Enhance – Estimate – Image: new processing approach for single-sensor and other seismic data with low pre-stack signal-to-noise ratio

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Summary

We propose a new approach to processing single-sensor and challenging data, dubbed Enhance → Estimate → Image. We present an initial implementation where smart supergrouping is utilized for the Enhance stage. A field example validates this approach, and shows obvious improvements compared to conventional single-sensor processing. Parameters for the Enhance part can be tuned differently for statics, deconvolution, and velocities. We also observe a need for better single-sensor data enhancement for the imaging phase that could be different from the Estimate phase.

Introduction

By 2030, International Energy Agency estimates that 60 % of daily production will come from onshore fields, which are dominated by carbonates (Johnson, 2013). Onshore reservoirs in the Middle East are often associated with extremely challenging seismic data quality, thus hindering effective characterization and monitoring due to their inherent complexity. As such, the quest to improve seismic imaging of carbonates has a very significant prize due to the prolific nature of such reservoirs. It is believed that a major factor driving improvement in seismic imaging is associated with the increase in trace density (May, 2016). This logic has driven acquisition geometries from "Heavy and sparse" to "Light and dense", i.e., toward finer spatial sampling, but with much lighter source and receiver field arrays, and ultimately to point-source, point-receiver configurations (Figure 1). "Dense" still means much coarser sampling than is typically used in field arrays and as such Light and dense is far from being a supervolume that would allow replicating "Heavy" conventional field arrays. As a consequence, processing of Light & dense seismic data becomes a significant challenge. Heavy field arrays are employed in desert environment for very good geophysical reasons to enhance weak reflection signals and attenuate noise. When field arrays are greatly reduced or replaced by point source and receivers, data quality is greatly reduced. Naturally, every processing step that relies on pre-stack signal becomes challenging to execute. Noise removal can help but only if the signal present on each trace is above a minimum useful threshold. Unfortunately, there are many datasets where we remain below such a threshold. In these cases, incorporating signal from neighboring traces becomes perhaps the only practical option. Here we present an approach called Enhance – Estimate – Image that can allow processing of such challenging data better than can be achieved with standard approaches.

Enhance – Estimate – Image (E^{2}I) approach

Figure 2 shows an example of point-source, point-receiver 2D data from Saudi Arabia. Pre-stack signal is extremely weak, both in raw as well as conventionally pre-processed data. Conventional pre-stack parameters cannot be estimated reliably using this data (deconvolution operators, statics, scalars, velocities). So we come to a natural cross-road. The traditional "do not mix" approach advocates: keep peeling off the noise, try harder and signal would appear on single-sensor data. We call the alternative a "mixer" approach: dramatically enhance signal using neighboring traces, then bootstrap. This alternative approach can be crystallized as Enhance - Estimate - Image:

- Enhance - Obtain a dramatically better estimate of the pre-stack signal with localized enhancement using an ensemble of neighboring traces

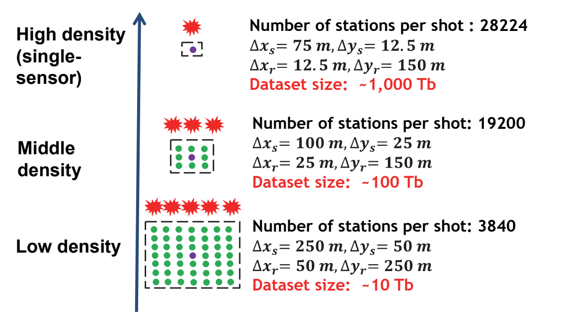

Figure 1. Examples of past acquisition geometries illustrating the trend to increase trace density and have finer spatial sampling. Observe that in practice this is accompanied by reduction of field source and receiver arrays.

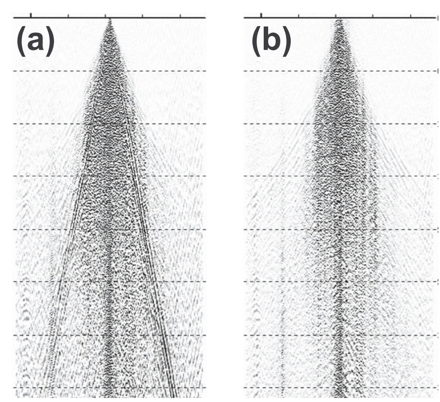

Figure 2. Single-sensor data as recorded in the field (a) before and (b) after standard noise removal. Observe low signal-to-noise ratio on (b) insufficient for standard time processing.

- Estimate - extract pre-stack parameters of the signal from enhanced data (deconvolution operators, statics, scalars, velocities)
- Image - apply estimated parameters and image.

