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

ecoPETROL

A new and comprehensive perspective on the role of primaries and multiples in seismic data processing for structure determination and amplitude analysis

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Recorded at UH on Nov. 9th, 2018
Invited address for Ecopetrol CT&F Journal Special Event on Dec. 9th, 2018
in Bogota, Colombia

- Removal and usage of multiples are not adversarial. In fact they are after the same single exact goal, that is, to image primaries: both recorded primaries and unrecorded primaries. There are circumstances where a recorded multiple can be used to find an approximate image of an unrecorded subevent primary of the recorded multiple.

- There are two types of primaries and multiples: those that are recorded and those that are not recorded. Recorded data consists of recorded primaries and recorded multiples.

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- Migration and migration-inversion are the methods used to locate structure and to perform amplitude analysis.

- Wave theory methods for migration have two ingredients: a wave propagation model and an imaging principle.

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

Wave Theory Seismic Migration

• Migration methods that use wave theory for seismic imaging have two components: (1) a wave propagation model, and (2) an imaging condition.

• We will examine each of these two components and the frequency fidelity of migration algorithms, and the impact on resolution.

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

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Three imaging principles

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

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Let’s examine Claerbout II (RTM) and III where only the imaging condition is the issue

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How do you know if a migration method has made a high frequency approximation?

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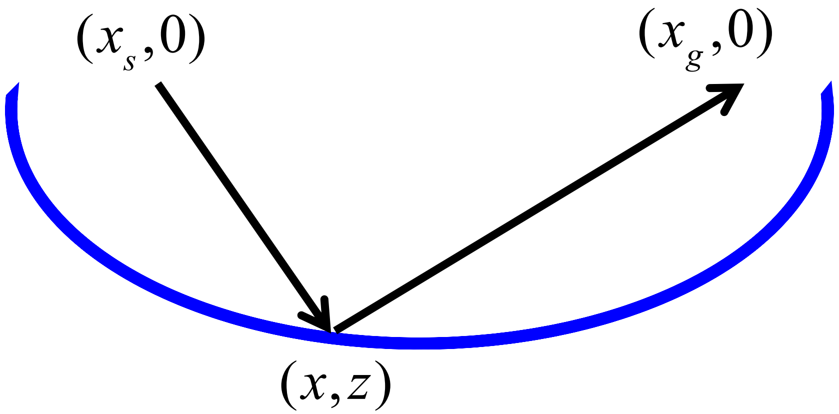
Ray theory is a high frequency approximation to wave theory

✓(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,

$$r = r_g + r_s$$
$$= \sqrt{(x_g - x)^2 + z^2} + \sqrt{(x_s - x)^2 + z^2}$$

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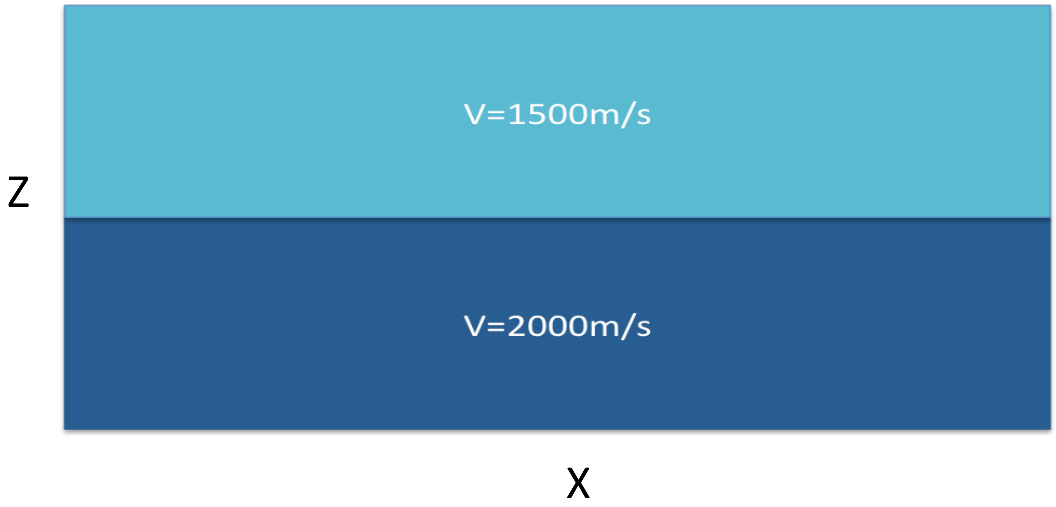
Model



Yanglei Zou and Weglein,
2014

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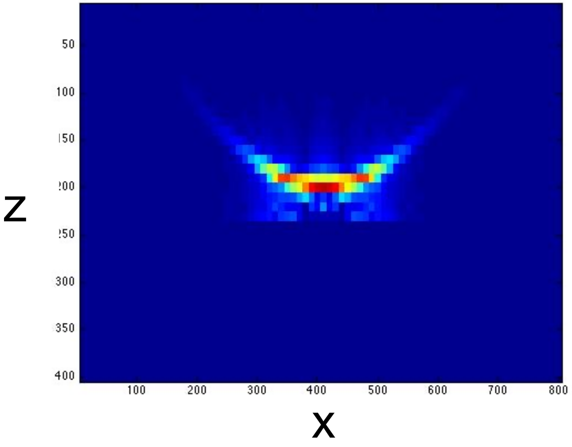
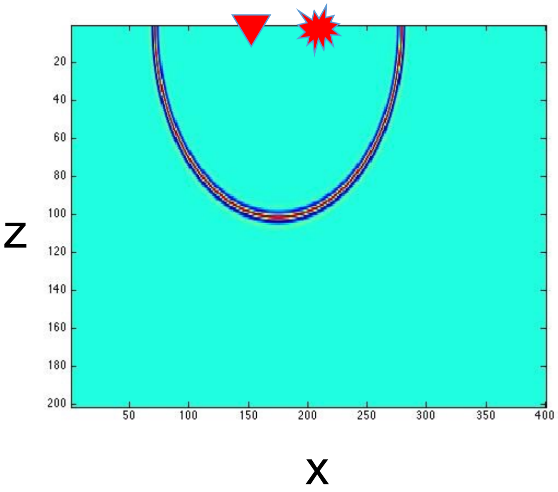
Imaging Conditions and High Frequency Assumptions

