# Applications of wave imaging technologies to improve onshore US prospecting

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Pacific Coast Section SEG Luncheon

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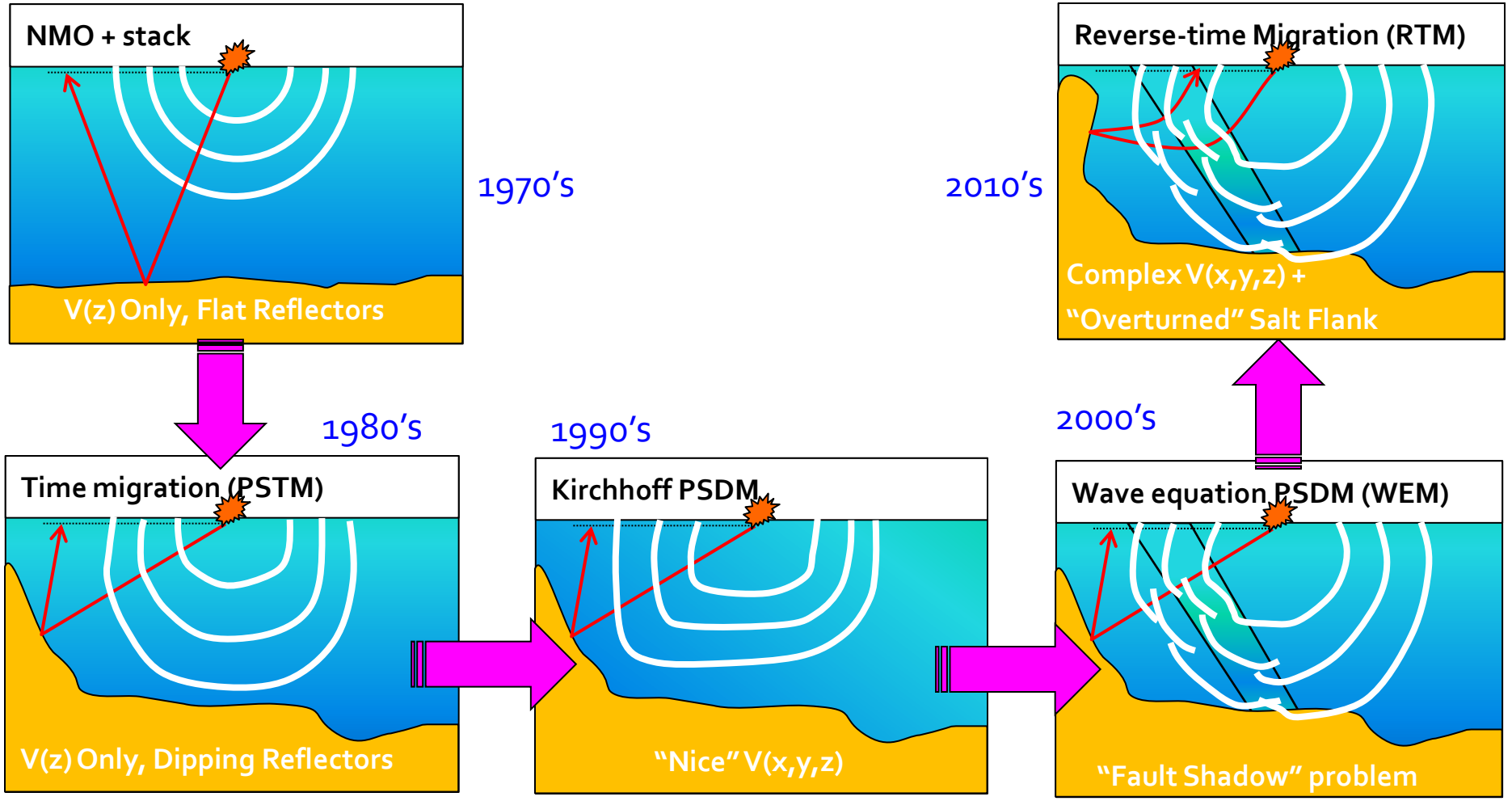
**Wave Imaging Technology Inc.**

# Talk Summary (45 min)

- WIT: Wave Equation Depth Imaging
  - Why Depth Migration?
  - Why Wave Equation?

- Case studies highlight three Wave Imaging technologies with impact:
  - High-effort depth migration velocity estimation
  - Reverse-time Migration (RTM)
  - Attributes from WEM angle gathers

# Imaging Technology Hierarchy

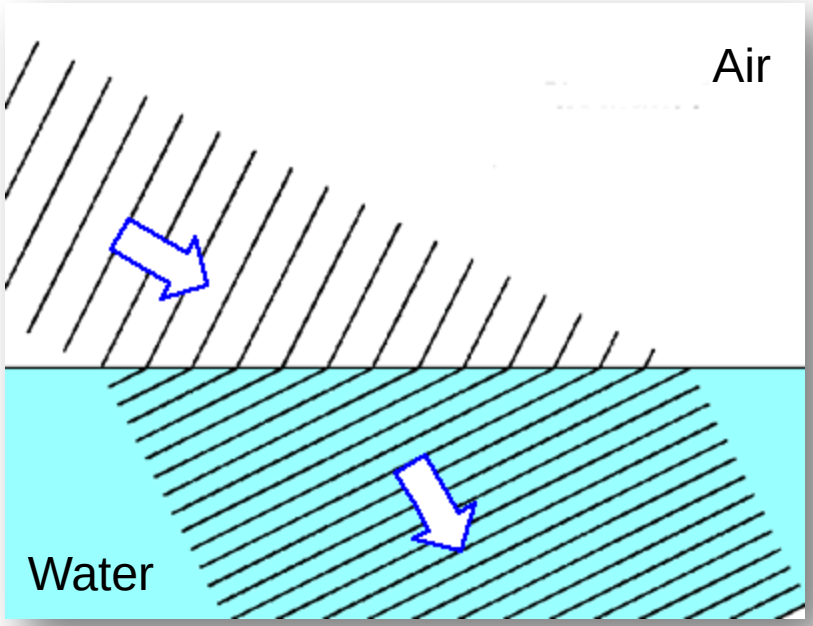


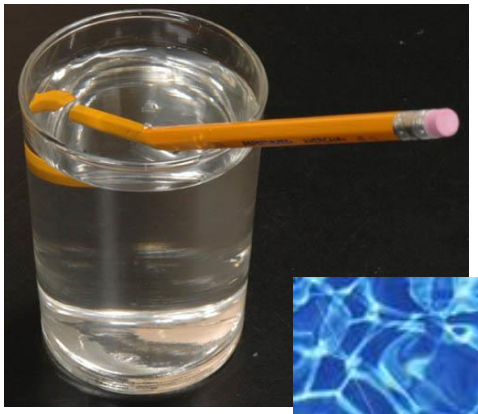
# Why PSDM? Why Wave Equation?

Kirchhoff PSDM handles simple refraction.

WEM also handles complex focusing.

RTM also images "overturned" beds.



Simple refraction

Complex focusing

# Why PSDM? Practically Speaking

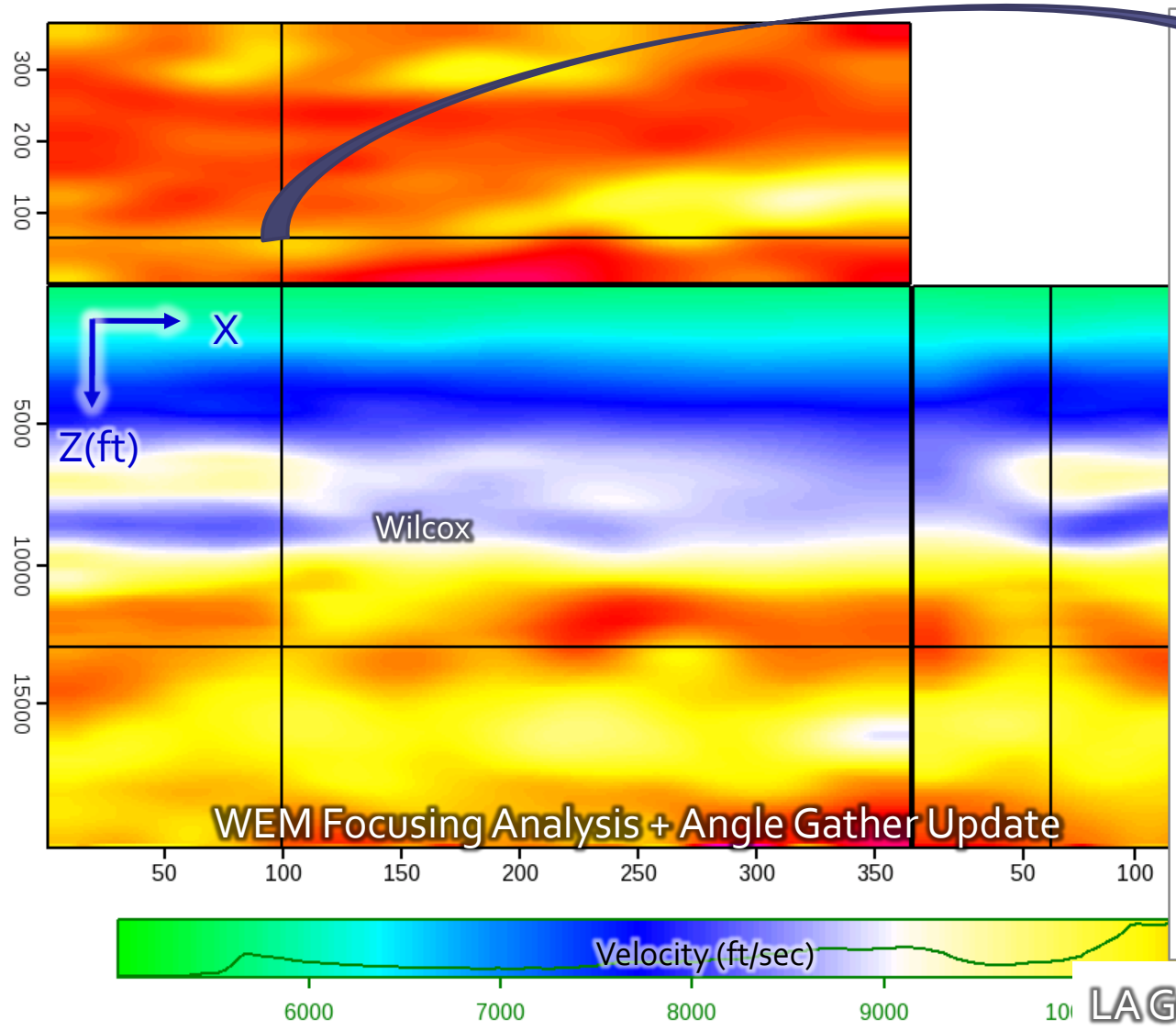
- Better faults
  - Even shallow
  - Sharper fault truncations
  - Fault plane reflections (especially with RTM)
- Better steep dips
  - Improved focusing
  - Improved positioning
  - RTM can image very steep

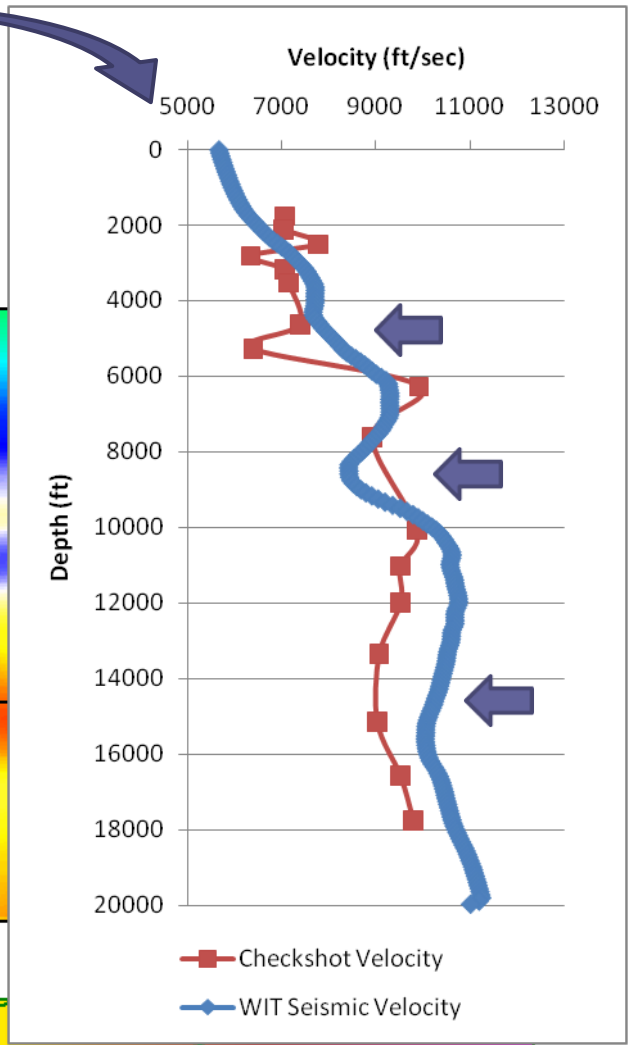
# Depth Migration Velocity Estimation

# Everything Depends on V(x,y,z)!

- PSDM got a bum rap (until recently):
  - (Theory) PSDM should always beat PSTM
  - (Practice) PSTM often won
- Salvation: compute power, volume-based update
  - Depth velocity analysis is iterative
  - *Constrained* volume-based vs. model-driven solutions
- WIT: two-phase velocity update
  - WEM Focusing Analysis (MVFA) → Robust
  - WEM Angle Gather Update → Accurate