The last step allows multiple choices: either apply to the original non-enhanced data, the same enhanced data or data enhanced differently for the image phase.

We will show examples where we apply and contrast both approaches and compare the results. In this study we show examples where the Enhance stage is done with supergrouping after NMO correction (Figure 3), as described by Bakulin et al (2016). There are different methods to enhance data based on local ensembles. Supergrouping may be one of the simplest and yet most useful for modern 3D data. While we are making flexible source and receiver groups – we effectively apply simple and efficient 1, 2, 3 and 4-dimensional filters. Efficiency becomes paramount for huge volumes (Figure 1) where enhancement needs to be done quickly and often in an iterative process.

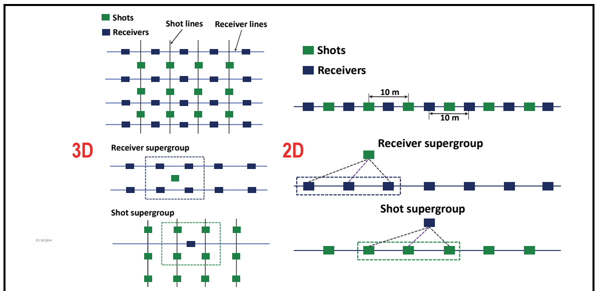

Figure 3. Supergrouping explained for 3D and 2D.

Case study: point-source point-receiver data

Point-source, point-receiver data is often believed to be the ultimate acquisition. Figure 2a shows raw field gathers from a 2D line acquired with a single vibrator and single sensors both with 10 m sampling. Traditional single-sensor pre-processing attempts to peel off the noise hoping for signal to show up but the signal remains hidden (Figure 2b). Intense scattering due to a complex near surface drowns reflected signal in a sea of noise. We know that signal is present from legacy seismic data. If we perform supergrouping after NMO using both inline source and inline receiver arrays, we observe that after summing sufficient ensembles, signal eventually emerges (Figure 4a). For 2D we adopt simplified notation (Figure 3) where a supergroup NxM means summing N source and M receivers inline. The corresponding frequency spectra after supergrouping are shown on Figure 4b.

We now compare two processing approaches using surface-consistent deconvolution as one example. We decide to apply small supergrouping 1x7 at the beginning and keep it for imaging. In the first approach, we use 1x7 supergrouped data for deriving deconvolution operators (Figure 5a). In the second approach, Enhance-Estimate-Image, we use greatly enhanced supergrouped 50x50 data (Figure 5b) to derive the operators, we apply them to the same 1x7 data previously stated. Comparing the spectra of 1x7 and 50x50 gathers, one can immediately observe an apparent loss of higher frequencies (blue oval) that may be initially interpreted as a reduction of signal resolution. We will revisit this point later. After performing deconvolution we compare the spectra of the CDP stacks. Contrary to our expectation that we might have lost the high frequencies to supergrouping in the Enhance stage, we see that higher frequencies were recovered best when we used operators designed from enhanced 50x50 data, whereas, they were not recovered when we used original 1x7 data to compute the operators (Figure 7). In fact, the spectra of the deconvolved stack with 1x7 data is very similar to the one before deconvolution (Figure 7ab) validating our point that conventional processing fails when pre-stack data quality is too low.

Inspection of the images further confirms these observations (Figure 8). We obtain sharper results with operators from 50x50 supergroups and managed to improve vertical resolution across the entire section both shallow and deep. How can this be interpreted? If we revisit the spectra of 1x7 and 50x50 supergrouped gathers (Figure 6), and now compare them to the spectrum of the entire stack shown in green – then we conclude that the high frequencies are very strongly contaminated by scattered

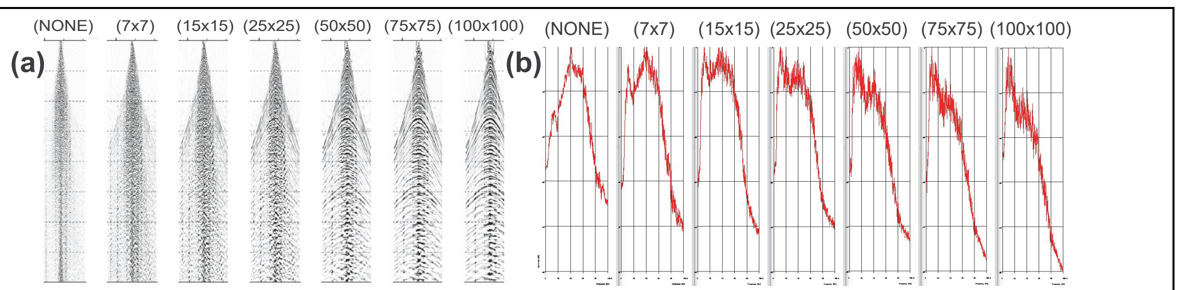

Figure 4. Pre-processed gathers with various levels of supergrouping after NMO (a) and corresponding frequency spectra (b).

