Satellite Altimetry and a Bathymetry Mission

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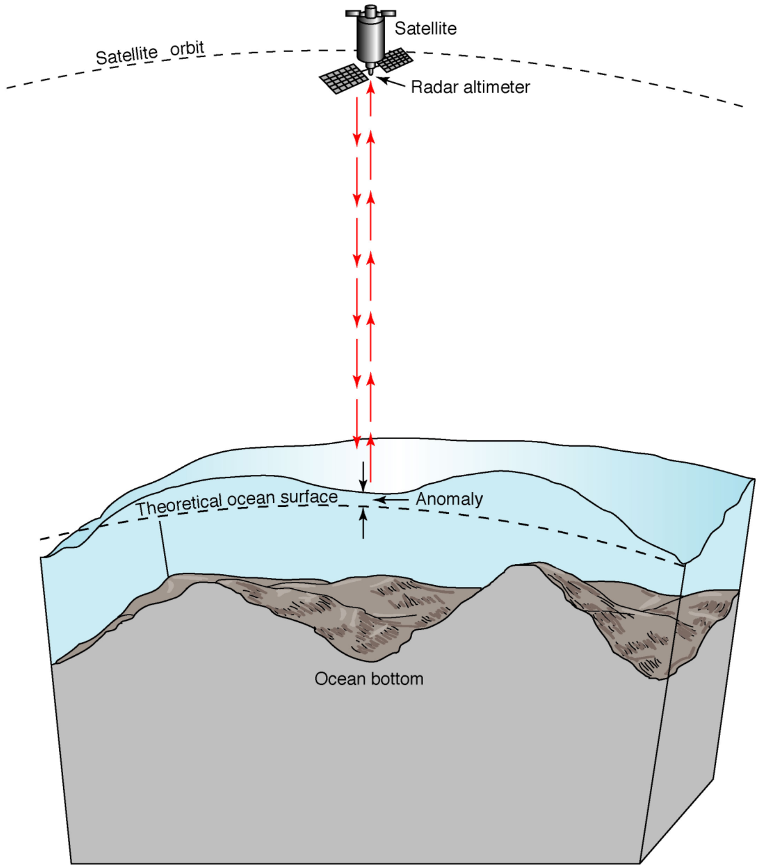
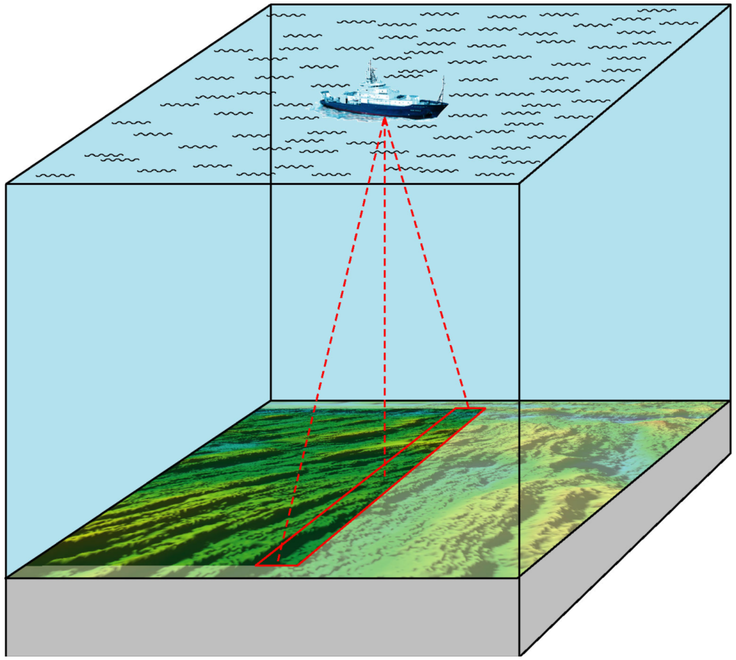
Presented at JHU APL, 17 November, 2011

Modern ocean mapping tools

satellite altimeter



multibeam echo sounder



In situ echosounding by ships

Advantages:

Direct measurement of depth

High horizontal resolution in last 20 years (~200 m in deep ocean)

High vertical accuracy in last 20 years (~10 m in deep ocean)

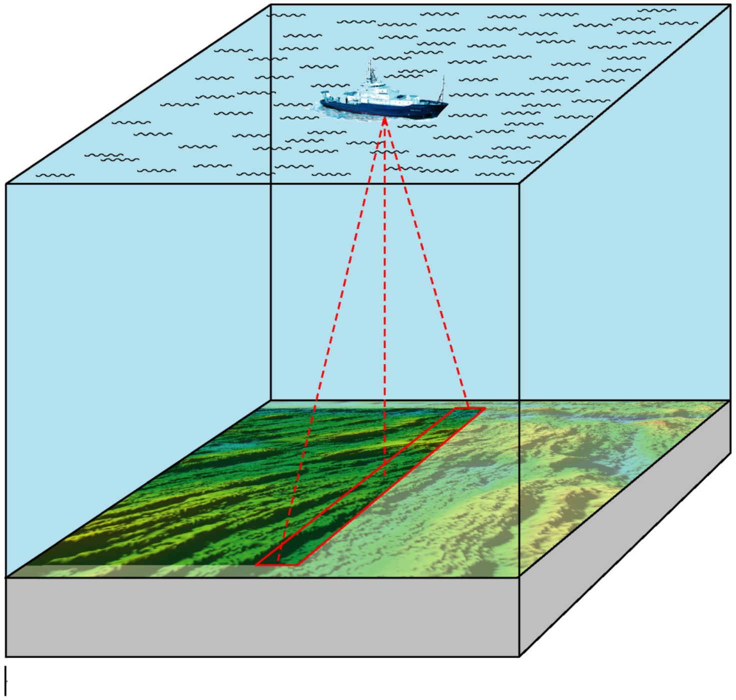
Disadvantages:

High cost (ship centuries, G$)

Sparse and biased coverage (few %, ports, coasts of developed world).

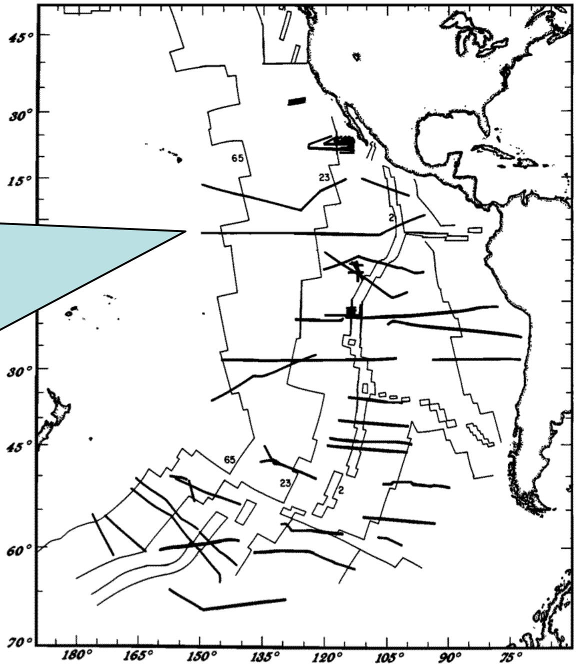
Most data is old, low tech (single beam), inaccurately measured and located.

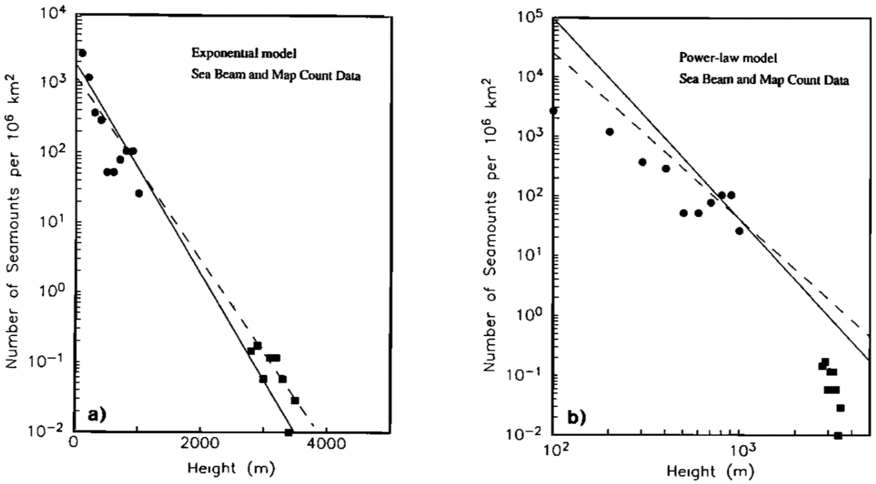
multibeam
echo sounder



Echosounders resolve seamounts

Studies based on sparse ship tracks.





Small seamounts more common than large ones.

Effective width usually about 5 times height, *H*.

Abundance varies regionally.

# of seamounts taller than *H* per unit area can be fit by a Poisson model [$\exp(-H/H_0)$, scale dependent, bounded] or by a fractal model [H^{-p}, scale independent, unbounded].

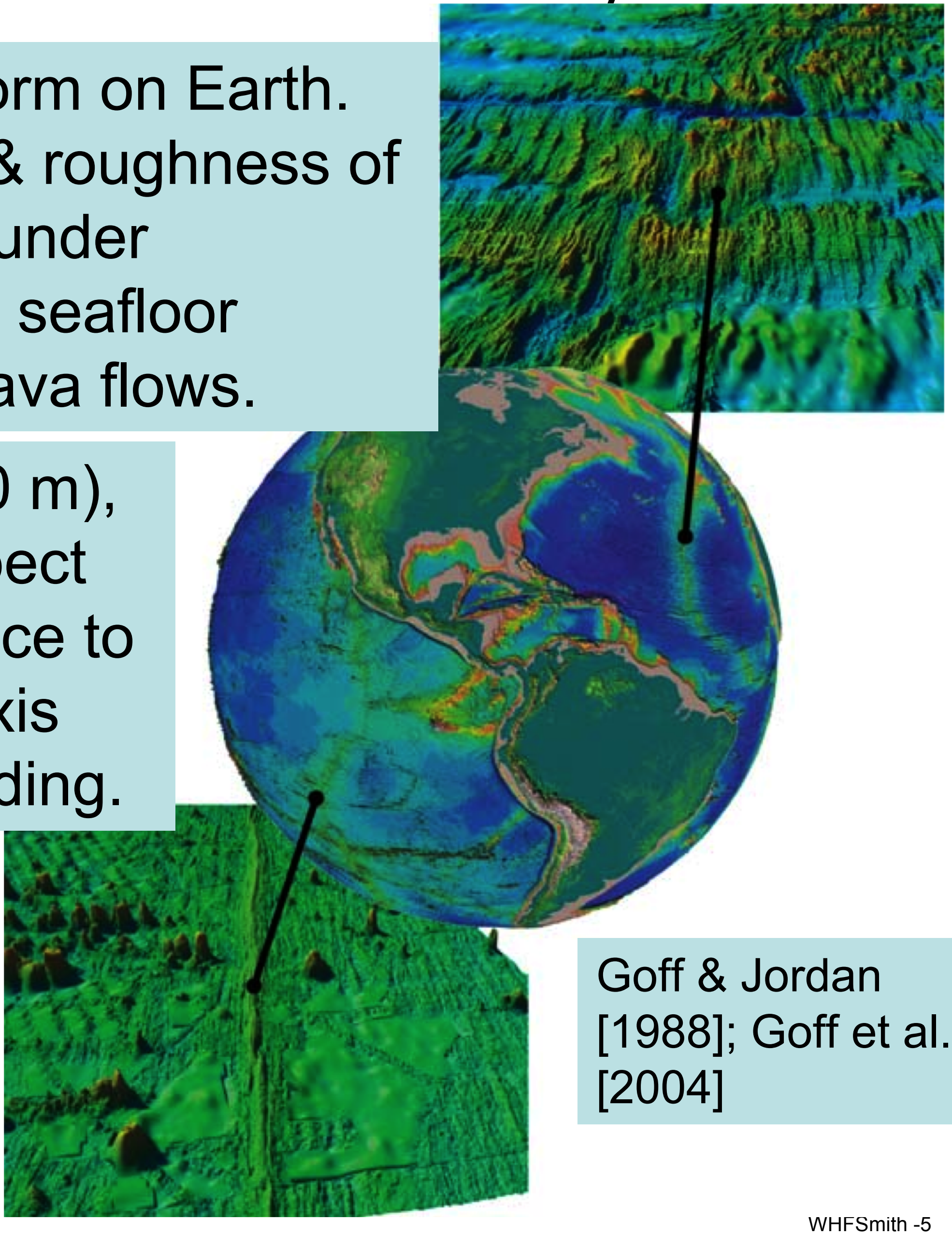
[Jordan et al., 1983; Smith & Jordan, 1987; 1988]

Multibeam echosounders resolve abyssal hills

The most common landform on Earth. The background texture & roughness of the seafloor, until buried under sediment. Formed during seafloor spreading by faults and lava flows.

RMS amplitudes (60–240 m), widths (2–8 km), and aspect ratios (3–7) vary from place to place; oriented w/ long axis parallel to seafloor spreading.

Roughness spectrum follows a power law.

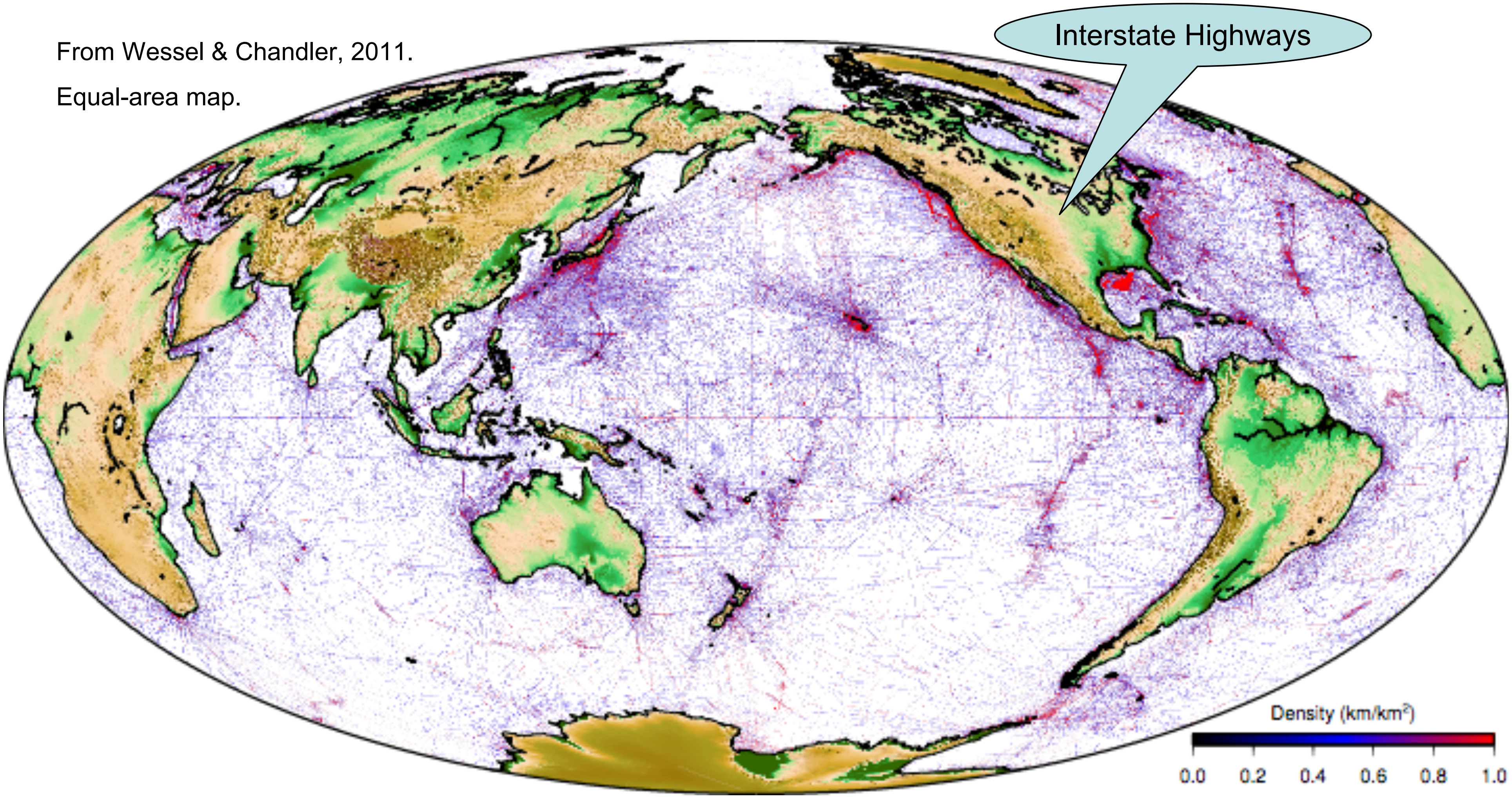


Goff & Jordan [1988]; Goff et al. [2004]

