A bigger picture view of separated wavefields and marine broadband seismic

Andrew Long[1]* considers present and future opportunities using separated wavefield data to illuminate, resolve, characterize and monitor reservoir properties and production in various marine settings.

Introduction

The advent of dual-sensor 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). 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 focused on the benefits of low frequencies in broadband seismic data (ten Kroode et al., 2013), and indeed where ultra-low frequency phase integrity is preserved as a complement to accurate amplitude-versus-angle fidelity, deghosted data also enables more accurate pre-stack quantitative interpretation (Reiser et al., 2015a, 2015b). However, it has also become clear that some long-standing imperfections in the seismic method remain. The rapid decay in air gun output below about 7 Hz (Parkes and Hegna, 2011) is not satisfactorily addressed by deghosting, compensation for high-frequency attenuation remains a fundamental challenge, and traditional challenges to wavelet processing, denoise, multiple removal, velocity estimation and imaging may in fact be more complicated for some broadband methods, or unaffected for others. The key benefit of dual-sensor methods are accurate access to the various separated wavefields, in addition to enhanced recoverable frequency bandwidth. Reservoir monitoring is enhanced by the elimination of the down-going pressure wavefield from 4D differencing, reservoir illumination can be enhanced by the incorporation of the down-going pressure wavefield into wave theoretic imaging, reflectivity inversion can be enhanced by isolating the up-going pressure wavefield in imaging, and overall we expect to see ‘complete wavefield’ reservoir imaging and characterization solutions mature rapidly. Furthermore, increased focus on spatial frequency content courtesy of ‘wave equation inversion’ imaging solutions is also taking broadband seismic past the historical focus upon only temporal frequency content.

Isolating the seismic wavefields

Historical acquisition with hydrophone-only streamers necessitated something of a juggling act with streamer depths customized to the target depths and anticipated signal-to-noise content (Long and Buchan, 2004; Soubaras and Dowle, 2010), but this was overcome when dual-sensor streamer acquisition provided a platform that removes the receiver ghost effects in a manner that is independent of local receiver depth variations (Carlson et al., 2007; Day et al., 2013). Operationally, the availability of dual-sensor streamers means that the streamer depths can be configured with any depth profile that minimizes drag and weather impacts while maximizing efficiency, and does not create any challenges for data processing (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

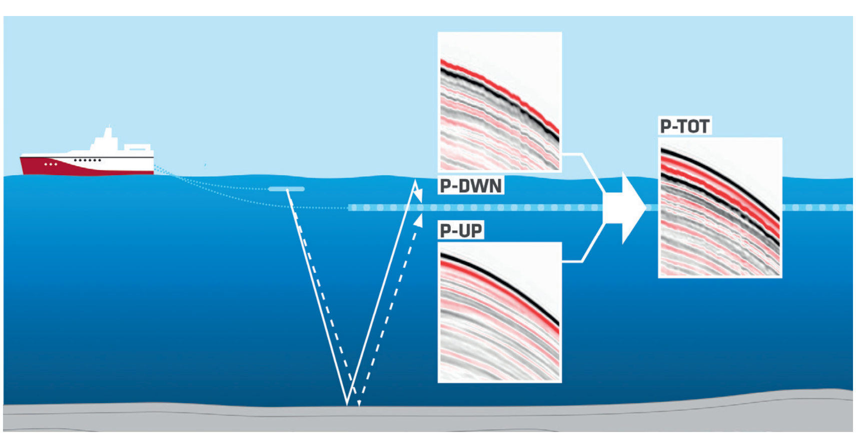

Figure 1 Schematic illustration of the up-going (‘P-UP’) and down-going (‘P-DWN’) pressure wavefields that combine to yield the total pressure (‘P-TOT’) data recorded by hydrophone-only streamers. Note the dynamic sea-surface effects inescapably embedded within all arrival times on P-DWN (and therefore, P-TOT) data.