Claerbout III **Stolt migration**
(one source one receiver)



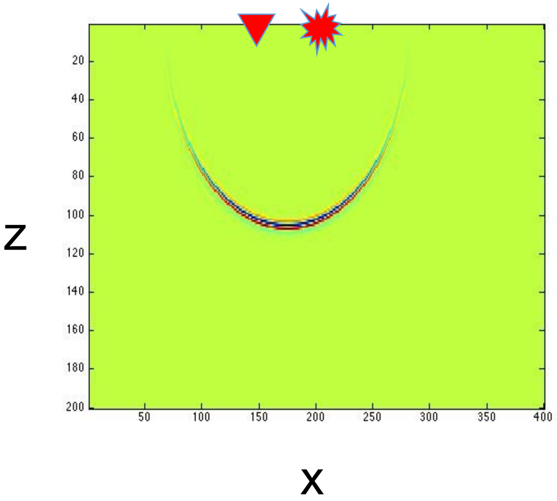
No high frequency assumption

Claerbout II **RTM** (2D)
(one source one receiver)



High frequency assumption

Kirchhoff migration (2D)
(one source one receiver)



High Frequency approximation from a stationary phase approximation

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Wave theoretical and high-frequency approximation

- CII → RTM (the imaging principle behind RTM and LSRTM is a high frequency approximation, with constructive interference of ray-based candidates for structural images)

- CIII → Stolt CIII (wave theoretical imaging principle)

Claerbout II and III have been extended and generalized

- For Claerbout II

  e.g., Yu Zhang, Sheng Xu and Norman Bleistein

  ----- introduce **a geometric optics reflection coefficient** model relating the reflection data and the incident source wavefield.

- For Claerbout III

  Stolt and collaborators

  ----- non-zero offset at t=0 provides amplitude information

  ----- outputs **plane wave reflection coefficient** or point scatterer reflectivity for specular and non-specular reflection

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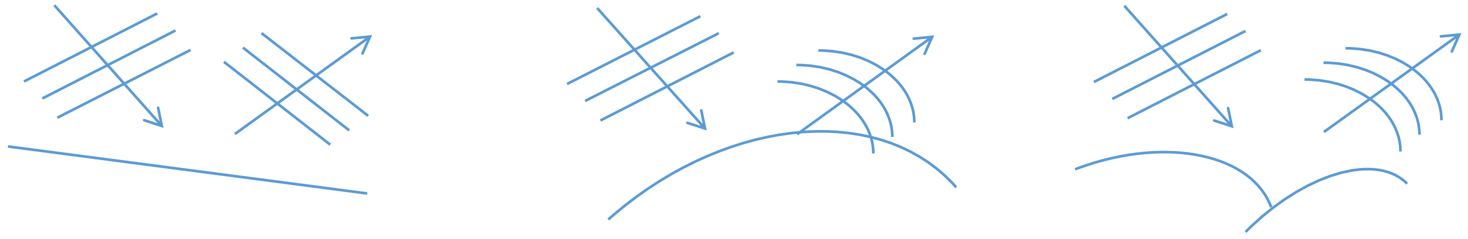
Benefits of Claerbout III imaging (extended by Stolt and colleagues) for specular and non-specular imaging

1 2 3



specular non-specular non-specular

1. Specular

outputs actual plane wave reflection coefficient data for specular reflection (unique to Claerbout III)

2. Non-Specular reflection

a point scatterer model for structure and inversion of non-specular reflections (unique to Claerbout III)

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

- M-OSRP has recently extended 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 able to input primaries and multiples and for a continuous or discontinuous velocity model is equally effective at all frequencies.

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New from M-OSRP

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

$$P = \int_{S_s} \left[\frac{\partial G_0{}^{DN}}{\partial z_s} \int_{S_g} \left\{ \frac{\partial G_0{}^{DN}}{\partial z_g} P + \frac{\partial P}{\partial z_g} G_0{}^{DN} \right\} dS_g + G_0{}^{DN} \frac{\partial}{\partial z_s} \int_{S_g} \left\{ \frac{\partial G_0{}^{DN}}{\partial z_g} P + \frac{\partial P}{\partial z_g} G_0{}^{DN} \right\} dS_g \right] dS_s$$

Green's theorem for two way waves with measurements on upper surface
For details, see Weglein et al. (2011a,b) and F. Liu and Weglein (2014)

New SCIII migration beneath a single reflector with a <u>discontinuous</u> 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

