

Optimal migration aperture for compact ultra-dense land surveys: Insights from field data

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SUMMARY

The migration aperture for compact ultra-dense land seismic surveys is evaluated, given field data sampled with a 7.5 m by 7.5 m receiver carpet and a 30 m by 7.5 m source grid. The acquired seismic data are processed and imaged for a shallow target at 500 m depth, considering different aperture widths. Classical formulas based on constant velocity predict an aperture of about 300 m. The impulse response and wavefield inspection suggest a smaller value of roughly 200 m. However, the isopach thickness analysis and the average 2D wavenumber spectra indicate that an aperture of about 100 m provides the most consistent and stable post-stack time-migrated image of the target without compromising amplitudes. These results demonstrate that theoretical aperture assessment can significantly overestimate requirements for ultra-dense compact surveys. The presented analysis provides practical guidance for designing small-area reservoir characterization and monitoring surveys.

INTRODUCTION

The migration aperture, in the context of seismic survey design, refers to the extent of the seismic survey area required to image the target subsurface. Small extents might yield survey coverage insufficient to focus post-migration seismic amplitudes and achieve good illumination of the geological target. Large extents of the survey layout might result in shooting and receiver areas that render the project financially and operationally unfeasible. The definition of the optimal migration aperture is a pertinent issue for compact but dense seismic layouts aimed at local reservoir characterization and subsurface monitoring with 3D seismic data.

When a detailed velocity model is available, the migration aperture can be determined by modeling the elastic wavefield and testing different migration algorithms on synthetic data. For example, in a recent case study by Borba et al. (2025), the migration aperture for the Tupi field was estimated using ray-tracing and full-wave equation modeling, followed by reverse-time migration. Although concrete aperture width values can be obtained using a modeling-based approach, the approach is computationally expensive and requires a detailed velocity model. Vidal et al. (2026) used previously acquired data to avoid the need for seismic modeling and to enhance confidence in the design of receiver and shooting areas.

Designing a survey for new areas with limited geophysical and geological data requires the use of alternative tools. The calculation of the Fresnel volume is a classical method for estimating the required aperture width, which leverages our understanding of the physics of seismic wave propagation (Sheriff, 1985; Lindsey, 1989; Sheriff, 1996).

Theoretical results, such as those by Sun (1998), can be used to apply the concept of the Fresnel volume and define the minimum migration aperture width required for Kirchhoff migration, but imaging field data may require additional considerations. Yilmaz (2001) suggests using an aperture width smaller than the theoretically estimated one to avoid the adverse effects of noise. The impulse response function can also be inspected to select the aperture width (Klokov and Fomel, 2013). To summarize, since migration algorithms only approximate the inverse process of a seismic experiment (Biondi, 2006), a numerical assessment of the aperture width is needed.

We present a practical approach for selecting a migration aperture for ultra-dense, compact land seismic data (Figure 1). The thickness of the target formation is used to quantify the effect of the aperture width on the post-stack time-migrated image. The proposed workflow, supported by insights from field data, is of interest for the design and acquisition of seismic surveys with limited area coverage.

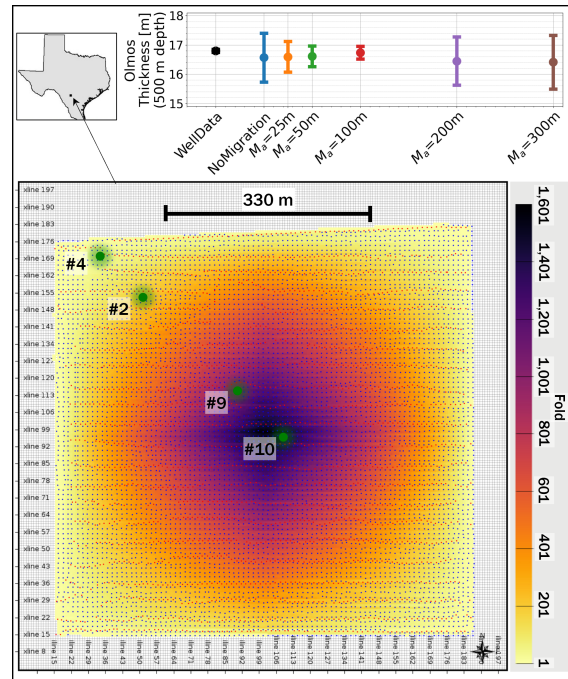


Figure 1: Overview of the study area showing the layout of the 3D seismic survey in Medina County, Texas. Red and blue points correspond to sources and receivers, respectively. The fold values range from 1 (yellow) to 1,601 (indigo). The well locations are in green and labeled with the well numbers. The upper plot shows that, for the migration aperture M_a of 100 m, the imaged thickness of the target formation, Olmos, is closest to that calculated using the geological markers (formation tops from well logs).