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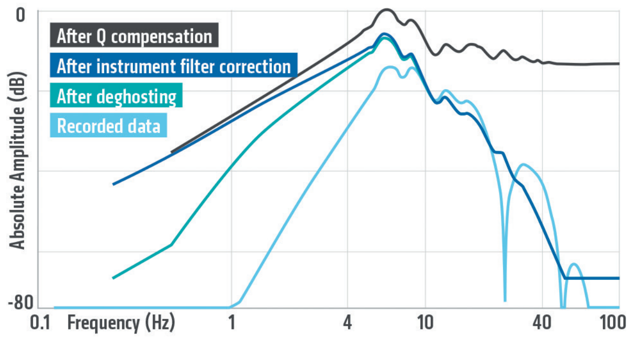

Figure 2 Superimposed amplitude spectra for a standard air gun array output at various stages of signal processing. The pale blue curve shows the recorded signal that is affected by both source and receiver ghost effects. The green curve shows the result after deghosting. The dark-blue curve shows the result after compensation for recording filter effects. The grey curve shows the result after compensation for attenuation effects: A significant benefit at higher frequencies.

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, clean and high-resolution seismic images of the earth —without the unwanted contributions of P-DWN that contaminate all forms of hydrophone-only streamers.

Assumptions and shortcomings during spectral enhancement and recovery

Nevertheless, many signal processing-based 'broadband seismic' alternatives were subsequently developed after the launch of dual-sensor streamers, all using a flat sea-surface assumption, with each attempting to remove the ghost effects while recovering a frequency spectrum that meets some preconceived idealized output. Most broadband seismic results also incorporate spectral recovery solutions that primarily claim to compensate for the inescapable effects of anelastic attenuation and dispersion during seismic wavefield propagation throughout the earth. Figure 2 models the frequency spectra that are recovered during various stages of broadband signal processing, assuming that full source and receiver deghosting works perfectly, as does attenuation compensation. Note the rapid amplitude decay below about 6 Hz for all stages of processing that is owing to the fundamental physics of air gun arrays (Parkes and Hegna, 2011), and how the 'reinforcing' effect of the ghosts at mid-frequencies is reduced by deghosting. No impulsive source solution exists that can output significantly stronger ultra-low frequency amplitudes than air guns. Dellinger et al. (2016) demonstrate how an alternative source concept using marine vibrator units needs to displace significant volumes of water every cycle at very low frequencies, and no commercial solution is available today. Overall, the full deghosting and spectral recovery sequence in Figure 2 improves both low and high frequency content, but the amplitudes below about 6 Hz decay rapidly, and the high-frequency amplitudes shown in this simple modelling make no consideration for the increased noise that inevitably affects seismic data.

Viscoelastic imaging has emerged in recent years as a powerful means to attenuate higher frequency noise during attenuation compensation within the migration kernel while simultaneously correcting for dispersion effects on pre-stack data (Valenciano et al., 2011; Klochikhina et al., 2016). The low frequency broadband seismic story is more controversial as different vendors claim different success with 'deghosting', often recovering uniform amplitudes down to about 2 Hz. A quick examination of Figure 2 suggests that substantial spectral shaping must accompany deghosting to achieve such an outcome.

Figure 3 shows a hydrophone-only vs. dual-sensor streamer comparison from the Browse Basin, Australia (Long et al., 2016). While the up-going pressure (P-UP) result demonstrates substantial improvements in low-frequency content, particularly at the deeper Triassic and Jurassic levels, the low frequencies have not been boosted in an artificial manner such that temporal resolution has been compromised. Furthermore, amplitude-versus-angle (AVA) compliant processing was subject to careful amplitude and phase quality control (QC) throughout the entire flow.

