Technology Advances Reveal Unseen Seismic Reflectivity

The EAGE and the SBGf will host the 'First EAGE/SBGf Workshop on Least Squares Migration' in Rio de Janeiro, Brazil, on November 27-28 (https://events.eage.org/-/media/files/events/2018/la/first-eage-sbgf-workshop-on-lsm/18lsmla.pdf).

Least-Squares Migration (LSM) is an imaging technique that has gained attention in recent years for its ability to improve images obtained by traditional seismic migration methods; minimizing the presence of artifacts, mitigating illumination variations, and increasing spatial resolution. In fact, LSM is the latest step in a continuous path towards revealing the reflectivity information recorded within the *full* wavefield of any marine seismic dataset.

Ten years ago, marine seismic images were overwhelmingly derived from arrays of hydrophone-only streamers. Seafloor seismic was wildly expensive, and a period of industry experimentation with converted-wave processing had failed to demonstrate any compelling motivation to use multisensor receiver packages, apart from imaging through gas clouds. Most technology focus for towed streamer deployment was on survey design templates that collectively improved subsurface illumination and that attenuated complex coherent noise types not easily addressed by conventional signal processing methods—either multi-azimuth (MAZ) or wide-azimuth (WAZ) configurations (refer to Long, 2010). If we fast-forward to 2018 there have been three significant advances in the recovery of the earth's seismic reflectivity—information that was masked or discarded by the technologies used only a decade ago.

In this paper I discuss how these advances can be summarized as follows:

- Removing the effects of ghost reflections (wavefield separation),
- Imaging the earth with the full wavefield (using what was once regarded as 'noise' to instead be valuable signal), and
- Compensating for non-uniform illumination and acquisition aperture artifacts, and recovering much higher wavenumber information (Least-Squares Migration)

Collectively, the use of multisensor marine seismic acquisition complemented by imaging of the full recorded wavefield—preferably within a Least-Squares framework—finally reveal the earth's reflectivity without artifacts introduced by ghost wavefields, acquisition imprints, and the deficiencies within conventional imaging solutions.

The Full Seismic Wavefield was Contaminated by Ghosts

The advent of multisensor recording for towed seismic streamers enabled the true separation of the up-going and down-going pressure wavefields (Carlson et al., 2007), and heralded the 'broadband' seismic revolution seen in marine seismic exploration over the past decade (Widmaier et al., 2015). A simple summation and subtraction of two measured seismic wavefields, pressure and the vertical component of particle velocity, yields two new seismic wavefields: 1. the up-going pressure wavefield ('P-UP') that has been scattered upwards from the earth without interacting with the acoustic mirror of the ocean surface; and 2. the down-going pressure wavefield ('P-DWN') that is a version of P-UP reflected downwards from the dynamically moving ocean surface (Figure 1). If we sum P-UP and P-DWN we yield the total pressure seismic wavefield ('P-TOT') recorded by hydrophone-only streamers; heavily contaminated by 'ghost notches' and various noise related to weather and environmental conditions at the surface of the ocean. By isolating P-UP we can derive broad bandwidth, high-resolution seismic images of the earth—without the unwanted contributions of P-DWN that contaminate all forms of hydrophone-only streamers. In reality, 'broadband' typically means deghosting accompanied by some additional forms of spectral conditioning. In most cases, the post-stack interpretation of deghosted data is enhanced by improved geological texture, improved event coherence and deeper signal penetration. Recent attention has particularly focused upon the benefits of low frequencies in broadband seismic data to suppress the side lobes on zero phase events and enhance thin bed resolution (ten Kroode et al., 2013; and see Figure 2). Furthermore, where accurate amplitude-versus-angle (AVA) fidelity is achieved, deghosted data also enables more accurate pre-stack quantitative interpretation (Reiser et al., 2015a,b).