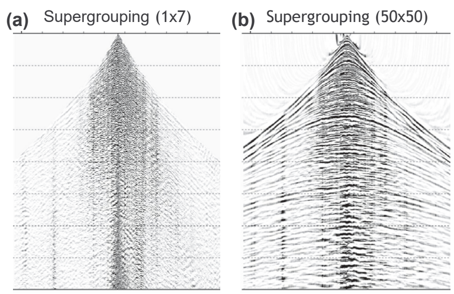

Figure 5. Pre-stack shot gathers with supergrouping 1x7 and 50x50.

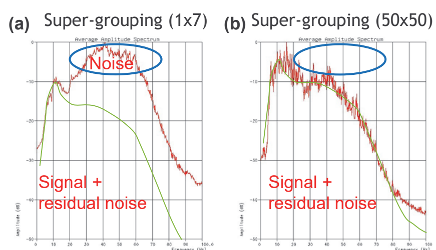

Figure 6. Spectra of shot gathers shown in Figure 5. Observe immediate loss of higher frequencies on 50x50 data.

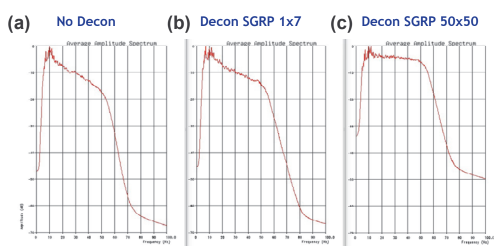

Figure 7. Spectra of the stacks after (a) no deconvolution, (b) deconvolution derived on 1x7 supergrouping and applied to the same data and (c) deconvolution derived on 50x50 and applied to 1x7 supergrouping. Observe much better recovery of higher frequencies in case (c). Also note similar spectra of (a) and (b).

noise. With supergrouping we suppress this noise very efficiently but still very locally – pre-stack spectra after 50x50 supergrouping is similar to the full stack. We have collected enough signal with supergrouping (Figure 6b) so that deconvolution can effectively enhance weak reflected signal and produce the improvements that were observed on the image and spectra. In contrast, when using 1x7 supergrouped data as an input, the deconvolution is purely designed on the noise and cannot achieve any meaningful recovery of the higher frequencies. So what is the lesson learned? While theoretically it may not be desirable to mix signals from different traces, in practice if the signal is so tiny and so overwhelmed by noise – mixing for the Enhance stage may be a very fruitful approach that allows to bring this signal back. The pros clearly outweigh the cons in this case.

Figure 9 shows averaged autocorrelations of the shot gathers, before and after deconvolution and confirms the same message – all the high-frequency variations in 1x7 supergrouped data are most likely induced by scattering noise and prevent us from getting good estimates of the reflected signal. In contrast, Figure 9b exhibits more geologically plausible behavior for a 20 Hz wavefield, where one should expect smooth variations from one point to another when signal with wavelengths above 100 m propagates through a complex near surface. After deconvolution, autocorrelations of the 50x50 supergrouped data show greater spatial consistency than the 1x7 supergrouped data.

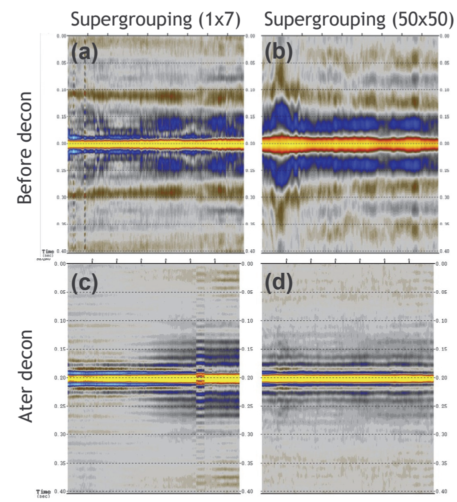

Figure 9. Summed shot autocorrellations for supergrouped data including cases (a) 1x7, (b)50x50, (c) post-decon 1x7 and (d) post-decon 50x50. Observe rapid fluctuations caused by near surface on (a) and more geologically plausible behavior on (b). After deconvolution note the greater consistency of (d) as compared to (c).