Time to direct attention to the pre-stack domain

Indeed, the fidelity of dual-sensor wavefield separation becomes most obvious in the pre-stack domain. An often overlooked pitfall with aggressive multi-channel signal processing such as that applied to hydrophone-only streamer data is that what looks good on migrated seismic stacks (highly coherent, low frequency events) may not translate to pre-stack data suitable for quantitatively accurate seismic inversion; particularly at frequencies below about 6 Hz. As seismic datasets are typically delivered for basic geological mapping and interpretation, the implications of aggressive low-frequency signal processing may not be discovered for a couple of years. Reiser et al. (2015a,b) demonstrate that dual-sensor deep-tow seismic data typically contains pre-stack information with stable amplitude and phase behaviour down to 3 Hz. Complete wavefield solutions that extend this information down to 0 Hz are discussed later. Accurate and reliable low-frequency information enables the use of AVA information for elastic and reservoir property estimation, including lithology-fluid distribution and porosity estimates with less need to use any available well information for building the required low frequency model. In this way, seismic inversion using the up-going pressure pre-stack data (P-UP) offers significant opportunity to reliably de-risk the interpretation of prospects and decrease uncertainties about the geological characteristics of assets. Furthermore, Du et al. (2017) demonstrate how efficient towed-streamer CSEM and dual-sensor seismic data can be integrated together with limited rock physical knowledge in a prospect area to estimate the total volume of hydrocarbon in place.

4D reservoir monitoring with higher repeatability

Another application where pre-stack up-going pressure data is demonstrably beneficial is 4D (time-lapse 3D). The collocated dual-sensors enable the separated up-going (P-UP) and down-going (P-DWN) wavefields to be independently redatumed and summed (re-ghosted) to emulate the total pressure wavefield (P-TOT) as recorded by conventional acquisition systems at any recording depth. One of the 4D repeatability requirements for traditional hydrophone-only marine streamer seismic is to be able to repeat the acquisition configuration as much as possible. In particular, the streamer tow depth of a monitor survey is required to be the same as in the corresponding base survey. For dual-sensor or multi-component streamers, however, this tow depth requirement can be relaxed as the dual-sensor reconstruction process treats the amplitude and phase of the seismic signal correctly. Thus, dual-sensor or multi-component streamers may be towed at any depth also in a 4D context (Widmaier et al., 2015). The tow depth may be deeper than what has been used for conventional 4D acquisition surveys, takes advantage of the quieter recording environment, and increases the bandwidth of the data. This fundamental benefit as well as 4D backward compatibility were validated in an early field trial in 2009 (Day et al., 2010). Barros et al. (2014) demonstrate that the receiver ghost is not 4D friendly, and the availability of P-UP data for both the baseline and monitor surveys preserves the most repeatable part of the reservoir signal by eliminating sea-state effects. Figure 4 shows a conceptual modelling example where 4D difference results are derived by subtracting baseline survey data from monitor survey data. In both scenarios shown, the monitor survey had 'flat' sea conditions (or alternatively, P-UP data was available for both surveys), but the baseline survey data was either flat or 'rough' (the scenario when P-DWN is present in one or both datasets). This simple example illustrates that sea-surface height variations are dynamic, non-repeatable, and contribute unwanted uncertainty during 4D differencing. Both the baseline and monitor surveys preferably have P-UP available and no contribution from P-DWN.

Note that the explicit measurement of the vertical component of particle velocity and pressure satisfy all theoretical requirements to pursue 3D wavefield separation in scenarios of low dip, but the traditional receiver sampling in the cross-line direction (the streamer separation) is far coarser than the inline receiver sampling along each streamer, so errors in how the vertical wavenumbers

