UNIVERSITY of HOUSTON

M-OSRP
Mission - Oriented Seismic Research Program
Solve The Right Problem

Department of Physics
College of Natural Sciences
and Mathematics

A Perspective on Advances and Challenges in Seismic Exploration (2024)

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Outline of this presentation

- The role of primaries and multiples in seismic processing
- Demonstrating that multiples must be removed in all seismic processing methods (all Direct and Indirect Methods), without exception.
- Specific challenges for land and shallow water exploration — a suggested response
- How to start a research program
- The big picture (and overview)
- Conclusions

- The recorded events in seismic reflection data are catalogued as either primary or multiple
- We start with a new perspective and understanding of the role that primaries and multiples play in seismic processing and exploration
- Let's begin

Introduction

- We 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.**

A chart with all direct and indirect seismic processing methods

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

Wave equation migration methods have two ingredients: (a) an imaging condition and (b) a propagation model.

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

We will refer to the original imaging conditions in Claerbout (1971) 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.

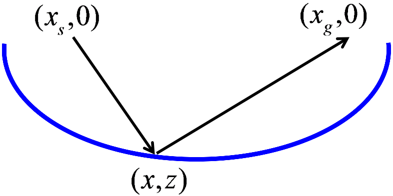
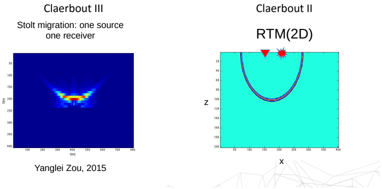


Figure 1: *(1) If there is a travel time curve of candidate images within the method, it is a high frequency "ray theory" approximation/assumption.* $t = r/c$ *where,* $r = r_g + r_s = \sqrt{(x_g - x)^2 + z^2} + \sqrt{(x_s - x)^2 + z^2}$.



Claerbout III

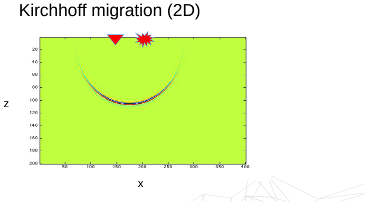
Stolt migration: one source one receiver

Yanglei Zou, 2015

Claerbout II

RTM(2D)

Figure 2: *Imaging Conditions and High Frequency Assumptions. Left panel: No high frequency assumption. Right panel: High frequency assumption.*



Kirchhoff migration (2D)

Figure 3: *Kirchhoff migration for a single source and receiver (Yanglei Zou et al, 2015). High Frequency approximation from a stationary phase approximation.*

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

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.

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

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

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

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 without one-way high frequency approximations and in discontinuous velocity models

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

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

New from M-OSRP

Discontinuous velocity Stolt CIII migration

where G_0^{DN} vanishes along with its normal derivative on the bottom surface of the finite migration volume

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:

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

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).

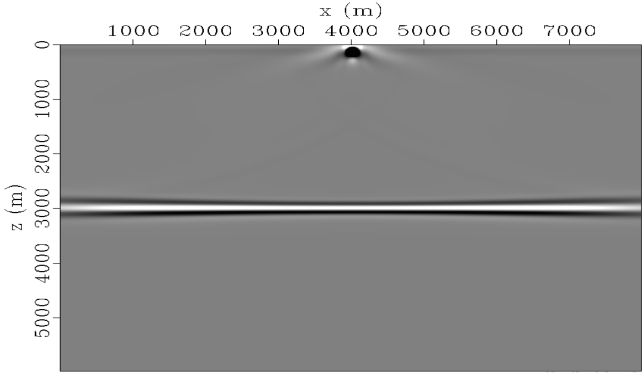


Figure 4: *Claerbout II RTM image from beneath the reflector (in Figure 2) after artifacts (rabbit ears) removal. Please note the inconsistent image along the reflector.*

Figure 5:

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 6: *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)*

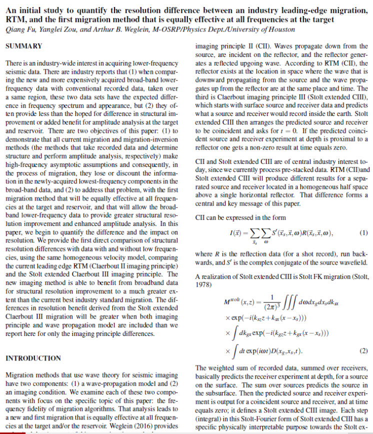
RTM cannot accurately image (above or) beneath a single horizontal reflector even with perfect analytic data The new SCIII for heterogeneous continuous and discontinuous media eqn (5)

$$\begin{aligned} D(at\ depth) = \int_{S_S} \Bigg[\frac{\partial G_0^{DN}}{\partial z_S} \int_{S_g} \Bigg\{ \frac{\partial G_0^{DN}}{\partial z_g} D(m.s.) - \frac{\partial D(m.s.}{\partial z_g} \\ - G_0^{DN} \frac{\partial}{\partial z_S} \int_{S_g} \Bigg\{ \frac{\partial G_0^{DN}}{\partial z_g} D(m.s.) - \frac{\partial D(m.s.)}{\partial z_g} G_0^{DN} \Bigg\} dS_g \Bigg] \end{aligned} \tag{6}$$

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

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

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)

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

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) [please see references in the link]

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>.

