A perspective on the role of primaries and multiples in seismic data processing: Keynote address

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2022 SEG Workshop: FWI/FWM: exploring new concepts of seismic imaging

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- Since this workshop involves the use of primaries and multiples for certain processing objectives
- I thought that it would be useful to provide an overall perspective of the role that primaries and multiples play in seismic processing, hence, the title.
- Let's begin

Introduction

- Let's start with multiples
- Multiple removal has been a long-term objective in seismic exploration. Recent methods that use multiples for different processing goals and objectives can be worthwhile. However, their use can also be a source of confusion as to whether the removal is no longer essential, a priority, or even necessary since some may now view multiples as "rehabilitated" and sit along side primaries as entirely useful events.

Introduction

One purpose of this presentation is to disabuse us of that seriously flawed and erroneous thinking and to understand that the **use of multiples for imaging and the removal of multiples have the same exact goal and objective: the imaging of primaries.**

Introduction

- Multiples (continued)
- Furthermore, we explain exactly why multiples need to be removed in **all direct** and **indirect** seismic processing methods — and therefore why **multiple removal remains a key and central issue and challenge in seismic exploration.**

The role of multiples in Direct and Indirect Seismic Processing Methods

In what follows, we will explain why all direct and indirect seismic processing methods remove multiples at some step or stage within the method. Within indirect methods that analysis will include FWI/FWM.

The role of multiples in Direct and Indirect Seismic Processing Methods

Among references that define (and distinguish between) direct and indirect seismic processing methods are: Weglein (2013) [A timely and necessary antidote to indirect methods and so-called P-wave FWI, The Leading Edge]

The role of multiples in Direct and Indirect Seismic Processing Methods

Among references: Weglein, 2017, Interpretation, Invited Paper [A direct inverse method for subsurface properties: The conceptual and practical benefit <u>and added value of direct methods in comparison with all current indirect methods</u>, for example, <u>amplitude-variation-with-offset and full-waveform inversion</u>]

The role of multiples in Direct and Indirect Seismic Processing Methods

Among references: Weglein (2018) [Direct and indirect inversion and a new and comprehensive perspective on the role of primaries and multiples in seismic data processing for structure determination and amplitude analysis, CT&F — Ciencia, Tecnologia y Futuro].

Why? (Weglein, Journal of Seismic Exploration, exactly why all multiples must be removed in all direct seismic processing methods. What about indirect methods?)
How? (Weglein, Jing Wu, Fred Melo, and John Etgen, Journal of Seismic Exploration, a toolbox approach to multiple removal)

The role of multiples in Direct and Indirect Seismic Processing Methods

We can view this presentation as the first of a two part set, with the first one here (basically asking "why") and the second presentation asking "how?". In the link below please find the second presentation.
http://mosrp.uh.edu/news/two-papers-to-appear-in-jse-in-february-2022

An overview of this presentation

Seismic Processing

Direct ↙		↘ Indirect
• Direct with a velocity	• Direct without subsurface information	• Satisfy a property CIG flatness
• Migration	• Inverse scattering series	• Forward problem in an inverse sense AVO
• Using recorded multiples to find an approximate image of an unrecorded primary. FWM.	• Isolated task subseries that remove free surface and internal multiples	• model matching FWI
• Illumination		

Direct Seismic Methods

For the purposes of this presentation, it is useful to separate direct methods that require or do not require a velocity model.

- Direct seismic methods with a velocity model
- Migration is a direct method that requires a velocity model
- We examine migration for homogeneous, continuous and discontinuous velocity models

- Migration only has meaning for primaries
- Methods that employ the wave equation for migration have two ingredients: (1) a wave propagation concept and (2) an imaging condition or principle.

Three imaging principles

- For one way propagating waves, Jon Claerbout (1971) [Toward a unified theory of reflector mapping, Geophysics] described three imaging principles
  - (1) the exploding reflector
  - (2) time and space coincidence of up and down going waves, and
  - (3) predicting a source and receiver experiment at a coincident-source-and-receiver subsurface point, and asking for time equals zero

Direct seismic methods with a velocity model — towards migration in homogeneous, continuous and discontinuous velocity models

We will refer to these original imaging conditions as Claerbout I, II and III. Claerbout I (the exploding reflector model) only relates to stacked or zero offset data. Claerbout II and Claerbout III are valid for prestack data. The third imaging condition, CIII, stood alone in terms of clarity and definitiveness and in its potential to be extended for complex structure and associated amplitude analysis.

Wave Theory Seismic Migration

- All current migration methods make high frequency approximations in either the imaging principle and/or the propagation model.

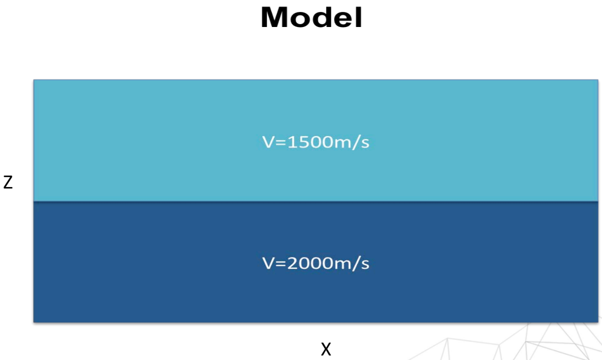

Figure 1: *Model used to compare CIII, CII (RTM) and Kirchhoff migration for one source and one receiver, using analytic data.*

Imaging Principles and High Frequency Assumptions

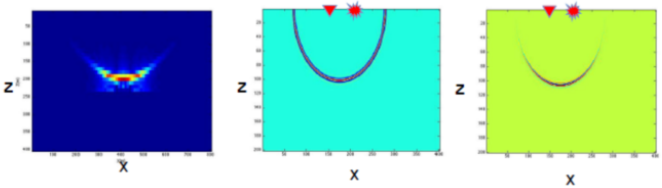

Figure 2: *The response from one source and one receiver above a single horizontal reflector. Left: No high frequency assumption, CIII. Center: High frequency assumption, RTM. Right: High frequency approximation from a stationary phase approximation, Kirchhoff. The ray theory travel time curves for RTM and Kirchhoff migration indicate an intrinsic high frequency approximation in those methods. CIII doesn't have ray theory candidate images. It's a yes or no at every subsurface point.*

The evolution of the CII and CIII imaging principles

CII in depth $\rightarrow$ RTM in time Whitmore (1983); McMechan (1983) $\rightarrow$ RTM + geometric optics, high frequency approximate reflection coefficient (Zhang et al., 2007; Xu et al., 2011)
CIII $\rightarrow$ SCIII extension automatically allowed for migration-inversion (i.e., structure followed by amplitude analysis) for planar (a reflection coefficient), and a point scatterer for curved and pinchout reflectors
CIII $\rightarrow$ SCIII $\rightarrow$ for homogeneous or smooth velocity models (with WKBJ high frequency approximation) Stolt and Weglein (1985, 2012)
$\rightarrow$ SCIII for heterogeneous smooth and discontinuous velocity models without high frequency approximation Weglein et al. (2016)

The evolution of the CIII imaging principle

Stolt Claerbout III extended the Claerbout III imaging principle in two ways:
(1) non-coincidence of the predicted source-receiver experiment (at t=0) allowed for amplitude analysis at the imaged point
(2) the point scatterer model allowed for imaging and inversion at planar, curved and pinchout reflectors

CIII Imaging Principle Evolution to SCIII: References for SCIII evolution

Stolt and Weglein (1985) [Migration and inversion of seismic data, Geophysics] and Stolt and Weglein (2012) [Seismic Imaging and Inversion: Application of Linear Inverse Theory, Cambridge University Press] extended the original CIII imaging principle for more physically complete and accommodating structural models, and in addition provide a detailed angle dependent amplitude analysis at the target, for both specular and non-specular reflection. (curved and pinchout reflectors) We label the latter imaging principle extension of CIII as Stolt Claerbout III migration (or SCIII).