Ship bathymetry track density

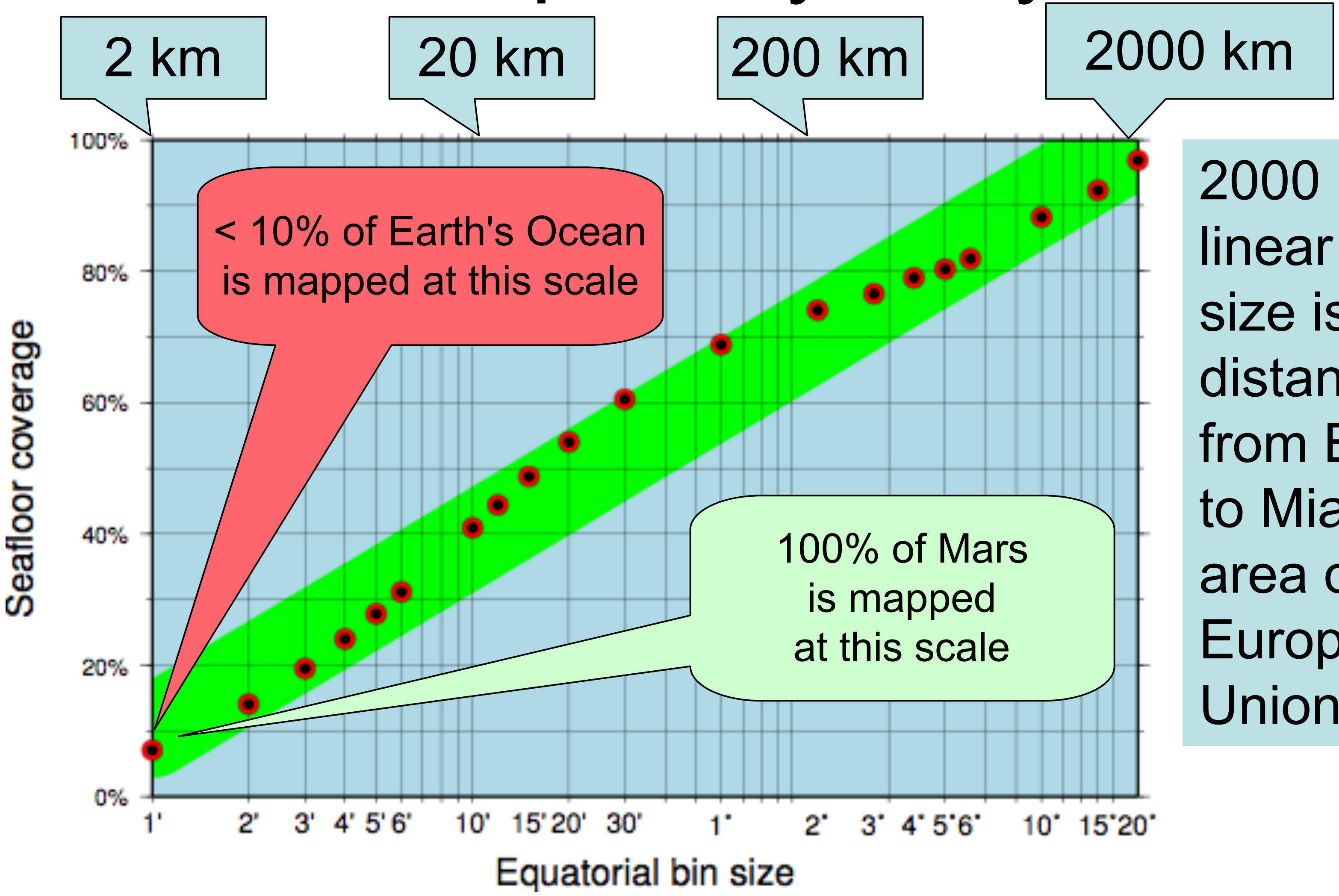
From Wessel & Chandler, 2011.

Equal-area map.



The majority of the data in southern oceans is also very old (celestially navigated, analog, error prone) [Smith, 1993].

Global ship bathymetry coverage



2 km

20 km

200 km

2000 km

< 10% of Earth's Ocean is mapped at this scale

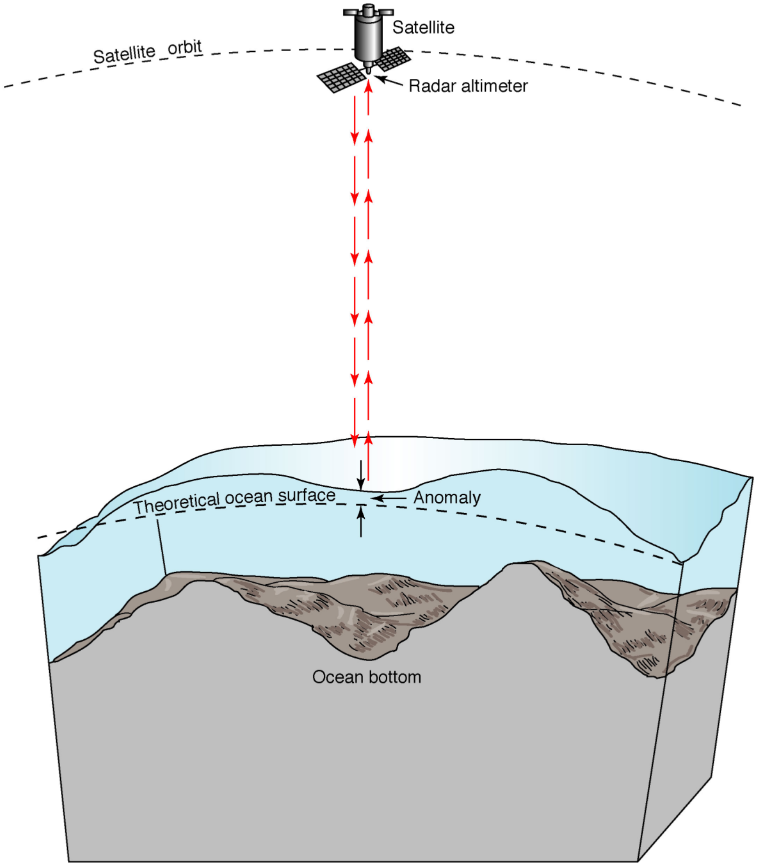
100% of Mars is mapped at this scale

2000 km linear bin size is distance from Boston to Miami, area of European Union.

Wessel & Chandler [2001]

Satellite reconnaissance of depth

satellite altimeter



Advantages:
Global, uniform, dense, unbiased coverage
Low cost (~0.1 G$)
Fast (~6 years)

Disadvantages:

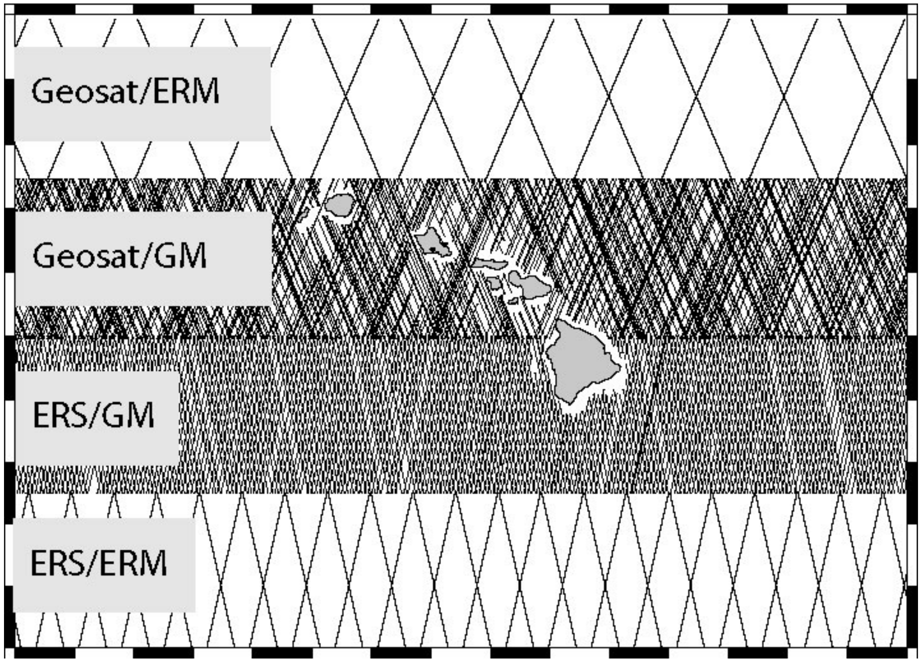
Indirect measurement

Correlation between depth and measurement is variable

Vertical accuracy 250 m and horizontal resolution ~12-15 km in current data, in deep ocean.

Would be better w/ new mission.

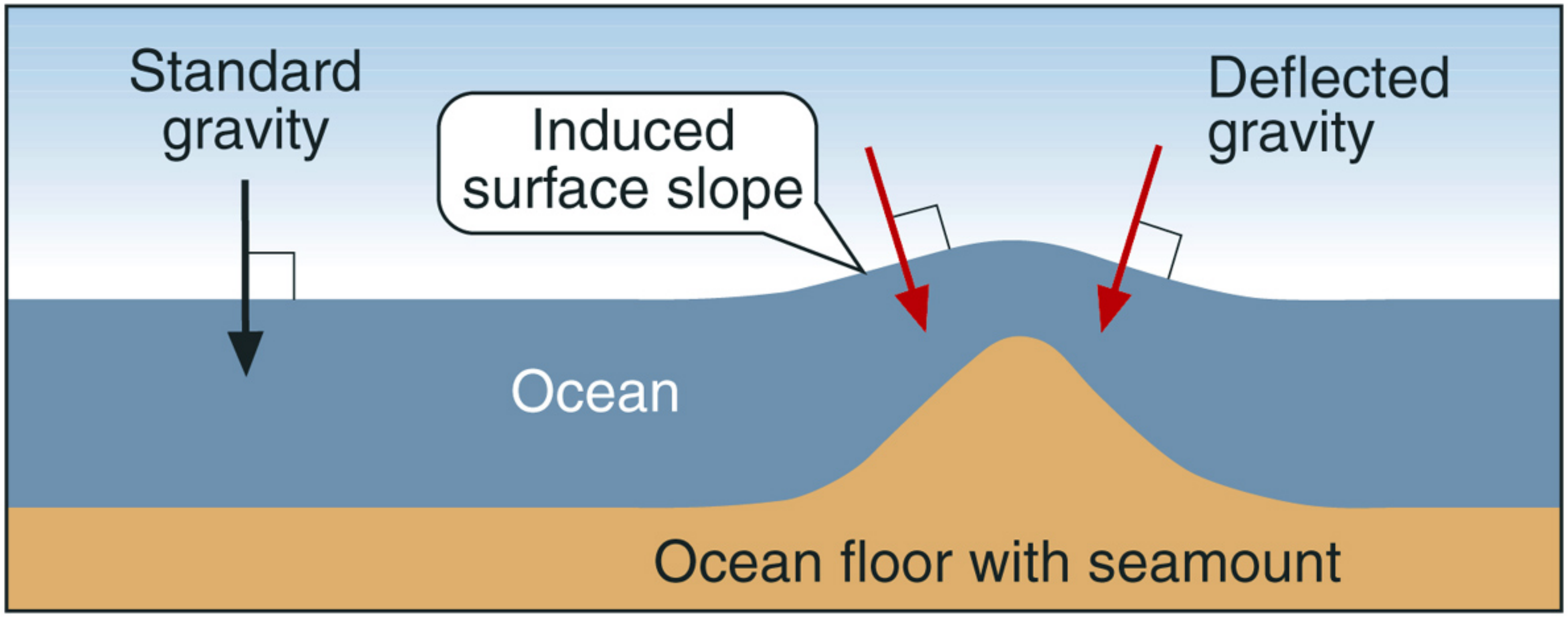
Satellite altimeter track density



Until the 2010 launch of CryoSat-2, spatially dense coverage came only from the Geosat Geodetic Mission *(APL!)* (1985-6) and the ERS-1 Geodetic Phases (1994-95). Diamond-shaped gaps average ~5 km east-west.

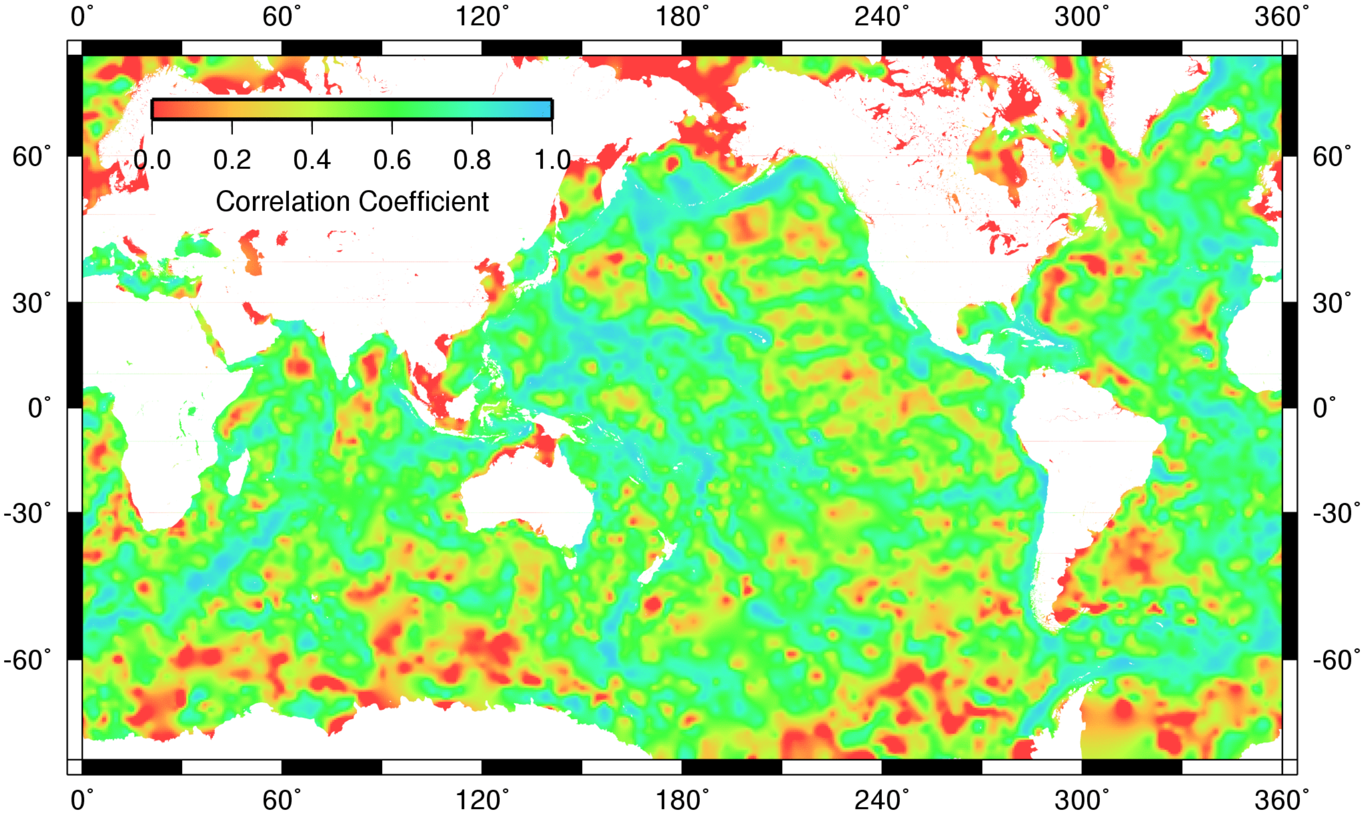
Geosat (17-day, ~165 km e-w) and ERS-1 (35-day, ~80 km e-w) exact repeat mission (ERM) track spacing also shown. Not shown: 10-day, 315 km e-w ERM of Topex, Jason-1&2; CryoSat-2 369-day, 7.5 km e-w pattern.

Satellite bathymetry is via gravity



Space radar can sense ocean surface slopes, manifestations of gravity anomalies in the form of deflections of the vertical. These may be correlated with sea floor structure.