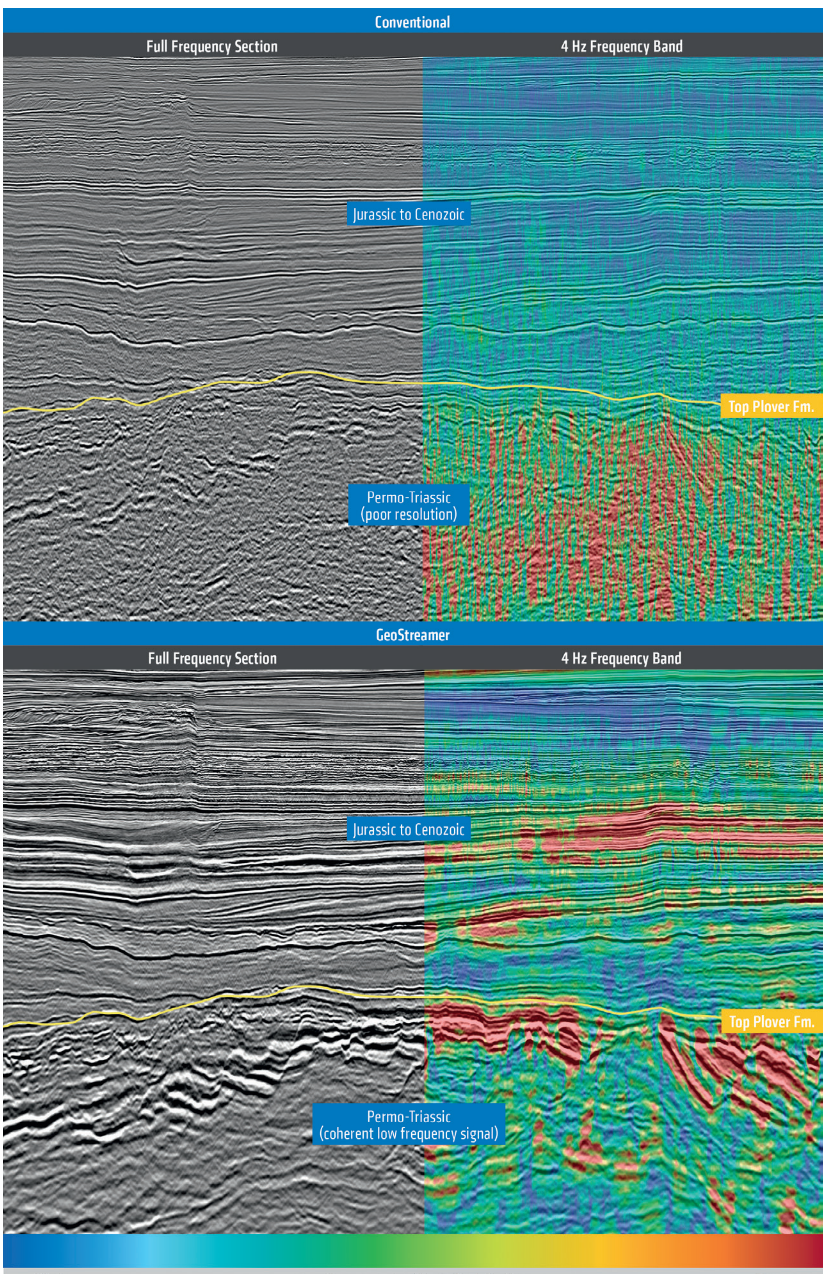

Figure 3 Comparison of legacy (upper) versus dual-sensor broadband (lower) PSTM stacks. The transparent colour rendering on the right of each image shows the dominant frequency at each sample. Note the enhanced signal-to-noise ratio of the low-frequency dual-sensor data.

are estimated can occur for very steep and very shallow dips. Nevertheless, Day et al. (2013) provide a rigorous analysis of the sensitivity of 3D wavefield separation to errors/uncertainties in various acquisition parameters, and illustrate that the methodology of Carlson et al. (2007) is technically valid for all 3D wavefield phenomena at typical target depths and depths of interest for seismic investigations. The addition of cross-line sensors to dual-sensor seismic streamers can be motivated by geophysical or operational considerations. Caprioli et al. (2012) argue that the availability of cross-line sensor information can be used for aggressive spatial interpolation between the streamers, thereby providing a platform for more accurate 3D wavefield separation (albeit with a flat sea assumption). In practice, the accuracy of interpolation rapidly decays away from the physical streamer locations, the methodology relies upon streamers being no more than 75-100 m apart, success is limited to the near-surface and will typically be band-limited — particularly when the shallow geology has large dips in the cross-line direction. Furthermore, additional complex noise modes measured by three-component streamers (Teigen et al., 2012) contribute to the fact that the attendant overheads when building such streamers are not trivial.