The imaging principle for maximum reflector type accommodation and effectiveness

- The most physically complete and accommodating imaging principle is what we call Stolt Claerbout III or SCIII migration.

Wave propagation model evolution for SCIII imaging principle for heterogeneous and discontinuous media

- M-OSRP has recently extended that SCIII imaging principle and migration method to
  - (1) to avoid high frequency one-way wave asymptotic approximations in smooth velocity models.
  - (2) accommodate discontinuous velocity models, and

Item (1) assures that SCIII makes no high frequency approximation in both the imaging principle and propagation model, and (2) makes it the only migration method that can be analyzed for data consisting of primaries and multiples.

Wave propagation model evolution for SCIII imaging principle for heterogeneous and discontinuous media

Again, only CIII or SCIII could be extended to accommodate imaging within a discontinuous medium, the latter required to analyze (for the first time) and to unambiguously define the role of primaries and multiples in migration. To have a consistent theory that analyzes a data consisting of primaries and multiples, we must have the ability to migrate in a discontinuous medium, above and beneath each reflector.

Wave propagation model evolution for SCIII imaging principle for heterogeneous and discontinuous media

The predicted coincident source and receiver experiment at depth consists of all the events that experiment would record, if you actually had a source and receiver at that subsurface location.

Wave propagation model evolution for SCIII imaging principle for heterogeneous and discontinuous media

Weglein et al. (2016) [The first migration method that is equally effective for all acquired frequencies for imaging and inverting at the target and reservoir, SEG Expanded Abstracts]
Yanglei Zou, Qiang Fu, and Arthur Weglein, (2017),
"A wedge resolution comparison between RTM and the first migration method that is equally effective at all frequencies at the target: Tests and analysis with both conventional and broadband data," *SEG Technical Program Expanded Abstracts* : 4468-4472.

Wave propagation model evolution for SCIII imaging principle for heterogeneous and discontinuous media

- The most physically complete and accommodating imaging principle is what we call Stolt Claerbout III or Stolt CIII migration.
- M-OSRP has recently extended the propagation model for that imaging principle and migration method to
  - (1) accommodate discontinuous velocity models, and
  - (2) to avoid high frequency one-way wave asymptotic approximations in smooth velocity models. The latter is the only migration method that is: (1) able to input primaries and multiples and for a continuous or discontinuous velocity model, and (2) is equally effective at all frequencies.

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The RTM imaging condition is usually implemented by using crosscorrelation between **R** and **S** as follows:

$$\mathbf{I}(\mathbf{x}) = \sum_{\mathbf{x_s}} \sum_{\omega} \mathbf{S}'(\mathbf{x}, \mathbf{x_s}; \omega)\mathbf{R}(\mathbf{x}, \mathbf{x_s}; \omega) \tag{1}$$

where $\mathbf{x} = (x, y, z)$ is each image position, ω is the angular frequency, and $\mathbf{x_s} = (x_s, y_s, z_s)$ is each source position. **R** and **S'** denote the receiver and source wavefields, respectively (Whitmore et al., 2010).

RTM (its ad hoc nature)

The sum over $\mathbf{x_s}$ in eqn (1) is an "ad hoc fix" to the inconsistent image from above a single horizontal reflector for one-shot record. There is no physics behind that sum over $\mathbf{x_s}$.

It's amazing that the method of migration, RTM, (that begins and ends the topic of migration for many individuals) doesn't have a physics derivation, and resorts to ad hoc fixes within its "derivation". The CII (RTM) imaging principle is supposed to "work for one-shot record" — and the stacking over shot records, seeks to address an intrinsic problem, with a form of "stacking" as if the CII (RTM) intrinsic shortcoming produces a form of coherent noise.

Stolt Claerbout III migration for a homogeneous, and smoothly varying high frequency one way propagation assumption at every point

For one-way wave propagation in a homogeneous or smoothly varying 2D medium (with a high frequency approximation) the predicted source and receiver experiment at depth, $D(x_g, z_g, x_s, z_s, \omega)$ is

$$D(x_g, z_g, x_s, z_s, \omega)(\text{at depth}) = \int_{S_s} \frac{\partial G_0^{-D}(x_s, z_s, x_s', z_s', \omega)}{\partial z_s'} \times \left[\int_{S_g} \frac{\partial G_0^{-D}(x_g, z_g, x_g', z_g', \omega)}{\partial z_g'} D(x_g', z_g', x_s', z_s', \omega)\, dS_g' \right] dS_s', \quad (2)$$

where the inner integral over dS_g' produces $D(x_g, z_g, x_s', z_s', \omega)$ and the outer integral then produces the left hand side of equation (2), $D(x_g, z_g, x_s, z_s, \omega)$, where (x_g, z_g) and (x_s, z_s) are the coordinates of the predicted receiver and source at depth, and D in the integrand is the data, D(on the measurement surface). (Clayton and Stolt, 1981; Stolt and Weglein, 1985)

Stolt Claerbout III migration for a homogeneous, and smoothly varying high frequency one way propagation assumption at every point

G_0^{-D} is the anticausal Green's function for a homogeneous or smoothly varying medium with Dirichlet boundary condition on the measurement surface, s connotes shot, and g, receiver, respectively. **The high frequency approximation assumes** that at every point in the continuously varying medium the **propagation is one way** (Clayton and Stolt, 1981; Stolt and Weglein, 1985).

New from M-OSRP: Direct seismic methods with a velocity model — SCIII migration, in continuous media <u>without one-way high frequency approximations and in discontinuous velocity models</u>

Weglein et al. (2016) [The first migration method that is equally effective for all acquired frequencies for imaging and inverting at the target and reservoir, SEG Expanded Abstracts] provided that wave propagation extension of SCIII to allow a continuous medium without a one way propagation at each point and a discontinuous medium above a target and to image above and below each reflector, without any artifacts or issues such as "rabbit ears". That new migration algorithm is represented in equations (3), (4) and (5) below.

New from M-OSRP
Stolt Claerbout III migration for two-way propagation globally and locally at every point, in smoothly varying continuous media and <u>discontinuous</u> media

For two-way propagation, e.g., in a discontinuous medium above the image point (i.e., above the target reflector), we begin with the recorded data $D(x'_g, z'_g, x'_s, z'_s, \omega)$ on horizontal measurement surfaces, with $z'_g = $ constant and $z'_s = $ constant.

New from M-OSRP

Discontinuous velocity Stolt CIII migration

The predicted experiment for the receiver at x_g, z_g, at depth, and the source at x'_s, z'_s (on the measurement surface) is

$$\int \left\{ \frac{\partial G_0^{DN}}{\partial z'_g}(x_g, z_g, x'_g, z'_g, \omega)\, D(x'_g, z'_g, x'_s, z'_s, \omega) \right.$$
$$\left. - G_0^{DN}(x_g, z_g, x'_g, z'_g, \omega)\, \frac{\partial D}{\partial z'_g}(x'_g, z'_g, x'_s, z'_s, \omega) \right\} \underbrace{dx'_g}_{dS_g}$$
$$= D(x_g, z_g, x'_s, z'_s, \omega) \qquad (3)$$

Stolt Claerbout III migration in smoothly varying or discontinuous media

A second application of Green's theorem inputs (3) and then predicts the experiment for both the receiver at x_g, z_g and the source at x_s, z_s, at depth, using equation (4) below

$$\begin{aligned}
&\int \Big\{ D(x_g, z_g, x_s', z_s', \omega) \frac{\partial G_0^{DN}}{\partial z_s'}(x_s, z_s, x_s', z_s', \omega) \\
&\quad - G_0^{DN}(x_s, z_s, x_s', z_s', \omega) \frac{\partial D}{\partial z_s'}(x_g, z_g, x_s', z_s', \omega) \Big\} \underbrace{dx_s'}_{dS_s} \\
=& D(x_g, z_g, x_s, z_s, \omega) \qquad (4)
\end{aligned}$$

Equation (4) is the prediction required for Stolt Claerbout III migration for heterogeneous (and discontinuous) media. G_0^{DN} is the Green's function for wave propagation in the finite volume that vanishes along with its normal derivative on the lower surface of the finite volume. $dS_g = dx_g'$ and $dS_s = dx_s'$ in a 2D prediction. An integral of equation (4) over ω, and setting $z_g = z_s$, produces the predicted experiment at t=0 and SCIII migration.

