Seismic Imaging of Salt Diapirs: Problems and Pitfalls

Ian Davison[1], Ian F. Jones[2], Dave Waltham[3] (1. Earthmoves Ltd. Camberley, Surrey, UK; and 2. ION GXT Egham, Surrey UK; 3. Department of Earth Science, Royal Holloway, University of London).

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 (e.g. Bernitsas et al., 1997), 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 evaporite minerals

Velocity model building 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.

Pure halite has a velocity of 4500 ms^{-1}. It is often assumed to be a constant in velocity modelling. However, salt bodies contain varying amounts of anhydrite (velocity 6500 ms^{-1}),or K- Mg-rich salts with velocities down to 3500ms^{-1}. A thick cap rock of anhydrite (up to 400m) can also occur due to salt dissolution along the top salt surface and lateral margins of a salt diapir (Lewis and Jackson 2012), so it is recommended that varying 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 (Fig.1): vertical in salt diapirs and horizontal in source layers. The P wave seismic velocity anisotropy has been measured at up to 7% faster in the flow direction (Raymer et al. 2000). Individual interbeds of anhydrite and dolomite may also increase velocity anisotropy within the salt body if they maintain intact layers for long vertical distances. So far, there has been little attempt to incorporate salt anisotropy into velocity model building, and this is a promising area for future improvement in seismic imaging.

Figure 1: Halite from the Al Salif Diapir in Yemen showing vertical elongate grains due to flow in the diapir neck. Grain size approximately 1 cm and grain elongation ratio 1:3. P wave anisotropy in single crystals reaches up to 7% and s wave anisotropy can reach 16% which produces shear wave splitting.

Internal Structures in Salt Diapirs

When salt flows into a salt body the flow rates locally vary due to heterogeneities in the salt, variable salt thickness etc. Flow instability leads to folding of the salt layers, even if there is very little rheological contrast between layering. Flow folding is observed throughout the Louann salt in the Gulf Coast of Mexico even when the layering is produced by slightly higher (4-5%) dispersed anhydrite content (Fig. 2; Muelhberger and Clabaugh, 1968).

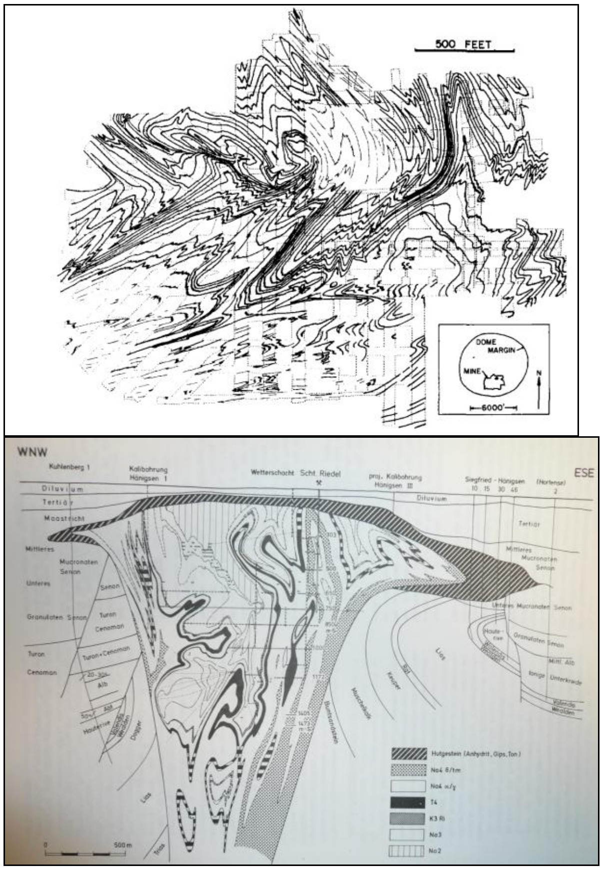

Fig. 2 a) Map of internal folding within the Grand Saline Dome, USA. From Muelhberger and Clabaugh 1968. Reproduced with the permission of the AAPG. B) Cross section of the Reidel Salt Dome NW Germany. From Schachl 1988.

The hinge zones of the tight to isoclinal folds within the diapir necks are very steeply dipping (curtain folds) because hinges rotate into the flow direction. Hence, the internal layering is hardly ever imaged. Previous interpretations of seismic from the Santos Basin (Brazil) (Fig.3) have suggested that the non-reflective diapir cores are pure halite cutting though layered reflective salts of tachyhydrite, anhydrite and salt. However, a much more likely interpretation is that the diapirs have the similar layered strata that is intensely folded.

