Understanding acquisition and processing challenges in the desert environment through SEAM Arid and Barrett models

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Summary

Seismic acquisition and processing in a desert environment is a complex business. We attempt to identify the exact nature of most fundamental imaging issues by conducting processing and imaging exercise on the synthetic elastic SEAM Arid model. Contrasting it to the Barrett model, we demonstrate the primary role of high-contrast vertical heterogeneity caused by alternating high and low-velocity layers in the near surface. We speculate that 3D heterogeneity caused by karsts plays a secondary role, along with reduced density contrasts. Processing land data brings significant uplift in SNR not achievable with the migration of raw data. Conventional 3D orthogonal geometry struggles to image Arid data, especially in the shallow subsurface. We showcase raw gathers and migrated images of raw and processed data to support these conclusions and achieve a better understanding. The next step is designing better acquisition geometry coupled with processing to address these challenges.

Introduction

Seismic data quality in a desert environment can be quite variable and, at places, extremely challenging. It is believed that the near surface is the culprit. Yet, we lack a detailed understanding of what precisely controls the data complexity and how to replicate and capture it for acquisition design and processing studies. We attempt to build an initial understanding of desert environment seismic challenges through realistic synthetic models from the SEAM Phase II project (Oristaglio, 2012; Regone et al., 2017).

SEAM Arid model study

We primarily focus our attention on the SEAM Arid model that attempted to capture first-order details of near-surface complexity typical for the Middle East (Oristaglio, 2012; Regone, 2017). Figure 1 shows a zoom of the near-surface part highlighting several distinct features:

- High-contrast layering with multiple velocity inversions;
- Strong velocity gradient in the shallowest section – going from 1000 m/s to 4000 m/s within 20-50 m; and
- Shallow and deep karst fields.

While a number of other important details were not included (no surface topography, lowest Vp velocity is relatively high with 1000 m/s etc.), the Arid model still presents the best-documented case for elastic near surface from the desert environment. The deeper part below ~ 500 m was primarily borrowed from Barrett's unconventional model (Oristaglio, 2015) except for lower density contrasts in the deeper subsurface (Figure 2). This created an opportunity to contrast data and images in both models to further isolate the impact of the near surfaces on seismic imaging.

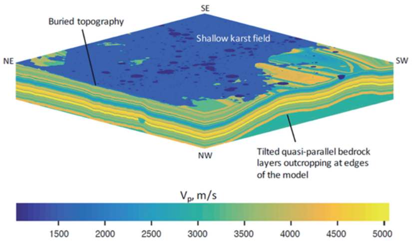

Figure 1: Near surface part of the SEAM Arid model.

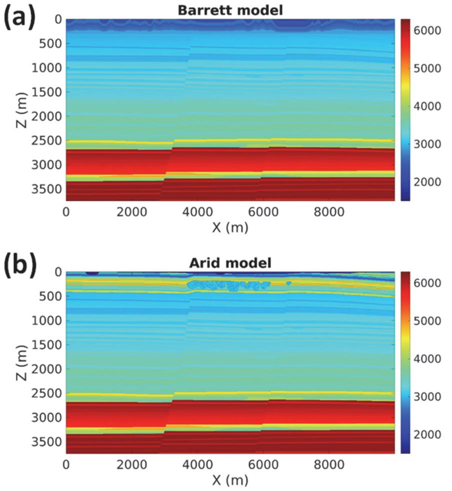

Figure 2: Cross-section through the middle of the model: (a) Barrett, (b) Arid.

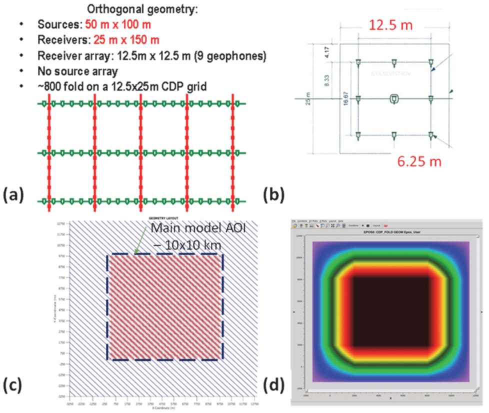

Figure 3: Orthogonal acquisition geometry (a) was used for processing exercise with the following details: (b) 9-geophone array; (c) source and receiver coverage, (d) fold map.

