Extracting structural parameters from chaotic seismic reflection images of mass-transport deposits

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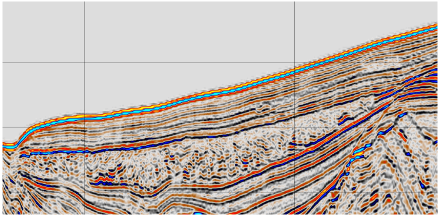
Introduction

Goal:

Characterise internal structure of submarine mass-transport deposits from seismic reflection data

- Fossil mass-transport deposits – complex internal structure
- Reflection images often appear chaotic or "low-reflectivity", without laterally continuous horizons
- Classical interpretation difficult $\Longrightarrow$ geostatistical approach?

From Yamamoto et al. [2007]



Nankai Trough, Japan

Estimating geostatistical parameters from reflection images

Irving and Holliger [2010] link geostatistical parameters of a band-limited, self-similar random medium to the power spectrum of the corresponding reflection image, P_d:

$$P_d(k_x, k_z) \propto \frac{P_w(k_z) \cdot P_h(k_x)}{(k_x^2 a_x^2 + k_z^2 a_z^2 + 1)^{\gamma+1}}$$

$\implies$ We can invert for characteristic scale lengths a_x and a_z, roughness γ (related to fractal dimension) of v_p heterogeneity from reflection image

Idea: v_p heterogeneity is related to deformation from mass-transport – a_x, a_z, γ can characterise internal structure, strain history?

Caveats:

- Assumption: **image approximates a primary reflectivity section (PRS)**
- Only aspect ratio $\alpha = a_x/a_z$ and γ can be estimated from reflection images alone – **need an independent estimate of a_z**

Inversion workflow

$$P_d(k_x, k_z) = \frac{P_w(k_z) \cdot P_h(k_x)}{(k_x^2 a_x^2 + k_z^2 a_z^2 + 1)^{\gamma+1}}$$

1. Estimate source power spectrum $P_w(k_z)$ and filter representing lateral resolution $P_h(k_x)$ for chosen window
2. Choose candidate model $\mathbf{m} = (\alpha, a_z, \gamma)$ from prior PDFs
3. Forward model ideal power spectrum $P_d(k_x, k_z)$
4. Calculate $P_{obs}(k_x, k_z)$ for window (normalised)
5. Compute likelihood $P(\mathbf{m}|P_{obs}) = \exp\left(-\frac{\|P_d - P_{obs}\|^2}{2\sigma^2 \|P_{obs}\|^2}\right)$

Estimate posterior PDFs for each parameter using a Bayesian Monte Carlo Markov Chain (Metropolis-Hastings). For long chains, distribution of accepted models is proportional to joint posterior PDF.

For vertical borehole logs, use a similar strategy in 1-D.

Synthetic submarine MTD model

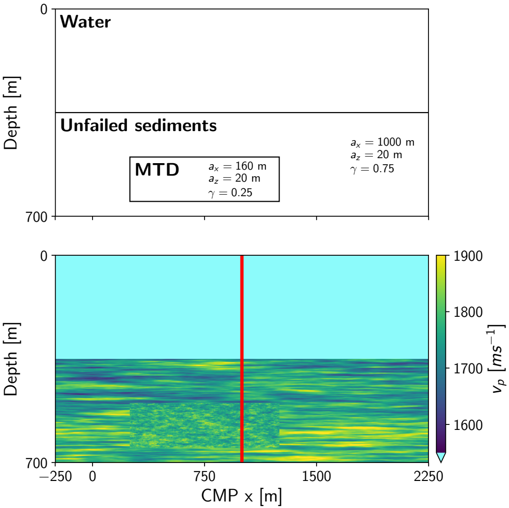
Common marine seismic data for geohazard studies:

- Multi-channel airgun seismic reflection data
- Complex overburden
- Processing and imaging

Previous synthetic benchmarks in literature have used zero-offset data [e.g, Scholer et al., 2010].

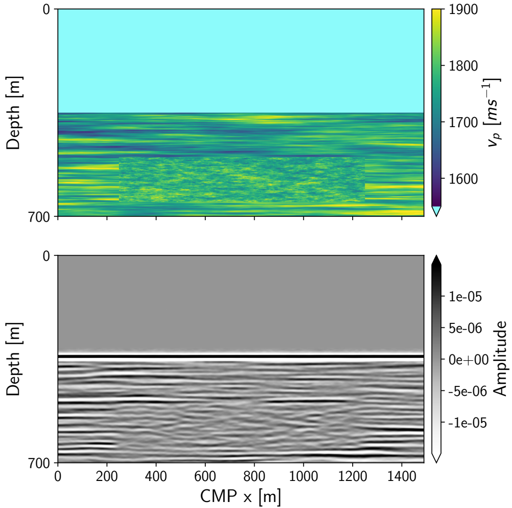
Aims

1. Is the PRS approximation sensible for multi-channel seismic images of submarine MTDs?
2. Can we use information from a borehole log to resolve a_x and a_z?