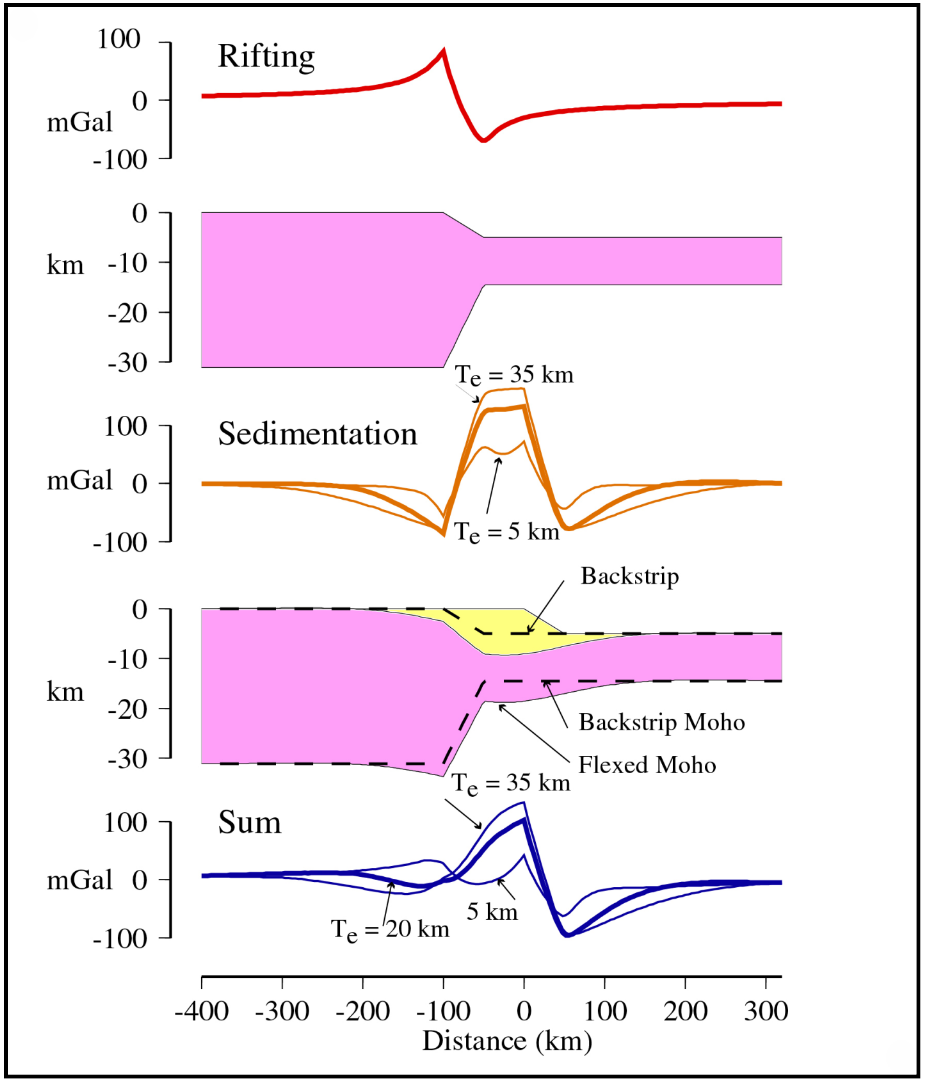
Gravity-Bathymetry Correlation

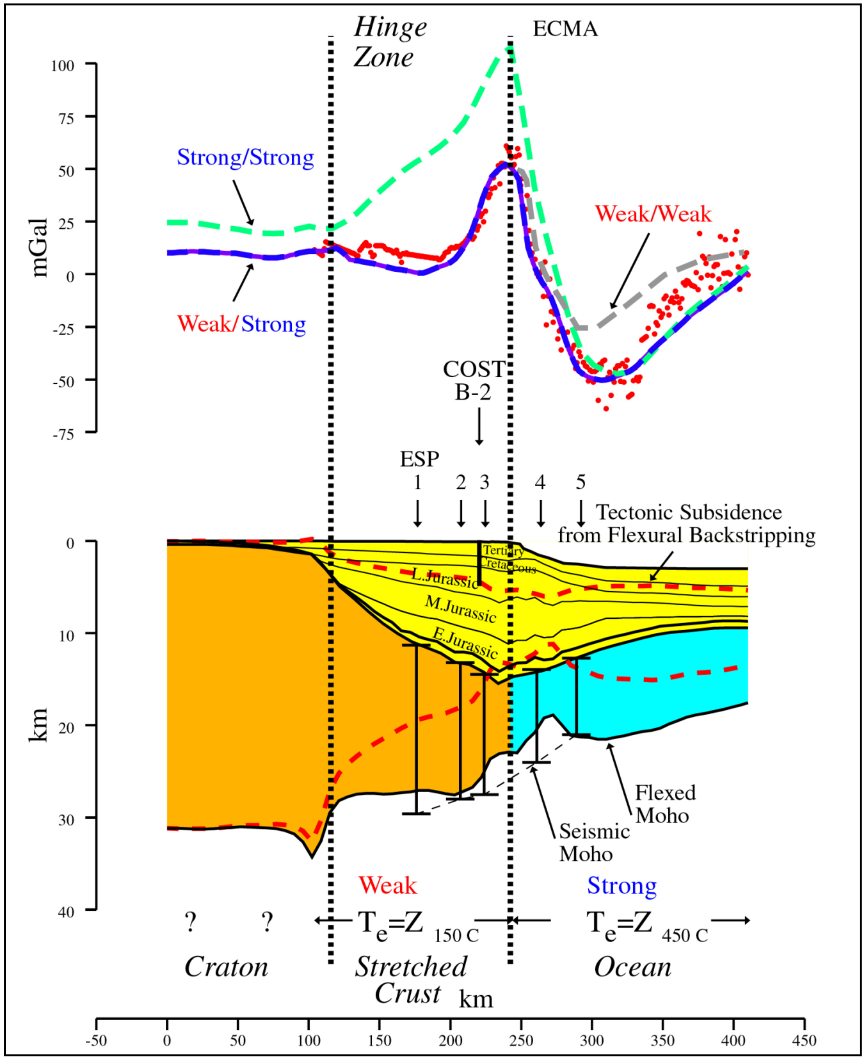


Strong over rough topography in the deep ocean where sediment is thin. Weak on continental margins and abyssal plains. Values above include decorrelation effect of altimeter noise, and will improve with a new mission.

Smith[1998]

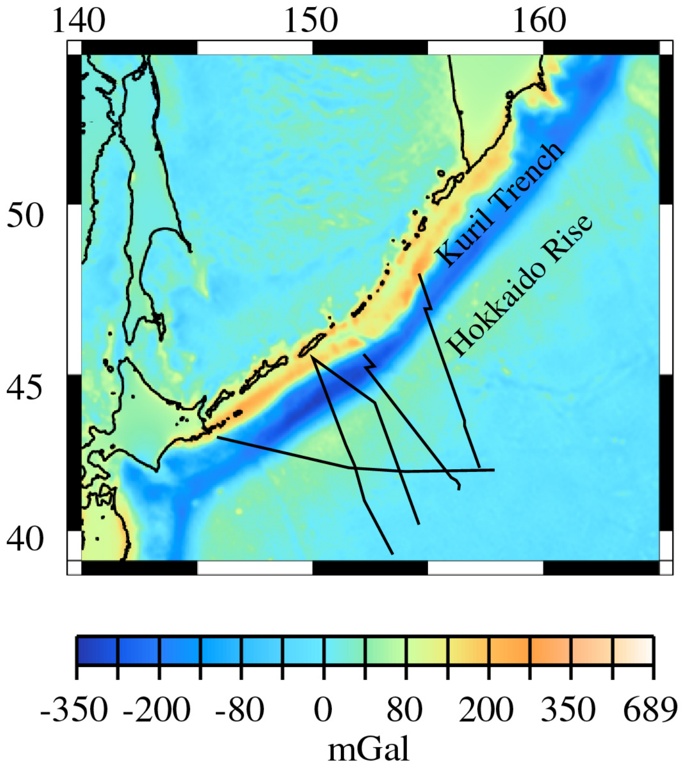
Continental margin gravity anomalies indicate sub-seafloor processes, not depth variations

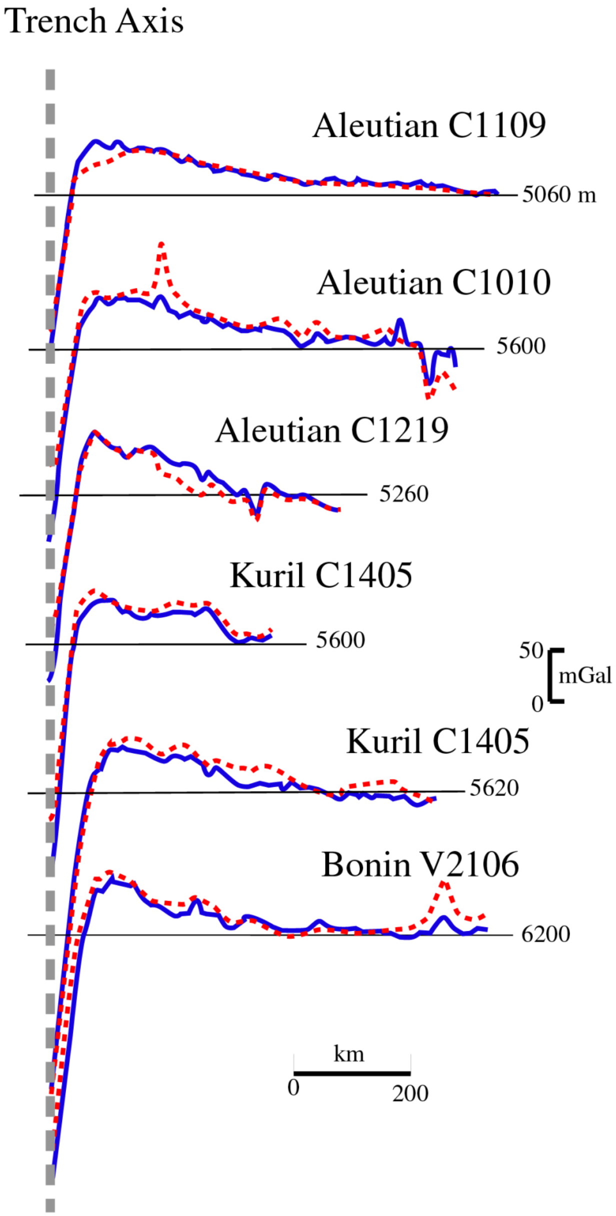




Watts [2001]

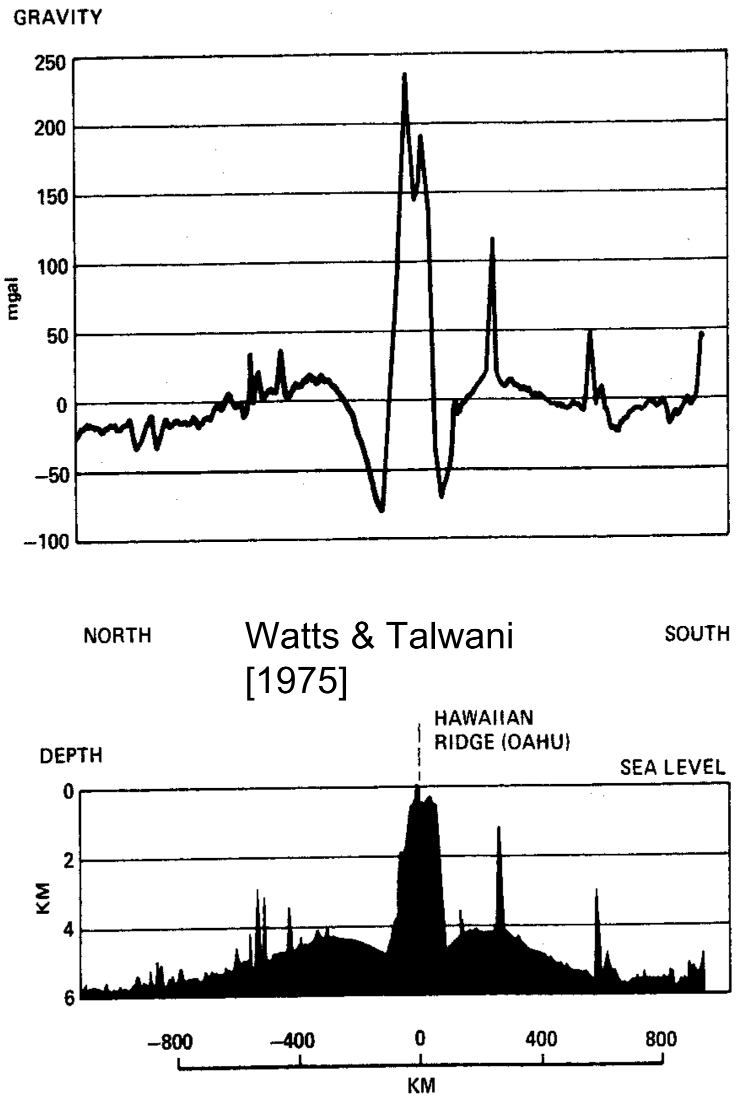
Gravity in the deep oceans is simple, 1: trenches.