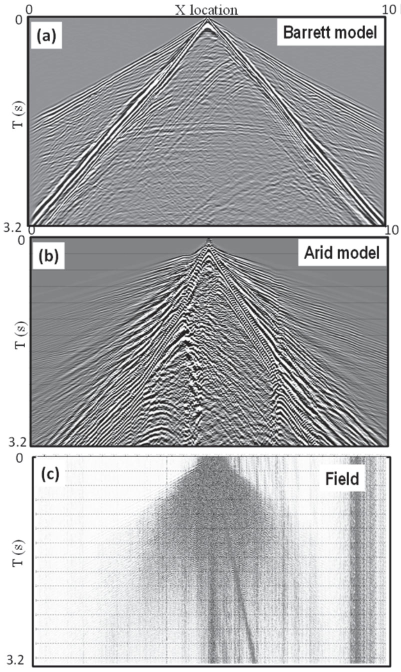

Figure 4: Representative shot gathers from a (a) Barrett model, (b) Arid model, (c) field data.

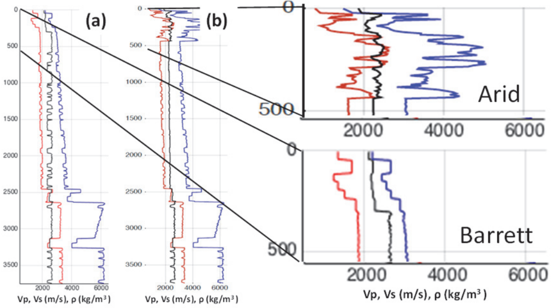

Figure 5: Property profiles and near-surface zoom for one location through: (a) Barrett, (b) Arid models.

Acquisition geometry

We start with a typical orthogonal data acquisition geometry used in the Middle East (Figure 3). Inline receiver spacing is 25 m, while cross-line distance is 150 m. While typical geometries also use 25 m inline shot spacing, the Arid dataset only contained a 50x50 m source grid. To avoid recomputing the data, the inline spacing of 50 m was used along with a crossline distance of 100 m (Figure 3a). The presence of a fine grid of receivers at 6.25x6.25 m in the original Arid dataset also allowed us to reproduce 9-geophone groups, albeit with slightly smaller spatial dimensions (Figure 3b). Shots and receivers covered areas of 10x10 km and 16.5x16.5 km, respectively (Figure 3c). Only a square receiver patch of 7x7 km was active for each shot, resulting in a maximum offset of 3,500 m. The fold map is shown in Figure 3d, with the fold in the central area reaching 800.

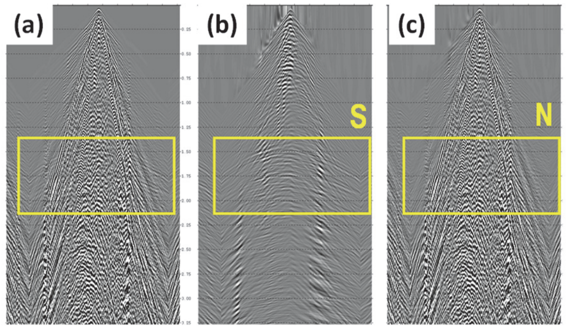

Figure 6: Shot gather in Arid model before (a) and after (b) linear noise removal; (c) shows a difference between (a) and (b). SNR computed inside yellow box is estimated at ~ -19 dB. The box contains strongest subsurface reflectors (2500-3500 m, Figure 5).

Prestack data comparison

Figure 4 shows a comparison of representative shot gathers for two models. Several important differences are worth highlighting. Reflections are mostly visible in Barret despite groundroll and scattered noise, whereas reflections are invisible on the Arid model. Smaller density contrasts (~1/2) for sections of 500-2,500 m of the Arid model (Figure 5) may explain some of this. Even the strongest reflectors at 2500-3500 m (1.5-2 s) with equal contrast do not show up in the Arid gathers due to the thick carpet of scattered groundroll and other elastic events. Indeed, the area inside the cone bounded by direct groundroll branches is mostly filled with scattered groundroll, diffractions, and other events created by complex interference chiefly associated with the near surface. Even with this not very dense acquisition geometry, data processing can remove the bulk of this energy (Figure 6). Reflected events represent only a minor portion of the overall energy with SNR around -20 dB.

