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Diffraction Modeling and Imaging of Sand Injectites

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Summary

In this paper we use a conceptual model to investigate the diffraction response of sand injectites. Unlike conventional seismic attributes derived from a migrated image using a local averaging process, the diffraction image provides the full resolution of the wavefield. We model a dike representing a typical injectite wing. This is of particular interest due to the advantage in illumination provided by diffraction over reflection for the steep flanks of the dike. We show that the model produces three type of diffraction response. These are associated with the host rock reflector terminations, with discontinuities in reflectivity along the flanks of the dike due to layering of the host rock, and with the pinchout of the dike. In each case the diffraction response is the resultant of a pair of edge diffractors, and the interference of the imaged diffractors depends on the geometry of the injectite. These results illustrate the potential for diffraction imaging to provide additional resolution of injectite geometries.

Introduction

Sand injectites are one of the more complex play types for clastic reservoirs. The geometries include sills, dikes and feeder systems. A comprehensive reference on the role of sand injectites in E&P is given by Hurst and Cartwright (2007). Various approaches to improve the definition of injectite reservoirs and feeder systems have included multi-component and broadband acquisition and the application of AVO inversion and spatial attributes. In recent years, the attributes are derived typically from pre-stack time/depth (PSTM/PSDM) data. However, the potential to characterize injectites using the additional resolution provided by seismic diffraction is largely untapped. Unlike attributes, which are derived using various averaging operators applied post-migration, the diffraction image is a fundamental wavefield, and by definition offers improved resolution of the subsurface discontinuities from which the diffracted waves emanate. In this paper we illustrate this potential using forward modeling of elementary models of dikes, along with PSDM and diffraction imaging applied to the synthetic responses.

Diffraction imaging of dikes and feeder systems is of special interest since these have a rich diffraction response which does not have the same illumination restrictions as reflection for sub-vertical features. Reflectors truncated against sub-vertical features produce edge diffraction which can aid in the resolution and detectability. Diffraction is also produced by changes in reflectivity on the injectite boundary with the host rock. Moreover, the interface between the host rock and the injectite does not generally present a smooth reflecting surface. For example, stepped sills and dikes are common, and the various steps will produce diffraction. An important feature of the sub-vertical injectites are the pinchouts, both vertically and laterally. These pinchouts also give rise to diffraction. As noted by Hurst and Cartwright (2007) a close association has been documented between sand injection and polygonal faulting in de-watered shales. Diffraction imaging can also help to better define the polygonal fault systems, providing additional resolution as compared to seismic attributes.

Our approach is to work with geologically organized elementary diffractors to construct a conceptual model. From the model response we can gain an intuitive understanding into the associated diffraction phenomena from first principles. We have used this same approach for fracture intersections on GPR data (Grasmueck et al., 2015), for fluid escape pipes (Moser et al., 2017) and for faults with small throws (Pelissier et al., 2017). A common denominator of these model studies is that diffraction imaging provides benefits in both resolution and detectability. Interference and tuning are as important in diffraction modeling as they are in reflection modeling. As we will show below, the basic seismic diffraction building block for the injectite modeling is edge diffraction from a half-plane. This response is treated in the classic work by Sommerfeld (1896, 2003), and forms a cornerstone of the geometric theory of diffraction (Keller, 1962) and its application to the seismic problem (Klem-Musatov and Aizenberg, 1984). The edge diffraction response is of fundamental importance in seismic diffraction as it applies also to faults, fractures, stratigraphic edges and pinchout and fluid escape pipes.

Modeling and imaging approach

A seismic modeling study by Holte (2011) used realistic geometries based on injectites in a number of basins. Finite difference was used for the forward model and time migration for the imaging. As such, the model responses incorporate both reflection and diffraction responses. In this paper we consider a much simpler elementary model for an isolated dike, using some of the properties in Holte's (2011) modeling. The forward model uses the ray-Born method as detailed by Moser (2011). The scattering model was constructed by including the most singular parts of the impedance model and populating these by scattering points, honouring the true impedance contrasts. The modeled data has been used for input in pre-stack depth migration and diffraction imaging, respectively. The diffraction imaging has been effectuated by specularity gather analysis and a proper selection of the specularity taper (Sturzu et al., 2013). In this paper we study both the combined reflection and diffraction image provided by PSDM, as well as the image of the separated diffraction provided by the diffraction imaging.

In the diffraction imaging forward problem, the diffracted events are governed by the *law of edge diffraction* (Keller, 1962). The geometric behaviour of diffracted rays is fundamentally different from that of reflected rays, which are constrained to follow Snell's Law. An incident ray oblique to the edge on a half-plane produces a cone of diffracted rays; these rays can be recorded at all offsets. Unlike a point diffractor, both the modeled and imaged edge diffractors are characterized by a polarity reversal about the edge. To distinguish reflection and diffraction events and thereby leverage the resolving power of seismic diffraction, we need to apply a pre-stack, pre-migration method (Khaidukov, Landa and Moser, 2004).

