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Improved Reservoir Imaging Using Specular Dip-angle Migration

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Summary

In this paper we show that specular imaging in the dip-angle domain significantly reduces 4D imaging noise. Specular imaging limits the migration aperture to rays obeying Snell's law. Since it is based on improved image formation, specular imaging is superior to signal processing methods applied to a noisy image. In the context of 4D, the improved imaging can prove useful in simplifying, and therefore speeding up, the 4D processing. By better imaging the data, based on a physical principle, we can avoid extraneous signal processing, such as dip-filtering, and thereby avoid signal damage and additional processing time. Separating the seismic energy at the imaging stage into specular and non-specular components in the dip-angle domain additionally provides the opportunity to identify diffraction energy. The particular behaviour of diffracted energy in the dip-angle domain, i.e. creating flat events across the whole dip-angle range, makes them separable from both specular energy and migration artefacts. We present the performance of the proposed specular imaging approach on a 4D dataset from the Caspian Sea. Significant uplift is obtained not only on the 4D image, but also on the 3D pre-stack gathers leading to improved AVO.

Introduction: Less is more

Time-lapse seismic processing with imperfectly repeated data needs to remove acquisition differences between the two datasets in order to retrieve the true hydrocarbon related changes in the reservoir, as well as in the overburden. In order to minimize the non-repeatable noise, a key step in the processing of time-lapse data, 4D binning, removes traces from either vintages with significantly different acquisitions. Using less of the acquired data to create a cleaner 4D image is thus not a new idea. A similar principle underlies the method presented here: We propose to create cleaner 4D images by optimizing the size of the migration aperture used in the imaging of both vintages. As stated by Schleicher et al. (1997) in the context of Kirchhoff migration: “In contrast to the common opinion that it is always the greatest possible aperture that yields the best signal-to-noise enhancement, it is in fact the selection of a minimum aperture that should be desired.” Whilst aperture arguments based on Fresnel zone considerations are well rehearsed in the literature, it is less commonly discussed how limiting the migration aperture yields improved reflection amplitude imaging and AVO. By selecting only specular rays obeying Snell’s law, the migration aperture can be limited, reducing noise, and giving more reliable amplitudes. We apply this idea to 4D imaging for the benefit of improved amplitudes and reduced non-repeatable 4D imaging noise.

Theory: Dip-angle gathers, reflections and diffractions

Following Qin et al. (2005) we organize the image gathers output in Kirchhoff Pre-Stack Depth Migration (KPSDM) according to dip-angle. At each depth point the dip-angles describe the direction of the migration slowness vectors, which point along the normal to the migration isochrones (see figure 1). Dip-angle gathers contain all of the data, but with the added information of migration dip. No a priori dip information is needed in their creation. In principle, Kirchhoff migrations use global apertures, meaning summation over all dip-angles at each offset. However, constructive interference occurs only for a much smaller part of the isochrone surface, where rays are specular and obey Snell’s law. Data outside of this zone can generate imaging artefacts (Sun, 1998; Hertweck et al., 2003), which in 4D means non-repeatable noise from base and monitor summing constructively into the 4D difference. It is now easy to see how this noise can be avoided in principle: We limit the migration apertures to specular rays. As long as we sum over an aperture equal to or larger than the first Fresnel zone, this yields the correct imaging amplitudes for AVO analysis (Schleicher et al. 1997). For obvious reasons, we call this “specular imaging”.