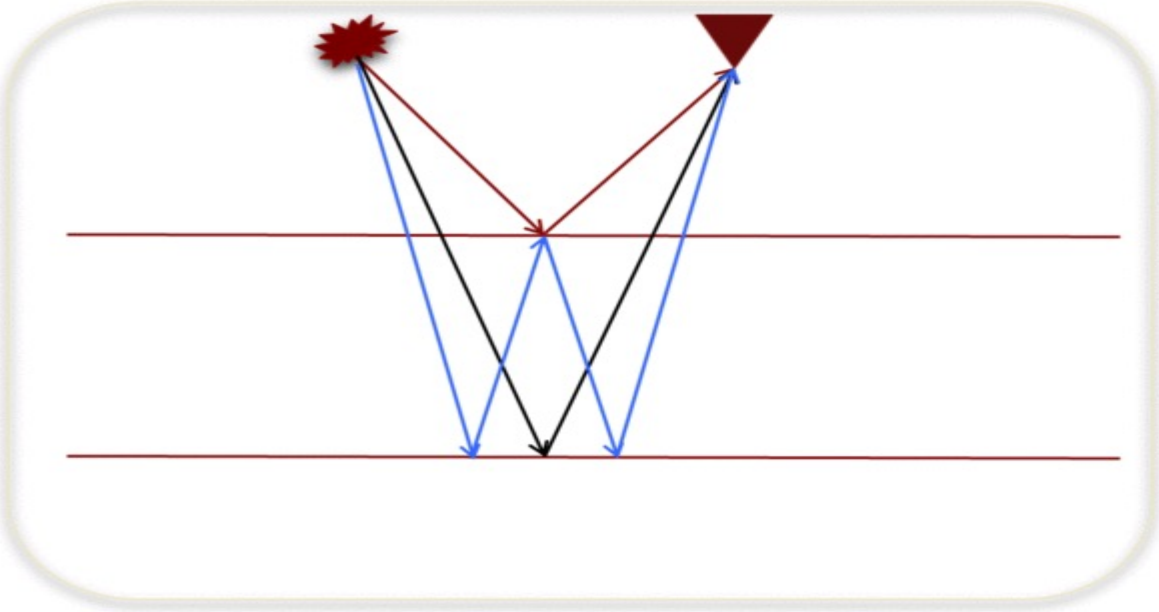
Qiang Fu et al

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

•No "rabbit ears"
•Consistent image along the reflector

New Stolt CIII migrating through layers

Case 1: two primaries and an internal multiples

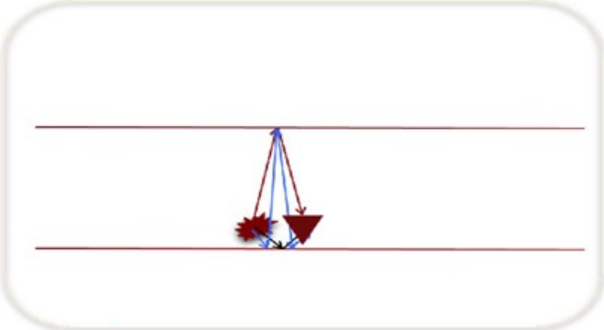


New Stolt CIII migrating through layers

Case 1: two primaries and an internal multiples

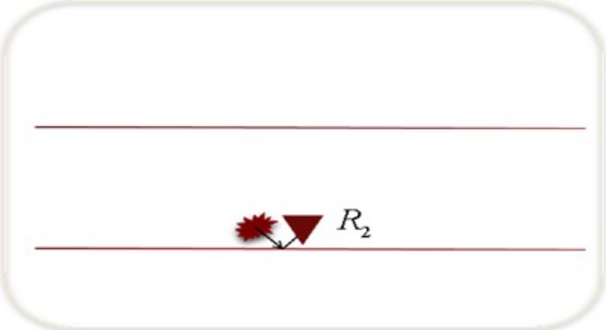
Above the second reflector (predicted experiment at depth)

Coincident source and receiver at depth for all times



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

Coincident source and receiver at depth for t = 0



Black event: primary from the second reflector

1. Given an accurate discontinuous velocity model above a reflector, free surface and internal multiples will provide neither benefit nor harm in migration and migration-inversion and need not be removed

2. For a smooth velocity model above a reflector, multiples will produce false images and hence must be removed prior to migration.
   - the industry standard smooth migration velocity model drives the need to remove free surface and internal multiples
   - the distinct inverse scattering series algorithms for removing free surface and internal multiples are the only methods that do not require subsurface information

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- **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

- In the evolution of seismic processing, methods have been developed to attempt to address issues caused by less that the necessary data
  - 2D data collection plus asymptotics for a 3D earth
  - Single component on-shore acquisition
  - Single cable methods to do wave separating and deghosting

- Eventually, there is no option but to advance the acquisition and provide the required data.

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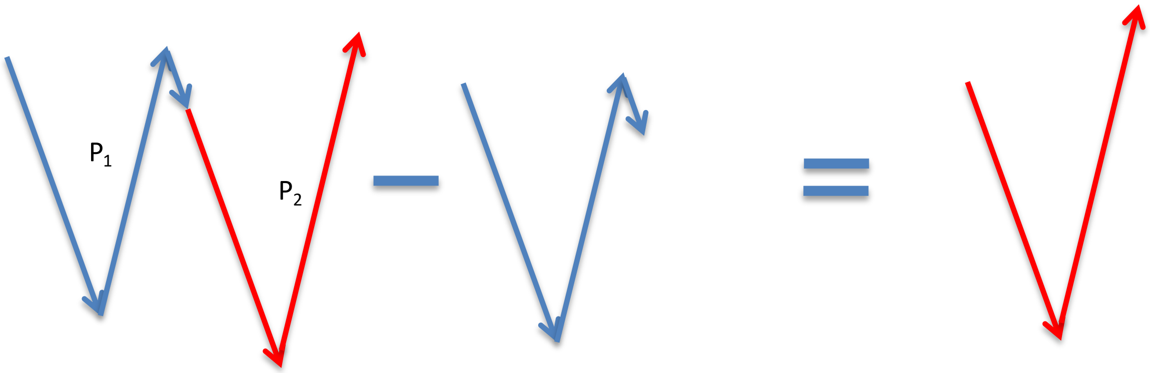
Hence, with an accurate discontinuous velocity model, only recorded primaries contribute to migration and inversion, and only primaries are signal. For a smooth velocity model, it is possible to correctly locate primaries in depth, but all multiples (if not removed) will result in artifacts and spurious images.