Wave propagation model evolution for the SCIII imaging principle for heterogeneous and discontinuous media

Stolt CIII migration for heterogeneous media for layers and continuous media without making a high frequency approximation in either the imaging principle or the propagation model. Combining equation (3) and (4) we have:

$$D(at\ depth) = \int_{S_S} \left[\frac{\partial G_0^{DN}}{\partial z_S} \int_{S_g} \left\{ \frac{\partial G_0^{DN}}{\partial z_g} D(m.s.) - \frac{\partial D(m.s.)}{\partial z_g} G_0^{DN} \right\} dS_g - G_0^{DN} \frac{\partial}{\partial z_S} \int_{S_g} \left\{ \frac{\partial G_0^{DN}}{\partial z_g} D(m.s.) - \frac{\partial D(m.s.)}{\partial z_g} G_0^{DN} \right\} dS_g \right] dS_S \quad (5)$$

D(m.s.) is the data on the measurement surface, D(at depth) is the left hand side of equation (4). Constructing the Green's function, G_0^{DN}, for SCIII equation (3), (4) and (5), for continuous and discontinuous media can be found in all five references: Weglein et al. (2011a), Weglein et al. (2011b), F. Liu and Weglein (2014), Weglein et al. (2016) and Y. Zou et al. (2017).

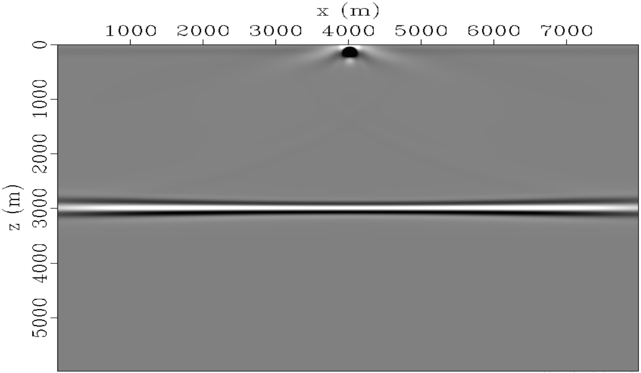


Figure 3: *Claerbout II RTM image from beneath the reflector (in Figure 2) after artifacts (rabbit ears) removal. Please note the inconsistent image along the reflector.*

Figure 4:

New SCIII migration beneath a single reflector with a discontinuous velocity model (please, e.g., imagine migrating through top salt). The new M-OSRP Claerbout III (Stolt extended) migration for 2 way wave propagation (for heterogeneous media)

- The example with $\frac{c_0}{c_1}$ velocity
- The image both above and beneath the reflector

Qiang Fu et al

Light color – image from above
Dark color – image from below

•No “rabbit ears”
•Consistent image along the reflector

Figure 5: *Zoom-in of Figure 4 The new M-OSRP Claerbout III (Stolt extended) migration for 2 way wave propagation. The example with c_0/c_1 velocity. The image both above and beneath the reflector. No "rabbit ears". Consistent image along the reflector. Light color – image from above. Dark color – image from below. (Qiang Fu and Weglein, 2015)*

RTM cannot accurately image (above or) beneath a single horizontal reflector even with perfect analytic data
The new SCIII for heterogeneous continuous and discontinuous media eqn (5)

$$D(at\ depth) = \int_{S_S} \left[\frac{\partial G_0^{DN}}{\partial z_S} \int_{S_g} \left\{ \frac{\partial G_0^{DN}}{\partial z_g} D(m.s.) - \frac{\partial D(m.s.)}{\partial z_g} \right. \right.$$

$$\left. - G_0^{DN} \frac{\partial}{\partial z_S} \int_{S_g} \left\{ \frac{\partial G_0^{DN}}{\partial z_g} D(m.s.) - \frac{\partial D(m.s.)}{\partial z_g} G_0^{DN} \right\} dS_g \right] \tag{6}$$

can accommodate discontinuous media, naturally, without artifacts (or image damage caused by artifact removal).

- Weglein et al. (2016) introduced SCIII for heterogeneous continuous and <u>discontinuous</u> media and demonstrated the high frequency approximation within all current migration methods (e.g., all forms of RTM). Hence, SCIII is the only migration method able to analyze the role of primaries and multiples in migration.
- Yanglei Zou et al., (2017) [A wedge resolution comparison between RTM and the first migration method that is equally effective at all frequencies at the target: tests and analysis with both conventional and broadband data, SEG Expanded Abstracts]
- Quantifying the resolution differences between RTM and SCIII

For the same bandwidth, SCIII could identify a layer where RTM predicted it was a single reflector.

An initial study to quantify the resolution difference between an industry leading-edge migration, RTM, and the first migration method that is equally effective at all frequencies at the target

Qiang Fu, Yanglei Zou, and Arthur B. Weglein, M-OSRP/Physics Dept./University of Houston

SUMMARY

There is an industry-wide interest in acquiring lower-frequency seismic data. There are industry reports that (1) when comparing the new and more expensively acquired broad-band lower-frequency data with conventional recorded data, taken over a same region, these two data sets have the expected difference in frequency spectrum and appearance, but (2) they often provide less than the hoped for difference in structural improvement or added benefit for amplitude analysis at the target and reservoir. There are two objectives of this paper: (1) to demonstrate that all current migration and migration-inversion methods (the methods that take recorded data and determine structure and perform amplitude analysis, respectively) make high-frequency asymptotic assumptions and consequently, in the process of migration, they lose or discount the information in the newly-acquired lowest-frequency components in the broad-band data, and (2) to address that problem, with the first migration method that will be equally effective at all frequencies at the target and reservoir, and that will allow the broad-band lower-frequency data to provide greater structural resolution improvement and enhanced amplitude analysis. In this paper, we begin to quantify the difference and the impact on resolution. We provide the first direct comparison of structural resolution differences with data with and without low frequencies, using the same homogeneous velocity model, comparing the current leading edge RTM (Claerbout II imaging principle) and the Stolt extended Claerbout III imaging principle. The new imaging method is able to benefit from broadband data for structural resolution improvement to a much greater extent than the current best industry standard migration. The differences in resolution benefit derived from the Stolt extended Claerbout III migration will be greater when both imaging principle and wave propagation model are included than we report here for only the imaging principle differences.

INTRODUCTION

Migration methods that use wave theory for seismic imaging have two components: (1) a wave-propagation model and (2) an imaging condition. We examine each of these two components with focus on the specific topic of this paper: the frequency fidelity of migration algorithms. That analysis leads to a new and first migration that is equally effective at all frequencies at the target and/or the reservoir. Weglein (2016) provides

imaging principle II (CII). Waves propagate down from the source, are incident on the reflector, and the reflector generates a reflected upgoing wave. According to RTM (CII), the reflector exists at the location in space where the wave that is downward propagating from the source and the wave propagates up from the reflector are at the same place and time. The third is Claerbout imaging principle III (Stolt extended CIII), which starts with surface source and receiver data and predicts what a source and receiver would record inside the earth. Stolt extended CIII then arranges the predicted source and receiver to be coincident and asks for $t=0$. If the predicted coincident source and receiver experiment at depth is proximal to a reflector one gets a non-zero result at time equals zero.