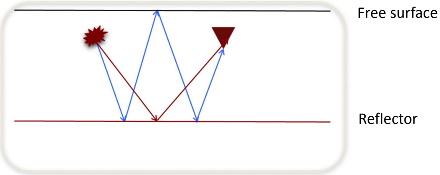
Imaging from above and beneath reflectors in a layered medium with the recent extension of SCIII, with data consisting of primaries and multiples

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: a primary and a free surface multiple



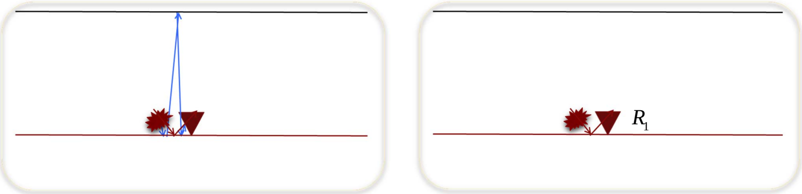
Red event: primary
Blue event: free-surface multiple

Figure 7: *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

Coincident source and receiver at depth for t = 0



Red event: primary
Blue event: free-surface multiple

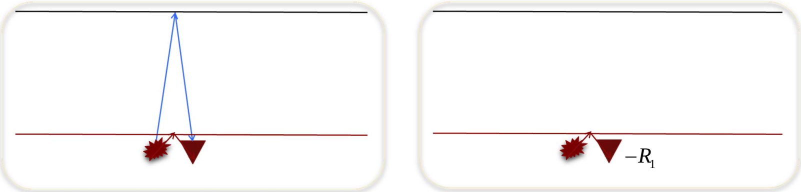
Red event: primary

Figure 8: *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

Coincident source and
receiver at depth for t = 0

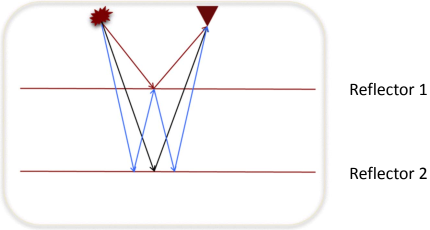


Red event: primary (downward
reflection at the reflector)
Blue event: primary (downward
reflection at the free surface)

Red event: primary (downward
reflection at the reflector)

Figure 9: *the predicted experiment (and t=0 image) at depth beneath the reflector, from a recorded data consisting of a primary and free surface multiple*

Inputting data with primaries and multiples into SCIII migration for heterogeneous discontinuous media: two primaries and an internal multiple

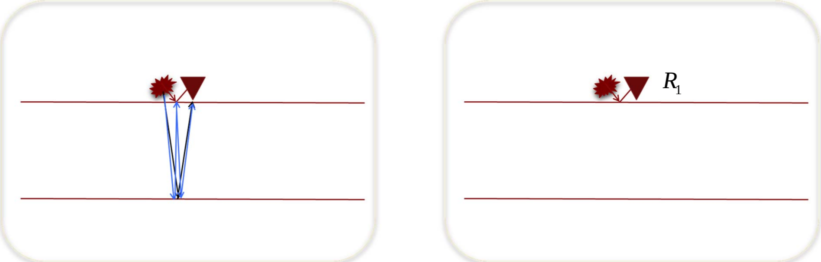


Red event: primary from the first reflector
Black event: primary from the second reflector
Blue event: internal multiple

Figure 10: *the recorded data consisting of two primaries and an internal multiple*

Coincident source and
receiver at depth for all times

Coincident source and
receiver at depth for t = 0



Red event: primary from the first reflector

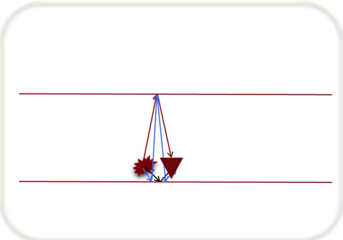
Black event: primary from the second reflector

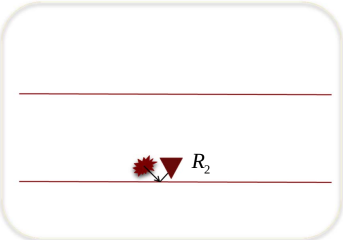
Blue event: internal multiple

Red event: primary from the first reflector

Figure 11: *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)





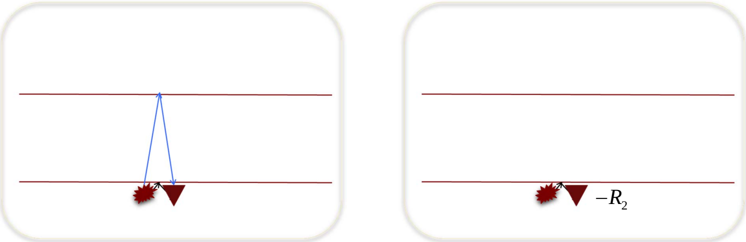
Coincident source and receiver at depth for all times	Coincident source and receiver at depth for t = 0
Red event: primary from the first reflector Black event: primary from the second reflector	Black event: primary from the second reflector

Figure 12: *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

Coincident source and receiver at depth for t = 0



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

Black event: primary from the second reflector

Figure 13: *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`

when using a smooth velocity model when the actual medium has a discontinuous velocity

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.

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

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.

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

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.

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

Since the industry leading edge migration velocity methods can at best find an improved smooth velocity model — and there are currently no candidates to produce an accurate discontinuous velocity model, recorded multiples must be removed now and for the foreseeable future. See e.g. the 2021 SEG/DGS Workshop on Velocity Model Building (Saad et al., 2021) and the final/wrap-up presentation by Weglein (Weglein, 2021)

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.

With the properties of SCIII (for smooth and discontinuous heterogeneous media) established we can continue to show how all seismic processing methods require multiples to be removed either initially or at some point in the process

A chart with all direct and indirect seismic processing methods

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

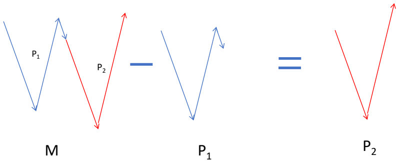
Two types of primaries

- 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.

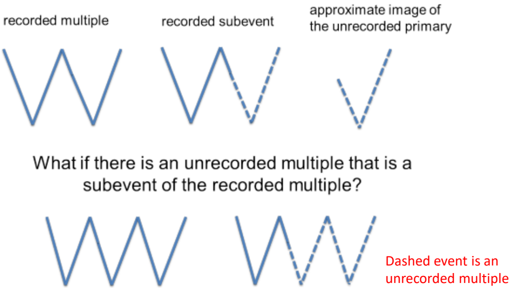
- Usage of a recorded multiple



Decompose the composite

Figure 14: *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?



