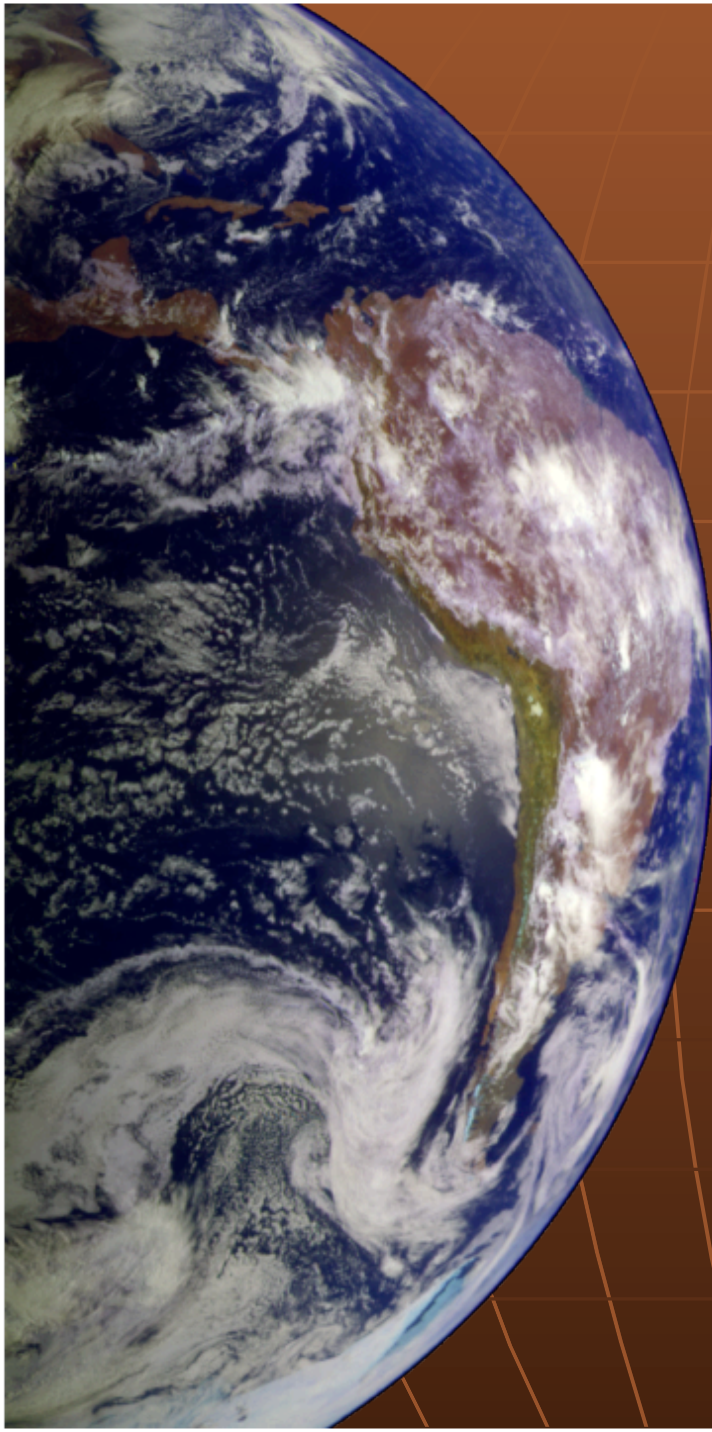

Free-surface Multiple Attenuation Using Inverse Data Processing in the Plane Wave Domain

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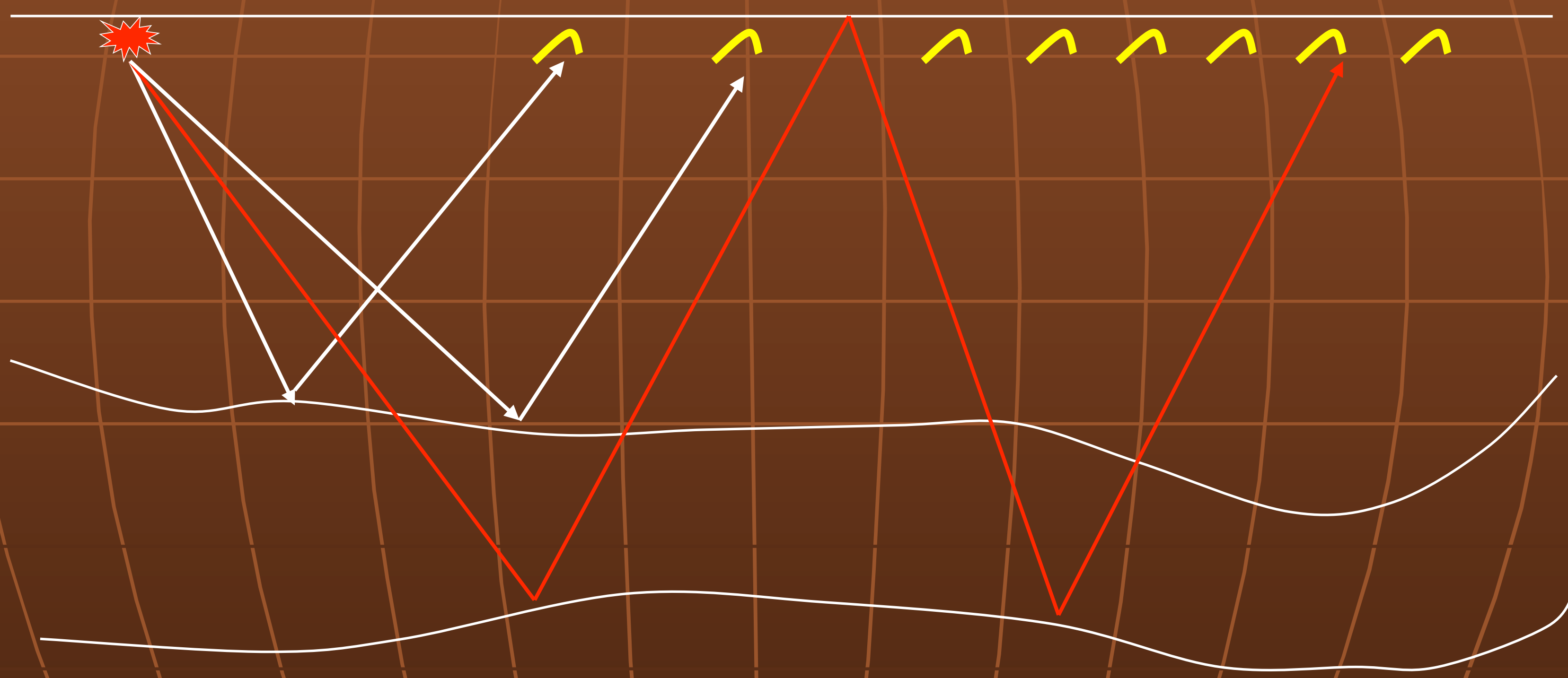
Outline

- Introduction to Multiple Attenuation
- Inverse data processing theory
- Inverse data processing in the coupled plane wave domain
- A field data example
- Discussion and conclusions

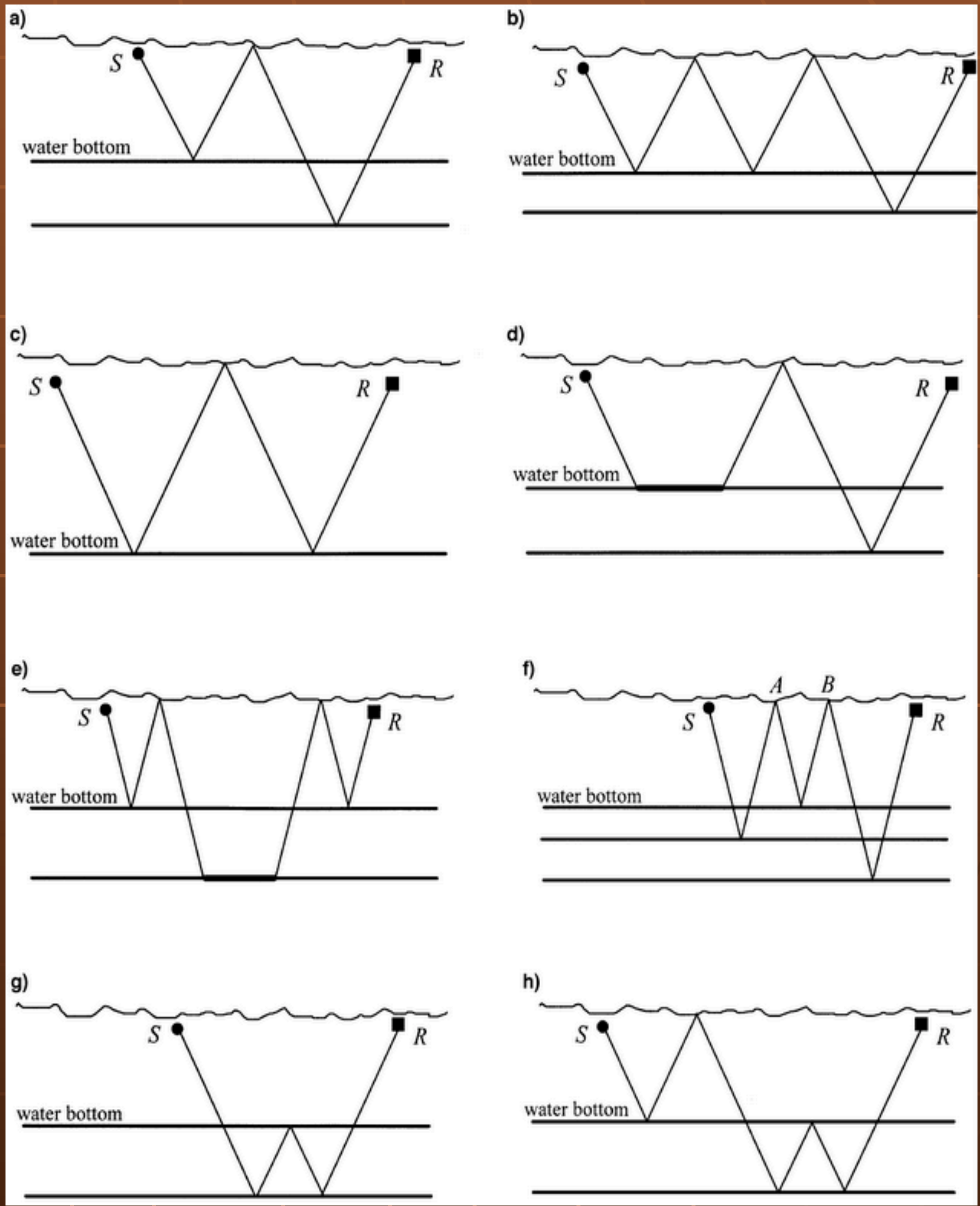
Introduction

Primary and multiples



Introductio

Typical Multiples



Reference:

Dragoset, W.H. and Jericevic, Z., 1998, Some remarks on surface multiple attenuation: Geophysics, 63, 772-789.

Introductio
n

Multiple Attenuation methods

Filtering method (Assumptions)

periodicity, separability

Predict deconvolution, stack, F-K filtering, Radon transform

Prediction-subtraction method (No assumptions, acquisition information required)

Wavefield extrapolation -- Wiggins, 1988

Free surface multiple attenuation:

Feed back method: Verschhur, 1992

Inverse-scattering method: Weglein, 1997.

Invariant embedding technique: Sen, 1998; Faqi Liu, 2000

Introduction

Prediction subtraction method

Predict multiples well, subtraction may damage primary energy.

Introduce adjacent traces to constrain the subtraction:

- Monk, D.J., Constrained cross-equalization, 1993
- Spitz, S, Pattern recognition, 1999
- Wang Y.Expanded multichannel matching, 2003
- Lu, W, Independent component analysis, 2006
- Li Peng, pseudomultichannel matching, 2007
- Fomel Sergey, regularized nonstationary regression, 2008
- ....

Introduction

Inverse data processing

- A development of prediction-subtraction theory (Mainly SRME).
- Can separate multiples and primaries in a very natural way.
- In inverse data space (IDS v.s. Forward data space FDS), multiples will be focused around zero time and offset, while primaries are at negative time.

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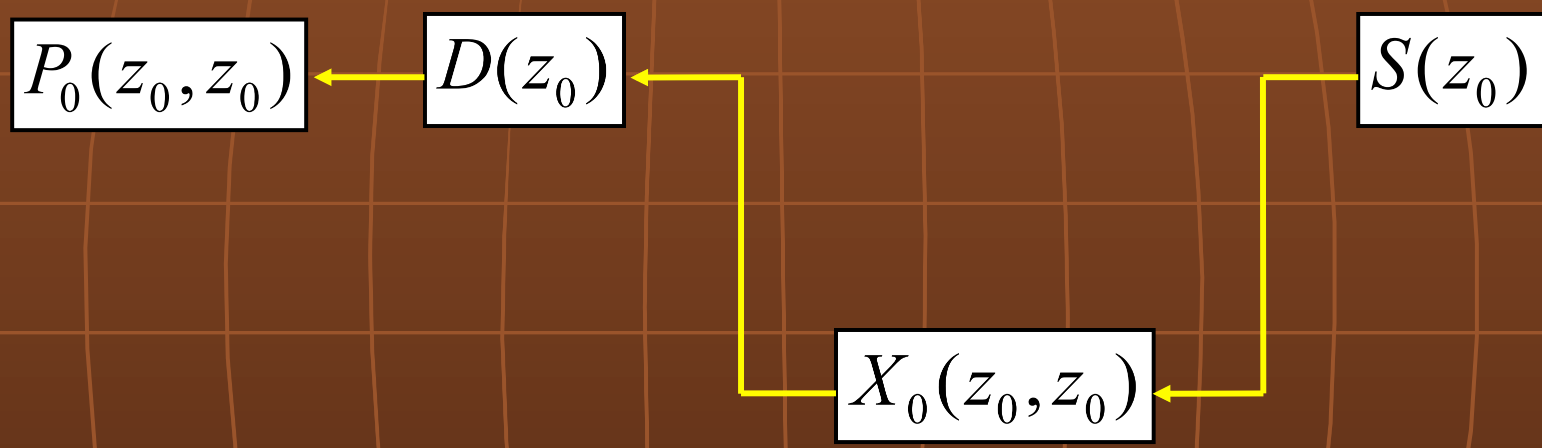
IDP in x-t domain

SRME theory: Feedback model without the free surface



$$P_0(z_0, z_0) = D(z_0) X_0(z_0, z_0) S(z_0)$$

$S(z_0)$ source function

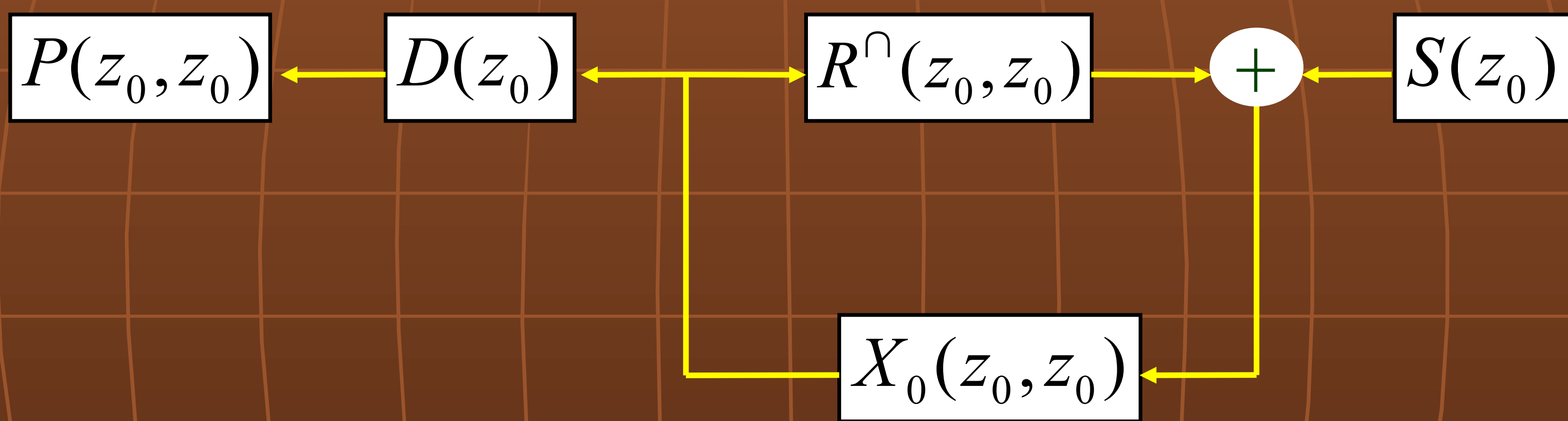
$X_0(z_0, z_0)$ primary reflectivity matrix