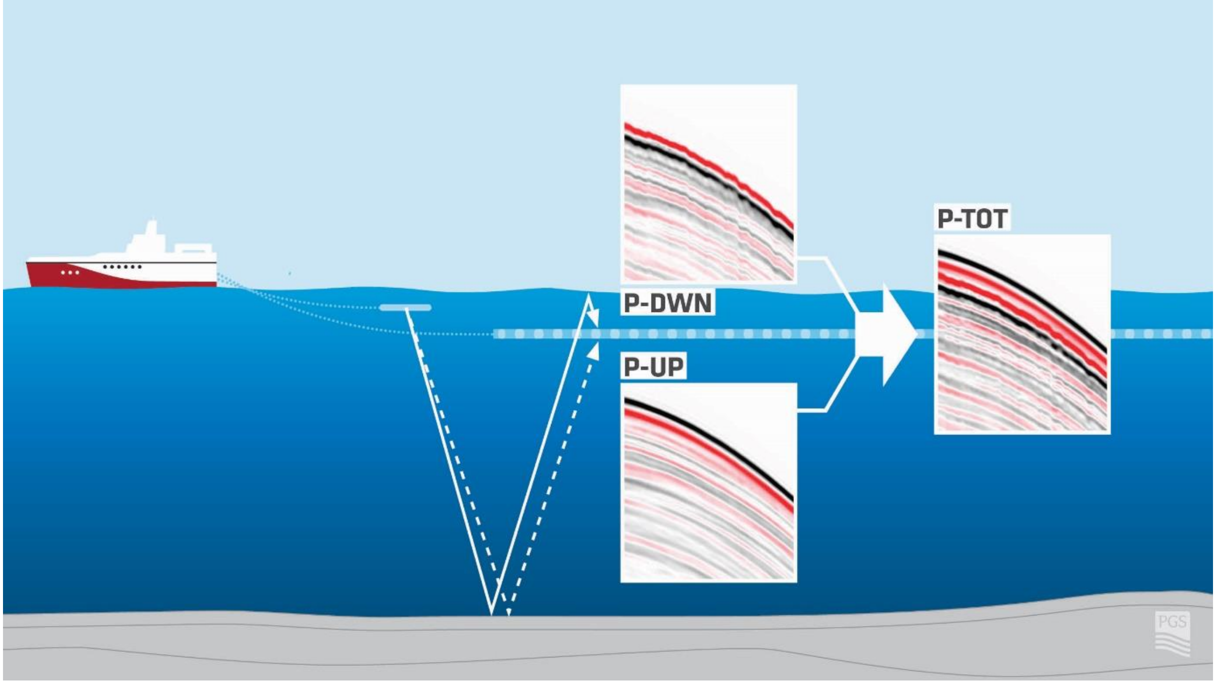


Figure 1. Schematic illustration of the up-going ('P-UP') and down-going ('P-DWN') pressure wavefields that combine to yield the total pressure ('P-TOT') data recorded by hydrophone-only streamers.

Note that wavefield separation of multisensor marine seismic data, whether it be acquired as multisensor towed streamer or multisensor seafloor data, removes the receiver-side ghost effects from the *full* seismic wavefield—no effort has been made in pre-processing to remove multiples. Similarly, the full seismic wavefield remains after the source-side deghosting that typically follows wavefield separation. However, processing flows historically attempted a suite of steps to remove the various multiples that mask the underlying primary reflections. This is where the second advance has occurred in recent years.

Primary Reflections Poorly Illuminate Shallow Depths

The acquisition geometry used for any marine seismic survey, towed streamer or seafloor, inevitably compromises shallow CMP fold and offset/angle illumination—notably for shallow water—and a strong acquisition 'footprint' is typically observable on cross-line stack images and shallow time/depth slices. The upper-left of Figure 3 illustrates that for outer streamers in particular, near angle reflections are not recorded for any offset, and the CMP fold is also penalized by the outer trace mute—resulting in the strong acquisition footprint observed on shallow time/depth slices (the upper-right panel in Figure 3). In this context, it is irrelevant whether total pressure (ghost effects included; P-TOT) or up-going pressure (ghost effects removed: P-UP) data is used for imaging—standard migration only images the illumination provided by primary reflections.

