2(3)D convolution modelling of complex geological targets beyond – 1D convolution

Isabelle Lecomte¹,³*, Paul Lubrano Lavadera¹, Charlotte Botter², Ingrid Anell¹, Simon J. Buckley⁴,⁵, Christian Haug Eide⁵, Antonio Grippa⁶, Valentina Mascolo⁷ and Sigurd Kjoberg³ claim that 1D convolution is too simplistic and discuss ray based methods, which allow for easier, faster and more flexible modelling for geologists and interpreters.

Seismic modelling is necessary to understand elastic-wave propagation in the subsurface. Modelling is cost-effective and insightful, as long as adequate methods are used. An ideal seismic-modelling strategy is to generate complete synthetic seismograms for realistic earth models, then process them as performed with real seismic data. These complete seismograms are best obtained by full-wavefield (FW) approaches. FW methods are therefore used in extensive benchmarking studies, which may require the joint effort of several institutions owing to high resource costs. Though computer power continues to increase, we are still a long way from applying ideal modelling to all cases where synthetic data is necessary to constrain results. This is especially true in interpretation and sensitivity analysis, where the influence of multiple parameters must be assessed.

In many situations, ray-based (RB) methods are suitable alternatives, especially when rays, traveltimes, etc., are useful information for the problem at hand (Gjøystdal et al., 2007). However, standard RB methods do not allow modelling of detailed target structures owing to smoothness requirements. Geoscientists needing seismic modelling of such targets will then often resort to 1D convolution (Lecomte et al., 2015). 1D convolution has been successfully used for decades, and is still the method behind most standard well calibration, seismic inversion, etc. However, its conceptual validity is in reality very limited.

Still using a convolution approach, while making better use of RB information, it is possible to simulate 2(3)D seismic Prestack Depth Migration (PSDM) images at a cost similar to 1D convolution (Lecomte et al., 2003; Lecomte, 2006-2013). The method applies 2(3)D spatial convolution operators, called Point-Spread Functions (PSFs), i.e., point-scatterer responses, as generated from RB information (Lecomte, 2008). This accounts for realistic 2(3)D angle-dependent illumination and resolution effects as a function of parameters including, e.g., background velocity, survey and wavelet. This allows a better understanding of PSDM images as 2(3)D interferences between actual scattering structures and PSFs (Lecomte et al., 2015).

A similar concept was derived in parallel by Toxopeus et al. (2008), using FW-generated PSFs instead. PSFs are equivalent to what are called local Hessian operators, especially in FW-based migration approaches (Tang, 2009; Toxopeus and Thorbecke, 2010), and are thus key elements characterizing a migration operator. Tang (2009) and Letki et al. (2015) demonstrate the use of such information for improving seismic imaging. Both RB and FW approaches of PSF are equally valid in their applications to 2(3)D-convolution modelling. Bakke et al. (2011) make use of the FW-based approach for applications similar to those presented here. We focus on the RB method, which allow easier, faster and more flexible modelling for geologists and interpreters. RB approaches also give access to raypath information and other key parameters (e.g. amplitudes), which help with understanding resolution and illumination issues.

Modern digital outcrop mapping, with increasing detail, now allows for far more realistic geological models, leading to more insightful applications in e.g. seismic interpretation. After a review of the RB-modelling method, especially in comparison with 1D convolution, the versatility of such a 2(3)D convolution is illustrated by various geological models: numerical (folds, faults), lab (hydrothermal vent) and outcrop analogues (carbonates, faults, clinoforms, sand injectites, magmatic intrusions). 2(3)D convolution is as educational as 1D. It is efficient (RB approach), but allows for more realistic propagation/imaging effects affecting illumination and resolution. This gives flexibility and interactivity of changing various parameters, and thus leads
geologists and interpreters to a better understanding of seismic images, especially towards PSDM.