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MIGRATION APERTURE: THEORY AND METHODS

As introduced by Denham and Sheriff (1981) and analyzed by Ebrom et al. (1995) using a physical model experiment, the relationship between the horizontal Δ_H and vertical Δ_V resolutions for the *migrated* seismic section is described as

$$\Delta_H = \Delta_V / \sin \alpha = \lambda_{min} / (4 \sin \alpha), \quad (1)$$

where λ_{min} is the minimum unaliased wavelength and α is the migration aperture defined as the maximum ray angle that contributes to migration. In seismic interpretation, it is considered that, for high-quality 3D-migrated seismic data, the horizontal and vertical resolutions are equal (Hardage et al., 2011). For $\alpha = 90$, the above relationship can indeed be reduced to $\Delta_H = \Delta_V$, since $\sin(90) = 1$. However, in practice, $\alpha = 90$ can be difficult to attain.

For a constant-velocity medium, the migration aperture α is defined as

$$\alpha = \arctan(A/d), \quad (2)$$

where d is the depth of the target and A is half the line length (Ebrom et al., 1995). The latter is often referred to as the migration aperture width. Considering an accepted limit on the diffraction hyperbola extension α as 30 degrees (Chaouch and Mari, 2006), the additional distance that needs to be covered on one side of the survey area can be estimated as $A = d \tan(30)$. Considering $\alpha > 30$ would imply a substantial extension of a survey area since starting from 45 degrees, $\tan \alpha > 1$ and A becomes larger than d ($A > d$).

Another aspect of the migration aperture concerns migration displacements. When geologic layering is not flat, and the reflection points are no longer beneath the source-receiver mid-points, the survey area needs to be extended by $A_{dip} = d \tan \beta$, where β is the geologic dip (Evans, 1997). For flat reflectors with a small geologic dip $\beta \approx 0$, $\tan \beta \approx 0$, and $A_{dip} \approx 0$.

FIELD DATA EXAMPLE

We analyze 3D land seismic data, which is well-suited to the problem of migration aperture evaluation given its acquisition parameters and the characteristics of the target formation. We compare the aperture width calculated using classical formulas with that estimated from wavefield-based analysis. Then, we perform migration tests with different apertures and assess the image stability. We introduce the isopach thickness analysis as a geological metric for selecting the aperture width, which, unlike theoretical considerations, can explicitly quantify the impact of aperture on the data.

Target Formation and Survey Geometry

The study area is located at the Devine test site, Medina County, Texas (BEG, 2026). The target formation is the Upper Cretaceous sandstone unit deposited in the eastern half of the Maverick Basin (Tyler and Ambrose, 1985). In the study area, the Olmos sandstone is 17 m thick at 500 m depth and has a regional geological dip of less than 2 degrees in the NS direction. A recent analysis of core data from the Big Foot field, located near the study area, suggests that the Olmos deposits are open-marine sand (Ambrose, 2025).

The ultra-dense 3D seismic data were acquired in 2024 for the reservoir characterization of the Devine site (Bakulin et al., 2025). The 3D survey layout covers an area of about 650 m by 650 m, with a source grid of 30 m by 7.5 m and a receiver carpet of 7.5 m by 7.5 m (Figure 1). The parameters of the vertical vibroseis are as follows: a 24 s sweep length, a 5 s listening time, and a 2 to 110 Hz frequency range.

On seismic data, the direct observation of the target reflector is difficult due to the strong elastic energy. Given a 7.5 m spacing, the seismic wavefield is properly sampled for frequencies below 20 Hz and is strongly aliased for frequencies above 33 Hz. Despite that, the target reflector was identified in the brute stack computed without applying any noise-removal steps, thanks to the high trace density. The time-processing workflow followed a standard sequence: loading correlated gathers, linear and incoherent noise attenuation, surface consistent (SC) amplitude correction, SC static correction, SC deconvolution, and velocity analysis. The zero-offset VSP and sonic and density logs at well 9 were used to derive the seismic-to-well tie.