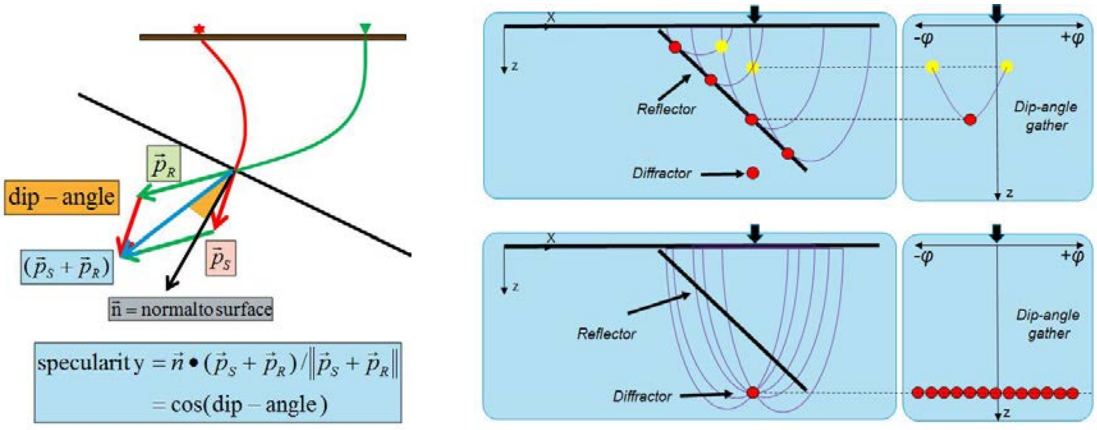

Figure 1: Left: *Schematic diagram showing rays from source and receiver to an image point on a reflector in depth.* Right: *Schematic diagram showing how a reflection forms a concave shape in dip-angle domain (at constant offset) with an apex at the reflector location. A diffractor is registered flat across the whole dip-angle range (at constant offset, assuming correct migration velocity.*

So far we have considered only the imaging of reflections. However, the dip-angle domain is also ideally suited for the imaging of diffractions, since the shapes of reflectors and diffractions are different in this domain (see figure 1): Diffractions create flat events across the whole dip-angle range (assuming correct migration velocity) and thus require a full dip-angle migration aperture. Reflectors are concave in the dip-angle domain, with an apex at the reflector dip, around which the optimal specular dip-angle limited refection Kirchhoff summation is then performed (Audebert et al., 2002). This can be achieved by a wide range of methods including following a guiding dip volume or filtering common dip-angle volumes in a convenient domain such as FK or Tau-p. We can thus separate reflections from diffractions by projecting out these two components of the image in the dip-angle domain. An example of this, from a 3D North Sea processing project is shown in Figure 2.

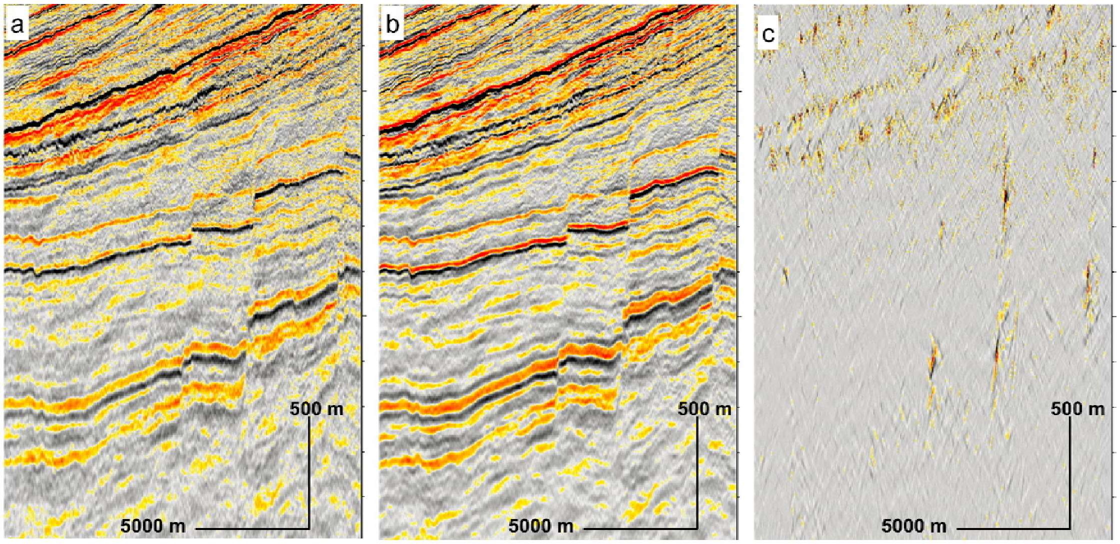

Figure 2: *North Sea example with from left to right: (a) conventional Kirchhoff PSDM, (b) specular PSDM for improved reflection imaging, and (c) diffraction imaging.*