PSF-based convolution modelling

The RB 2(3)D convolution method (Lecomte et al., 2003; Lecomte, 2006-2013) was developed as a by-product of “ray + Born” seismic imaging (Lecomte et al., 2005). A key element of such RB modelling/imaging is the so-called illumination vector \( I_{SR} \) (Figure 1). For a given velocity model, the illumination at a reference point of where to calculate the PSF for a shot (S) and receiver (R), is described by \( I_{SR} = p_s - p_r \) (Figure 1b). The two slowness vectors \( p_s \) and \( p_r \) are inversely proportional to velocity \( V \) at that point (e.g., P-wave velocity). For the sake of simplicity, we assume the following isotropic propagation and no wave conversion at the reference point, thus constant velocity \( V \) at that point (e.g., P-wave velocity). From \( I_{SR} \), the next step towards RB-PSF is to generate so-called scattering wavenumbers \( K_{SR}(N) = N I_{SR} \), where \( N \) is the frequency, and map them into the wavenumber domain (i.e., Fourier transform of the space domain) to generate PSDM filters (Lecomte, 2008). Various weights can be attached to each \( K_{SR}(N) \), but the most important one is the frequency spectrum of a given wavelet. Figure 2a (left) shows such a frequency-dependent mapping of a symmetric dip-limited \( I_{SR} \) span (±45°) for a 20-Hz Ricker wavelet, a velocity of 3 km/s and 0° incident angle. The PSDM filter is Fourier-Transformed (FT-ed) to generate the corresponding PSF (Figure 2a-right; note the cross pattern due to filter truncation). Figure 2b (left and right) corresponds to a perfect-illumination case (±90° \( I_{SR} \) span). The resulting PSF (Figure 2b-right) is dot-wise, as the cross-pattern is removed, but the thickness of the dot is still controlled by frequency content, \( V \) and \( \theta_{SR} \). The dot size in Figure 2b-right is proportional to the wavelength \( \lambda \), i.e., a dot of size \( \sim \lambda /4 \), as expected when \( \theta_{SR} = 0° \). A larger \( \theta_{SR} \) will induce a larger dot in space because of the shorter \( I_{SR} \) (Figure 1b when the opening angle increases), hence there is a shorter cone. The longer and
wider the cone is when mapped in the wavenumber domain, the sharper the PSF is in the space domain (better resolution).

Though each $I_{\text{SR}}$ is indicative of the illumination of a specific reflector dip (Fig. 1c), the RB-PSF, which is obtained from a range of $I_{\text{SR}}$, shows in practice the point-scatterer (diffraction) response of PSDM. The RB-PSFs compare correctly with FW-modelled point-scatterer PSDM images (e.g., Lecomte et al., 2015, Figure 8) and similar PSF images are shown in Toxopeus et al. (2008), Tang (2009), Letki et al. (2015), thus indicating that both the centre shape and the cross-pattern (Figure 2a-right) are inherent to PSDM. We will see that seismic images result from interferences of diffractions, reflections being just a specific case of in-phase diffractions (Huygens’ 2nd principle).

The RB-PSF-based convolution modelling uses 2(3)D reflectivity grids as input and the modelling corresponds to convolution of reflectivity structures with PSFs to generate PSDM images. That convolution modelling can be applied in a single-PSF mode, i.e., only one PSF is applied to the selected image zone. The convolution process is then very efficient in the wavenumber domain (Lecomte, 2008). When the target zone corresponds to significant spatial variations of the PSFs, according to wave propagation effects and velocity model (e.g., for large zones, VSP cases, etc), multi-PSF convolution is required, which is then performed in the spatial domain. Multi-PSF convolution is more time-consuming than single-PSF convolution, though still very reasonable compared to the actual modelling alternatives.

For simplicity, we use 2(3)D’ convolution for the applied modelling method, to distinguish from ‘1D’ convolution. All examples were obtained with RB PSFs, in single-PSF mode and using either generic $I_{\text{SR}}$ spans (Figure 1e) – particularly relevant to the geophysicists’ model/survey-based ones if applicable. To further simplify, we only consider $\theta_{\text{SR}} = 0^\circ$, though incident angles also affect resolution in a similar manner to the velocity $V$ at the considered reference point (Lecomte et al., 2015).