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

Dashed event is an unrecorded multiple

Figure 15: *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 recorded 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. This use of multiples is itself a testament to the fact that a complete set of recorded primaries is sufficient for imaging the subsurface.

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.

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]

We will cover so-called Full wave migration (FWM) method later in this presentation within the topic of FWI

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.

A chart with all direct and indirect seismic processing methods

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		

What about 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.”

Illumination

- 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.
- SCIII migration can accommodate all specular and non-specular reflectors, for imaging and inversion, and do not compromise the wave nature of seismic data.

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 inconsistent structural maps, and discounted amplitude analysis, resolution and illumination.

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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].

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.

A chart with all direct and indirect seismic processing methods

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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`].

A chart with all direct and indirect seismic processing methods

Seismic Processing

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• Illumination		

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.

A chart with all direct and indirect seismic processing methods

Seismic Processing

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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 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.

Why direct inverse methods play a fundamentally important role in defining the goals of a relevant research program that seeks added value in target identification and successful drilling.

A direct inverse method assures that you have solved the problem you set out to solve, but equally if not more important it communicates whether the problem you are interested in solving is the relevant real problem you need to be solving. If a direct inverse method doesn't increase the drill success rate, the problem that you are solving is not the problem that you need to be solving.

Why direct inverse methods play a fundamentally important role in defining the goals of a relevant research program that seeks added value in target identification and successful drilling. (continued)

With an indirect model matching method like FWI, if you don't improve the drill success rate — you don't know if you are solving the wrong problem, or whether your indirect method is the issue, or both. Defining and solving the right problem is the key and essential first step in a research program and project.

What about FWM?

- A word about so-called FWM (Full wave migration).
- FWI promised to deliver absolutely everything you could wish to know about the properties of the subsurface
- FWI went from promising everything to desperately grasping for anything.
- FWI was “too big to fail”.
- One of the “grasping for anything” outcomes was the so-called FWM.
- The idea was since FWI was at best producing an approximate smooth velocity — to then “differentiate” the velocity as a function of depth and call it FWM.

As we have noted, the Stolt Claerbout III migration (and migration-inversion), for smoothly varying and discontinuous media, is currently the most complete and effective method for migration and inversion. SCIII is the high water mark of migration (and migration-inversion) capability.

FWM is the most incomplete and ineffective method for migration (and there is no extension of FWM for inversion).
FWM is the low water mark of migration capability. Put another (more “positive” way) it is the high water mark of seismic imaging stupidity.

We might hope that in the FWI matching procedures that all free surface and internal multiples would be removed to not produce false changes in “velocity” due to a multiple that hasn’t been modeled and subtracted. That’s a very tall order! And in fact is never achieved in practice.

Once again the “grasping for anything” from FWI causes a purposeful collective amnesia regarding one of the most important advances in modern seismic processing: the direct removal of all multiples with absolutely no subsurface information known, estimated or determined.

FWM: A major step backwards? Why?

The original idea of migration was to seek the spatial location where any mechanical property experienced a rapid change.

That evolved into migration-inversion (Stolt and Weglein, 1985), a two step process (like NMO-AVO) where the first step determined the location of a rapid change in any mechanical property (or properties).

The second step involved a weighted sum (of the new SCIII migration) to find the relative changes in specific mechanical properties at the image point for both specular or diffractive reflectors.

In contrast, FWM in principle (and practice) by differentiating a velocity function and operator cannot determine a reflector where only v_s or ρ vary (or is interpretable where a combination varies) and can never allow amplitude analysis for specular and diffractive reflectors

Perhaps the biggest conceptual flaw and purposeful or unintentional seismic processing amnesia in the FWM thinking is the overall conceptual and practical lesson in seismic processing starts with the two domains where processing takes place.

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

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

- lesson (1) the further a process deviates from the data domain, the more challenging it is to achieve
- wave equation migration — straddles the two domains — the output is in the data domain (data-like) but its location of reflectors is in the model domain —
- for FWM — it begins by immediately going to the model domain, to determine a velocity configuration, $v(\vec{r})$, and then it differentiates that function to find a FWM migration

Only SCIII migration can image and invert:

(1) without artifacts above and beneath top salt
(2) specular or diffractive targets
(3) can automatically image and invert for R or V and then changes in v_p, v_s and ρ
(4) can image and invert targets without high frequency approximations — e.g. no geometric optics R.C. — no one way wave assumptions in a smooth velocity model
(5) maximal amplitude and resolution capability, no compromise in illumination

On-shore and shallow off-shore challenges

Onshore challenges begin with the complex ill-defined near surface issues where identifying the model type and medium properties are a major obstacle and largely unsolved problem.

On-shore and shallow off-shore challenges

A new embryonic seismic processing method has been developed that removes the need for near surface and subsurface information to be known, estimated, or determined (Weglein, 2024). Early tests are encouraging.

On-shore and shallow off-shore challenges

Responding to on-shore challenges: (1) A method to remove the need to know, estimate or determine near surface information for seismic preprocessing and processing methods and (2) a response to the multiples generated by near-surface subresolution reflectors: Part I, the basic concept and first examples

Arthur B. Weglein
Jan 2024

Abstract

The current inability to provide adequate information about the overburden above a target has been and remains an open and very serious issue for seismic preprocessing and processing. There are current methods for preprocessing based on Green's theorem, and for processing that derive from the inverse scattering series, that do not need or require subsurface information. That is, they do not require any information about the earth starting at some depth below where sources and receivers reside (that is, beneath the measurement surfaces). However, they do require information at, and immediately beneath, the measurement surface (and the latter defines the "near surface"). For on-shore and OBS applications, the need for near-surface information (information that is often hard to define, let alone to determine) is a major hurdle, a largely unsolved problem, open issue and challenge. In this paper, we introduce a new concept and method for preprocessing and processing that removes the need to know, estimate or to determine both subsurface and near surface properties. We introduce the concept with the first step in the seismic processing chain, namely, the separation of the reference wave (that would include the direct wave and ground-roll for on-shore application) and the recorded scattered wavefield (the data that has experienced the subsurface and near surface). We use an analytic data example to demonstrate how the method works and we point out how it would be applied in practice. This paper introduces a new concept and method. It will be followed by both more complicated synthetic and field data examples within this paper's objective and to the next steps in the processing chain (for example, for deghosting, multiple removal and imaging and inversion). In addition, a response to the issue of multiples generated by subresolution reflectors (often in the near surface) is proposed. This paper responds to two currently intractable on-shore exploration problems: the need for near-surface information and subresolution multiples.