Wavefield Based Aperture Estimates

The imaging was carried out using a 1D velocity model derived using stacking velocities, values of which overall increase with depth. Figure 2 shows the impulse response with a 30-degree aperture, which represents a conventional production choice for large-scale seismic surveys. For the target horizon at about 500 m depth, the 30-degree impulse response is almost entirely bounded by the spatial extent of 200 m.

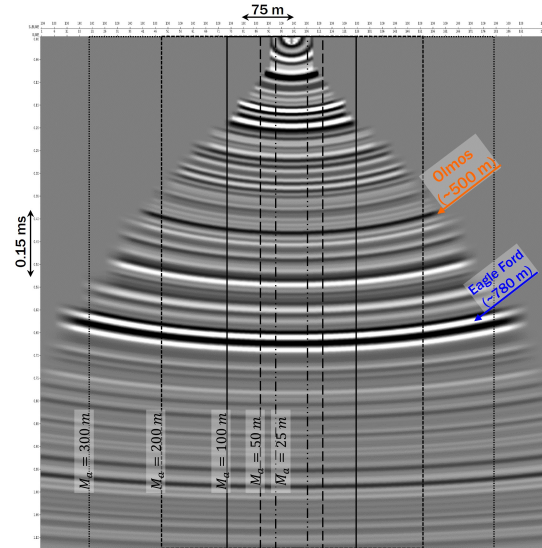


Figure 2: The impulse response with a 30-degree aperture calculated using a 1D velocity model and a seismic trace from the central area of the stack. M_a labels different horizontal extents computed as the distance from the center of the impulse function to its left (or right) side. For the target horizon at about 500 m, almost all energy of the 30-degree impulse response is encompassed by the spatial extent of 200 m. The aperture calculated as $500 \tan(30)$ yields a larger value of 300 m.

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Evaluating equation 2 for $\alpha = 30$ and $d = 500$ yields $A = 300$ m, which is larger than $M_a = 200$ m obtained from the analysis of the impulse function (Figure 2). The overestimated migration aperture arises due to the use of a constant-velocity approximation in Equation 2.

For the calculation of the impulse response function, the anti-aliasing filter with crossline and inline spacing parameters equal to 3.75 m was applied (Abma et al., 2008).

Wavenumber Spectrum of Time Slices

The use of small apertures ($M_a < 200$ m, given the target depth of 500 m) requires the truncation of the impulse response function. As a consequence, a taper function is needed to attenuate edge effects in the migrated image. The results of the post-stack time migration with different apertures and tapers were analyzed using the average 2D wavenumber spectrum of time slices. This spectrum was calculated by applying the Fourier transform to a time slice and stacking it with spectra computed for other time slices in the selected time window.

Figure 3 shows the average 2D wavenumber spectrum computed for the time slices in a 0.04 s window centered on the target, Olmos. For $M_a = 25$ m and 10% taper, the oscillations are observed, and the patterns at the corners can suggest the presence of a “wrap-around” energy. The use of a longer taper function with a 50% taper reduced the adverse effect of these oscillations. As the taper length and aperture width increase, the ring-like oscillations fade. This 2D wavenumber analysis led to the selection of a taper length of 50% for all subsequent migration tests with different aperture widths.

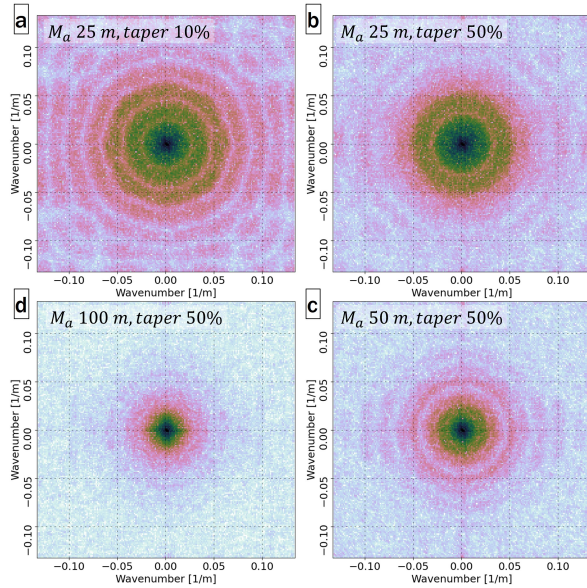


Figure 3: The average 2D wavenumber spectra of the target interval from post-stack time-migrated data with: (a) $M_a = 25$ m and 10% taper, (b) $M_a = 25$ m and 50% taper, (c) $M_a = 50$ m and 50% taper, and (d) $M_a = 100$ m and 50% taper. As the taper length increases, the ring-like pattern fades; the same applies to the increase in aperture width.