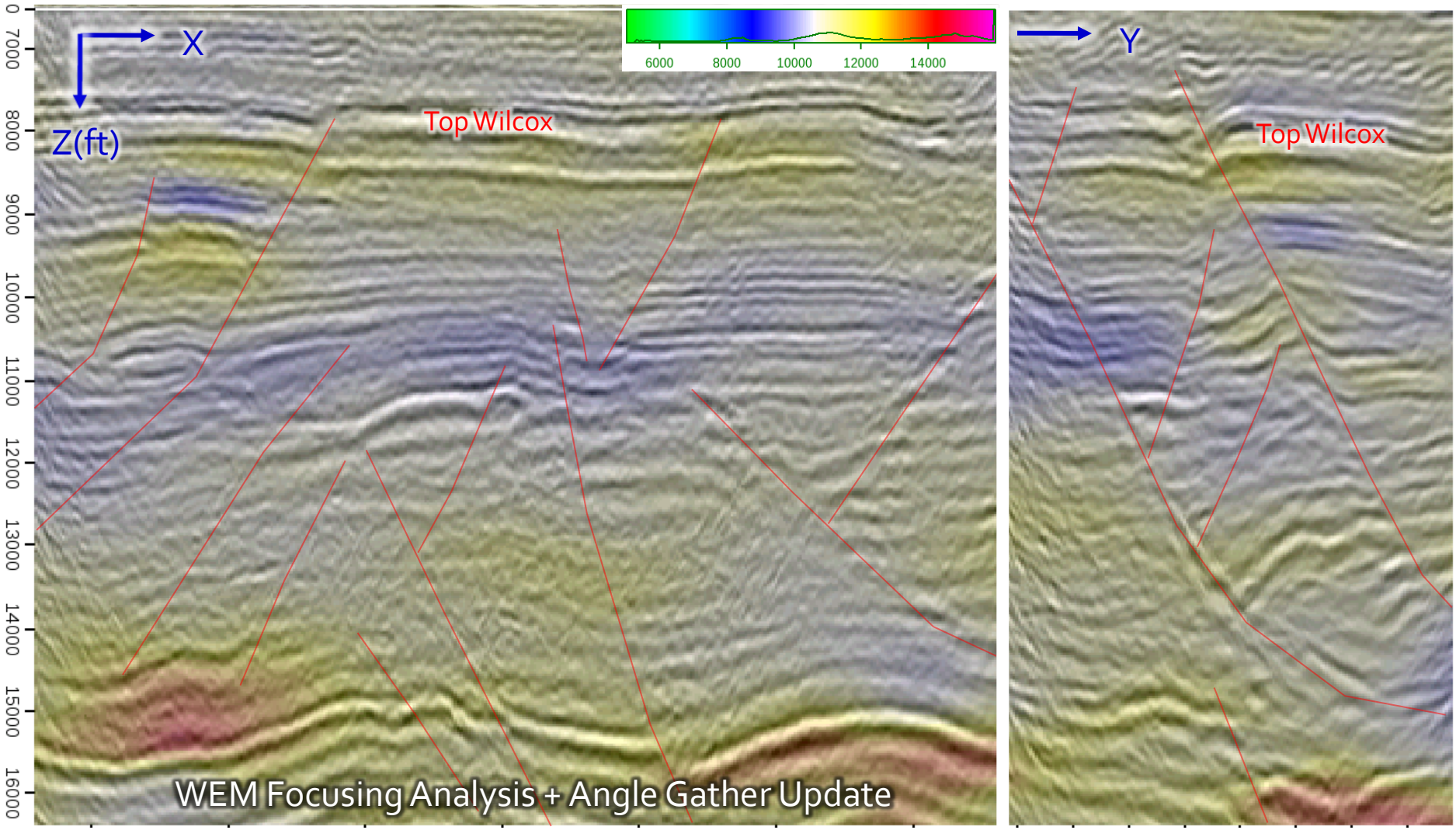
# Checkshot vs. Seismic Velocity



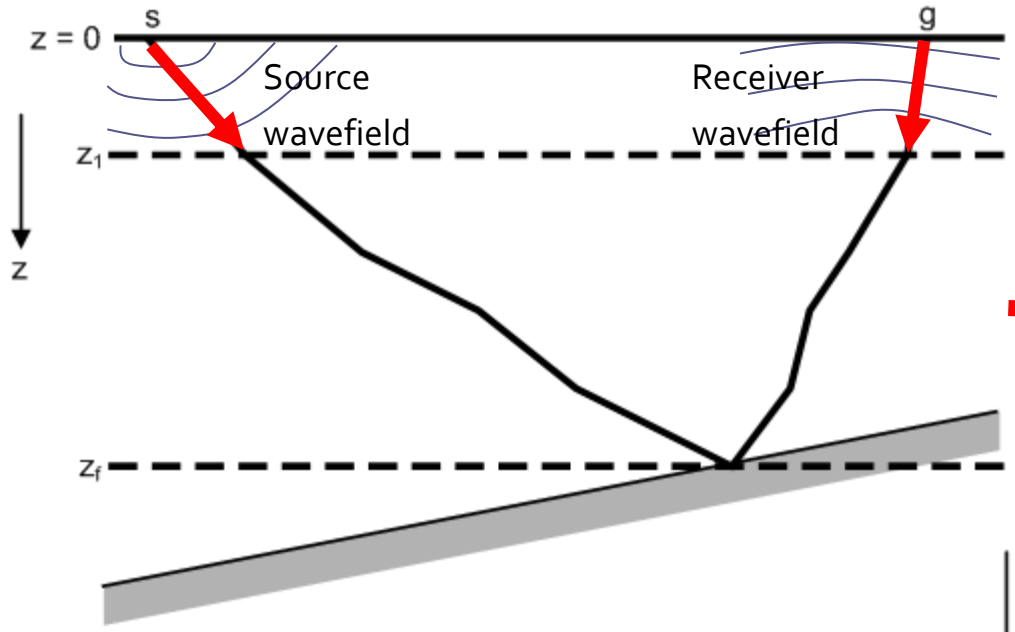

LA Gulf Coast – Well 10 miles away

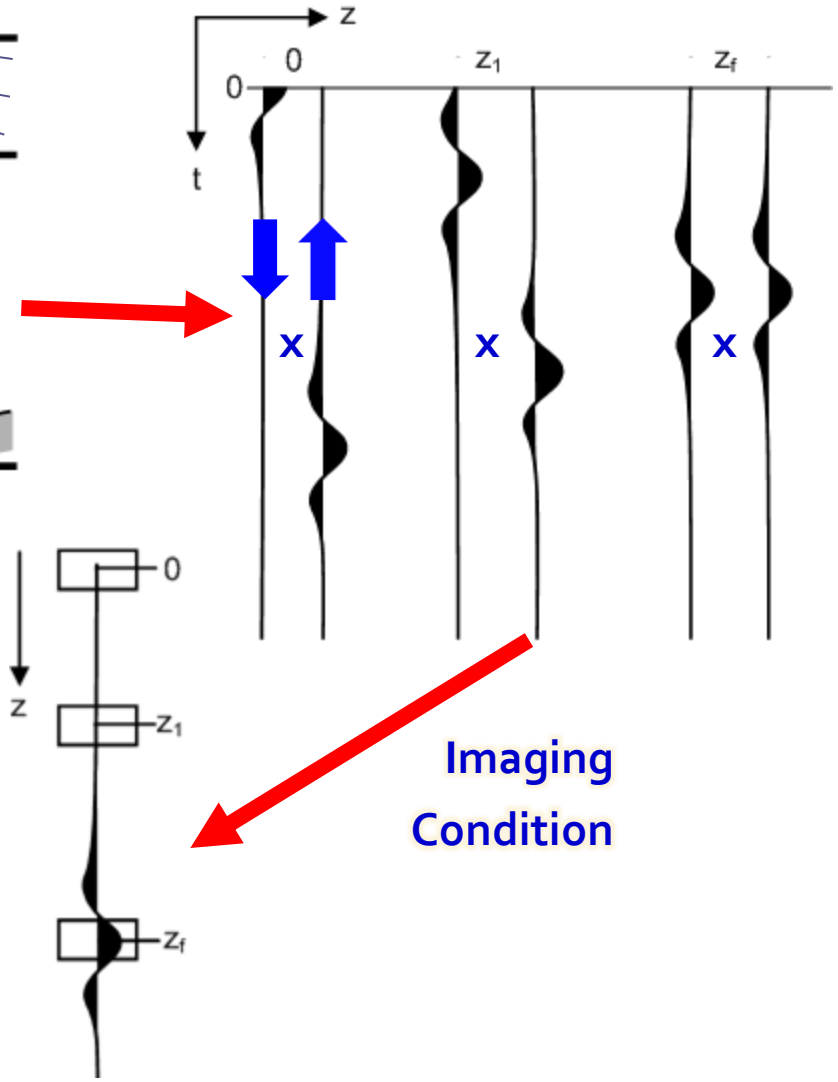
# Velocity Model has Interpretive Value



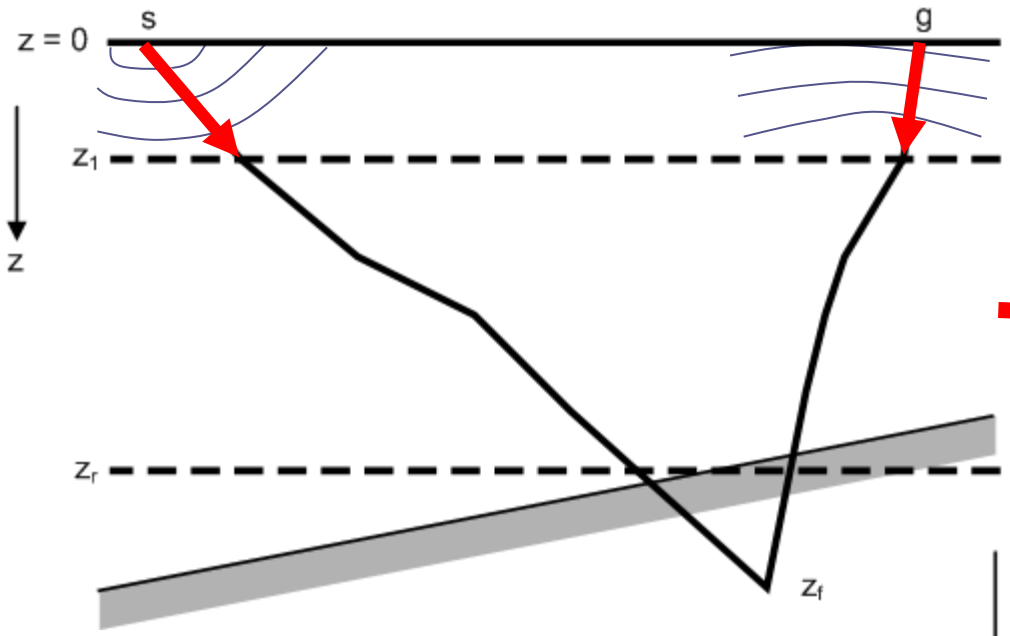

Data courtesy ECHO Geophysical

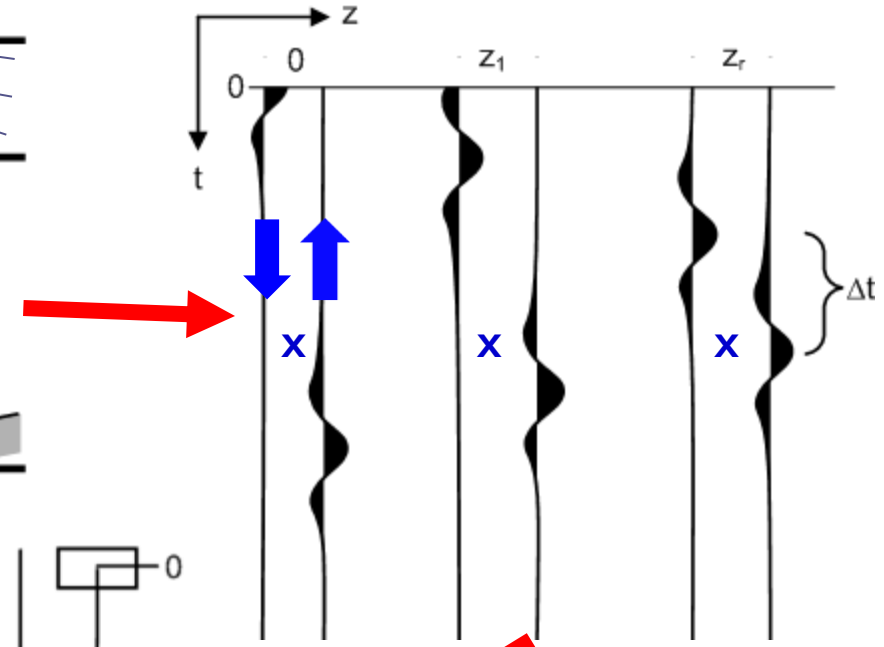
# Shot Record Migration with Correct Velocity

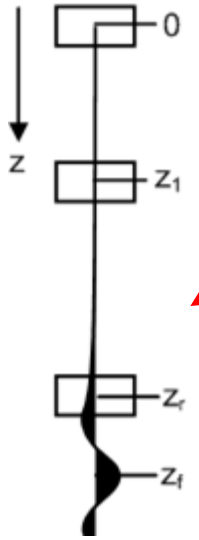


# Shot Record Migration with Too-fast Velocity



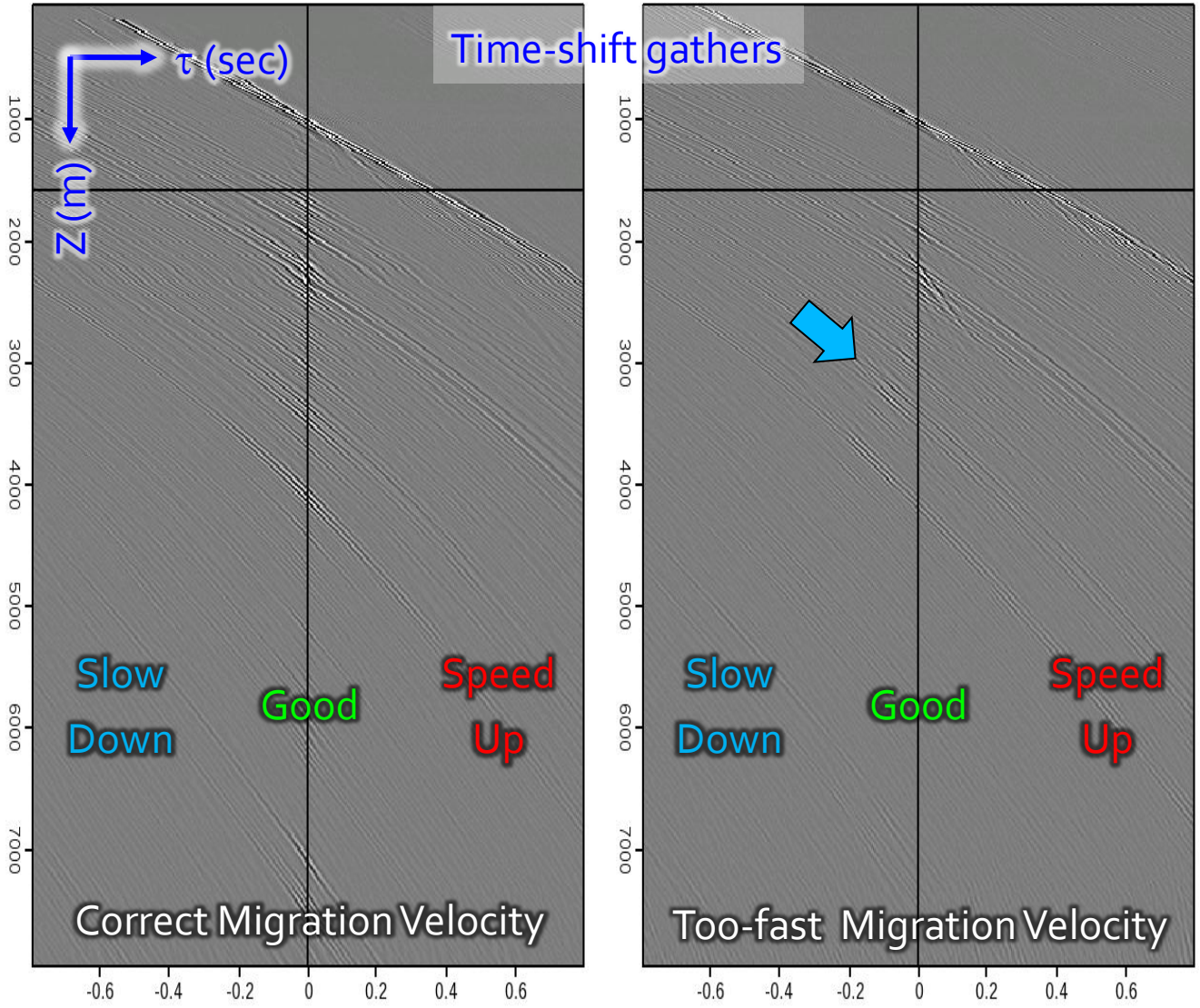




**Focusing Analysis**

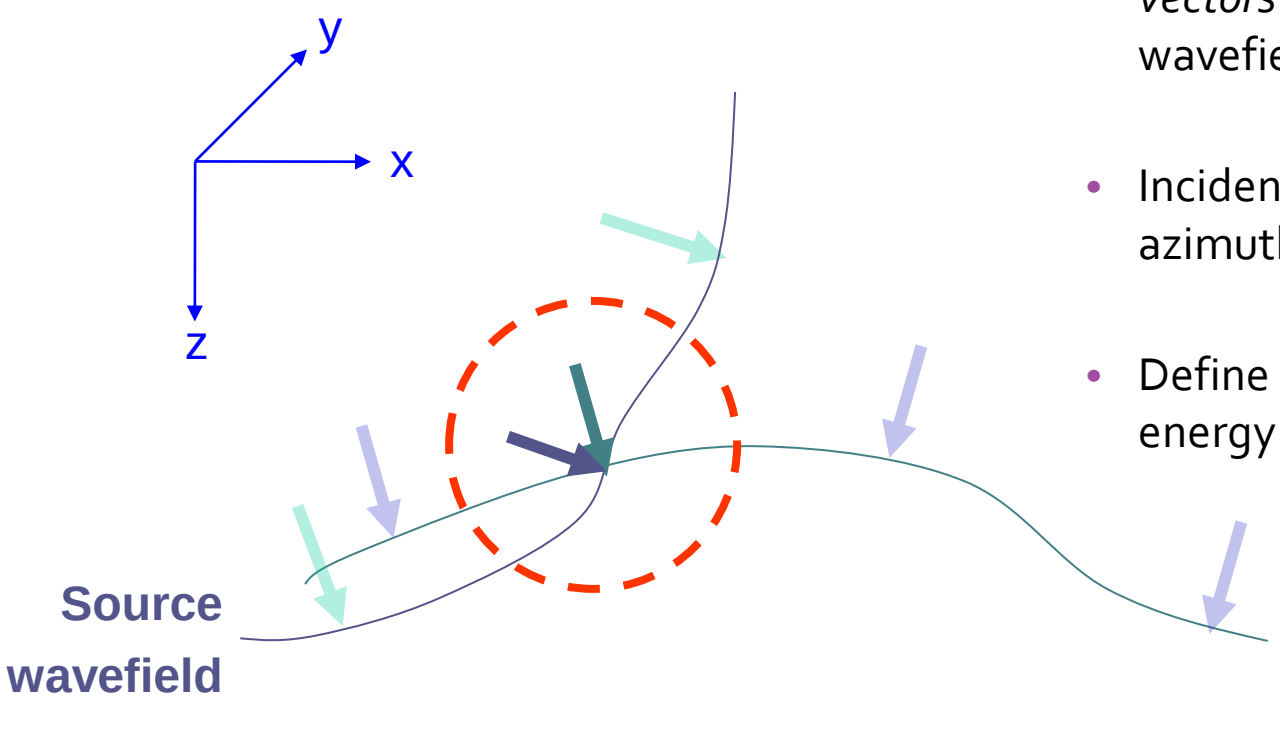
If we knew $\Delta t$, we could estimate velocity error

# WEM Focusing Analysis




- Phase 1 of 2
- Relate best-focusing $\tau$ to $\Delta v$
- Every shot point
- Robust to:
  - Large velocity errors
  - Low fold
- Good for land data