On-shore and shallow off-shore challenges

Jing Wu et al (2015) present a new method to separately predict ground roll and reflection data without filtering and harming either one.

On-shore and shallow off-shore challenges

Preprocessing in displacement space for on-shore seismic processing: removing ground roll and ghosts without damaging the reflection data

Jing Wu and Arthur B. Weglein, M-OSRP, University of Houston

SUMMARY

This paper derives an elastic Green's theorem wave separation method for on-shore data in displacement space. Applying the algorithm presented in this paper only once, both the reference waves (including the direct wave and the surface wave) and the ghosts can be effectively removed. The method is tested on a layered elastic earth model. The results indicate its effectiveness for reducing the ground roll and ghosts at the same time, and without harming the up-going reflections, in preparation for on-shore processing.

INTRODUCTION

On-shore seismic exploration and processing seeks to use reflection data (the scattered wavefield) to make inferences about the subsurface. The measured total wavefield consists of the reflection data and the reference wave that contains the direct wave and the surface wave/ground roll; hence, one prerequisite is to separate the reference wave and scattered wave. Filtering methods are typically employed to remove the reference wave, particularly the ground roll. That can be at the expense of damaging reflection data when ground roll is interfering with the scattered wavefield.

In addition, for buried sources and receivers, not only up-going waves are in the reflection data but also ghosts, whose existence can cause notches in the spectrum. Thus, removing the ghosts from the reflection data is another prerequisite. In this study, we will assume the source is located slightly above the air/earth surface (could be infinitely close, or on the air/earth surface), and the receivers are slightly beneath the air/earth surface. Therefore, there are receiver ghosts but no source ghosts in our study.

As a flexible and useful tool, Green's theorem provides a method to satisfy both prerequisites; i.e., removing the reference wave without damaging the reflection data and removing the ghosts from the reflection data without destroying the up-going reflected data. The distinct advantages of applying the method based on Green's theorem in off-shore plays have been demonstrated by Weglein et al. (2002); Zhang (2007); Mayhan et al. (2011); Mayhan and Weglein (2013); Tang et al. (2013); Yang et al. (2013).

Basically, wave separation from Green's theorem has a model of the world that consists of the **reference medium** and the **sources**. The choice of reference medium is arbitrary, and the choice of reference will determine what the sources have to be to arrange for the reference medium and sources together to correspond to the actual medium and experiment (Weglein et al., 2003). For on-shore plays, Green's theorem wave separation method is applicable for data either in displacement space (Pao and Varatharajulu, 1976; Weglein and Secrest, 1990) or in the PS space (Wu and Weglein, 2014). In this paper, for data in displacement space, we choose a homogeneous elastic whole space as the reference, then both the reference wave and receiver ghosts can be removed in one step while applying the elastic Green's theorem wave separation algorithm. In a companion paper (Wu and Weglein, 2015b), and for data in the PS space, the reference medium is chosen to be composed of two homogeneous half-spaces, an air/acoustic half-space over an elastic half-space, then Green's theorem method can extinguish the reference wave (including the ground roll) without harming the reflection data. After obtaining the reflection data, Green's theorem provides a reflection data deghosting algorithm with a choice of a whole-space homogeneous elastic reference (Wu and Weglein, 2015b).

DESCRIPTION OF THE MODEL: REFERENCE MEDIUM + SOURCES

As shown in Figure 1, the model consists of an air half-space and an elastic-earth half-space. Receivers are buried in the earth, and the active source in the form of a vertical force is applied on the free surface (F.S.). Therefore, ghosts exist at the receiver side only. The measurement surface (M.S.) can be infinitely close to the free surface, like on-surface acquisition, or several meters below the free surface, like buried-receiver acquisition; however, the receivers are coupled with the elastic medium in both situations.

Figure 1: A generic model describing the land experiment

In this paper, we will assume that the portion of earth along the measurement surface is homogeneous and known. Within this assumption, we choose the reference medium to be a homogeneous elastic whole space, as shown in Figure 2, whose property agrees with the actual earth along the measurement surface.

There are three sources acting on the homogeneous reference medium that is described in Figure 2. As shown in Figure 3, one is the active source (or the vertical force S_1) and the other two are passive sources (or the perturbations S_2 and S_3) on two sides of the measurement surface, respectively. S_1 produces the direct waves. S_2 produces the ground roll; it also produces

DOI http://dx.doi.org/10.1190/segam2015-5879845.1

On-shore and shallow off-shore challenges

Among major shallow water issues, is the fact that the nearest phone to the source can be in the postcritical regime. That is a major impediment to multiple removal methods that depend on recorded subevents.

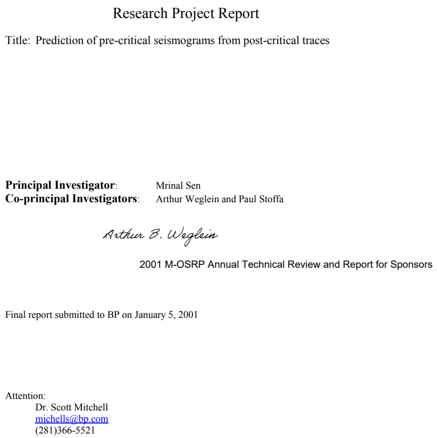
On-shore and shallow off-shore challenges

To arrange for those required subevents there is typically an extrapolation to nearer offsets when the nearest phone is in the precritical region that is often successful. However, extrapolation methods will fail when the nearest phone is postcritical region and the sought after data is precritical.