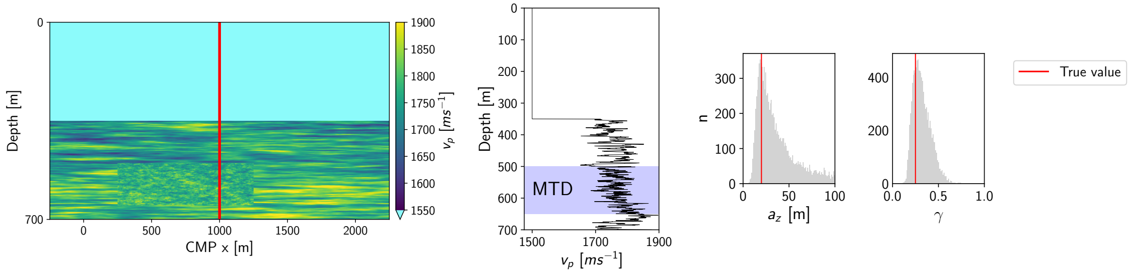
Synthetic landslide model — multi-channel seismic modelling

- Acquisition: $\Delta x_{rec} = 20$ m, $\Delta x_{source} = 40$ m, cable length 520 m, $f_{source} = 40$ Hz Ricker
- Forward modelling: pseudo-spectral, elastic, time-domain scheme [Carcione, 2014], perfectly absorbing boundary conditions
- Elastic model: constant density in sediments, $v_p/v_s = 2$
- Processing: add 5% noise, PreSTM migration, stack, time-to-depth conversion



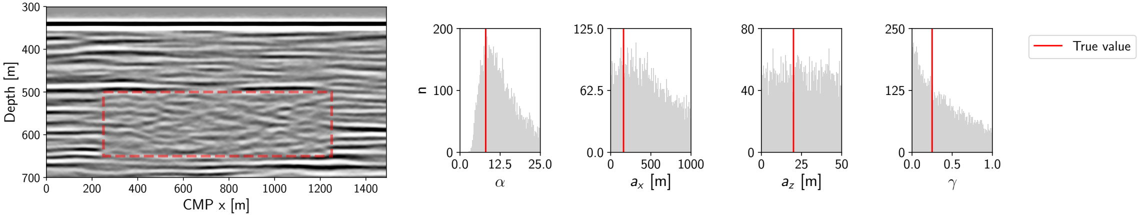
MCMC inversion results – borehole

Uniform priors for $a_z \sim U(0, 100)$, $\gamma \sim U(0, 1)$; $n_{accepted} = 10000$



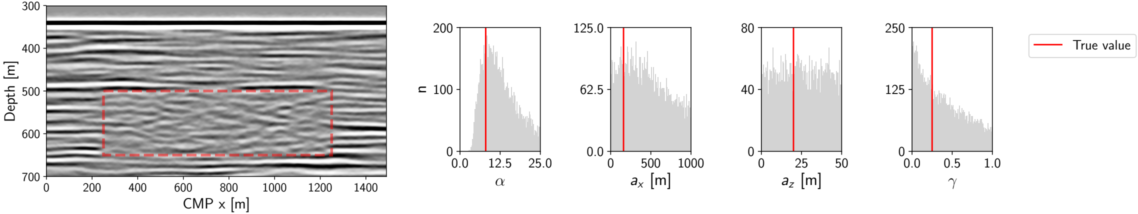
MCMC inversion results – seismic image

Uniform priors for $\alpha \sim U(0, 100)$, $a_z \sim U(0, 100)$, $\gamma \sim U(0, 1)$; $n_{accepted} = 10000$

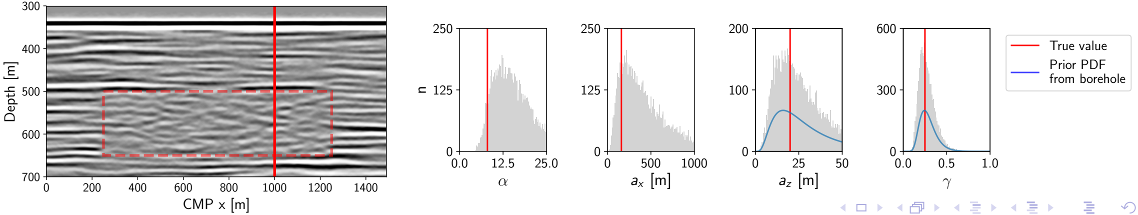


MCMC inversion results – seismic image

Uniform priors for $\alpha \sim U(0, 100)$, $a_z \sim U(0, 100)$, $\gamma \sim U(0, 1)$; $n_{accepted} = 10000$