**1D versus 2(3)D convolution**

The primary goal of this paper is to show that 1D convolution is too simplistic and does not reflect the current state-of-the-art in efficient seismic modelling. To facilitate the comparison, and as standard 1D convolution is strictly applied to the time-migrated domain, we implemented a spatial 1D-equivalent convolution using a ‘1D-PSF’ built from a 2(3)D PSF (Figure 3d), leading to 2(3)D-based seismic images (Figures 3e-f). Making use of generic $I_{\text{SR}}$ spans, Figure 3e corresponds to a symmetric illumination ($45^\circ$-max-dip), while Figure 3f shows the perfect illumination case ($90^\circ$-max-dip).

Figure 4a is a zoom of the reflectivity log of Figures 3a-b. It shows a gap in reflectivity for the considered position (between the dashed lines) and 1D convolution keeps this gap (Figure 4b; impedance model in Figure 4c). On the contrary, 2D convolution (Figure 4d-e as a zoom of Figure 3f) fills in the gap – as it should – due to lateral resolution effects contained in the PSF, even when the illumination is perfect as in Figure 3f. Seismic signals thus appear in the reflectivity gap of Figure 4a (Figure 4e). See also the apparent thinning of the near-vertical fold walls wrongly induced by 1D convolution (Figure 4b, green ellipse) in comparison to perfect illumination (Figure 4e, green ellipse). Seismic signals thus appear in the reflectivity gap of Figure 4a (Figure 4e). Such ‘lateral-smeared’ signals would be misleading in traditional 1D-based well-ties, seismic inversion, etc. See also the apparent thinning of the near-vertical fold walls wrongly induced by 1D convolution (Figure 4b, green ellipse) in comparison to perfect illumination (Figure 4e, green ellipse).

Figure 5a is another zoom of the fold model (Figure 3a), to allow easier comparisons between 1D convolution (Figure 5b), 2D convolution with perfect illumination (Figure 5c), and 2D convolution with limited illumination (Figure 5d). The thinning effect of 1D convolution is removed by 2D convolution (Figure 5b/c). Figure 5d shows an interpretation issue: the same fold (black arrows) is ‘split’ artificially due to both lateral-resolution effects and lack of illumination.

**Geological model examples**

To further illustrate illumination and resolution issues in seismic images, as well as the versatility of 2(3)D convolution modelling over 1D convolution, a selection of ongoing geological case studies are briefly presented.

**Hydrothermal vent complexes**

Large igneous provinces are characterized by the presence of voluminous basaltic complexes (e.g. extrusive lava sequences, intrusive sills and dykes, and hydrothermal vent complexes). Examples are found on, e.g., the More margin (mid-Norway; Planke et al., 2015). Emplacement of hydrothermal vent complexes is accommodated by deformation of the sedimentary host rock. The edges of igneous intrusions mobilize fluids by heat transfer into the host. Fluid expansion may lead to formation of piercing structures due to upward fluid migration. Hydrothermal vent complexes further induce bending of overlying strata, leading to the formation of dome structures at the paleo-surface. 3D seismic data from the Tulipan prospect (West More Basin) were first studied, to define the
morphological characteristics of upper parts and underlying conduit-zones of hydrothermal vent complexes, before comparing these with laboratory analogues.

Figure 6a is a photo of one of the analogue models: compressed air induced fluid pressure into a bedded material (layers of olivine-sand or aluminium-silicate). The photo was first converted into a grey-scale picture (Figure 6b), then transformed into an input reflectivity structure for convolution modelling. The zone is up-scaled to match the size of similar structures identified in the Tulipan prospect; corresponding elastic properties are used. Figures 6c-f show 1D convolution, and 2D convolution with perfect illumination, up to 25° and up to 45° max-dip illumination, the PSFs being superimposed. This example illustrates both lateral resolution effects and illumination issues not possible to model with 1D convolution.