On-shore and shallow off-shore challenges

One approach for addressing this challenge can be found in the 2001 M-OSRP Annual Report by Mrinal Sen, Paul Stoffa (UTIG) and A. Weglein (M-OSRP) present a method for predicting precritical data from postcritical data.

On-shore and shallow off-shore challenges



Research Project Report

Title: Prediction of pre-critical seismograms from post-critical traces

Principal Investigator: Mrinal Sen
Co-principal Investigators: Arthur Weglein and Paul Stoffa

Arthur B. Weglein

2001 M-OSRP Annual Technical Review and Report for Sponsors

Final report submitted to BP on January 5, 2001

Attention:
Dr. Scott Mitchell
michells@bp.com
(281)366-5521

On-shore and shallow off-shore challenges

A frequent challenge in land seismic processing is a series of subresolution internal multiple generators at the near surface.

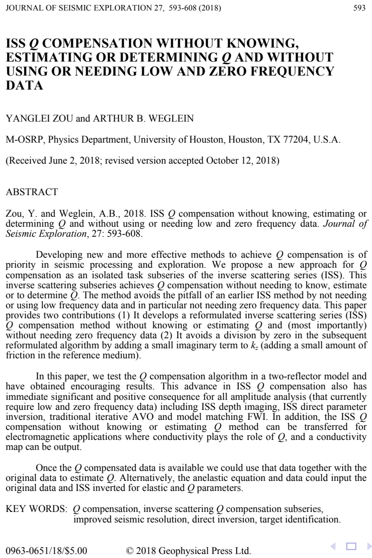
On-shore and shallow off-shore challenges

Those subresolution multiple generators produce a chain of troublesome multiples that cannot currently be removed. That is a prioritized challenge that does not have an effective response — not even an embryonic concept or theory

On-shore and shallow off-shore challenges

We propose the following response:
(1) apply the ISS Q compensation algorithm [Zou and Weglein (2018)] to boost the high frequency content of the recorded data, and hence the resolution of currently subresolution multiple generators.

On-shore and shallow off-shore challenges



JOURNAL OF SEISMIC EXPLORATION 27, 593-608 (2018) 593

ISS *Q* COMPENSATION WITHOUT KNOWING, ESTIMATING OR DETERMINING *Q* AND WITHOUT USING OR NEEDING LOW AND ZERO FREQUENCY DATA

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ABSTRACT

Zou, Y. and Weglein, A.B., 2018. ISS *Q* compensation without knowing, estimating or determining *Q* and without using or needing low and zero frequency data. *Journal of Seismic Exploration*, 27: 593-608.

Developing new and more effective methods to achieve *Q* compensation is of priority in seismic processing and exploration. We propose a new approach for *Q* compensation as an isolated task subseries of the inverse scattering series (ISS). This inverse scattering subseries achieves *Q* compensation without needing to know, estimate or to determine *Q*. The method avoids the pitfall of an earlier ISS method by not needing or using low frequency data and in particular not needing zero frequency data. This paper provides two contributions (1) It develops a reformulated inverse scattering series (ISS) *Q* compensation method without knowing or estimating *Q* and (most importantly) without needing zero frequency data (2) It avoids a division by zero in the subsequent reformulated algorithm by adding a small imaginary term to k_z (adding a small amount of friction in the reference medium).

In this paper, we test the *Q* compensation algorithm in a two-reflector model and have obtained encouraging results. This advance in ISS *Q* compensation also has immediate significant and positive consequence for all amplitude analysis (that currently require low and zero frequency data) including ISS depth imaging, ISS direct parameter inversion, traditional iterative AVO and model matching FWI. In addition, the ISS *Q* compensation without knowing or estimating *Q* method can be transferred for electromagnetic applications where conductivity plays the role of *Q*, and a conductivity map can be output.

Once the *Q* compensated data is available we could use that data together with the original data to estimate *Q*. Alternatively, the anelastic equation and data could input the original data and ISS inverted for elastic and *Q* parameters.

KEY WORDS: *Q* compensation, inverse scattering *Q* compensation subseries,
improved seismic resolution, direct inversion, target identification.

0963-0651/18/$5.00

On-shore and shallow off-shore challenges

(2) apply the ISS IME algorithm with its water speed SCIII migration to maximize the ability to locate and delineate multiple generators

On-shore and shallow off-shore challenges

A new multidimensional method that eliminates internal multiples that interfere with primaries, without damaging the primary, without knowledge of subsurface properties, for off-shore and on-shore conventional and unconventional plays

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

SUMMARY

Multiple removal is a longstanding problem in exploration seismology. Many methods have been developed including: stacking, FK filter, Radon transform, deconvolution and Feedback loop. They make statistical assumptions, assume move-out differences, or require knowledge of the subsurface and the generators of the multiples (e.g., Foster and Mosher, 1992; Verschuur et al., 1992; Berkhout and Verschuur, 1997; Jakubowicz, 1998; Robinson and Treitel, 2008; Wu and Wang, 2011; Meles et al., 2015; da Costa Filho et al., 2017; Lomas and Curtis, 2019). As the industry moved to deep water and more complex on-shore and off-shore plays, these methods bumped up against their assumptions. The Inverse Scattering Series (ISS) internal-multiple-attenuation algorithm (Araújo et al., 1994, Weglein et al., 1997 and Weglein et al., 2003) made none of the assumptions of previous methods (listed above) and stands alone, and is unique in its effectiveness when the subsurface and generators are complicated and unknown. It is the only multi-dimensional internal-multiple-removal method that can predict all internal multiples with exact arrival time and approximate amplitude without requiring any subsurface information. When internal multiples and primaries are isolated, the ISS internal-multiple-attenuation algorithm is usually combined with an energy-minimization adaptive subtraction to remove internal multiples. For isolated internal multiples, the ISS attenuator combined with energy-minimization adaptive subtraction is successful and effective. However, when internal multiples are proximal to and/or interfering with primaries or other events, the criteria behind energy-minimization adaptive subtraction can fail (e.g., the energy can increase rather than decrease when a multiple is removed from a destructively interfering primary and multiple). With interfering events, energy-minimization adaptive subtraction can lead to damaging the target primary, which is the worst possible outcome. In this paper, we provide the first multi-dimensional ISS internal-multiple-elimination algorithm that can predict both the correct time and amplitude of internal multiples. This is an important part of a three-pronged strategy proposed by Weglein at the 2013 SEG International Conference (Weglein 2014). Herrera and Weglein (2012) proposed a 1D ISS internal-multiple-elimination algorithm for all first-order internal-multiples generated at the shallowest reflector. Y. Zou and Weglein (2014) then went further and developed and illustrated an elimination algorithm that can eliminate all first-order internal multiples generated by all reflectors for a 1D earth. In this paper we provide the first multidimensional ISS internal-multiple-elimination method that can remove internal multiples interfering with primaries, without subsurface information, and without damaging the primary. We also compare the ISS elimination result with ISS attenuation plus energy-minimization adaptive subtraction for an interfering primary and internal multiple. This ISS internal-multiple-elimination algorithm is more effective and more compute-intensive than the current most capable ISS attenuation-plus-adaptive-subtraction method. We provide it as a new capability in the multiple-removal toolbox and a new option for circumstances when this type of capability is called for, indicated and necessary. That can frequently occur in offshore and onshore conventional and unconventional plays. We are exploring methods to reduce the computational cost of these ISS attenuation and elimination algorithms, without compromising effectiveness.

