First field data examples of inverse scattering series direct depth imaging without the velocity model

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Summary

In Weglein et al. (2010) an update and status report were provided on the progress on the inverse scattering series (ISS) direct depth imaging without the velocity model.

In that report, results on synthetics with sufficient realism indicated that field data tests were warranted. This paper documents those first field data tests. These first early tests are encouraging and indicate that ISS direct depth imaging on field data is possible. The next steps on the road between viable and providing relevant and differential added value to the seismic tool-box are described and discussed.

Introduction / Background

All currently applied direct depth imaging methods and indirect imaging concepts firmly believe that depth and velocity are inextricably linked. That cornerstone of all current imaging means that any direct imaging method requires an accurate velocity model to produce an accurate image in depth.

It is essential to understand the significance of the term 'direct' in 'direct depth imaging'. Given an accurate velocity model, all current leading-edge imaging methods (e.g., Kirchhoff, FK, Beam and RTM) are able to directly output the depth (the actual spatial configuration) of reflectors.

Indirect imaging methods (e.g., flat common image gathers, differential moveout, CFP, CRS and 'path integral' approaches) seek to satisfy a property or condition that an image with an accurate velocity would satisfy. Those properties are necessary conditions, but not sufficient, and hence satisfying the indirect proxy for an adequate velocity model is not equivalent to knowing the velocity and direct depth imaging. Hence, satisfying these indirect criteria is no guarantee, and can lead to the correct depth or to any one of a set of incorrect depths. The latter truth is rarely (if ever) spoken and even rarer to find mentioned in print. Most importantly, these indirect approaches fervently believe that a direct depth imaging method would require and demand a velocity model, and that there is absolutely no way around it, and that depth and velocity are inextricably connected. That thinking is clear, and 100% correct within the framework of current imaging concepts and methods.

However, that thinking is superseded by the new broader framework for imaging provided by the ISS.

Amundsen et al. 2005, 2006, 2008 have developed direct inversion methods for 1D acoustic and elastic media. The ISS is the only direct inversion for both a 1D and a multi-D acoustic, elastic and anelastic earth.

In addition to being direct and applicable and applied for a multi-D earth, the ISS (Weglein et al. (2003)) allows for all processing objectives (including multiple removal and depth imaging) to be achieved directly and without subsurface information.

In the same 'direct' sense, that current imaging methods can directly output the spatial configuration of reflectors with a velocity model, ISS imaging algorithms can directly output the correct spatial configuration without the velocity model. It is the only method with that capability.

The ISS subseries for direct depth imaging communicates that depth and velocity are not inextricably linked.

The ISS provides a new superseding theory that views the current velocity-depth relationship and framework as a special limiting case, as quantum mechanics and relativity view classical physics as a limiting and special case, within a new comprehensive and broader platform and framework.

The new broader framework for imaging reduces to current imaging algorithms when the velocity model is adequate, and most amazingly it determines on its own for any particular data set, or portion of a data set, whether the new framework is needed, or whether the current conventional imaging framework will suffice. The new imaging framework determines if its services are called upon, and then and only then, will it activate the new ISS imaging framework terms and call them into action.

All current leading edge migration methods, such as, beam, Kirchhoff and RTM, are linear. In contrast, the ISS direct depth imaging without the velocity algorithm is a non-linear relationship between data and the wavefield at depth.

ISS task specific subseries for multiple removal, depth imaging and direct non-linear AVO

Each and every term and portion of any term within the ISS is computed directly in terms of data. All tasks associated with inversion (e.g., multiple removal, depth imaging, non-linear direct AVO, and Q compensation) are each contained within the series. Hence, these individual tasks are each achievable directly in terms of data, without subsurface information. Every seismic processing objective is carried out as a subseries of

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the ISS, and operates without subsurface information, by involving distinct non-linear communication of the recorded seismic data. Only the ISS communicates that all seismic objectives can be achieved in basically the same way that free surface multiples are removed.

The free surface and internal multiple removal subseries have not only been shown to be viable but have also demonstrated added value and stand alone capability for predicting the amplitude and phase of multiples (See, e.g., Luo et al. 2011; Weglein and Dragoset 2005; Fu et al. 2010), in particular, demonstrated under complex marine and on-shore circumstances. In this paper, we examine for the first time the issue of ISS depth imaging viability on field data.

