Seismic imaging in and around salt bodies: problems and pitfalls

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Introduction

Salt movement often results in steeply-dipping complex structures, which pose significant challenges for model building and migration. In recent years, advances in seismic imaging algorithms have permitted imaging of steep structures by exploiting the two-way wave equation via the introduction of reverse time migration (RTM). With such imaging algorithms, double bounces and turning wave reflections can be imaged, thereby enabling the imaging of vertical and overturned salt flanks. However, despite advances in the migration algorithms, the derivation of a suitable earth model incorporating the anisotropic behaviour of the velocity field, remains a significant challenge, requiring tight integration of geological interpretation, and geophysical skills.

A major contributing factor to the successful execution of a complex salt imaging project, is the understanding of the many and varied pitfalls involved at every stage of the process. Here we describe and discuss some of these issues.

Physical properties of evaporites

Pure halite has a velocity of 4500 ms\(^{-1}\) and this often is assumed to be a constant in velocity modelling and processing. However, many salt bodies contain varying amounts of anhydrite, (velocity 6500ms\(^{-1}\)), or K-Mg-rich salts such as sylvinite, carnallite, and tachyhydrite (velocities as slow as 3500ms\(^{-1}\)). It is recommended that several velocities are used in initial velocity model testing in areas where the evaporite composition is unknown. All deformed salt bodies contain mineral grains which are preferentially elongated in the flow direction; vertically in salt diapirs and horizontally in source layers. The inherent seismic velocity anisotropy has been measured at up to 7% faster in the flow direction (Kendall and Raymer, 1999, Landrø et al. 2011). However, there has been little attempt to incorporate salt anisotropy into velocity model building.

Velocity Model Building

This remains the least well addressed issue in contemporary imaging today (Jones 2010). There is great promise for dealing with the very near surface offered by waveform inversion, but deeper problems are still very problematic. Even for laterally invariant velocity fields, the reduction in ray-angle coverage associated with a velocity inversion (such as often occurs at the base of salt) severely limits velocity estimation procedures based on observed residual moveout in CRP gathers. Given that the complex raypaths associated with salt bodies often involve laterally propagating energy, in order to construct a reliable image, we must have a good understanding of the relationship between the vertical and horizontal components of velocity: in other words, the anisotropy parameters.

Migration

It is now widely accepted that reverse-time migration (RTM) is most appropriate for complex imaging (Leveille et al. 2011), but perhaps the reasons why, are not generally understood. The main advantages of RTM are that a high-order finite difference (FD) operator can handle rapidly varying velocity fields such as those associated with salt bodies. Solving simultaneously for both the downgoing and upcoming wavefields is required to image double bounces and turning arrivals (e.g. Berntsen et al., 1997). Failure to adequately deal with any of these issues can result in spurious and misleading images. Figure 1 shows one such example: a salt diapir with a stem, but no base (other than the deep autochthonous mother salt) was modelled, and then migrated with the perfect model, but using a conventional (non-RTM) imaging scheme. Complex arrivals in the data (such as double bounces, and through salt reflection travel paths) can produce what appears to be a false ‘base salt’ in the diapir. Some of these complex raypaths are indicated in Figure 2.

Another source of spurious reflection is produced by reflected critical refractions along stratal boundaries adjacent to steep salt bodies, where a false Christmas tree like structure can be produced (Figure 3).
Figure 1a: Synthetic modelling results for conventional Kirchhoff migration of salt body without a base salt in the model. The image gives a false base salt reflection. b) Shows corresponding real data result.

Figure 2a: PSSP mode converted internal salt reflections. b) Upward turning reflected refractions within salt.
Fig. 3a). Ray path of reflected critical refraction from a diapir wall (red). A series of these rays will produce a straight reflection emanating from the intersection point of the reflector (arrowed) with the diapir wall producing an apparent Christmas tree. a) Courtesy of Dave Waltham and b) seismic section from NW Germany courtesy of Markus Mohr (pers. comm).

In addition to the migration, we must also consider the pre-processing procedures employed prior to migration. Conventional processing strategies have traditionally been designed with only one-way propagation in mind. Hence many conventional approaches to pre-processing can damage or entirely remove two-way energy from the data, thus limiting the potential of a subsequent RTM (e.g. Jones 2008). Figure 4 shows an RTM image with and without a ‘conventional’ processing route, the former significantly damns the image. In this case, the deleterious pre-processing comprised a mute in the tau-p domain (applied during tau-p deconvolution, and 2D diffracted multiple attenuation using a shifted-apex approach).

Even for conventional marine streamer acquisition, where we routinely ignore the existence of shear mode wave propagation, for salt bodies, we need to concern ourselves with PSSP and PSPP/PSPP arrivals for two reasons: firstly because energy propagating on these mode-paths will contaminate a conventional image, as seen in Figure 5 (e.g. Lafond et al., 2003), and secondly, if we migrate the data with a shear-wave velocity model, we can sometimes obtain a useful shear image of the base salt (e.g. Lewis 2006).

References
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Figure 4a: RTM image with inappropriate conventional pre-processing; 
b) RTM image with same model without the deleterious pre-processing (from Jones 2008).

Fig. 5. a) Converted mode reflections from the base salt give misleading images on the P-wave migrated result (from Lafond et al., 2003). b) Four possible wave-mode conversions through salt.