$D(z_0)$ detector property matrix

$P_0(z_0, z_0)$ wavefield without

IDP in x-t domain

SRME Theory: Feedback model with the free surface



$$P = P_0 + (P_0 A)P_0 + (P_0 A)^2 P_0 + \ldots\ldots$$

$$P_0 = D X_0 S$$

$$A = S^{-1} R^{\cap} D^{-1}$$

$R^{\cap}$ free surface reflectivity

P wavefield with free surface effect

A surface operator

IDP in x-t domain

Inverse data processing in the x-t domain (Berkhout, 2006)

$$P = P_0 + (P_0 A) P_0 + (P_0 A)^2 P_0 + \ldots\ldots$$

$$P = P_0 + (P_0 A) P$$

$$P_0 = (I - P_0 A) P$$

$$P = [I - P_0 A]^{-1} P_0$$

$$P^{-1} = P_0^{-1} [I - P_0 A]$$

$$P^{-1} = P_0^{-1} - A$$

P_0^{-1} primaries with time information located at negative times

A surface operator without time information located around zero time

Requirement for the data (Same as SRME)

1. Full wavefield data upto zero offset – extrapolation

2. Regular geometry, equal distance between shot and receiver points – interpolation

Reference :

Berkhout, A. J., 2006, Seismic processing in the inverse data space: Geophysics, 71, no. 4, A29–A33.

IDP in x-t domain

Advantages

1. Very simple compared with multiple elimination in the forward space;
2. Does not harm any primary energy;

Key point: Matrix Inversion Least squares inversion and SVD inversion

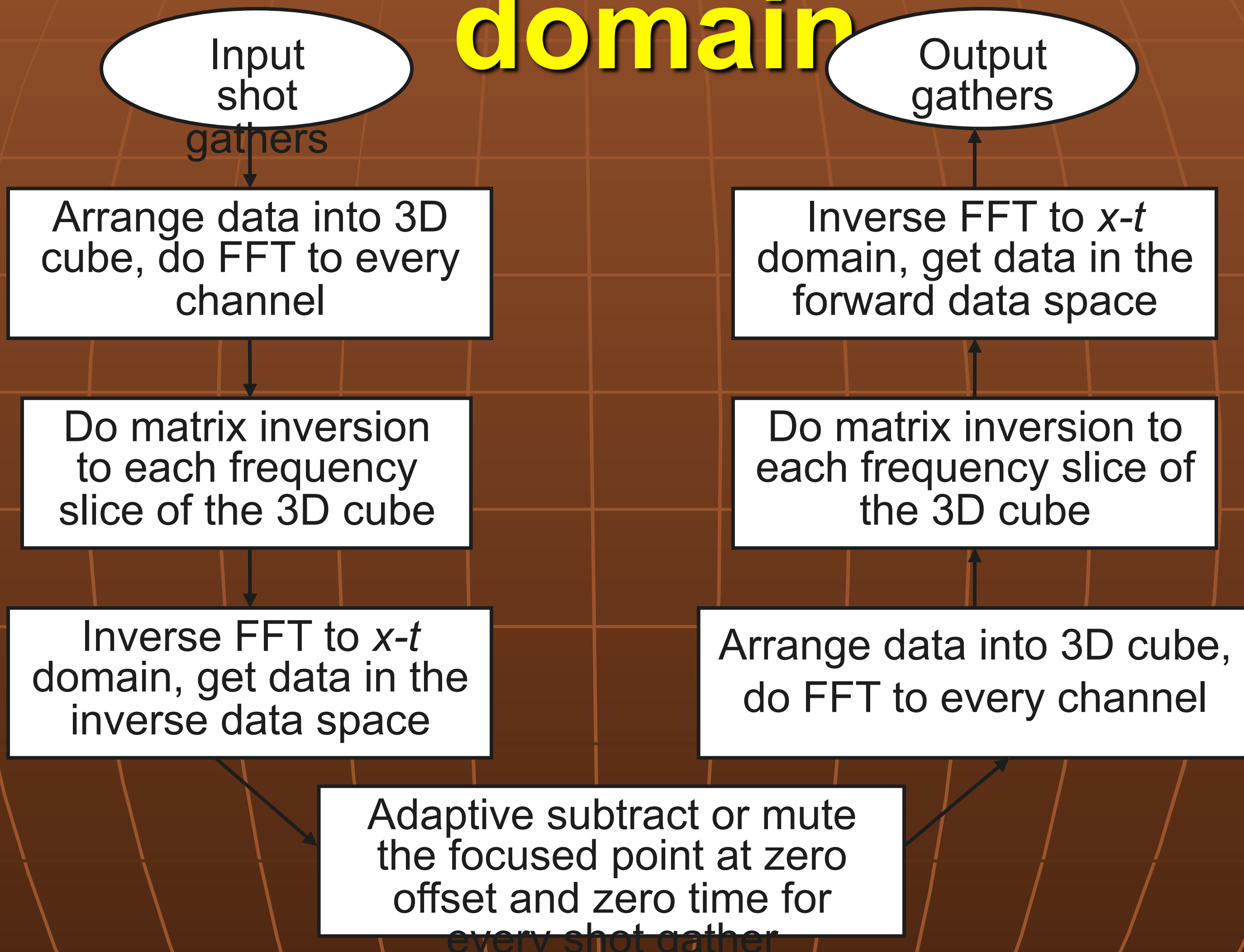
$$\begin{cases} P^{-1} = BP^{H} \\ B = (P^{H}P + \varepsilon^{2}I)^{-1} \end{cases}$$

$$\begin{cases} P = U[diag(\omega_j)]V^{T} \\ P^{-1} = V[diag(1/\omega_j)]U^{T}, j < N \end{cases}$$

First two eqations from:

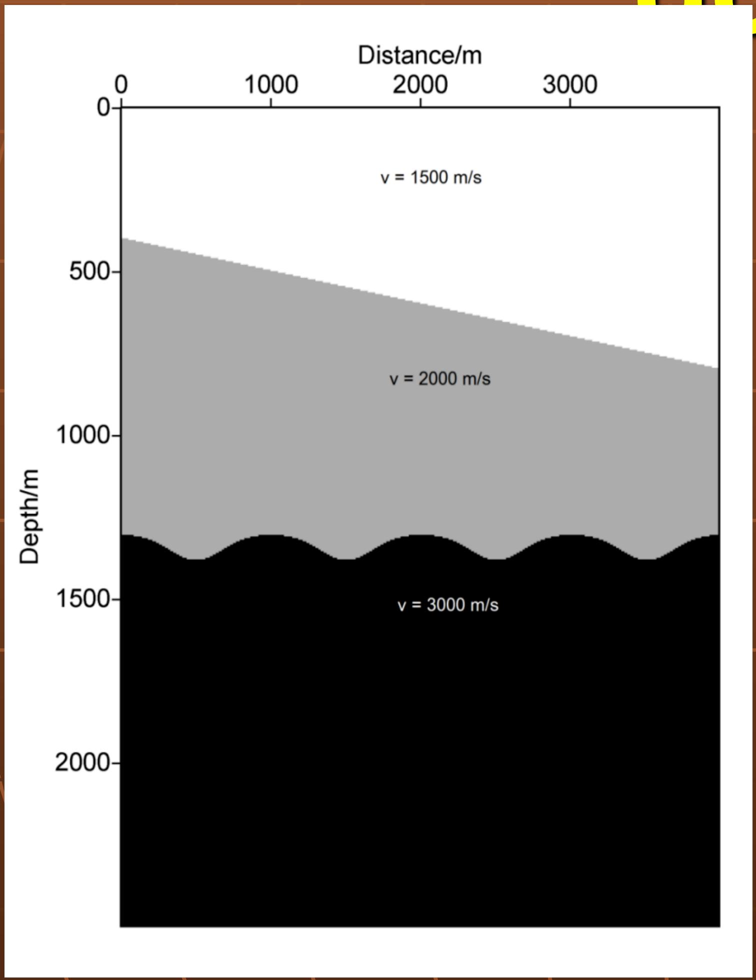
Berkhout, A. J., and D. J. Verschuur, 2006, Focal Transform, an imaging concept for signal restoration and noise removal: Geophysics, 71, no. 6, A55–A59.