For smooth velocities, multiples produce false images and must be removed in any migration of primaries and multiples.

- What if we have a incomplete recording of primaries, i.e., some primaries are recorded and some are not.

Seeking an approximate image of an unrecorded primary that is a subevent of a recorded multiple

- <u>Usage of a recorded multiple</u>

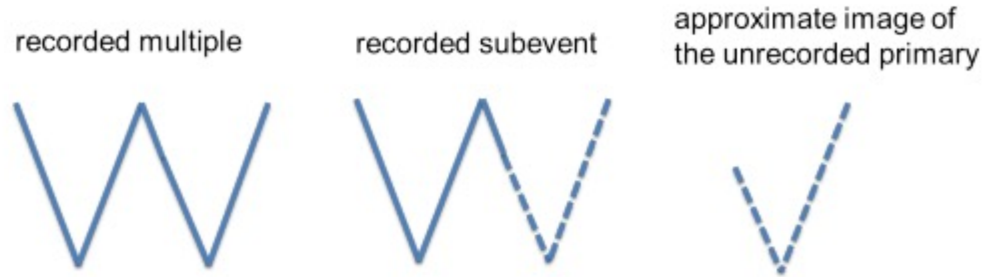


Decompose the composite

M | P_1 | P_2
Recorded | Recorded | Image of P_2 is approximated from M and P_1

To find an 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

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

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

Dashed event is an unrecorded multiple

- Therefore to image recorded primaries, recorded multiples must be removed and to find an approximate image of an unrecorded primaries, unrecorded multiples must be removed.

- A multiple is only useful if it has a recorded subevent that corresponds to an unrecorded primary.

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- 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.

- The prediction of multiples is possible only for multiples that have no use. If it’s useful we cannot predict it.
- That’s good news!
- Treating the entire data set of primaries and multiples as though they were multiples is the origin of a problem called ‘cross-talk’.

- The ‘useful’ recorded multiple must be removed before imaging recorded primaries.

- To predict a recorded multiple requires recording <u>all</u> the subevents of the multiple. The use of multiples assumes a subevent of the multiple has <u>not</u> been recorded.

- We often hear that multiples are needed to improve upon the illumination provided by primaries.

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- 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.

- We often hear that multiples are needed to improve upon the illumination provided by primaries.

- A response begins with paraphrasing a famous quote by Jon Claerbout ‘waves (and primaries) in the subsurface are ubiquitous, they go everywhere, and they have no illumination issues’

- However, methods that are used to process and image recorded data can make asymptotic or ray theory like assumptions --- and these methods result in illumination issues (Kirchhoff migration, and all RTM methods, including LSRTM are ray theory and high frequency approximation based.)

- And hence migration methods (like e.g., RTM and LSRTM) generate and create resolution and illumination issues that discount and diminish the information in recorded seismic data.

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- 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.

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Multiple removal: an update

- In the history of the seismic processing as methods for imaging and multiple removal became more capable they had a commensurate increase in the need for subsurface information
- That evolution ran into a problem as the industry trend to deep water and a more complex geologic on-shore and off-shore plays made that requirement difficult or impossible to satisfy.
- The Inverse Scattering Series (ISS) communicates that all processing objectives can be achieved directly and without subsurface information
- Isolated ISS task-specific subseries were developed
  - Free-surface multiple elimination
  - Internal multiple attenuation/elimination
  - Q compensation without knowing Q
  - Depth imaging
  - Inversion (parameter estimation)

- More effective prediction is required when multiples interfere with or are proximal to other events
  - ISS free-surface multiple elimination rather than SRME
  - ISS internal multiple elimination

ISS free-surface multiple elimination (Carvalho and Weglein, 1991, Weglein et al 1997,2003)

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

$$D'_n(k_g, k_s, \omega) = \frac{1}{2\pi A(\omega)} \int dk\, e^{iq(z_g+z_s)} D'_1(k_g, k, \omega)(2iq) D_{n-1}{}'(k, k_s, \omega)$$