Discussion

Various modifications of Enhance-Estimate-Image (E^2I) are often needed when dealing with challenging data. For instance, in the single-sensor example above we made another round of enhancement (supergrouping 1x7) for imaging due to the poor signal quality, so it effectively became Enhance I – Estimate – Enhance II – Image (E^3I). This may be a typical configuration for land data from a desert environment. In other cases, the first two steps require iteration with some adjustment of the Enhance stage to refine the parameters making it Enhance – Estimate – Iterate – Image $(EI)^2$.

Conclusions

Seismic data with small field arrays or single sensors in a desert environment is often below the signal-to-noise threshold for conventional processing. We have presented a new approach that can effectively address this problem called Enhance – Estimate – Image. The Enhance phase obtains a dramatically better estimate of the pre-stack signal by stacking an ensemble of neighboring traces. The Estimate phase extracts improved pre-stack processing parameters from the enhanced data (including velocity, deconvolution operators, surface-consistent scalars, statics). The Image phase is where we apply the improved parameters either to the original or enhanced data or data enhanced differently for imaging. Such an approach is critical for modern high-channel count data both for imaging as well as for data conditioning for estimation of pre-stack attributes and inversion. The amount of enhancement may vary for each task (decon, scalars, residual statics, and velocities) based on wave propagation physics and signal quality. While supergrouping with NMO corrections is powerful, it will average local parameters such as statics and scalars. Other enhancement methods may allow better preservation of local values and are being pursued. Trade-offs between averaging and resolvability of parameters need to be studied in detail. An acceptable size of the local ensembles for enhancement needs to be evaluated and may be case-by-case dependent. If the required ensemble size starts to negatively impact imaging, then the acquisition design may need to be adjusted, perhaps using larger arrays. If formalized, these considerations should become the foundation of data-driven acquisition survey design for complex areas.

Acknowledgments

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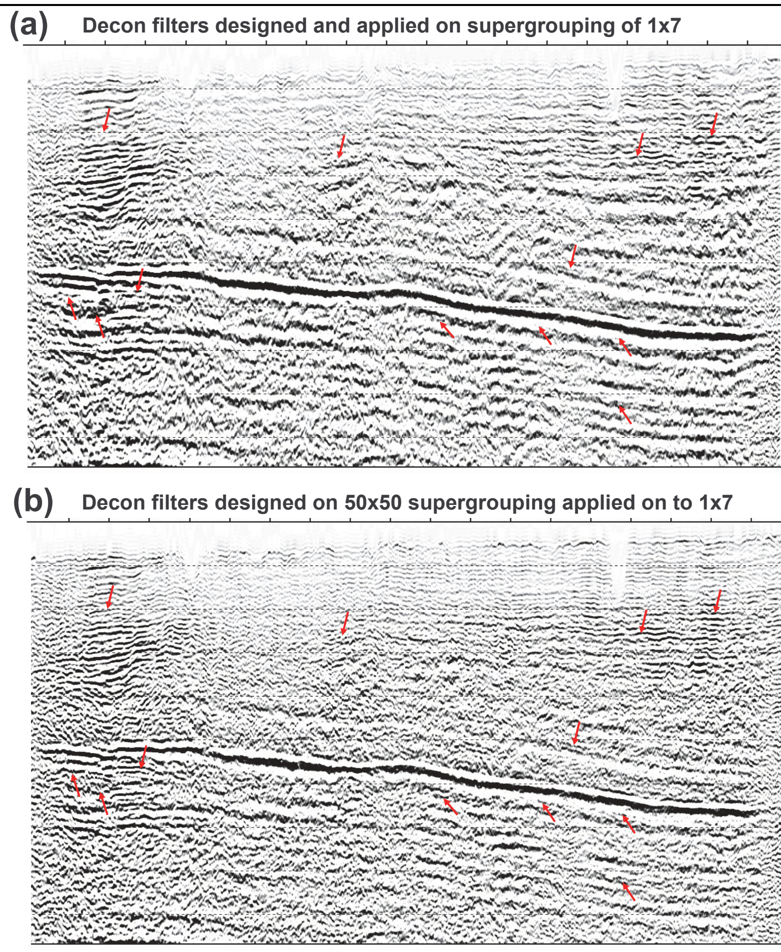

Figure 8. CDP stacks obtained after surface-consistent deconvolution (a) using filters designed and applied using the same supergrouped 1x7 data and (b) using filters designed on 50x50 supergrouped data and applied to 1x7 supergrouping. Observe better vertical resolution and more resolved shallow and deep events.

EDITED REFERENCES

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