Developments in AVO and 4D Statistical Inversion

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Outline

- fundamentals of statistical inversion
- rock property model
- AVO and 4D model
- statistical AVO and 4D implementation
- results on a synthetic dataset

Applicability of AVO and 4D inversion

- AVO with tuning
- multiple surveys
- uncertainty estimate
- probability of different geologic scenarios

Statistical inversion solves for probability of model

petrophysics
(trend curves,
neural networks)

$P(m|d_{petro})$ = probability of model given petrophysical data

seismic

$q_{<n>}(n)$ = noise distribution

$= \exp(-\Sigma\, n_k^2 / <n_k>^2)$

$s(m)$ = synthetic seismic given model (forward modeling)

$d_{seismic}$ = seismic data

==> $P(d_{seismic}|m) = q_{<n>}(d-s(m))$
= probability of seismic given the model

$$P(m|d_{seismic},d_{petro}) \sim P(d_{seismic}|m)\ P(m|\,d_{petro})$$

Iterative solution for N equally probable models

construct a sequence { $P_n(m)$ } such that

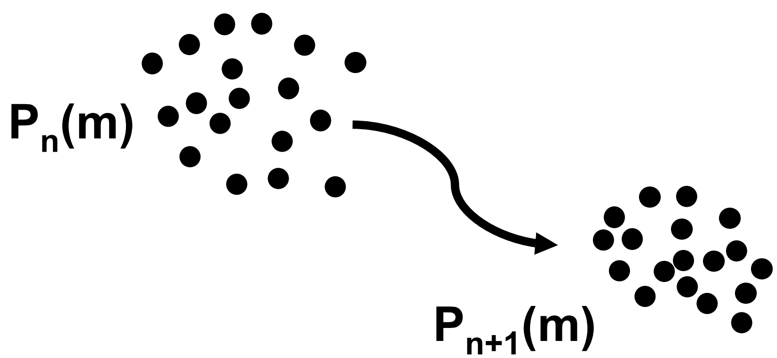
$$P_n(m) \rightarrow P(\, m \mid d \,) \quad \text{as} \quad n \rightarrow \infty,$$

$$P_0(m) = P(m),$$

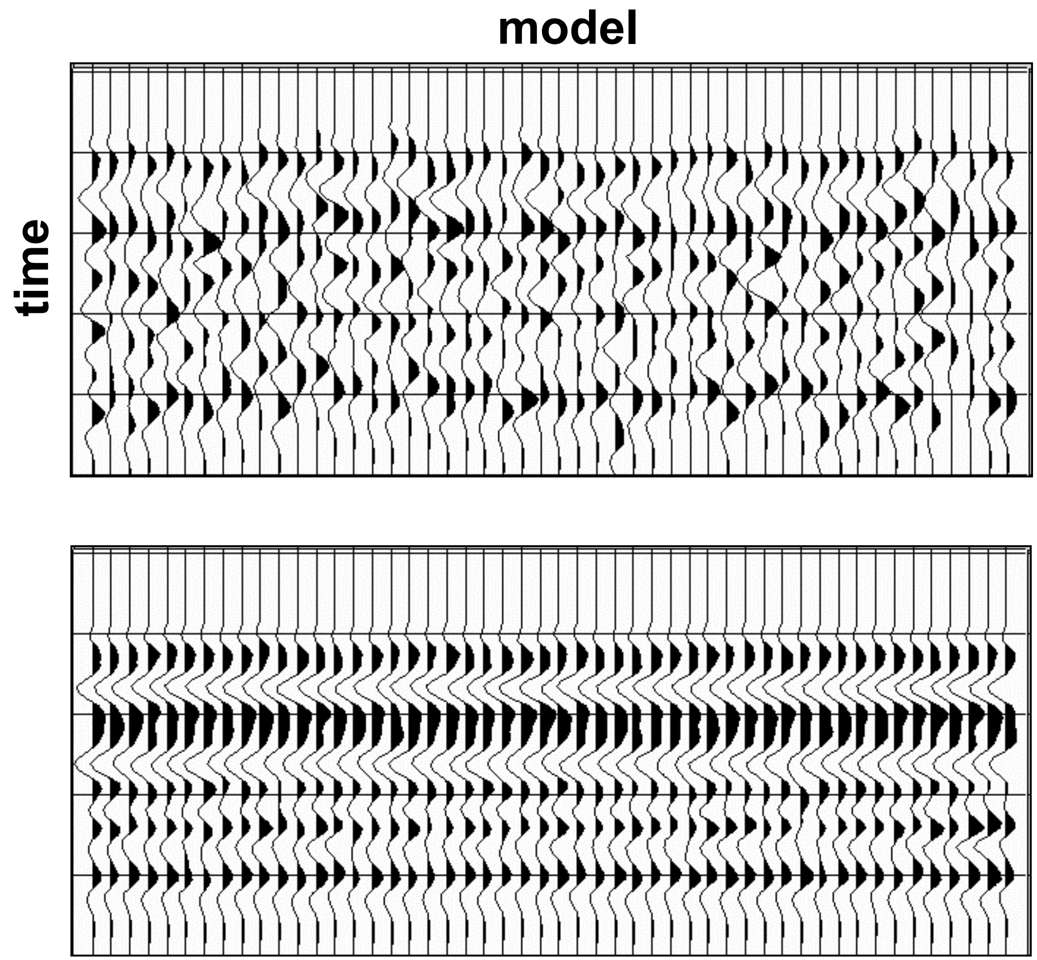
and

$$P_{n+1}(m) = \mathbf{F}(\, P_n(m) \,)$$

$\mathbf{F}$ = conjugate gradient or metropolis



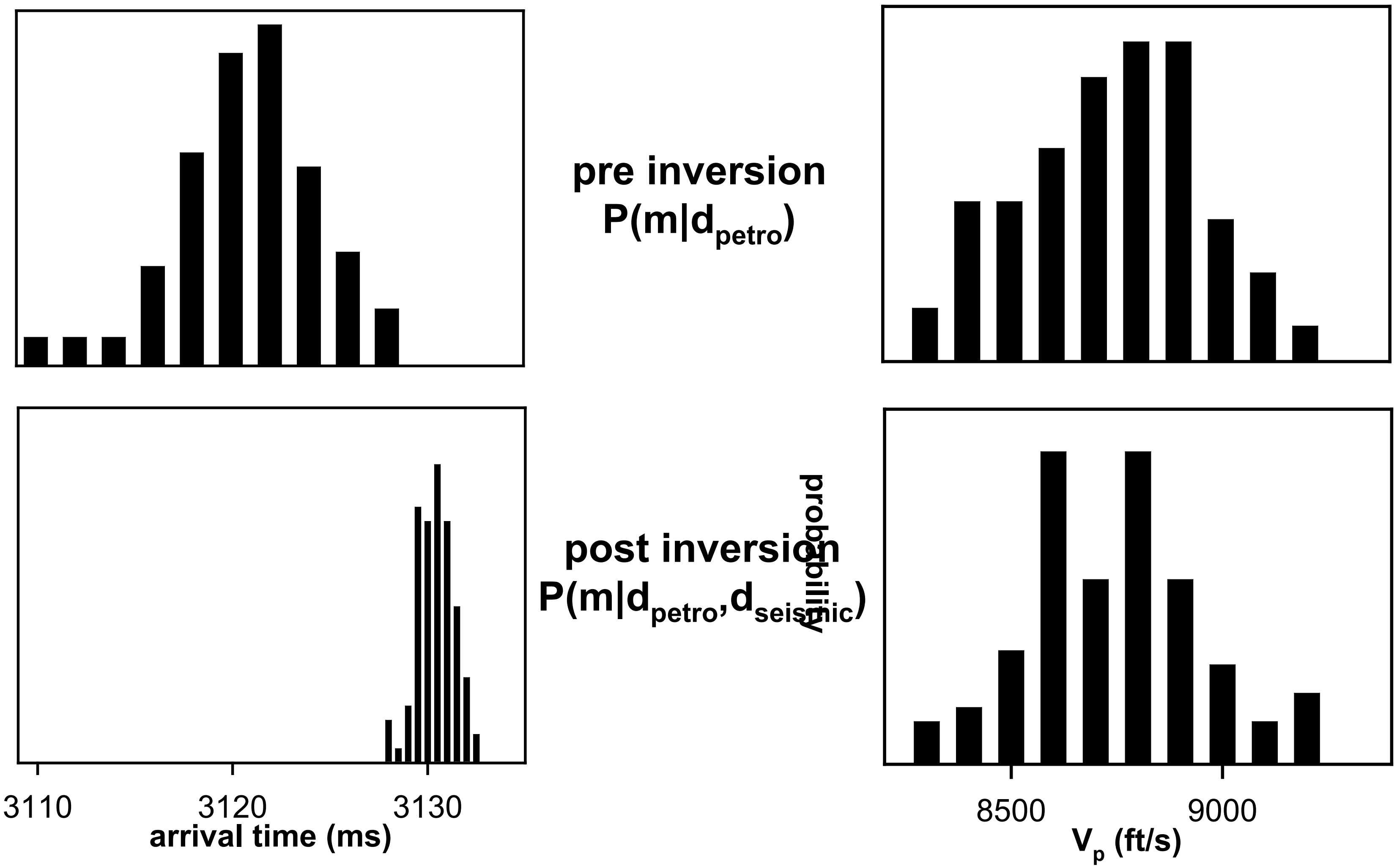
Inversion improves match with seismic data