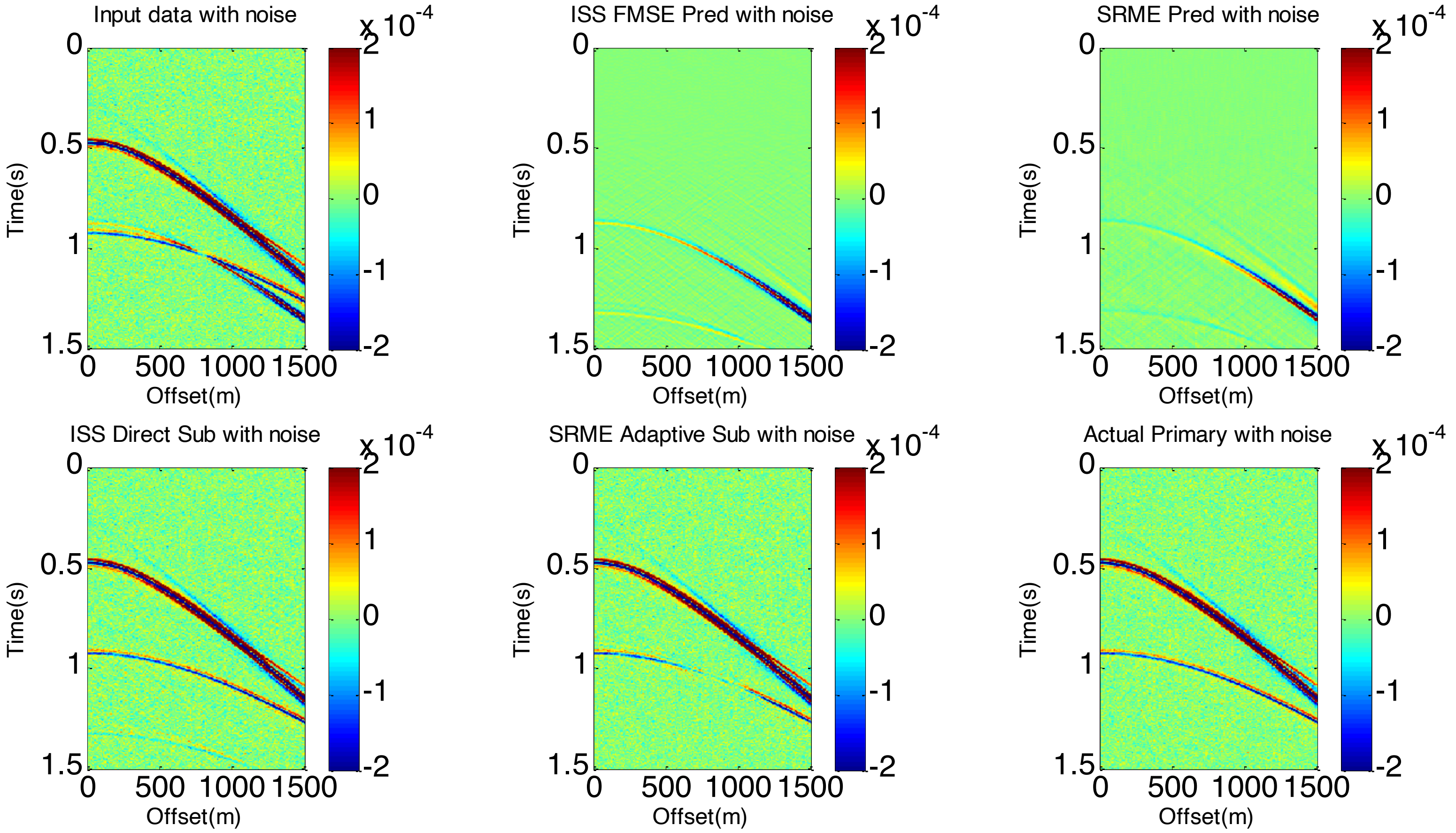
$$\text{n} = 2,3,4, \ldots$$

- The input $D_1{}'(k_g, k_s, \omega)$, in a 2D case, which are the Fourier transform of the deghosted prestack data, and with the direct wave removed.
- The output $D'(k_g, k_s, \omega)$ are free-surface multiple eliminated data.

SRME (Berkout, 1985; Verschuur, 1991)

$$M(x_g, x_s, \omega) = \int D'_1(x_g, x, \omega)D'_1(x, x_s, \omega)$$

Conclusion: SRME can be an effective choice for isolated FS multiples. For proximal or interfering free-surface multiples, ISS FS elimination (that doesn't rely on an energy minimization adaptive subtraction) can be the more effective and appropriate choice.



Chao Ma, Qiang Fu and Weglein, MOSRP report (2018)
(Submitted to Geophysics)

A sampling of the documented impact of the ISS internal multiple attenuation algorithm from M-OSRP

Service companies

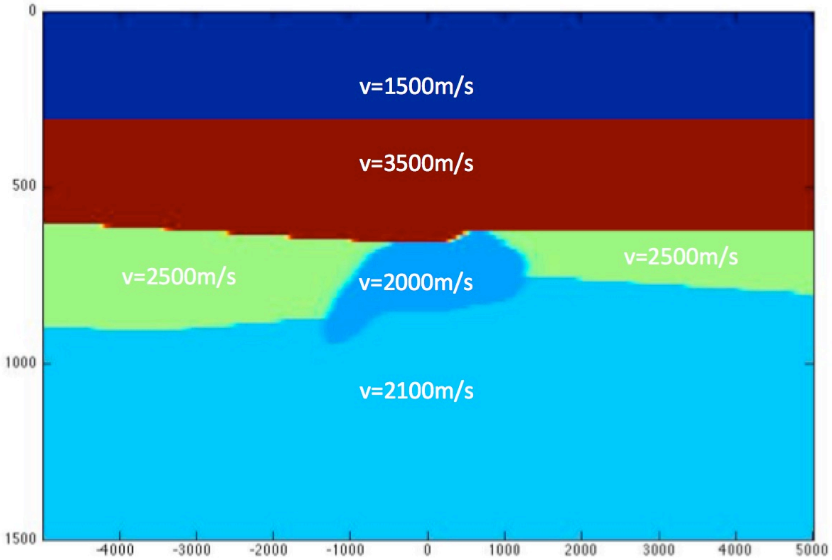
- Dragoset,2013 (Schlumberger)
- Frederico Xavier de Melo et al.,2013 (Schlumberger)
- Griffiths et al., 2013 (CGG)
- Hegge et al.,2013(PGS)
- Hung and Wang, 2014 (CGG)

