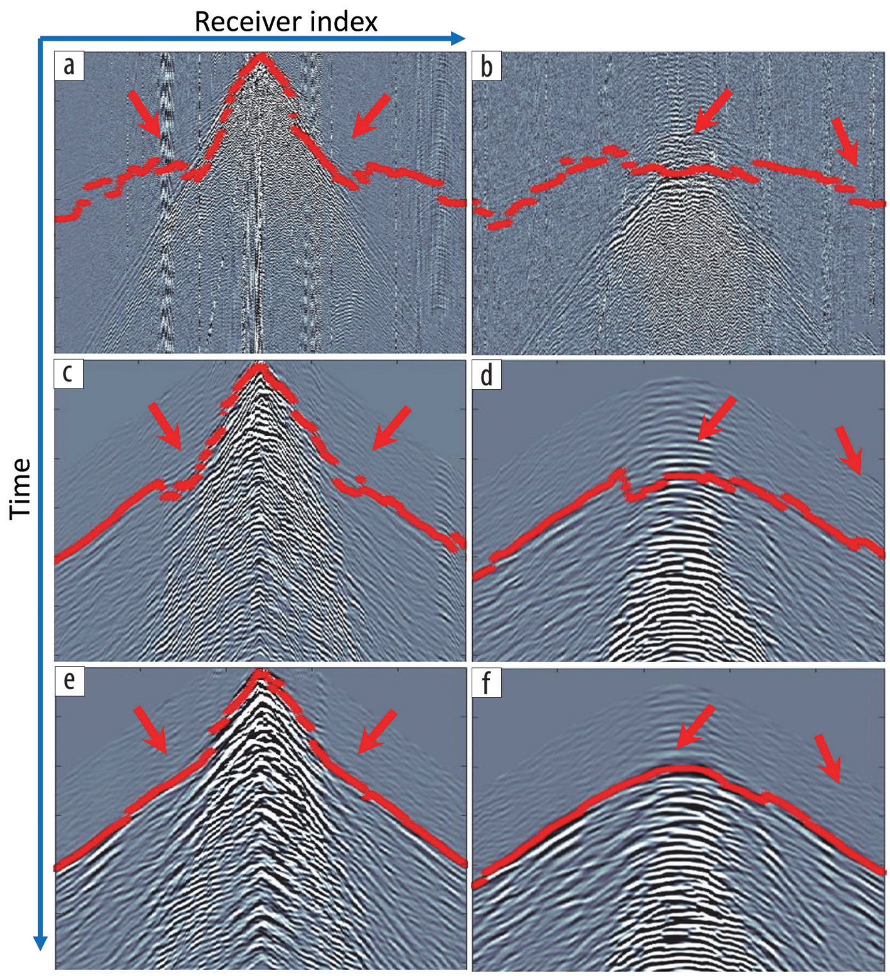

Figure 4. Example of data enhancement for automatic first-break picking. (a) and (b) Raw field data with first breaks shown by red dots for near and far cable. (c) and (d) Same as (a) and (b) but after standard preprocessing for automatic first-break picking and (e) and (f) after applying both standard preprocessing and 3 × 5 × 1 × 1 shot supergrouping. Source and receiver grids are 100 by 25 m and 25 by 150 m, respectively.

be the ultimate acquisition design. In a desert environment, such data often contain no visible signal whatsoever. To process and image such data, we have to be able to find this signal, apply appropriate corrections, remove noise (Figure 3), and then image. Here we examine 2D point-source and point-receiver data from the northern part of Saudi Arabia and compare results from conventional single-sensor processing versus processing involving supergrouping with relatively small group size (seven receivers inline).