pre inversion
$P(m|d_{petro})$

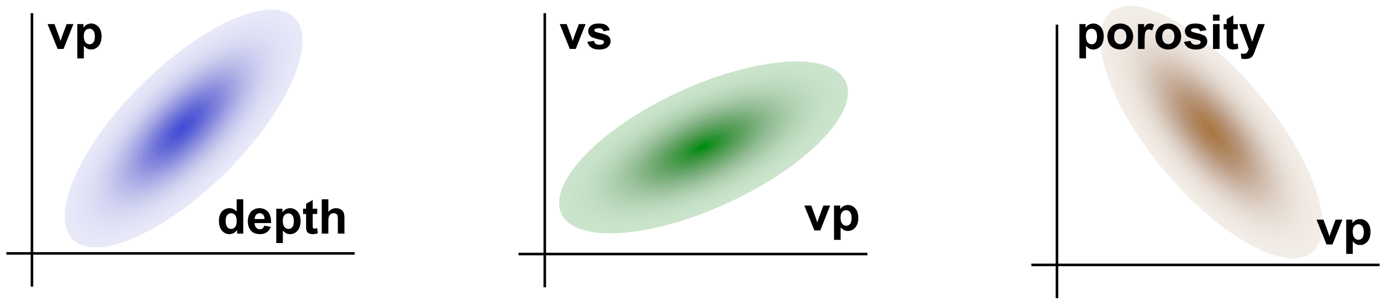
post inversion
$P(m|d_{petro},d_{seismic})$

Inversion improves estimate of some reservoir properties



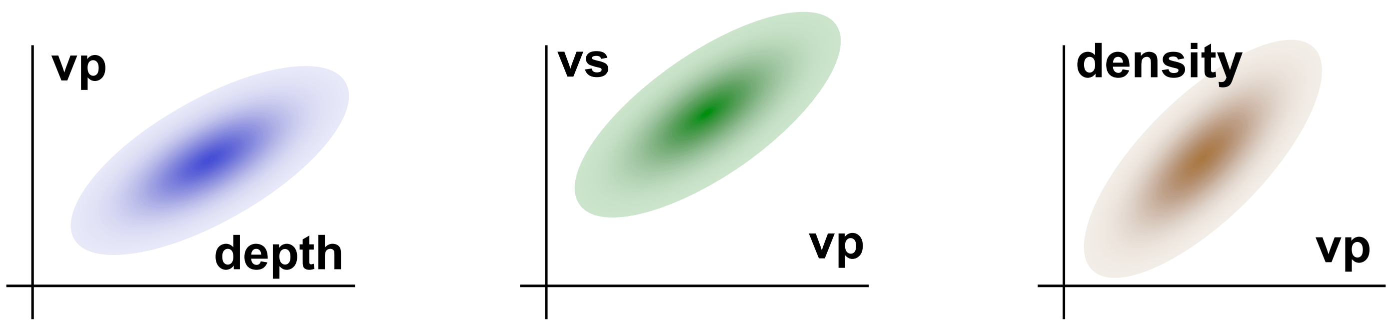
GOM petrophysical end member trends used in prior probability

wet sand



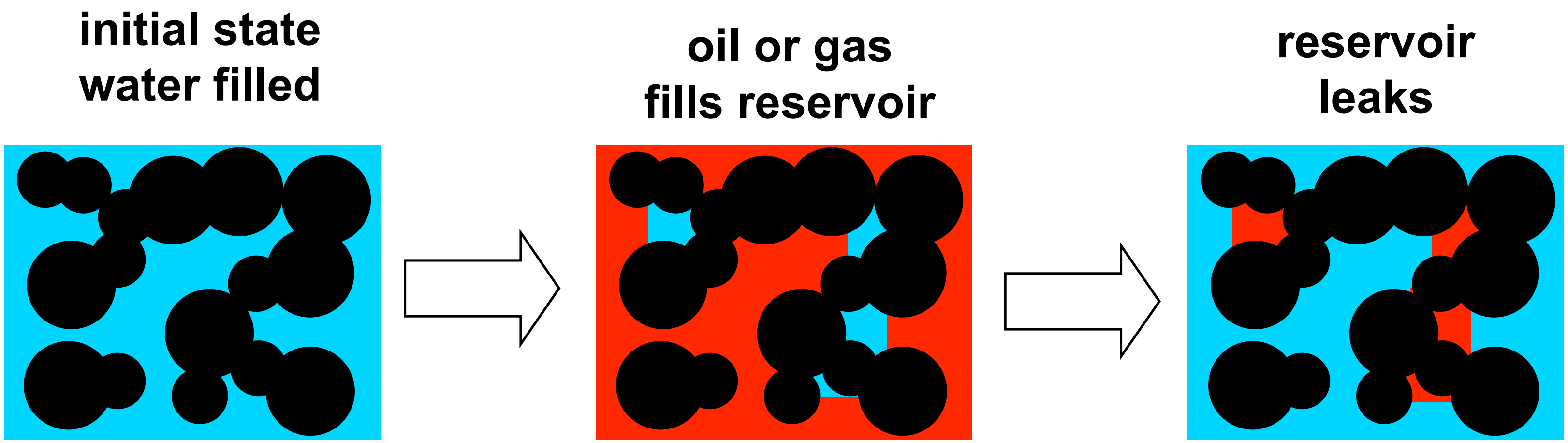
mix with net/gross ± σ

mud-stone



note: separate trend for each layer

Discrete cases of fluid fill are used

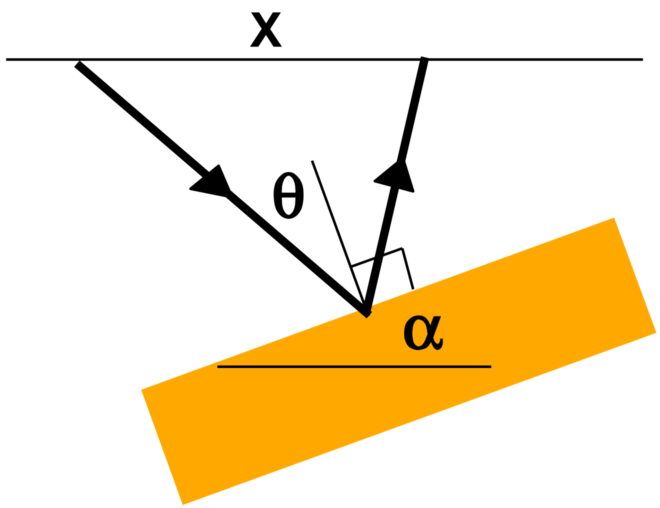


- **prior probability of each fluid fill case**
  - neural network fluid prediction
  - regional information (trap probability, leak probability, etc.)
- **posterior probability of each fluid fill case**
  - adds seismic AVO information