CII and Stolt extended CIII are of central industry interest today, since we currently process pre-stacked data. RTM (CII)and Stolt extended CIII will produce different results for a separated source and receiver located in a homogeneous half space above a single horizontal reflector. That difference forms a central and key message of this paper.

CII can be expressed in the form

$$I(\vec{x})=\sum_{\vec{x}_s}\sum_{\omega}S'(\vec{x}_s,\vec{x},\omega)R(\vec{x}_s,\vec{x},\omega), \quad (1)$$

where R is the reflection data (for a shot record), run backwards, and S' is the complex conjugate of the source wavefield.

A realization of Stolt extended CIII is Stolt FK migration (Stolt, 1978)

$$\begin{aligned} M^{stolt}(x,z) &= \frac{1}{(2\pi)^3}\iiint d\omega dx_g dx_s dk_{sx} \\ &\times \exp(-i(k_{sz}z+k_{sx}(x-x_s))) \\ &\times \int dk_{gx}\exp(-i(k_{gz}z+k_{gx}(x-x_s))) \\ &\times \int dt\exp(i\omega t)D(x_g,x_s,t). \end{aligned} \quad (2)$$

The weighted sum of recorded data, summed over receivers, basically predicts the receiver experiment at depth, for a source on the surface. The sum over sources predicts the source in the subsurface. Then the predicted source and receiver experiment is output for a coincident source and receiver, and at time equals zero; it defines a Stolt extended CIII image. Each step (integral) in this Stolt-Fourier form of Stolt extended CIII has a specific physically interpretable purpose towards the Stolt ex-

Imaging from above and beneath reflectors in a layered medium with the recent extension of SCIII, with data consisting of primaries and multiples

For a layered medium, and a normal incident plane wave G_0^{DN} is computed analytically in F. Liu and Weglein (2014) and Weglein (2016)
From surface recorded data and G_0^{DN} for a layered medium, and equations (3), (4) and (5) we predict the coincident source and receiver experiment <u>at depth</u>.

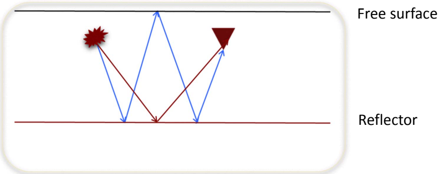
Imaging from above and beneath reflectors in a layered medium with the recent extension of SCIII, with data consisting of primaries and multiples

Then we compute that experiment above and beneath each reflector, and the SCIII migration result at those locations, by evaluating equation (5), the coincident experiment at t=0. Detail can be found in the above two references.

Imaging from above and beneath reflectors in a layered medium with the recent extension of SCIII, with data consisting of primaries and multiples

In the figures that follow we illustrate graphically, what the latter results represent, first the predicted experiment at depth, and then evaluating each experiment at $t=0$. We assume that the exact discontinuous velocity is known. That provides a definitive analysis of a key and central purpose and message of this talk.

Inputting data with primaries and multiples into SCIII migration for heterogeneous discontinuous media

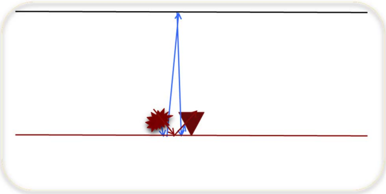


Red event: primary
Blue event: free-surface multiple

Figure 6: *a primary and a free surface multiple (recorded data)*

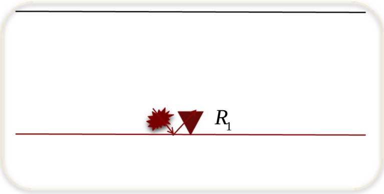
Above the reflector (predicted experiment at depth)

Coincident source and receiver at depth for all times



Red event: primary
Blue event: free-surface multiple

Coincident source and receiver at depth for t = 0

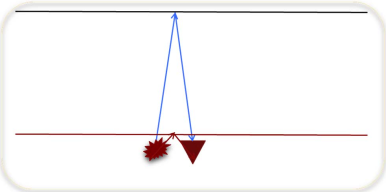


Red event: primary

Figure 7: *the predicted experiment (and the t=0 image) at depth (above the reflector) from a recorded data consisting of a primary and a free-surface multiple*

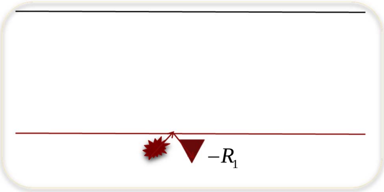
Below the reflector (predicted experiment at depth)

Coincident source and receiver at depth for all times



Red event: primary (downward reflection at the reflector)
Blue event: primary (downward reflection at the free surface)

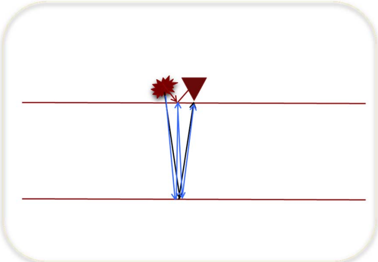
Coincident source and receiver at depth for t = 0



Red event: primary (downward reflection at the reflector)

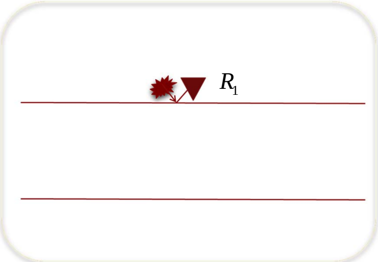
Figure 8: *the predicted experiment (and t=0 image) at depth beneath the reflector, from a recorded data consisting of a primary and free surface multiple*

Coincident source and receiver at depth for all times



Red event: primary from the first reflector
Black event: primary from the second reflector
Blue event: internal multiple

Coincident source and receiver at depth for t = 0

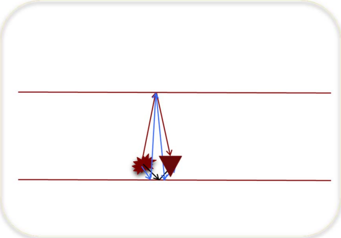


Red event: primary from the first reflector

Figure 9: *the predicted experiment (and image) above the first reflector, for a recorded data consisting of two primaries and an internal multiple*

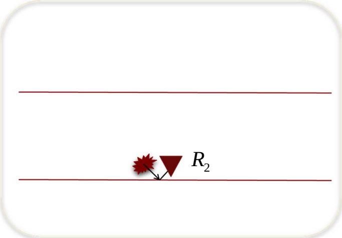
Above the second reflector (predicted experiment at depth)

Coincident source and receiver at depth for all times



Red event: primary from the first reflector
Black event: primary from the second reflector

Coincident source and receiver at depth for t = 0

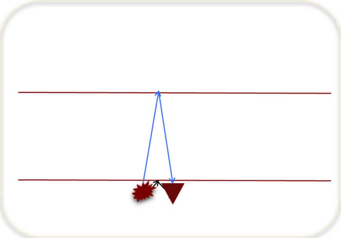


Black event: primary from the second reflector

Figure 10: *The predicted experiment (and image at t=0) above the second reflector for a recorded data consisting of two primaries and an internal multiple*

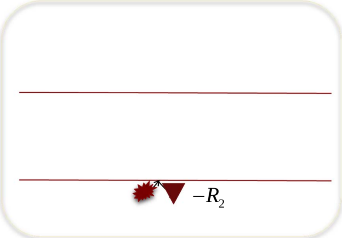
Below the second reflector (predicted experiment at depth)

Coincident source and receiver at depth for all times



Blue event: primary from the first reflector
Black event: primary from the second reflector