All conventional imaging methods require knowledge of the velocity model to determine the spatial locations of reflectors. Hence, the ISS series project began by assuming that only the velocity was variable and unknown. Figures 1-3 illustrate the ISS imaging results for an earth in which only velocity varies. The algorithms are described in Liu (2006); Liu et al. (2005); Zhang et al. (2007).

Imaging methods that require the velocity use only the phase of the data to determine depth. In contrast, all ISS tasks achieve their goals without subsurface information by using both the amplitude and phase of seismic data. The latter difference requires the exclusion of events from imaging subseries that do not relate to or contribute towards the task of depth imaging. Reflections that correspond to density only changes must be precluded from exclusively depth imaging tasks. The ISS depth imaging in an acoustic earth where V_p and density (and for an elastic earth with V_p, V_s and density), can all vary and all are initially (and remain, completely) unknown was formulated and the results were summarized in Weglein et al. (2010).

The impact of data limitations on ISS subseries

Table 1 summarizes the dependence/sensitivity of different ISS subseries on seismic bandwidth. As the latter table indicates, there is an increased dependency as we progress from the ISS free surface multiple case to the depth imaging subseries where (in the current "box-moving" formulation) the absence of low frequency in the data can have a deleterious effect on the ability of the ISS to move from the original linear incorrect depth image to the correct depth.

There are many other issues that need to be taken into consideration in developing practical ISS depth imaging algorithms. Among these issues are: (1) have the appropriate number and types of terms from the inverse series been included to match the imaging challenge due to the difference between the actual and reference velocity, and the duration of that difference; and (2) have the density only reflections been excluded from the ISS depth imaging algorithm. All of these issues need to be addressed to have the ISS depth imaging algorithm produce an accurate depth section. The moveout becomes flat and the imaging series directly produces a flat common image gather (CIG) at the correct depth.

In contrast to all current imaging methods where CIG flatness is a necessary but not a sufficient condition for depth imaging accuracy, the CIG flatness is a by-product of ISS imaging, and a necessary and sufficient indication that depth has been found. It's a direct depth finding machine, and when it stops it is done. With ISS imaging CIG flatness is an indication that a direct method is done, not an in-direct proxy for velocity used to find the depth, where for the latter conventional use it is necessary but not sufficient for depth location.

The overriding requirement and number one issue for field data application of ISS depth imaging is being able to address the sensitivity to missing low frequency components in the data (or low vertical wave number). If that low frequency sensitivity is not addressed, then gathering or not gathering appropriate and necessary ISS imaging terms or excluding density only reflections will not matter, and will be of no practical consequence. Hence, addressing the bandwidth issue for ISS imaging is the number one priority, the make or break issue for field data application, viability and delivery of its promise of high impact differential added value. A regularization scheme has been developed in Liu and Weglein (2009) to directly address that low frequency challenge. The purpose of this paper is to examine whether this regularization method will allow the ISS imaging algorithms to be effective and work on field data. Therefore, with this first field data examination, we relax all of the other requirements for ISS depth imaging and consider the field data as though it were generated by a velocity only varying earth. Within that parallel world where only velocity varies, the ISS depth imaging will need to address the band-limited nature of field data, and also will require having enough ISS imaging terms (within an acoustic velocity only varying subsurface assumption) to be effective for accurately locating reflectors.

In Figure 4, we present an acoustic model with no density variations and the water speed migration for the data from that model. Figure 5 (a) shows the inverse scattering imaging series ideal result, with full band-width data. In (b), the data has been altered by a sine squared taper up to $10Hz$ which damped the low frequency information and the ISS imaging without regularization is ineffective. In (c), with the regularization applied, the ISS depth imaging successfully corrects the data move-out and reveals the correct depth.

A similar approach is followed for a CMP gather selected from the Kristin data-set (Figure 7, Majdanski et al. (2010)). Figure 8 (a) shows a water-speed migration of the data in Figure 7, while Figure 8 (b) shows the ISS imaging result after regularization.