First, let us review surface-consistent deconvolution and residual statics. Deconvolution operators are derived from autocorrelations shown in Figures 5a and 5b. Those obtained from the supergrouped data are better behaved without extreme trace-to-trace variations likely caused by near-surface noise rather than actual reflection signatures (Figures 5a and 5b). For wavelengths of 100 m or more, wave propagation physics suggests that we should not expect large waveform changes between receivers that

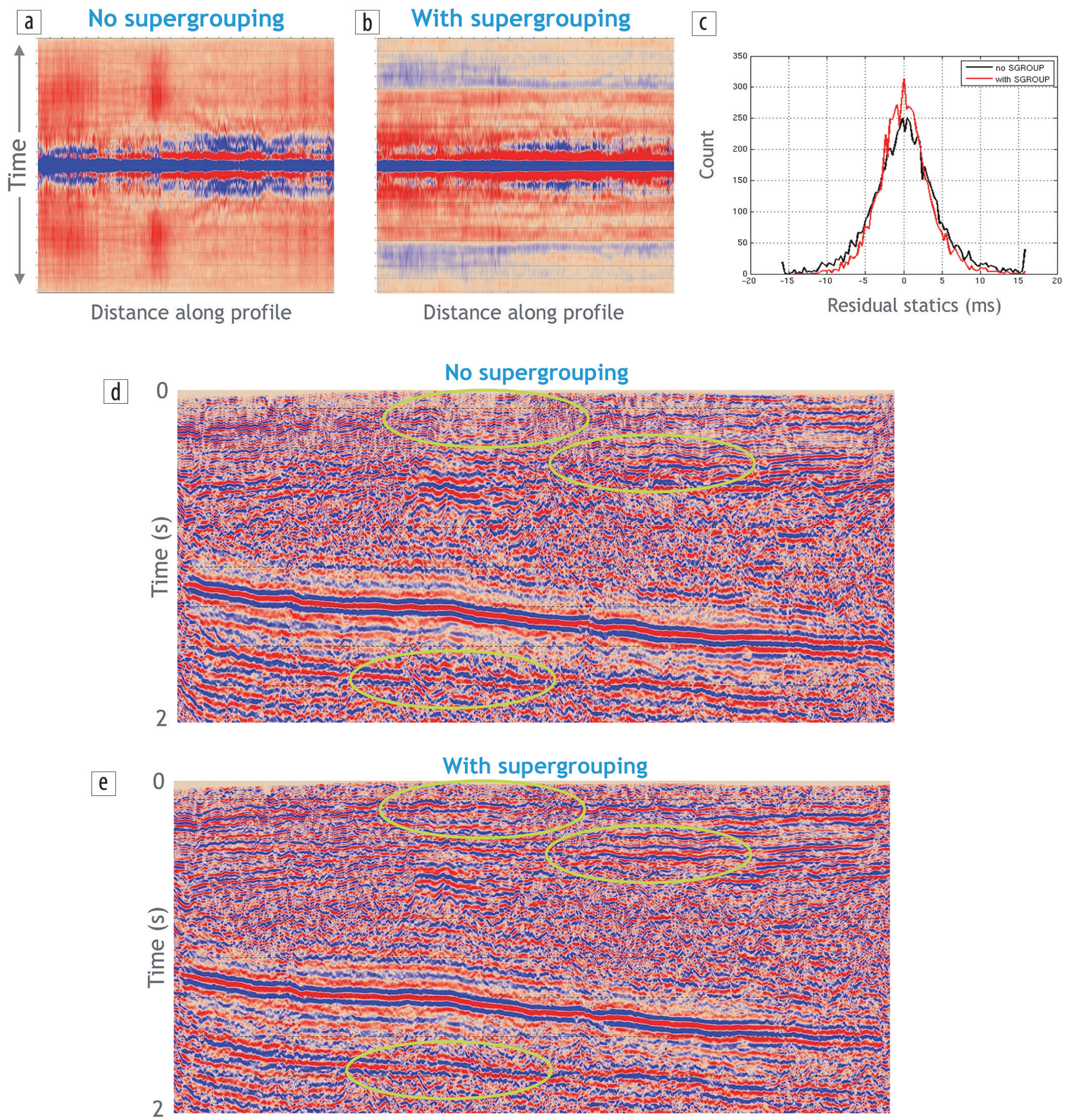

Figure 5. Surface-consistent processing for challenging point-source, point-receiver 2D data. Summed autocorrelations (a) before and (b) after supergrouping with seven receivers (7 × 1) show that input to deconvolution is cleaner and less contaminated when supergrouping is applied. (c) Comparison of residual shot statics is shown with and without supergrouping. Improved prestack parameters (statics and deconvolution) as well as the use of supergrouping for imaging lead to significantly improved stack (e) compared to standard stack (d) after single-sensor processing. Observe better continuity of deep and shallow events on the supergrouped image.

are 10 m apart. Therefore, the observed rapid variations are likely the imprint of near-surface scattering and noise.

Likewise, estimated residual shot statics for single-sensor data often exceed user-specified bounds, suggesting that prestack traces are simply lacking enough signal to determine accurate values based on simple crosscorrelation (Figure 5c). On supergrouped data, statics values cover a narrower range with a smaller standard deviation suggesting the results are more stable. Comparing stack images in Figures 5d and 5e clearly suggests that these parameter improvements (statics, deconvolution, etc.) after supergrouping are geologically meaningful. Supergrouped data show both deep and shallow events with better continuity and exhibit a more stable wavelet along the line. In this case, we use supergrouped data for further processing since we feel that single-sensor data are not meeting the minimum signal requirement for reliable imaging.

Surface-consistent deconvolution: 3D OBC data. Another example of the benefits of smart supergrouping for surface-consistent deconvolution is from 3D ocean-bottom-cable (OBC) data from the Arabian Gulf. These shallow marine data, acquired in only 50 m of water, have similar near-surface complexity as land data in Saudi Arabia. As such, this is often referred to as "land data covered by a layer of water."