Coincident source and receiver at depth for t = 0



Black event: primary from the second reflector

Figure 11: *the predicted experiment at depth (and image at t=0) beneath the second reflector for a recorded data consisting of two primaries and an internal multiple*

2. Given an accurate discontinuous velocity model and a Stolt CIII migration for heterogeneous media equation (5) above a reflector, free surface and internal multiples will provide neither benefit nor harm in migration and migration-inversion and need not be removed

http://www.mosrp.uh.edu/news/key-note-address-at-the-seg-koc-workshop-dec-3-5-2019

Let's see why

1. For a smooth velocity model every event in the data will output a structure and multiples will produce false images, therefore multiples must be removed prior to migration.
    - the industry standard smooth migration velocity model drives the need to remove free surface and internal multiples

Summary for Stolt CIII migration in a layered medium with data consisting of primaries and multiples

The analytic analysis of equation (5) for a layered medium is found in Weglein (2016) [Multiples: Signal or noise?, Geophysics], (following Fang Liu and Weglein, 2014) and demonstrates, for the first time, how the actual individual recorded events (within the recorded data on the measurement surface) contribute to the predicted coincident source and receiver experiment at depth, and to each individual event in that predicted experiment. That analysis can output the source and receiver experiments predicted above and below each reflector.

Summary for Stolt CIII migration in a layered medium with data consisting of primaries and multiples

At each depth, z, below the measurement surface, the predicted coincident source and receiver experiment cares about (depends on) all the actual recorded primary and multiple events on the measurement surface. At the predicted source and receiver experiment, any point at depth, that doesn't correspond to a location above or beneath a reflector, will produce a zero result when the $t = 0^+$ imaging condition is applied. However, when using an accurate discontinuous velocity model and the imaging condition $t = 0^+$ is applied to the coincident source and receiver experiment at depth, z, above or beneath a reflector only the recorded primaries on the measurement surface contribute to the migration result.

Summary for Stolt CIII migration in a layered medium with data consisting of primaries and multiples

The conclusion: multiples do not contribute to the image at any depth, when using a Stolt CIII migration for heterogeneous media equation (5) and an accurate discontinuous velocity model above the reflector to be imaged. That is, if we migrated data consisting of primaries and multiples with an accurate discontinuous velocity model, and used Stolt CIII migration for heterogeneous media, equation (5) at t=0, then multiples in the recorded data on the measurement surface will not contribute to the image above or below a reflector.

Summary for Stolt CIII migration in a layered medium with data consisting of primaries and multiples

However, if the migration (in a discontinuous medium) uses a smooth velocity for the data consisting of primaries and multiples, the "predicted" source and receiver experiment at depth will not be the actual source and receiver at depth. That difference and error results in every multiple causing a false image. Hence for a smooth velocity model, multiples must be removed.

In the previous set of slides we reviewed a new (and first) migration method (Weglein et al., 2016, Yanglei Zou et al., 2017 [A wedge resolution comparison between RTM and the first migration method that is equally effective at all frequencies at the target: tests and analysis with both conventional and broadband data, SEG Expanded Abstracts], Weglein, 2016) that can image above and below reflectors in a discontinuous medium, (without artifacts) and can accommodate primaries and multiples. The conclusion of that analysis is when using that new migration (SCIII migration for heterogeneous media) with an accurate discontinuous media, multiples provide no harm or benefit, and there is no reason to remove them.

However, when using a smooth velocity model, multiples will cause false images that can interfere with or masquerade as reflectors. The latter analysis is not possible with all current methods of migration, e.g., RTM, since RTM cannot image in a discontinuous medium (without artifacts) even with an accurate discontinuous velocity model.

The methods that seek to remove these intrusive RTM artifacts (see e.g. Faqi Liu et al., 2011) have their own serious artifacts that damage the structural and amplitude fidelity of images. SCIII for heterogeneous media (Weglein et al., 2016) images in a discontinuous medium without artifacts.

An overview of this presentation

Seismic Processing

Direct ↙ ↘ Indirect

• Direct with a velocity	• Direct without subsurface information	• Satisfy a property CIG flatness
• Migration	• Inverse scattering series	• Forward problem in an inverse sense AVO
• Using recorded multiples to find an approximate image of an unrecorded primary. FWM.	• Isolated task subseries that remove free surface and internal multiples	• model matching FWI
• Illumination		

Direct methods using multiples (to estimate the RTM image of an unrecorded primary)

All of the migration methods we have been discussing assume that the recorded data coverage is adequate to carry out their function. What about when the set of recorded primaries is inadequate?
Some primaries are recorded and some are not.
Some multiples are recorded and others are not.

Only primaries are migrated
Two types of primaries

- 1. Recorded primaries
- 2. Unrecorded primaries

Multiples can be used at times to provide an approximate image of an unrecorded primary

Seeking an approximate image of an unrecorded primary that is a subevent of a recorded multiple. The fact that this use of multiples is seeking an approximate image of an unrecorded primary, speaks to the fact that primaries are prime, and are the events required for imaging. If you had a complete (or adequate) set of recorded primaries there would be no "use" for multiples.

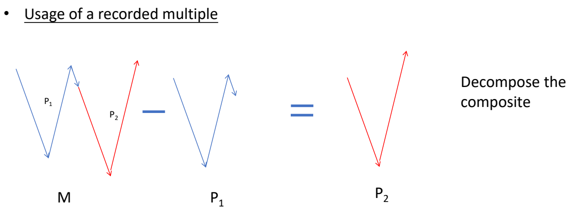


Figure 12: *To find an approximate image of unrecorded primary P_2. M is recorded multiple, P_1 is recorded subevent of the multiple M, and P_2 is RTM approximate image of unrecorded primary P_2.*

What if the unrecorded subevent of the multiple is not a primary?

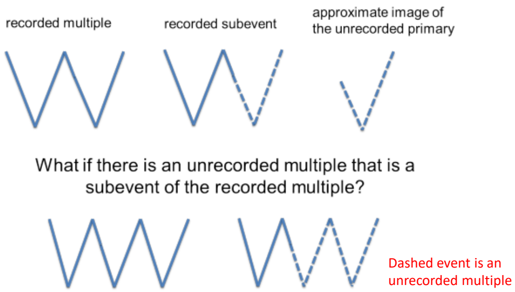


Figure 13: *Using a recorded multiple to find an approximate image of an unrecorded primary of the multiple: illustrates the need to remove unrecorded multiples. A solid line (—) is a recorded event, and a dashed line (- - -) connotes an unrecorded event.*

The unrecorded multiple subevent will produce an imaging artifact, with RTM and a smooth velocity model

What if there is an unrecorded multiple that is a subevent of the recorded multiple?

Dashed event is an unrecorded multiple

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- Therefore to image recorded primaries, recorded multiples must be removed and to find an approximate image of an unrecorded primary, unrecorded multiples must be removed.
- A multiple is only useful if it has a recorded subevent that corresponds to an unrecorded primary.

- Even if a multiple is useful, the 'useful' recorded multiple must be removed before imaging recorded primaries.
- To predict a recorded multiple requires recording all the subevents of the multiple. The use of multiples assumes a subevent of the multiple has not been recorded.
- To use a multiple, we need to be able to predict a multiple.
- If a multiple is predictable it has no use. If a multiple is useful it cannot be predicted.

The above methodology (of using multiples) assumes, e.g., that a recorded free surface multiple consists of two subevents, one that is recorded, and that the second subevent is a primary that is unrecorded. The idea is to extract and predict, from the recorded multiple and its recorded subevent, the approximate image of the unrecorded primary.

If all the subevents of the multiple are recorded, the multiple has no use. <u>This use of multiples is itself a testament to the fact that a complete set of recorded primaries is sufficient for imaging the subsurface.</u>

Constrained by our ability to find (at most) a smooth velocity model for migration, the removal of recorded multiples is necessary to image recorded primaries, and the removal of unrecorded multiples is required to find an approximate image of an unrecorded primary.