Elementary dike modeling and imaging

A cross-section of an idealized dike model is shown in Figure 1. Diffraction events emanate from the pinchout at the upper termination of the injectite, and from the truncation of the lateral reflectors against the flanks of the injectite. For the pinchout, as well as the lateral termination, a pair of half-planes provides the basic building block for the diffraction response. The pinchout involves the interference of two edge diffraction events, and this in turn depends on the angle of the pinchout. A pair of half-planes is also used for the diffraction response of the lateral terminations. Depending on the width of the injectite cross-section, the edge diffractors can interfere constructively or destructively, or, for a large width, not at all. In investigating the model response, we also need to take into account the interference of the reflected events, as noted by Holte (2011). Finally, we also need to address the interference of reflection from the flanks of the injectite with diffraction, both at the pinchout, and at the reflector terminations.

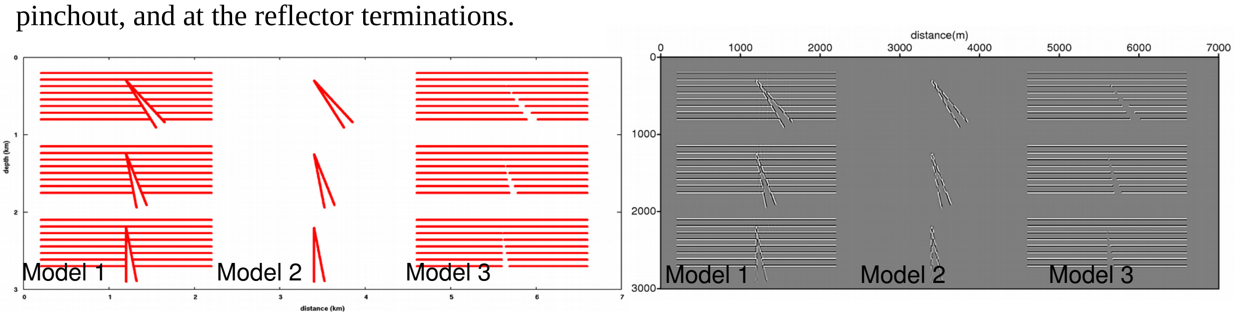

Figure 1: *Conceptual building blocks for the injectite model and corresponding PSDM.*

The basic seismic diffraction building blocks for injectites are shown in Figure 1. A typical injectite segment, for example, representing a wing, can be represented by a reflecting wedge embedded in a layered system, as shown in Model 1. This model includes three sub-models, with the wedges at various inclinations and a constant opening angle. The bottommost wedge is inclined such that one of the reflectors is vertical, and hence cannot be illuminated by a surface experiment. Model 1 can be decomposed into the reflecting wedges, and the layers only, as shown in Models 2 and 3. Diffraction events associated with the model are produced in several ways, but in each case by edge diffraction pairs. Two half-planes forming an aperture produce the edge diffraction on the flanks of an injectite. For a large aperture, there is no interference of the imaged diffraction events, which feature a polarity reversal about the edge. Although the 3D geometries of dikes and fluid escape pipes are very different, for dikes we can expect an interference pattern of the diffraction image associated with reflector terminations to be similar to what is observed in the modeling of fluid escape pipes (Moser et al., 2017). As the aperture width decreases, the imaged events interfere, at first constructively and then destructively, such that the diffraction response disappears as the aperture width decreases to zero. Illumination of the edge by diffracted waves, which are not limited by Snell's Law, and the interference pattern can help to improve the detectability and definition of narrow dikes in the same manner as small diameter fluid escape pipes. The reflecting wedge also has a diffraction response from the two edges which merge at the pinchout. In addition, since the reflectivity along the flanks of the injectite varies due to the impedance changes in the various layers of the host rock, diffraction is produced by the reflection coefficient discontinuities, as was demonstrated in a model study by Zavalishin (1982). In our figure, the wedges have a constant opening angle, at various inclinations.

To gain an understanding of the illumination differences between the reflection and diffraction we show the zero-offset model response before migration in Figure 2. For all models, the dominant response of the injectite is from diffraction. Depending on the slope of the injectite flank, reflection from it emerges at the acquisition surface at a very different location than diffraction and at much later time (for some vertical slopes even not at all). By contrast, diffraction from discontinuities at the injectite flanks is always observable at the acquisition surface. In this respect, diffraction has a decisive illumination benefit compared to reflection. Note that for the wedge in Model 2, the diffraction response is due only to changes in reflectivity, whereas in Model 3, diffraction is only due to the reflector terminations (for clarity, in Figure 2 we are not showing diffraction response from the model edges of Figure 1).