However, Whitmore et al. (2010) showed how access to both P-UP and P-DWN enables each receiver to act as a virtual source, thereby allowing the illumination surface multiples to yield complementary separated wavefield imaging (SWIM) of the earth. The spatial aperture imaged for each shot is greatly extended, most notably for shallow depths, very small incidence angles can be recorded from very shallow reflectors for each streamer in modern wide-tow streamer spreads (the lower-left panel in Figure 3), and therefore, acquisition footprint effects can be mitigated (the lower-right panel in Figure 3; and Long et al., 2013); velocity model building integrity is improved at all depths (Rønholt et al., 2014); and shallow AVO inversion becomes feasible (Feuilleaubois et al., 2017). Note that both depth slices on the right side of Figure 3 are imaged with multisensor GeoStreamer data from the same survey. The difference in the lower-right panel arises from SWIM being able to exploit the shallow illumination provided by all orders of surface multiples.

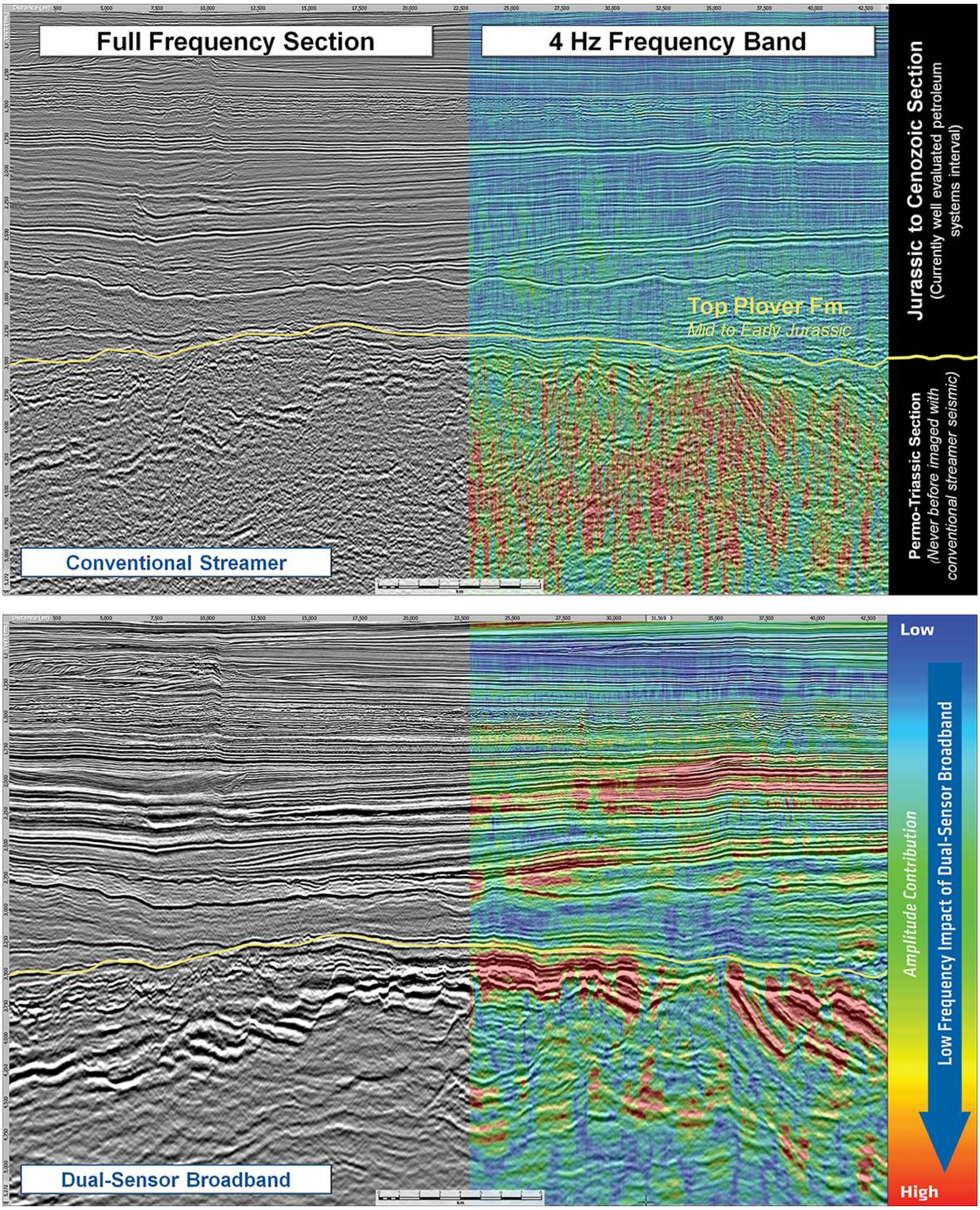


Figure 2. Comparison of legacy (upper) versus dual-sensor broadband (lower) PSTM stacks from the Browse Basin, Australia. The up-going pressure (P-UP) result demonstrates substantial improvements in low frequency content, particularly at the deeper Triassic and Jurassic levels, complemented by enhanced high frequency content at shallow to medium depths. The transparent color rendering on the right of each image shows the dominant frequency at each sample. Note the enhanced signal-to-noise ratio of the low frequency GeoStreamer data (from Long et al., 2016).

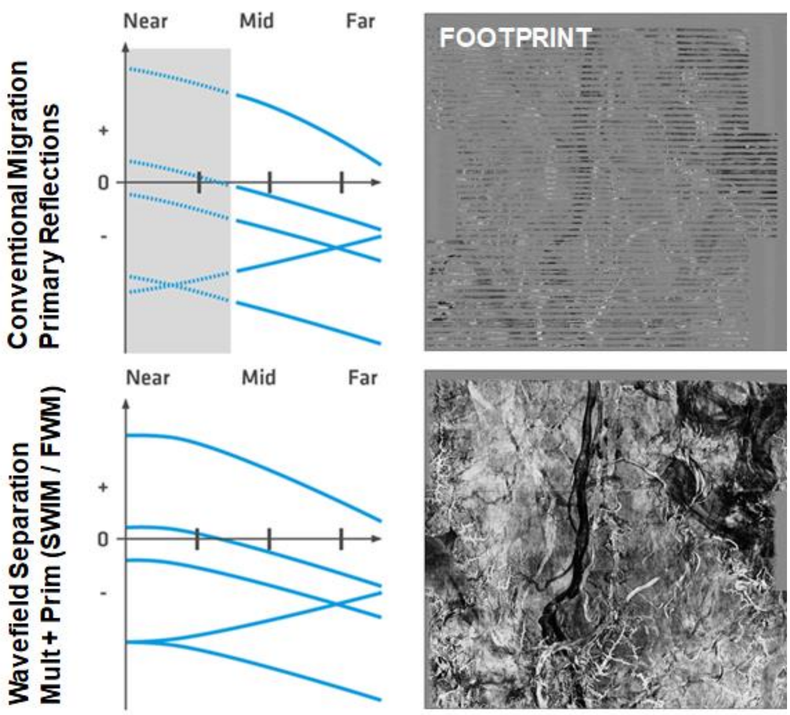