Further detail on this topic can also be found in several previous key note addresses

All multiples must be removed to image primaries, recorded and unrecorded primaries. Weglein (2018, 2017), Weglein (2019a) [A new perspective on removing and using multiples — they have the same exact goal — imaging primaries — recent advances in multiple removal, Presentation given at the SEG | KOC Workshop: Seismic Multiples - The Challenges and the Way Forward, Kuwait City, Kuwait]

Full wave migration. Full wave migration?

The imaging of recorded primaries and the use of recorded multiples to attempt to find the approximate image of an unrecorded primary has now a new catchy marketing label as "Full wave migration". Sorry, but migrating multiples is not taking place. In fact migrating multiples has no meaning.

The smooth velocity model and removing multiples

The fact that our most capable migration velocity models (today and for the foreseeable future) are smooth and continuous, remains the key and central reason that all multiples must be removed for imaging and inversion when using any method that requires a velocity model.

An overview of this presentation

Seismic Processing

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• Illumination		

Illumination

We often hear that multiples can be useful to enhance illumination. To paraphrase Jon Claerbout “Waves, and the reflected seismic wavefield, are ubiquitous, and have no illumination issues.

Illumination

However, seismic processing methods that are asymptotic high frequency approximations, ray-like in nature, (e.g., Kirchhoff and RTM migration) (Weglein et al., 2016) can "squeeze" the wave into ray paths, that leave gaps and produce illumination issues and challenges." In contrast, Stolt CIII migration (Weglein et al., 2016), equations (3)-(5), are the only migration methods that make no high frequency approximation in either the imaging condition or the propagation model.

Illumination

- RTM and Kirchhoff migration have a limited capability to image and invert complex structure and they discount the ubiquitous wave nature of seismic data. The high end versions of those migration methods produce structural, amplitude analysis, resolution and illumination issues. SCIII migration can accommodate all specular and non-specular reflectors, for imaging and inversion, and do not compromise the wave nature of seismic data.

An overview of this presentation

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What about Direct Seismic Methods that do not require subsurface information?

- The only direct multidimensional inversion (Weglein et al., 1981; Stolt and Jacobs, 1980) is the inverse scattering series. The inverse scattering series is direct and achieves all processing objectives without subsurface information.
- The distinct inverse scattering series algorithms for removing free surface and internal multiples are the only methods that do not require subsurface information

What about Direct Seismic Methods that do not require subsurface information?

- ISS has isolated task subseries that remove free surface and internal multiples. If the only direct multidimensional inverse method needed multiples for imaging or inversion it would not have subseries whose purpose is to remove them

Direct imaging methods and primaries and multiples

Hence, all direct seismic imaging methods require multiples to be removed. In other words not only does “migration” not make sense for anything but primaries, we have demonstrated that only primaries contribute to imaging for structure and amplitude analysis for both methods that require a velocity model, and methods that do not require any subsurface information to be known, estimated or determined.

Direct seismic methods without subsurface information

There are distinct subseries that directly remove free surface and internal multiples (e.g. Weglein et al., 2003 [Inverse scattering series and seismic exploration, Inverse Problems], Yanglei Zou et al., 2019 [A new multidimensional method that eliminates internal multiples that interfere with primaries, without damaging the primary, without knowledge of subsurface properties, for offshore and on-shore conventional and unconventional plays, SEG Expanded Abstracts]).

Direct methods without a velocity model (ISS) beyond multiple removal

See, e.g., Weglein et al. (2012) [Inverse scattering series direct depth imaging without the velocity model: First field data examples, Journal of Seismic Exploration], Haiyan Zhang and Weglein (2009a) [Direct nonlinear inversion of 1D acoustic media using inverse scattering subseries, Geophysics], Haiyan Zhang and Weglein (2009b) [Direct nonlinear inversion of multiparameter 1D elastic media using the inverse scattering series, Geophysics], Hong Liang et al. (2013) [General theory for accommodating primaries and multiples in internal multiple algorithm: Analysis and numerical tests, SEG Expanded Abstracts], Yanglei Zou and Weglein (2018) [ISS Q compensation without knowing, estimating or determining Q and without using or needing low and zero frequency data, Journal of Seismic Exploration].

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INVERSE SCATTERING SERIES DIRECT DEPTH IMAGING WITHOUT THE VELOCITY MODEL: FIRST FIELD DATA EXAMPLES

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ABSTRACT

Weglein, A.B., Liu, F., Li, X., Terenghi, P., Kragh, E., Mayhan, J.D., Wang, Z., Mispel, J., Amundsen, L., Liang, H., Tang, L. and Hsu, S.-Y., 2012. Inverse scattering series direct depth imaging without the velocity model: First field data examples. *Journal of Seismic Exploration*, 21: 1-28.

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 article, 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. Each member of a set of three distinct data or algorithmic conditions and requirements are identified and shown to be necessary for inverse scattering direct depth imaging, without a velocity model, to be effective and to produce the accurate structural configuration of reflectors and interfaces in the subsurface. Taken together, that set represents both necessary and sufficient conditions. In addition, for ISS imaging, the CIG flatness condition is a necessary and sufficient indication that an accurate depth image has been reached. The latter property is in contrast to conventional velocity dependent imaging methods where common image gather (CIG) flatness is a necessary but not a sufficient condition that a correct depth image has been achieved. The next steps, and open issues, on the road between viable and providing relevant and differential added value to the seismic tool-box are described and discussed.

KEY WORDS: imaging, migration, inverse scattering series, field data, velocity, CIG flatness.

0963-0651/12/$5.00

Direct methods without a velocity model

If multiples were needed to perform tasks such as depth imaging, Q compensation and parameter estimation the ISS would not have subseries whose entire purpose is to remove them.

An overview of this presentation

Seismic Processing

Direct ↙ ↘ Indirect

- Direct with a velocity
- Migration
- Using recorded multiples to find an approximate image of an unrecorded primary. FWM.
- Illumination

- Direct without subsurface information
- Inverse scattering series
- Isolated task subseries that remove free surface and internal multiples

- Satisfy a property
CIG flatness
- Forward problem in an inverse sense
AVO
- model matching
FWI

Indirect seismic methods: CIG flatness, AVO and FWI

There are different types of indirect inverse methods. Among them are:
(1) seeking to satisfy a property that an imaging or inverse solution would possess (e.g., CIG flatness);
(2) solving a forward problem in an inverse sense (e.g., AVO), and
(3) model matching (e.g., FWI).

Indirect seismic methods, e.g., CIG flatness, AVO and FWI

The CIG flatness criteria is in the first category, while solving an elastic inverse in terms of PP data (AVO) and FWI are in the second and third category, respectively. Why each of these is "indirect" is fully detailed in Weglein (2013) [A timely and necessary antidote to indirect methods and so-called P-wave FWI, The Leading Edge and references therein], Weglein (2018,2017), Weglein (2020) [YouTube video with interview of Arthur B. Weglein for the Bahia, Brazil student chapter of the EAGE, `https://www.youtube.com/watch?v=iir4cuk50Cw&feature=youtu.be`].

An overview of this presentation

Seismic Processing

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Indirect seismic methods: CIG flatness

Indirect methods like CIG flatness represent a necessary but not sufficient imaging condition that a correct migration velocity model has been found. The CIG flatness criteria assumes that the data consists of primaries and that multiples have been removed. You can achieve a flat CIG and have the wrong depth. That tended to occur exactly where improved velocity analysis was needed, e.g. in rapidly varying horizontal and vertical media.