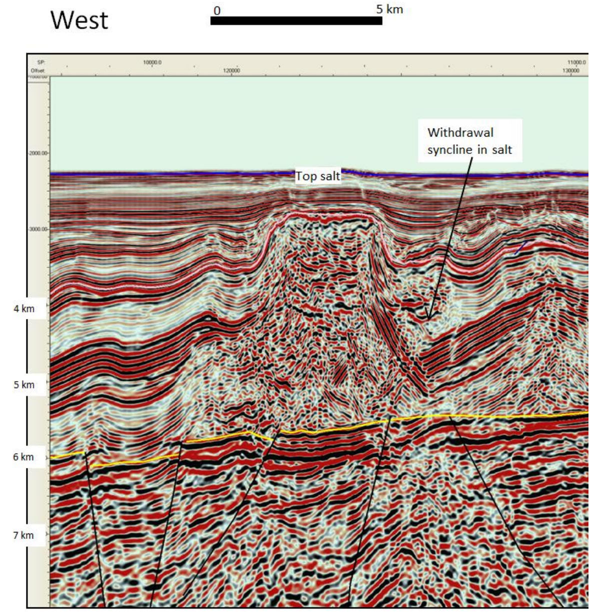

Fig. 3. Seismic section through layered salt in the Santos Basin, Brazil. Salt has become diapiric during later salt deposition before any clastic sediment was deposited. The non-reflective diapirs are interpreted to be tightly folded layered salt. From Davison et al. 2012, reproduced with permission of the Geological Society of London.

Imaging of beds adjacent to salt diapirs

Reflections from beds adjacent to salt diapirs are poorly imaged due to ray paths passing though the salt. On the stacked section (Fig. 4) the true dip of the beds may be still preserved, but once the time data is migrated with increasing velocity at depth the adjacent reflectors tend to be overmigrated and pulled into too far towards the diapir centre. Hence, many diapirs are interpreted as teardrop shapes whereas in reality they are vertical cylinders (Fig. 4).

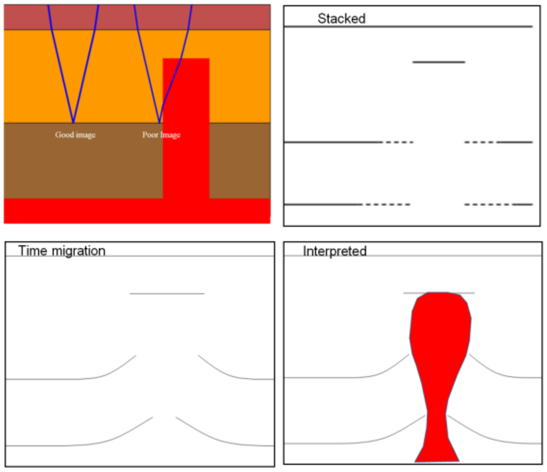

Fig. 4. Explanation of the false tear-drop shape often produced on interpreted time-migrated seismic sections.

Migration

It is now widely accepted that reverse-time migration (RTM) is most appropriate for complex salt 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. Bernitsas et al., 1997): in other words, solving the two-way wave equation. Failure to adequately deal with any of these issues can result in spurious and misleading images.

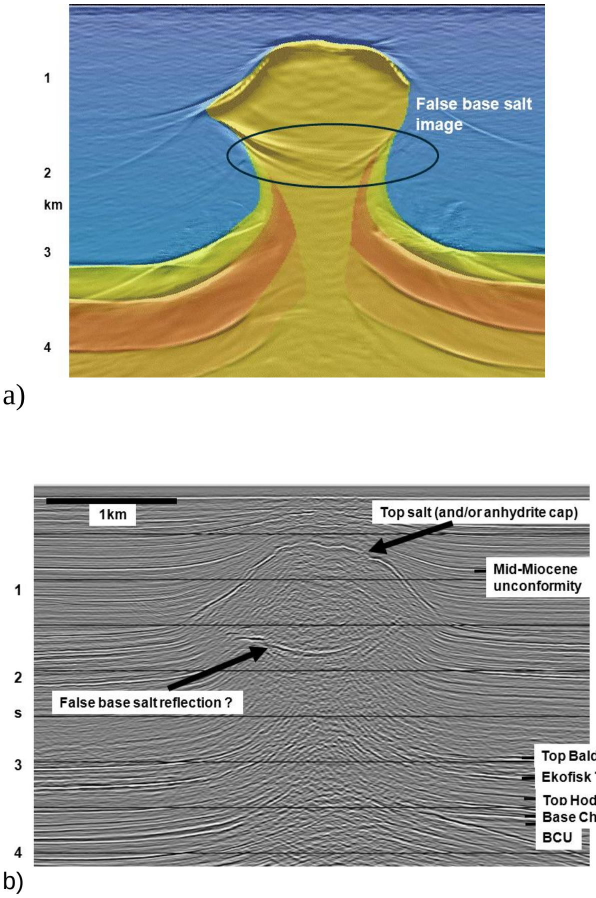

Figure 5a: Synthetic modelling results for conventional Kirchhoff migration of salt body without a base salt in the model. The image gives a false base salt reflection.
b) Shows corresponding real data result.