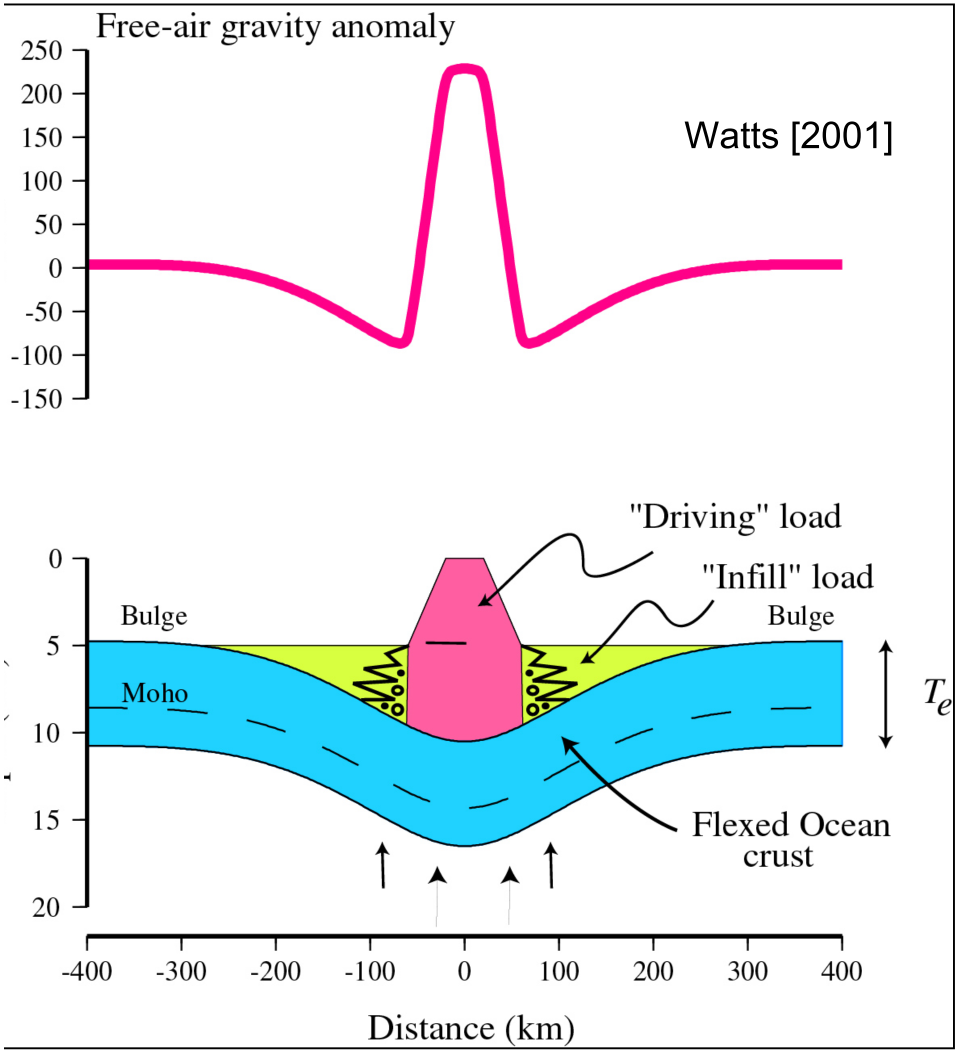


After Watts; Sandwell

Gravity in the deep oceans is simple, 2: seamounts

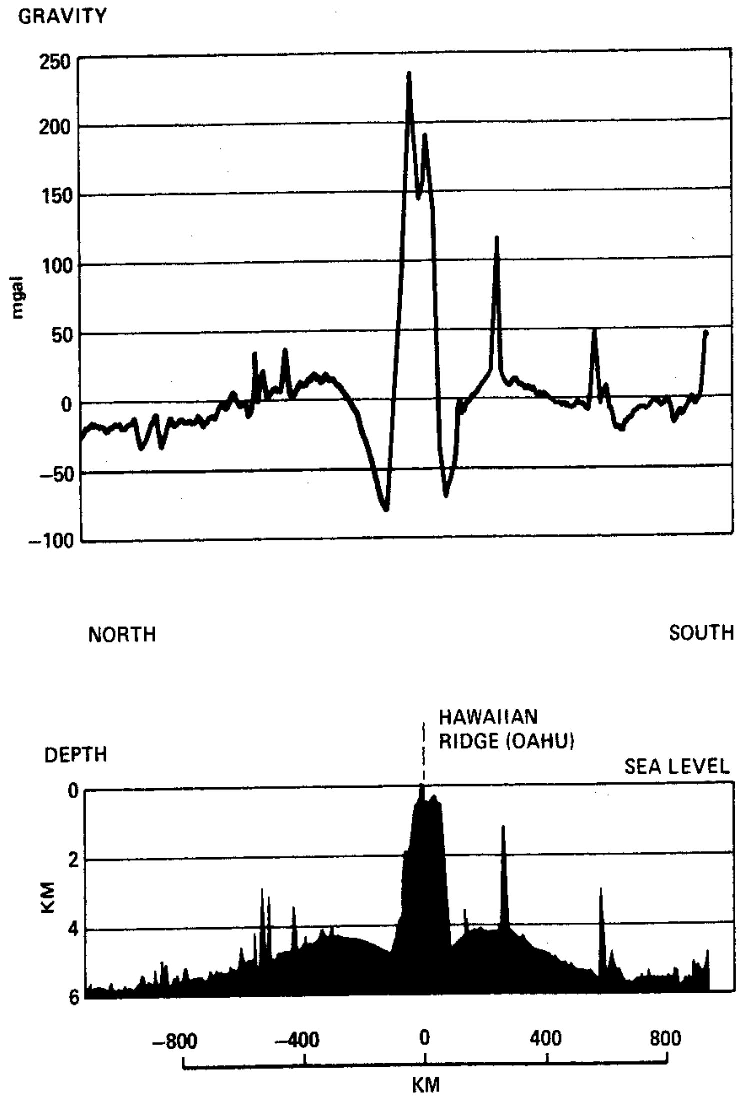


Watts & Talwani [1975]

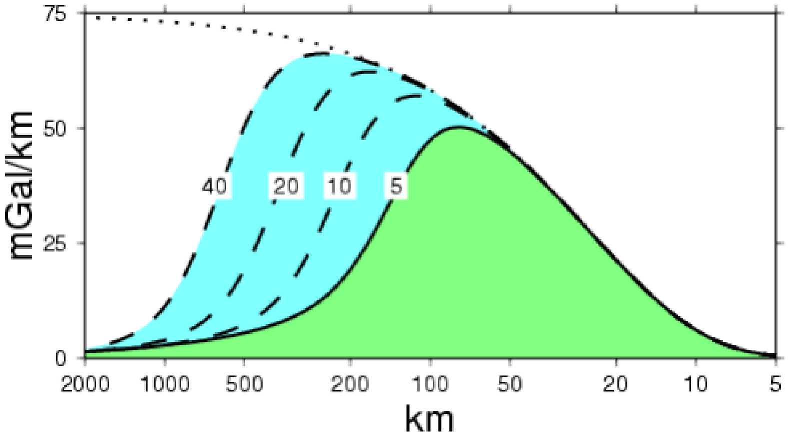


Watts [2001]

Gravity and bathymetry can be correlated

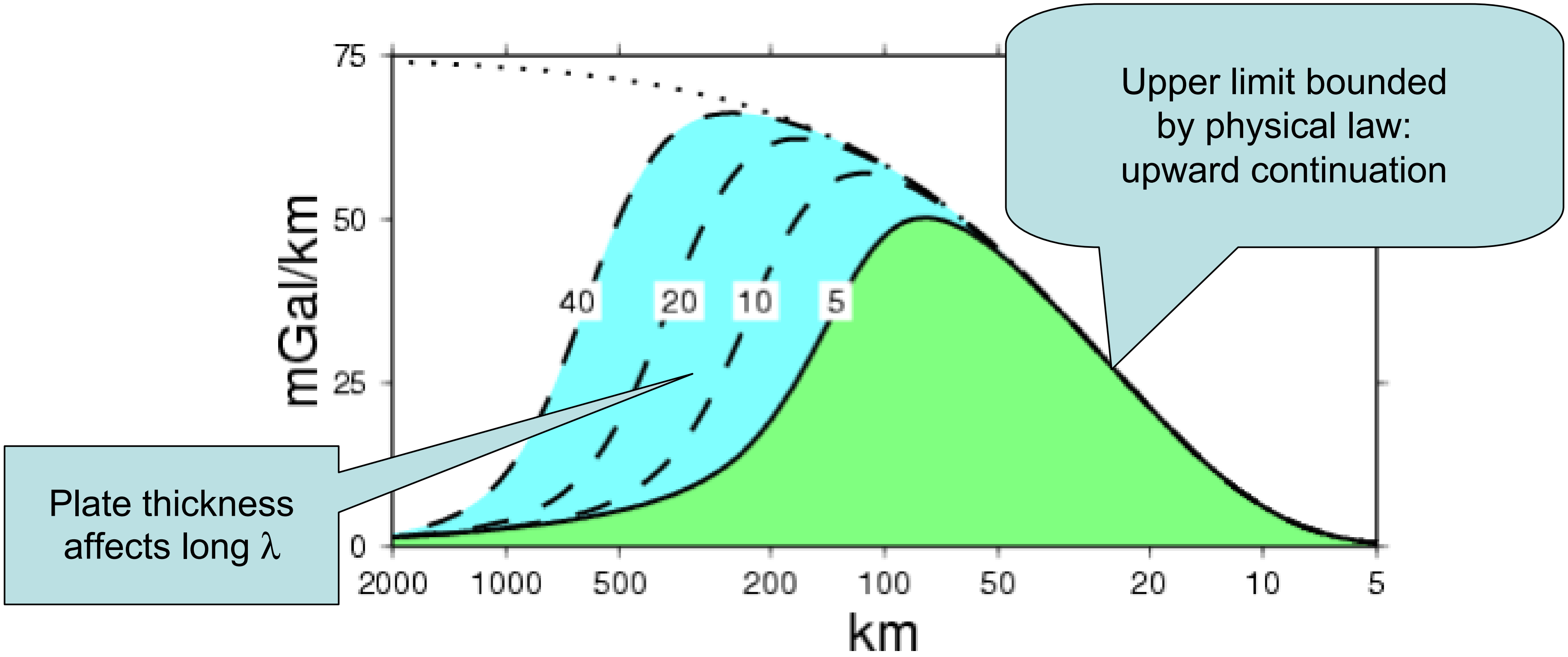


Theory and observation yield a topography in, gravity out, band-pass filter, ~6 to ~160 km.



Estimating depth from altimetry is gravity in, bathymetry out (the inverse). It is limited to a band of wavelengths. Resolution is increasingly limited by noise as horizontal scale decreases.

Topography to gravity bandpass filter

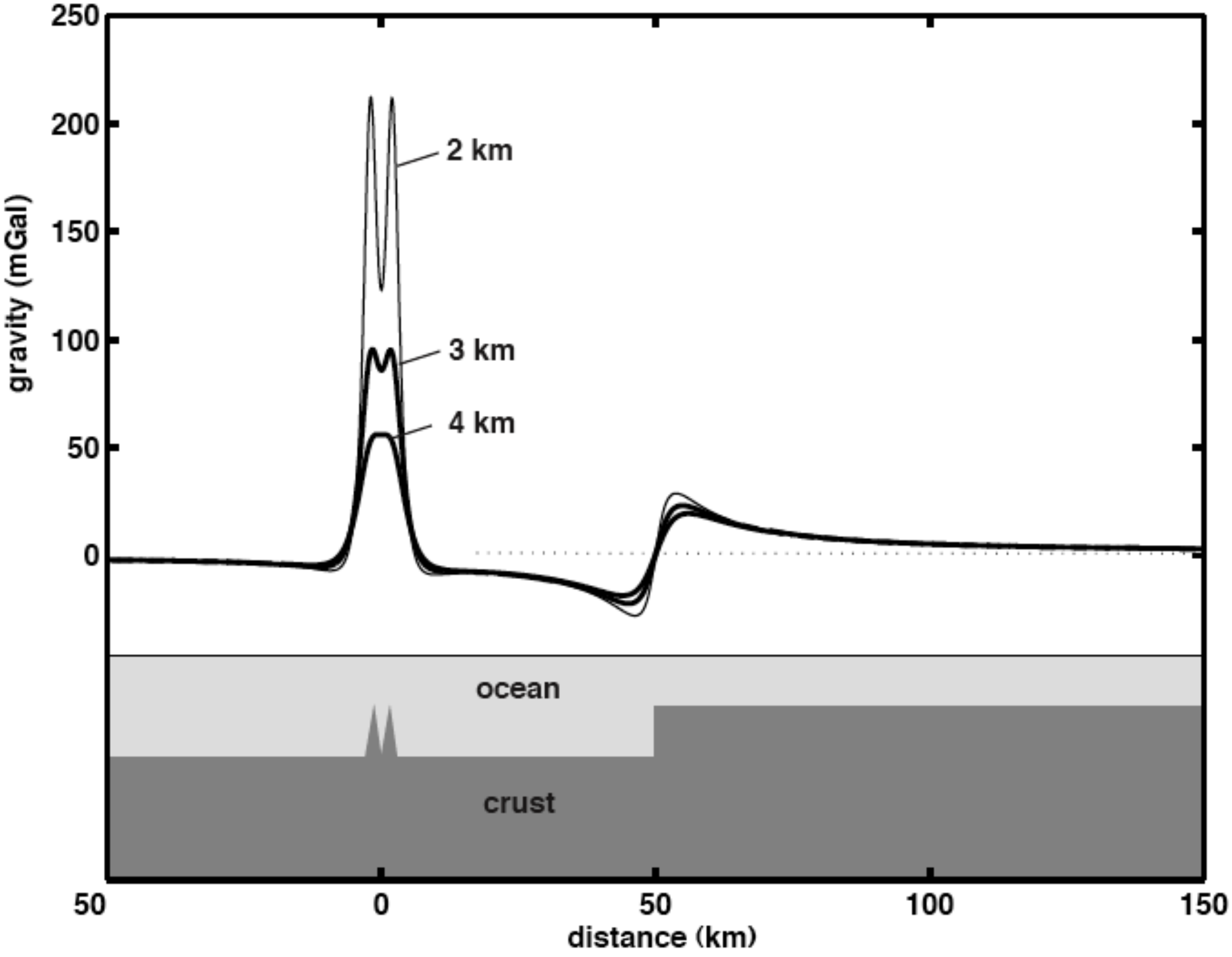


Upper limit bounded by physical law: upward continuation

Plate thickness affects long λ

“Isostatic compensation” attenuates topographic gravity at λ > ~160 km. “Upward continuation” causes amplitude to decay as exp[-2$\pi d/\lambda$], when source is a depth *d* below observations.

Band-pass filter consequences

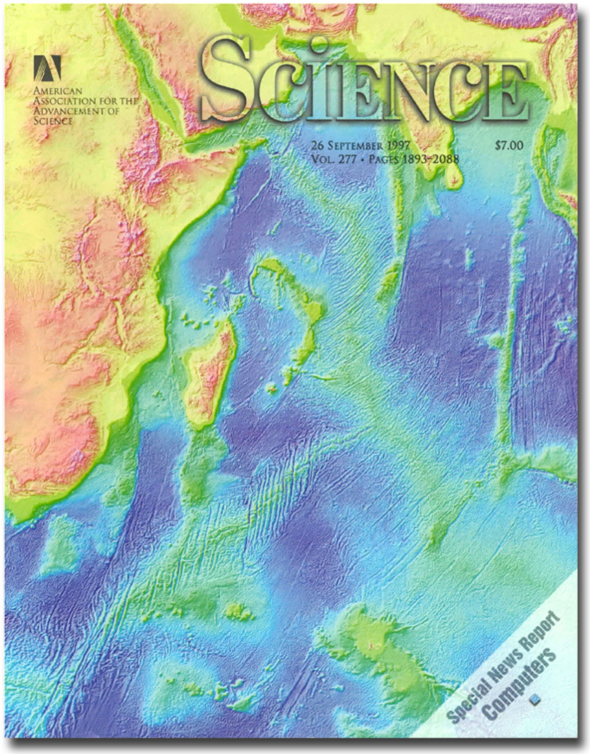


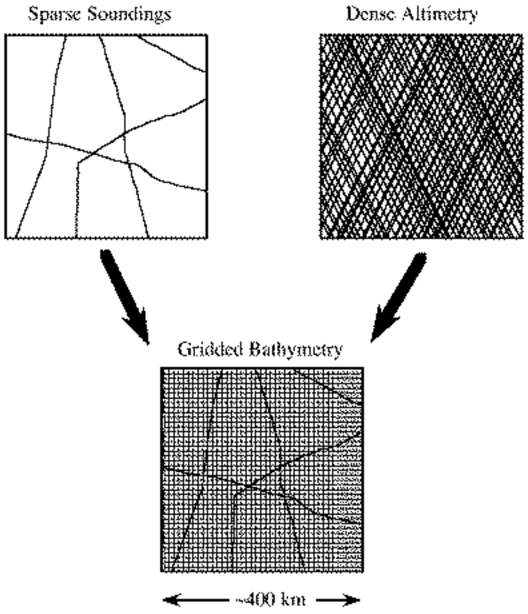
Sandwell & Smith [2001]

Horizontal resolution and signal amplitude (hence, sensitivity to noise) are a function of regional water depth.

Absolute depth is not resolved; the step function response is a decaying dipole.

Altimetric Bathymetry Estimation

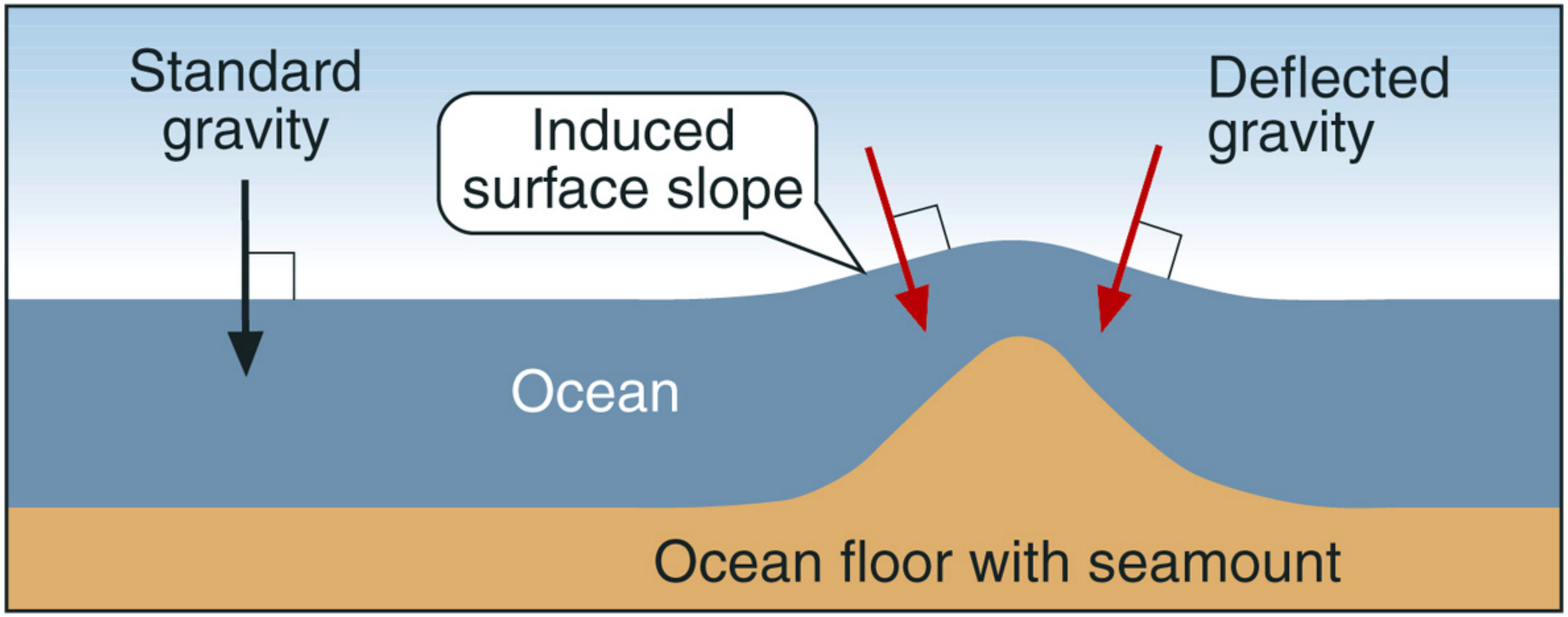




Smith & Sandwell [1994; 1997]

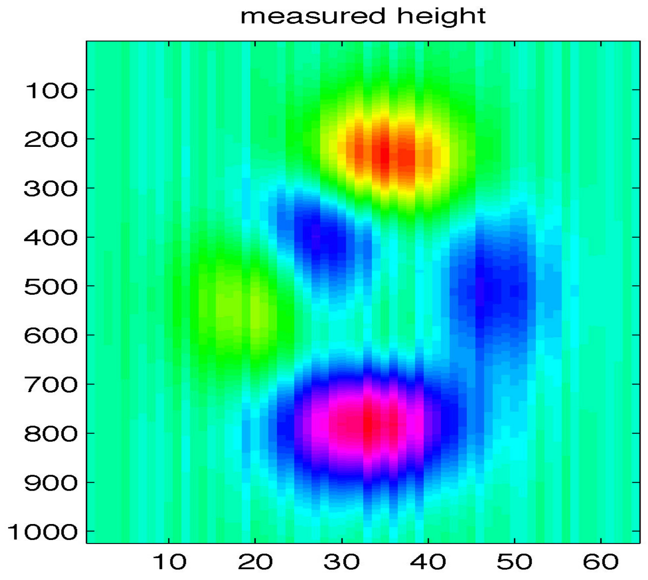
Regional (λ > 160 km) depth must come from ship data. Shorter scale features may be estimated from altimetric gravity anomalies. Bandpassed grav and depth correlation determined locally, fitting soundings.