A time migration approximation is used to model AVO

expansion in (X / V T) and (V dT/dx) << 1

where, X = offset
V = migration velocity
T = migrated time of reflector
x = migrated subpoint
v = interval velocity



θ = (v/V) (X / V T) + 3rd order

α = 0.5 (V dT/dx) + 3rd order

Equations that are used to model AVO

reflection coefficient

$$R(X) = A\,L + B\,M\,\overbrace{(v/V)^2\,(\,X / V\,T\,)^2}^{\sin^2\theta} + \text{4th order}$$

wavelet stretch

$$S(X) = 1 + \overbrace{0.5\,(\,X / V\,T\,)^2}^{\text{NMO}} + \overbrace{0.125\,(\,V\,dT/dx\,)^2}^{\text{dip}} + \text{4th order}$$

offset average wavelet & reflection coefficient

$$\text{wavelet} = W(\,X\,,\,t\,) = W_0(\,t / S(X)\,)$$

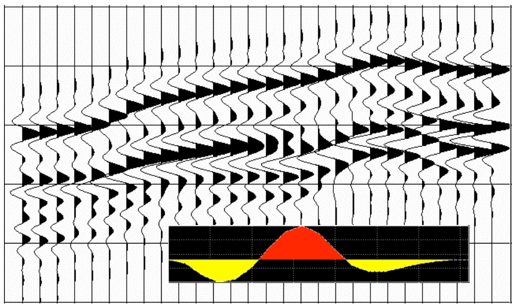
$$<R\,W>_X \;= \;<R>_X\,<W>_X + \text{4th order}$$

What effects are addressed in model

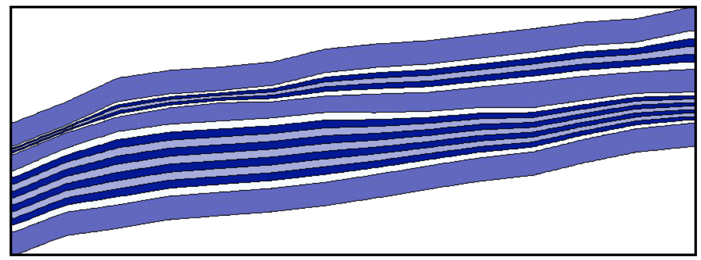
- amplitude variation with offset
- dip dependant NMO wavelet stretch
- background normal rotation
- buried absorbers and diffractors (statics)