IDP in x-t domain

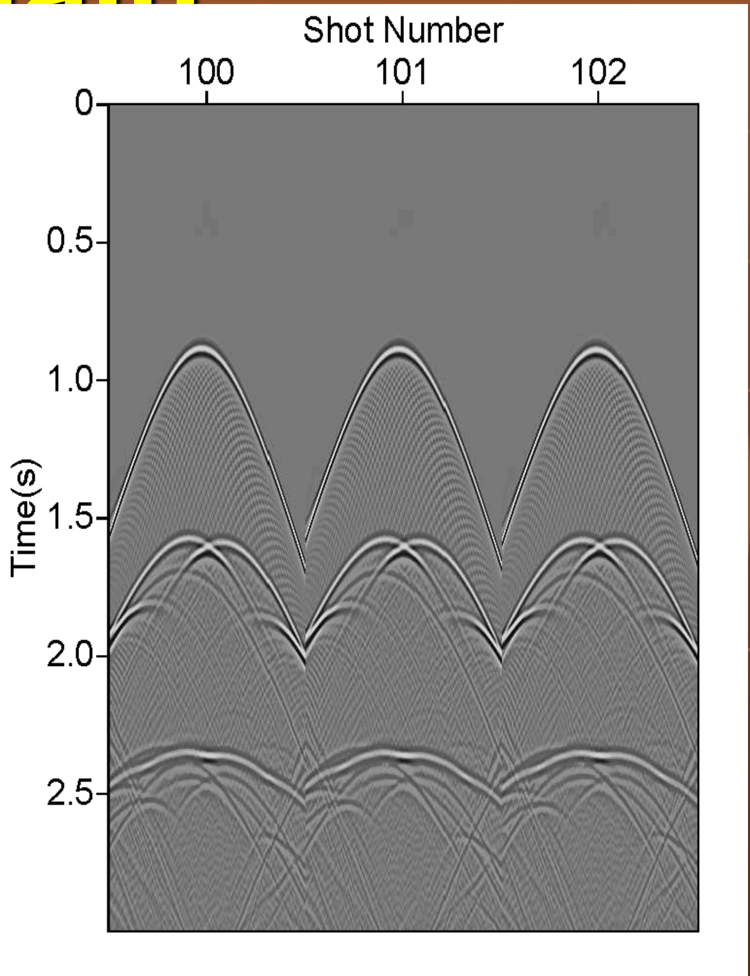


Workflow of *x-t* domain inverse data processing

IDP in x-t domain

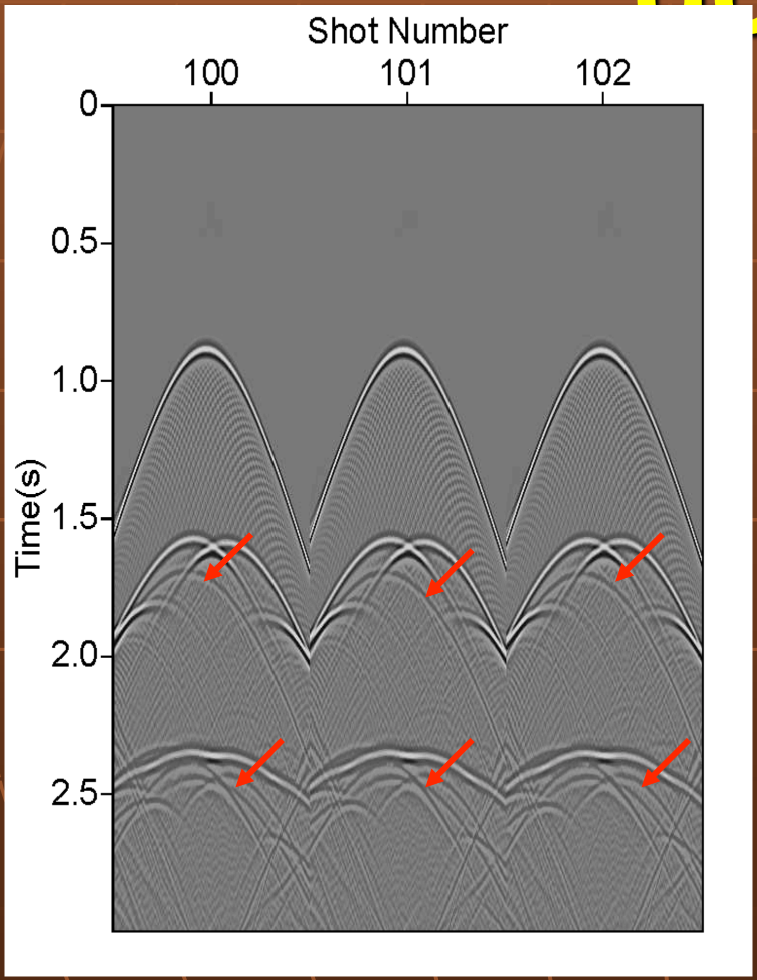


Velocity model

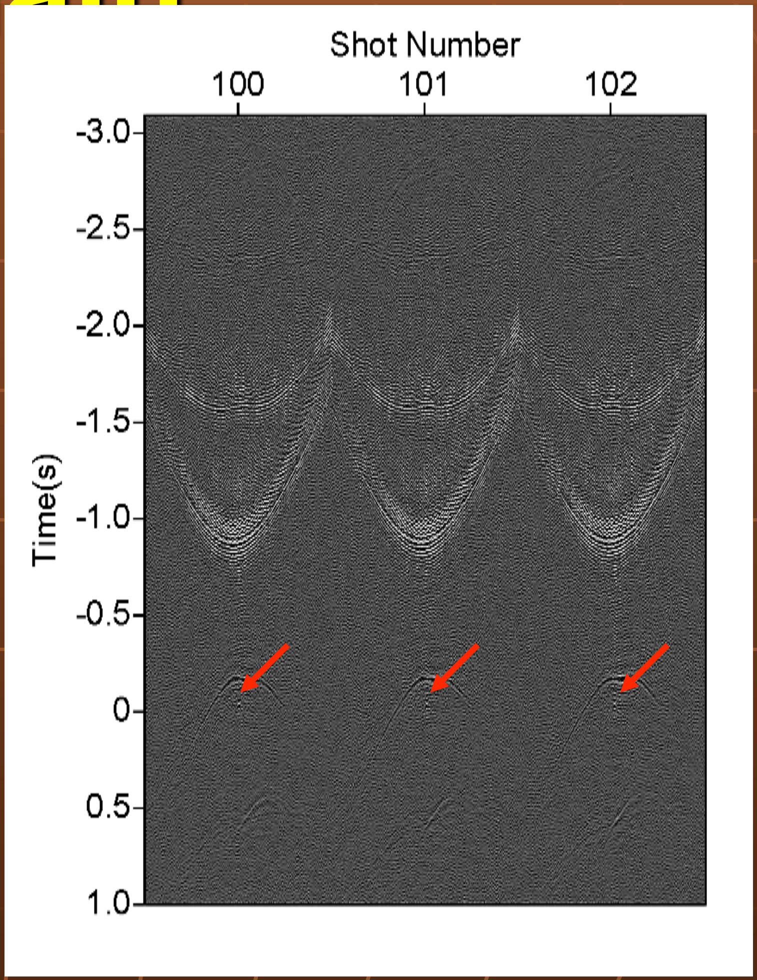


Three typical shot gathers

IDP in x-t domain

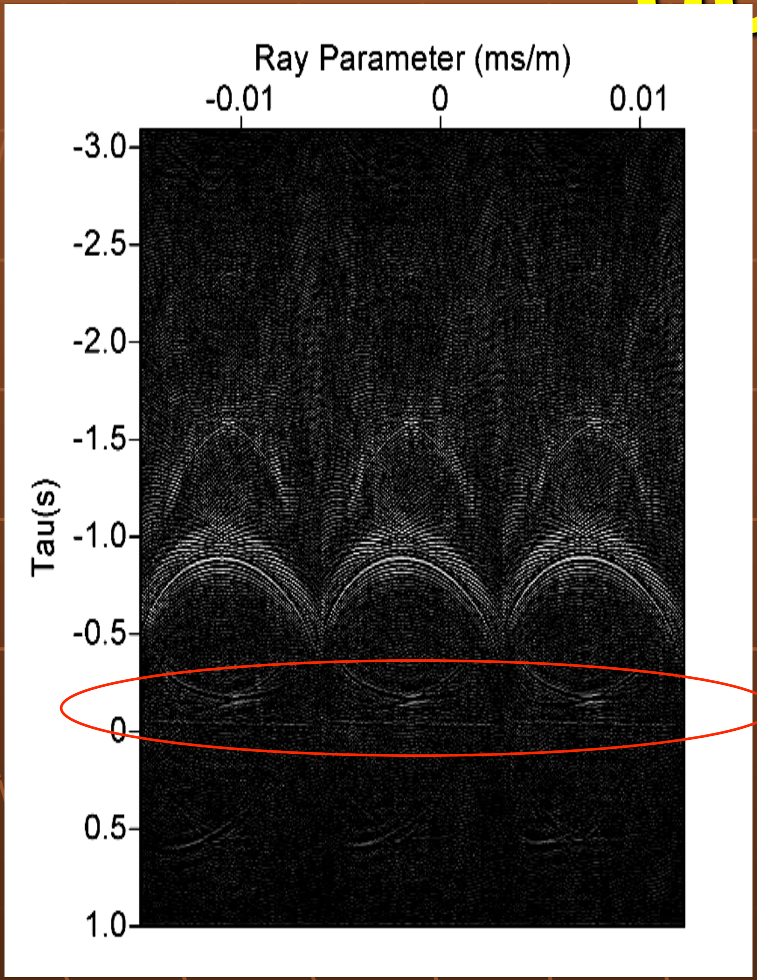


Three typical shot gathers

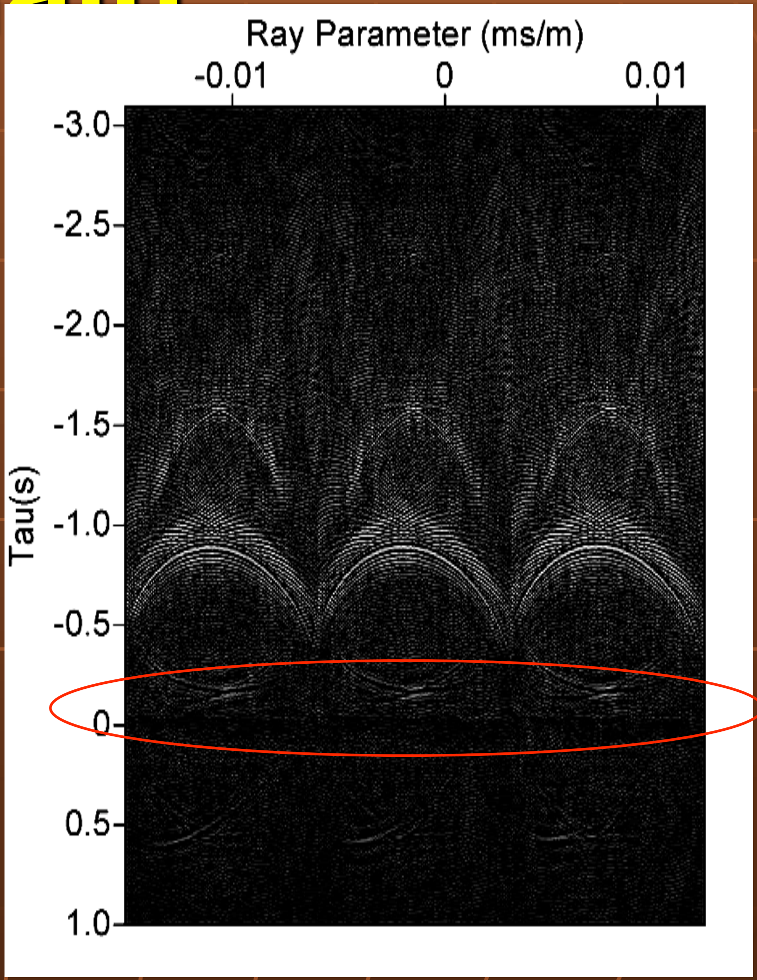


Data in the inverse data space

IDP in x-t domain

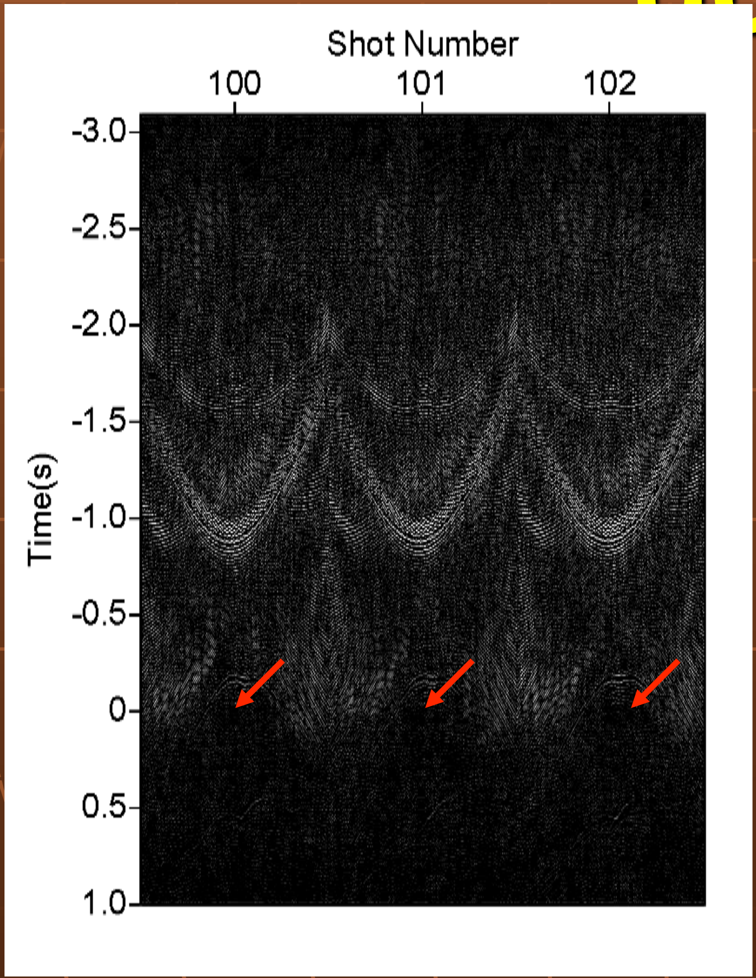


Tau-p transform of inverse data

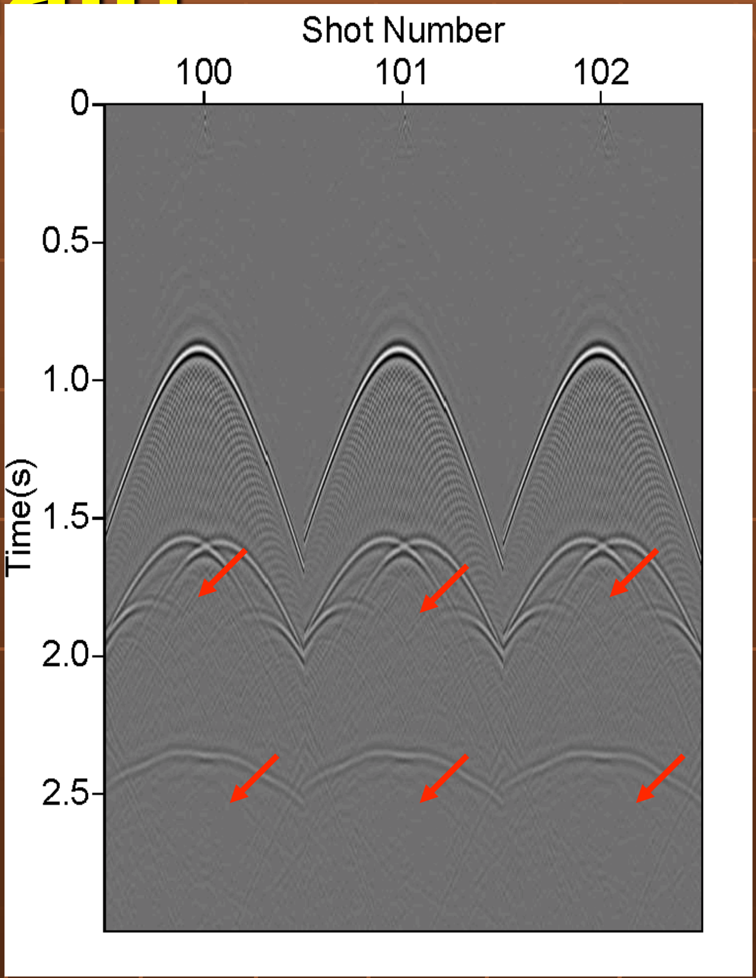


Adaptive subtraction of the line

IDP in x-t domain

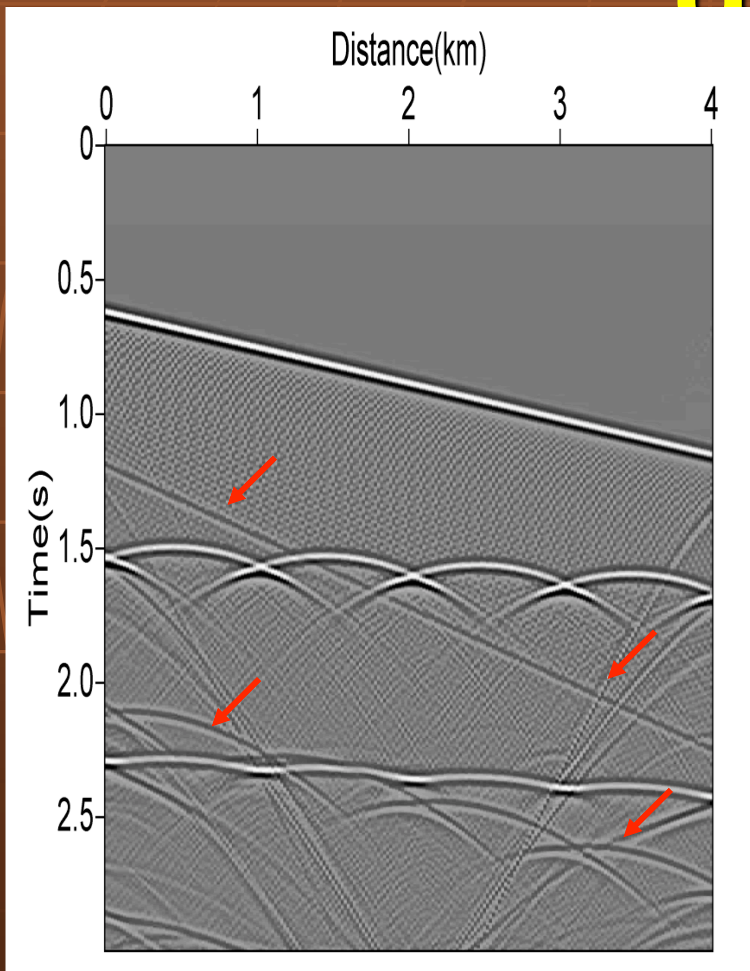


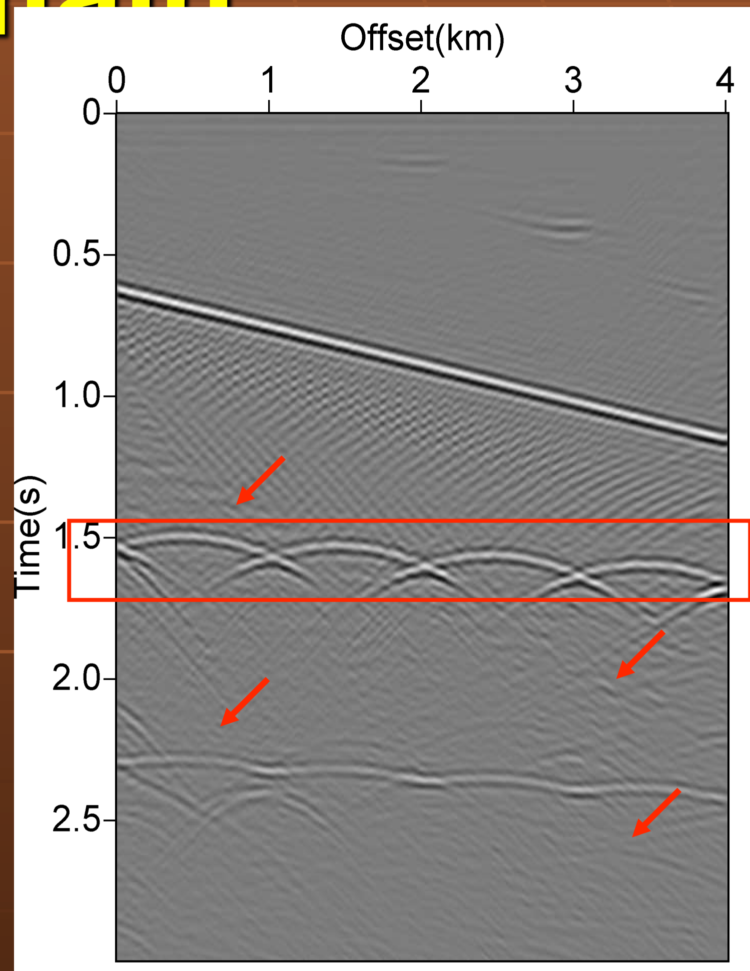
Data in the IDS after point muting



Data transformed back

IDP in x-t domain





Zero offset comparion before and after inverse data processing

Outline

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IDP in plane wave domain

Motivation:

- Infinite relationship between primaries and multiples can not be satisfied;
- Matrix inversion introduce noise and artifacts;
- Tau-p transformation can compress seismic data, while focus seismic energy around the main diagonal, which will stabilize the inversion.