Oil companies

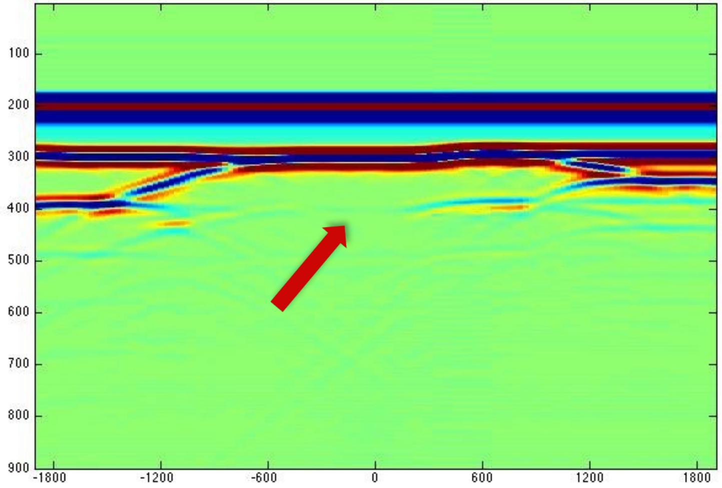
- Matson et al., 2000 (ARCO) first marine field data test
- Yi Luo et al., 2010 (Aramco) first on-shore field data test
- Qiang Fu et al., 2010 (Aramco/UH)
- Degang Jin et al., 2013 (CNPC)
- Ferreira et al., 2013(Petrobras)
- Goodway (Apache) and Mackidd (Encana), 2013
- Kelamis et al.,2013 (Aramco)

Multi-Dimensional ISS internal multiple elimination (numerical test)

model



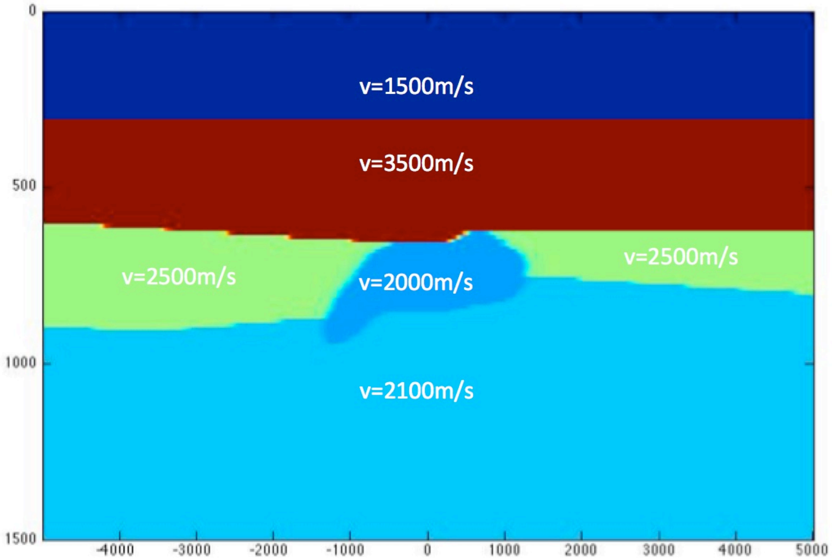
after internal multiple attenuation
+ energy minimization adaptive subtraction
(0-offset traces)



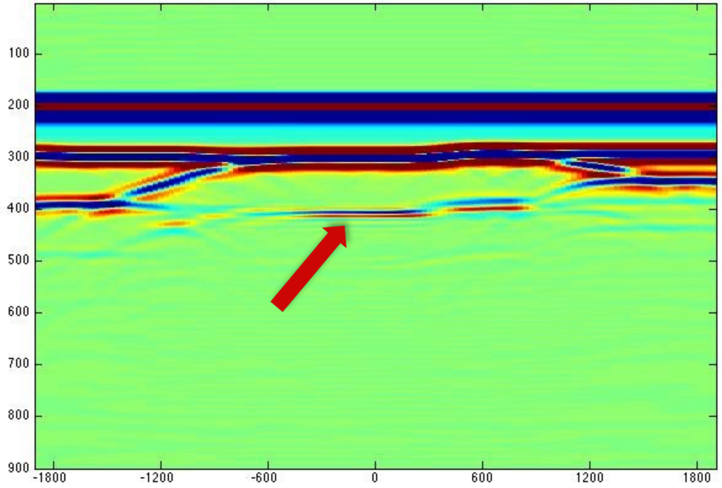
For the case of an interfering internal multiple and base salt primary, the ISS internal multiple attenuation + adaptive damage the primaries
(Yanglei Zou, Chao Ma and A. Weglein, 2018)

Multi-Dimensional ISS internal multiple elimination (numerical test)