# Angle Decomposition for WEM

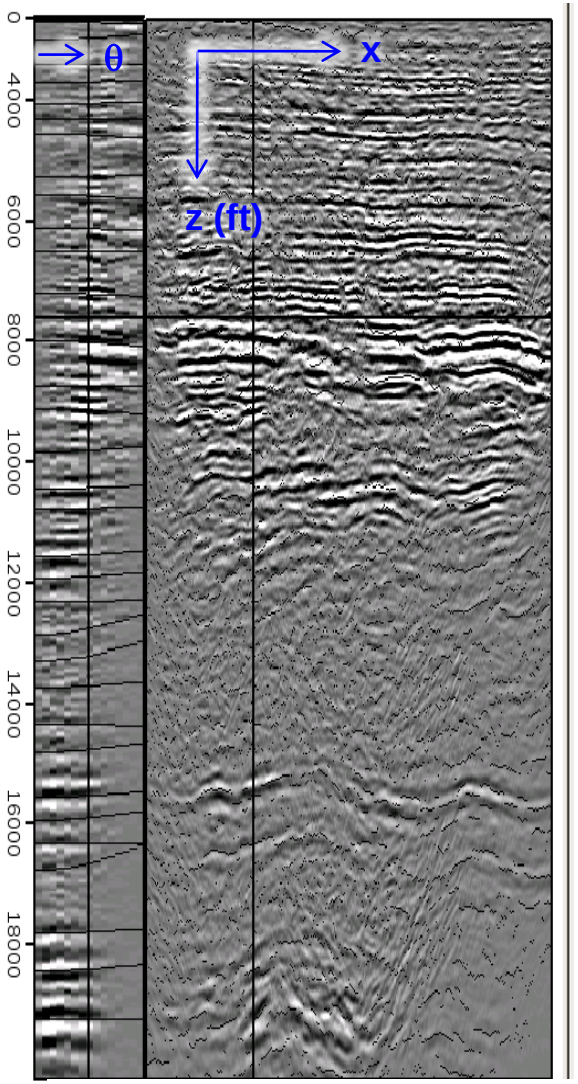



- Compute *propagation direction vectors* for source and receiver wavefields
- Incidence angle, dip angle, and azimuth angle from two vectors
- Define angle "bins", put image energy at (x,y,z) into correct bin

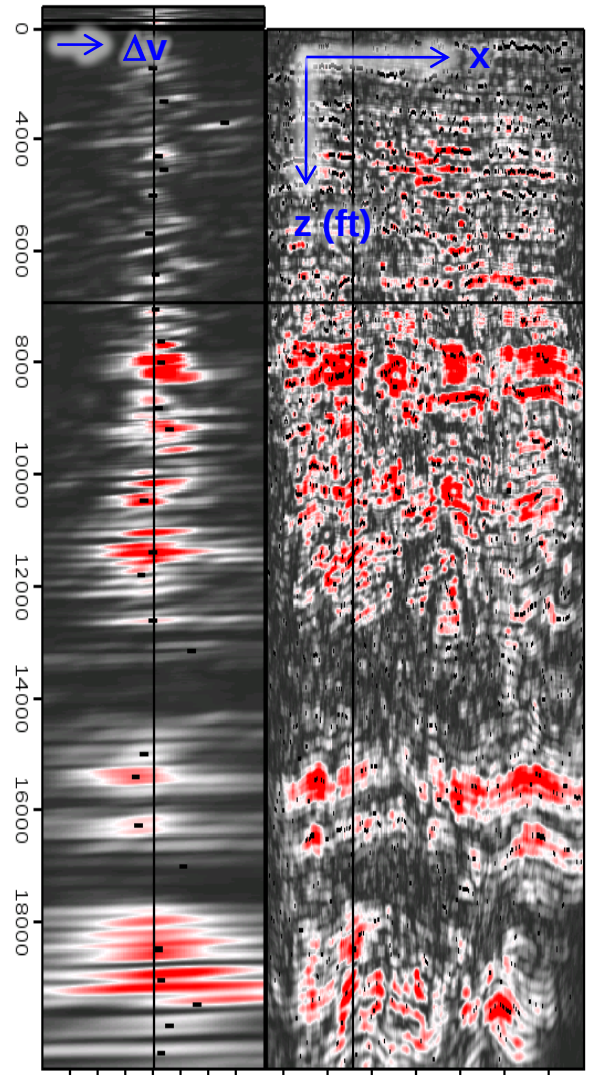
# WEM Angle Gather Velocity Update

## Incidence angle gathers

- Phase 2 of 2
- Velocity estimation:
  - Curving up: velocity too slow
  - Curving down: too fast
  - Automatic picking of large angle gather volumes
  - Update velocity at every image point




Angle gather target line




Residual Velocity panel

Data courtesy ECHO Geophysical

# South Texas

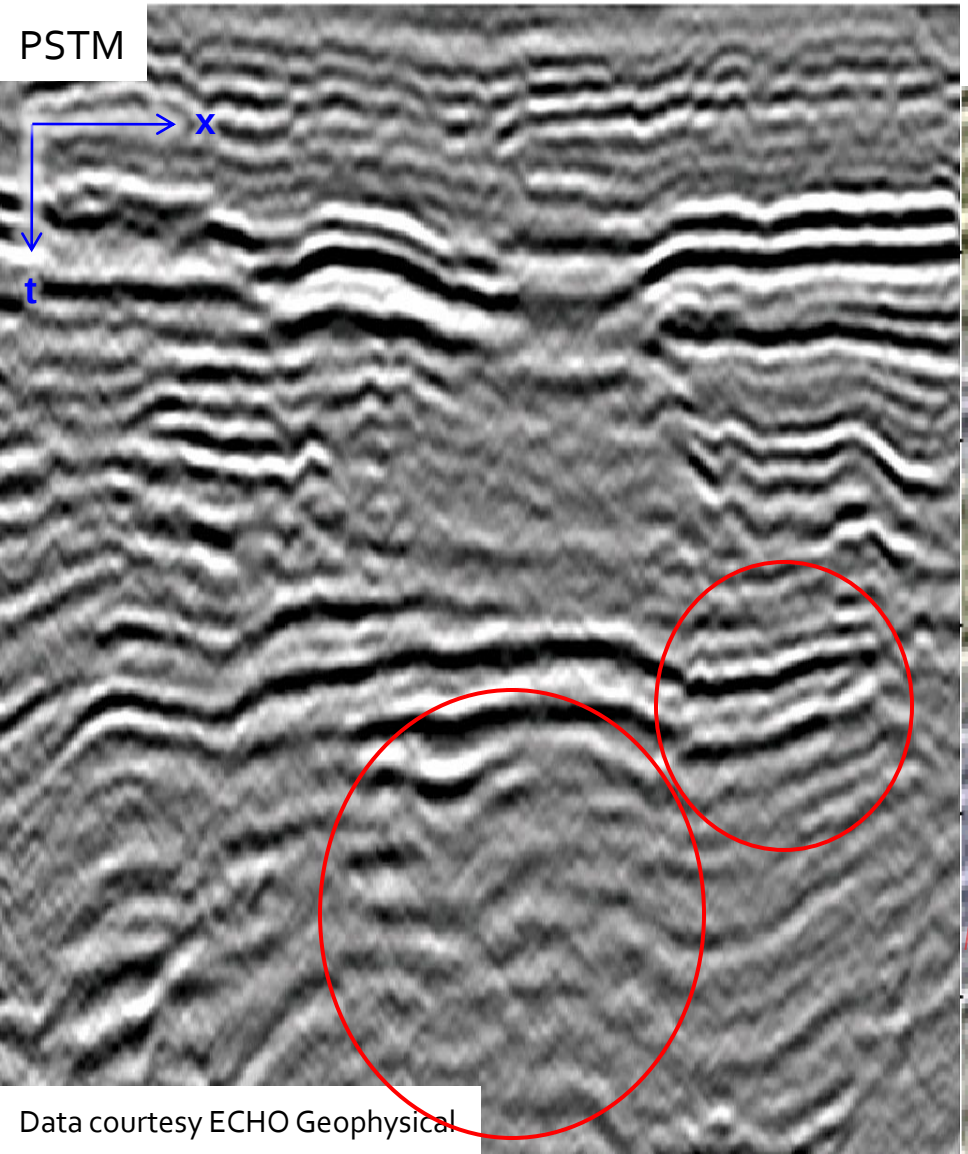
- Not a typical "fault shadow" problem—lots of little fault shadows

- Look below velocity anomalies for:
  - Improved event geometry (remove "time sags")
  - Improved event focusing
  - Improved fault resolution

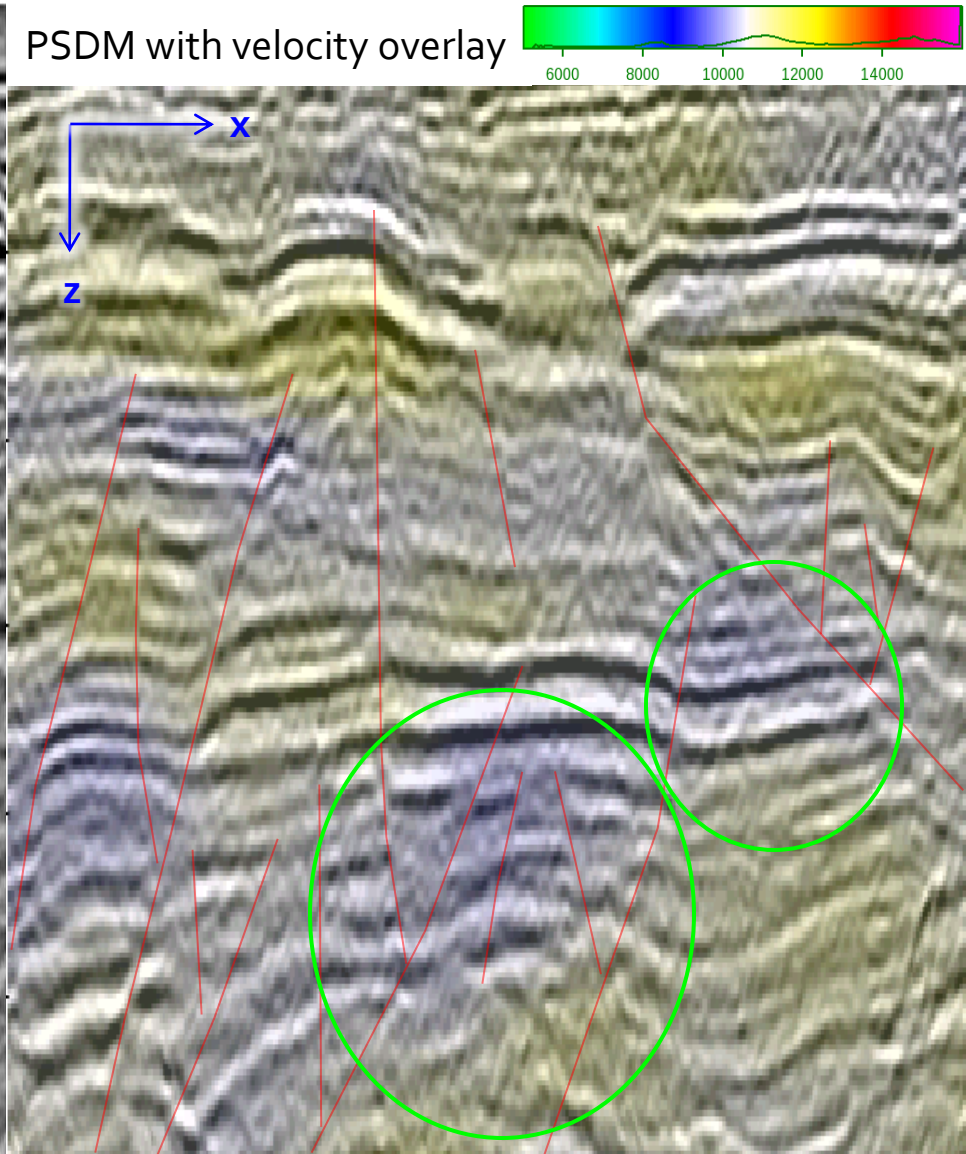
- PSTM works well here → We need PSDM to be as good/better at all locations

# South Texas

PSTM

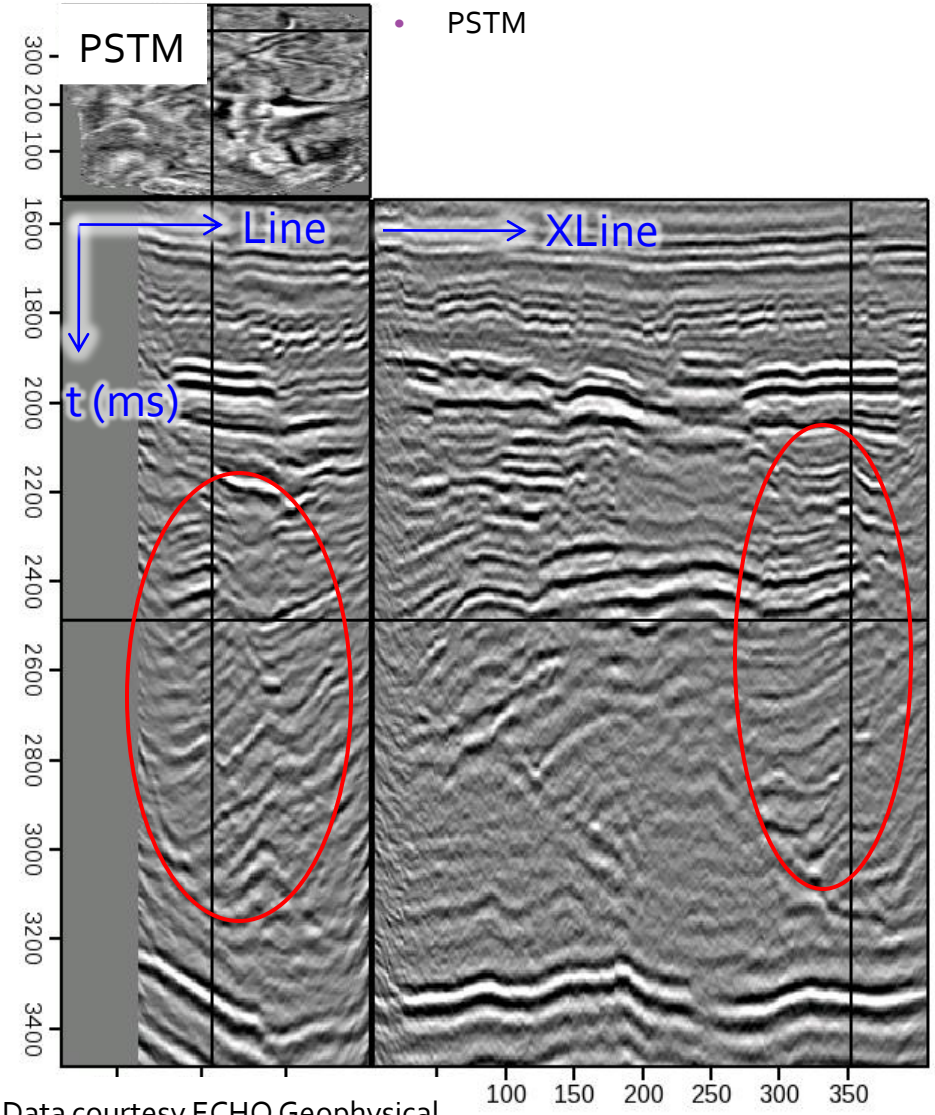



PSDM with velocity overlay

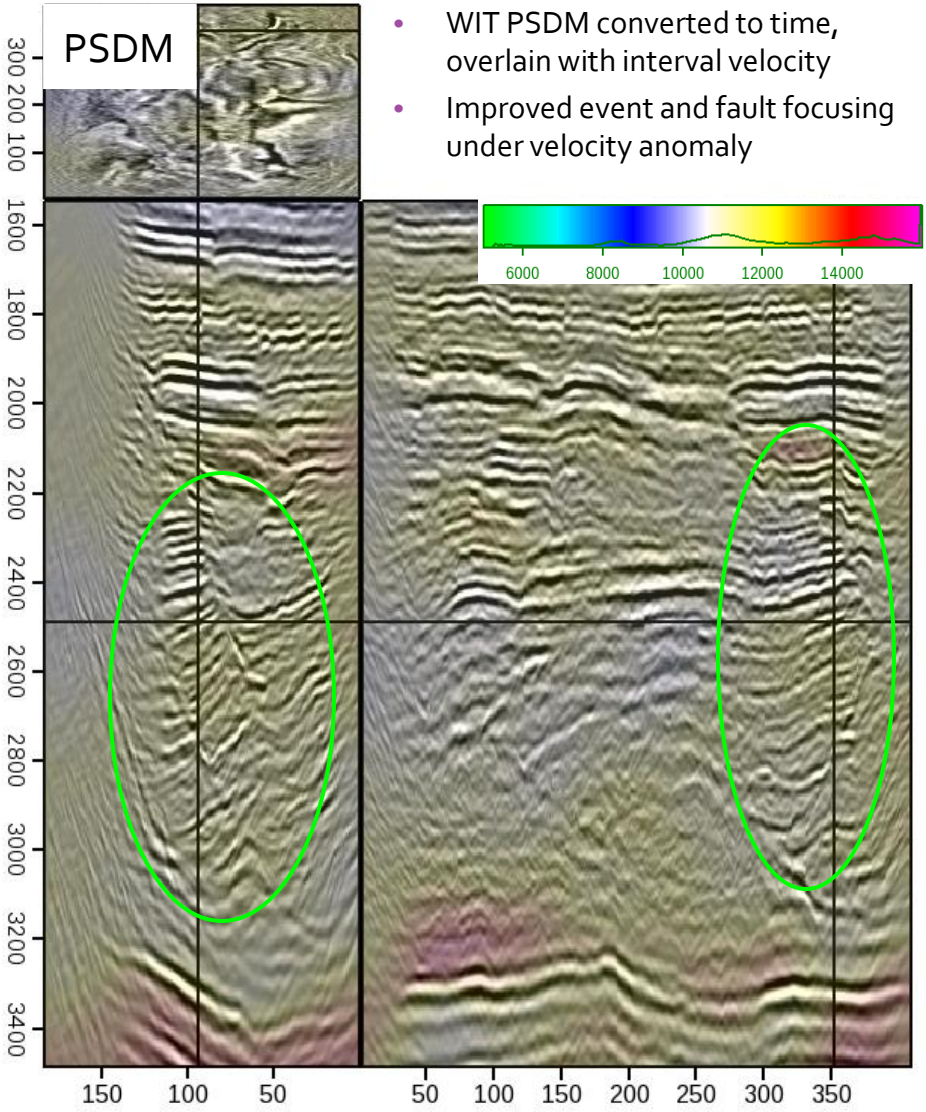



Data courtesy ECHO Geophysical

# South Texas




- PSTM




- WIT PSDM converted to time, overlain with interval velocity
- Improved event and fault focusing under velocity anomaly