IDP in plane wave domain

Inverse data processing in the plane wave domain (Ma et al, 2009)

$$\bar{U} = (I+R)^{-1} RS$$

$$U_0 = RS$$

$$\rightarrow \quad \bar{U} = (I+R)^{-1} U_0$$

$$\bar{U}^{-1} = U_0^{-1}(I+R) \quad \rightarrow \quad \bar{U}^{-1} = U_0^{-1} + S^{-1}$$

$\bar{U}_0^{-1}$ primaries with time information

located at negative times

S^{-1} surface operator without time information

located around zero time

First two eqations from:

Faqi Liu, Mrinal K. Sen and Paul L. Stoffa, 2000, Dip selective 2D multiple attenuation in the plane wave domain, Geophysics, 65(1), 264~274

IDP in plane wave domain

Advantages compared with IDP in *x*-*t* domain

1. Compress seismic data using Tau-p transform, reduce computation cost;

2. Focus energy around the diagonal, stabilize the inversion.

Key point: Matrix Inversio… …version and SVD

$$\begin{cases} \bar{U}^{-1} = B\bar{U}^{H} \\ B = (\bar{U}^{H}\bar{U} + \varepsilon^{2} I)^{-1} \end{cases}$$

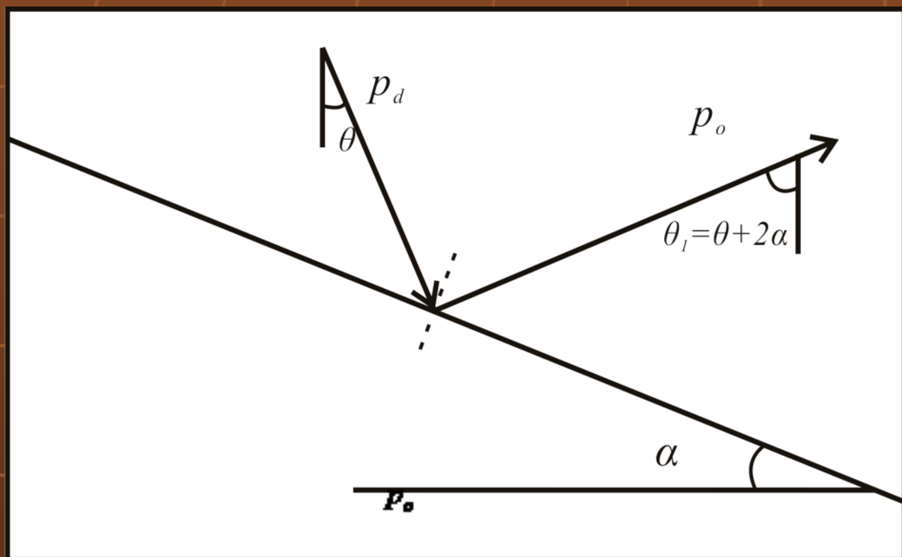
$$\begin{cases} \bar{U} = U[diag(\delta_j)]V^{T} \\ \bar{U}^{-1} = V[diag(1/\delta_j)]U^{T}, j < N \end{cases}$$

First two eqations from:

Berkhout, A. J., and D. J. Verschuur, 2006, Focal Transform, an imaging concept for signal restoration and noise removal: Geophysics, 71, no. 6, A55–A59.

Plane-wave Domain Theory

Feature： Band-limited matrix (Liu et al, 2000)



Geometry of an incident and reflected plane waves at a dipping interface

$$p_o = \frac{\sin(\theta + 2\alpha)}{\upsilon} = p_d \cos 2\alpha + q_d \sin 2\alpha$$

$$|p_o - p_d| \le \frac{2\sin\alpha}{\upsilon}$$

p_d=sinq/u downgoing plane wave ray parameter

$$q_d = \sqrt{1/\upsilon^2 - p_d^2}$$

upgoing plane wave ray parameter

vertical slowness of incident ray

Plane-wave Domain Theory

Linear mapping relationship (Liu et al, 2000)

Data in the source-offset coordinates v.s. plane wave data

$$d(x_s,x,t)=\frac{\omega^2}{4\pi^2}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}D_{pl}(p_d,p_o,\omega)e^{i\omega p_o x}e^{i\omega(p_o-p_d)x_s}dp_o dp_d$$

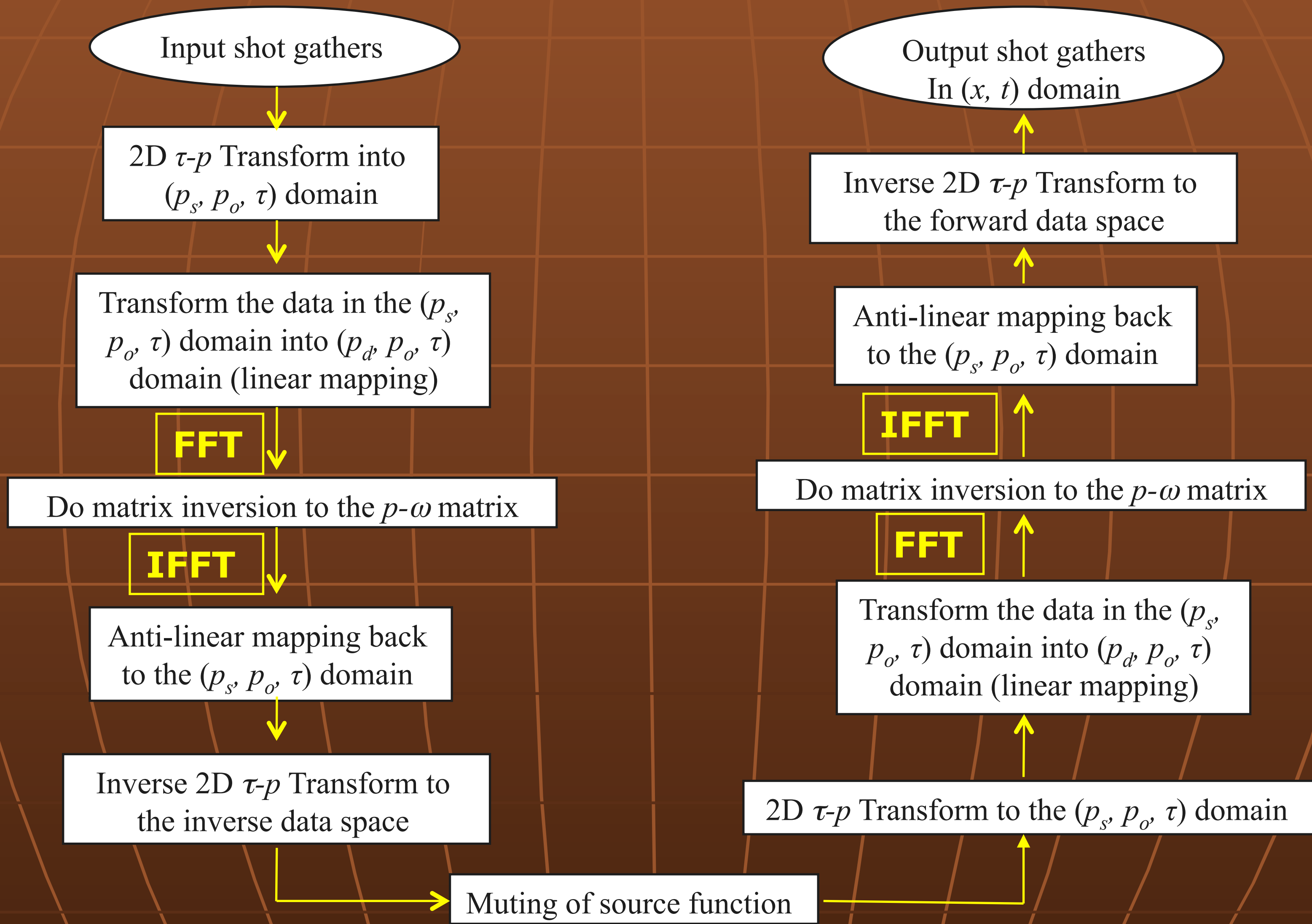
Inverse 2D *t-p* transform

$$d(x_s,x,t)=\frac{\omega^2}{4\pi^2}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}D_{\tau p}(p_s,p_o,\omega)e^{i\omega p_o x}e^{i\omega p_s x_s}dp_s dp_d$$

Linear mapping

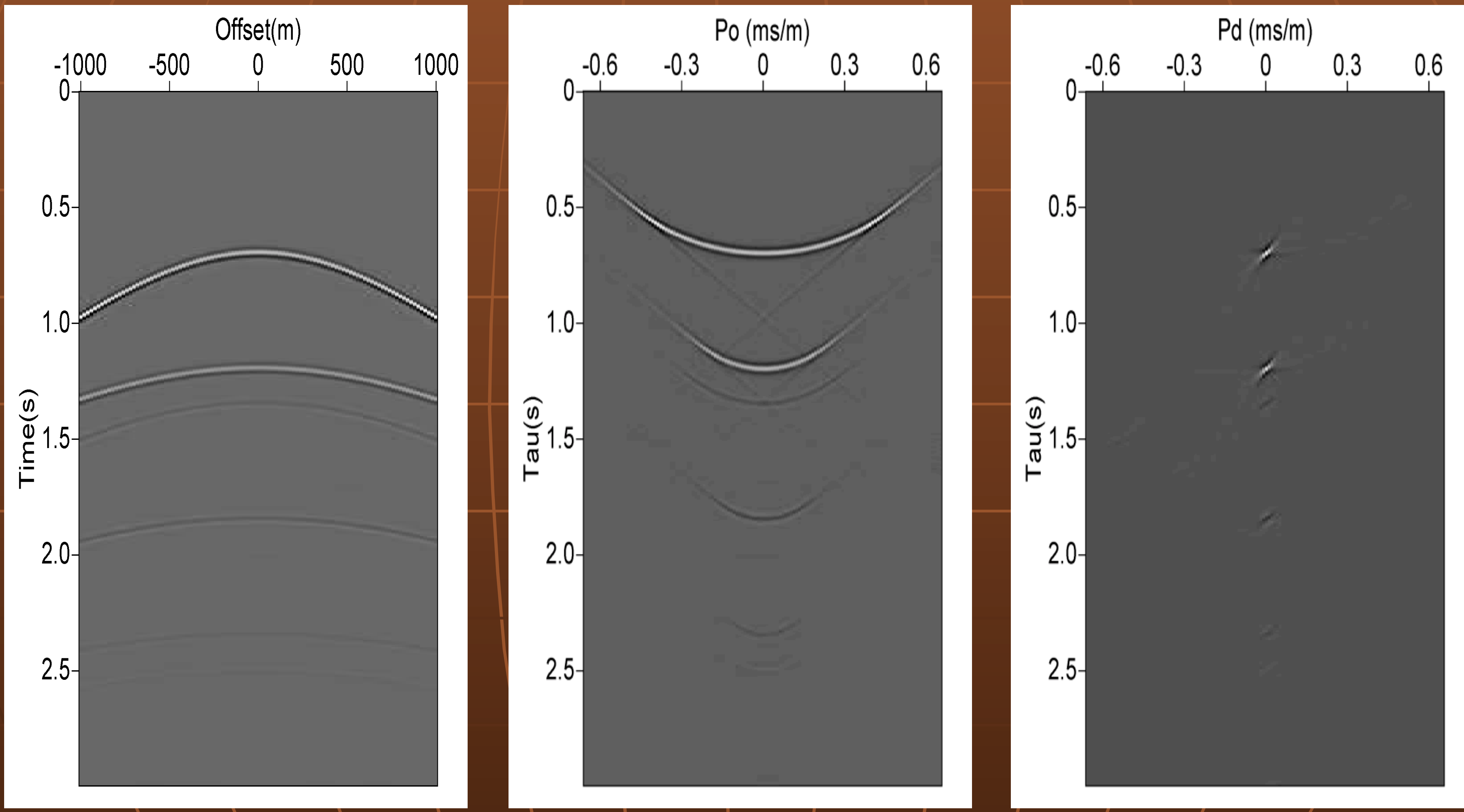
$$D_{pl}(p_d,p_o)=D_{\tau p}(p_o-p_s,p_o)$$

IDP in plane wave domain



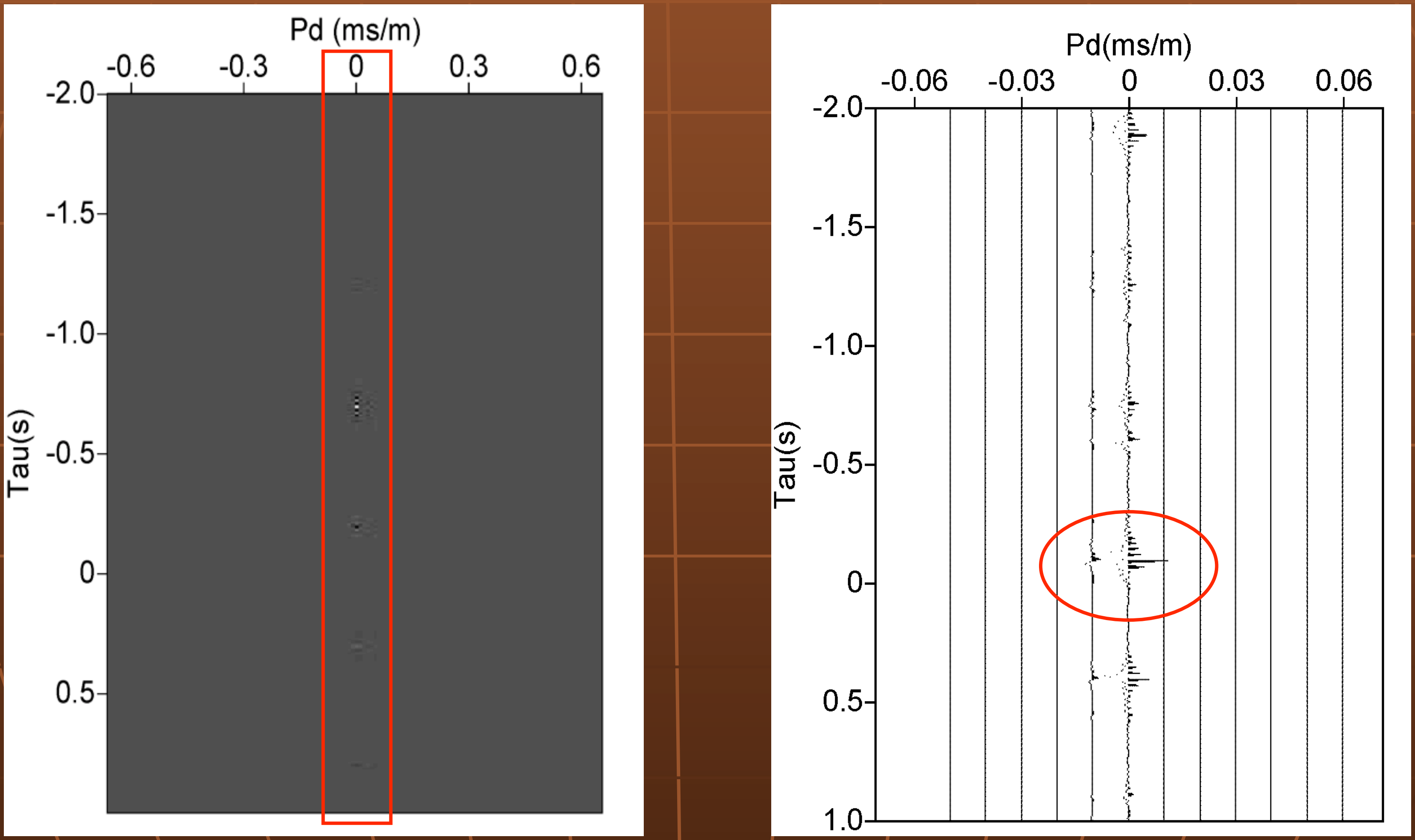
Workflow of *plane wave* domain inverse data processing