INTRODUCTION

The ISS (Inverse-Scattering-Series) allows all seismic processing objectives, e.g., free-surface-multiple removal and internal-multiple removal, depth imaging, non-linear amplitude analysis and Q compensation to be achieved directly in terms of data, without any need for, or determination of subsurface properties (e.g., Weglein et al., 2012; Zhang and Weglein, 2009a,b; Zou and Weglein, 2018). The ISS internal-multiple attenuation algorithm is the only method today that can predict the correct time and approximate amplitude for all first-order internal multiples generated from all reflectors, at once, without any subsurface information. If the multiple to be removed is isolated from other events, then the energy minimization adaptive subtraction can fill the gap between the attenuation algorithm and the amplitude of the internal multiples. However primary and multiple events can often interfere with each other in both on-shore and off-shore seismic plays. In these cases, the criteria of energy minimization adaptive subtraction can fail and eliminating internal multiples is beyond the current capability of the petroleum industry.

For dealing with this challenging problem, Weglein (2013) proposed a three-pronged strategy:

1. For on-shore applications, predicting ground roll and reflection data: all current methods are filtering techniques that remove ground roll while damaging reflection data. The latter is harmful for all subsequent processing goals (e.g., multiple removal, imaging and inversion). Recent significant progress in predicting ground roll and reflection data (without filtering or damaging either), e.g., Wu and Weglein (2015) without needing or determining subsurface properties, but requiring near surface information. Similarly, Matson (1997) and Matson and Weglein (1996), Zhang and Weglein (2006) provide methods for on-shore and OBC demultiple and deghosting, respectively, and did not require subsurface information but required near-surface information. A new and general method (Weglein, 2019) for seismic preprocessing and processing, not only doesn't require

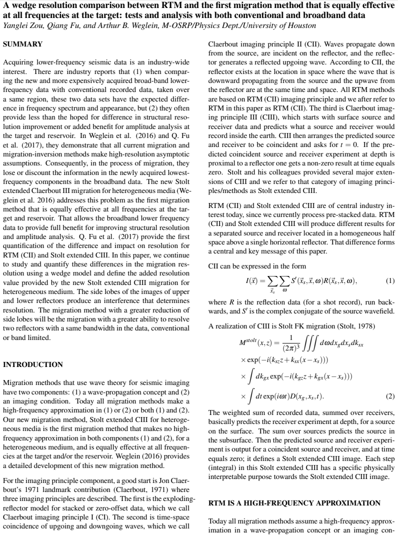
SEG International Exposition and 89th Annual Meeting

10.1190/segam2019-3215218.1

On-shore and shallow off-shore challenges

(3) use SCIII migration with heterogeneous and discontinuous medium to (avoid high frequency approximation) and have the benefit of all frequency components in the source wave field.

On-shore and shallow off-shore challenges



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

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

SUMMARY

Acquiring lower-frequency seismic data is an industry-wide interest. 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 resolution improvement or added benefit for amplitude analysis at the target and reservoir. In Weglein et al. (2016) and Q. Fu et al. (2017), they demonstrate that all current migration and migration-inversion methods make high-resolution asymptotic assumptions. Consequently, in the process of migration, they lose or discount the information in the newly acquired lowest-frequency components in the broadband data. The new Stolt extended Claerbout III migration for heterogeneous media (Weglein et al. 2016) addresses this problem as the first migration method that is equally effective at all frequencies at the target and reservoir. That allows the broadband lower frequency data to provide full benefit for improving structural resolution and amplitude analysis. Q. Fu et al. (2017) provide the first quantification of the difference and impact on resolution for RTM (CII) and Stolt extended CIII. In this paper, we continue to study and quantify these differences in the migration resolution using a wedge model and define the added resolution value provided by the new Stolt extended CIII migration for heterogeneous medium. The side lobes of the images of upper and lower reflectors produce an interference that determines resolution. The migration method with a greater reduction of side lobes will be the migration with a greater ability to resolve two reflectors with a same bandwidth in the data, conventional or band limited.

INTRODUCTION

Migration methods that use wave theory for seismic imaging have two components: (1) a wave-propagation concept and (2) an imaging condition. Today all migration methods make a high-frequency approximation in (1) or (2) or both (1) and (2). Our new migration method, Stolt extended CIII for heterogeneous media is the first migration method that makes no high-frequency approximation in both components (1) and (2), for a heterogeneous medium, and is equally effective at all frequencies at the target and/or the reservoir. Weglein (2016) provides a detailed development of this new migration method.