Combining the seismic wavefields

Separated wavefield imaging (SWIM) uses both the up-going (P-UP) and down-going (P-DWN) pressure wavefields to treat each dual-sensor receiver as a virtual source, thereby significantly extending subsurface illumination and seismic image quality (Lu et al., 2014). As modern wide-tow hydrophone-only streamer configurations compromise shallow target angle/offset coverage to the detriment of shallow gather/stack fold and event continuity, such data are affected by the well-known cross-line acquisition footprint, and are unfit for shallow velocity model building or reservoir characterization — particularly in shallow water environments. Errors in shallow velocity estimation cascade to uncertainties in image reconstruction and depth positioning at larger depths, thereby increasing drilling risk and uncertainty. In contrast, SWIM mitigates the acquisition footprint (Long et al., 2013), facilitates very accurate shallow velocity model building and imaging (Rønholt et al., 2014), and has been extended to seafloor seismic applications (Lu et al., 2015). Most recently, Lecerf et al. (2017) used a permanent monitoring case study to demonstrate the potential of 'high order multiple imaging' to enable very sparse seabed acquisition; this could have significant economic impact upon future OBC or OBN deployment as a larger area can be covered with a smaller number of sensors.

Assisted by improvements in the imaging condition (Ramos-Martinez et al., 2016) used in full waveform inversion (FWI), Feuilleaubois et al. (2017) present a novel quantitative interpretation workflow using SWIM and FWI to identify leads in the absence of direct well information. SWIM is shown to be as AVA-compliant as Kirchhoff pre-stack depth imaging, and improves the pre-stack amplitude analysis in the shallow water context discussed. The case study also demonstrates that SWIM can be

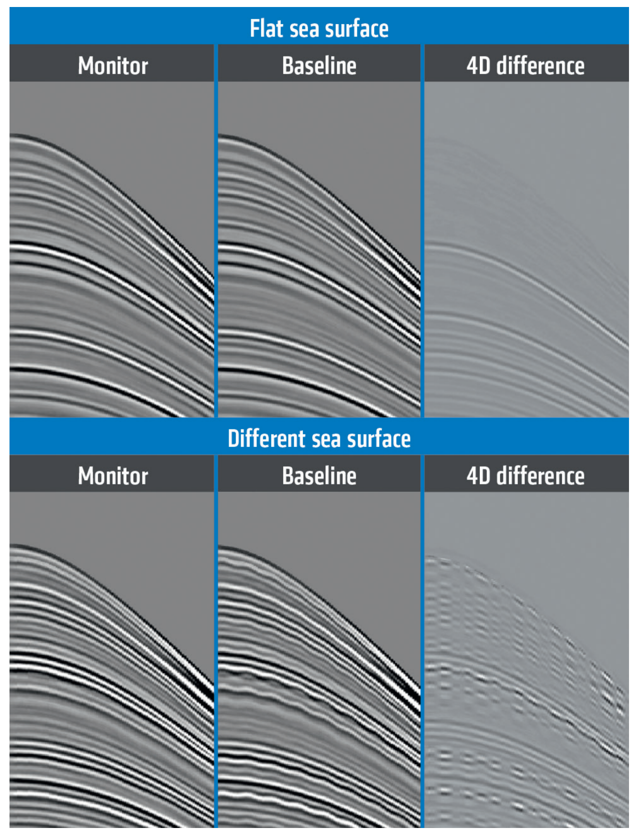

Figure 4 Modelling example for 4D differencing. (Upper) comparable flat sea conditions for hydrophone-only surveys, or P-UP data being available for both surveys, (Lower) different sea conditions for hydrophone-only surveys.