IDP in plane wave domain



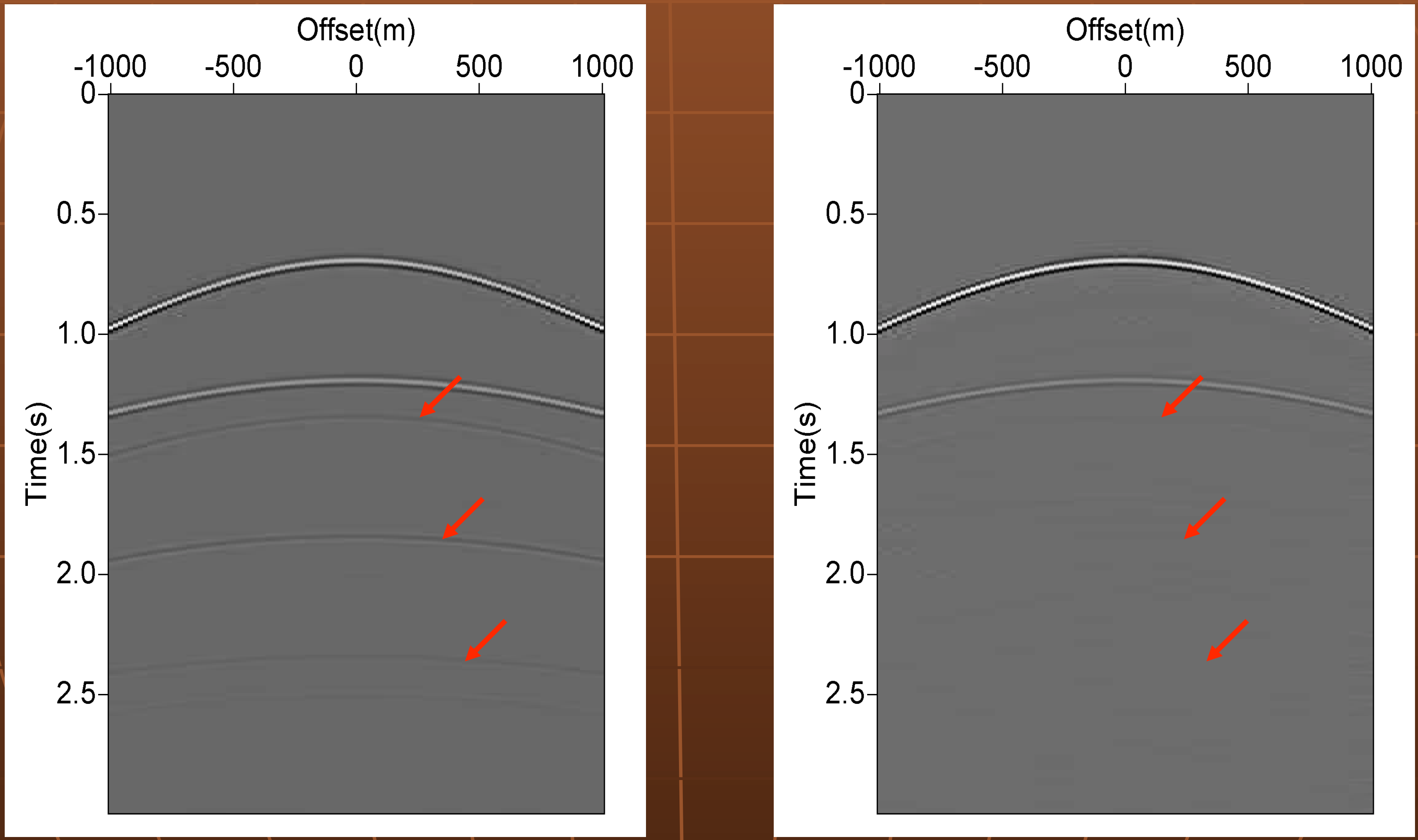
1D shot gather and its 1D and 2D Tau-p transform

IDP in plane wave domain



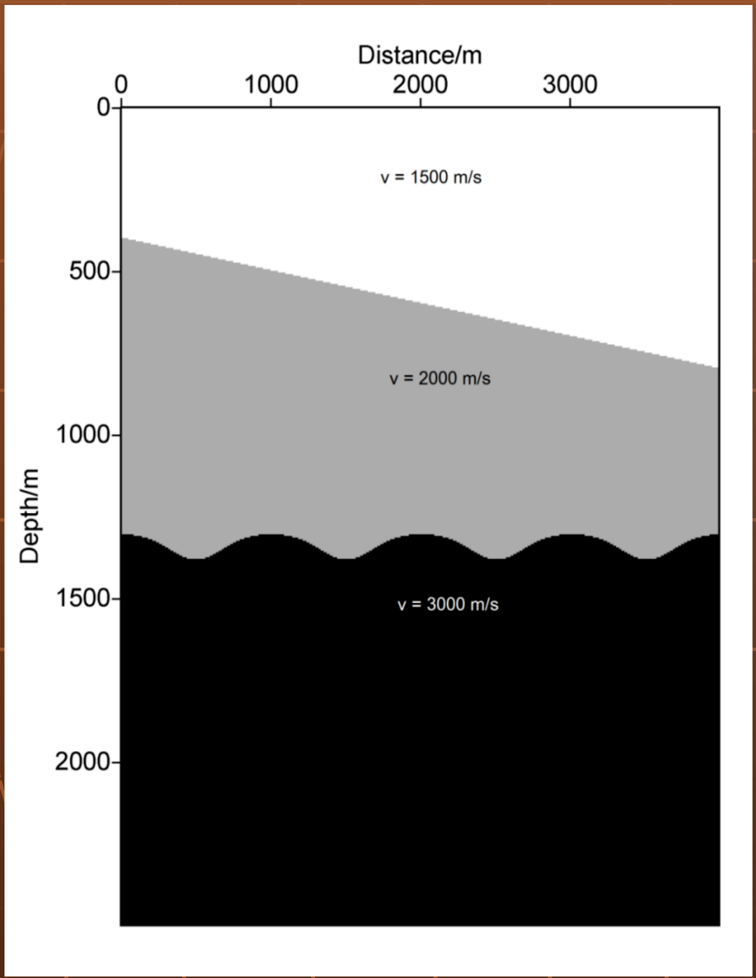
Data in the inverse data space in the plane wave domain