Indirect seismic methods: AVO

AVO is solving a forward (modeling) problem for P reflection data from a horizontal target in terms of relative changes in mechanical properties. It typically assumes a plane wave (often a geometric optics approximate) reflection coefficient — and solves the forward problem for P in an inverse sense for the changes in mechanical properties.

(1) Solving a forward problem in an inverse sense is <u>not</u> the same as solving an inverse problem directly. See e.g. Weglein (2013) and Zhang (2006). A direct inverse for changes in earth mechanical properties needs a full data matrix $PP, PS_V, PS_H, S_V S_V \ldots$ and there are explicit direct solutions without searching or model matching

(2) For a more realistic amplitude analysis we suggest SCIII migration-inversion, that can locate and invert planar, curved and pinchout targets Stolt and Weglein (1985, 2012)

(3) The forward problem in AVO assumes that multiples have been removed.

An overview of this presentation

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Indirect seismic methods: FWI

Another type of indirect method, FWI, is a model matching methodology that can input any data set, consisting of primaries, free surface multiples and internal multiples.
FWI is popular because it's accessible.
It's accessible because it's easy to understand.
It's easy to understand because there is nothing to understand.

Indirect seismic methods: FWI

Take a trace and take a trace from a model and move the model properties around trying to get the two traces to match.

Indirect seismic methods: FWI

What events to match?
Often, primaries are considered not enough, and primaries and all multiples too much to match. Internal multiples are first removed and then primaries and free surface multiples are matched.
If one asks why match such and such a data the best and honest answer is: "Why not?" There is no theory.
There is a great sense of comfort when pursuing FWI. If things don't work, call for bigger and faster computers.
And all future research will require bigger and faster computers, still.

The difference between science and scientists

FWI has been oversold and marketed as the final and ultimate seismic method. Like all methods, FWI has issues (maybe more than most) but the issues of overpromising and marketing are not issues with the method

As was documented in a recent SEG/DGS Workshop on Velocity Model Building Saad et al. (2021) and the final/wrap-up presentation by Weglein (2021), FWI has been useful in providing an improved smooth velocity for migration. As we pointed out earlier in this presentation, with a smooth migration velocity model, all multiples must be removed.

Indirect seismic methods, e.g., CIG flatness, AVO and FWI

Therefore either initially or ultimately all multiples must be removed in all indirect seismic methods.

Conclusions

Direct methods

All current migration velocity analysis methods can (at best) produce a smooth continuous migration velocity model. For direct seismic methods, for example, migration with a smooth velocity model, all multiples will cause false images and artifacts — and need to be removed. To clearly analyze the role of primaries and multiples in imaging requires a new form of migration (that we label Stolt Claerbout III for heterogeneous media) that can image in a discontinuous medium without artifacts.

Conclusions

To use a recorded multiple, we assume it contains two subevents, one recorded and the other not recorded. Let's further assume that the unrecorded subevent is an unrecorded primary.

Conclusions

When using a recorded multiple, and the recorded subevent of the multiple, to seek an estimate of the image of an unrecorded primary subevent of the multiple — to satisfy the latter assumption, unrecorded subevents of the recorded multiple, that are (not unrecorded primaries but rather) unrecorded multiples, must be removed. Furthermore the original recorded multiple must be removed to image recorded primaries. Hence, recorded and unrecorded multiples must be removed to image recorded and unrecorded primaries.

The use of recorded primaries and approximate images of unrecorded primaries (with an assist from recorded multiples) is now referred to as full wave migration (FWM). A bit of marketing at play.

Conclusions

The inverse scattering series, is the only direct inversion method for a multi-dimensional earth that doesn't require any subsurface information (including velocity) to be known, estimated or determined. It contains distinct isolated task subseries that remove free surface and internal multiples.

Conclusions

Only primaries are called for in task specific subseries for structure determination, parameter estimation and Q compensation without knowing, estimating or determining Q (Yanglei Zou and Weglein Journal of Seismic Exploration 2018).

- Multiple removal is as permanent as the inability to find an accurate discontinuous velocity model. Multiple usage provides something less than what a corresponding recorded primary can deliver with SCIII. Missing data fixes always diminish as acquisition becomes more complete.
- Only recorded primaries can provide SCIII imaging benefits. Multiple removal is a permanent and multiple usage is transient. In the near term, we encourage progress and advance on both.
- SCIII migration requires recorded primaries and has advantages for resolution, amplitude analysis and illumination compared to RTM and Kirchhoff.

Conclusions

Indirect methods

For indirect methods, based on a criteria that only relate to primaries, e.g., CIG flatness, multiples must first be removed. Solving a forward problem in an inverse sense, e.g. AVO assumes multiples have been removed. FWI is model matching of primaries and multiples and currently is able to output a smooth velocity for migration. For a smooth velocity for migration all multiples must be removed.

Conclusions

Multiples must be removed when using a smooth velocity for migration. For the smooth migration velocity output of FWI to be useful, for imaging and inversion, multiples must first be removed.

Conclusions

Hence, all direct and indirect seismic processing methods require all multiples to be removed, either initially or eventually.

OVERVIEW

Removing and using multiples are not adversarial — they both are seeking the images of primaries, recorded and unrecorded primaries, respectively.

FWI and FWM are not adversarial: At most FWI can estimate a smooth velocity for migration, and FWM requires a smooth migration velocity, for migrating the recorded primaries (hopefully with SCIII migration) and unrecorded primaries (with RTM).

New Concepts for Seismic Imaging

If you are interested in a new and more effective imaging method that requires a velocity model, then we suggest Stolt Claerbout III migration for continuous and discontinuous media. If you are interested in a fundamentally new and much more effective migration, while avoiding the need for a velocity model, then we suggest you consider the inverse scattering sub-series that directly outputs an accurate depth section without knowing, estimating or determining a velocity model. If the latter makes you uncomfortable, then please try to remember what you thought when you first heard that internal multiples could be removed without subsurface information. If a concept makes you feel comfortable, then it isn't new, and vice versa.

New Concepts for Seismic Imaging

There is nothing wrong with making cosmetic changes to current concepts and methods (and some might even call that "research") — but it's an entirely different enterprise from fundamental directed research, that begins with identifying real problems, and then seeks to solve them, to provide increased capability and effectiveness. The major challenges in seismic exploration (e.g., the one in ten drill success rate in the frontier region in the deep water Gulf of Mexico) will require fundamentally new concepts, thinking, and methods.

Acknowledgements

A. B. Weglein is enormously grateful to Mariana Gherasim and the organizers of this 2022 SEG Workshop on FWI/FWM and new imaging concepts for the invitation to present this Keynote Presentation. We appreciate the encouragement and support of M-OSRP sponsors. J. D. Mayhan is thanked for his assist with preparing the slides.

A new perspective on removing and using multiples — they have the same exact goal — imaging primaries

Arthur B. Weglein
M-OSRP, Physics Department, UH

The removal and the usage of multiples have the same precise goal: imaging primaries.

To analyze and define the role of primaries and multiples in seismic exploration, the M-OSRP group has recently developed a first and new migration method with the capability to accommodate reflectors (Weglein et al., 2016; Fu and Weglein, 2014; Weglein, 2018b) — in addition it has improved resolution, amplitude analysis, and illumination, beyond all current migration methods, including RTM.