Fault-zone modelling
Faults are often simplified in reservoir models and interpreted similarly from seismic data. They are, however, 3D zones with rock properties that differ from the host-rock. Seismic modelling may improve characterization and interpretation of reservoir fault zones if diffracting structures are properly included (Botter et al., 2014a, b). Figure 7 illustrates a complete workflow to model large-scale normal-faults in a siliciclastic sequence. The fault model is first simulated using a Discrete Element Method (DEM), and initial elastic properties (shales/sandstones) are modified based on volumetric strain after faulting. Using the 0°-reflectivity grid, a given overburden and a standard 3D survey, 3D convolution modelling gave a seismic cube. While the seismic signatures of the fault can be discerned on both crosslines and depth views, with complex interactions between footwall and hanging wall reflectors and associated diffractions, the use of an attribute-based seismic interpretation workflow helps to better define the fault volume (Botter et al., 2014b). Combining three attributes (dip, semblance and tensor), a geobody corresponding to the inner part of the fault zone is extracted. This geobody is directly sensitive to the larger changes of elastic properties induced by faulting and to the shale-to-sandstone contacts.

Outcropping carbonate system
The Maiella mountain is a major carbonate outcrop of the central Apennines, Italy (Figure 8a). The depositional setting and geometries of platform-to-basin systems provide models for hydrocarbon exploration in carbonate systems. Seismic modelling was first carried out with standard RB modelling on models derived from outcrop data and petrophysical parameters (Mascolo et al., 2015). To further analyse illumination and resolution effects on detailed structures, 2(3)D convolution modelling is used (Mascolo et al.,
ences in 2D convolution images are significant due to the degraded lateral resolution for low frequencies. Frequency content does not only affect vertical resolution, indeed.

**Digital outcrop mapping**

The current state of the art in digital outcrop mapping provides quantitative and qualitative data for research and education. Laser scanning (lidar) is now widely used as a source of detailed 3D topography for outcrop analogue interpretation, analysis and cross-disciplinary communication (Buckley et al., 2013). Photogrammetry also developed as a low-cost and powerful method to capture field data. Both methods give a basis for anchoring different field data types, for e.g. structural mapping and reservoir modelling. The result is a 3D photorealistic model that portrays the outcrop form with high resolution and detail, which facilitates interpretation. For synthetic seismic, models spatially linked to the digital outcrop model can be created, allowing maintaining geometry and spatial relationships. This can be performed in 3D, using the digitized geometry, or in 2D, where ortho-rectified interpretation panels are used to condition property zones. In both cases, the resulting seismic model is returned with the original spatial coordinates, making it possible to view the result together with the input photorealistic model. For the 2D case, the synthetic image is draped over the outcrop model, allowing geologists to visualize how an outcrop section may be represented in real seismic data; this will be illustrated in the following.

**Triassic development on the NW Barents Shelf**

A photogrammetric model was captured for Kvalpynten, Edgeøya (Figure 9a-b), providing high-resolution
meantime, deriving input models from images generated by interpreters provides a simple workflow accommodating complex and detailed cases, as will now be illustrated.

**Architecture of a sand-injection complex**

Reservoirs characterized by sandstone intrusions are widely detected (Hurst et al., 2011). Although this reservoir type potentially hosts significant oil and gas reserves, very few sandstone intrusions have been deliberately drilled. The main challenge is caused by the geometric complexity of such reservoirs, as well as the abundance of sub-seismic facies making the reservoir difficult to describe (connectivity and petrophysics). If not taken into account, all these characteristics increase uncertainty during drilling and hydrocarbon production. To help minimize such risks, data collected from exposed areas of sandstone intrusions were used to obtain a 2D cross-section
Volcanic intrusions in brittle reservoir rocks