IDP in plane wave domain

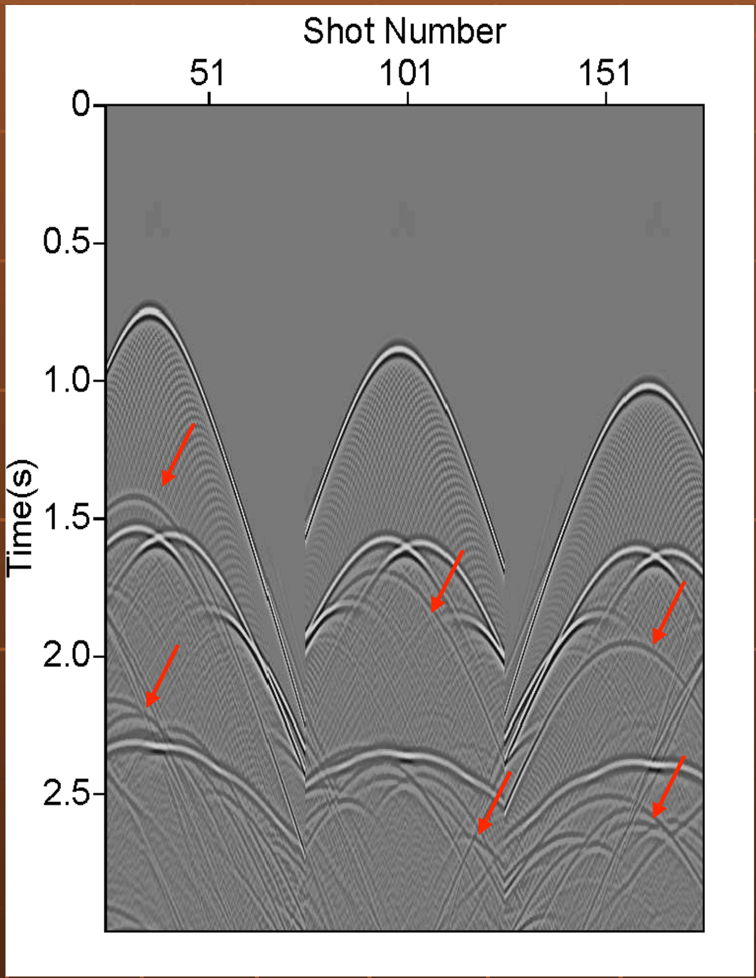


Comparison of data before and after multiple elimination using IDP

IDP in plane wave domain

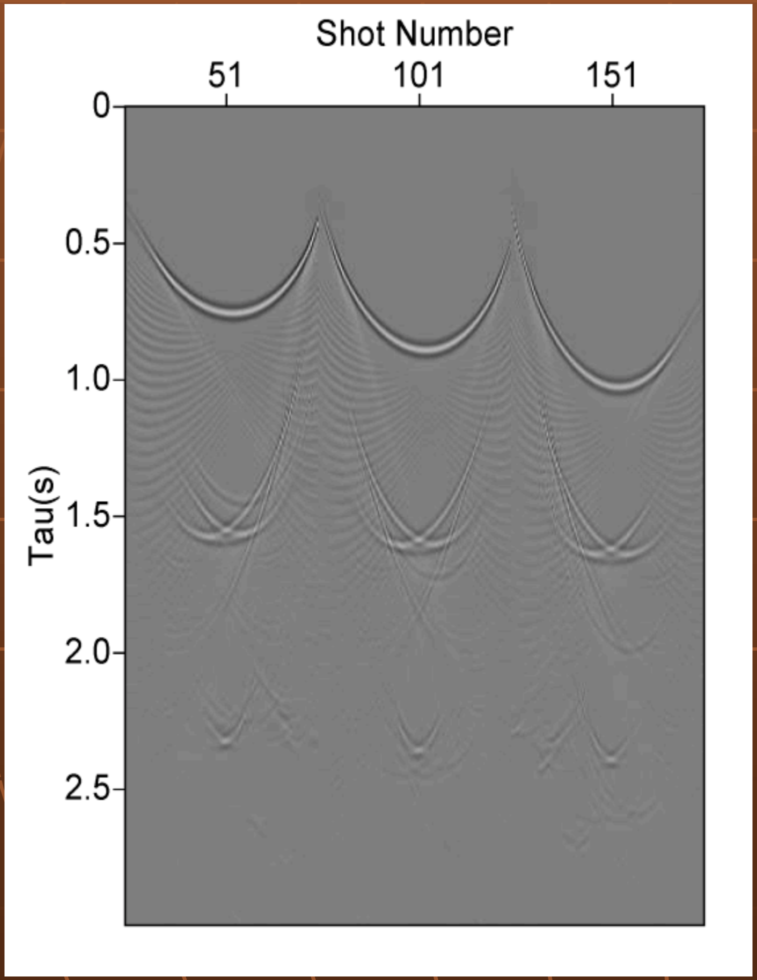


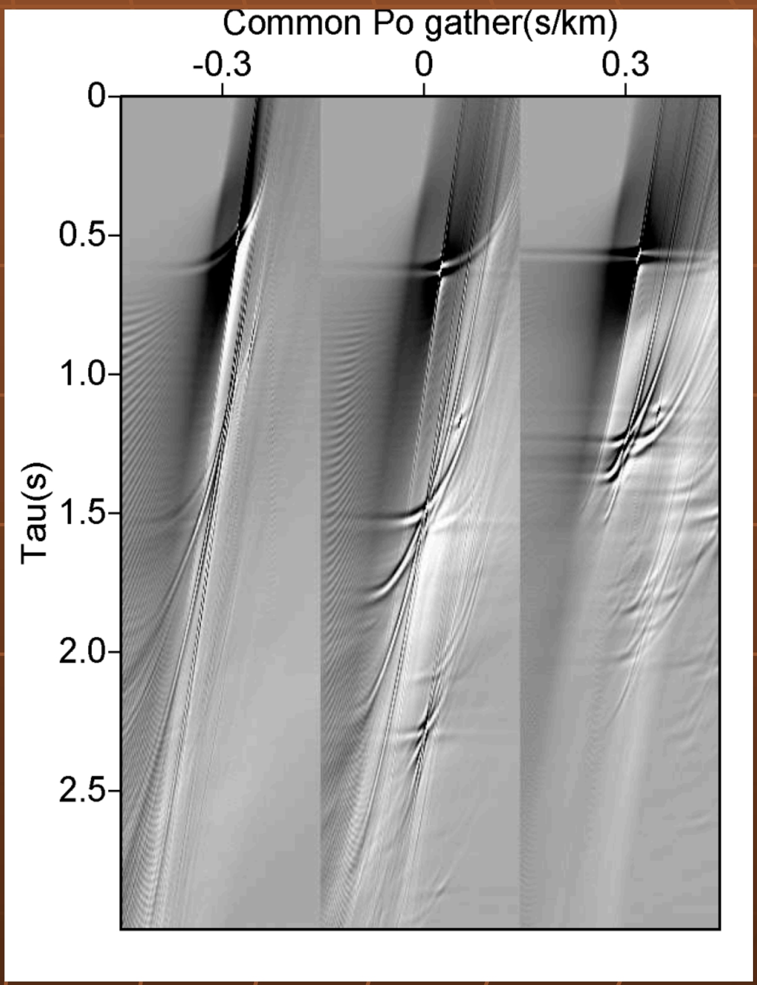
Velocity model



Synthetic shot gathers

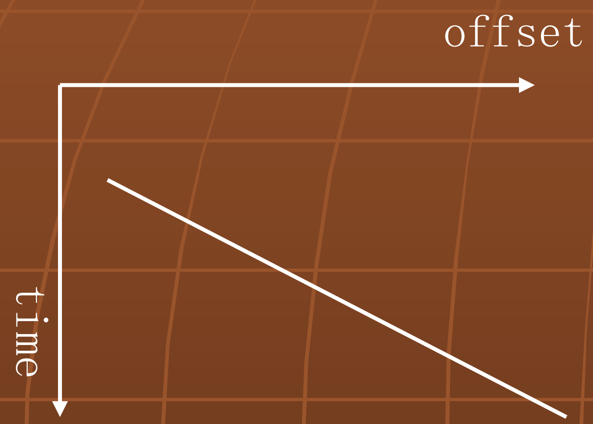
IDP in plane wave domain

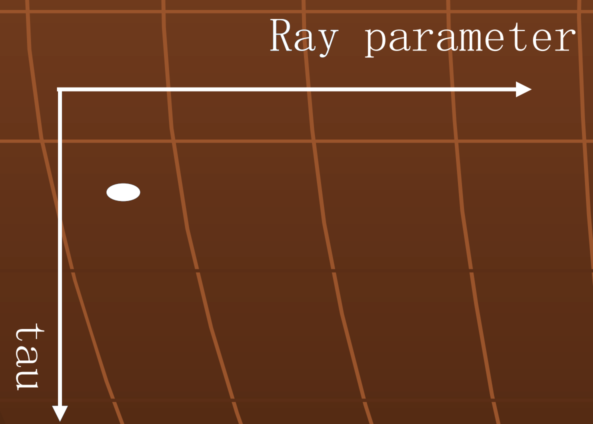




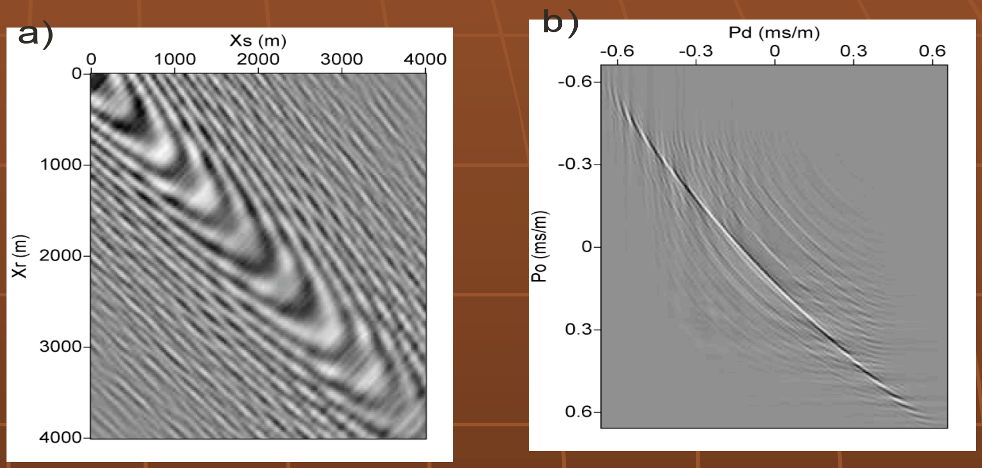
Data in the 1D and 2D Tau-p domain

IDP in plane wave domain

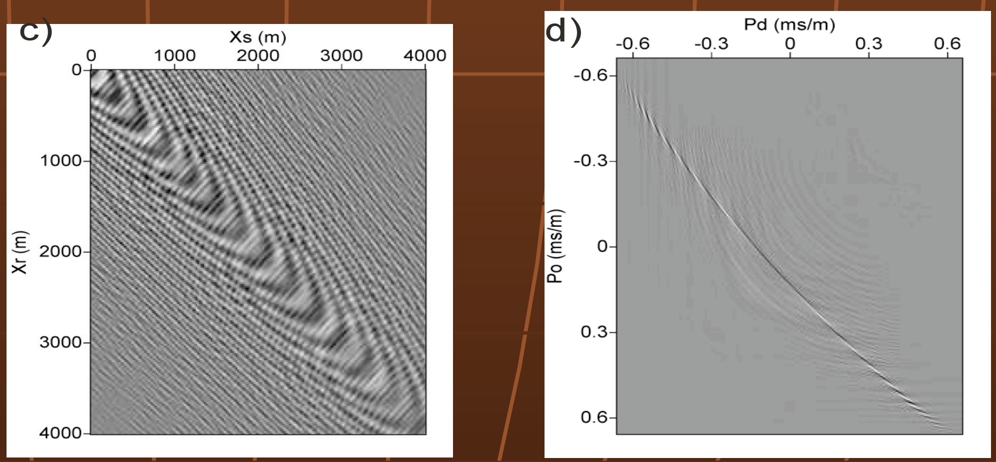




compressive feature of Tau-p transform

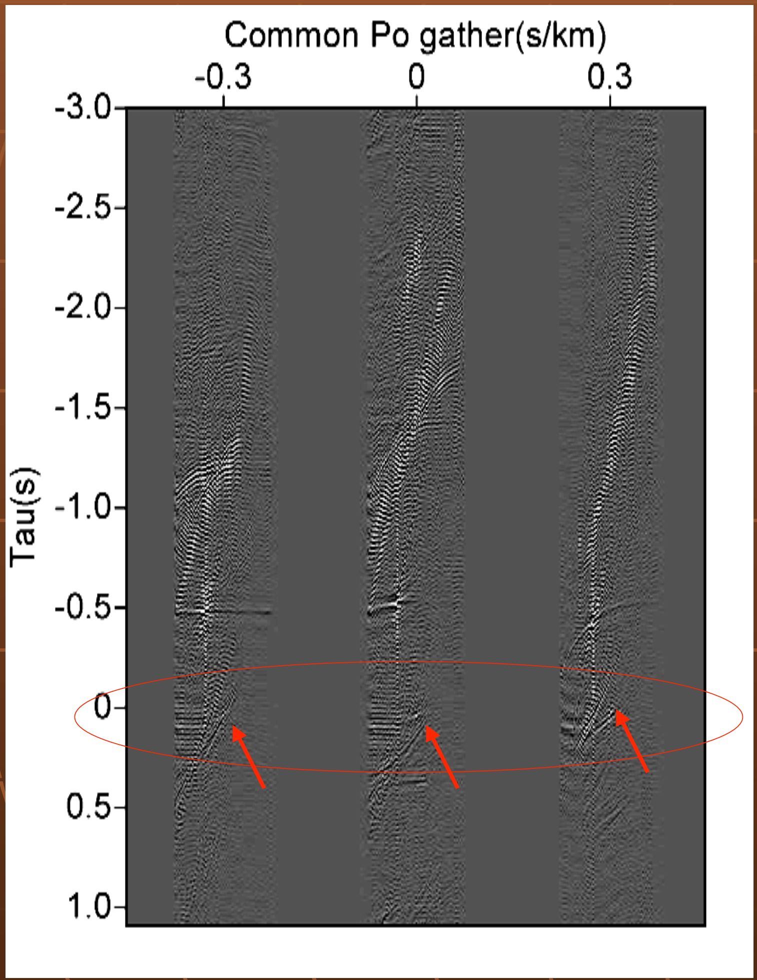


15Hz data matrix



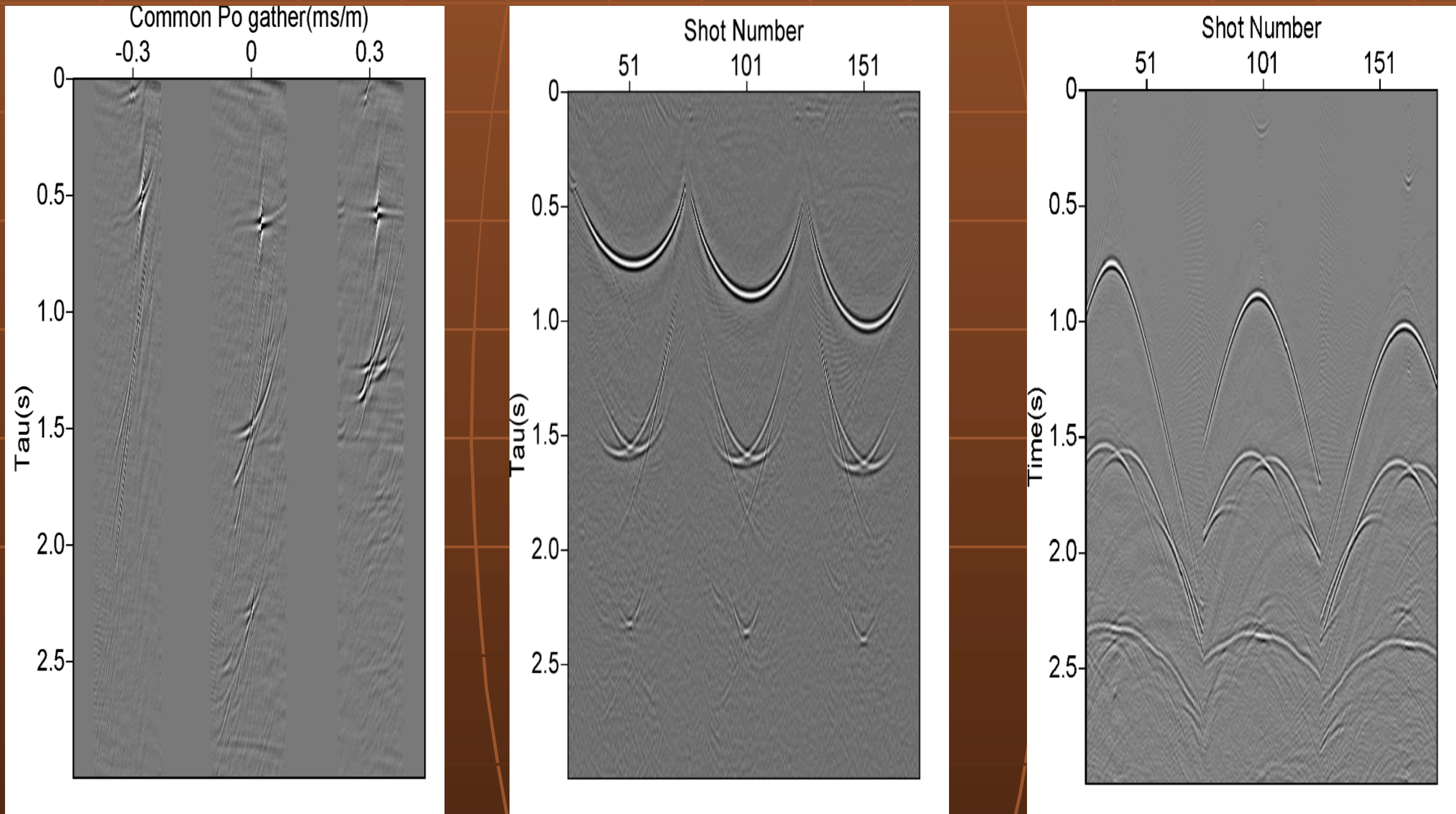
25Hz data matrix

IDP in plane wave domain



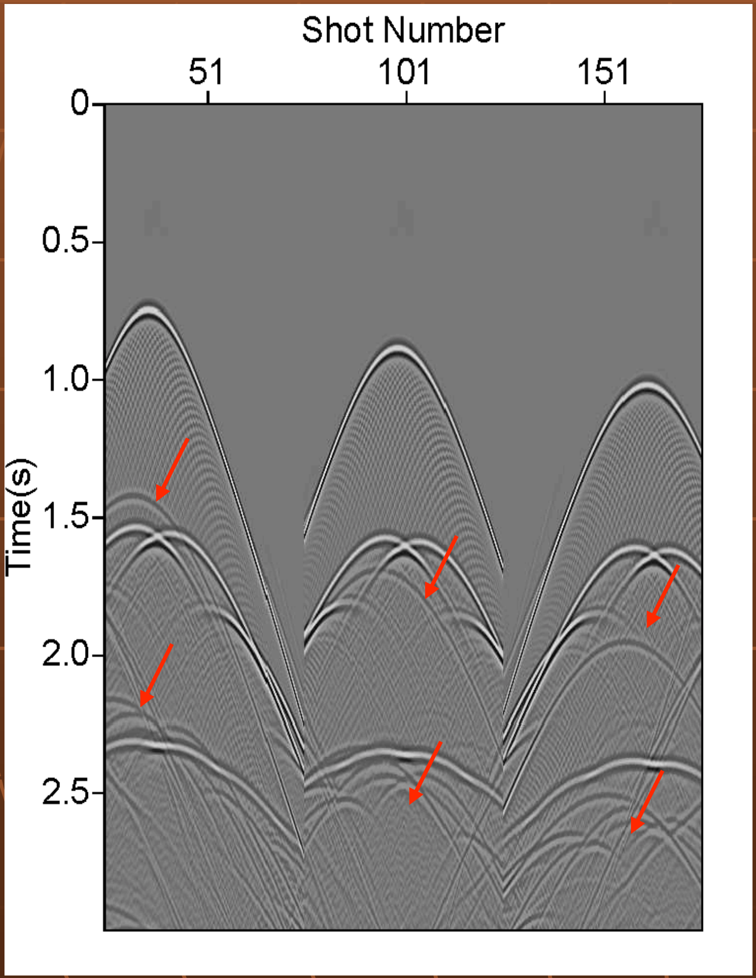
Data in the inversed plane wave domain. Arrows points at the focused point, namely, multiples.