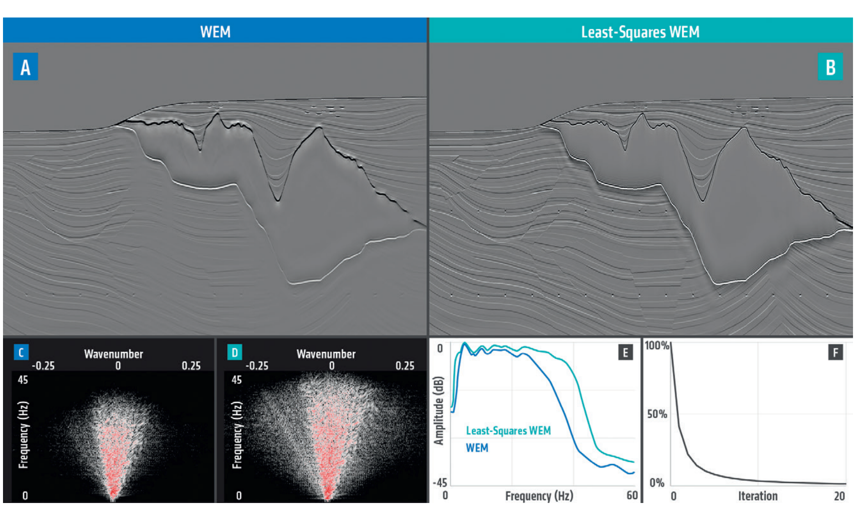

Figure 5 Sigsbee2b 2D ghost-free synthetic example: (A) WEM image; (B) LS-WEM image; (C) F-K spectrum of WEM; (D) F-K spectrum of LS-WEM; (E) frequency spectra of WEM and LS-WEM; (F) LS-WEM objective function convergence rate. From Lu et al. (2017).

used for qualitative and quantitative interpretation in areas where the reservoir is only a few hundred metres below the seabed. Lu et al. (2016) describe means to attenuate the crosstalk noise that historically affected deeper SWIM images, and the methodology is being used for increasingly deeper target imaging and characterization.

More spatial frequencies

Imaging of steeper dips and greater geological complexity implies the recovery of a larger range of spatial frequencies in addition to a larger range of temporal frequencies. When coupled to appropriate acquisition geometries, wave theoretic imaging solutions such as SWIM are part of a family of emerging imaging solutions that recover enhanced temporal and spatial frequency bandwidth from seismic data. The dispersion term in the viscoelastic imaging solution of Valenciano et al. (2011) includes both real and imaginary terms. While the real part controls the kinematics of the image, the imaginary part recovers the high vertical wavenumbers in the seismic image; therefore improving temporal resolution and amplitude balance. Valenciano et al. (2015) discuss a new and efficient wave equation solution for broadband imaging that poses depth migration as a wave equation reflectivity inversion; enhancing the resolution and balancing the wavenumber content of the depth migrated images. Klochikhina et al. (2016) applies the methodology of Valenciano et al. (2015) to full-azimuth (FAZ) dual-sensor streamer data from the Gulf of Mexico, successfully reducing the effects of irregular subsurface illumination that arise from complex propagation of the seismic wavefields through salt bodies, combined with incomplete acquisition geometry. Note this wave equation reflectivity inversion (WEI) solution requires explicit computation of the point-spread functions (PSFs) as part of the linear inversion workflow. Alternatively, Lu et al. (2017) introduce an efficient iterative (implicit) least-squares wave-equation migration (LS-WEM) solution for broadband imaging. The least-squares migration is implemented using a one-way wave-equation wavefield propagator, which is able to fully utilize both the broader seismic bandwidth and the high-resolution velocity information from FWI. Application to datasets from the North Sea and the Gulf of Mexico demonstrate the ability of LS-WEM to generate high-resolution images with better balanced amplitudes, broader frequency bandwidth and larger wavenumber content. Figure 5 demonstrates the improved illumination, enhanced imaging of steep geological contacts and faults, reduced shadow zones, and uniform amplitudes achievable using LS-WEM.

Conclusions

Most attention in marine broadband seismic has focused on deghosting and the recovery of relatively equal amplitudes over a large range of temporal frequencies, challenged by the inescapable effects of high-frequency attenuation and the rapid decay of air gun output below about 7 Hz. Separation of the up-going and down-going pressure wavefields using dual-sensor towed streamer or seafloor systems creates many opportunities beyond post-stack spectral enhancement, illustrating where the next steps in our 'broadband' journey are: 1. Resolving, characterizing and monitoring the reservoir with correct amplitude and phase fidelity using data after the down-going pressure wavefield has been eliminated, 2. Better illuminating the reservoir with both the up-going and down-going pressure wavefields, creating new and more efficient ways to resolve, characterize and monitor the reservoir, and 3. The pursuit of subsurface information with a broader range of both temporal and spatial frequencies using wave theoretic imaging solutions that capitalize on the availability of complete wavefield data, enable the recovery of remarkably accurate velocity models, and compensate for irregularities in subsurface illumination and imperfect acquisition geometry.

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