Figure 5 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 'base salt' for the diapir: which is false. Some of these complex raypaths are indicated in Figure 6.

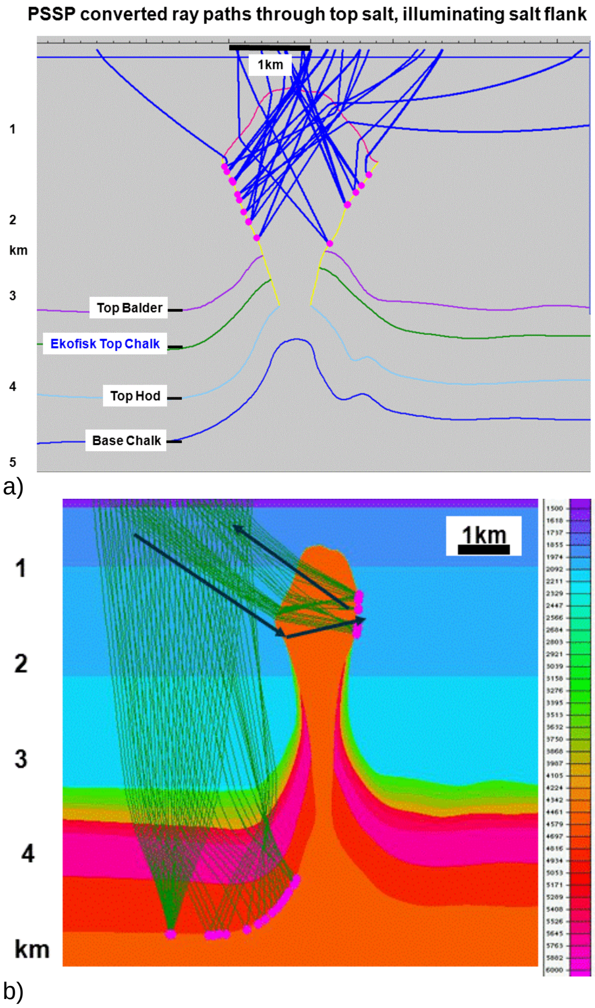

Figure 6a: PSSP mode converted internal salt reflections.
b) Upward turning reflected refractions within salt.

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 (e .g. Fig. 7)

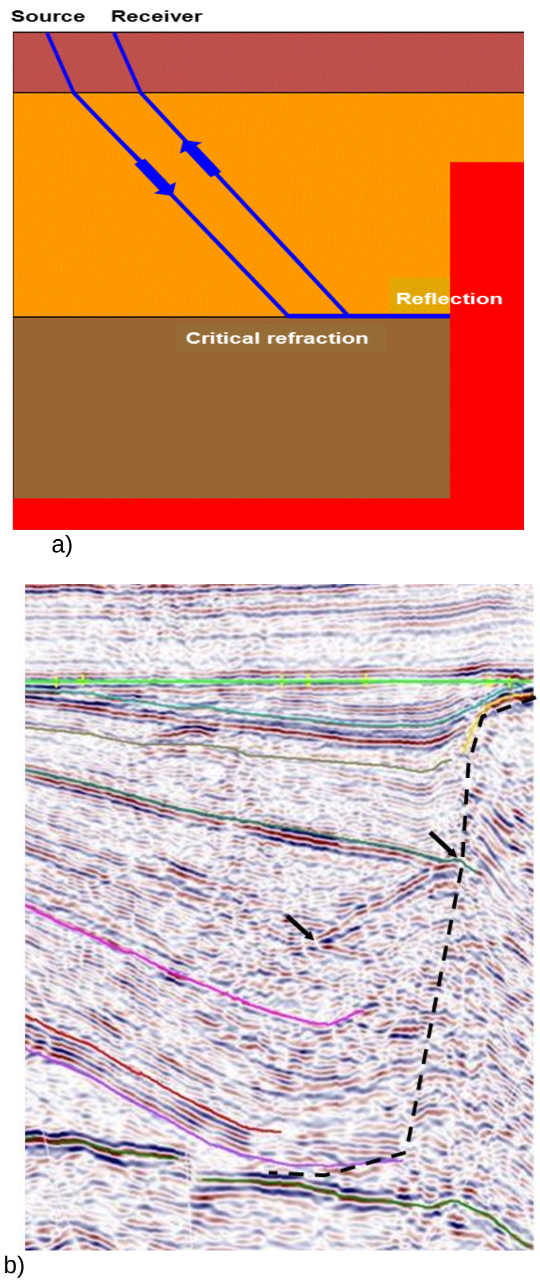

Fig. 7a). Ray path of reflected critical refraction from a diapir wall (red). A series of these rays will produce a straight reflection emanating from the intersection point of the reflector with the diapir wall producing an apparent Christmas tree. b) seismic section from NW Germany. Reflected refraction is arrowed 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 8 shows an RTM image with and without a 'conventional' processing route, the former significantly dames 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).