Event 1 is the water bottom primary, event 2 is the subwater bottom primary, event 3 is the internal multiple between event 1 and 2 and event 4 is a third primary. Event 4, the third primary has a moveout with a water

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speed migration.

It turns out that event 1, the water-bottom primary, represents a density change but no velocity change. Hence, the layer below the water-bottom has the same acoustic velocity as water. Further, the first order internal multiple (event 3) in that first sub-water-bottom layer also has a water-speed move out. Hence, events 1, 2, and 3 all have flat CIGs with a water-speed FK Stolt migration (Figure 6). Event 4 has move-out due to a velocity change at the base of the first sub-water-bottom reflector.

With a regularized ISS depth imaging the result for the image of event 4 is a shifted and CIG flat output. Hence, the ISS depth imaging is working on the very shallow subsea-bottom portion of the Kristin data set within the context of a velocity only varying earth. The shifted ISS image and flat CIG of event 4, the third primary, indicates that bandwidth issues have been addressed, and sufficient capture of ISS imaging terms are within the ISS imaging algorithm. If for this field data set and ISS depth imaging test, either one of these conditions (addressing bandwidth sensitivity and adequate inclusion of ISS imaging terms) were a remaining and outstanding issue, then event 4 would not have moved and produced a flat CIG. The success of this test is thus defined. A more detailed and comprehensive analysis behind the logic and conclusions of this paper will appear in Weglein et al. (2012). The next steps are to apply the regularized ISS depth imaging to an acoustic variable velocity and density model for the very shallow and sub-water-bottom reflectors, and a Vp, Vs and density varying elastic earth model for the deeper reflectors, to preclude density only reflections, and for outputting actual depth. The M-OSRP imaging research team is engaged in moving from the current news and report that demonstrates field data viability for ISS imaging to providing added value. The ultimate goal is to have ISS imaging match the efficacy that ISS free surface and internal multiple removal have provided for the removal of coherent noise, and to extend that capability for extracting information from signal (the collection of all primaries).

Conclusions

In this paper, we have shown that the ISS depth imaging algorithm can address the most serious practical limitation/challenge field data will place on ISS depth imaging: that is, limitations in seismic bandwidth. With this accomplished, the further steps to extend these tests to variable density and velocity acoustic and elastic media are achievable, and realizing that is within the sphere of issues we can influence and make happen. The most significant difference between synthetic data and field data for ISS depth imaging has been examined and addressed.

Acknowledgment

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Figures

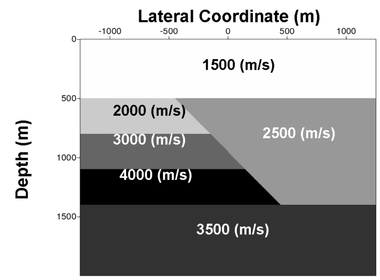

Fig. 1: The fault shadow zone model.

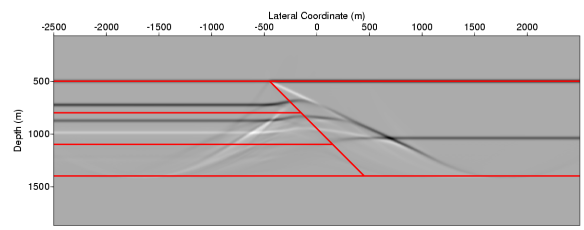

Fig. 2: The water speed pre-stack FK Stolt migration for the data from the fault shadow model.

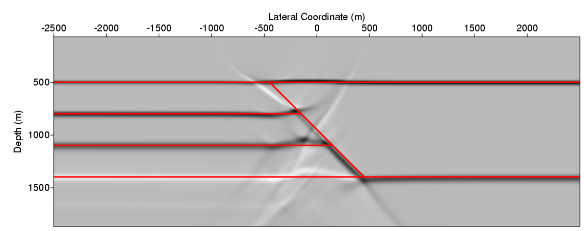

Fig. 3: The inverse scattering series image (with partial capture of ISS imaging capability) for the fault shadow model.