model



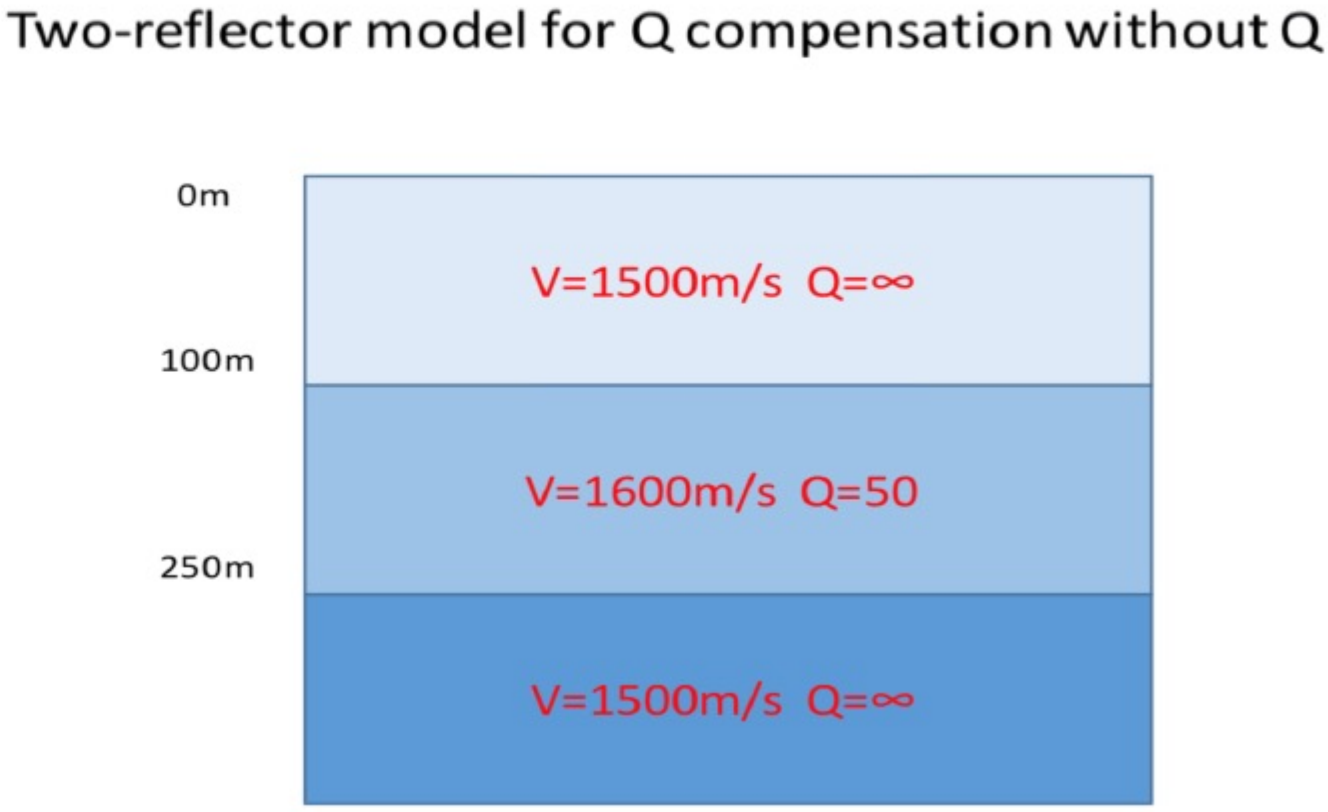
after internal multiple elimination
(0-offset traces)



For the case of an interfering internal multiple and base salt primary, the ISS elimination removed the internal multiple without damaging the primaries
(Yanglei Zou, Chao Ma, and A. Weglein, 2018)

ISS Q compensation without knowing or estimating Q

(Zou and Weglein, to appear JSE, Dec. 2018)



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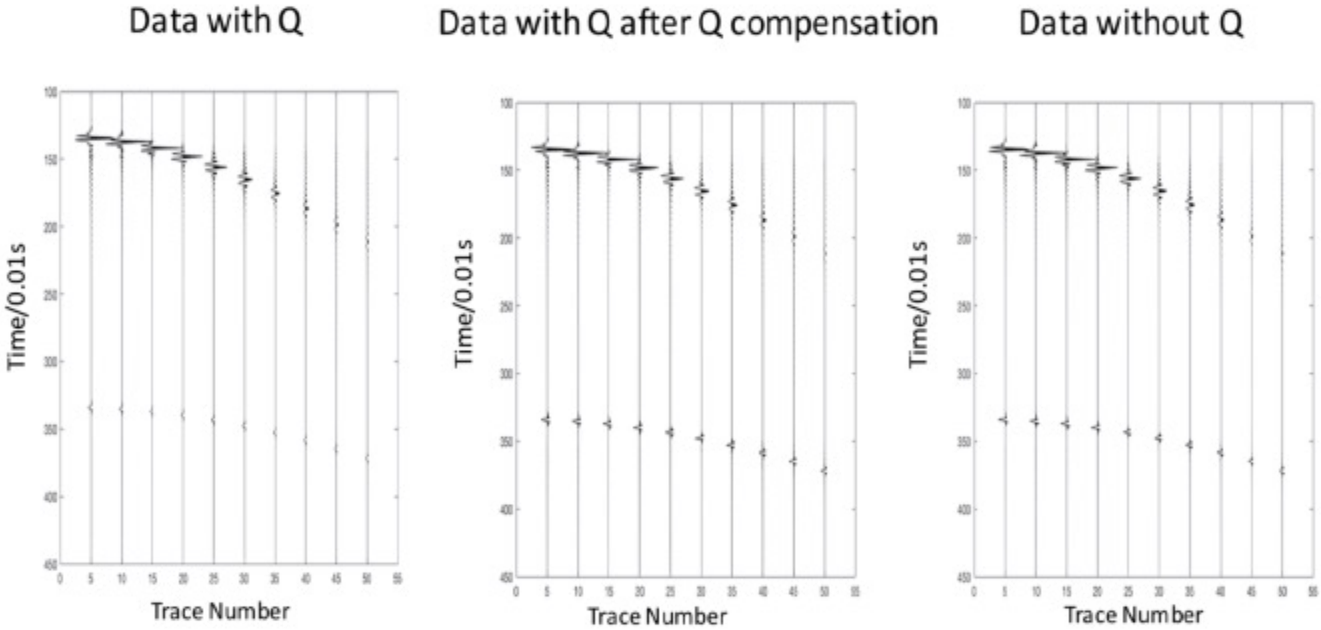

Fig. 2. Left: Data generated by the model with Q. Middle: The data (with Q) after ISS Q compensation without knowing or estimating Q Right: Data generated by the same model but without Q.