Figure 3. (upper-left) Schematic reflection angle plot for towed streamer acquisition, shallow target depths and primary reflections; (upper-right) Shallow depth slice (108 m below MSL, 80 m water depth) from P-UP imaging using primary reflections; (lower-left) Schematic reflection angle plot for towed streamer acquisition, shallow target depths and all orders of surface multiples; and (lower-right) Shallow depth slice (108 m below MSL, 80 m water depth) from SWIM where both P-UP and P-DWN are used to convert every receiver into a virtual source, thereby exploiting the shallow illumination provided by all orders of surface multiples.

Whitmore et al. (2010 and Lu et al. (2015b) describe how a deconvolution imaging condition enables the suppression of significant crosstalk artifacts and the improved recovery of reflectivity by comparison to a traditional cross-correlation imaging condition. The upper panel of Figure 4 shows an application of SWIM to synthetic data using a cross-correlation imaging condition. Several problems are immediately obvious: None of the events are properly focused, the illumination is highly non-uniform (particularly below the salt), the data are band-limited in terms of both temporal frequency and spatial frequency (wavenumber) content, and various crosstalk noise affects the data below the salt. In contrast, the use of a deconvolution imaging condition within SWIM yields several demonstrable benefits to the lower panel of Figure 4: The data are notably richer in temporal frequency content, the overall reflectivity is better, the shallow data above the salt are well resolved (circled), and the deeper illumination is improved. However, the illumination remains non-uniform, significant crosstalk remains in the deeper image, and steep dip imaging (i.e. spatial resolution) is variable.