IDP in plane wave domain

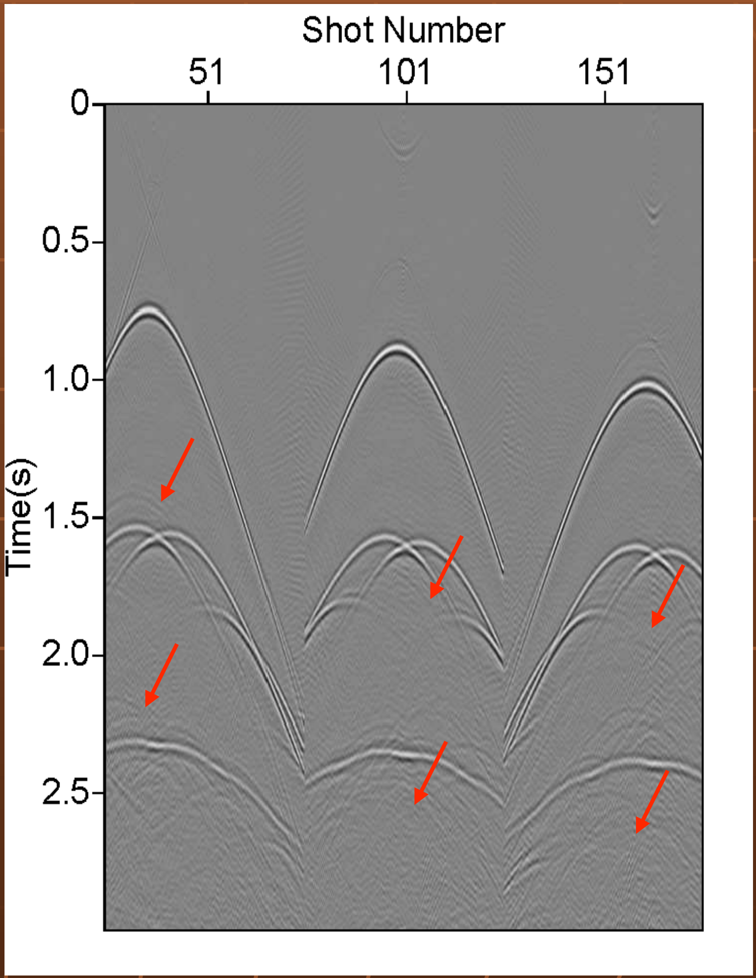


Demul results in Tau-p and x-t domain

IDP in plane wave domain

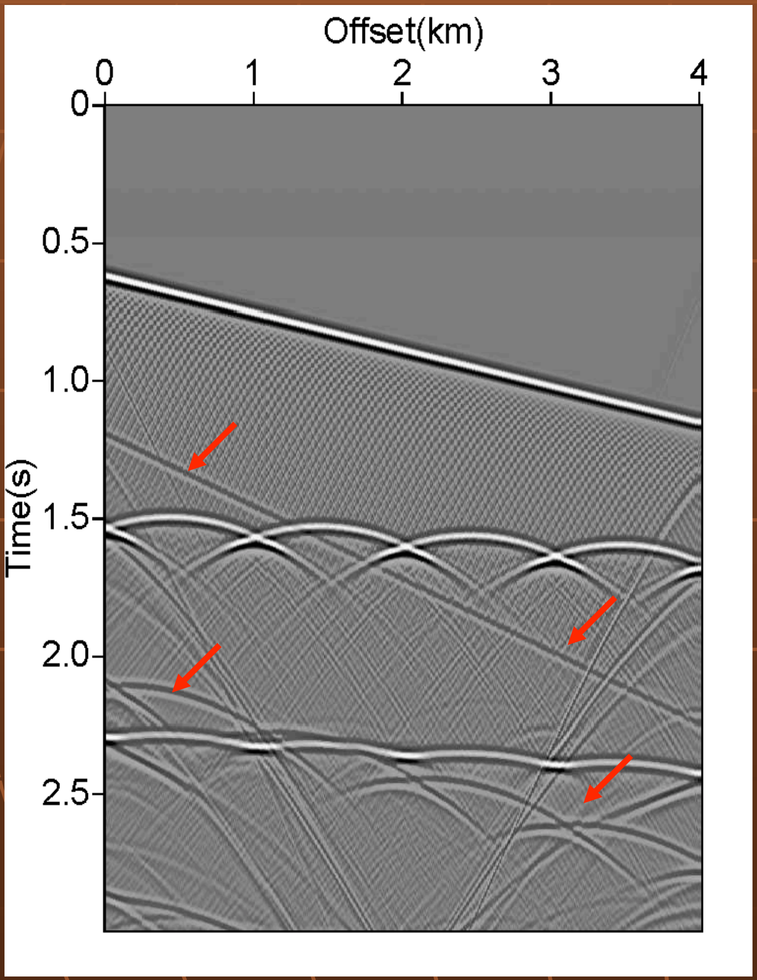


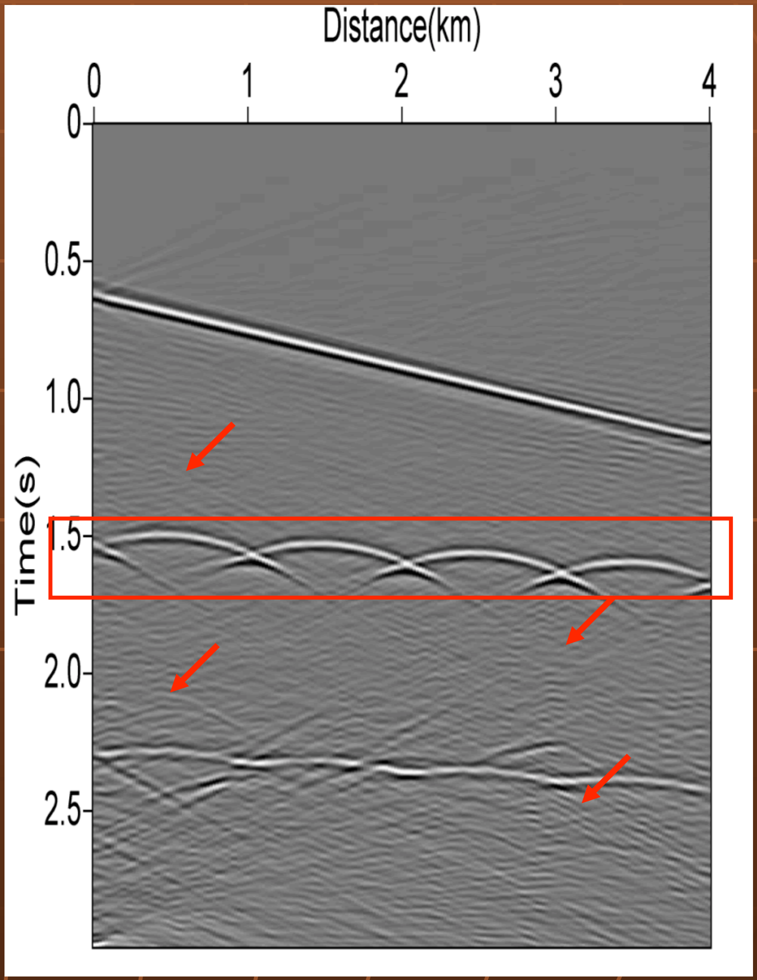
Original shot gathers



Demul Results

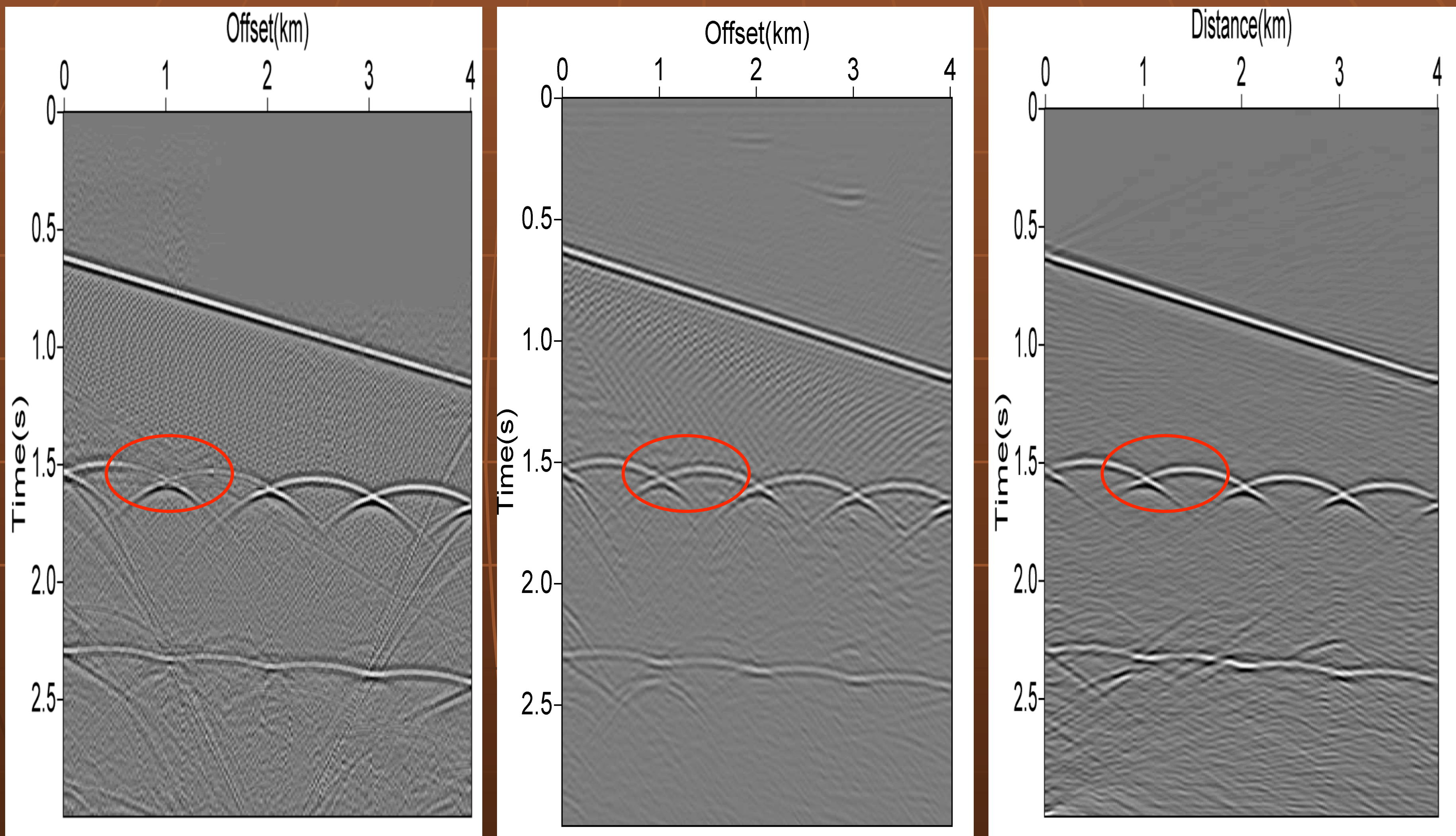
IDP in plane wave domain





Common offset sections comparison before and after demul

IDP in plane wave domain



Comparison of three different methods: prediction-subtraction(left), x-t domain inverse data processing (middle) and plane wave domain inverse data processing(right)

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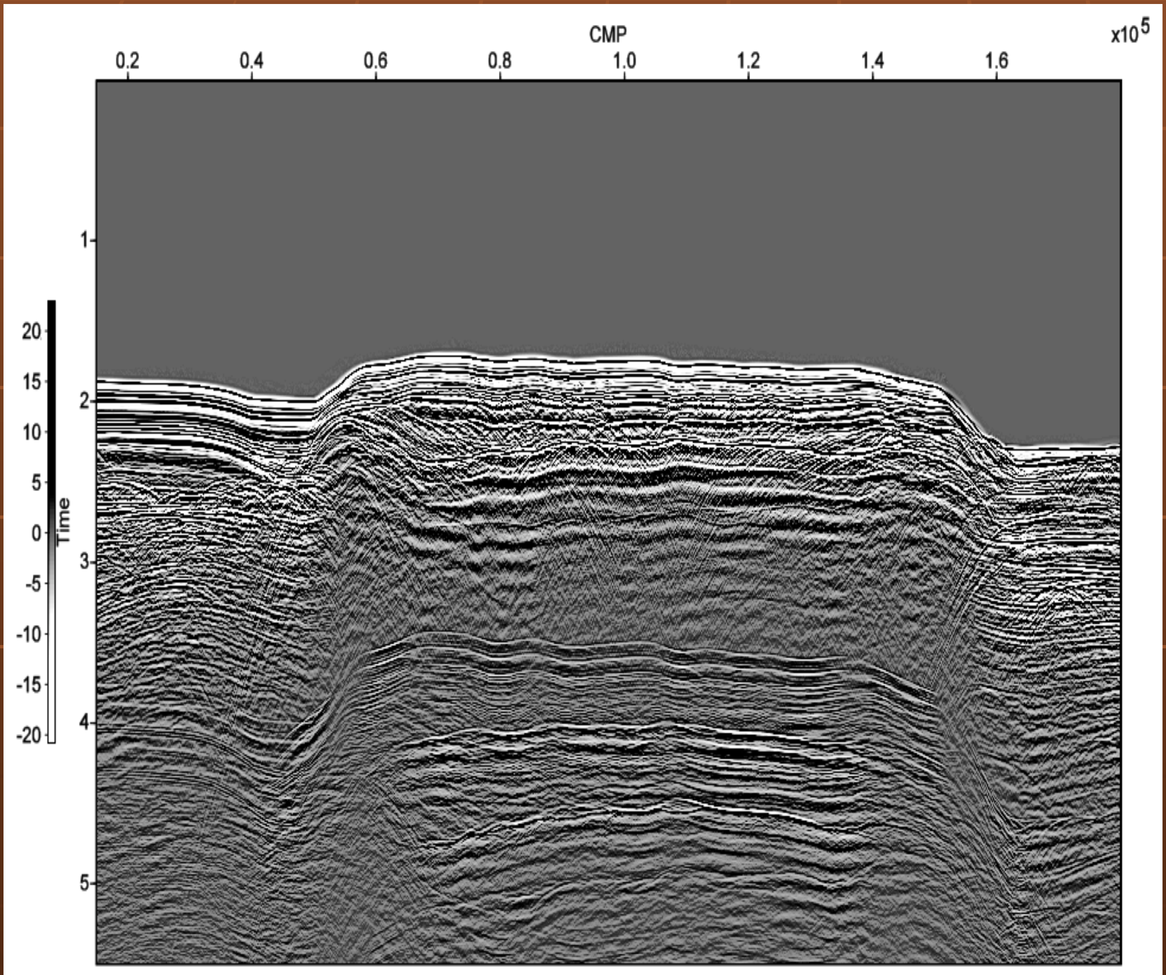
- Discussion and conclusions