For the imaging principle component, a good start is Jon Claerbout's 1971 landmark contribution (Claerbout, 1971) where three imaging principles are described. The first is the exploding-reflector model for stacked or zero-offset data, which we call Claerbout imaging principle I (CI). The second is time-space coincidence of upgoing and downgoing waves, which we call Claerbout 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 CII, the reflector exists at the location in space where the wave that is downward propagating from the source and the upwave from the reflector are at the same time and space. All RTM methods are based on RTM (CII) imaging principle and we after refer to RTM in this paper as RTM (CII). The third is Claerbout imaging principle III (CIII), which starts with surface source and receiver data and predicts what a source and receiver would record inside the earth. 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. Stolt and his colleagues provided several major extensions of CIII and we refer to that category of imaging principles/methods as Stolt extended CIII.

RTM (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

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

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 CIII is Stolt FK migration (Stolt, 1978)

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

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 extended CIII has a specific physically interpretable purpose towards the Stolt extended CIII image.

RTM IS A HIGH-FREQUENCY APPROXIMATION

Today all migration methods assume a high-frequency approximation in a wave-propagation concept or an imaging con-

A frequent confusion between the properties of the forward and inverse scattering series

There is sometimes a serious confusion and serious misunderstanding about the properties of the forward scattering series (a modeling method) and the inverse scattering series. The former, the forward scattering series, as a modeling method requires the specification of the earth model type, and the exact properties of the subsurface for that model type.

A frequent confusion between the properties of the forward and inverse scattering series (continued)

On the other hand, the inverse scattering series and every term within that series is directly computable in terms of the recorded seismic data and a constant reference (water) speed — and hence all isolated task subseries of the ISS share that property. Furthermore, Weglein et al (2003) prove that the distinct isolated task subseries of the ISS for free surface and internal multiple removal, are totally independent of the type of earth model (no line of code is changed for acoustic, elastic, anisotropic, heterogeneous, inelastic . . . models).

A frequent confusion between the properties of the forward and inverse scattering series (continued)

Unfortunately, there is literature e.g., ten Kroode (2002) that mistakenly seek to “derive” “something like” the ISS isolated task subseries for internal multiple attenuation by looking at the forward series. That fundamental misunderstanding about the different properties and function of the forward and inverse series, and the origin of the ISS internal multiple attenuator, leads to incorrect conclusions, that would be valid if the distinct ISS isolated task subseries were modeling methods—which they aren’t.

To start a research project

What is the suggestion for starting and pursuing a relevant research plan.

To start a research project

(1) Begin by examining the tool box of seismic processing methods

To start a research project (continued)

(2) Define the gaps in capability. Then in consultation with interpreters and those who make drilling decisions decide on the priority of open issues and challenges.

To start a research project (continued)

(3) Commit to finding a solution to the challenge — commit to the problem that needs to be addressed — not to a method that's looking for a problem

A recent counter example on how to start a relevant and purposeful research project

In our view, there is a recent method proposed for removing multiples that is a perfect example of exactly what not to do in developing a research program whose objective is to add new capability to the seismic toolbox. Those who put forward this method never took a serious look (and understanding) at the seismic toolbox of methods for multiple removal and imaging to identify shortcomings and limitations and gaps that needed to be identified and addressed.

A recent counter example on how to start a relevant and purposeful research project

In fact this recent multiple removal "method" adds assumptions and prerequisites to the toolbox of methods and hence is a step backward in multiple removal capability and effectiveness.
The assumptions that this new method makes, are precisely the limiting assumptions the current toolbox, with ISS methods were designed to avoid.
Why is that important?

A recent counter example on how to start a relevant and purposeful research project

Seismic failure contributes to dry hole drilling — seismic methods fail when their assumptions are violated; to increase seismic capability develop methods with fewer assumptions.

How to proceed?

Find a way to remove the violation of prerequisites or assumptions behind seismic processing method failure. There are two ways: (1) remove the violation of assumption or prerequisites by finding a new and more effective way to satisfy these requirements or (2) remove the assumption or prerequisite violation by removing the assumption or prerequisite — by developing fundamental new methods that can achieve the same processing objective without the current assumptions or prerequisites.

Increasing the number of (unnecessary and avoidable and unrealistic) assumptions in an undertaking that provides less capable methods

The difference between methods and people (between science and scientists) the latter often take a political and marketing route to “success”

political and marketing steps to “success”

(1) arrange to be in key SEG and EAGE positions in journals and workshop organizing committees, and special issue organizers that produce a steady publication of only their “method” without any assumptions and shortcomings ever pointed out, and no mention of what their method adds to the collective seismic toolbox. And avoid and block asking any real and relevant questions and the publication of any other views and methods.

political and marketing steps to “success” (continued)

(2) engage in a misrepresentation of the capability of methods that were already available in the toolbox and being used, that are, in fact, intrinsically more effective and capable than the new method (Weglein, Jing Wu, F. Melo, J. Etgen, J. Mayhan (2022))

political and marketing steps to “success” (continued)

(3) Avoiding a clear statement in papers and presentations of the serious and limiting assumptions made in the new methods, that taken together are a major step backward (compared to, e.g., ISS methods for attenuating and removing internal multiples)

political and marketing steps to “success” (continued)

(4) avoiding the clear connection to the much earlier methods e.g., the Jakubowicz method (1998) that is widely used, and whose assumptions and shortcomings are well known and understood — and can represent an informed cost-effective choice when the compromise between cost and effectiveness is appropriate and indicated.

The current toolbox of multiple removal methods

What is the current toolbox of multiple removal capability? The published paper (please see the link below) Feb. 2022, JSE, co-authored with John Etgen of BP and Fred Melo, Jing Wu of Schlumberger and Jim Mayhan of M-OSRP, provides a timely overview and describes when each option within the multiple removal toolbox might be the well-informed cost-effective choice — along with open issues and challenges.