Overall, wavefield separation of multisensor marine seismic data has enabled the illumination from all orders of surface multiples to significantly improve the shallow imaging—and a previously pernicious 'noise' (multiples) can now be used as signal—but the deeper image spatial resolution and illumination is still unsatisfactory. This leads to the final section in this article—imaging both primary reflections and all orders of multiples simultaneously; enhanced by Least-Squares migration.

Subsurface Illumination is Non-Uniform, Acquisition is Imperfect, and We Need High Wavenumbers

Lu et al. (2018) demonstrate how full wavefield migration (FWM) of both primary reflections and surface multiples within an iterative Least-Squares migration scheme (LS-FWM) can attenuate the crosstalk noise that historically challenged the applicability of SWIM beyond moderately shallow depths, and enables deep seismic imaging with optimized illumination and spatial resolution. Figure 5 shows the complementary result to Figure 4.

In brief, there are two general implementations of Least-Squares migration today. More commonly, an image domain methodology (Valenciano et al., 2006) is used to compute point spread functions (PSFs) that are then used to compensate for illumination variations on migrated images. Alternatively, Figure 6 shows the workflow for a methodology (Lu et al., 2018) formulated as a linearized inversion in the data domain where seismic data are simulated by Born modelling and iteratively updated until the misfit between the observed and modelled data becomes acceptably small. As observed in the Least-Squares SWIM example of Figure 5, the illumination becomes uniform, spatial resolution (and high wavenumber content) is better, and crosstalk artifacts are significantly attenuated at all depths.

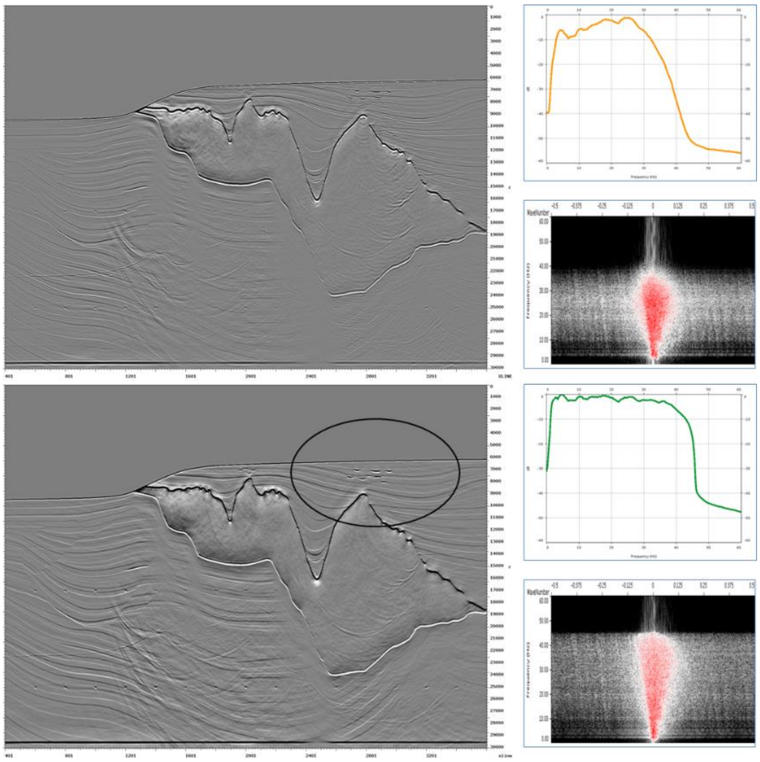


Figure 4. (upper) SWIM image using a cross-correlation imaging condition, the associated temporal frequency spectrum, and the associated wavenumber frequency spectrum; and (lower) SWIM image using a deconvolution imaging condition, the associated temporal frequency spectrum, and the associated wavenumber frequency spectrum. Compare also to Figure 5.