Inputs to inversion

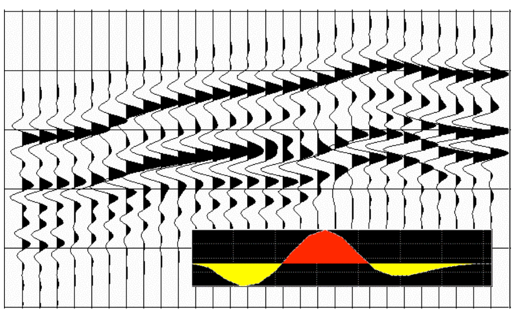
near stack and wavelet



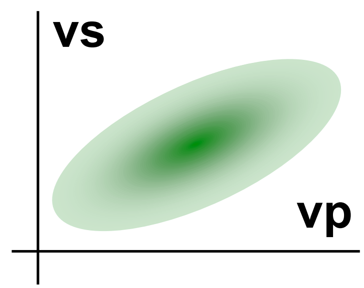
initial DepSim model



far stack and wavelet

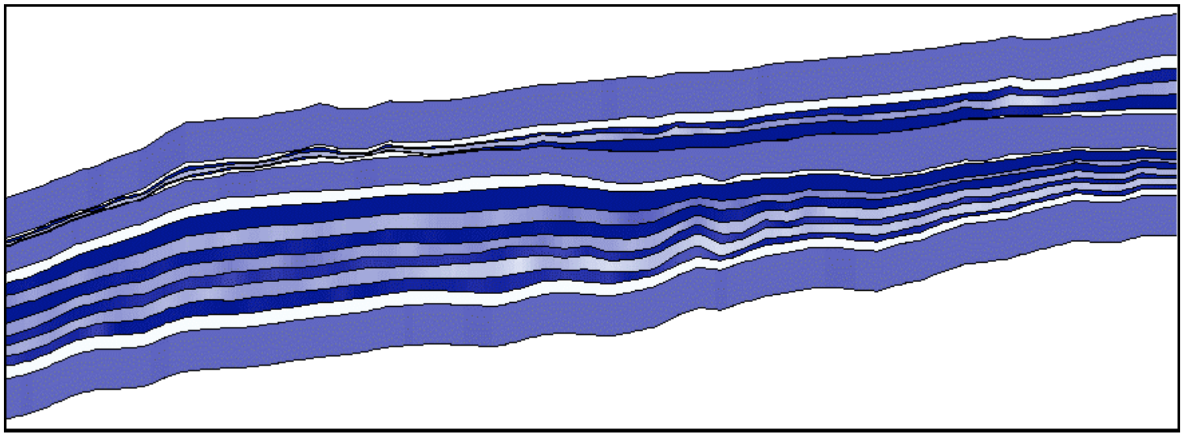


rock properties

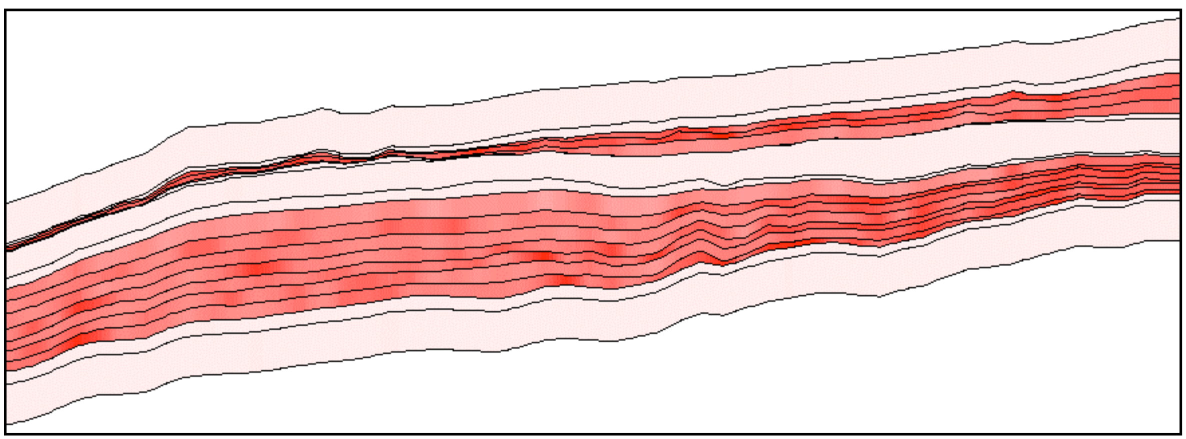


Output of inversion

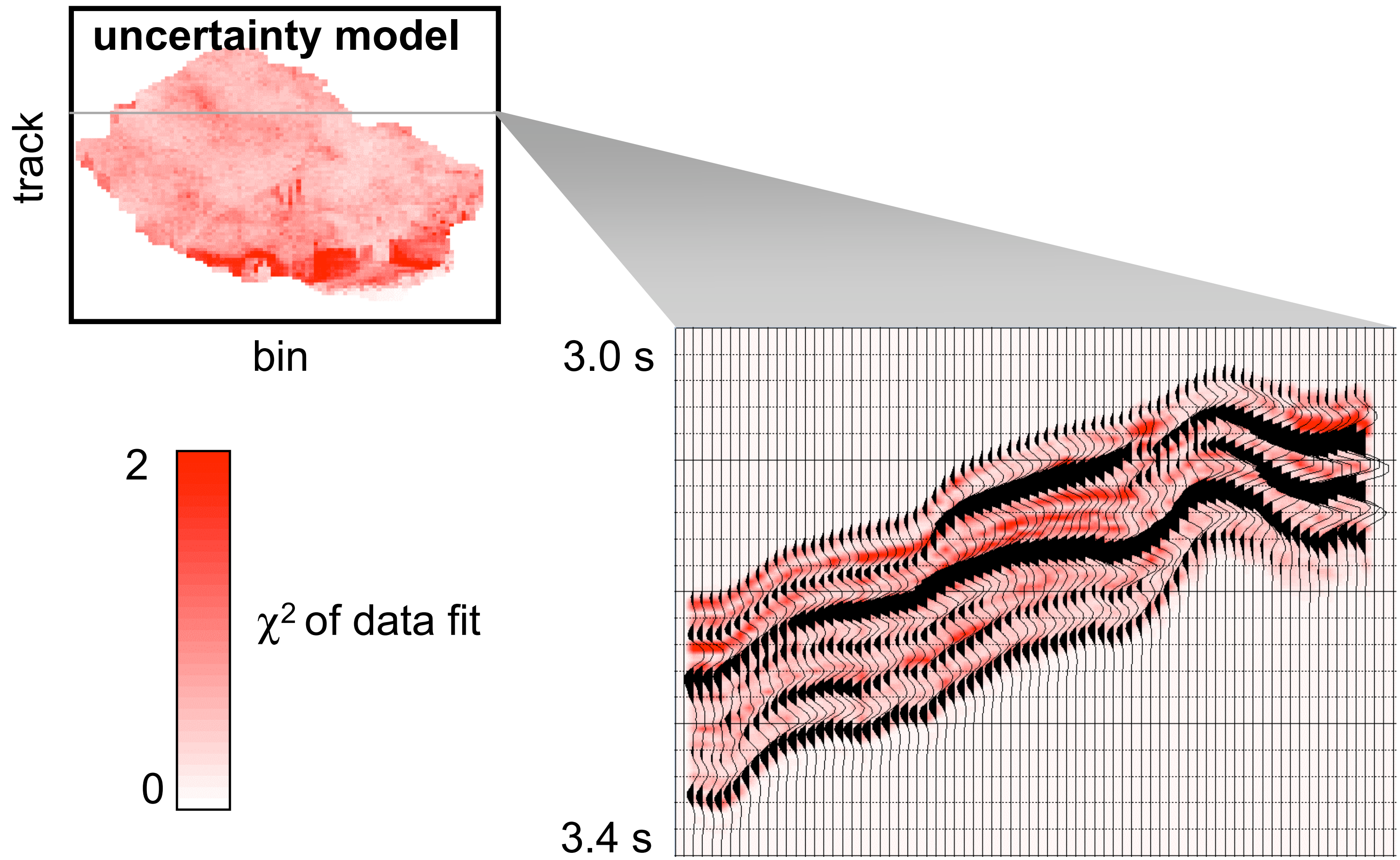
updated DepSim model



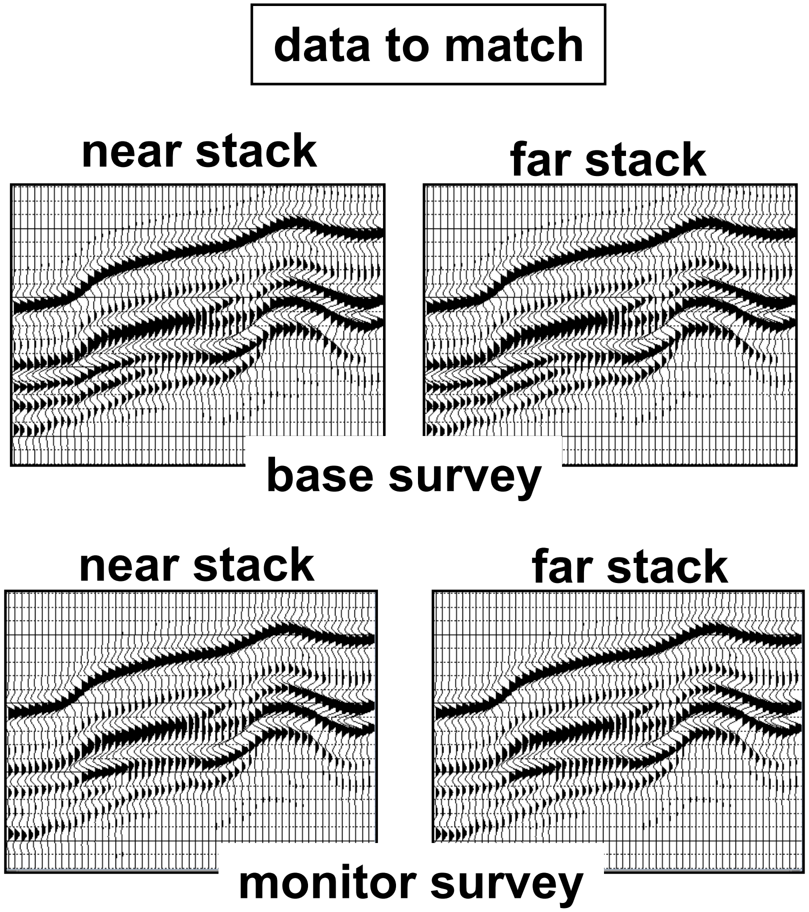
uncertainty in DepSim model

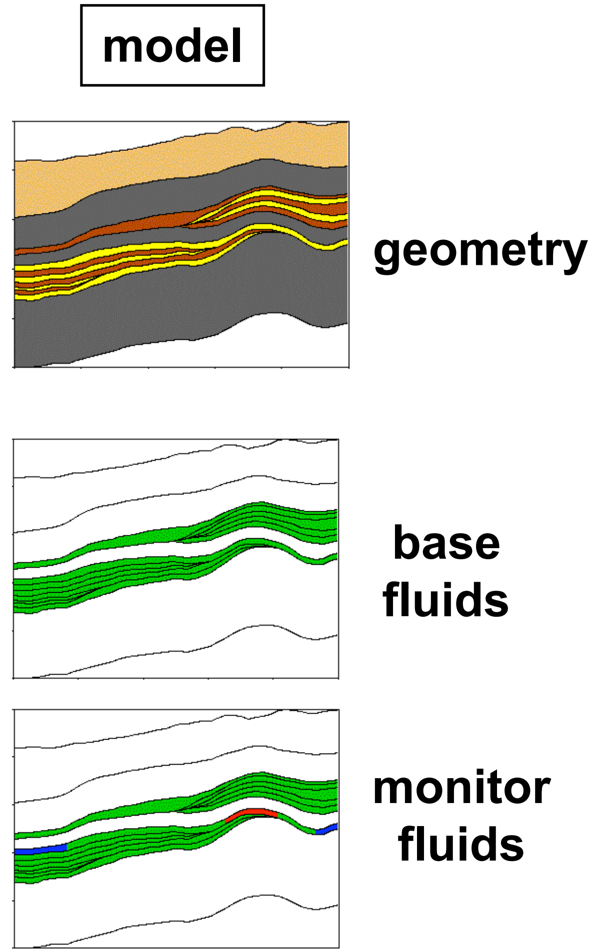


Some interesting and useful error estimates



Formalism has been extended to 4D inversion





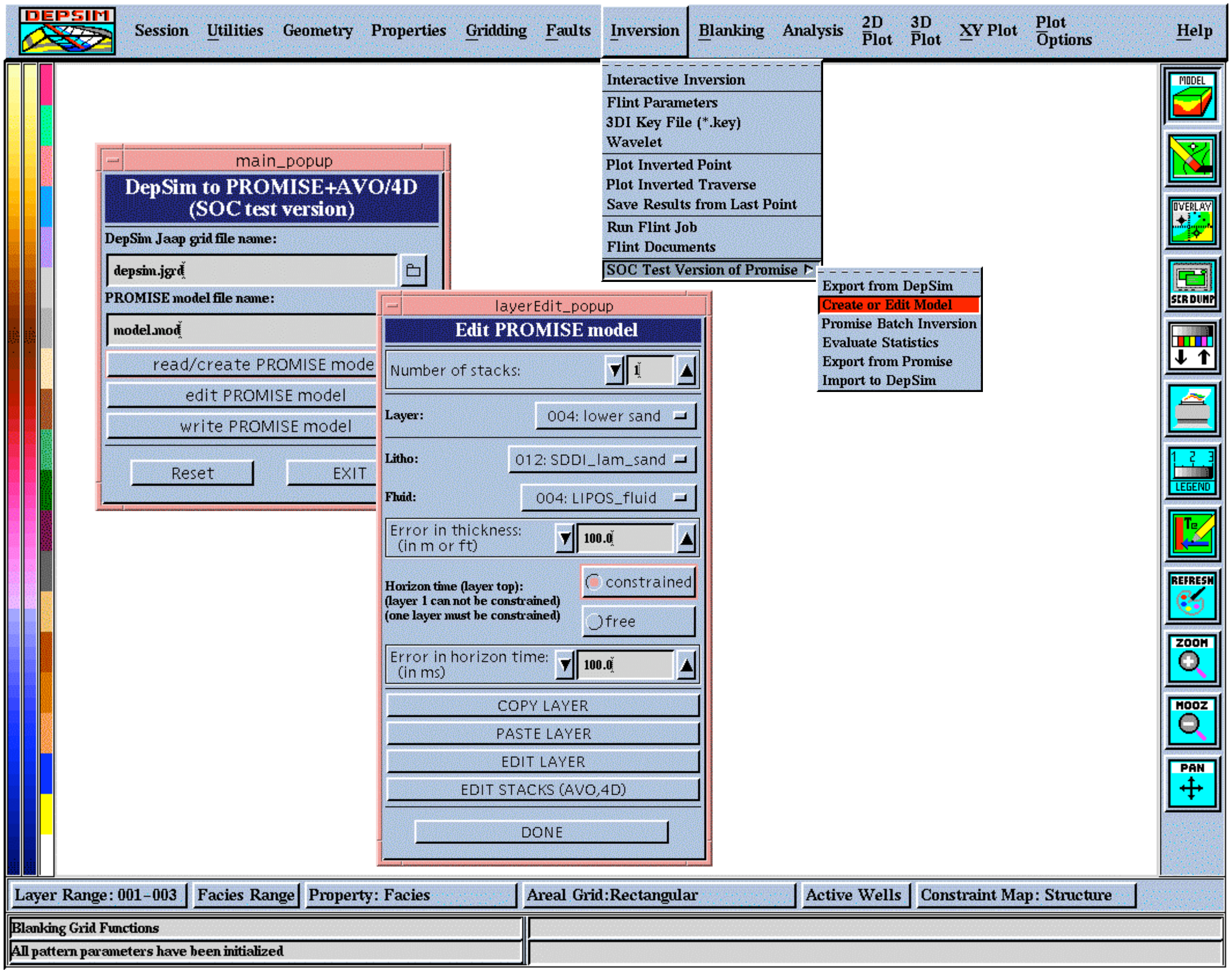