Uniform prior for $\alpha \sim U(0, 100)$, log-normal priors for a_z and γ from borehole; $n_{accepted} = 10000$



Summary of synthetic results

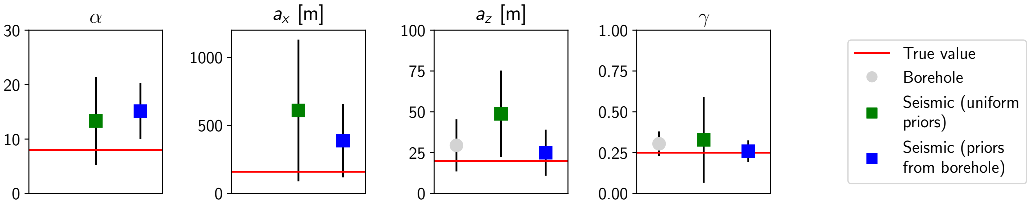
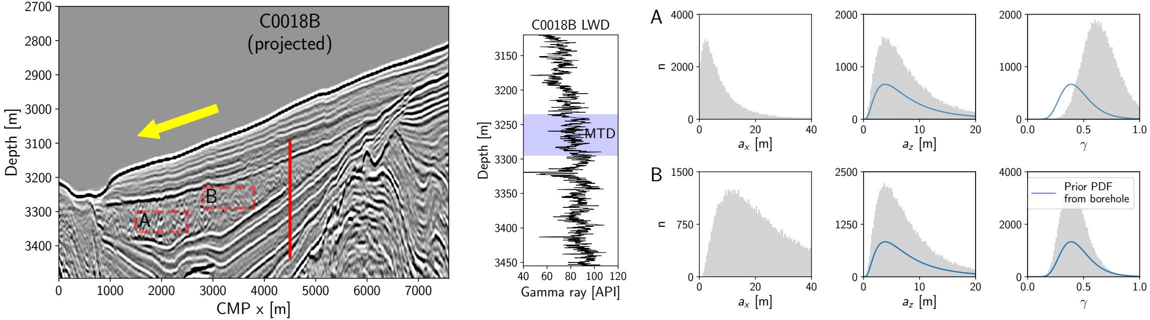


Figure: Distribution of MCMC results with and without constraint from borehole log. Centre point is maximum likelihood, error bars show quartiles of the distribution.

- The PRS approximation seems to hold for this multi-channel example – we can estimate posterior PDFs for $\alpha = \frac{a_x}{a_z}$
- Estimated PDFs for a_z and γ from a borehole v_p log
- Using the posterior PDFs for a_z and γ as priors, repeating the seismic inversion allows to estimate meaningful PDFs for a_x and a_z, with lower uncertainty

Seismic profile from a 3-D survey, intersects a large submarine landslide.

IODP borehole C0018B located ~1.5 km from profile – gamma ray log in MTD zone to estimate priors for a_z and γ

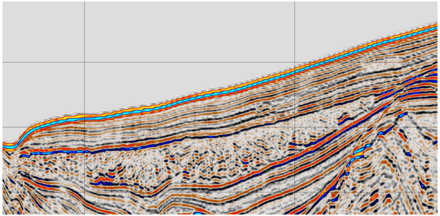


Decreasing a_x reflects increasing confinement/deformation towards toe of slide?

Conclusions 1/2

For chaotic seismic reflection images of submarine mass-transport deposits:

1. Estimated posterior PDFs for geostatistical parameters characterising internal structure
2. Assumptions from Irving and Holliger [2010] hold for this synthetic, multi-channel marine data (does this generalise?)
3. With priors for a_z from a borehole log, we can estimate a_x, a_z separately



Nankai Trough, Japan

From Yamamoto et al. [2007]

Conclusions 2/2

Characteristic scale lengths a_x and a_z related to deformation – extracting these geostatistical parameters a useful tool for imaging “chaotic” internal structure of MTDs from reflection seismic data?

Future work:

- Method: 3-D, dip, joint inversion with sub-bottom echosounder image
- Applications: validate outcrop analogue models, image strain distribution within MTD

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