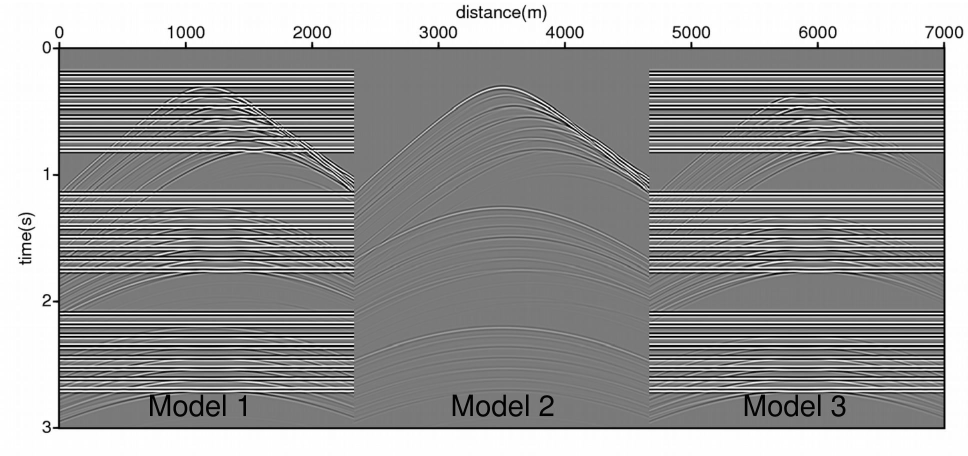

Figure 2: *Zero-offset model response.*

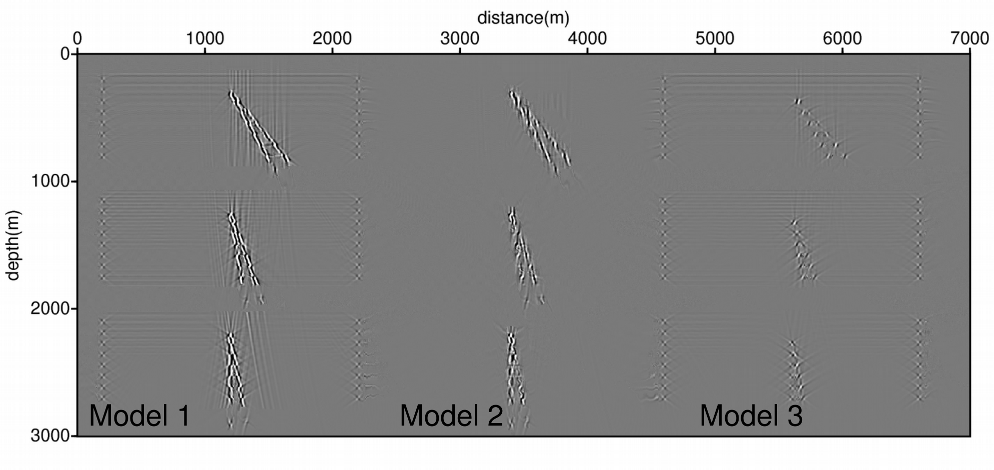

Figure 3: *Diffraction image.*

The diffraction image for the above models is shown in Figure 3. For Models 2 and 3, we see the diffraction from changes in reflectivity and from reflector terminations, respectively. The diffraction response for Model 1 is therefore a composite of two types of response. Although this is beyond the scope of the paper, we can also expect that there are tuning and interference effects related to this superposition.

The diffraction response of the injectite pinchout is also of interest. As noted by Brethaut et al. (2017) the diffraction amplitude is dependent on the geometry of the pinchout, in particular on its opening angle. This is because the amplitudes are due to the interference of diffraction events associated with the two half-planes, and this interference pattern will change as the imaged edge diffractors of the two half-planes are rotated relative to one another. The PSDM and diffraction image for a range of opening angles is shown in Figure 4. When both planes are flat (an opening angle of 180 degrees) then there is of course no diffraction response; this is due to the destructive interference. For a decreasing opening angle, the diffraction image increases in amplitude until interference comes into play. For smaller opening angles (sharper pinchouts), we observe that the diffraction response includes a polarity reversal. This is the result of the interference pattern of the imaged edge diffractors, each of which has a polarity reversal about the edge. This characteristic signature can help to identify the pinchouts. Note that the diffraction signature is also clearly visible on the PSDM.

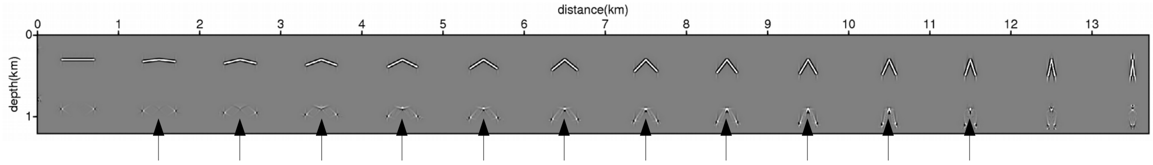

Figure 4: *PSDM (top) and diffraction image for edges with decreasing opening angle (arrows), in representative scale. Note increasing diffraction image amplitude for sharper pinchouts.*

Discussion and conclusions

Reflection from the steep flanks of dikes are generally difficult to image due to limited illumination. This affects both the quality of the imaged reflection as well as the positioning accuracy. Seismic diffraction imaging provides an illumination advantage since the diffraction is not constrained by Snell's Law. The diffraction response of an injectite dike can be modeled using pairs of edge diffractors as elementary building blocks. The polarity reversal is a fundamental signature of edge diffraction and the interference pattern of the modeled and imaged pairs of edge diffractors is sensitive to the injectite geometry. Based on the above fundamentals, it is clear that seismic diffraction imaging offers a means to improve the resolution and detectability of sand injection features.

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