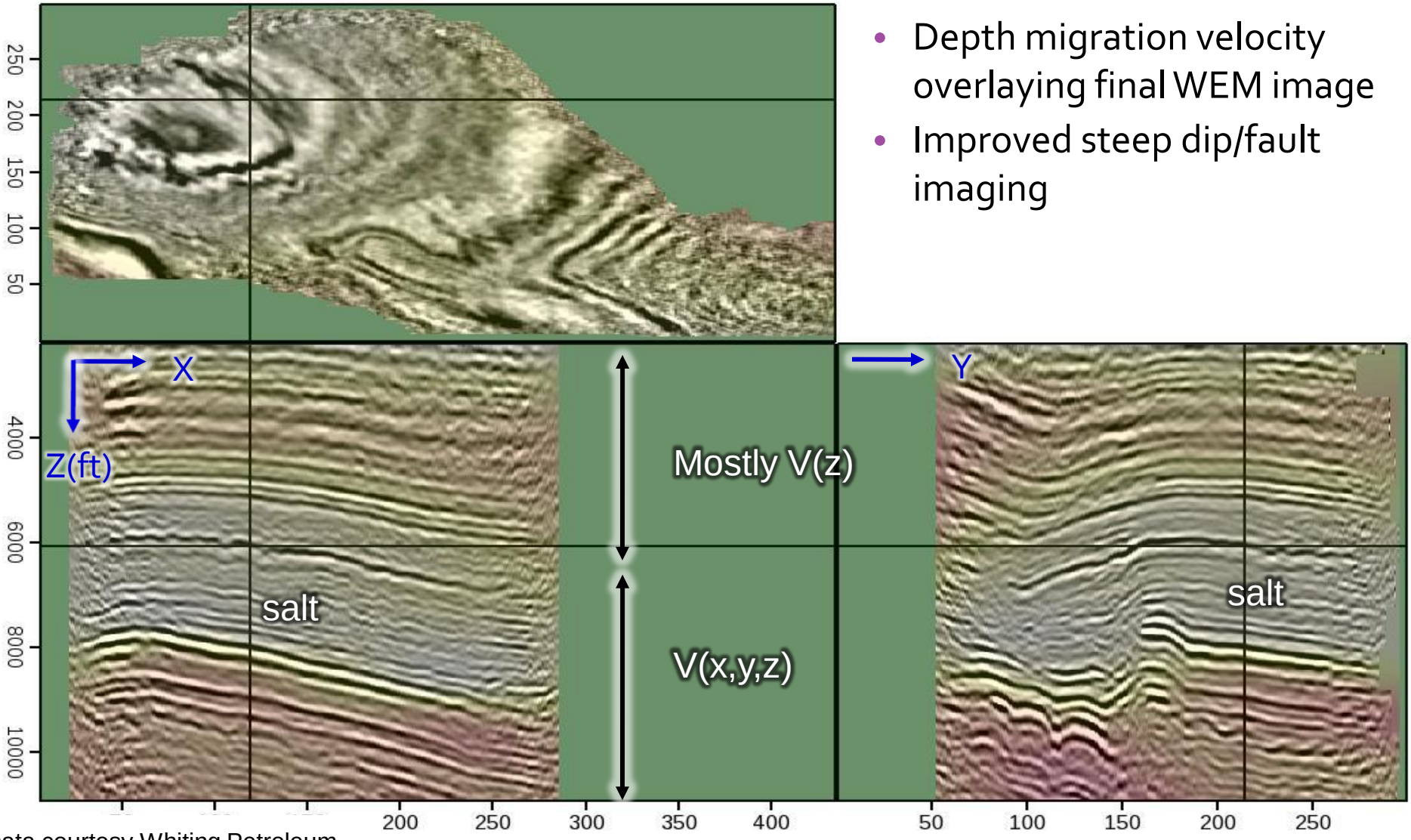
Data courtesy ECHO Geophysical

# Paradox Basin

- Thick salt layer = low velocity anomaly
- Tectonics warps salt, creates velocity lensing

- WEM + accurate velocity analysis:
  - Better fault imaging
  - Better steep dip imaging

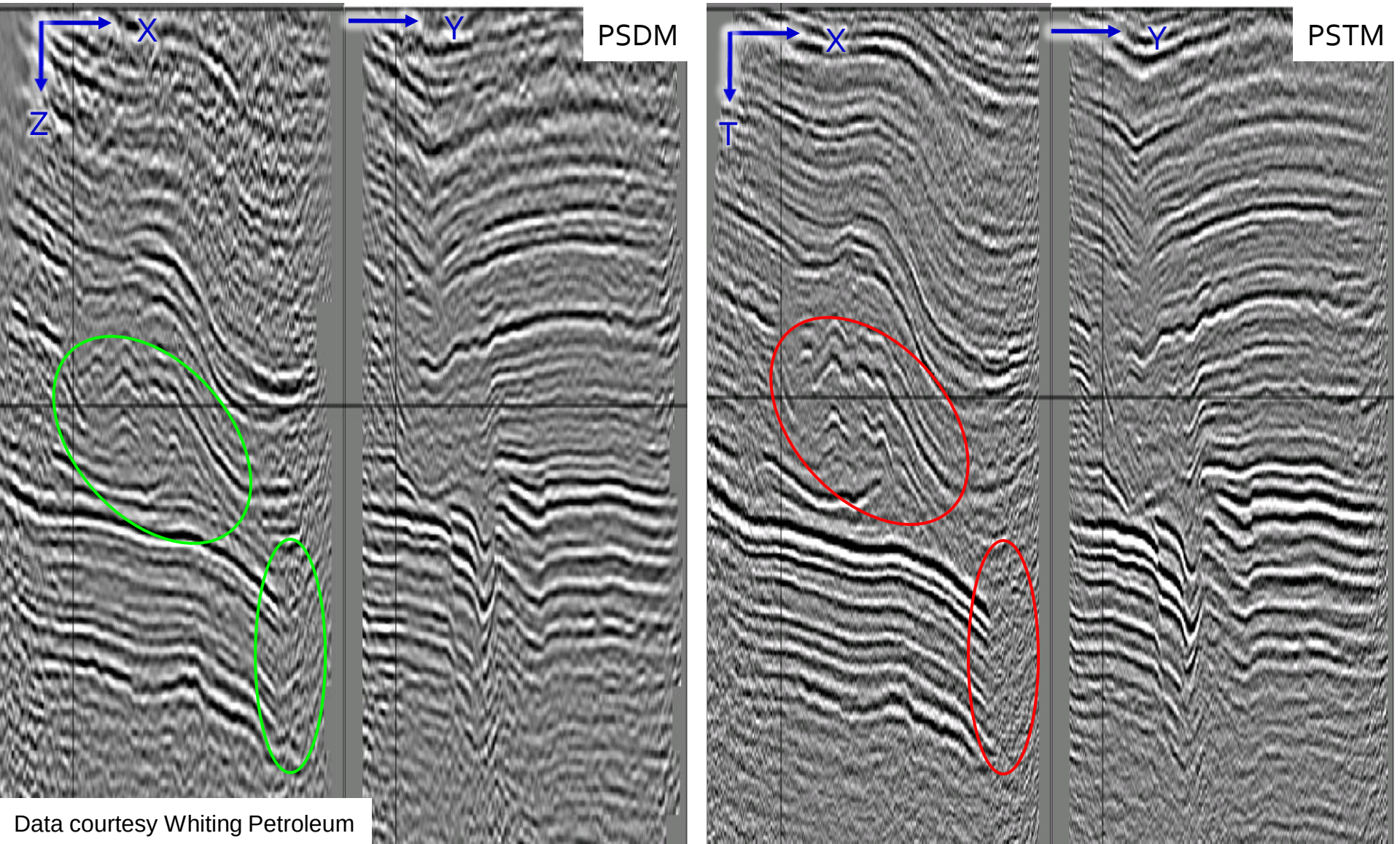
# Paradox Basin




- Depth migration velocity overlaying final WEM image
- Improved steep dip/fault imaging

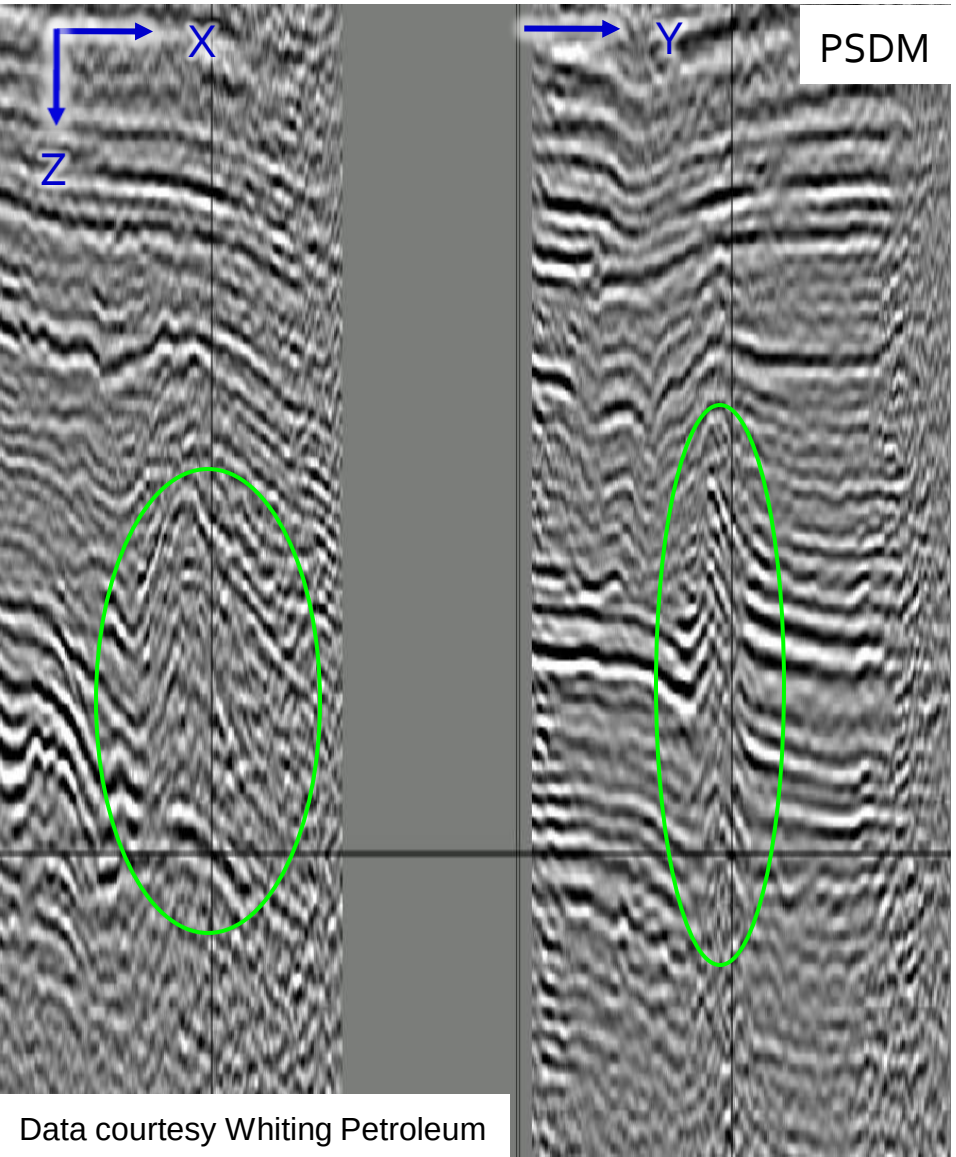
Data courtesy Whiting Petroleum

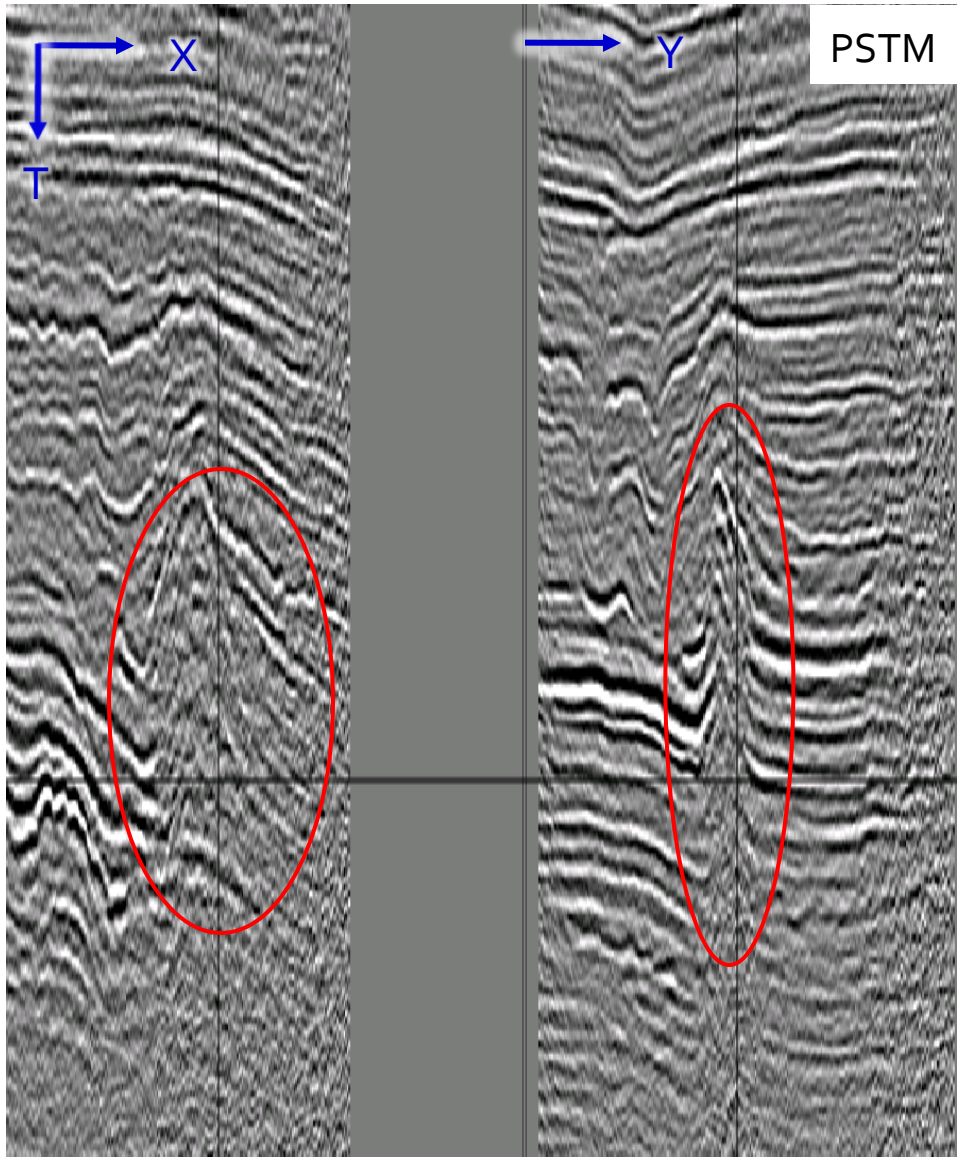
# Paradox Basin




Data courtesy Whiting Petroleum

# Paradox Basin




Data courtesy Whiting Petroleum

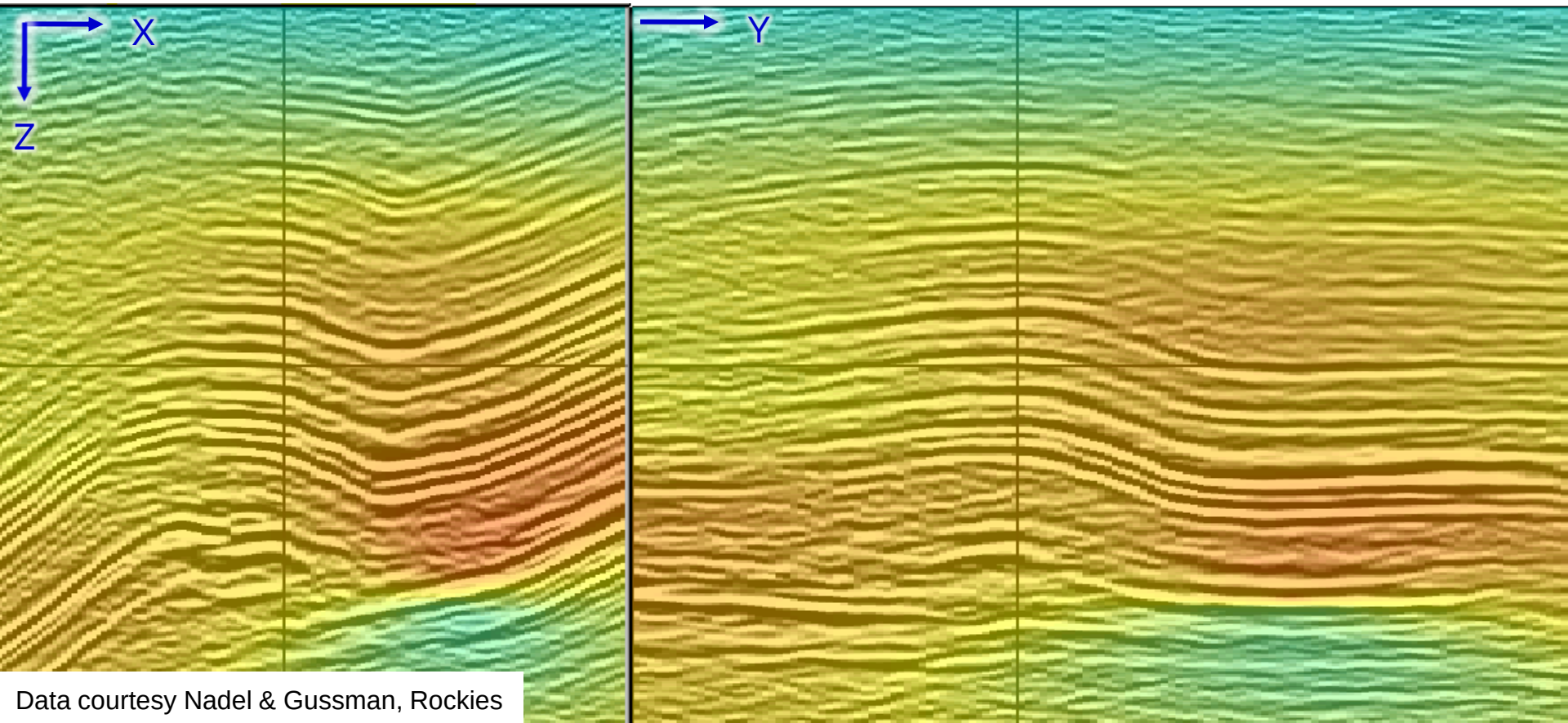
# Wyoming

- Monoclinal, hard-rock beds = lateral velocity variation…enough to “break” PSTM

- WEM + accurate velocity analysis:
  - Better fault imaging
  - Better steep dip imaging