Field data example



Data stack section

1001 shot gathers

180 channels per shot

1501 samples per trace

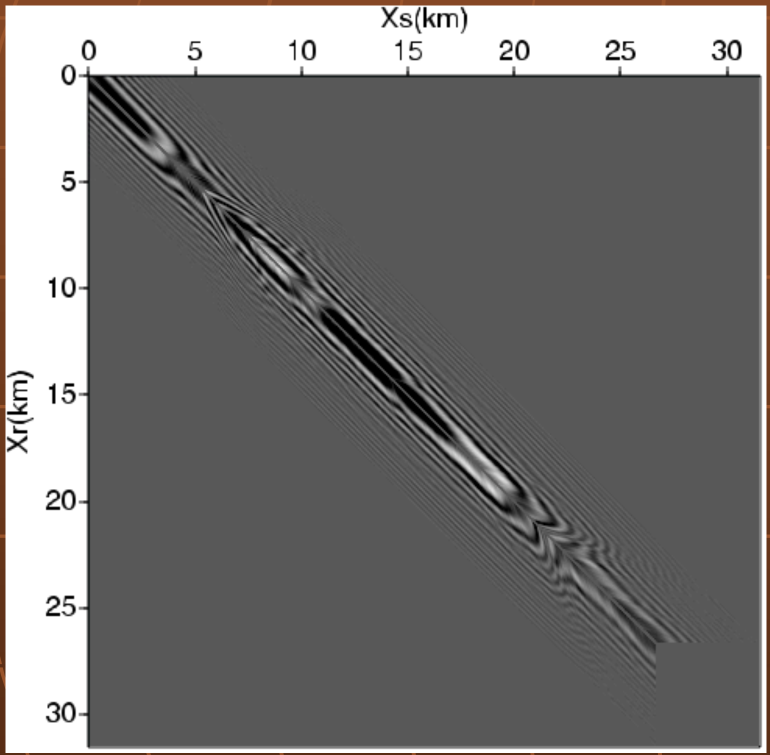
Shot interval: 26.67m

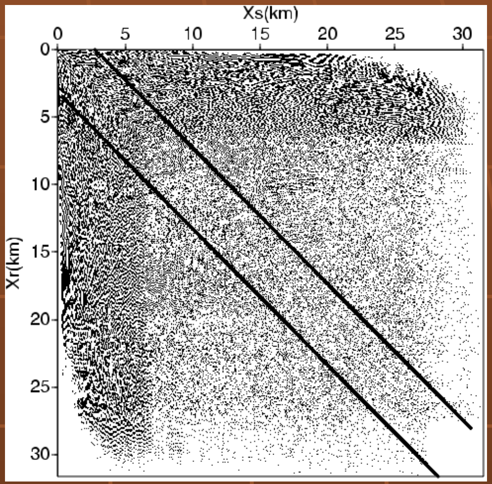
receiver interval: 26.67m

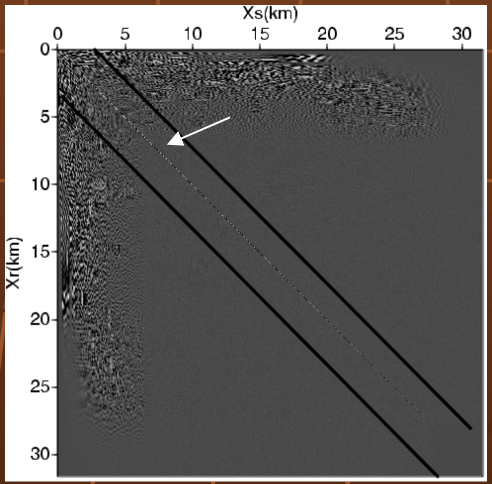
Offset: -100 ~ 4874.36m

Sample rate: 4ms

Field data example
x-t inverse



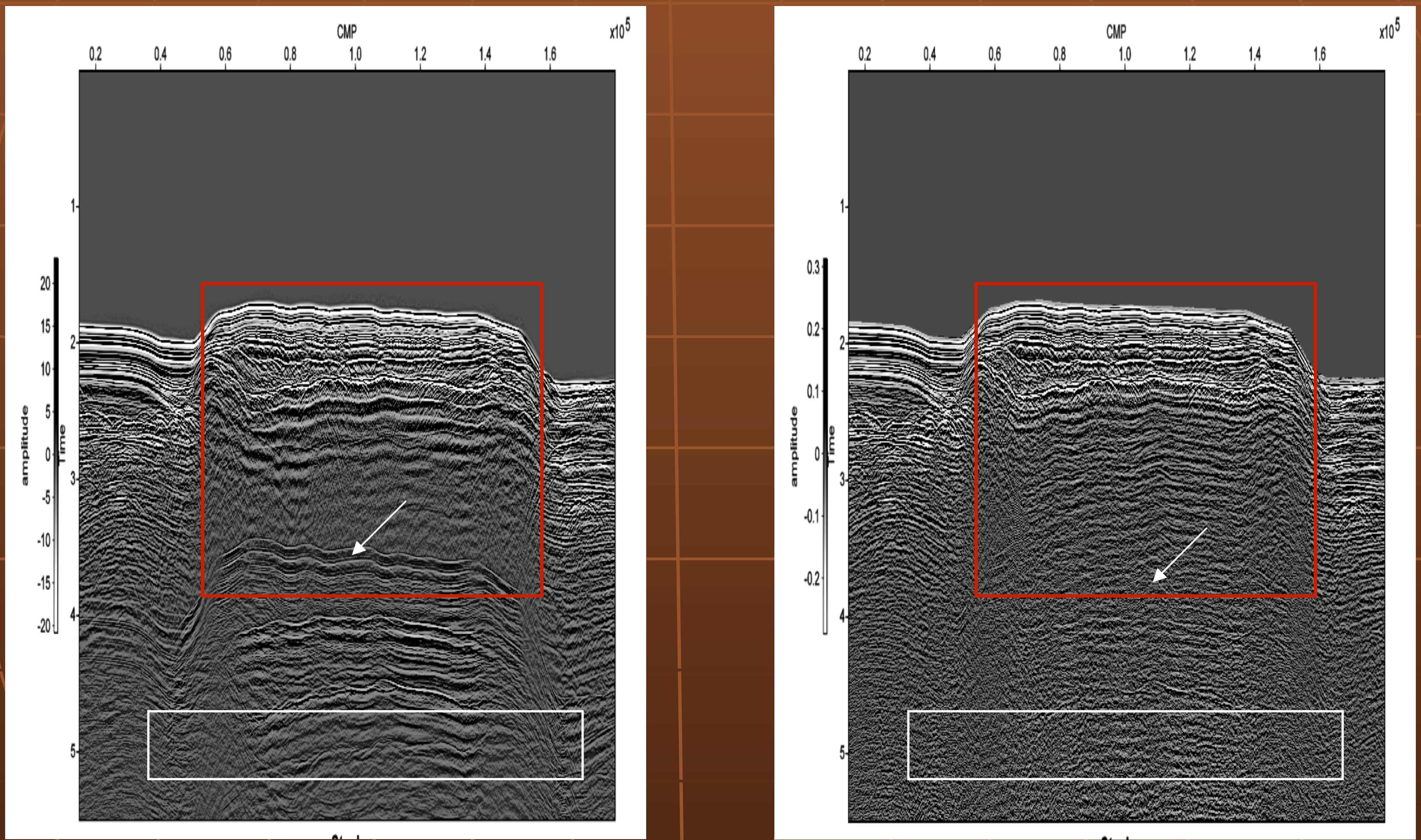




Data Matrix before and after Inversion

Field data example

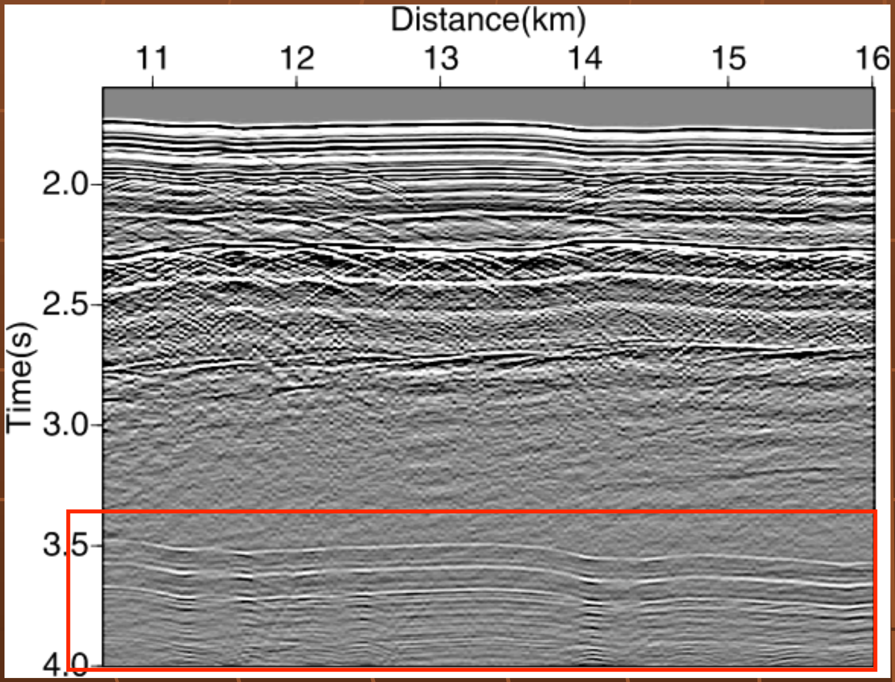
x-t inverse

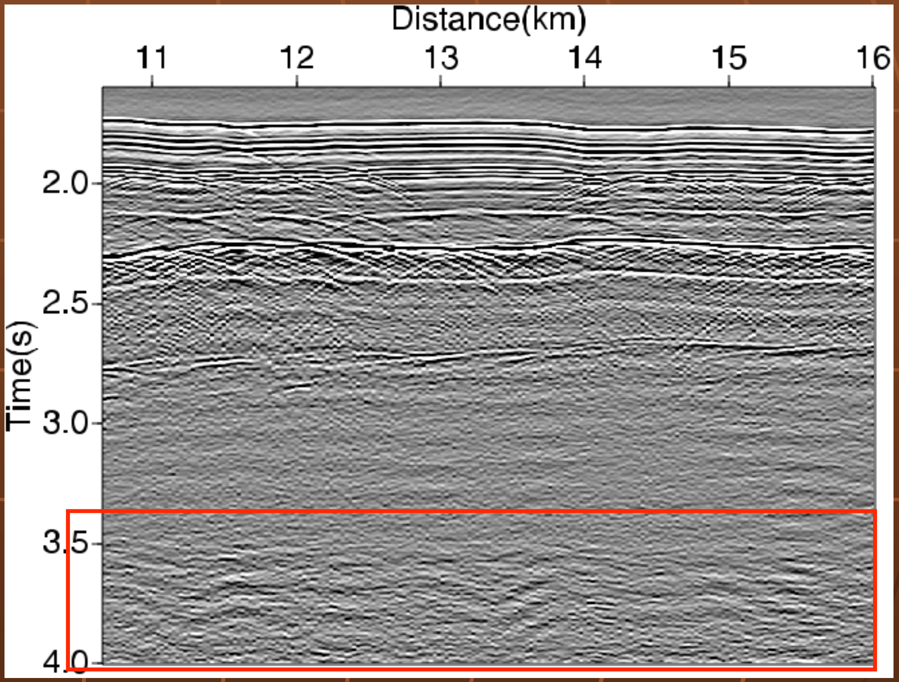


Data stack section before and after IDP

Field data example

x-t inverse

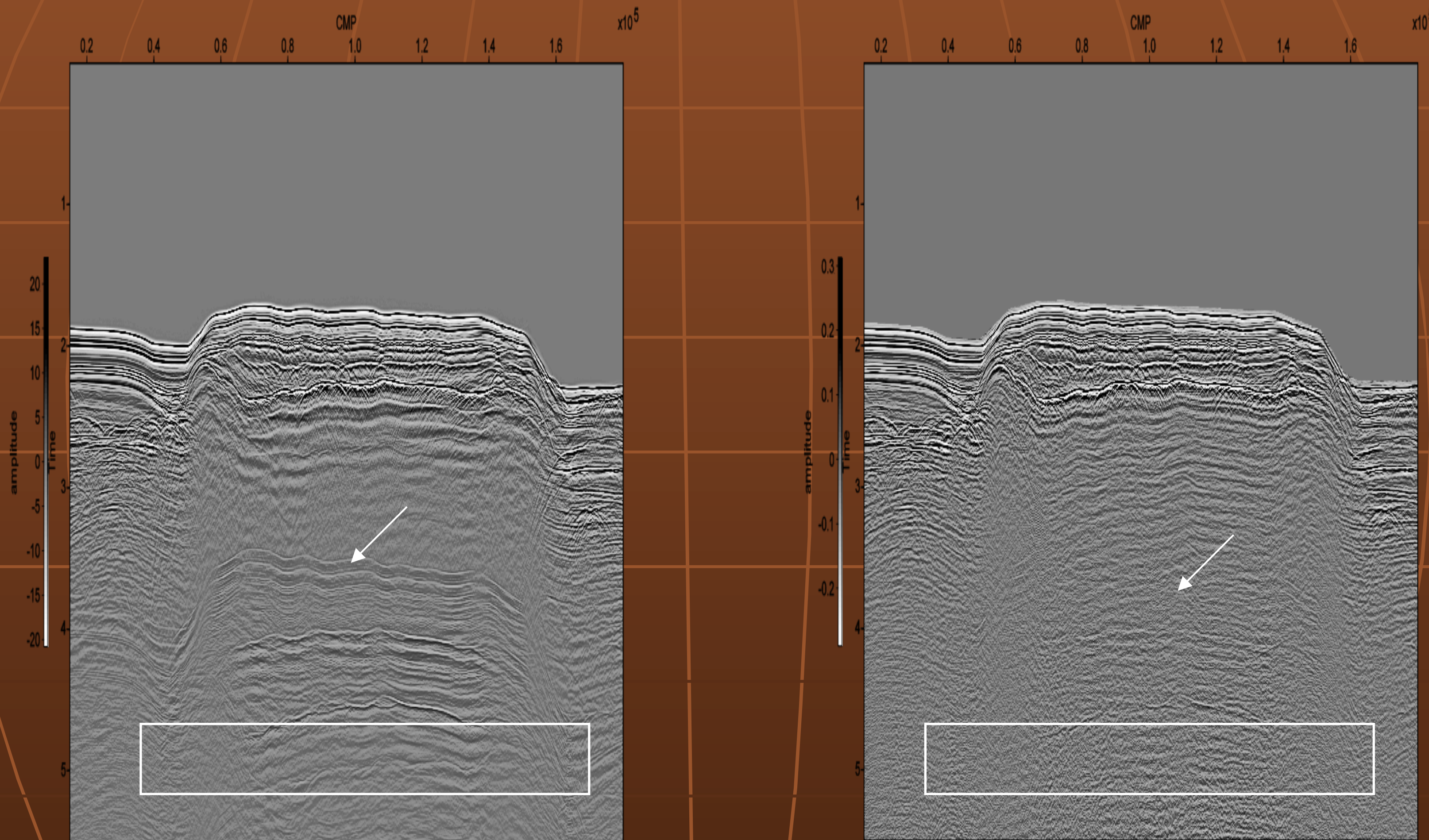




Zoomed part of stack section

Field data example

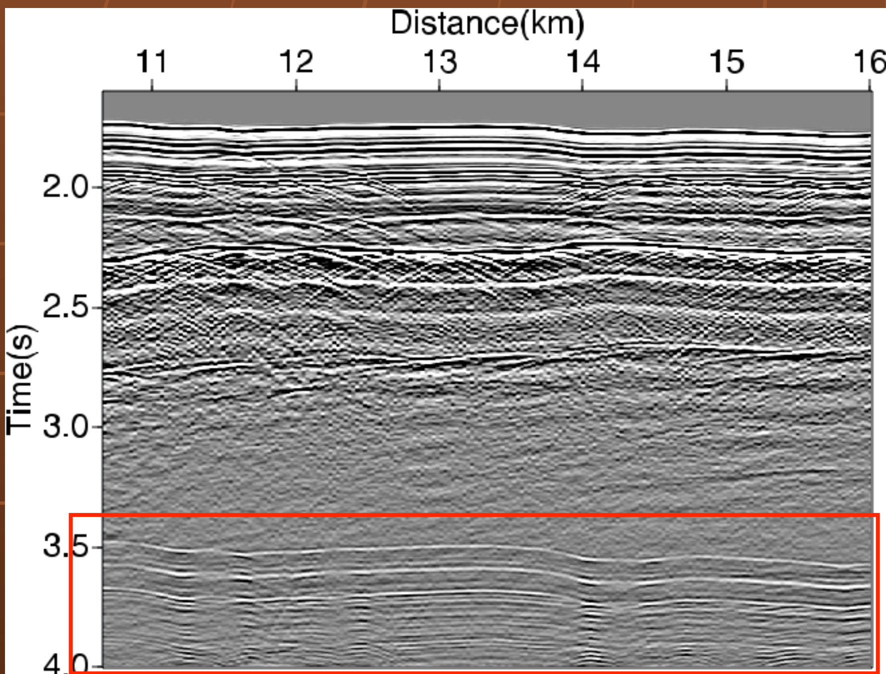
plane wave inverse

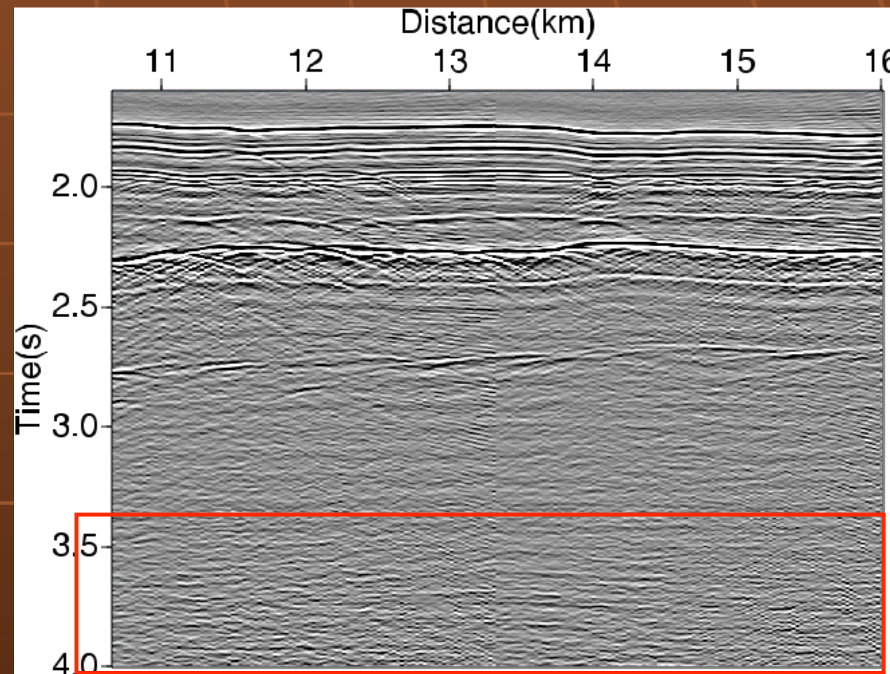


Stack section

Field data example

plane wave inverse





Zoomed part of stack section

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Discussion

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Inverse Data Processing

- Noise and artifacts are introduced. More advanced inversion method is needed.
- The method can be extended to 3D using super-matrices. Accurate inversion method will have to be developed to deal with coarse cross-line sampling problem.
- The method can be extended into internal multiple attenuation using a re-datuming technique.

Conclusion

1. Prediction-subtraction method can predict multiples well; subtraction may damage primary energy.
2. IDP is completely data driven. Fully covered data is needed to carry out the process.
3. IDP is an improvement over a prediction-subtraction method. The inverse data processing can separate multiples and primaries in a very natural way. A simple muting will eliminate all multiples.
4. Tau-p transform technique can compress seismic data efficiently, helping to store more data into memory and making the computation more efficient.
5. 3D extension is applicable.

Thanks!