Shallow geologic complexity as well as irregular and sparse acquisition geometry generally lead to a high level of noise, low vertical resolution, and degradation of both shallow and deep parts of the images (Figure 6a). Surface-consistent deconvolution applied to the original data only slightly improves vertical resolution in the shallow part but leaves the deeper section unchanged. This is because the prestack gathers contain weak reflections that remain strongly contaminated by residual noise. As a consequence, the deconvolution operator is largely driven by noise and unable to correct for actual signal variations. Supergrouping improves the prestack S/N and enables deconvolution to derive corrections truly addressing signal-shape variations. Here, deconvolution operators are derived on supergrouped data but applied to the original data since these data meet the minimum signal requirement for imaging and just need better prestack parameter estimation. Figure 6c shows the result with deconvolution operators estimated on relatively small groups (1 × 3 × 3 × 3) after interpolation. One may see that both shallow and deep reflections are much better resolved and are achieving the objective of surface-consistent deconvolution. Increasing group size for parameter estimation makes deconvolution even more successful both at shallow and deep levels (Figure 6d). Examining deconvolution operators obtained with supergrouping, we observe smoothly varying behavior that is more geologically plausible for 40 Hz data (not shown), whereas high-frequency fluctuations seen on operators derived from the original data are likely caused by residual noise and coupling variations.

Improving horizon continuity. Good S/N is crucial for automatic horizon picking. Our next example demonstrates the importance of data enhancement for improving horizon continuity and vertical resolution. The example comprises a challenging 3D land seismic data set with a highly irregular acquisition geometry caused by complex urban infrastructure (Figure 7a). As a consequence, poor S/N is observed despite using source arrays with five vibrators and geophone groups with 36 sensors. Shot spacing is 180 m inline by 30 m crossline; receiver spacing is 30 m inline by 180 m crossline. Isometric supergrouping was applied in the cross-spread domain using seven shots and seven receivers (1 × 7 × 7 × 1) because these data were intended to be used for azimuthal analysis (Figure 7a). Here, we also compare supergrouping with and without NMO