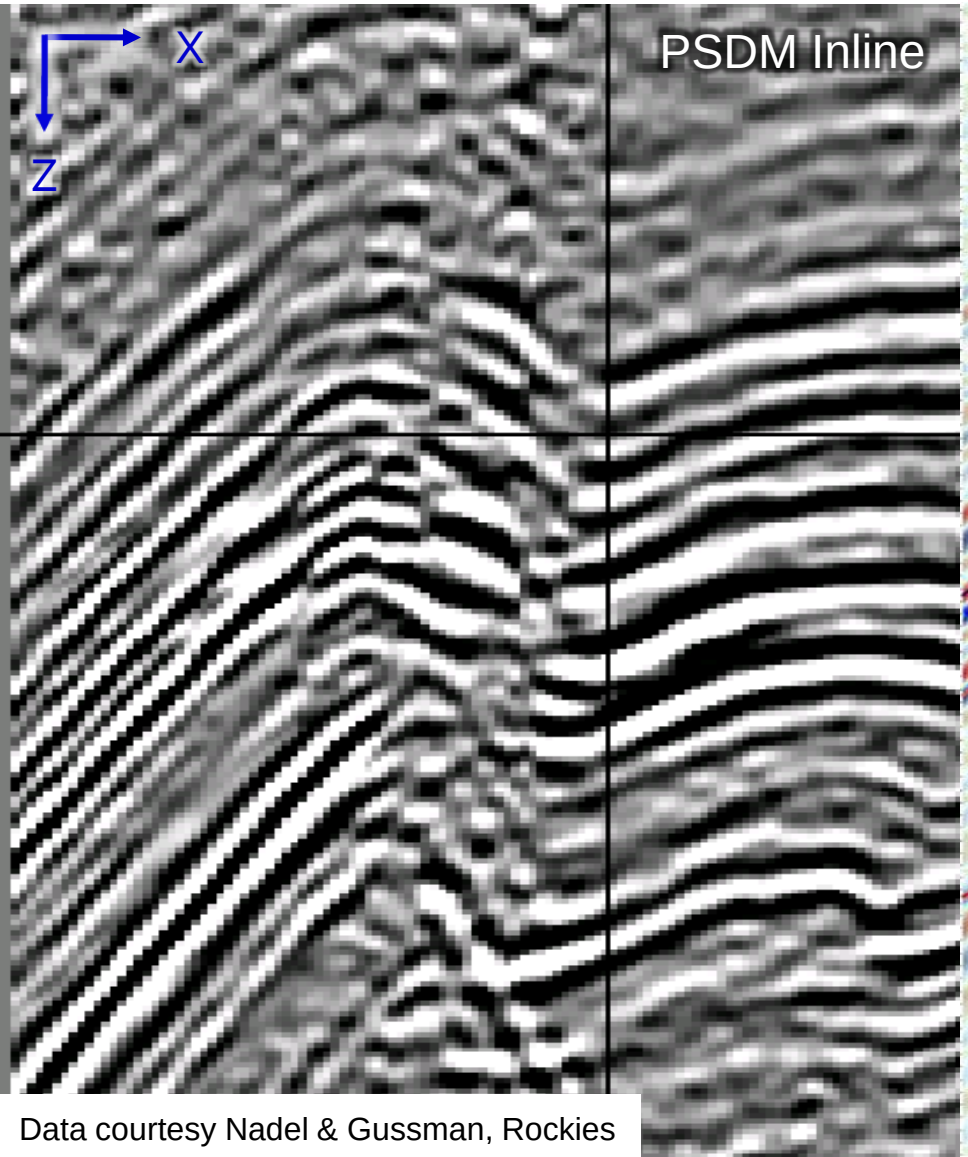
# Wyoming

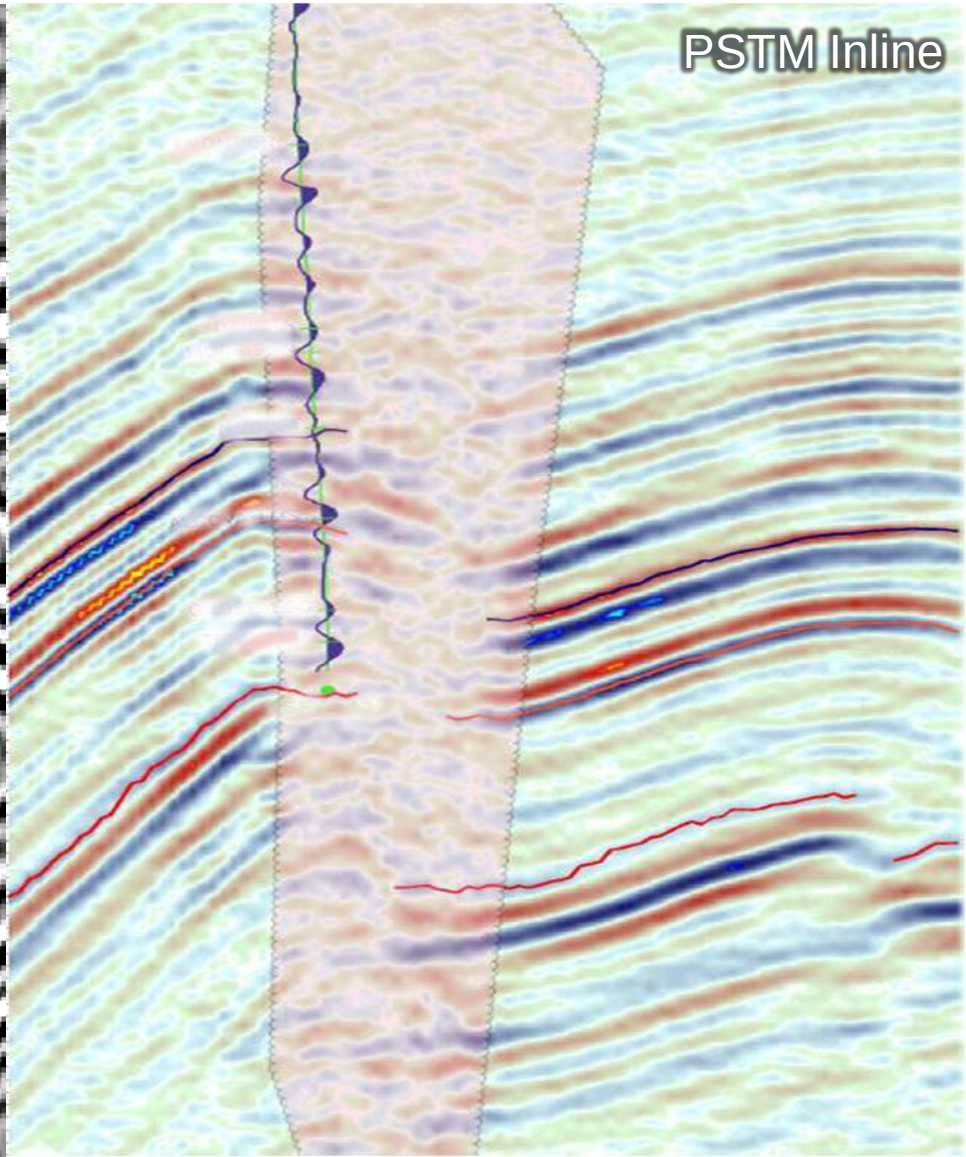
- Migration velocity overlaying final PSDM image
- Lateral velocity variation is subtle, but sufficient to harm time imaging




Data courtesy Nadel & Gussman, Rockies

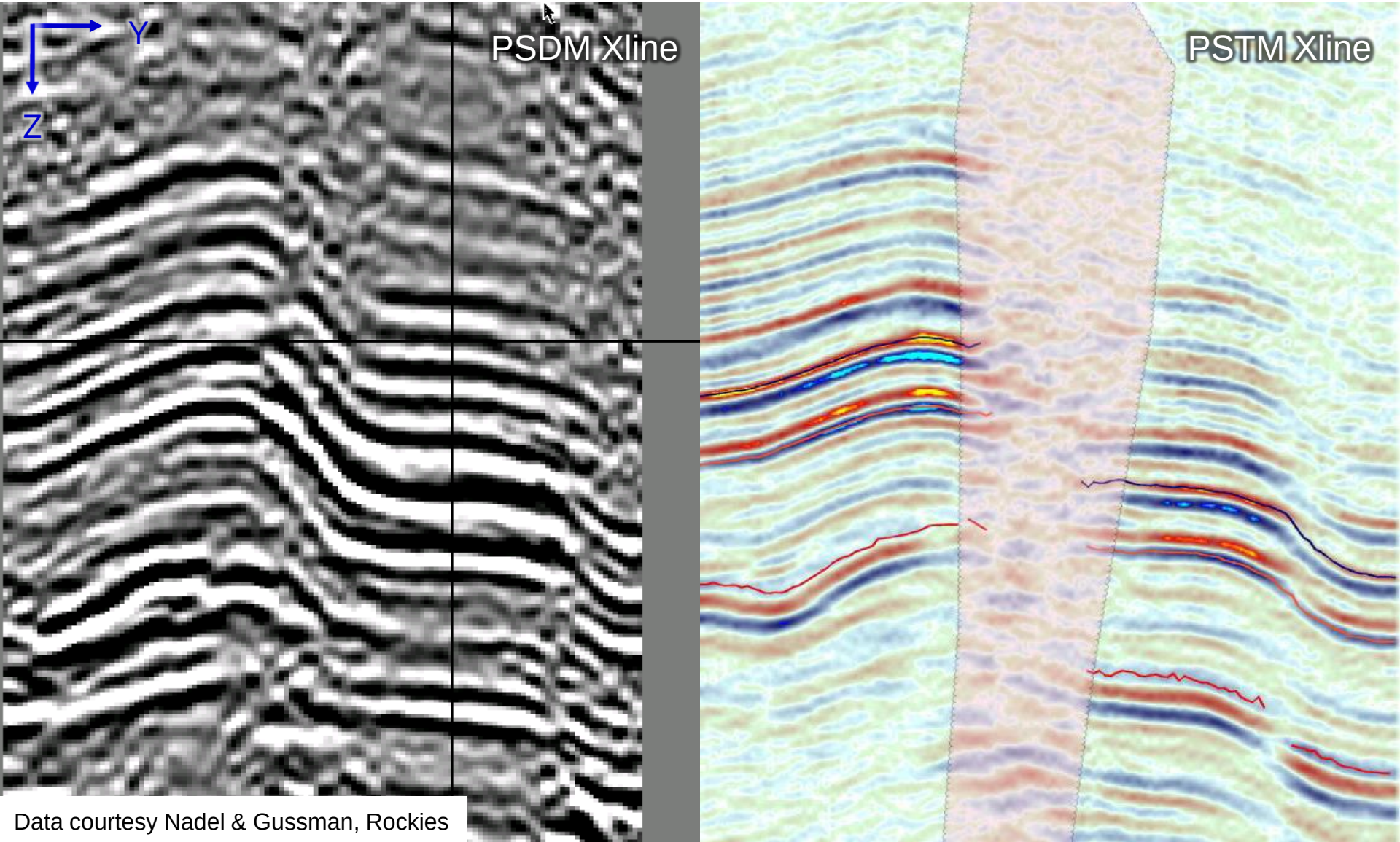
# Wyoming




Data courtesy Nadel & Gussman, Rockies

# Wyoming




Data courtesy Nadel & Gussman, Rockies

# Reverse-Time Migration (RTM)

# What is RTM?

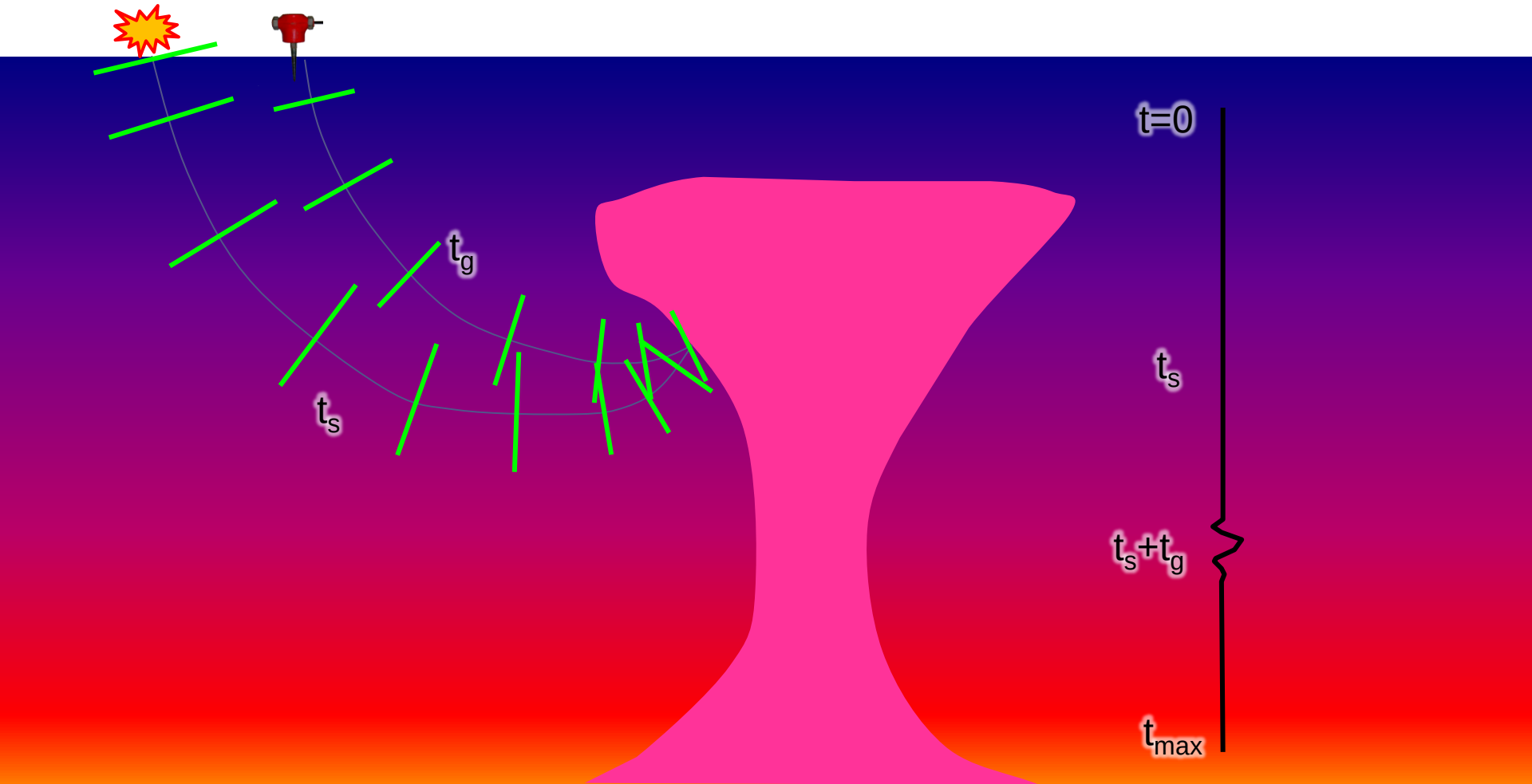
- RTM = Reverse-time migration, or "two-way" wave equation depth migration

| | WEM | Kirchhoff PSDM | RTM |
|---|---|---|---|
| Naturally handles complex velocity focusing | Yes | No | Yes |
| Can image steep (>70°) dips | No | Yes | Yes |
| Accurate amplitude "out of the box" | Yes | No | Yes |

- RTM: the best of Kirchhoff and WEM
- Downsides: More expensive, a bit "noisy"