Possible justifications for 4D inversion

- **higher fidelity data preserved**
  - data equalization done via wavelet derivations
  - no degradation of higher fidelity data to match fidelity of earlier data
  - higher fidelity data determines structure
  - earlier data determines original fluid saturations
- **significance of results calculated**
  - errors
  - probabilities

Philosophy of development

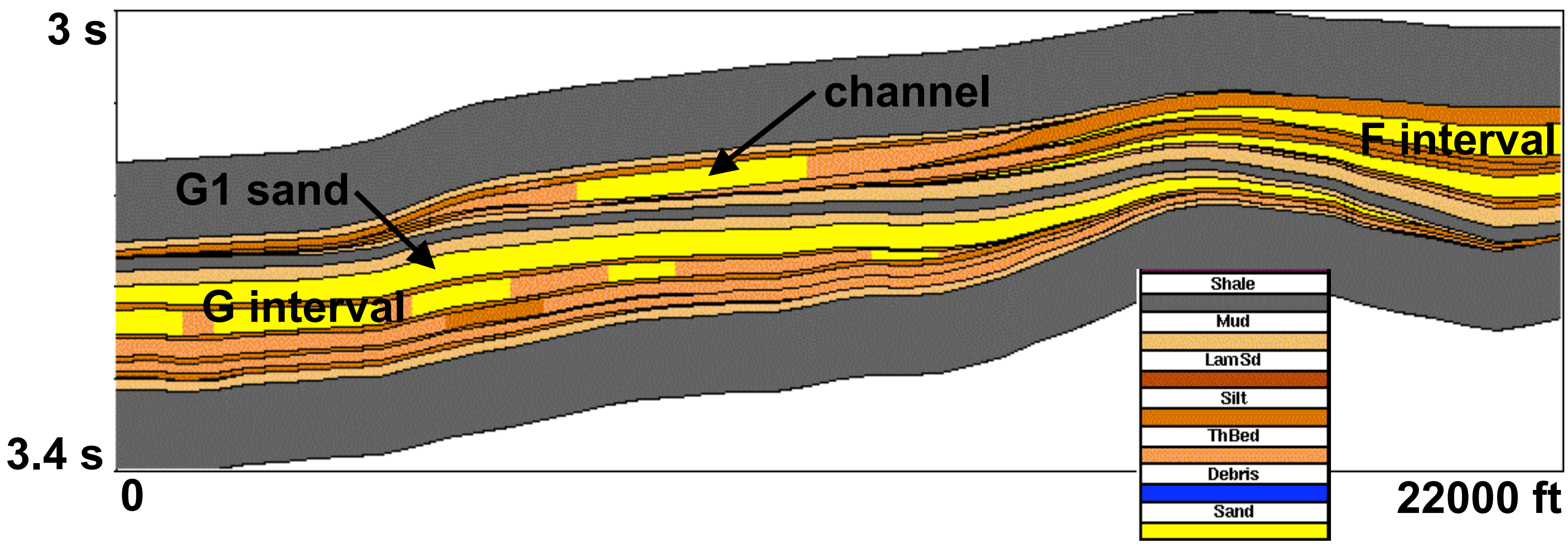
- **DepSim IO engine for PROMISE**
- **SPIRIT II wrapper on prototype PROMISE**
- **compatible and expandable**
  - AVOMOD
  - neural net (fluid prediction and beyond)
  - GOM petrophysics (trends and LIPOS)