Slope, not height: simple!

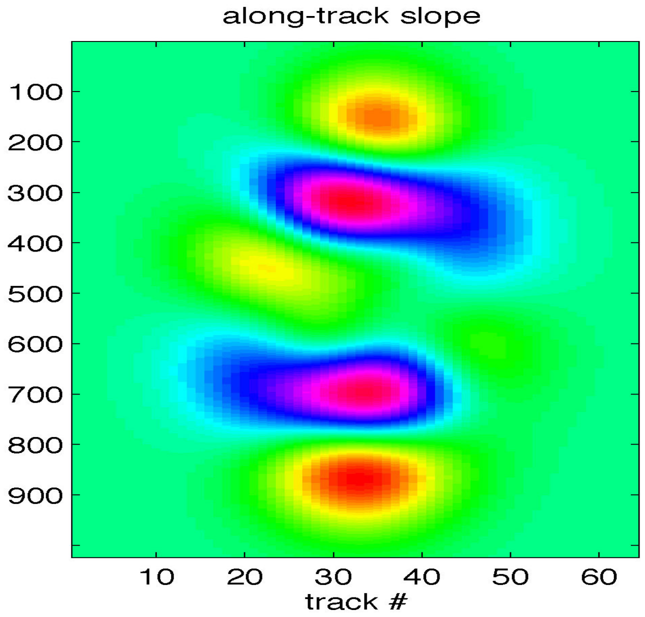


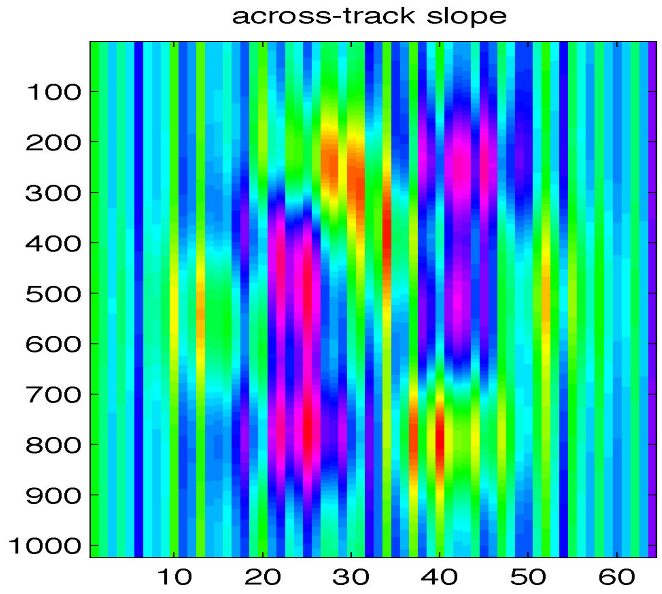
We need sea surface slope at $\lambda < 160$ km. Absolute height accuracy is irrelevant; no need for iono and meteo delays, tides, POD, SSB, etc. Desired slope precision: ideally 1 μ rad or better (1 mm height change per 1 km).

Why Not Construct Geoid Height Model and Then Convert to Gravity?

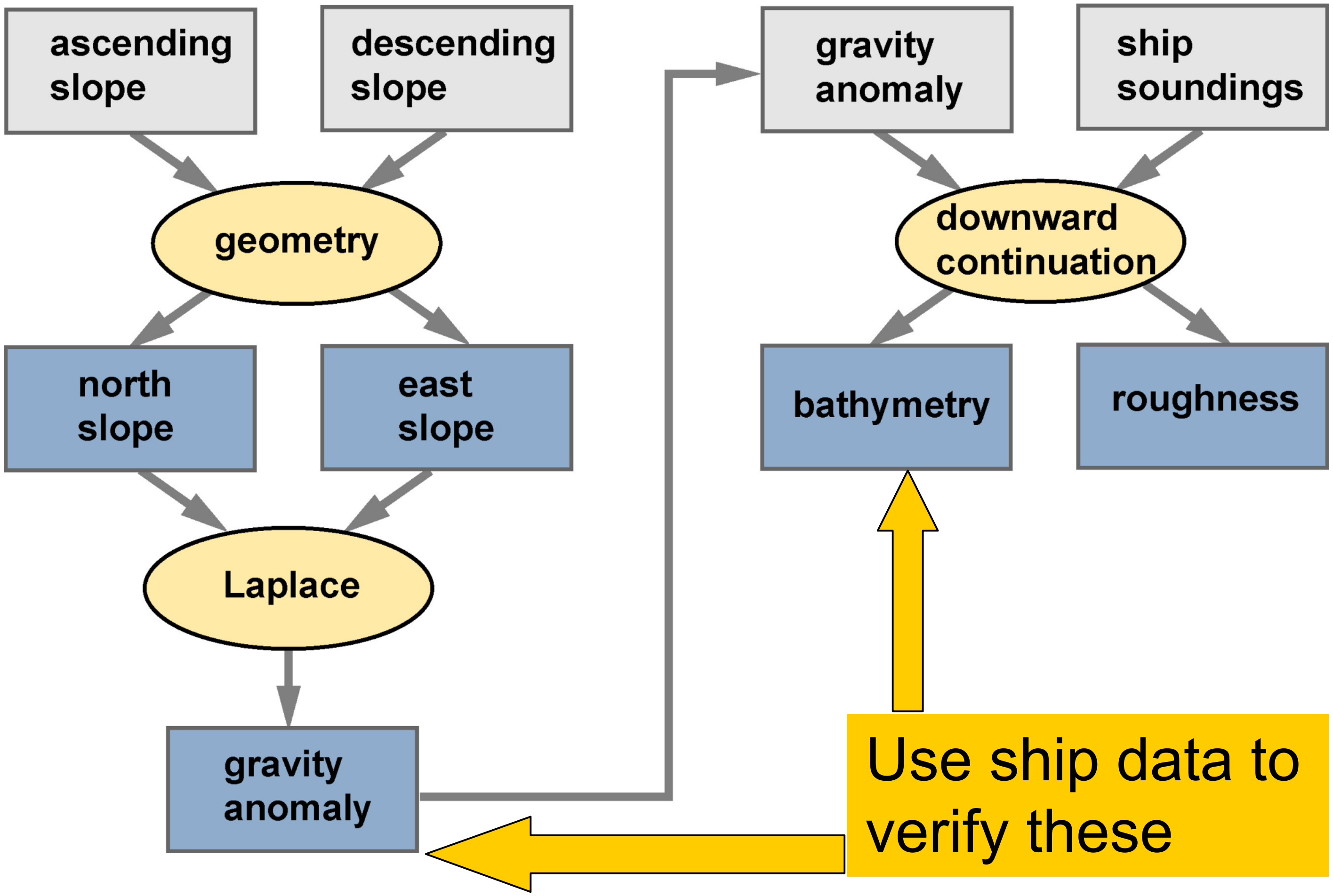


- Most errors vary slowly in time (i.e., long-λ along-track).
- Along-track derivative attenuates long- λ errors.
- Across-track derivative enhances long- λ errors.





Gridded Map Products — Flow Chart



ascending slope

descending slope

geometry

north slope

east slope

Laplace

gravity anomaly

gravity anomaly

ship soundings

downward continuation

bathymetry

roughness

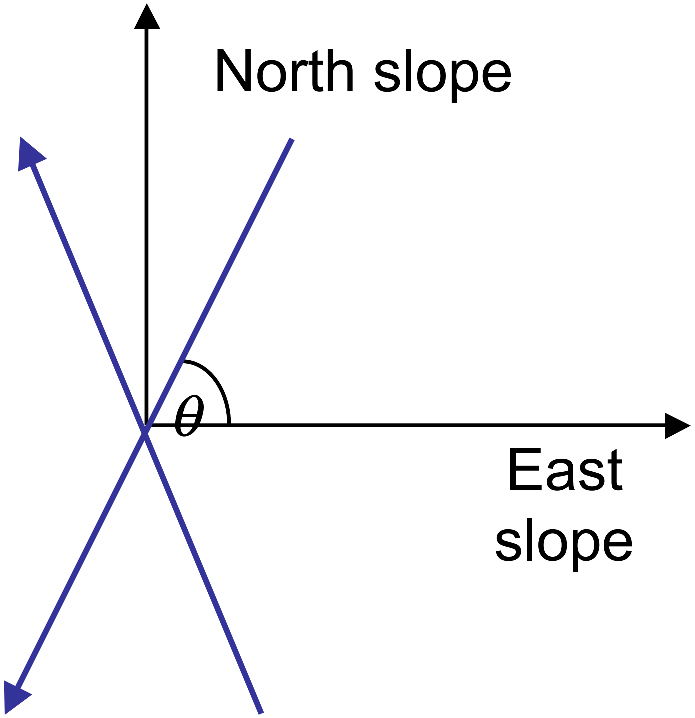
Use ship data to verify these

Orbit Inclination Controls North vs East Error Anisotropy, through Track Intersection Angle

- Error propagation
  - θ - local inclination of track
  - σ - error in along-track slope
  - σ_x - error in east slope
  - σ_y - error in north slope

$$\sigma_x = \frac{\sigma}{\sqrt{2}\cos\theta}$$

$$\sigma_y = \frac{\sigma}{\sqrt{2}\sin\theta}$$



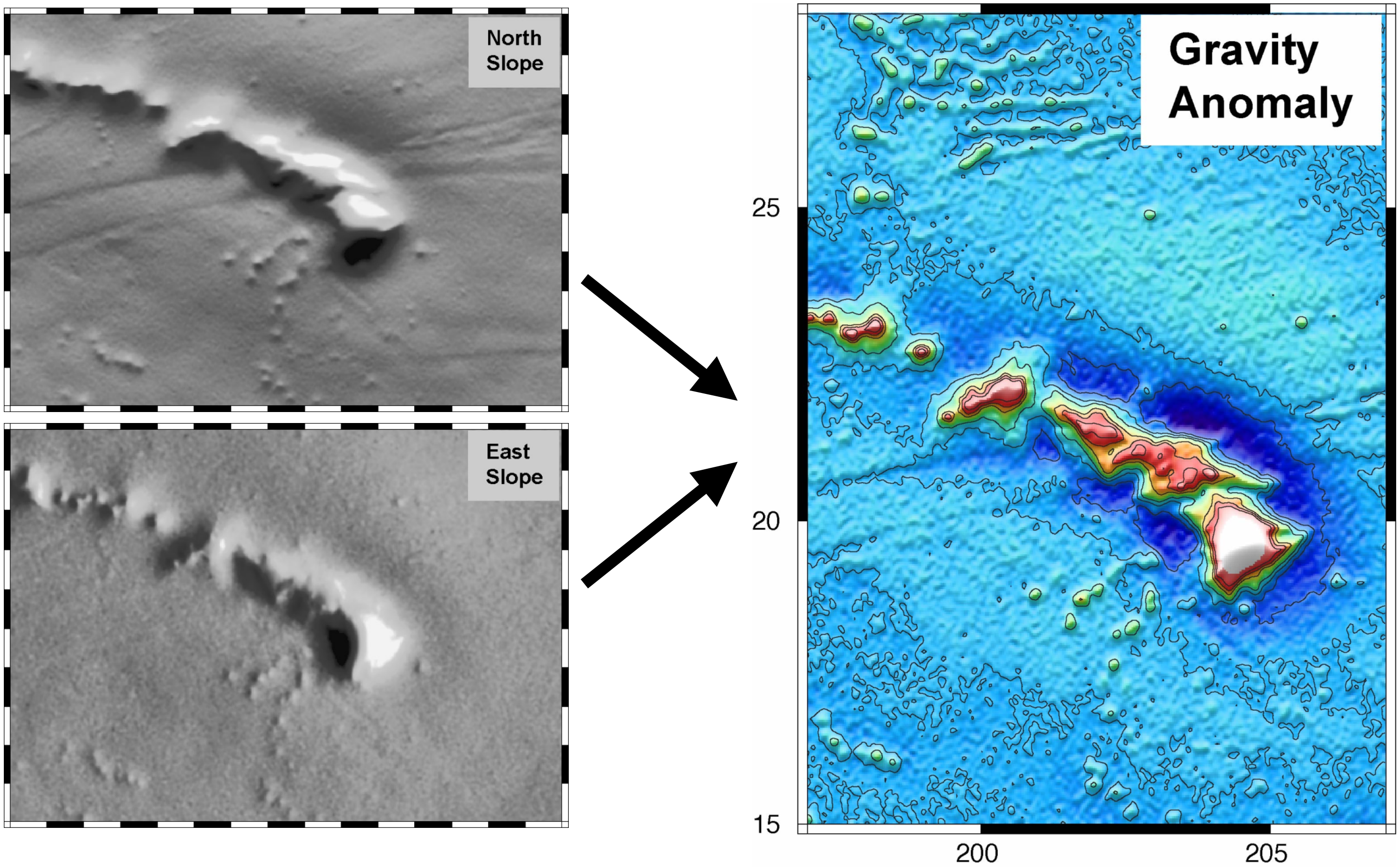
Orthogonal tracks are optimal

Gravity Grid Construction

[*Sandwell and Smith,* 1997; 2009]

Use Laplace equation to convert slopes to gravity anomaly.

Restore long-λ gravity from a model (EGM2008, GRACE, etc).