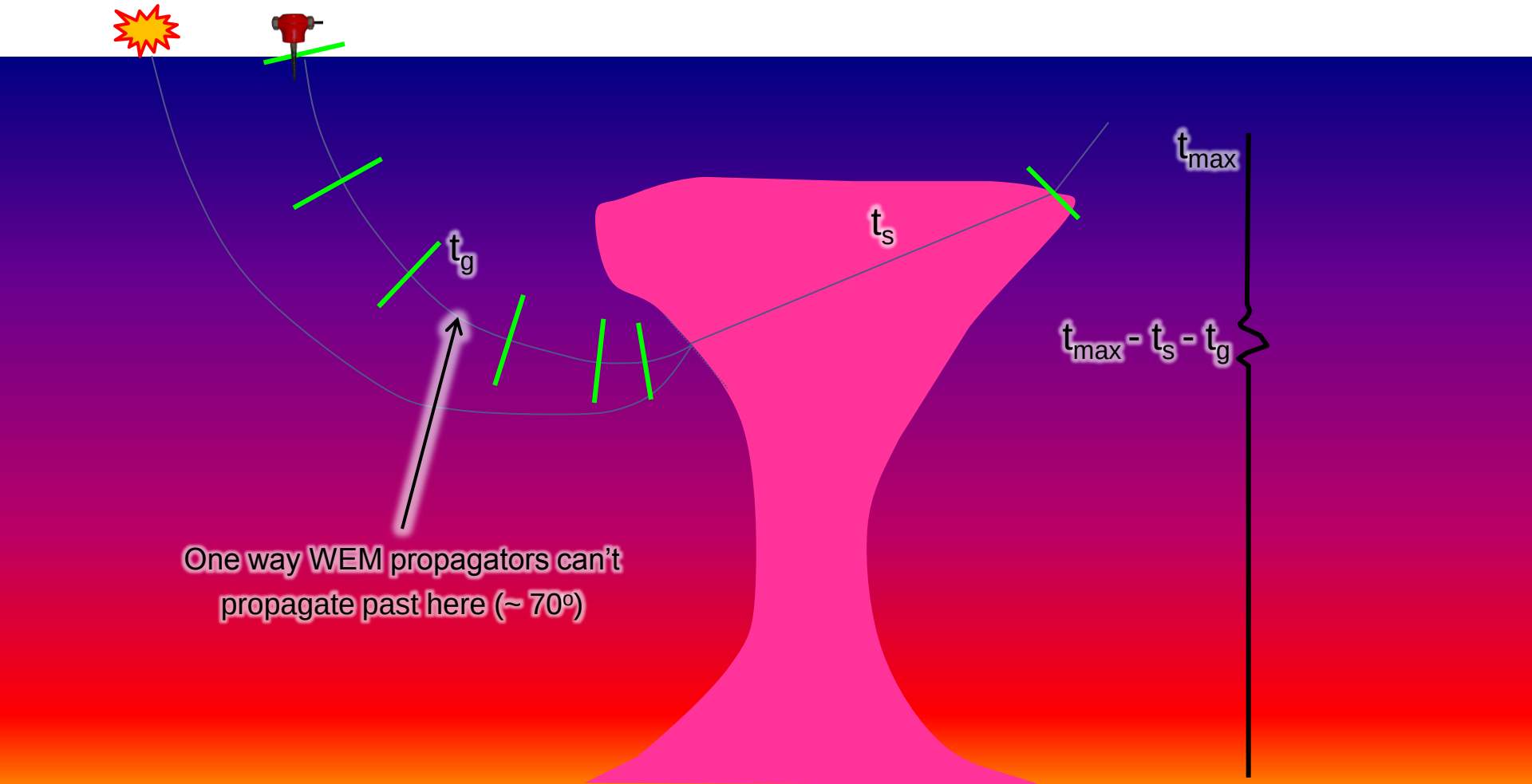
# RTM Tutorial

This animation shows a wave propagating from the surface, "overturning", and reflecting from an inverted salt flank. The time taken to propagate from source to target is $t_s$; from target to receiver is $t_g$.



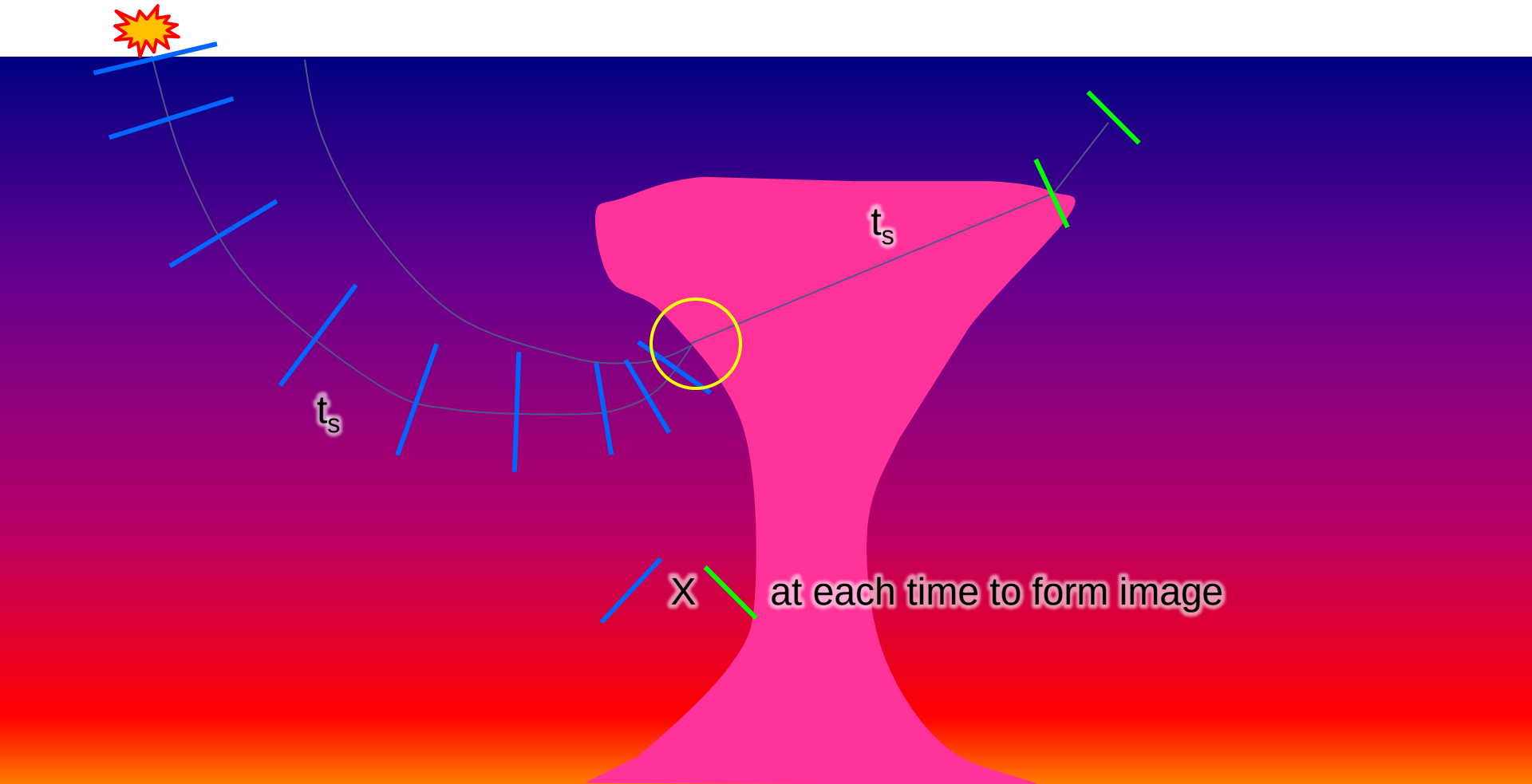
# RTM Tutorial

Next, we "flip" the trace in time (hence the name "reverse time migration") and use the flipped trace as a source function for modeling. The recorded event is injected into the earth at time $t_{max} - t_s - t_g$. It reaches the salt interface at time $t_g$ and propagates for a further time $t_s$ before reaching the maximum time.

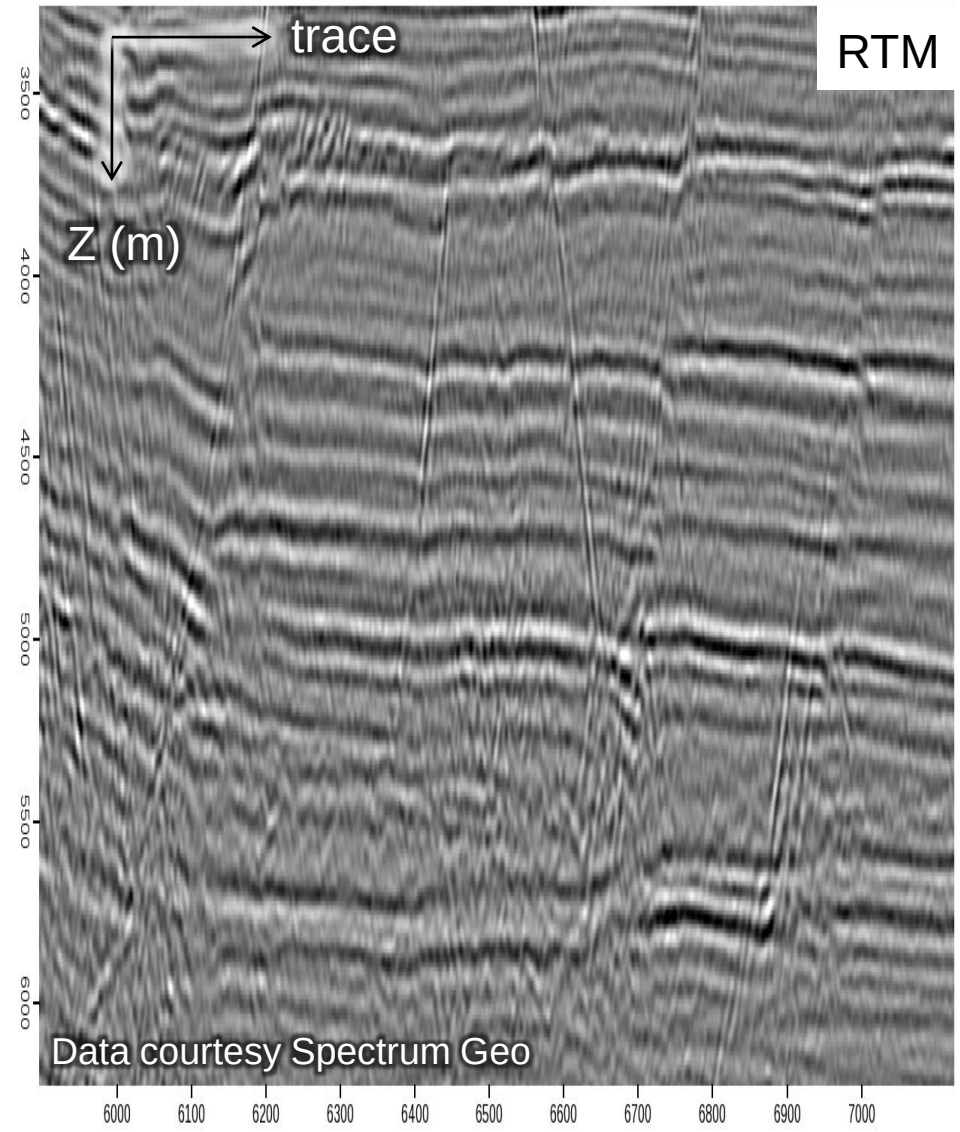


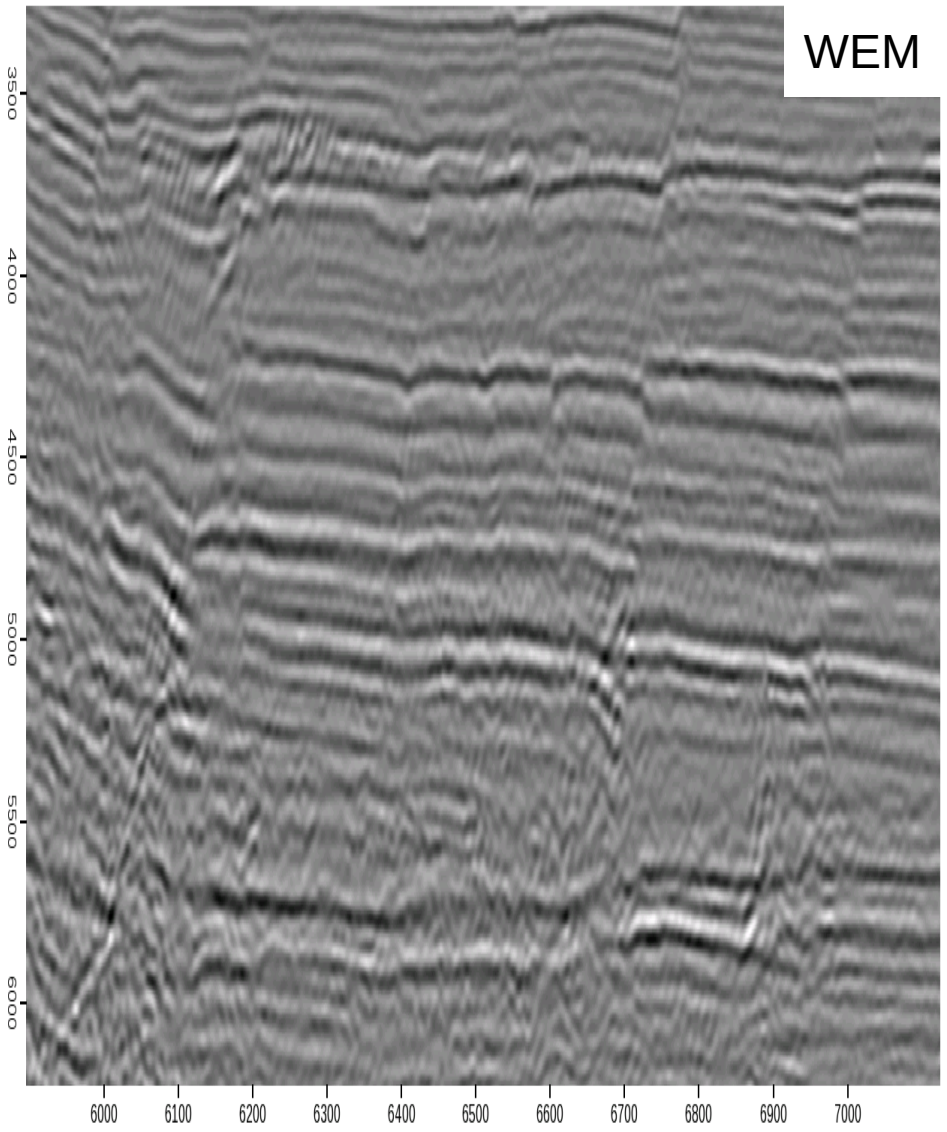
# RTM Tutorial

Next we propagate a synthetic source function into the earth. We also "back propagate" the receiver wavefield in time. At each time step, we multiply the source and receiver wavefields to form an image. **Here is the key to RTM: both the source and receiver wavefields are $t_s$ seconds from the salt face. We automatically form an image!**