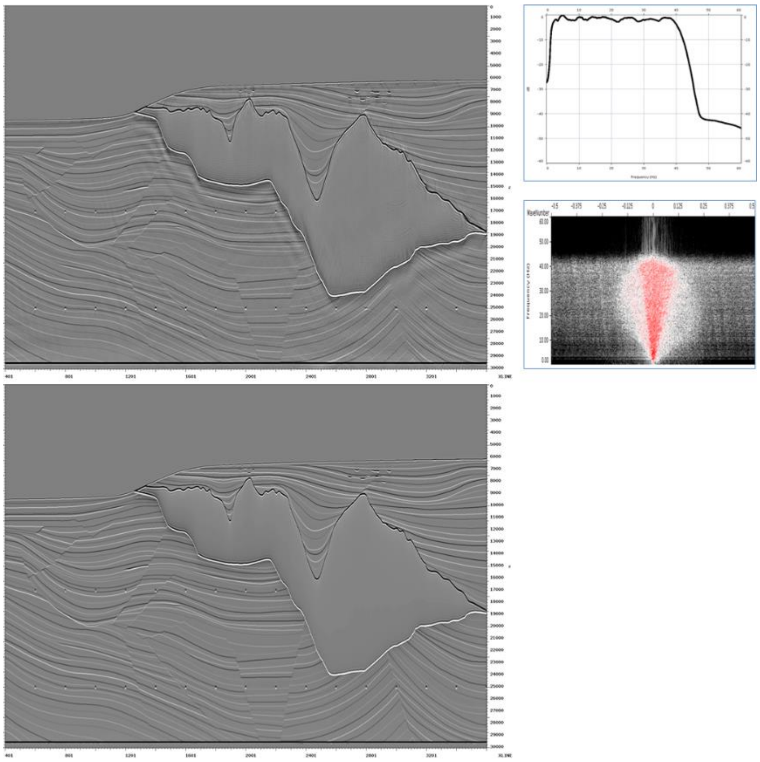
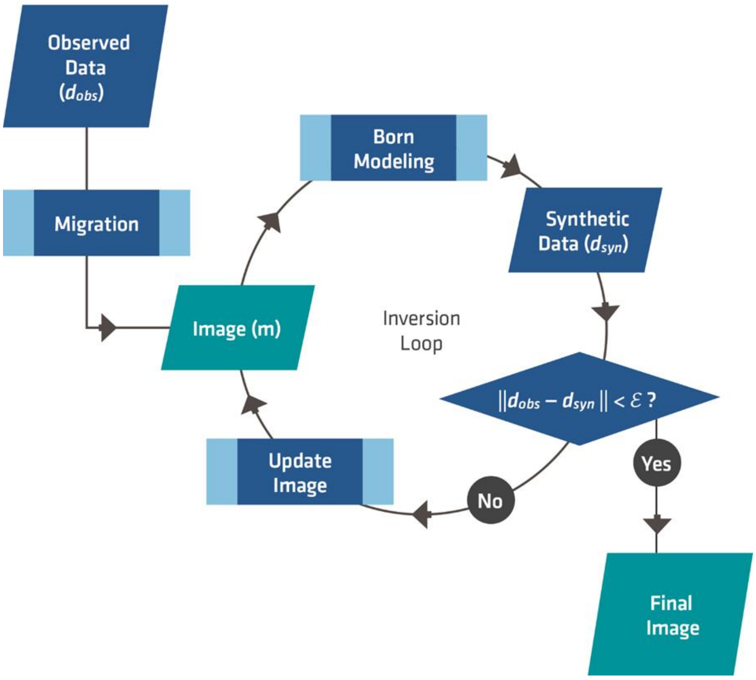


Figure 5. (upper) Least-Squares SWIM image using an iterative (global) inversion scheme to update the reflectivity and spatial resolution, the associated temporal frequency spectrum, and the associated wavenumber frequency spectrum; and (lower) The reference reflectivity model. Compare to Figure 4.

Figure 6. Schematic workflow for global (iterative) Least-Squares migration.