Altimetric gravity maps of Galapagos Triple Junction

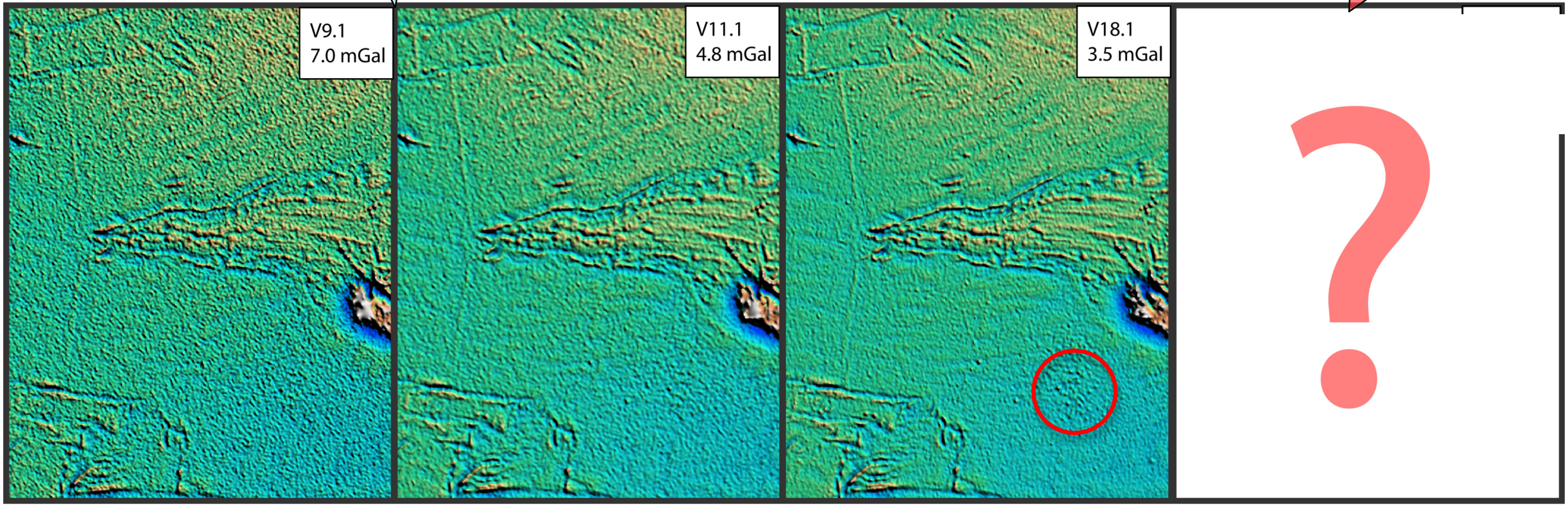
2001: ABYSS Proposal

Need new data.
CryoSat-2,
+ lower-*I* mission

original data

retracked ERS

retracked Geosat

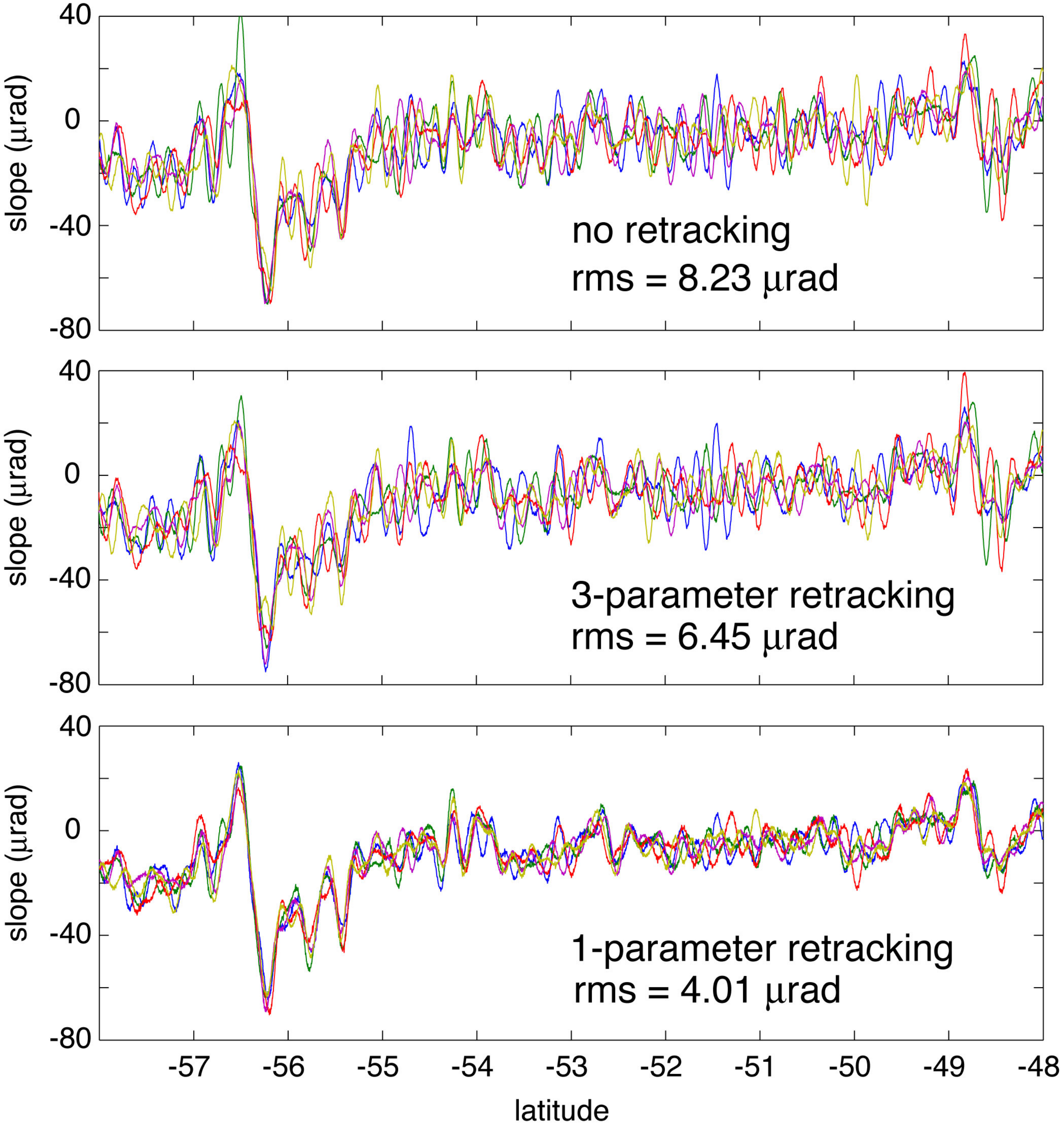


1997

2005

2009

2013 +



Retracking:

ERS-1, South Pacific, 35-day repeat profiles.

Along-track slope shown.

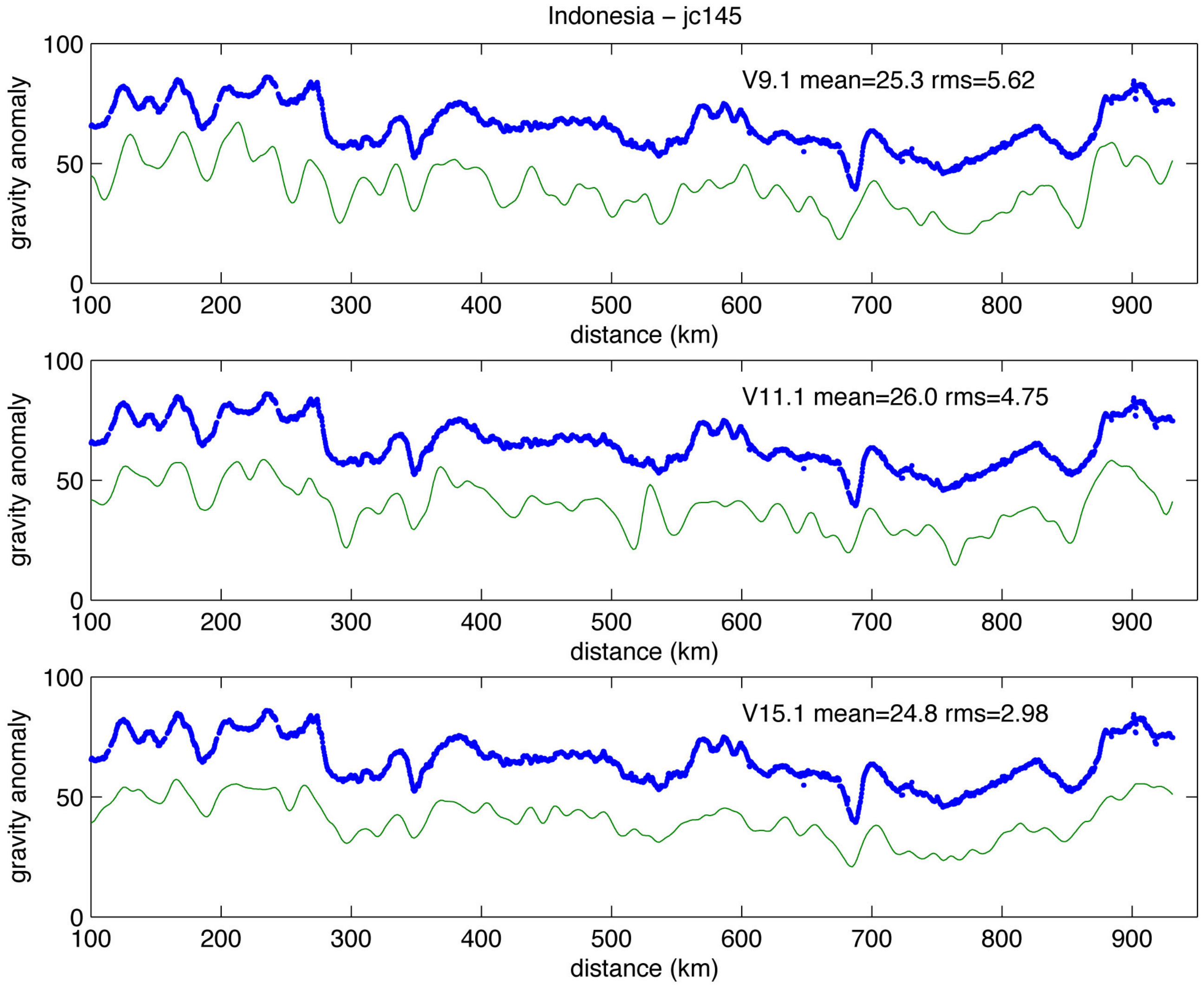
Top: on-board tracker data

Middle: 1st step.

Bottom: after smoothing SWH & refitting.

Sandwell & Smith [2005]

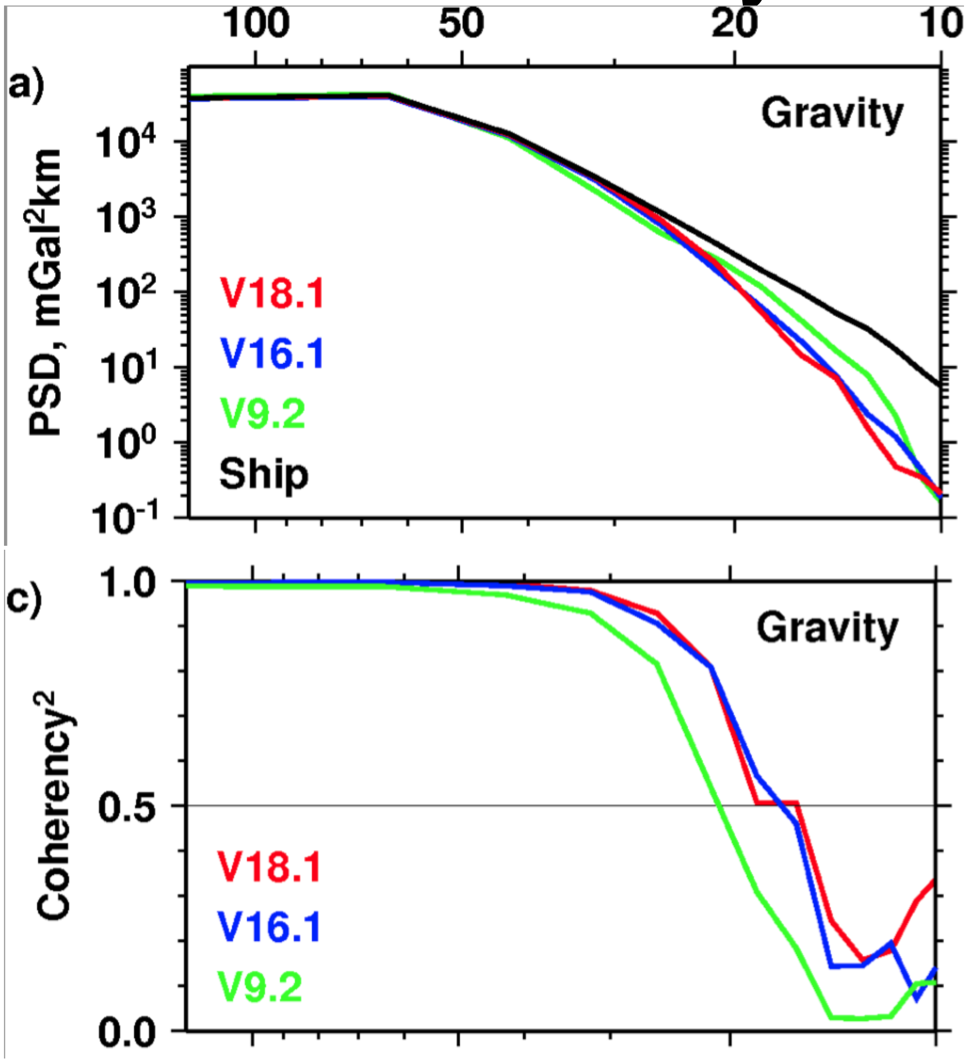
Verify altimetric *g* with ship gravimetry



Comparing our altimetric gravity with *g* measured by ships gives us a sense of the r.m.s. error, spatial resolution, and signal-to-noise ratio as a function of spatial wavelength, assuming that the ship's data are good enough.

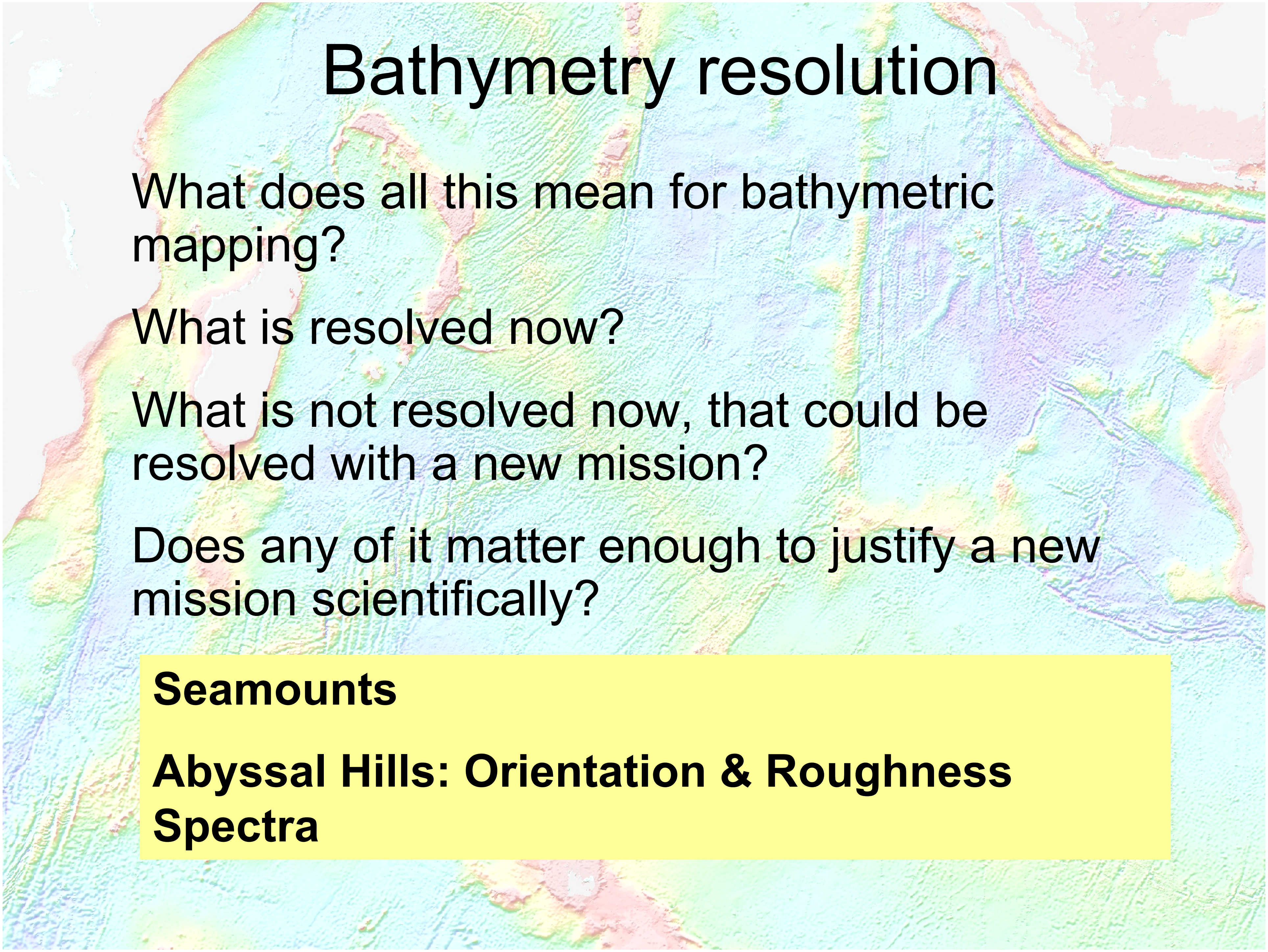
Most ship *g* is not good enough to beat our altimetry.