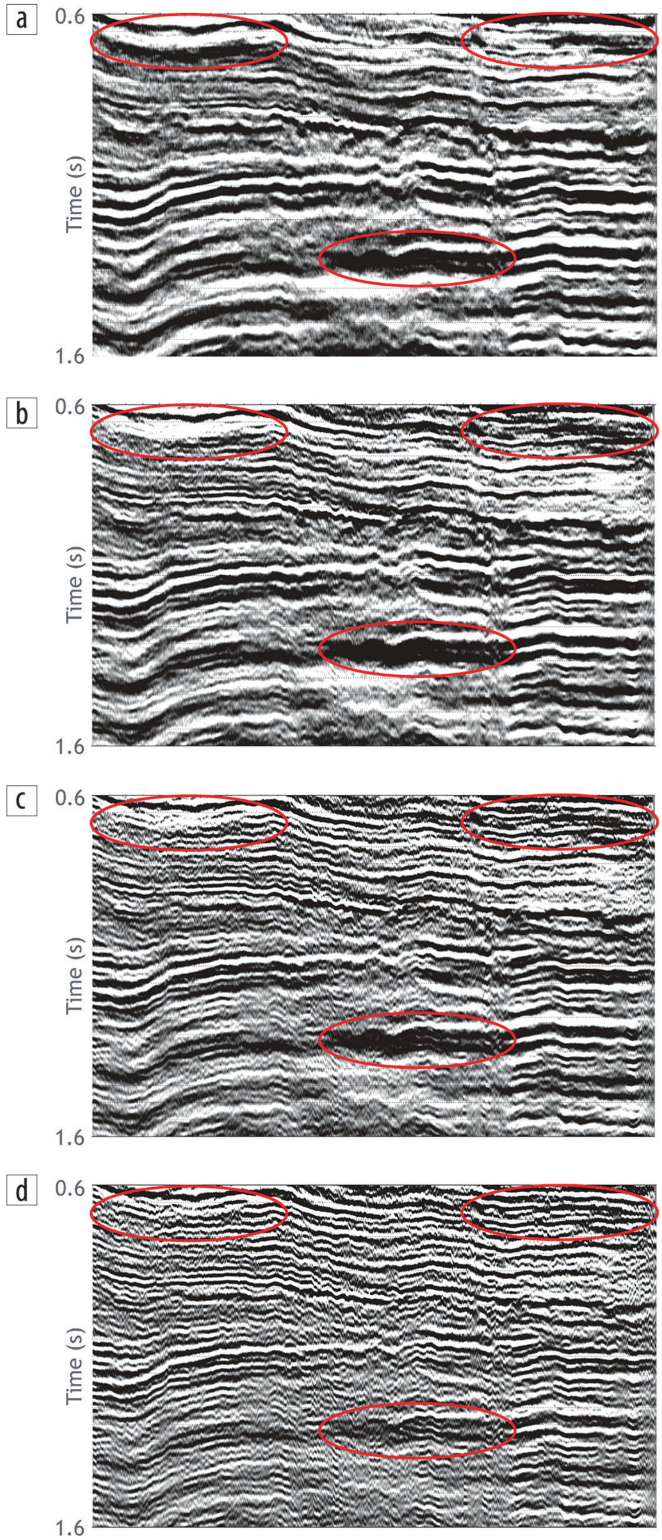

Figure 6. Comparison between (a) the input data stack and stacks after surface-consistent deconvolution with operators estimated on (b) the raw input data, (c) 1 × 3 × 3 × 3 supergrouped data, and (d) 5 × 7 × 7 × 7 supergrouped data. The deconvolution was applied to the raw input data in all cases.

corrections. The results of supergrouping are shown in Figure 7b for the prestack data and in Figure 7c for the poststack sections in the middle of the survey. It is obvious that supergrouping increases S/N and improves continuity of the main horizons. The combination of the NMO correction prior to supergrouping is clearly superior to supergrouping without NMO, as is most distinctly seen by better vertical resolution and improved continuity of the shallow reflectors. The horizon continuity attribute comparison (Figures 7d and 7e) confirms our observations and proves that supergrouping is essential for successful automatic horizon tracking on these challenging data.