Volcanic intrusions are common in rifted basins and margins and can have dramatic effects on hydrocarbon systems (Holford et al., 2013). They can act as seals, traps, may compartmentalize reservoirs and migration pathways, provide heat to increase maturation of source rocks, or act as migration pathways and even reservoirs when fractured. Understanding their architecture can therefore be critical from a hydrocarbon perspective. Deeply emplaced intrusions are challenging as they are generally poorly imaged in seismic data. To investigate which features in sill architectures are lost in seismic images, we used data from an outcrop in Jameson Land, east Greenland, based on field work and helicopter-lidar (Figure 11a). The intrusives are emplaced in Lower Jurassic sedimentary rocks (Eide et al., 2016), equivalent to the prolific Båt group on the Norwegian Continental Shelf. The geometry of intrusions is influenced by host rock lithology, and sills are fed by and change into oblique dykes over short intervals, interacting with contemporaneous vertical dykes to compartmentalize the rock volume.
Figure 11b shows a small area (green frame) selected to highlight illumination issues. The intrusions are characterized by very strong reflectivity compared to the host rocks. Beside rather steep dykes in the lower half, a near-vertical one (VD) is particularly difficult to represent on a gridded reflectivity structure despite rather small samplings. In particular, one point gets isolated, just above a weak reflector, and will act as a diffraction marker in the following modelling. Figures 11c-g correspond to a fixed frequency content while the illumination pattern is varying. Figure 11c is the 1D convolution image, automatically showing all structures as present in the reflectivity grid; hence also the point scatterer visible as a vertical depth wavelet \( w(z) \) of Figures 3-4. The 2D convolution images obtained when varying the illumination (Figures 11d-g) are instead showing significant differences in terms of illuminated structures and resolution. The upper point scatterer is also progressively revealed, turning from a weak elongated structure (10°-max-dip), seemingly part of the nearby horizontal reflector, into a stronger dot-wise pattern (perfect illumination). The variable lateral resolution is here entirely due to variable illumination patterns (e.g. survey aperture effects), this in opposition to Figure 8d, f where only the frequency content was varied.

**Conclusion**

1D convolution should be disregarded in favour of existing 2(3)D convolution approaches (RB and FW), not only for modelling with applications to interpretation issues, well ties and similar, but also for seismic inversion which relies much on the 1D model. 2(3)D convolution approaches open up for PSDM-image modelling and can account for realistic overburden effects and detailed target structures such as those provided by digital outcrop mapping. Understanding seismic images as resulting from 2(3)D spatial convolution of a scattering model with 2(3)D PSFs – the new convolution operator which still contains the time wavelet but much more than just that – should help interpreters and other seismic users to better grasp what seismic images are. Convolution with RB-generated PSFs is particularly efficient and versatile in use, allowing near-interactive analysis of various parameters, which facilitates that learning.

**Acknowledgements**

We would like to thank the Research Council of Norway for its annual basic research funding at Norsar; for grants #234152 (TriasNorth; co-sponsored by DEA, Edison, Lundin, Statoil, and Tullow) and #244155 (MIMES) at University of Oslo; for grant #210425 (PhD candidate C. Botter), and grant #193059 (Greenland dataset, co-sponsored by the FORCE SAFARI project). The two first authors would like to thank NORSAR colleagues in the seismic modelling department. I. Lecomte would like to thank D. Schmid for the fold model. Uni Research is thanked for a base-funding grant and K. Ringdal for workflows in LIME software. A. Grippa would like to thank the Sand Injectites Phase 3 (universities of Aberdeen and Manchester); G. Palladino (field data); Dr. D. Iacopini and Prof A. Hurst for discussions.

**References**


Lecomte, I. [2006-2013]. Method simulating local prestack depth migrated seismic images. Patents, Norway (2006, #322089), USA (2008, #7,376,539), Canada (2013, #2,521,919) and EU (2013, #1611461; validated in France, Germany, the Netherlands and UK).