Gravity cross-spectra



Altimetric gravity has improved with retracking the Geosat and ERS-1 waveform data. Coherency with ship *g* has improved. Resolution is now at λ ~= 16 km, RMS error around 2–3 mGal.

Altimetric *g* PSD remains too low at $\lambda <$ 25 km, due to filters required to suppress noise in slope.



Bathymetry resolution

What does all this mean for bathymetric mapping?

What is resolved now?

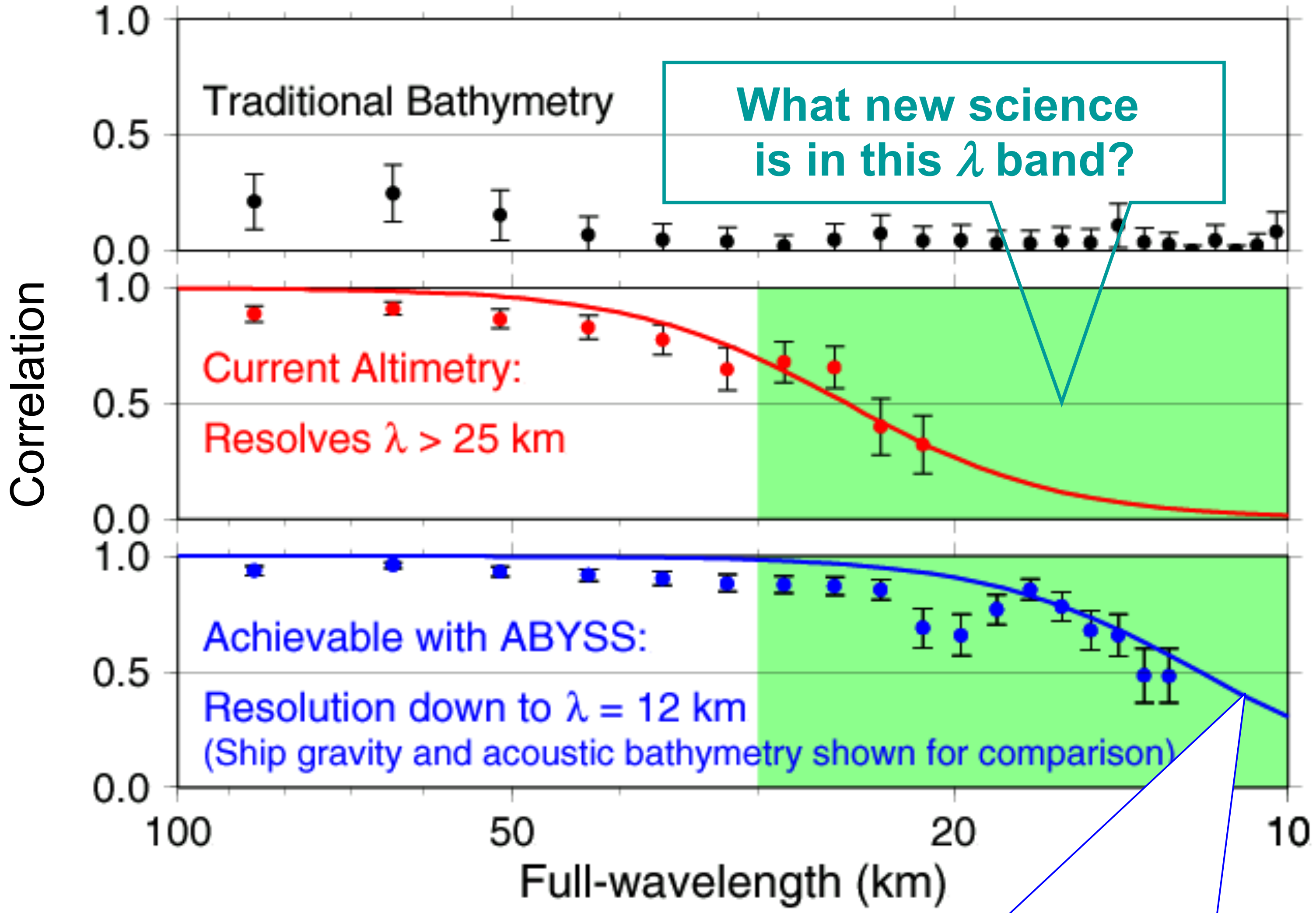
What is not resolved now, that could be resolved with a new mission?

Does any of it matter enough to justify a new mission scientifically?

Seamounts

Abyssal Hills: Orientation & Roughness Spectra

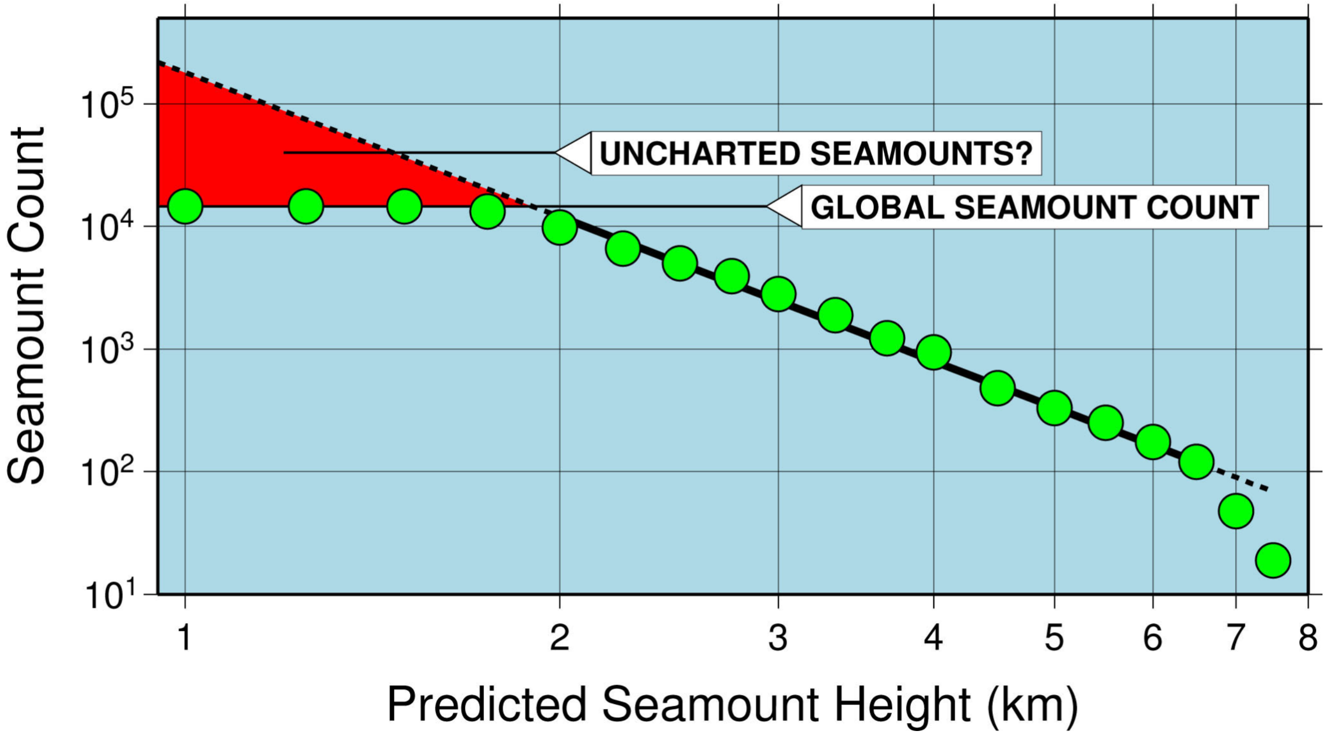
Best Possible Resolution: Measure Gravity as Well as a Ship Can (to ~1 mGal, or ~1 μrad of sea surface slope)



What new science is in this λ band?

This limit is physical, not instrumental

100,000 undiscovered seamounts

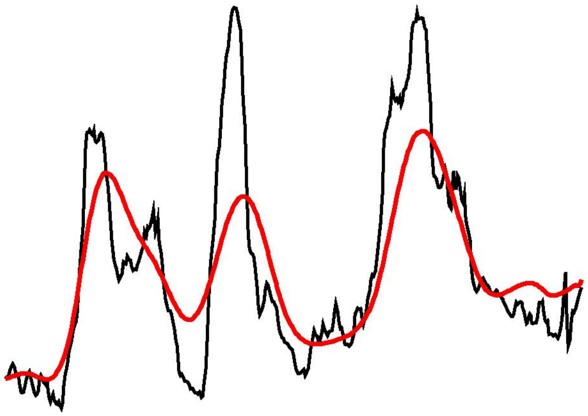


(From Wessel, JGR, 2001.)

Estimating how many things are not seen requires a statistical model.

Statistical models suggest that the number of seamounts found should continue to increase as the size of the seamounts counted gets smaller. It appears that existing altimeter data fail to find most of the seamounts that are between 1 and 2 km tall. The number of unseen seamounts > 1 km tall may be 100,000 [Wessel, 2001] or only 50,000 [Kim & Wessel, 2011].

Existing altimetry under-estimates seamount heights



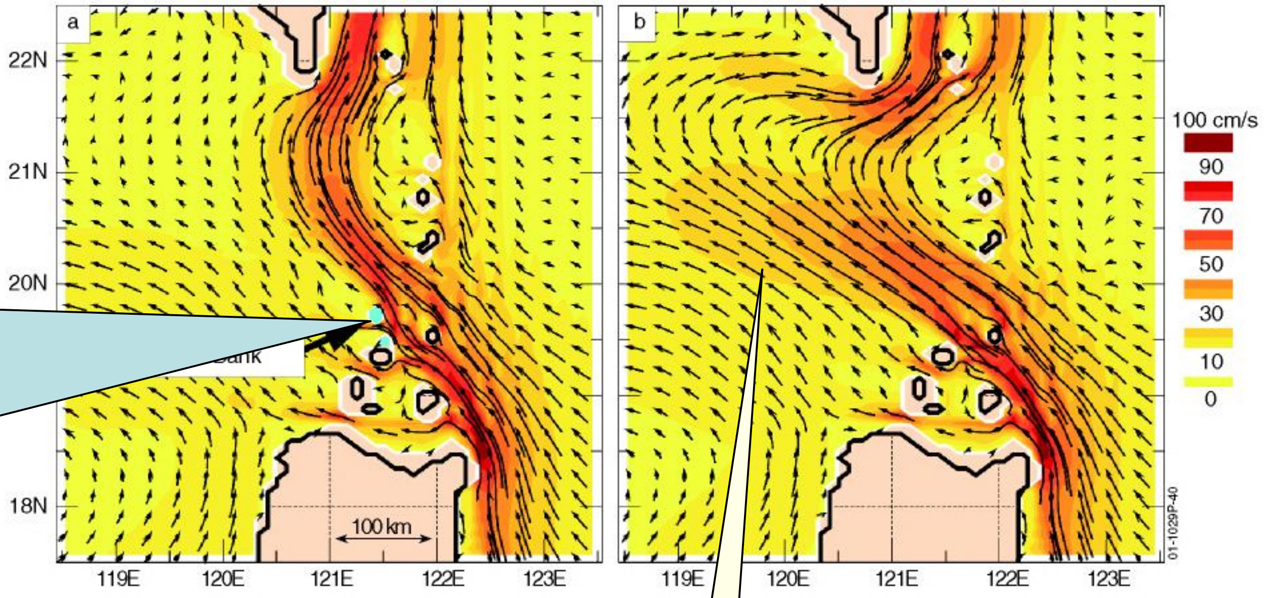
The height of seamounts estimated from altimetry (red), is often less than their true height (black).

(From work in progress by Karen M. Marks.)

This is because of the noise level in existing altimeter data. Some averaging is required to bring the noise down and this averaging produces a smoothing of the estimated sea floor. The smoothing lowers the peaks of the predicted seamounts, under-estimating the summit depth.

Fine-scale bathymetry steers currents

Forecast models require correct global bathymetry



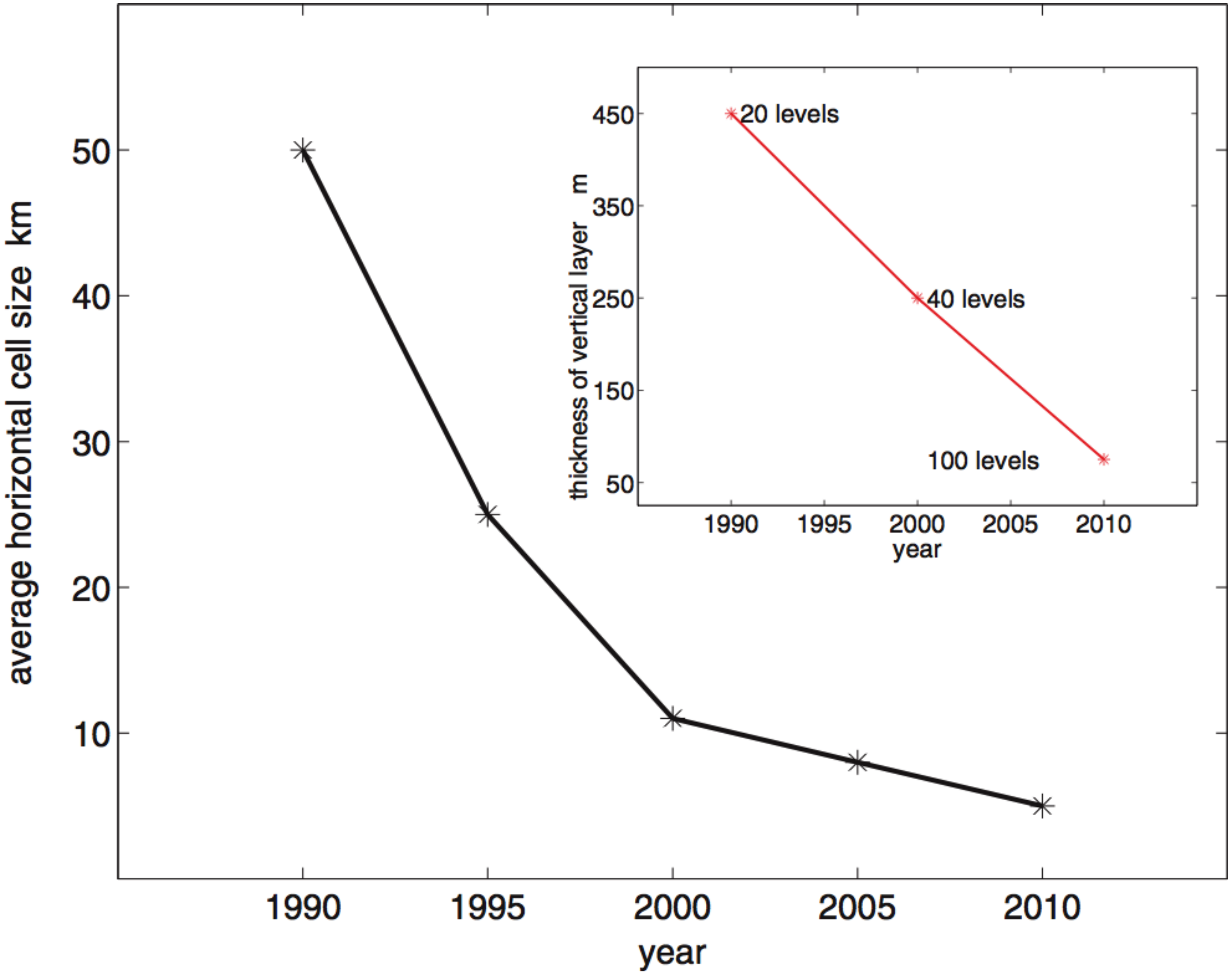
Model Bathymetry Changed Only Here

Approximates nature

Intrudes unnaturally

A single feature as small as 20 km across can steer a major current (Kuroshio mean flow in U.S. Navy model at 1/16°) [Metzger & Hurlburt, 2001]

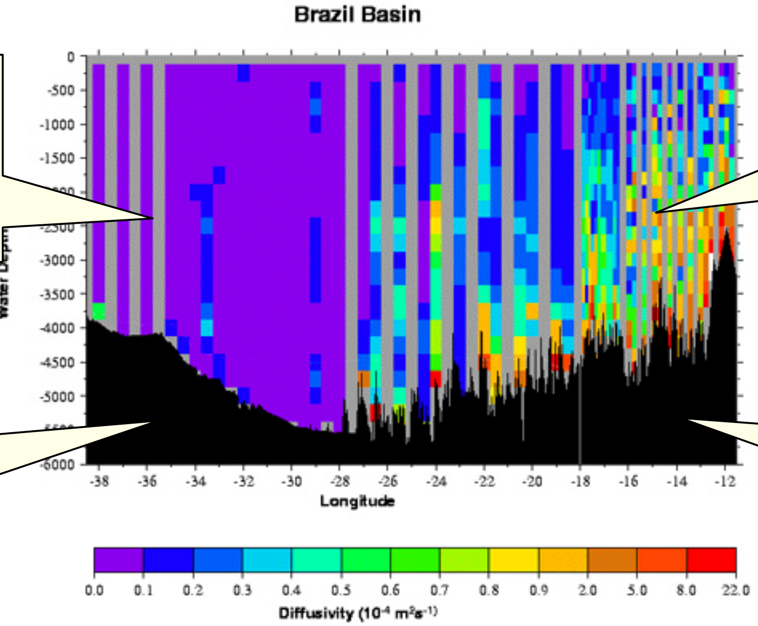
Ocean Model Resolution



Gille et al. [2004]

Ocean models need bathymetry in our λ band.