Migration using a true velocity model

Migration is an excellent noise attenuator. Figure 7a shows PSDM of the Barret model for nodal-type geometry with orthogonal geometry using source at 25x200 m and receivers 200x25 m grids (Regone et al., 2015). Migration of prestack data with reasonable SNR leads to further suppressing the noise and correct imaging of reflected data from a few hundreds of meters. Such a result is generally expected but should not be taken for granted. Figure 7b shows a similar PSDM result from the Arid model with orthogonal geometry from Figure 2a, which is quite similar to Barrett data. Only a deeper portion of the subsurface below ~ 2.2 km is adequately imaged, whereas the shallow portion is heavily obscured. At first glance, such a result appears unexpected. After some digestion, it appears more acceptable and inline with Regone et al. (2015) hybrid simulations in the Barrett model that combined two separately computed signal and noise datasets with variable SNR. Signal was approximated by acoustic stimulation in the full model. The noise was computed by elastic modeling of only the near-surface portion (<600 m). These hybrid simulations showed that even a better-behaved signal in the Barrett model could become overwhelmed by -20-30 dB of elastic noise with PSDM producing similarly heavily distorted images. In essence, migration has only so much noise reduction power. Eventually, large organized noise reaching a certain low SNR could overrun the migration powers too. Is migration the only power we have? Let us examine the role of the processing.

Role of processing

It may be tempting to simplify the real world and declare that if only we know the accurate velocity model – then migration will be the only processing we need to do. Let us verify this assumption on an Arid model. Data were processed using conventional time processing flow typical for desert environment data. Migration of processed data results in a depth image shown in Figure 8d similar in quality to what was obtained with time migration (not shown here). Examination of Figures 8c and 8d confirms that we have achieved significant image cleanup now up to ~1.2 km with an associated increase in SNR and event continuity. Processing effort was deemed acceptable for structural imaging of a deeper target at ~ 2,500 m. If target depth is set shallower, more sophisticated versions of the processing could have been used to deliver better results. Therefore, processing remains a critical and independent contributor to SNR improvement that could not be achieved with the final migration alone. Nevertheless, processing exercise suggests that imaging difficulties rapidly escalate when moving from the bottom to the top of the section (Figure 8d). This is evident comparing Figure 8d with the expected reflectivity of Figure 8a,b. Such behavior is typical for real data and is likely an imprint of insufficient fixed acquisition density with escalating consequences towards the shallower parts. It is expected that robust imaging of the first ~ 1,000 m would require denser acquisition geometry. Suppose we were to look at this exercise through the eyes of an acquisition geophysicist or an interpreter. In that case, the image of raw data with the true model remains an excellent predictor of the final processed image's quality. As such, migration with the true model is a useful tool for quick relative evaluation of acquisition geometries and prediction of processing challenges. We expect more studies to report for Arid data.

The central unanswered question is, what would the minimum acceptable pre-stack quality or SNR for successful processing? How do we derive near-surface and subsurface velocity models along with time-processing parameters (statics, decon operators, statics, etc.) from the data with such low SNR as in Figure 4c? Reliable time processing parameters are required to achieve uplift seen in Figure 8d vs. 8c and land processing in general. Parameter derivation requires certain minimum prestack SNR that is often not achievable. The same dilemma applies to various velocity model building techniques relying on prestack data. These are questions that should be answered to design better acquisition and processing for the desert environment.

What are the most critical factors?

What exactly creates such a big difference between Arid and Barrett imaging? Let us more closely examine velocity profiles through both models (Figure 5). They are very similar below 600 m (except for density contrasts in 500-2500 m); however, the near surface is undoubtedly very different. While there is an increased reflectivity of deeper subsurface in Barrett due to stronger density contrasts (Figure 8a), we still believe it is still a secondary explanation. Two primary near-surface explanations are high contrasts (strong 1D heterogeneity) and karst field (3D heterogeneity). While the structural complexity of the Barrett near surface may be similar or higher (Regone et al., 2017), low near-surface contrasts lead to a relatively benign "noise" wavefield and level. In contrast, the Arid model with high contrasts and alternating high- and low-velocity layers generates massive scattering. While karsts also contribute to the complexity, they are not present everywhere (Figure 1). Even parts of the image volume underlying areas where karsts are absent still show a similar level of deterioration as those below the karsts. We conclude that high near-surface contrasts are likely a first-order effect. This was further validated by a migration study in a series of simpler acoustic models without karsts (Bakulin et al., 2014), that exhibited severe image deterioration when increasing contrasts from low to high. Shallow screening and energy partitioning were discussed in some earlier work (Poley and Nooteboom, 1966). They perhaps needed deeper revisiting in the context of modern modeling capabilities and single-sensor recording.

Are we there yet?

While we have observed some similar data features and imaging trends typical for the field data from the desert environment, are we there yet to fully explain real data? Figure 4c suggests that we still have a long way to go. Going to nodal geometries, we can improve the acquisition density. Going to single sensors results in a significantly more complex wavefield displayed in Figure 4c. What are the key distinctions between the Arid model and the field data?