Enhancing low frequencies for FWI. Low frequencies are considered beneficial for seismic processing, particularly for full-waveform inversion (FWI). While it is challenging to generate them with standard broadband vibrators, the longer wavelengths permit efficient supergrouping with much wider apertures without jeopardizing the low-frequency signal.

A conventional broadband 3D land seismic data set was chosen to evaluate the effect of supergrouping on the lower frequencies. While the nonlinear vibrator sweep starts at 2 Hz, due to inefficient excitation, signal at lower frequencies remains very weak. For this data set, the receivers are spaced every 50 m inline and 250 m in the crossline direction with sources spaced every 50 m crossline (orthogonal to receivers) and 250 m inline. Note that each receiver station is actually a small geophone group of 25 elements, and each source station represents a linear array of three vibrators at 12.5 m spacing in the inline direction. At low frequencies, the apparently large sensor and source spacing is still sufficiently small compared to the seismic wavelength to perform summation without applying NMO correction. This is evident for the finely sampled directions (50 m spacing), such as inline for receivers and crossline for the sources. In the coarser sampled directions, where shot spacing is 250 m, we use common-offset summation as an alternative to moveout corrections.

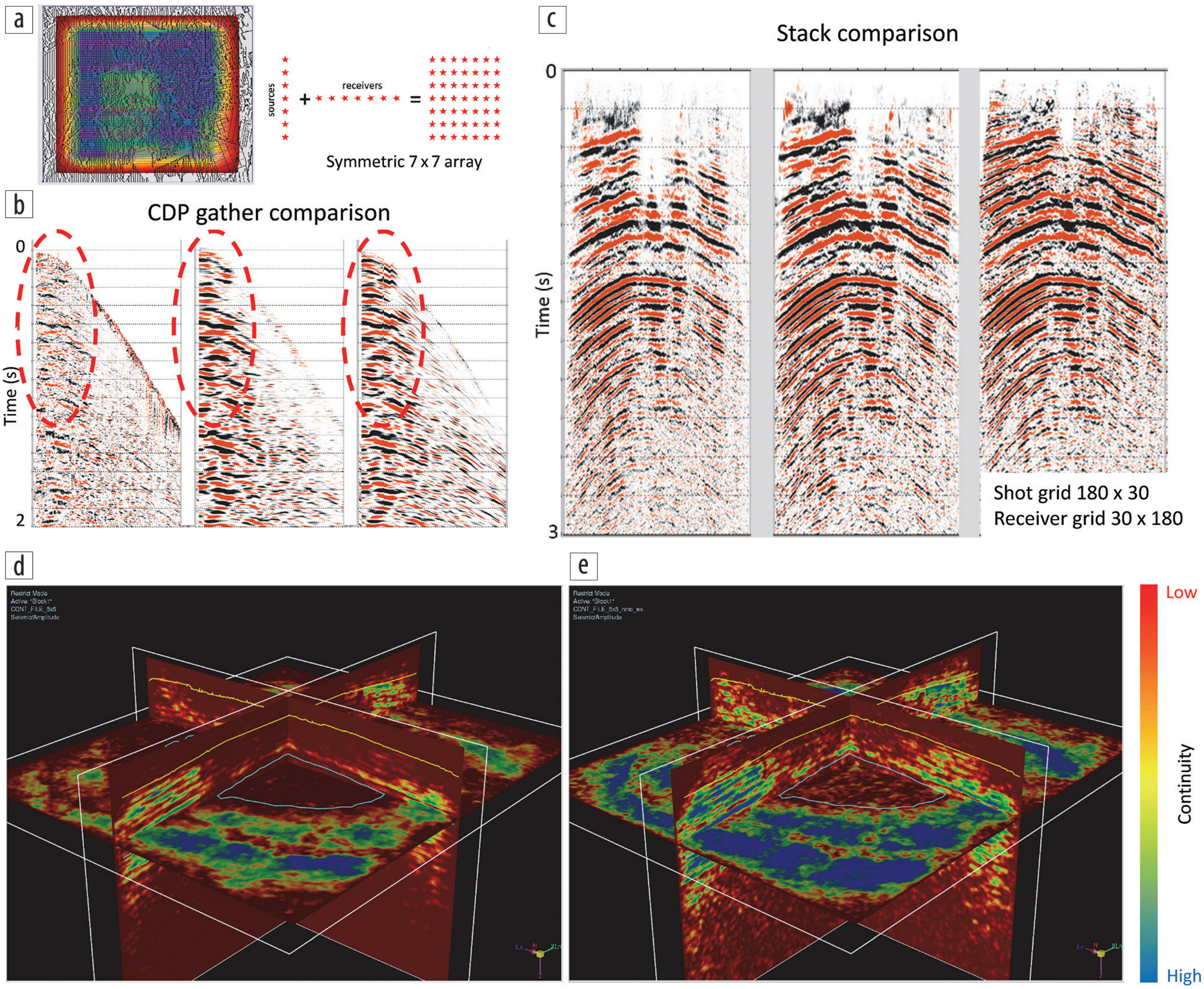

Figure 7. Supergrouping comparison showing (a) the 1 × 7 × 7 × 1 supergrouping geometry; (b) prestack gathers including raw, supergrouped raw data, and supergrouped data after NMO (from left to right); (c) stacked sections including raw, supergrouped data, and supergrouped data after NMO (from left to right); and continuity attributes (d) before and (e) after supergrouping where blue values indicate better continuity.