One of several conclusions of that recent overview paper (cited above) is that the most effective method for removing internal multiples is the inverse scattering internal multiple eliminator (ISS IME). Yanglei Zou et al, (2019) There are three properties that only this internal multiple (ISS IME) method possesses: (1) it predicts the exact amplitude and phase of the internal multiple at all offsets ; (2) there is no subsurface information known, estimated or determined, no interpreter intervention, and (3) it is one unchanged algorithm for every earth model type;

(4) it has a water speed Stolt-Claerbout III migration, and unlike Kirchhoff and RTM it can automatically accommodate multiple generators that are planar curved, and point scatterer diffractive pinch outs; (5) there is no need for an adaptive step since it predicts the exact phase and amplitude of the internal multiple at every offset- and (6) the key lower higher lower relationship is correct and in vertical time, not total time (the latter is erroneous (and deleterious) and called upon in Marchenko methods). The criteria behind energy minimization adaptive subtraction can fail with interfering or proximal events.

continued from Weglein, Jing Wu, Fred Melo, J. Etgen, J. Mayhan (2022)

No other multiple removal method (e.g., Radon, Jakubowicz, or Marchenko) satisfies one let alone all these beneficial properties — and that explains why ISS IME is currently the most effective internal multiple removal method.
The inverse scattering internal multiple attenuator (ISS IMA) predicts the exact time and approximate amplitude of all internal multiples — and hence ISS IMA often calls upon an adaptive step to remove the internal multiple.

continued from Weglein, Jing Wu, Fred Melo, J. Etgen, J. Mayhan (2022)

The inverse scattering free surface eliminator (ISS FSME) and the inverse scattering internal multiple eliminator (ISS IME) are the most effective methods for removing free surface and internal multiples, respectively. See e.g., Chao Ma et al 2018 for a direct comparison between ISS FSME and SRME, and Chao Ma et al (2020) for a comparison of internal multiple methods.

The Big Picture: Past, Present and Future

In the 1980's the methods for migration were conceptually and practically more advanced compared to methods for removing multiples. Now that situation is reversed

The Big Picture: Past, Present and Future

In 1985

- migration: multiD and needed the velocity model
- multiples: one-D methods, with statistical assumptions or filtering methods that needed a velocity model

The Big Picture: Past, Present and Future

In 2023

- migration (SCIII): multi-D and need the velocity model
- multiples (ISS): multi-D and with no subsurface information known, estimated or determined

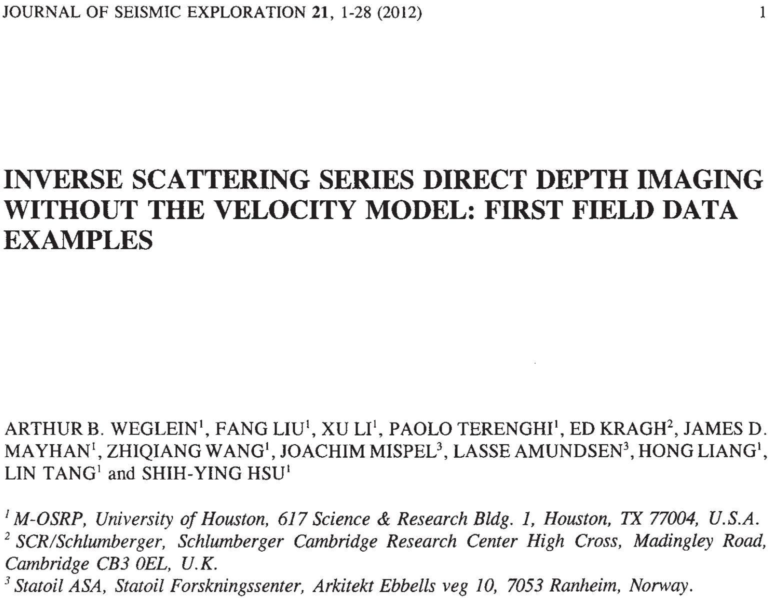
The Big Picture: Past, Present and Future

In 2043 we predict:

- migration (ISS direct depth imaging): multi-D and no need for subsurface information to be known, estimated or determined
- multiples (ISS removal of free surface and internal multiples): multi-D and with no need for subsurface information to be known, estimated or determined

The Big Picture: Past, Present and Future

migration needs to catch-up with multiple removal



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

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Conclusions

This Presentation has described the current state of multiple removal and imaging, and the open issues and challenges to all marine and onshore seismic processing.

Conclusions

We addressed specific prioritized obstacles to effectiveness for land and shallow water. Lastly new embryonic concepts, and methods that can begin to address these multiple removal and imaging and inversion challenges will be suggested and described.

Conclusions

- 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.

The ISS methods are often the well-informed cost-effective choice under the most complicated and daunting circumstances, with rapidly varying multiple generators (and for interfering and proximal events). Further detail and analysis can be found in the video presentations and publications in the links below. `http://www.mosrp.uh.edu/people/faculty/arthur-weglein`

We described:
What are the open issues for land and shallow water multiple removal? What are some of the approaches that could address these open issues on multiple removal and imaging and inversion?

Conclusions

A direct inverse method assures that you have solved the problem you set out to solve, but equally if not more important it communicates whether the problem you are interested in solving is the relevant real problem you need to be solving. If a direct inverse method doesn't increase the drill success rate, the problem that you are solving is not the problem that you need to be solving.

Why direct inverse methods play a fundamentally important role in defining the goals of a relevant research program that seeks added value in target identification and successful drilling. (continued)

With an indirect model matching method like FWI, if you don't improve the drill success rate — you don't know if you are solving the wrong problem, or whether your indirect method is the issue, or both. Defining and solving the right problem is the key and essential first step in a research program and project.

Conclusion with ISS FSME

- 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 unchanged for any earth model type
- ISS FSME eliminates all free surface multiples at all offsets, without 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

Conclusion

- Using some form of FWI to predict multiples, requires a modeling method, where one seeks to model the subsurface 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.

Conclusion

- 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.

Acknowledgements

I thank the sponsors of M-OSRP for their encouragement and support and Jim Mayhan for his assist with preparing these slides.

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Multiple attenuation and imaging and inversion remain the central objectives of marine and onshore seismic processing. While there has been progress, many major hurdles and serious and daunting challenges remain.