Implementation of AVO inversion



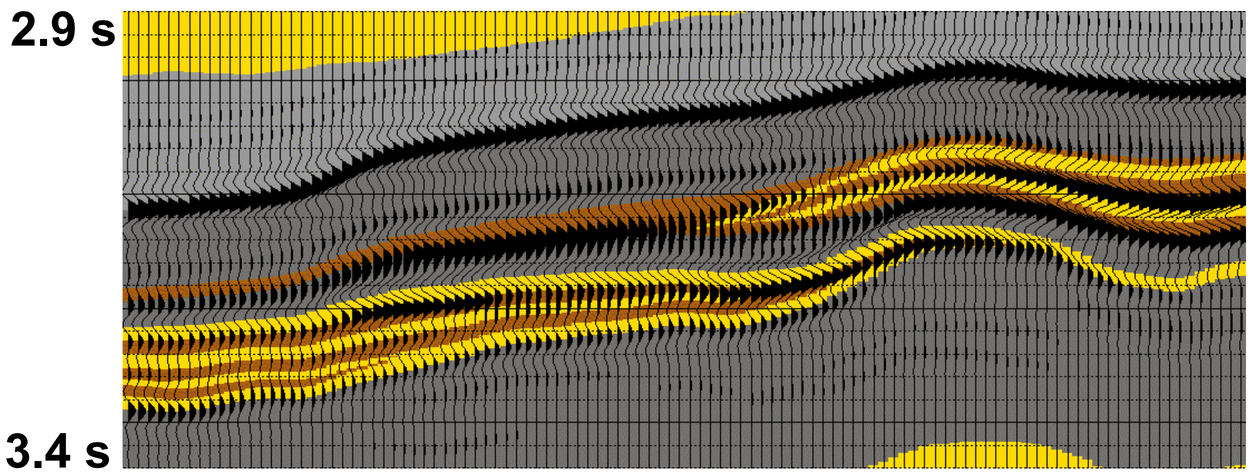
Uncertainty model - a testbed for inversion

- deepwater GOM, Ram-Powell structure
- typical turbidite sequence stratigraphy, 26 layers
- varying fluid in G1 sand