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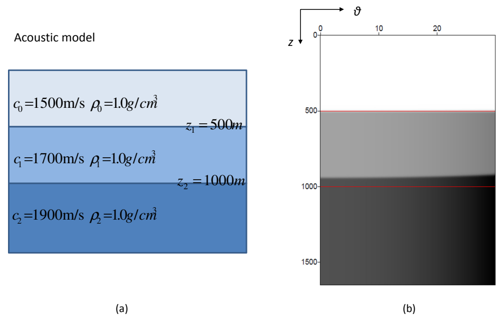

Fig. 4: Figure (a) shows the acoustic model we are testing for evaluating the dependence of ISS on seismic bandwidth. Figure (b) is the water speed FK Stolt migration, the red lines represent the true location of the reflectors.

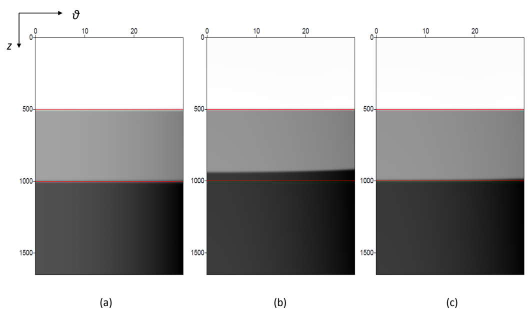

Fig. 5: This figure illustrates the imaging result for a velocity varying only earth model. Figure (a) shows ISS imaging with data which has low frequency information. Figure (b) shows ISS imaging with band-limited data. Figure (c) shows the imaging result with the regularization being applied. This ISS imaging bandwidth issue is documented in Shaw (2005).

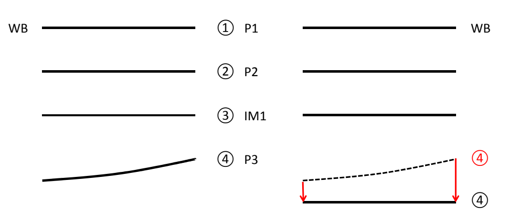

Fig. 6: This figure summarizes the results of the initial ISS depth imaging tests on the very shallow, near ocean bottom section of the Kristin data.

Dependence on temporal frequency content of the data	Specific subseries
None	Free surface multiple
Very mild	Internal mulitple
Some	Depth imaging

Table 1: This table shows the dependence of ISS specific subseries on temporal frequency content of the data.

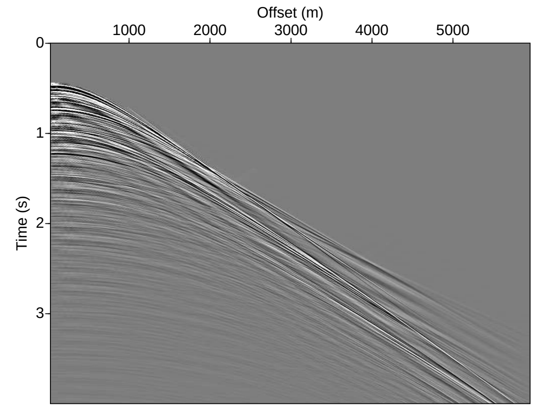

Fig. 7: The CMP gather we tested from Kristin data.

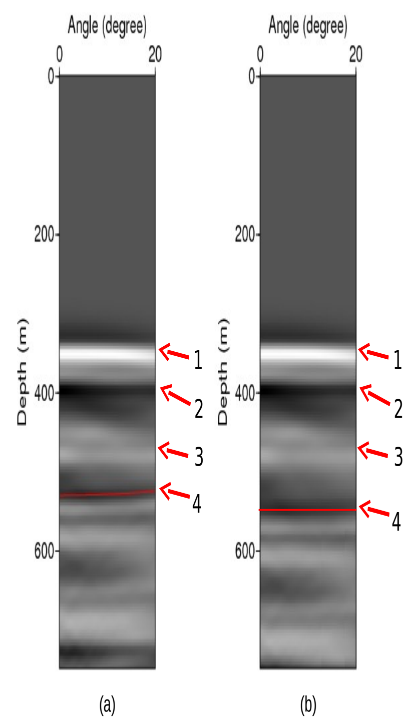

Fig. 8: For the Kristin data test: Figure (a) shows water speed migration. The red line indicate water speed migration image for event 4. Figure (b) shows ISS imaging result. The red line shows ISS image for event 4.

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