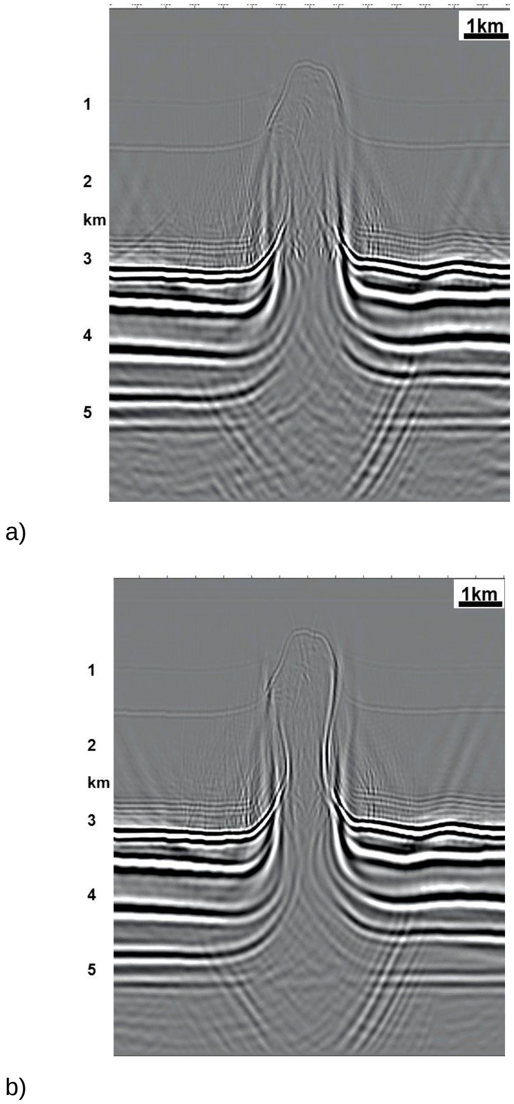

Fig. 8a: RTM image with inappropriate conventional pre-processing;
b)RTM image with same model without the deleterious pre-processing (from Jones 2008).
c)

Wave Mode Conversion

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 9 (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).

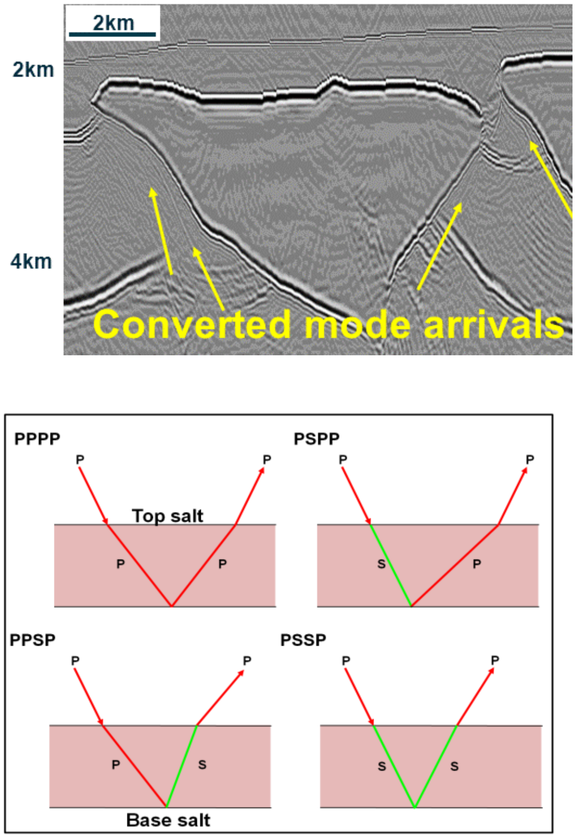

Fig. 9. a) Converted mode reflections from the base salt give misleading images on the P-wave migrated result (from Lafond et al., 2003). b) Four possible wave-mode conversions through salt.

Summary

In the above examples, we have outlined several factors that can mislead the unwary interpreter or seismic processor, when dealing with the seismic representation of complex salt bodies. It is imperative that when working in such complex geological areas, that a thorough understanding of these factors is taken into account, and we mitigate their effects to reach more reliable conclusions.

Acknowledgments

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