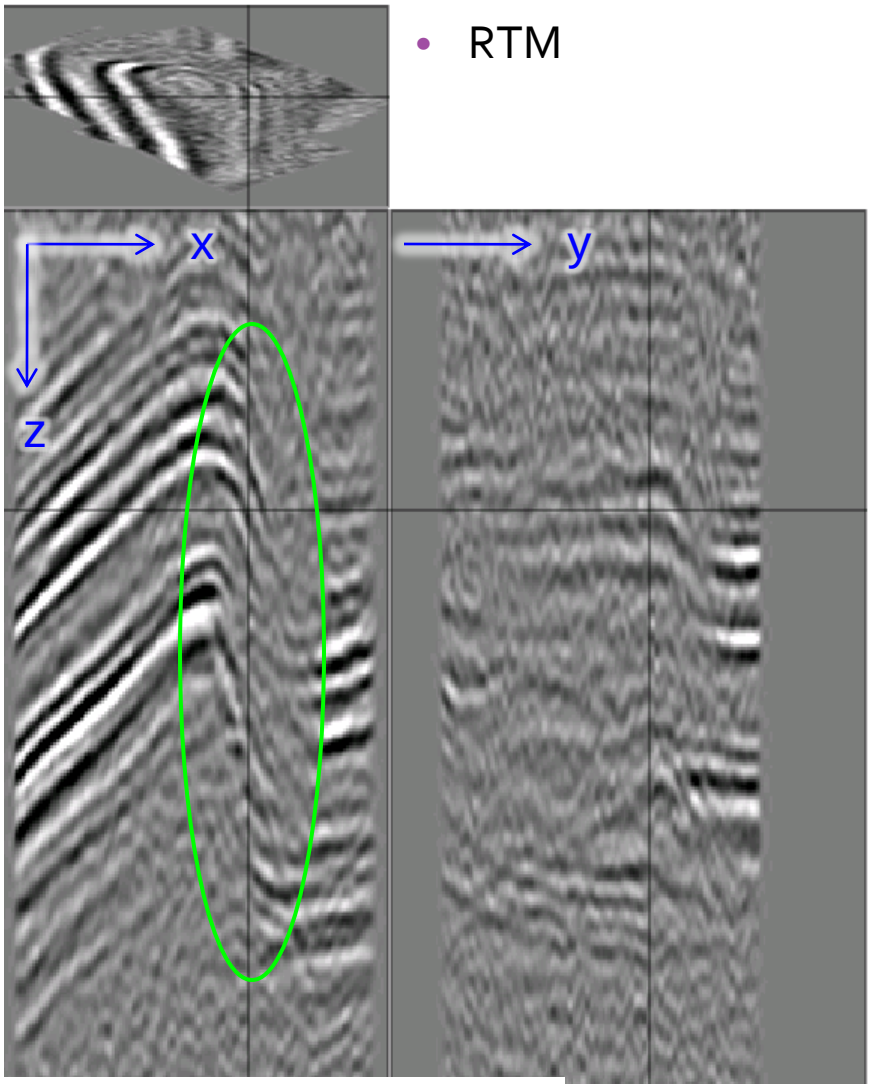


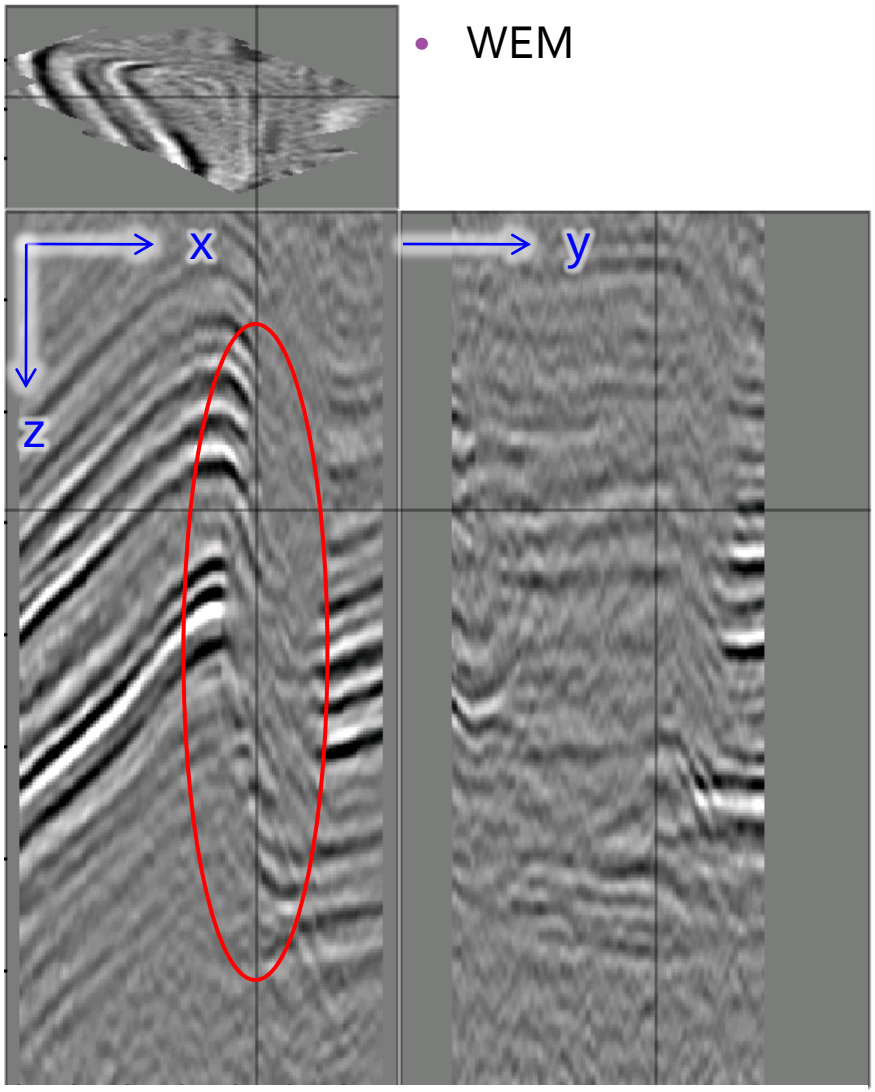
# Florida RTM


trace
Z (m)
RTM
3500
4000
4500
5000
5500
6000
Data courtesy Spectrum Geo
6000
6100
6200
6300
6400
6500
6600
6700
6800
6900
7000


WEM
3500
4000
4500
5000
5500
6000
6000
6100
6200
6300
6400
6500
6600
6700
6800
6900
7000

# Wyoming RTM

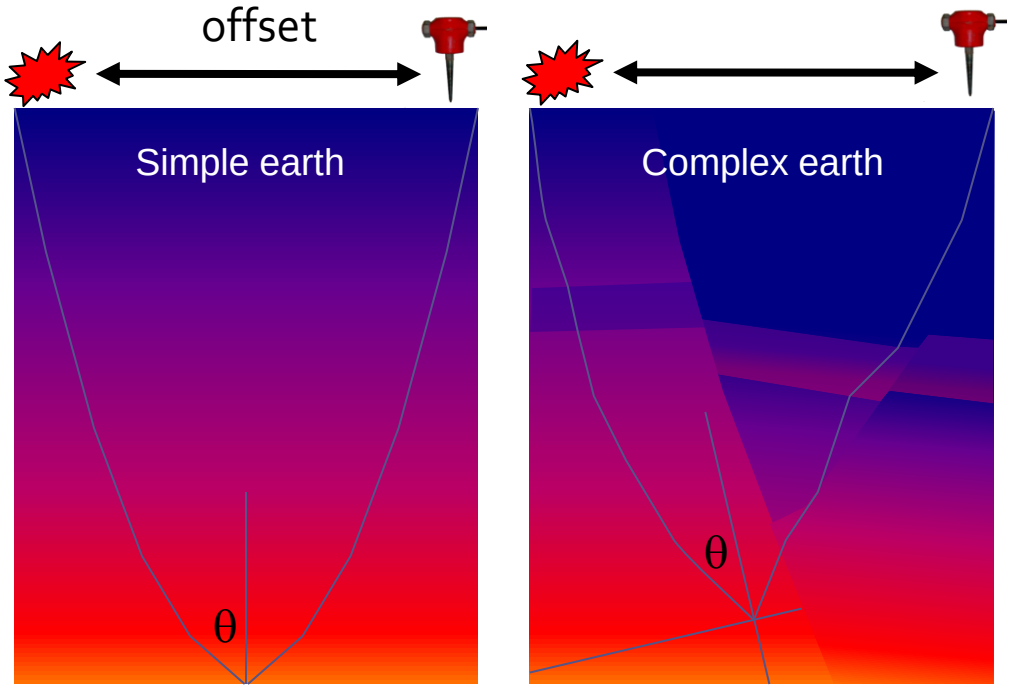


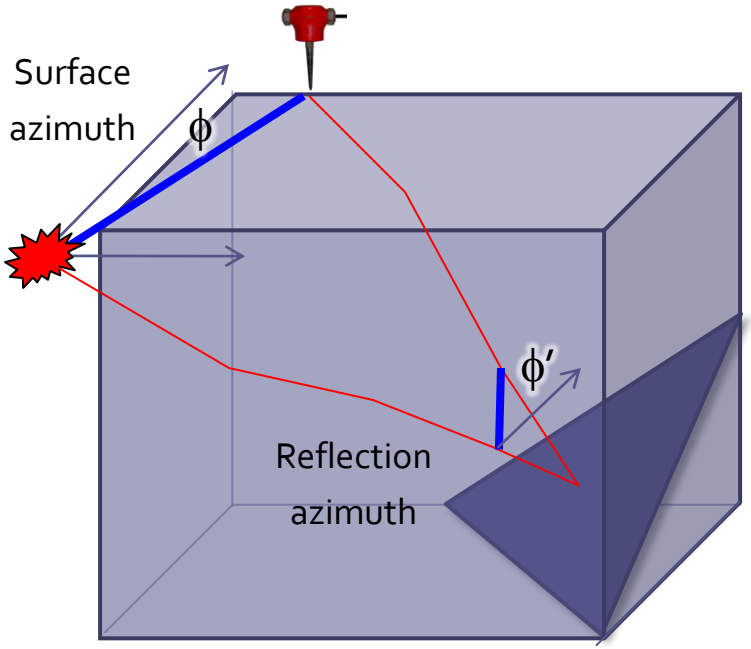

Data courtesy Nadel & Gussman, Rockies

# Rock Physics Attributes from WEM Angle Gathers

# AVO/Fracture attributes in complex geology




AVO: In a complex earth, surface offset is no longer a good proxy for incidence angle θ at the reflector

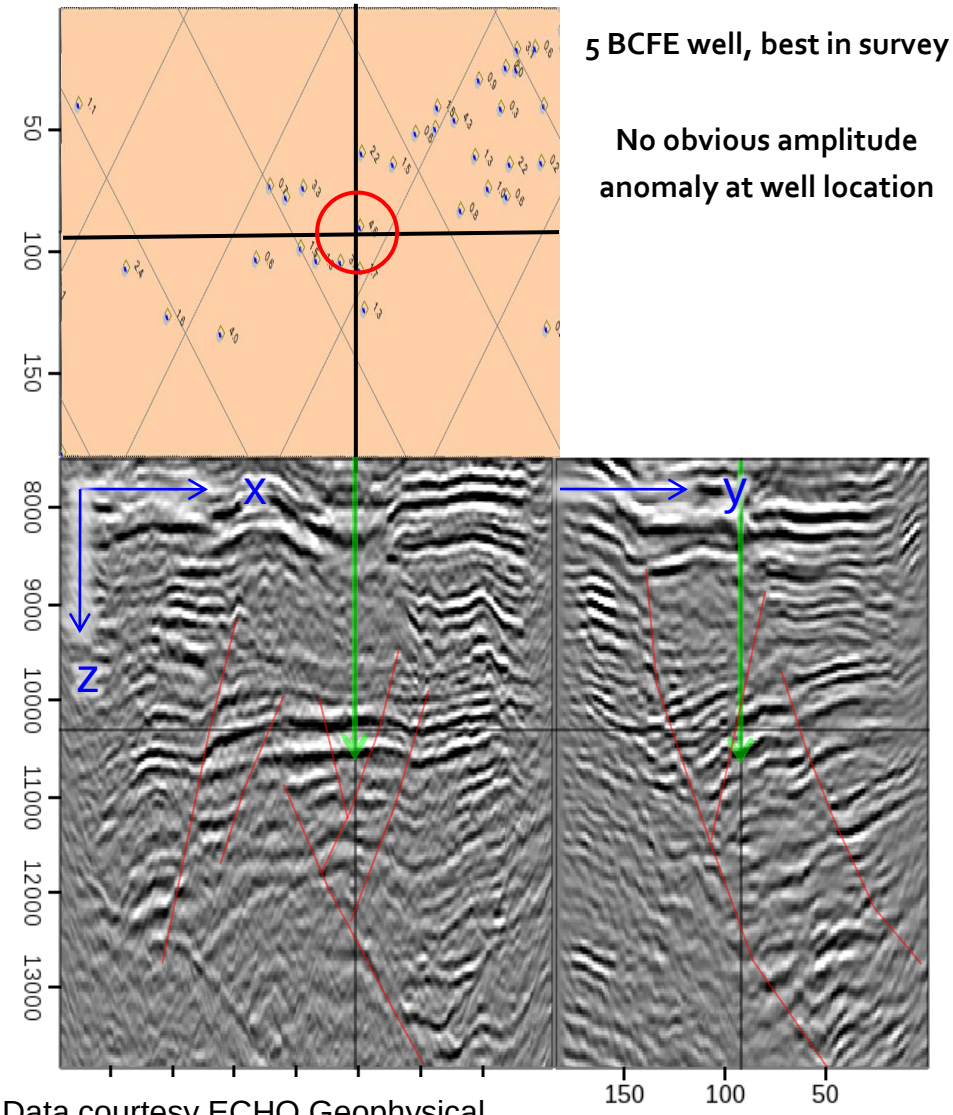



Azimuthal Fracture analysis: surface azimuth ϕ is not a good proxy for reflection azimuth ϕ′ in the presence of lateral velocity variation or "3D" dip.

# Improved AVO/Fracture attributes

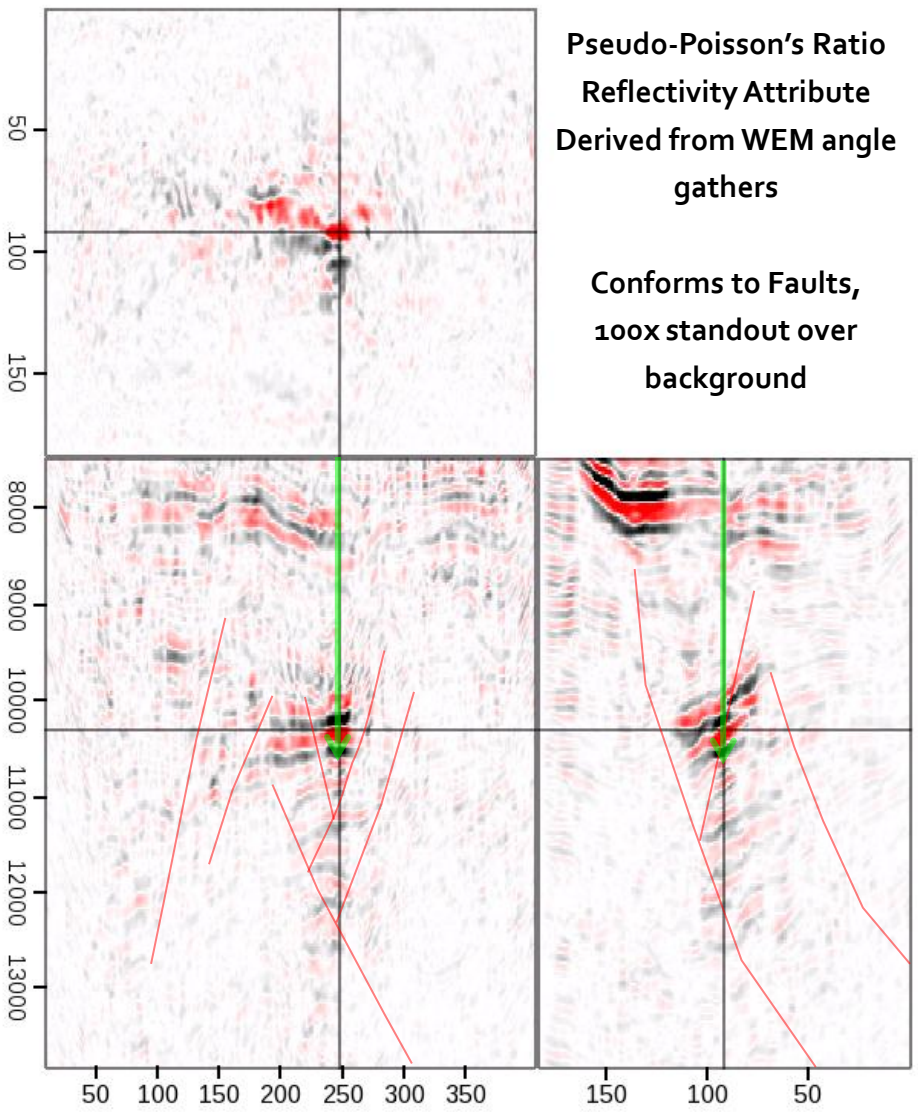
- WEM Angle Gathers
- Measure incidence angle or azimuth angle *at the reflector*, not at the surface
- More accurate AVA, more accurate fracture characterization
- Highly efficient algorithm