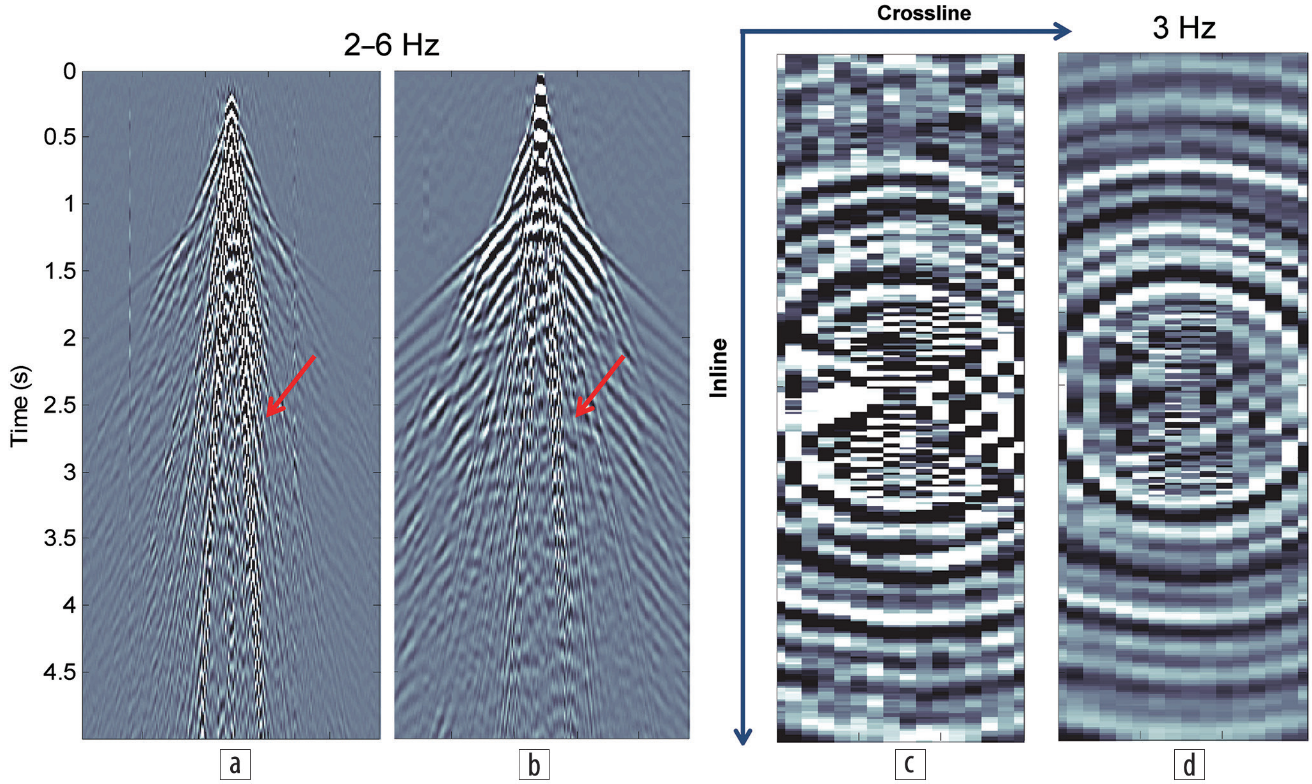

Figure 8. Broadband 3D land seismic data showing (a) preprocessed input gather in the band of 2–6 Hz, (b) the same gather after 5 × 5 × 5 × 1 supergrouping, (c) preprocessed input data in the frequency domain, and (d) the supergrouped data in the frequency domain.

Figure 8 displays low-frequency data in the band of 2–6 Hz preprocessed using a standard flow showing that a significant amount of noise remains after filtering. Supergrouping over 5 × 5 × 5 × 1 (5 × 5 shots and 5 × 1 receivers) was tested on synthetic data and shown to fully preserve refracted and reflected waves of interest up to frequencies of 8 Hz, while suppressing ground roll and shear waves. For synthetic data in acoustic media, supergrouped traces and point source/receiver responses were very similar, verifying that signal events of interest are preserved at low frequencies on all traces within the summation aperture. When applied to field data, supergrouping leads to a significant increase in S/N, particularly at the lower frequencies of 3 Hz and below that require significant enhancement to be used (Figures 8b and 8d). Frequency panels in Figure 8 show greatly improved S/N due to supergrouping (Figure 8d), which will be critical to enable effective use of frequency-domain FWI.

Summary and outlook

We presented a supergrouping method designed to improve prestack data quality for challenging 3D seismic data sets. Supergrouping goes beyond conventional group forming because it is applied after NMO correction and thus can preserve signal even with large source/receiver spacings that are impossible to use in conventional group forming. Supergrouping is akin to a four-dimensional filter that is typically applied in source and receiver inline and crossline directions. It can operate on already group-formed 3D data and does not