Application of specular imaging to 4D

We now show the application of specular imaging in a 4D setting. We focus on improved reflection imaging only as we have not yet observed a 4D diffraction response (Zavalishin, 1982). The data from the Caspian Sea consists of four vintages acquired in 1995, 2002, 2012 and 2016. Different acquisition geometries and environmental variations, such as changes in the water velocity, cause significant acquisition footprints and imaging artefacts, which in parts obscure the expected 4D signal within the reservoir intervals. In particular, cross-cutting noise on the flanks of the dipping geological structures (see figure 3, top) was difficult to remove even with advanced denoise techniques. A full 4D co-processing was performed, similar to what is described in Skinner et al. (2015), and using optimal pairwise 4D binning between vintages to minimize the imaging noise. Given the nature of 4D signals, we introduce a small change to our specular imaging algorithm. In order to guarantee the preservation of flat spots we increase the range of dip-angles over which we sum, to always include a small portion of the data around zero migration dip. Specular imaging is then performed independently on base and monitor.

Figure 3 shows a comparison of conventional Kirchhoff depth migration and specular imaging. The images on the left show a sum of negative amplitudes (SNA) attribute around a reservoir horizon. The images in the middle and right columns show the 3D base image as well as the 4D subtractions (for one of the monitors). We see that cross-cutting noise, in conflict with the dominant dip, is significantly reduced; the 4D section becomes more interpretable. No signal damage is visible either in section view or on the horizon map, and more detail seems visible on the SNA maps after specular imaging. The noise reduction is also visible on the AVO products shown in figure 4, particularly for the gradient. AVO signal is preserved.

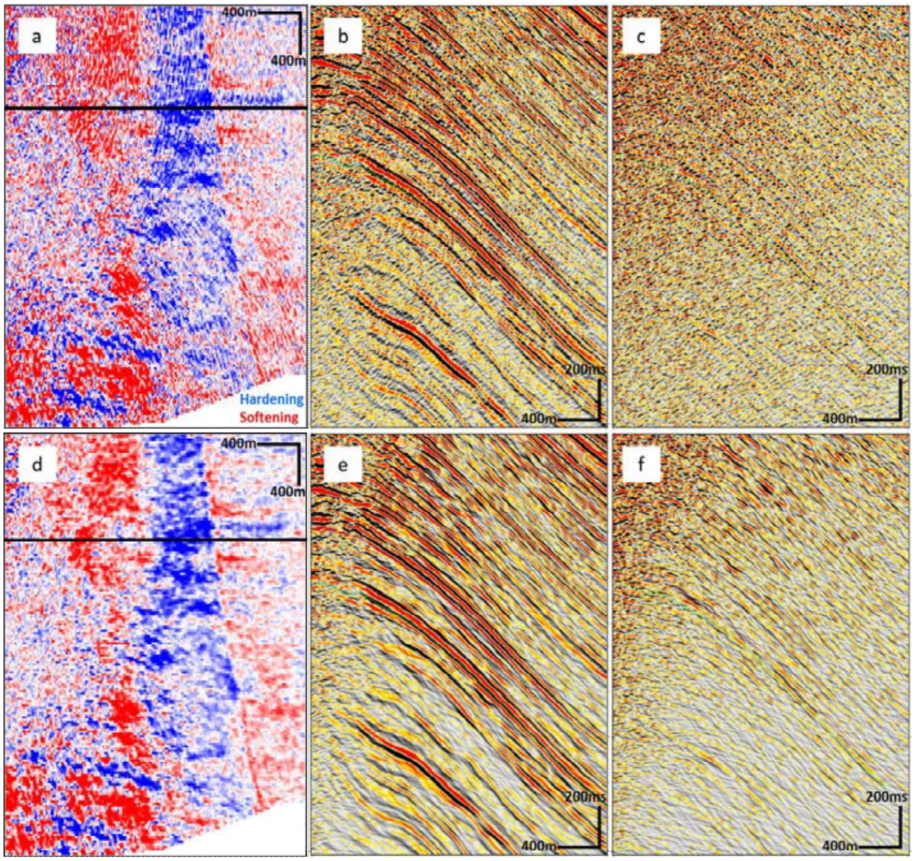

Figure 3: *Conventional KPSDM (a b c) compared to specular KPSDM (d e f) in map view (a and d), 3D section view (b and e) and in 4D difference section view (c and f).*