# Attributes from Angle Gathers




5 BCFE well, best in survey

No obvious amplitude anomaly at well location



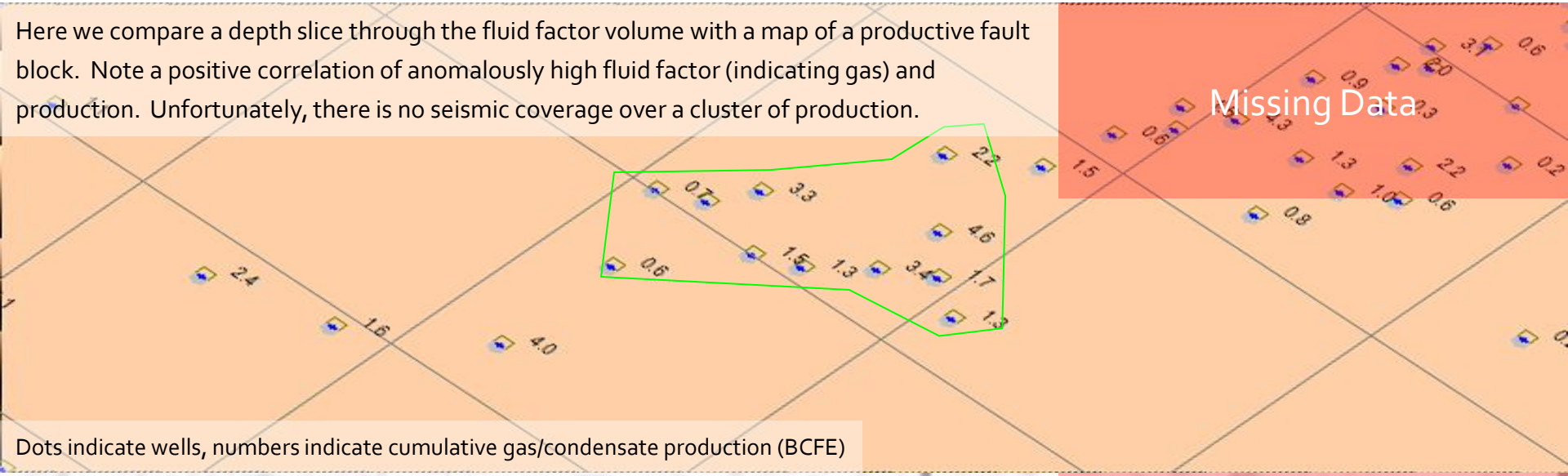

Pseudo-Poisson's Ratio Reflectivity Attribute Derived from WEM angle gathers

Conforms to Faults, 100x standout over background

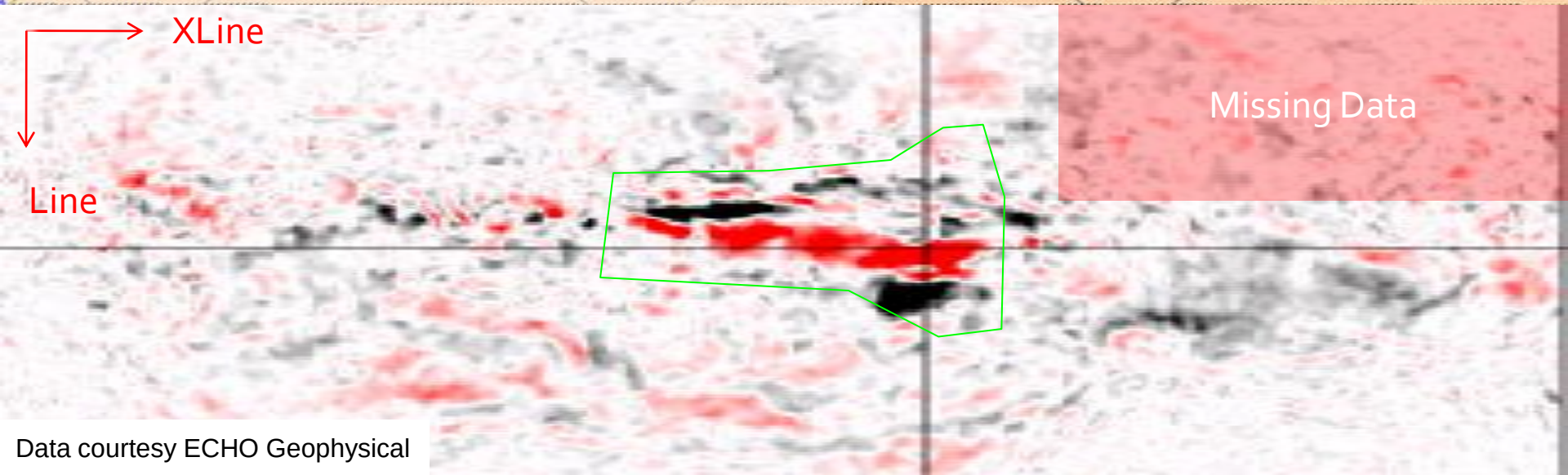
Data courtesy ECHO Geophysical

# Attributes from Angle Gathers

Here we compare a depth slice through the fluid factor volume with a map of a productive fault block. Note a positive correlation of anomalously high fluid factor (indicating gas) and production. Unfortunately, there is no seismic coverage over a cluster of production.

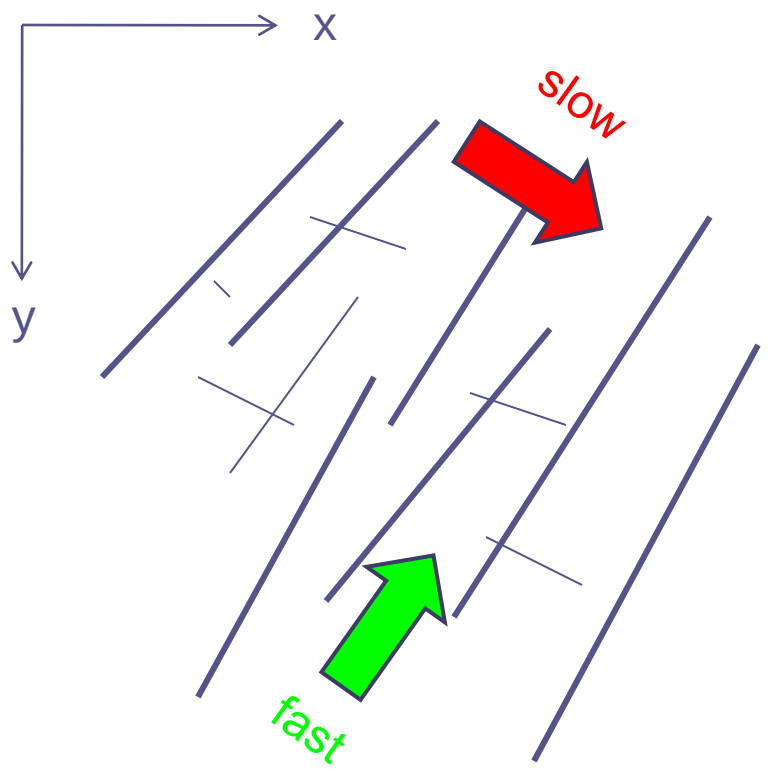


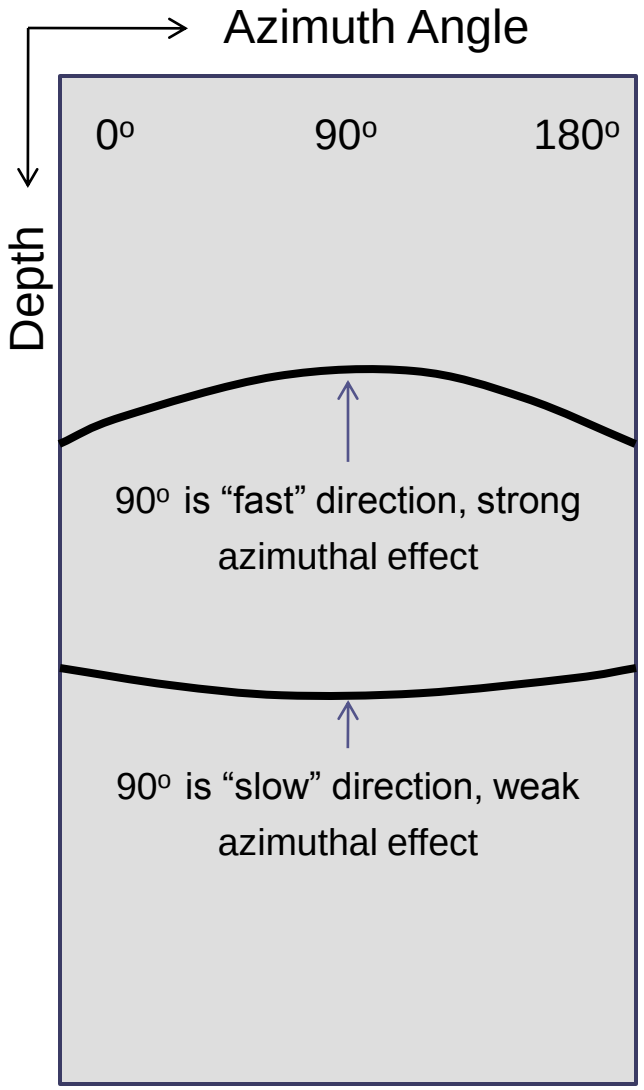

Dots indicate wells, numbers indicate cumulative gas/condensate production (BCFE)



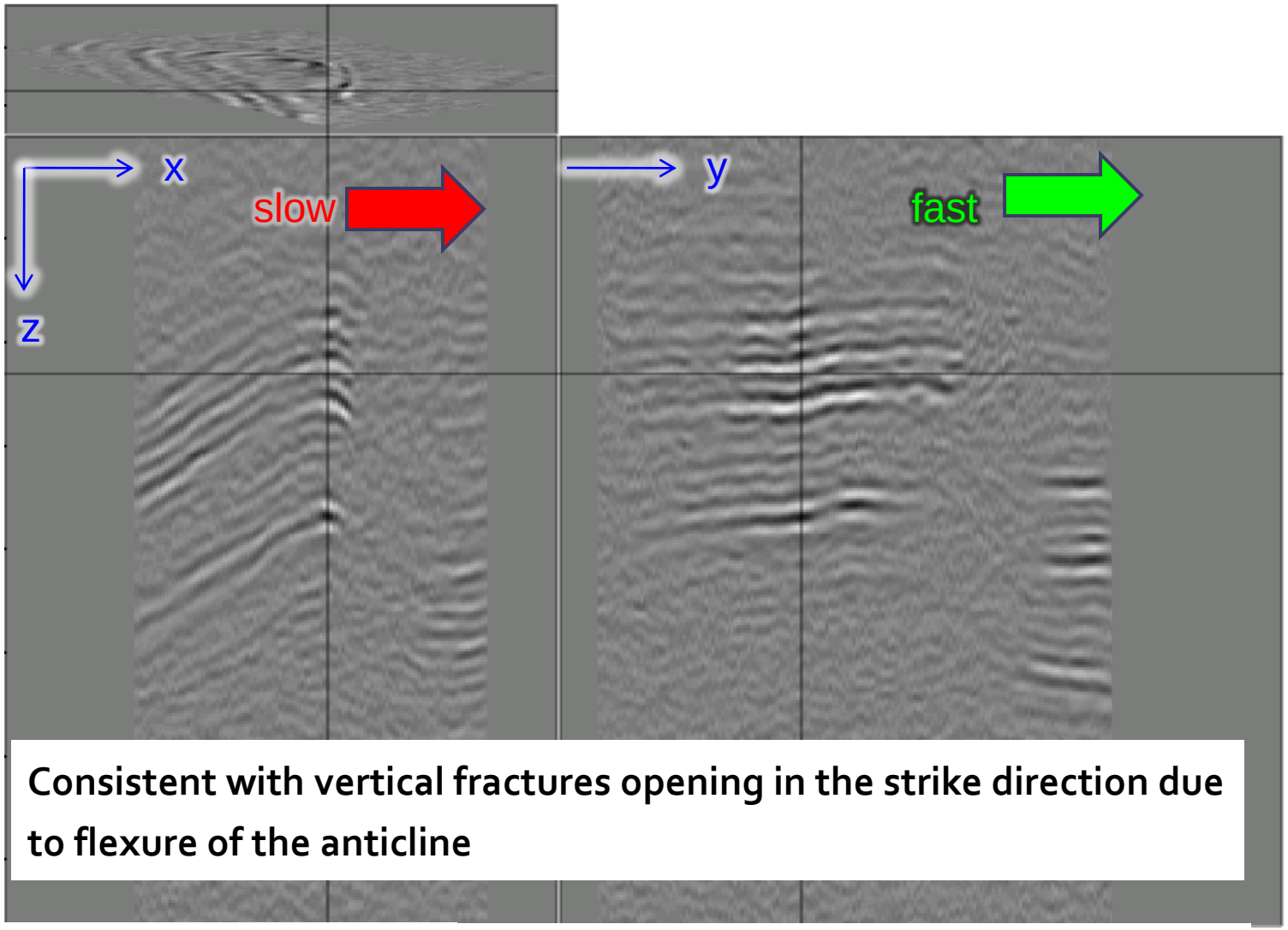

Data courtesy ECHO Geophysical

# Azimuthal fracture anisotropy

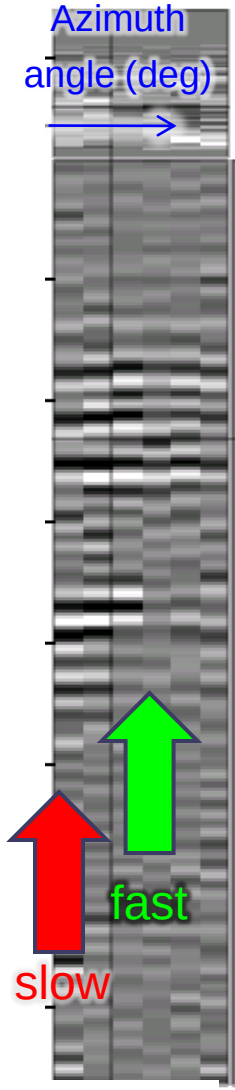


# Wyoming: Azimuth Angle WEM

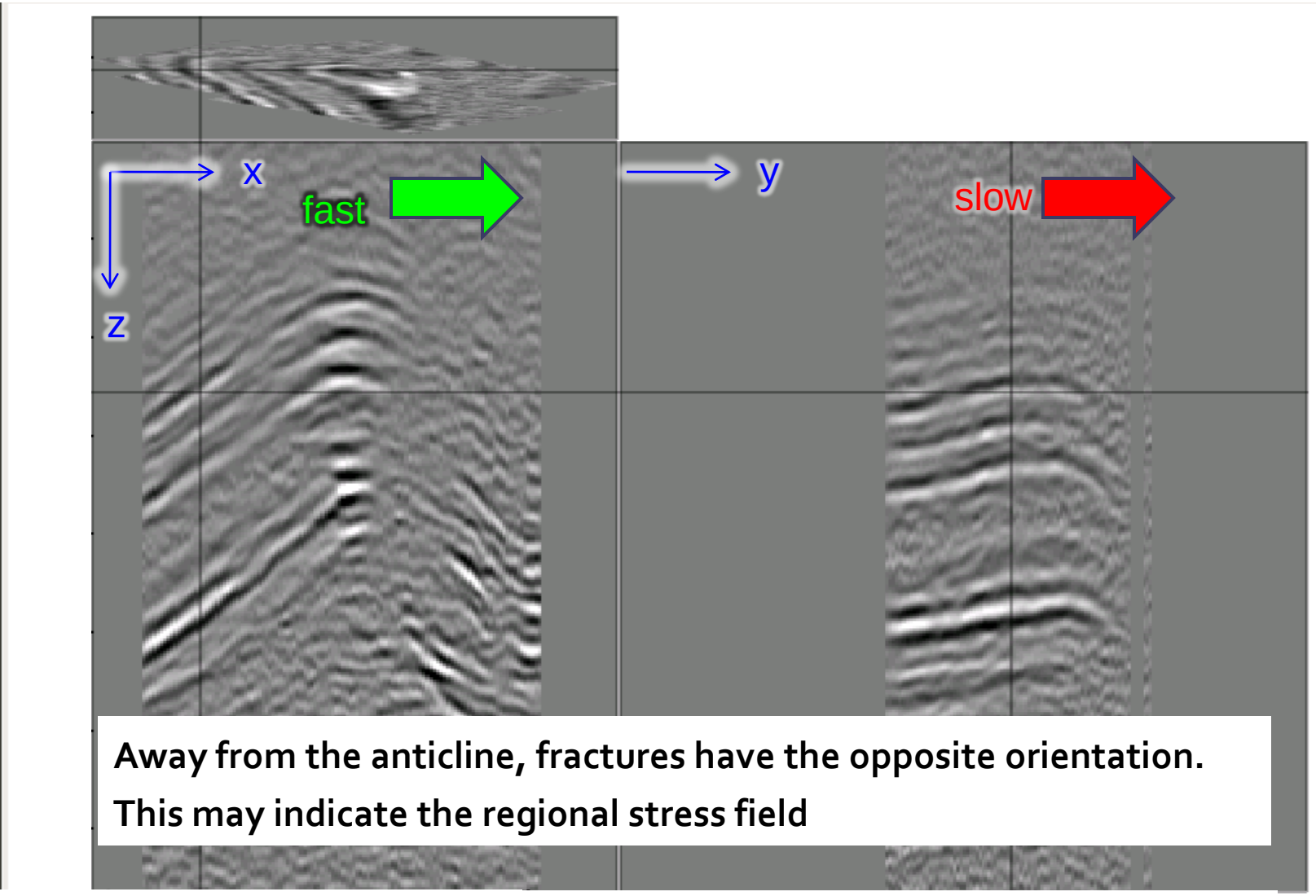


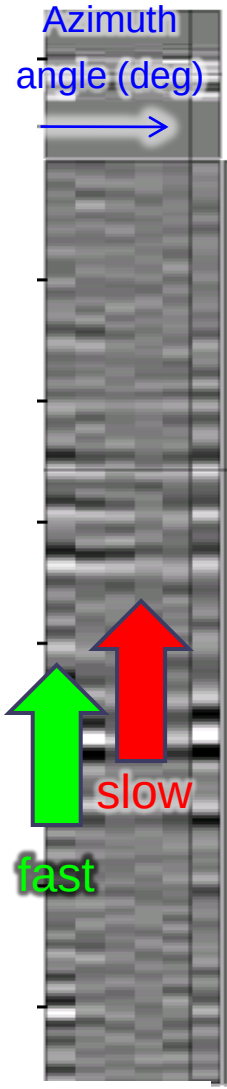

Consistent with vertical fractures opening in the strike direction due to flexure of the anticline




Data courtesy Nadel & Gussman, Rockies

# Wyoming: Azimuth Angle WEM




Away from the anticline, fractures have the opposite orientation.
This may indicate the regional stress field

Data courtesy Nadel & Gussman, Rockies

# Conclusions

- Intensive depth velocity estimation: the key to aligning PSDM theory and practice

- Reduced exploration risk from PSDM:
  - More accurate reflector position/attitude
  - Improved fault resolution
  - Improved event focusing
  - Drill in depth, see in depth

- RTM: Best of Kirchhoff and WEM
- WEM angle gathers: more accurate attributes

# Acknowledgements


- Whiting Petroleum (Larry Rasmussen, Pat Winkler, Scott Haberman)
- Nadel & Gussman, Rockies (Rick Morris, Greg Chapel, Lee Robinson)
- ECHO Geophysical
- Spectrum Geo
- The WIT team: Joe Higginbotham, Cosmin Macesanu, Jo Ottaviano, Oscar Ramirez
- Bob Clapp (Stanford)
- Doug Robinson