Recent applications of SWIM and LS-FWM have also produced data suitable for geohazard assessment on conventionally-acquired OBS (and deep tow multi-sensor streamer) data, mitigating the additional expenditure associated with performing this kind of analysis using site survey acquisition and processing. There is no theoretical limit on how many orders of surface multiples can contribute to SWIM, and it can be demonstrated that the density of seafloor receivers deployed can be decimated quite substantially without unacceptably compromising the image quality and resolution of OBC/OBN SWIM images, thereby promising efficiency and cost gains during acquisition (Lecerf et al., 2017).

Figures 7 and 8 show the resolution improvement obtained when full wavefield migration (FWM) is applied to a shallow water OBC dataset containing 428 receivers from the North Sea. The down-going pressure wavefield produced by P-Z subtraction was used for imaging. The depth slices in Figure 7 show how resolution is improved using a deconvolution imaging condition (Figure 7B) and Least-Squares inversion (Figure 7C) compared to the use of a cross-correlation imaging condition (Figure 7A). The deconvolution imaging condition improves the vertical resolution, while the Least-Squares inversion balances the illumination and enhances the resolution both vertically and laterally. In addition, the effects of the Least-Squares migration on crosstalk attenuation are clearly demonstrated in the vertical sections of Figure 8. The migration result using a cross correlation imaging condition is affected by strong crosstalk noise (Figure 8A). The deconvolution imaging condition is capable of attenuating most of the artifacts in the image while leaving some coherent residual events (indicated by red arrows in Figure 8B). The Least-Squares inversion eliminates the interference noise and produces an image with enhanced resolution (Figure 8C).

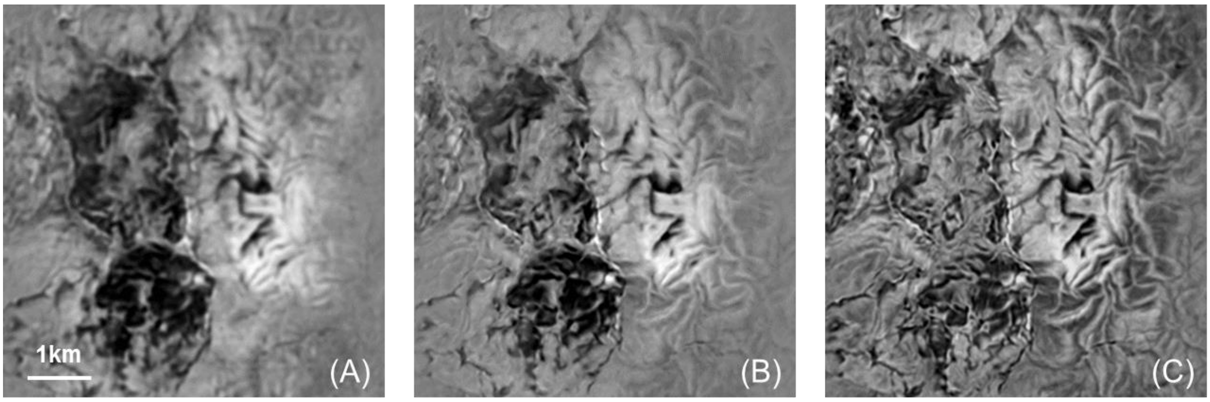


Figure 7. FWM depth slices at 1300m depth from shallow water OBC data: (A) FWM image with a cross-correlation imaging condition; (B) FWM image with a deconvolution imaging condition; and (C) LSFWM image.