- Even the strongest events on the raw data, such as early arrivals, groundroll, etc., become broken up and incoherent the field data, while they are well organized and coherent in the Arid model;
- While linear noise removal reveals coherent reflections on SEAM, this is no longer the case for single-sensor data. Field data reflections are similarly broken up.

We believe there is another layer of complexity not captured in the Arid model. It is associated with an even more abundant distribution of small- and medium-size heterogeneities. They could mess up all coherent events, including reflections and organized noise. Bakulin et al. (2020a,b) have presented random clutter models that exhibit real data features, such as Figure 4c. The most obvious of them is that reflections remain broken up with low coherency even after the entire noise removal flow, which is not the case for the Arid model (Figure 6). Those heterogeneities strongly distort the phase of the signal itself, making it less coherent and further reducing SNR estimates that rely on coherent signal stacking. Seismic Time-Frequency Masking (Bakulin et al., 2020) was proposed to declutter the data and bring it to a more coherent similar to what is observed in the Arid model (Figure 6).

Conclusions

We present the processing study's initial results on the SEAM Arid model and contrast it to the Barrett model sharing similar subsurface but more benign near surface. We conclude that multiple scattering in the highly contrasting near surface is a major complication. We believe that presence in the near surface of alternating high- and low-energy (screening) as well as the complexity of the remaining "noise" fields overlying the reflections. In the Arid model itself, 3D heterogeneity such as karsts appears to role in field data than what is observed in the Arid dataset. Additional investigation is ongoing on how to characterize velocity layers with strong contrasts is most likely a primary explanation of the significantly reduced level of reflected play a secondary role in further infilling the inner parts of the groundroll cone. In our opinion, 3D heterogeneities in small- and medium-size scatterers play a much more significant them properly so our simulations would match field data more closely in a desert environment. With all the limitations, the Arid model presents the best-documented attempt at replicating actual seismic challenges with complex near surface typical for the Middle East. We observe a significantly reduced amplitude level of reflected waves compared to the remainder of the wavefield. We also reproduce a trend in seismic image quality deteriorating towards shallower depths.

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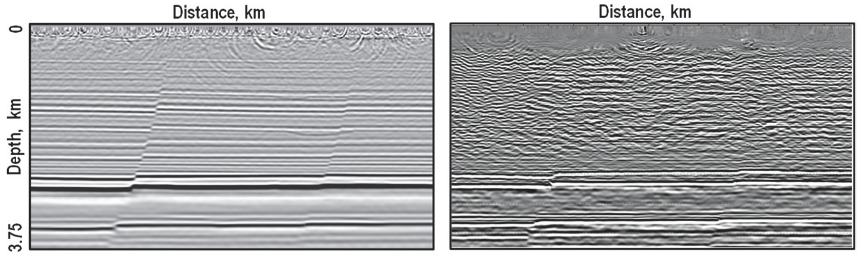

Figure 7: Cross-section from a 3D PSDM volume using raw data as an input from: (a) Barrett model with sources 200x200 m and receivers at 25x25 m grid (Regone et al., 2015); (b) Arid model with orthoghonal geometry 100x50 m sources and 25x150 m receiver (Figure 2a).

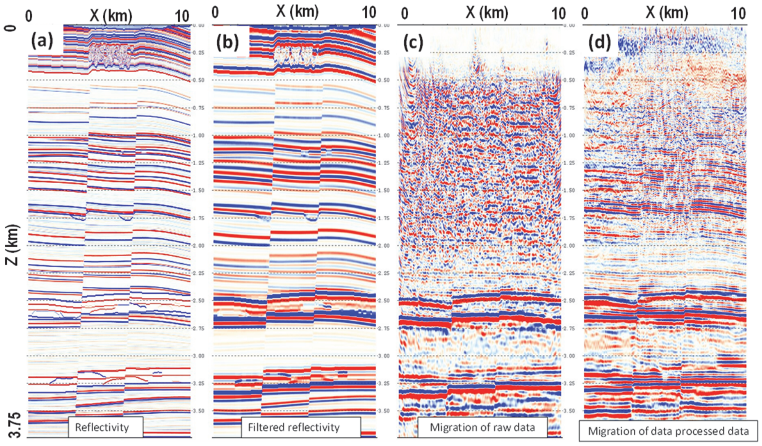

Figure 8: Cross-sections from a 3D volumes of: (a) reflectivity model, (b) filtered reflectivity (bandpassed). Cross-sections from a 3D PSDM volume obtained using true velocity model: (c) raw data as an input; (d) processed data as an input.

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