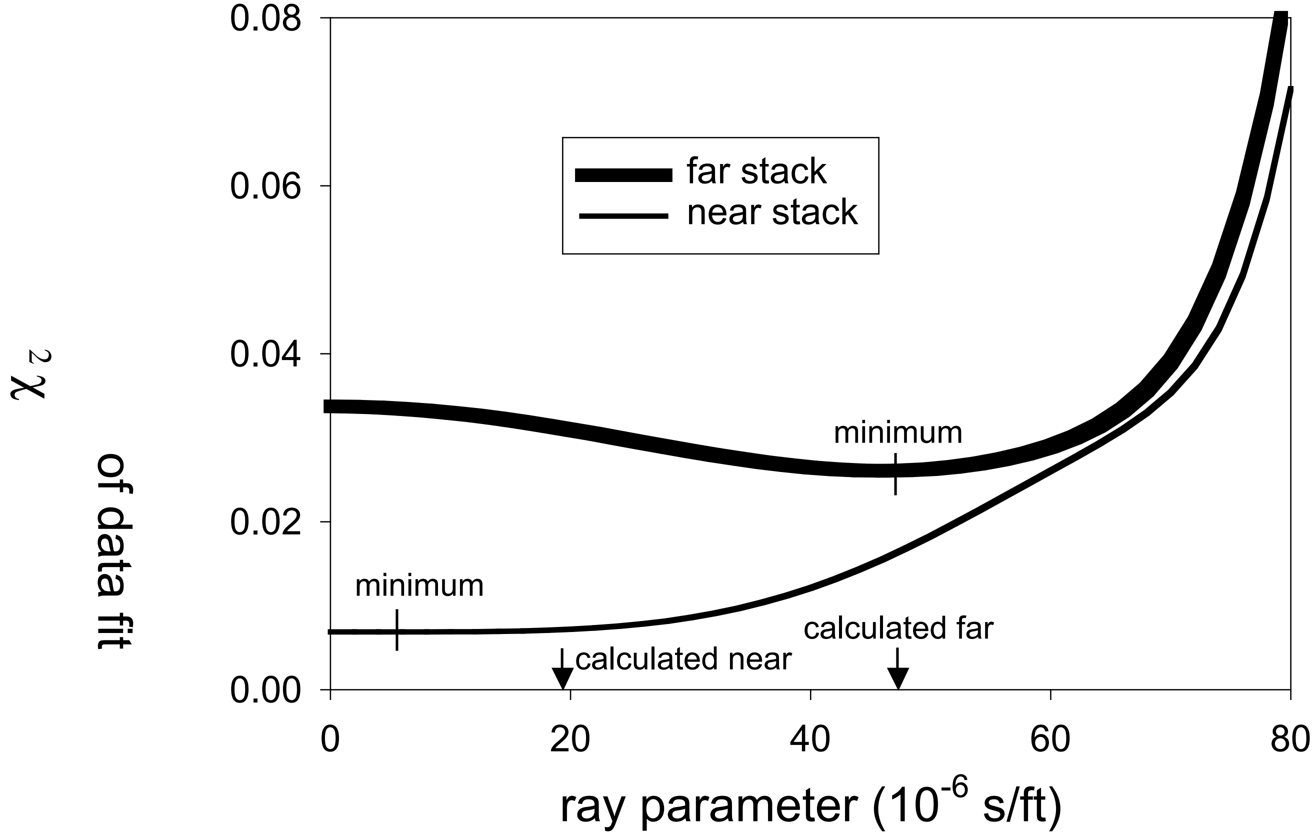


A typical inversion process is simulated

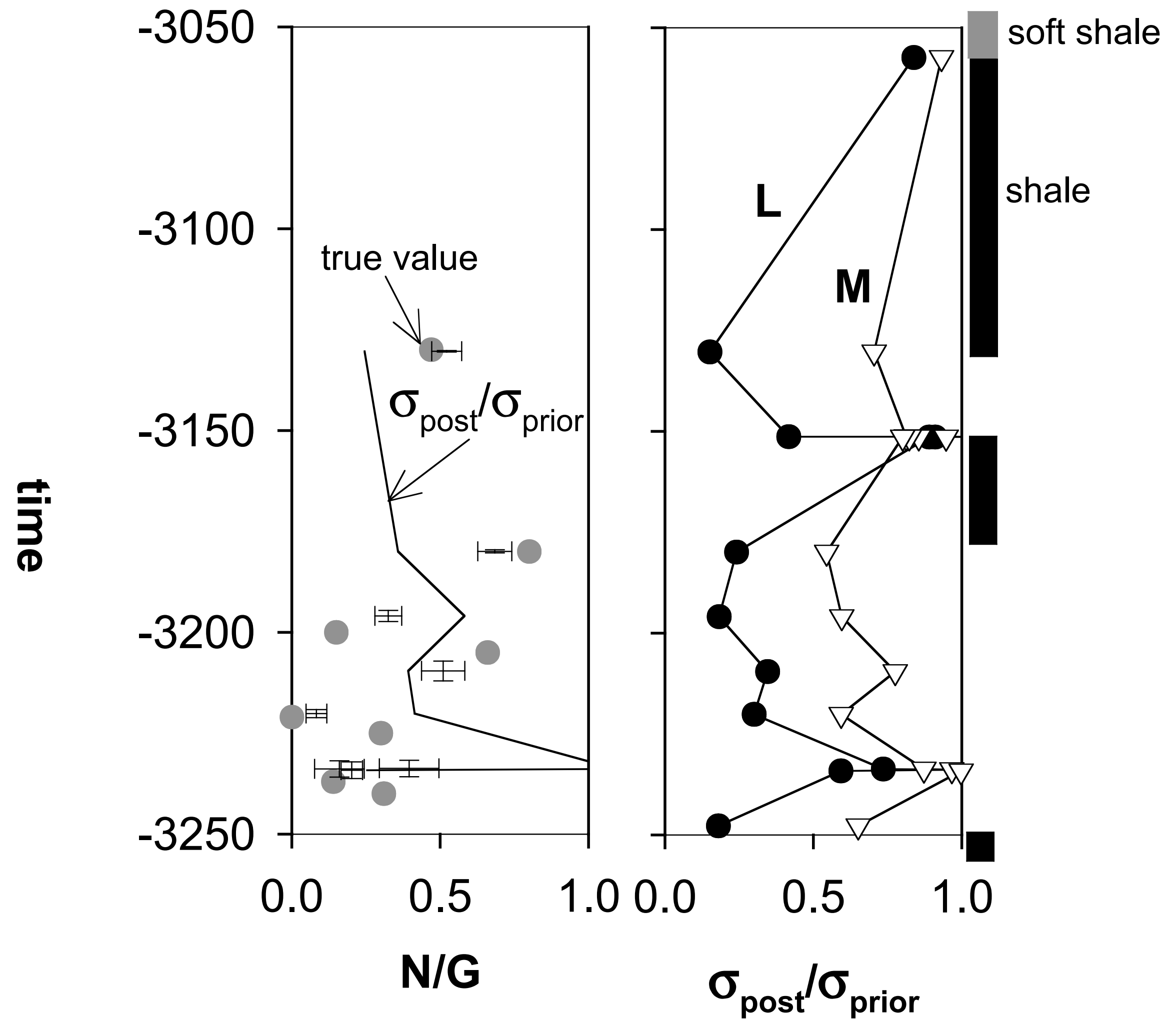
- **REX synthetic**
  - full elastic solution
  - interbed multiples
  - mode conversions
- **seeded from 16 lumped layers picked from seismic**
- **petrophyscial parameters set from "well" information and regional "information" on variability**



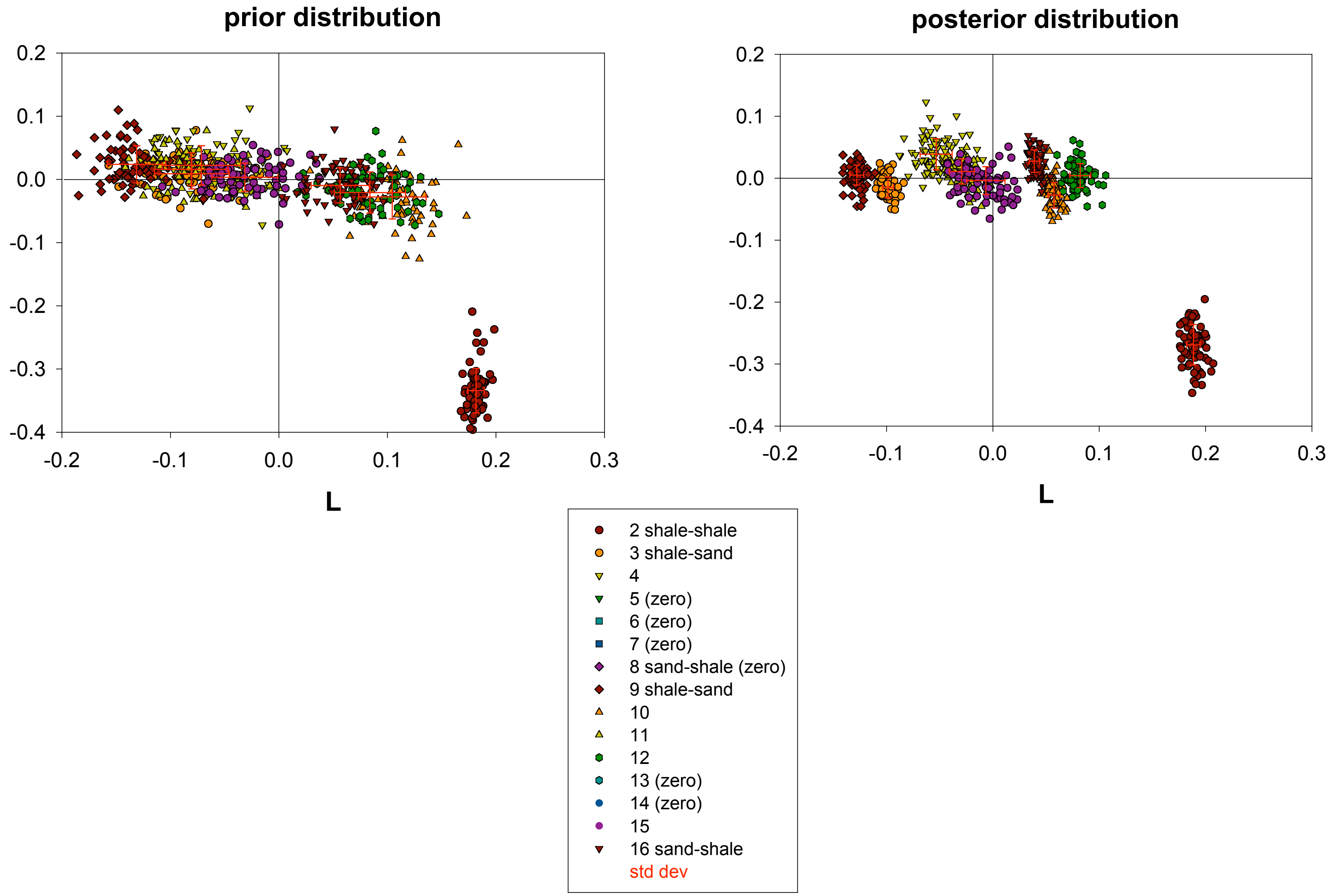
Effective ray parameter is determined by well matching during wavelet derivation



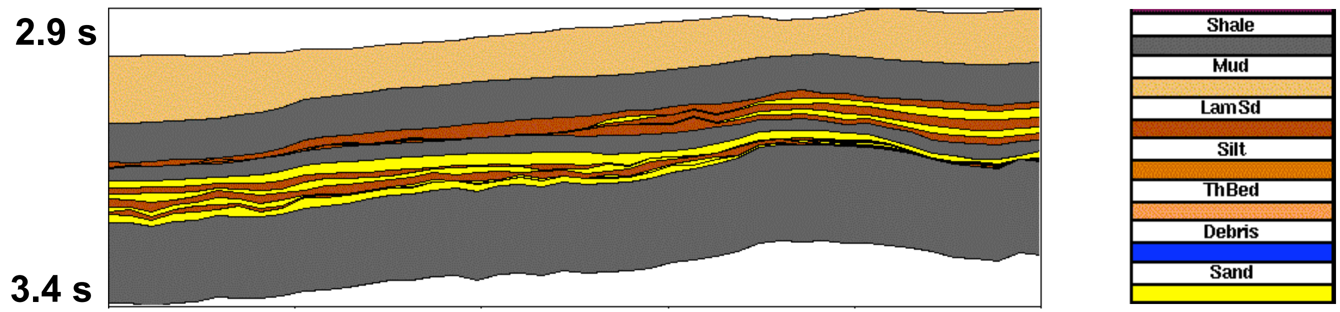
The quality of the well tie - inversion at the well