Discussion and Conclusions

Specular imaging significantly reduces 4D imaging noise. We emphasize that specular imaging is not a signal processing enhancement applied to the image, but a better way of forming the image to start. Only rays obeying Snell's law follow an AVO equation and adding in more data cannot improve the image. In practice, the quality of the separation of the signal into reflections and diffractions can vary, and depends mainly on the migration dip estimation and the accuracy of the migration velocity model.

In the context of 4D, the improved imaging can also prove useful in simplifying, and therefore speeding up, the 4D processing. By better imaging the data, based on a physical principle, we can avoid extraneous signal processing, such as dip-filtering, and thereby avoid signal damage and additional processing time. Dip-angles also provide an intuitive extra dimension in which to locate and attenuate un-cancelled migration operators in 4D. As always in 4D, we can think of creating a coupled version of the algorithm. An example of this was shown by Haacke et al. (2017) who applied 4D similarity filtering to better match towed streamer and OBN 4D data.

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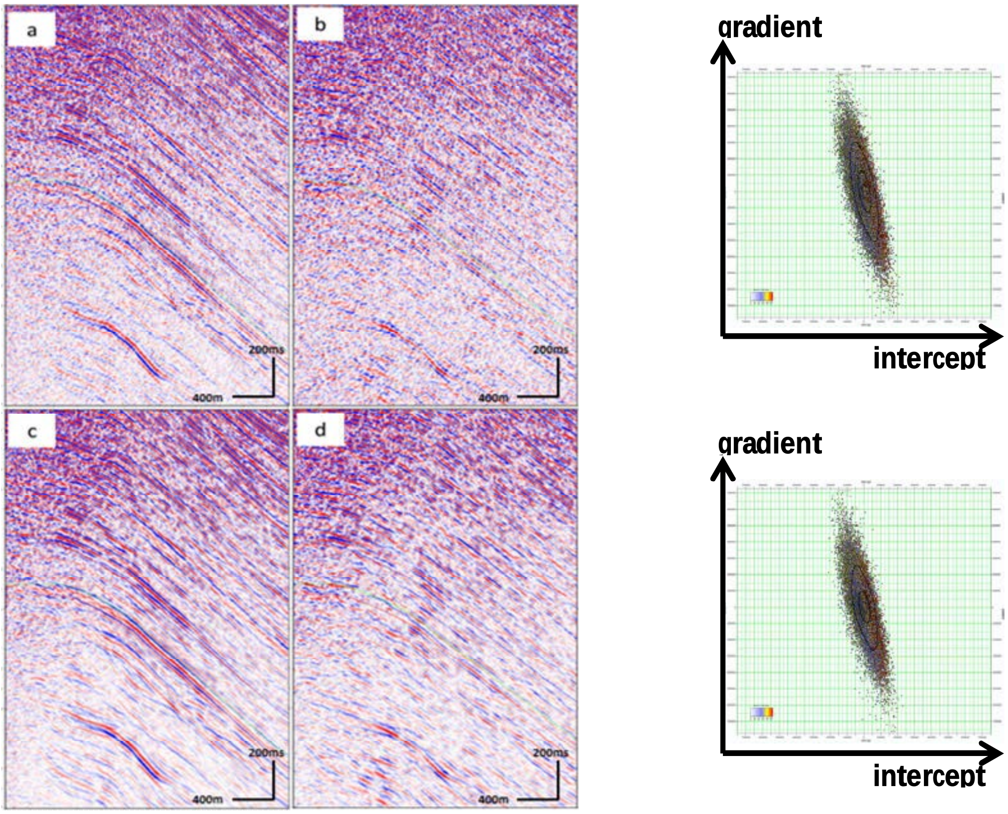

Figure 4: *Comparison of AVO products: Intercept R(0) on the left and Gradient G on the right, with conventional KPSDM (top) and with specular KPSDM (bottom).AVO crossplots around the target on the right.*

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