require regular geometry. Such an approach is especially useful to process high-channel-count data with small field arrays or point-source and point-receiver data. Single-sensor, low-S/N data often render conventional processing ineffective on the raw data. Supergrouping allows the creation of surrogate volumes of enhanced data with the same geometry that can be used for deriving prestack parameters as well as imaging. By adjusting the size of the supergroups, one can set a different level of enhancement for each processing task. For instance, strong enhancement with large supergroups may be perfectly acceptable for velocity analysis, while milder enhancement can be used for deriving residual statics with small enhancements for final imaging. One can think of supergrouping as being analogous to zoom and unzoom functions in Google Earth. There is an appropriate level of enhancement that gives required clarity for each task. Being simple and computationally effective, supergrouping allows the creation of iterative flows in which improved signal estimation can be refined using multiple passes.

Using 3D land and shallow OBC data from Saudi Arabia, we have presented applications of supergrouping from first-break picking to surface-consistent deconvolution to statics to FWI. More sophisticated stacking options such as diversity stack and smart-weighted stack can further improve results. Local corrections before summation may boost recovery of higher frequencies and enable more accurate estimation of processing parameters for original shot/receiver locations. This will be the subject of future studies. We conclude that supergrouping is an invaluable instrument in the processing toolbox for challenging modern seismic data based on reduced field arrays or point sources and receivers. TLE

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