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Interactive comment on "Coherent diffraction imaging for enhanced fault and fracture network characterization" *by* Benjamin Schwarz and Charlotte M. Krawczyk

Benjamin Schwarz and Charlotte M. Krawczyk

bschwarz@gfz-potsdam.de

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Dear referee,

many thanks for a very positive and encouraging review. We take your comments very seriously and will make sure to fully honour them during the revision of the manuscript. In the following, we provide you with our personal view on the issues you have raised and also indicate, how we intend to alter the manuscript to reflect the desired changes. For convenience, your individual comments appear bold, replies remain in standard font and intended textual modifications/additions are indicated by italic letters.

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Discussion paper

The results confirmed the success of the technique to detect faults and fracture networks, which later on can be implemented in qualitative interpretation. Generally, the article structure is clear and the content is rich. The concepts and techniques, presented in this paper, are novel, and they are supported with enough successful real data examples.
We are happy that you see merit in the proposed methodological framework and that you found the scale-spanning data examples convincing. Thanks for the encouraging feedback.

1. In page 3, line 86, the authors claim that since diffractions do not follow Snell's law, and they always have similar shape, therefore, diffracted signals are often an order of magnitude weaker than their reflected counterparts. Please elaborate on this matter and explain why the diffracted signals are often only an order lower than the reflected signals?
We realise that the way we have formulated these sentences might cause confusion. Instead of "*It is interesting to note that, in contrast to reflections and other wavefield components obeying Snell's law, diffractions always have a similar shape, no matter which data configuration is considered. This implies that diffractions not only provide improved illumination and encode highly resolved information on the structures that caused them, but it also explains why diffracted signals are often an order of magnitude weaker than their reflected counterparts.*" we will include the following sentence: "*In contrast to reflections, diffractions are not constrained by Snell's law and, thus, radiate uniformly in all directions. As a result, diffracted wavefields provide improved illumination and encode highly resolved structural information, but also rapidly decay with increasing distance from the scatterer.*"

2. Page 6, figure 2: please check the section numbering. I recommend to add a section referencing in the figure caption, for instance: While projection-type imaging schemes start directly in data space (refer to section 3.3), focusing techniques typically are image-centred (refer to section 3.2).

Thanks for noticing this mistake and for the good suggestion, we will correct the section numbering and will explicitly refer to the imaging sections via: "*While projection-type imaging schemes (Section 3.3) start directly in data space, focusing techniques (described in Section 3.2) typically are image-centred.*"

3. What is the criteria to define the n-th order of the beam energy and the semblance? Does the algorithm utilize any optimization procedure to find the optimum order? Please elaborate on this matter in the last paragraph of page 8.
This is quite an interesting remark and we fully agree that this could be optimized. However, we also found by means of trial and error in a variety of different scenarios that for values larger than n=10, changes become very subtle and barely distinguishable. Like in earthquake seismology, taking the n-th root leads to an equalization of different amplitudes with the benefit that weak and strong contributions are treated equally in the analysis. Following your advice we now include the following brief discussion in the last paragraph of Section 3.2: "*Taking the n-th root of the amplitude as suggested in expression (5) has the effect of making coherent arrivals of different strength more comparable. While the suggested value of 10 results from experience with a variety of data configurations, it can be shown that this equalization in amplitude typically saturates for a reasonably low n already. In principle, the problem of finding a suitable root order could be phrased as an optimization problem, driven by the amplitude content of the data. However, a fixed value of 10 was shown to be successful in bridging several orders of magnitude and, therefore, is deemed a reasonable choice in most practical scenarios.*"

4. Page 10, figure 4: please explain whether augmentation is applied on the phase reversed semblance, or on the semblance directly? Besides, the explanation in the text about the algorithm and order of applying both phase reversing and augmentation is not clear.
You are right, we should have spent some more time on sufficiently explaining the "*augmentation*". In line with referee 1 who had very similar remarks we will include

the following additional sentences to describe the process (starting in line 220): "*Every data point is once treated as a potential stationary point at which an artificial phase reversal is performed before evaluating the coherence measure. Both results, the one gained without reversing the phase, and the one for which the phase is reversed, are compared and the higher value contributes to the augmented image.*"

5. Do the diffraction images, obtained via the coherent focusing technique, have the capability to be employed for future quantitative interpretation purposes?
You are right, we believe this is quite important to stress. To account for your question, we will conclude the discussion section with a dedicated paragraph on the implications of coherent diffraction imaging for (structural and quantitative) interpretation. Specifically, we will include the following sentences: "*The non-normalized beam energy (n=1) directly relates to the diffraction's focusing intensity, which is proportional to the square of the beam's amplitude and, therefore, to the strength of the impedance contrast at which diffraction occurred. On the contrary, higher-order versions of the beam energy (n>1) no longer deal with accurate, but rather distorted amplitude and phase information and, accordingly, cannot be used for quantitative interpretation. The same holds for the semblance norm in general, as its intrinsic normalization "evens out" amplitude discrepancies due to material contrasts of different strength. While all of the coherence measures suffer from the loss of phase information in the final reconstruction, the semblance coefficient, due to its normalization, can be used as a reliable weight for artefact and noise suppression in conventional wavefield focusing. The resulting images have higher quality yet largely preserve amplitude and phase information critical for quantitative geological interpretation of the imaged geology.*" In order to properly account for the importance of interpretational implications, we will rearrange and subdivide the discussion section into the following distinct subsections: "*5.1 Potential and extension of the method*", "*5.2 Limitations and challenges*" and "*5.3 Geological interpretation*" and additionally address attribute analysis in the following new paragraph: "*While the presented workflow discusses the best use of the physical information content of the recorded data through diffraction-targeted processing, structural interpretation makes*

additional use of the growing amount of seismic attributes (Chopra and Marfurt, 2005; Barnes, 2016) – an integral approach of seismic interpretation aiming at mapping geological features. Like coherence (gained via cross-correlation of neighbouring traces in the reflection dominated migrated image), these attributes are often used on their own to improve the interpretation of fault structures. Alternatively, attributes can be assessed in combination or help in establishing cross-plotting maps (e.g. Endres et al., 2008; Lohr et al., 2008; Torrado et al., 2014; Wang et al., 2015). In this frame, coherent diffraction images can be viewed as physics-guided feature maps that naturally complement more conventional attributes commonly used for interpretation. To additionally foster the bridging from faults to fractures, data acquisition can likewise play an important role (see concept and example in Krawczyk et al., 2015). In near-surface applications in the field, using shear waves instead of compressional waves for seismic surveying has proven a powerful strategy for increasing structural resolution (e.g. Krawczyk et al., 2012; Beilecke et al., 2016). A combination of the proposed high-resolution imaging workflow with these new forms of data acquisition is expected to shed additional light on subsurface pathways, fault extent and fault connections in the subsurface, which are increasingly important for the assessment of structural integrity and fault behaviour or, ultimately, deformation monitoring in an area."

6. Page 17, line 347: what do the authors mean with "a high degree of structural completely" Please check the sentence.
Thanks for pointing this out, the word "*complexity*" was accidentally misspelled.

On behalf of the authors,
Benjamin Schwarz

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