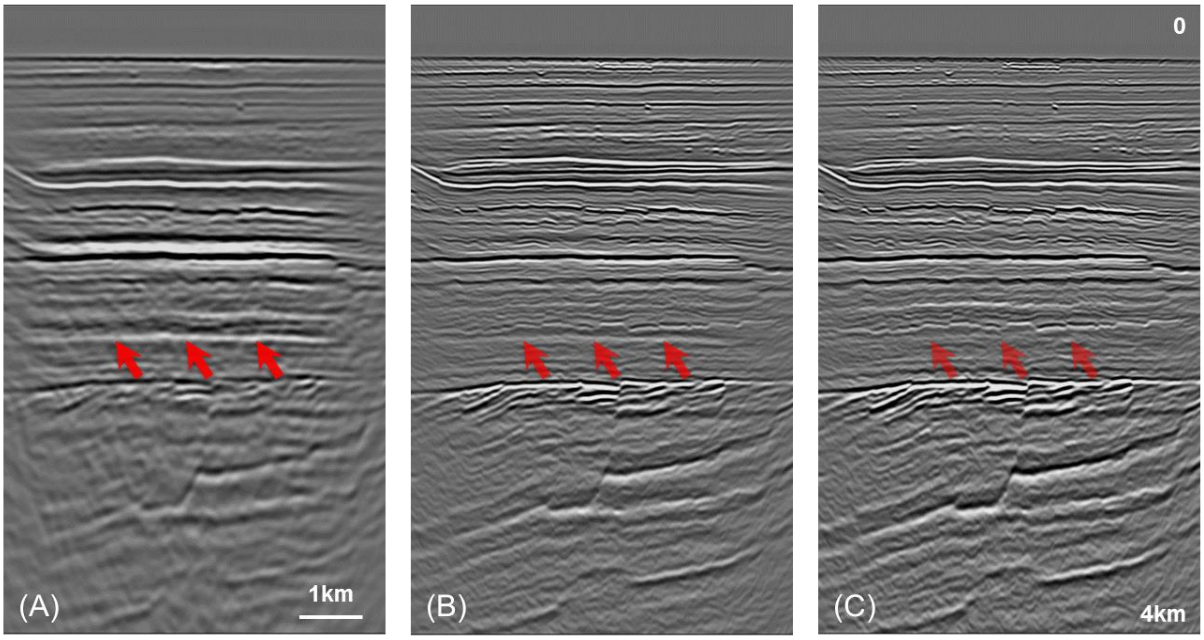


Figure 8. Inline FWM images from shallow water OBC data: (A) FWM image with a cross-correlation imaging condition; (B) FWM image with a deconvolution imaging condition; and (C) LSFWM image. Red arrows highlight crosstalk event locations (most obvious in A).

Summary

This article describes a progression in technology that reveals the high-resolution reflectivity hitherto obscured within conventional (primaries-only) migration of hydrophone-only marine seismic data that is contaminated by both source-side and receiver-side ghost effects. First, the use of multisensor towed streamer or multisensor seafloor seismic acquisition enables wavefield separation. All multisensor 'broadband' processing flows today successfully remove all source-side and receiver-side ghost effects, yielding (P-UP) seismic images that are richer in low and high frequency content, that better represent the geological texture, and have higher temporal resolution due to cleaner zero phase wavelets with negligible side lobe amplitudes (Long, 2017). On the assumption that multiple removal efforts are successful, the final migrated images represented the 'best in class' seismic deliverable only a few years ago.

Then, the development of separated wavefield imaging (SWIM) exploited the availability of the (P-UP and P-DWN) separated wavefields to effectively use every receiver as a virtual source for towed streamer data (or use every source location as a virtual receiver for seafloor data); thereby providing a complementary seismic deliverable that substantially improves shallow seismic image quality and resolution. The final ambition was obviously to simultaneously image the complementary illumination provided by both primary reflections and all orders of multiples, but contamination by crosstalk noise was problematic for the interpretability of deeper seismic events.

Finally, Least-Squares full wavefield migration extends the high resolution imaging benefits of SWIM to all depths—complemented by uniform illumination, the removal of the imprint of any acquisition geometry, improved high wavenumber content (i.e. higher spatial resolution), sharper event focusing around faults, suppression of crosstalk artifacts, and generally cleaner seismic images.

A perspective can be taken that the high-resolution reflectivity observable in Figures 5, 7 and 8 is based upon signal that was already present in hydrophone-only seismic data (P-TOT), but was collectively masked by source-side and receiver-side ghost effects, was unable to exploit the illumination associated with multiples ('noise'), corrupted by the imprint of the acquisition geometry, and imperfectly imaged. It is demonstrated that being able to exploit the complementary illumination of primary reflections and multiples, as enabled by the availability of the P-UP and P-DWN wavefields, and then implemented within a Least-Squares migration framework, finally reveals the true potential of modern multisensor seismic data.

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