Image Quality Assessment

The inspection of the seismic sections suggests that images obtained with different aperture widths are consistent with one another, although some distinctions can be observed. Figure 4a shows unmigrated data, which were stacked into a 3D volume without applying the migration algorithm. The unmigrated stack contains localized events that can be difficult to interpret as geological features. Orange arrows point to some of them: crossings between the horizons and, possibly, uncollapsed diffractions. Figure 4b shows post-stack time-migrated data with an aperture width of 100 m and 50% taper length. At the same time, the local features are present. For instance, the green arrow points to lens-like features, which are also observed in a dashed blue rectangle.

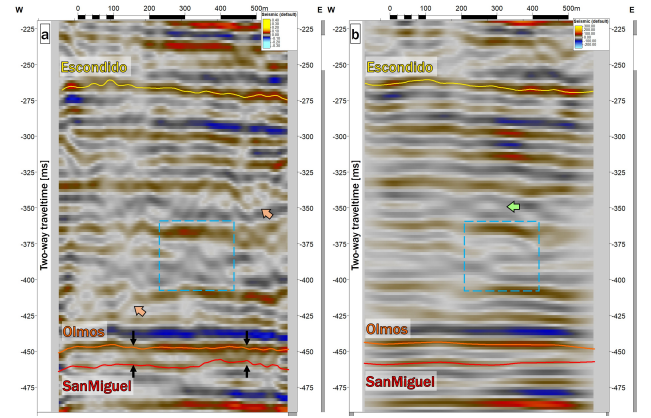


Figure 4: The interpreted seismic section from the (a) unmigrated and (b) migrated ($M_a = 100$ m) seismic data. The displayed amplitude range is different for panels (a) and (b). The seismic section corresponds to one of the central lines (xline 108, see Figure 1). The 3D migration improves the continuity of the events and reveals horizontally heterogeneous features.

The interpretation of seismic sections was carried out using a horizon auto-tracker tool. The interpreted horizons were labeled according to the formation tops as Escondido, Olmos, and San Miguel. The thick Escondido formation overlies Olmos, and the San Miguel forms the base of Olmos.

The time-structure maps of Olmos are shown in a 3D view in Figure 5. For an aperture width of 100 m, low-relief structures are identified in the central part of the survey and near the north-west corner. Analogous low-relief structures are present in other structure maps shown in Figure 5, as verified by applying a median filter to the maps. Different structural smoothing filters were tested, but the results were not further used because structural smoothing affects the amplitudes. In contrast, by migrating seismic data, it was possible to obtain a smooth structure map without compromising the data amplitudes.

In the study area, the geological dip of Olmos was estimated to be less than 1 degree by converting Olmos’s time-structure maps into depth. This estimate does not contradict the regional geological assessment.