ISS Q compensation without knowing or estimating Q

(Zou and Weglein, to appear JSE, Dec. 2018)

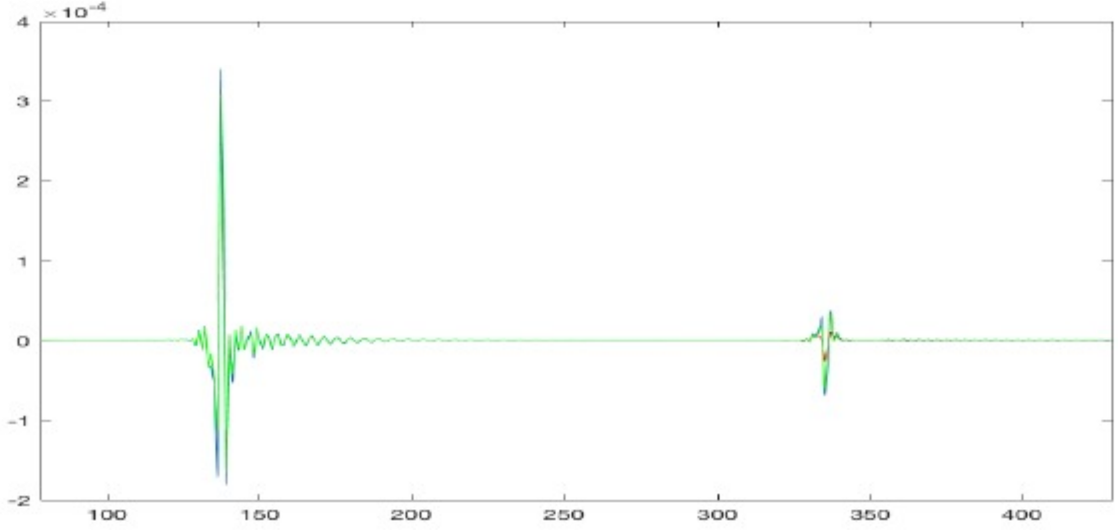

Fig. 3. One trace comparison. Red line: Data with Q. Green line: Data with Q after Q compensation. Blue line: Data without Q.

ISS Q compensation without knowing or estimating Q

(Zou and Weglein, to appear JSE, Dec. 2018)

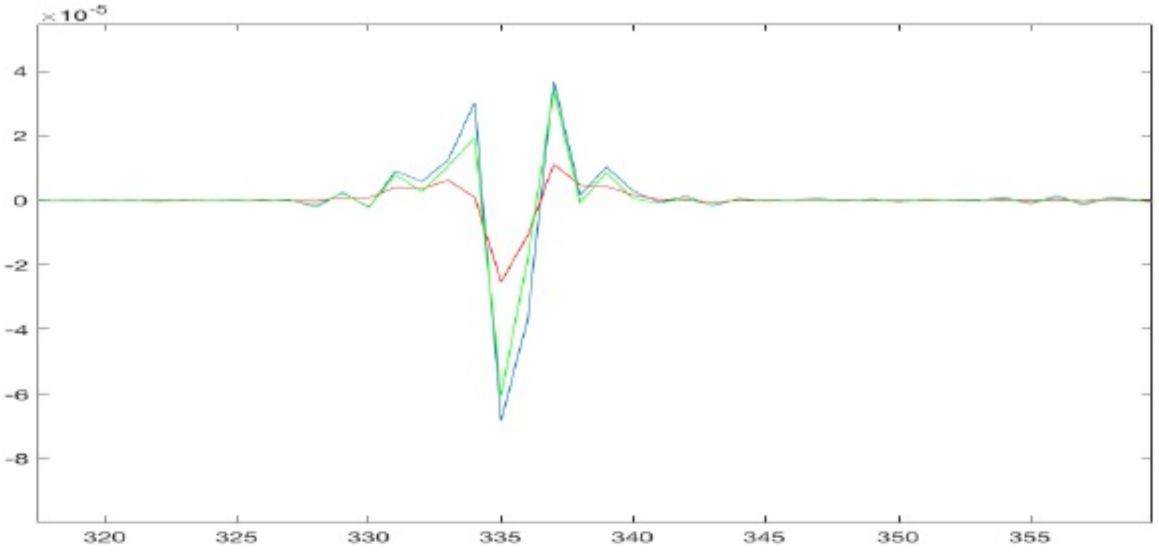

Fig. 4. One trace comparison magnifying the event in Fig. 3 between 3.2s-3.5s. Red line: Data with Q. Green line: Data with Q after Q compensation. Blue line: Data without Q.

- A suggested processing flow
  - Remove direct wave (Green's theorem)
  - Wavelet estimation (Green's theorem)
  - Deghosting (Green's theorem)
  - Eliminate FS multiples (ISS FS multiple elimination)
  - Remove internal multiples (ISS internal multiple attenuation or elimination)
  - Q compensation without knowing or determining Q (to boost the high frequency component of the data)
  - Stolt CIII for heterogeneous media (equally effectiveness at all frequencies)
  - Stolt CIII migration-inversion for structural and amplitude analysis of specular and non-specular reflectors

Our plan:

- Continue increasing multiple removal effectiveness without subsurface information,

- At each step in the process we define both the new capability, and practical added value, and the new circumstances that can be accommodated, and the open issues and challenges yet to be addressed

- Marchenko and interferometry are returning to needing subsurface information. Why use a method that requires subsurface information (and finds an approximation to internal multiples) when there are methods that require absolutely no subsurface information and can eliminate internal multiples without an adaptive step and potential harm to primaries?

- We seek additional capability in the seismic toolbox: it’s always a work in progress

- We seek to add more capability and effectiveness to the seismic toolbox. Seismic research is always a work in progress.

- We thank the M-OSRP sponsors for their encouragement and support

- Ecopetrol is thanked for this wonderful honor and opportunity of presenting an invited address at the Ecopetrol special event on December 9, 2018 in Bogota , Colombia.