REMOVING MULTIPLES: Please see the link below with a video recording presentation on this new migration
`https://drive.google.com/file/d/0B4HzpkppeJ-oZV90NzBoQUJ5T2c/view?usp=sharing--`
`https://drive.google.com/file/d/13Nv0MDJKDjxPYsQdBQ95stC3Z7Qwcjxs/view?usp=sharing`

The conclusions from this new migration method are (1) when imaging with **an accurate discontinuous velocity model primaries will contribute to the image and multiples will not**, with multiples causing no harm and providing no benefit and (2) **when imaging with a smooth and approximate velocity model, primaries can locate structure, and multiples are injurious and will ALWAYS produce false images. Since, the petroleum industry typically uses smooth velocity models for migration, multiples must first be removed before imaging primaries. Primaries are needed and they come in two varieties, recorded primaries and unrecorded primaries.**

USING MULTIPLES A multiple can at times be used to find an approximate image of an unrecorded primary, that is a subevent of the recorded multiple. Among issues: the unrecorded subevent might not be an unrecorded primary but an unrecorded multiple. Furthermore, to use a multiple you need to predict a multiple, and to predict a multiple all of its subevents must be recorded. Hence predictable multiples are useless and unpredictable multiples are useful. The use of multiples to seek an approximate (RTM) image of an unrecorded primary, taken together with the (hopefully SCIII) image of recorded primaries now has a new catchy marketing label "Full Wave Migration"?!

In conclusion, all multiples (recorded and unrecorded) must be removed to image recorded and unrecorded primaries, respectively.

RECENT ADVANCES Subsurface information has been and remains a key requirement of (and challenge for) many seismic processing methods — and, that is the unmentionable elephant in the room.

A few comments that we hope you find worthwhile and relevant to the purposes of this 2022 SEG Workshop on FWI/FWM and new concepts of imaging

The general rule is the farther you go away from Data space in processing the more difficult, and demanding and unstable (noise, bandwidth, ...) and unreliable methods become.

If your process can involve data in and data out without ever entering model space at any step, then your chance of producing a stable and reliable result is far superior than any method that requires entering model space at any point.

Lesson: Avoid model space whenever possible

Data space and Model space

In the world of seismic processing there are two “spaces”

Data	data space	$D(\vec{x}_g, \vec{x}_s, t)$
Model	model space (subsurface properties)	e.g. $V_p(\vec{x})$, $V_s(\vec{x})$, $\rho(\vec{x})$, $Q(\vec{x}, \omega)$

Migration: Migration space sits between D and M — migration looks like data and is located where model space properties have rapid variation

Model space is the most treacherous and dangerous to enter

Model Matching and multiple removal

The ISS series free-surface demultipled data, D', is given in terms of the deghosted data D'_1 as follows:

$$D'_n(k_g,k_s,\omega) = \frac{1}{i\pi\rho_0 B(\omega)}\int_{-\infty}^{\infty} dk\, q\exp(iq(\epsilon_g+\epsilon_s))\times$$
$$D'_1(k_g,k,\omega)D'_{n-1}(k,k_s,\omega),$$

n=2,3,4,... and

$$q \equiv \frac{\omega}{c}\sqrt{1-\frac{k_g^2}{\omega^2/c^2}-\frac{k_s^2}{\omega^2/c^2}}$$

$$D'(k_g,k_s,\omega) = \sum_{n=1}^{\infty} D'_n(k_g,k_s,\omega)$$

One temporal frequency of the data has its free surface multiples removed using that one frequency of the data

Model Matching and multiple removal

- one frequency of data enters and one frequency of data emerges
- no subsurface information is required to be known, estimated or determined
- the method is completely <u>unchanged</u> for any earth model type
- ISS FSME eliminates all free surface multiples at all offsets, <u>without</u> adaptive subtraction or Radon demultiple (the latter two are required for SRME). ISS FSME accommodates specular and non-specular reflectors, without requiring any knowledge of those reflectors or any subsurface information

Model Matching and multiple removal

- Using some form of FWI to predict multiples, requires a modeling method, where one seeks to <u>model</u> the <u>subsurface</u> and the reflectors that generate multiples — you have entered model space — and bandwidth immediately raises its head — and modeling top and base salt, and pinchout reflectors represent a fools errand.

Model Matching and multiple removal

- What about internal multiple removal?
- Model matching and subtracting internal multiples has absolutely no chance of success.
- The history of model matching to remove multiples, is that the actual multiples remain, and new modeled multiples are added, making the problem with multiples worse.

New Concepts for Seismic Imaging

The same exact mathematical physics within the inverse scattering series that produces algorithms that remove free surface and internal multiples directly and without knowing, estimating or determining any subsurface information (and are model type independent) also derives algorithms that determines depth without a velocity model known, estimated or determined and another algorithm that performs Q compensation directly without knowing, estimating or determining the absorptive mechanism. You either understand them all or you don't understand any one of them (since each one has the same exact logic, concept and derivation for a different inverse task).

New Concepts for Seismic Imaging

M-OSRP is committed to identifying and addressing prioritized seismic challenges — we are enormously fortunate for the encouragement and support we have received — and we are (and always will remain) deeply grateful and appreciative.

New Concepts for Seismic Imaging

To have an effective seismic processing strategy, we need direct methods for the part of our data that can be explained by our assumed physics and earth model types, and indirect methods for a part of our data that is beyond our assumed physics and earth model types. Having these two parts working in cooperation is a worthwhile goal. The problem is the current out of balance, with indirect model matching and ML and AI, totally ignoring the physics and real intelligence behind direct methods — with all next steps calling for buying more computers. Not only do the model matching methods require no thought but the next steps require no thinking as well. The total absence of intelligence and thinking — in terms of what you are doing, (and overselling) but in removing any concerns about what needs to be done next. That's the exact opposite of the "final and ultimate" seismic processing method. Methods are not the problem; methods do not have egos and ambition, and they don't overstate their capabilities and avoid their assumptions and shortcomings. That language "having an ultimate and final solution" has no place in any scientific endeavor and certainly not in seismic physics. The earth is more complicated and complex than our assumed physics, now and for the foreseeable future. While we can support and encourage (and celebrate) seismic processing progress, there is no final and ultimate seismic processing method, and there never will be.

A new perspective on removing and using multiples — they have the same exact goal — imaging primaries

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The removal and the usage of multiples have the same precise goal: imaging primaries.

To analyze and define the role of primaries and multiples in seismic exploration, the M-OSRP group has recently developed a first and new migration method with the capability to accommodate reflectors (Weglein et al., 2016; Fu and Weglein, 2014; Weglein, 2018b) — in addition it has improved resolution, amplitude analysis, and illumination, beyond all current migration methods, including RTM.

REMOVING MULTIPLES: Please see the link below with a video recording presentation on this new migration
`https://drive.google.com/file/d/0B4HzpkppeJ-oZV90NzBoQUJ5T2c/view?usp=sharing--`
`https://drive.google.com/file/d/13NvOMDJKDjxPYsQdBQ95stC3Z7Qwcjxs/view?usp=sharing`

The conclusions from this new migration method are (1) when imaging with **an accurate discontinuous velocity model primaries will contribute to the image and multiples will not**, with multiples causing no harm and providing no benefit and (2) **when imaging with a smooth and approximate velocity model, primaries can locate structure, and multiples are injurious and will ALWAYS produce false images. Since, the petroleum industry typically uses smooth velocity models for migration, multiples must first be removed before imaging primaries. Primaries are needed and they come in two varieties, recorded primaries and unrecorded primaries.**

USING MULTIPLES A multiple can at times be used to find an approximate image of an unrecorded primary, that is a subevent of the recorded multiple. Among issues: the unrecorded subevent might not be an unrecorded primary but an unrecorded multiple. Furthermore, to use a multiple you need to predict a multiple, and to predict a multiple all of its subevents must be recorded. Hence predictable multiples are useless and unpredictable multiples are useful. The use of multiples to seek an approximate (RTM) image of an unrecorded primary, taken together with the (hopefully SCIII) image of recorded primaries now has a new catchy marketing label "Full Wave Migration"?!

In conclusion, all multiples (recorded and unrecorded) must be removed to image recorded and unrecorded primaries, respectively.

RECENT ADVANCES Subsurface information has been and remains a key requirement of (and challenge for) many seismic processing methods — and, that is the unmentionable elephant in the room.

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