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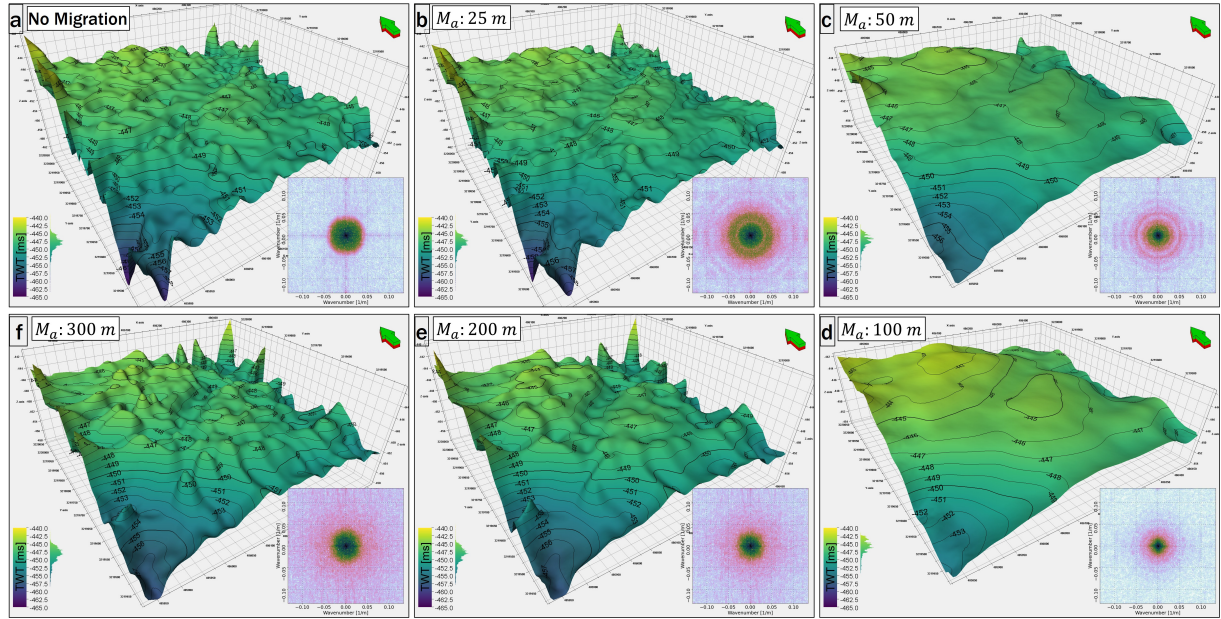


Figure 5: The time-structure maps of the top of Olmos interpreted using the unmigrated (a) and post-stack time-migrated data with the following aperture widths: (b) 25 m, (c) 50 m, (d) 100 m, (e) 200 m, (f) 300 m. This 3D view is shown with unequal vertical and horizontal scales. In the vertical direction, the structural variability spans about 10 – 15 ms. In horizontal directions, the maps cover the survey area of about 660 by 660 m. The averaged wavenumber spectrum computed from time slices in the 0.04 s window around the target is displayed in the bottom-right corner of each panel. $M_a = 100$ m in panel (d) was selected for pre-stack time- and depth-migration, which are not shown here, but were carried out to build a detailed reservoir model for the hydrogen storage.

Isopach Thickness Analysis

The thickness of Olmos is about 17 m, as estimated from four wells placed diagonally across the site (Figure 1). Given the open-marine depositional settings of the Olmos sandstone in the eastern half of the Maverick basin (Ambrose, 2025), the Olmos sandstone can be assumed to be laterally homogeneous with a uniform thickness distribution across the study area. Therefore, the target thickness can be considered as a metric for assessing migration results.

For each version of the post-stack time-migrated and unmigrated volumes, the isopach maps were computed as the difference between the two-way traveltime horizons of the Olmos and San Miguel. The isopach maps were further examined and cut to remove areas near the survey edges. After that, the mean and standard deviation of the cut isopach maps were calculated and further converted into depth by multiplying by $0.5V$, where the velocity V was set based on the sonic log. The results of this calculation are shown in the upper plot of Figure 1. As migration aperture M_a increases from 25 m to 100 m, the variability in the isopach maps, and thus imaged thickness of the target, decreases. For the large M_a values of 200 m and 300 m, the increased variability should be interpreted with caution, given the relatively small survey area compared to the aperture width.

CONCLUSIONS

Seismic migration is required to prepare 3D seismic data for seismic interpretation. The unmigrated stack already reveals

numerous small-scale heterogeneities; many of these features appear geologically ambiguous. Applying migration with an appropriate aperture setting improves event continuity and produces structures that appear geologically plausible and provide confidence in interpretation.

For the compact 3D survey at the Devine test site, different estimates of migration aperture were analyzed. Classical formulas based on the constant-velocity assumption predict an aperture of about 300 m for a target at 500 m depth. Impulse response analysis using a realistic velocity model suggests about 200 m. However, analysis of the migrated images and stability of the interpreted isopach thickness indicates that an aperture of approximately 100 m provides the most consistent imaging of the target.

The difference between theoretical and practical estimates reaches about 100 m, which is significant for compact surveys covering areas on the order of one square kilometer. For such surveys, the aperture width directly affects the required survey extent, with important financial and operational implications. The results from the presented workflow can lead to an increase in the efficiency of the designed surveys for high-trace-density monitoring experiments.

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