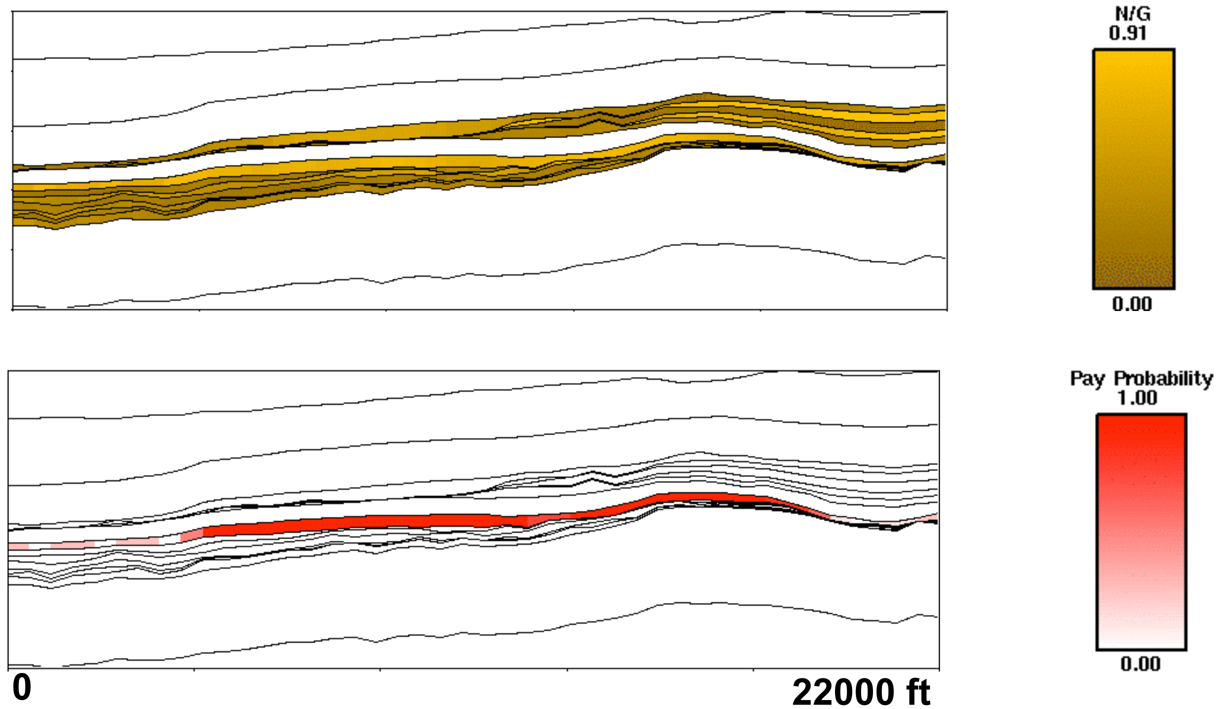


AVO inversion tightens clouds in L-M space



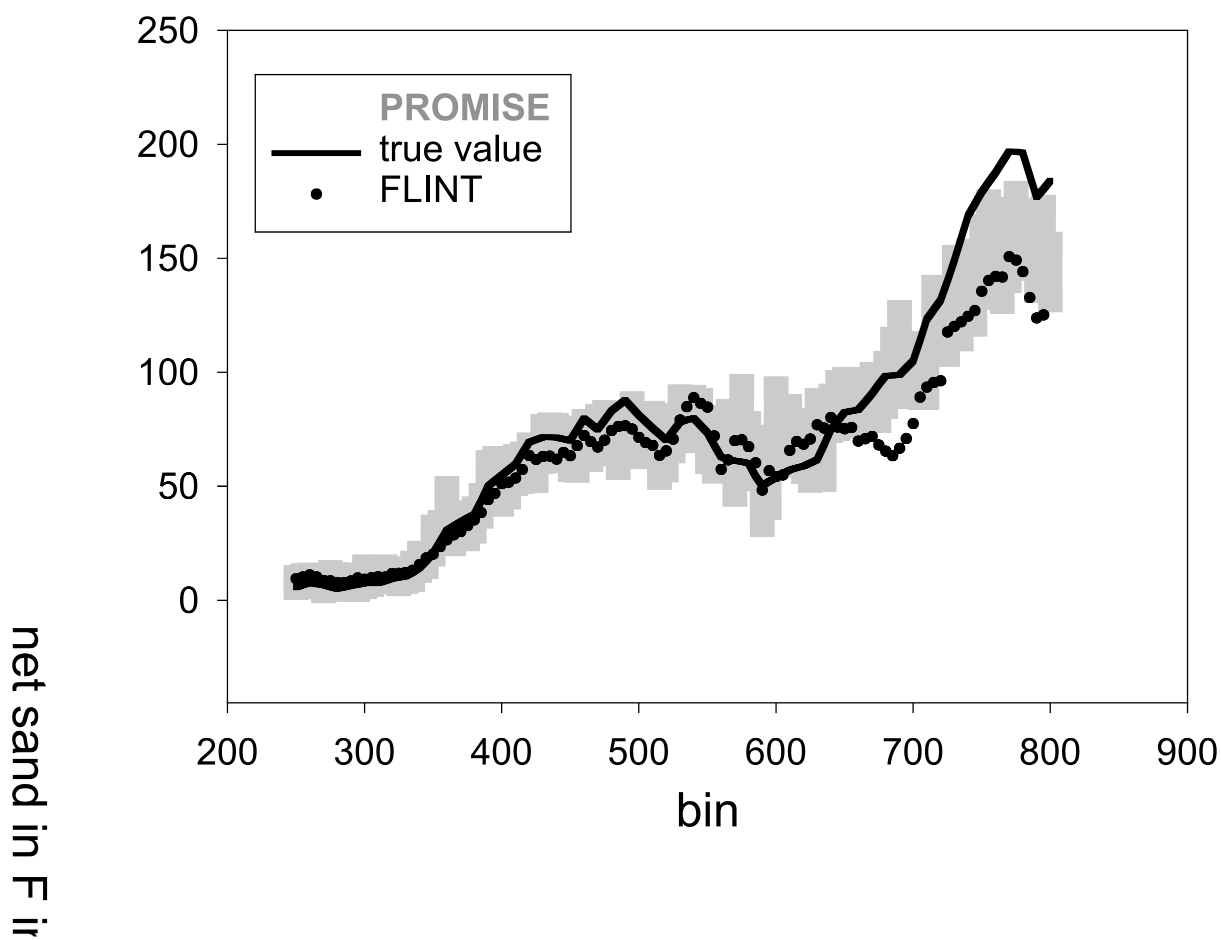
Uncertainty model after AVO inversion





note: synthetic seismic matches true to 15-20 dB

Results of AVO inversion compared to true value and FLINT inversion



Conclusions

- **PROMISE is integrated into DepSim**
- **AVO and limited 4D inversion is operational**
- **AVO inversion has worked with some success on synthetic data**
  - matches true value within the expected error

Future directions

- **establish the value of AVO and 4D inversion on real and synthetic data**
- **implement 4D inversion with effective stress changes**
- **integrate neural network fluid prediction into inversion**
- **couple multiple models into reservoir simulation**
- **AVF (Amplitude Variation with Frequency) inversion**
  – using seismic expression of bedding statistics as additional input to inversion
- **optimized and distributed version of PROMISE**
- **annealing to help prevent “loop skips”**