Bottom Roughness Controls Mixing



Less mixed water

More mixed water

Smoother bottom

Rougher bottom

Spatial variations in bottom roughness change mixing rates by order of magnitude (vertical diffusivity < 10^{-5} at left and > 10^{-4} at right; [Polzin et al., *Science*, 1997]).

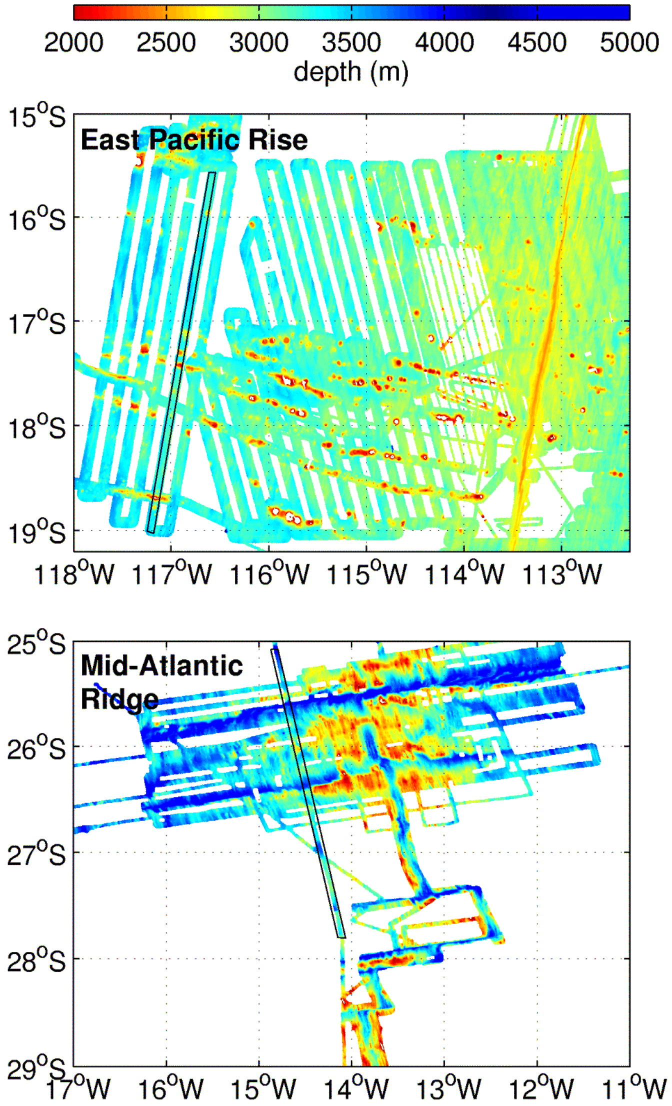
λ < 100 km bathymetry controls mixing

Seafloor spreading shapes bathymetry at these scales.

See also Ledwell et al. [1998; 2000]

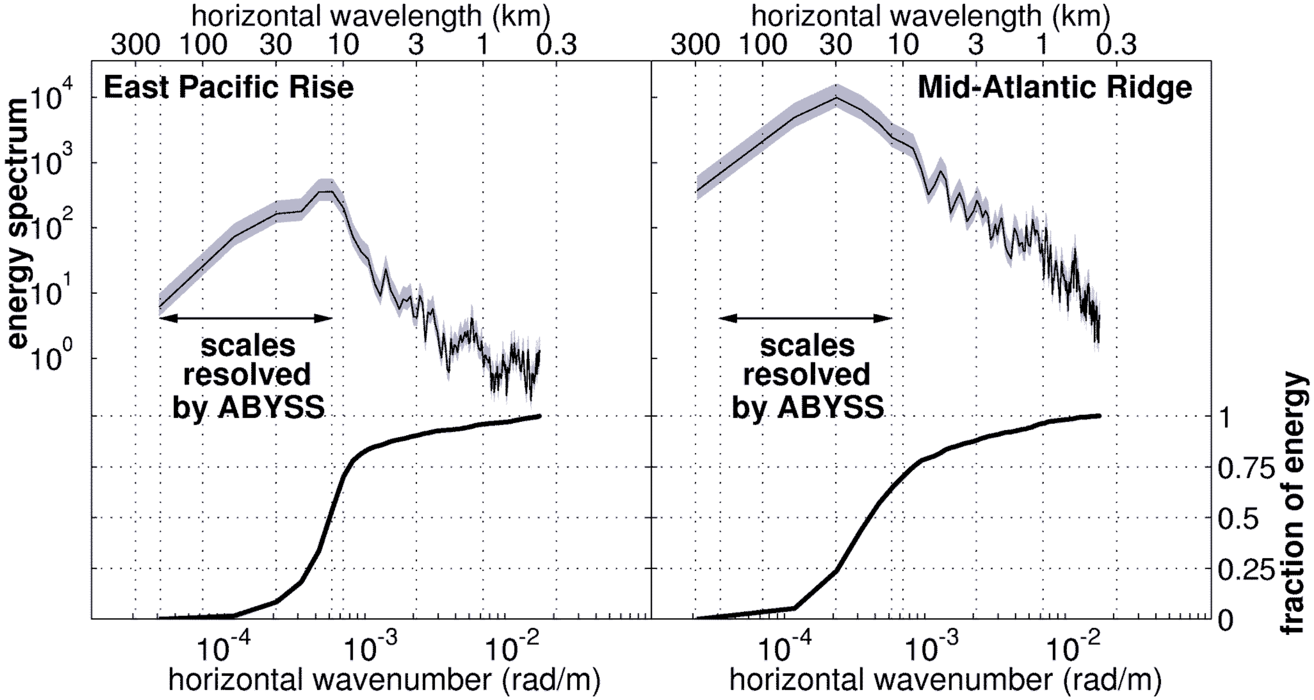
Bathymetry Data Is Needed for Modeling the Oceanic Internal Wave Field

- **Mid-ocean ridges are sites of enhanced wave generation by tidal flow**
- **The current bathymetry is <u>not</u> sufficient to resolve the spatial scales at which the majority of the internal wave generation takes place (St. Laurent and Garrett, 2002)**
- **Global coverage from space can yield the required data**



Energy Levels of Internal Waves

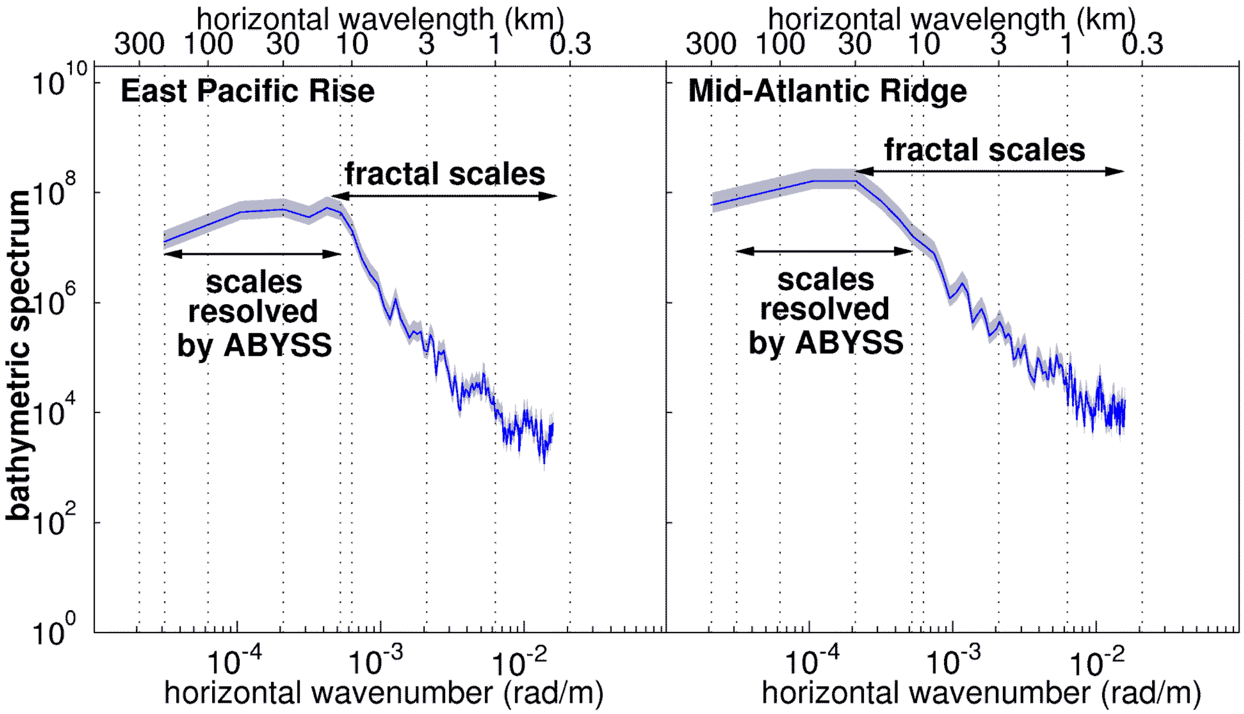
Bathymetry data is used in wave generation models to compute internal wave energy



- **Peak wave energy levels occur at a scale resolvable by an altimeter. It can capture 60-70% of the wave energy scales.**

Bathymetry Spectra Important in Mixing Studies

Algorithms exist for estimating wave energy levels supported by tidal flow (Jayne and St. Laurent, 2001), but current bathymetry data does not resolve the scale of the peak energy. A new mission can resolve this scale.

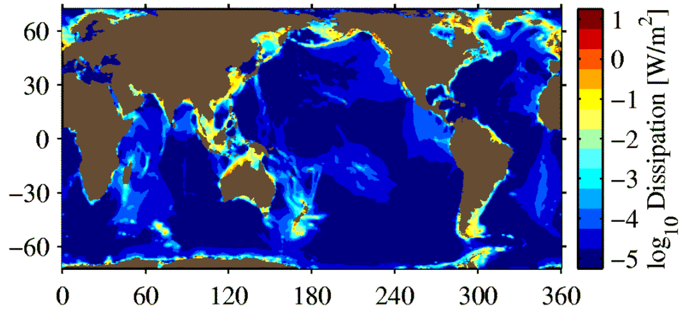


Fractal models can be used at smaller scales

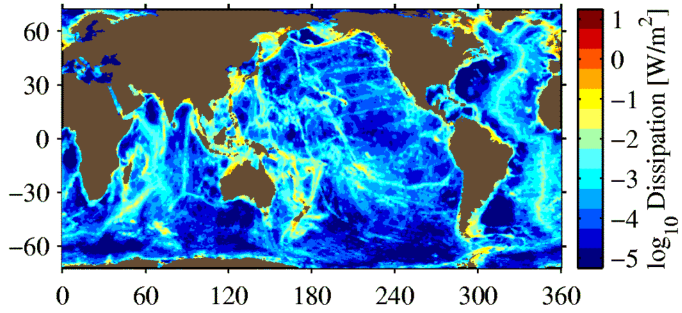
Short-scale Roughness Dissipates Tidal Energy

- **Including internal wave drag in a model of the ocean tides significantly improves the simulated tides**
- **It also significantly modifies the distribution of the tidal dissipation (Jayne and St. Laurent, 2001) to be closer to the inferred dissipation from altimetry (Egbert and Ray, 2000).**

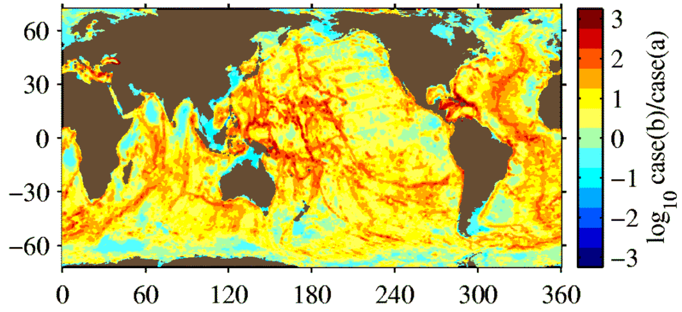
a Dissipation with bottom drag only



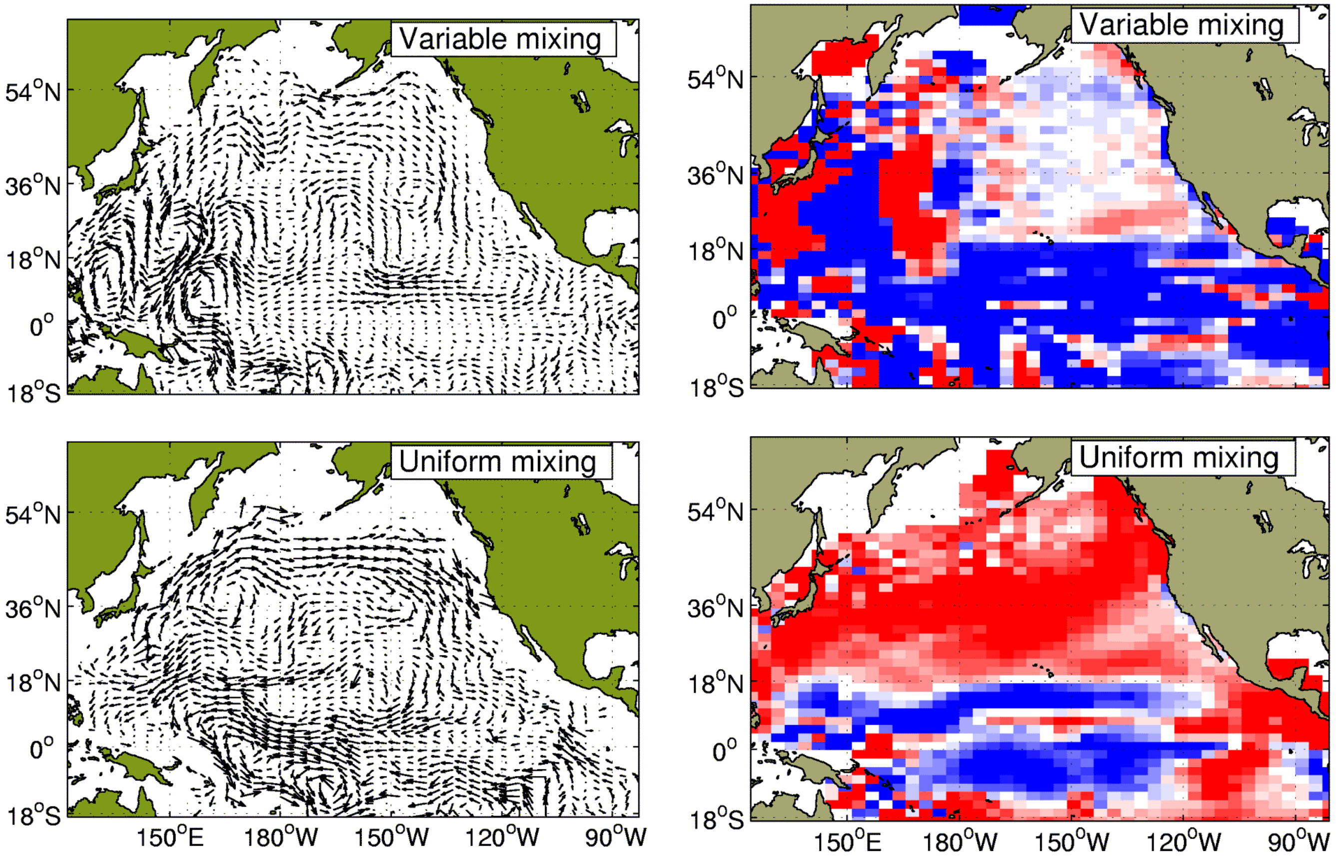
b Dissipation with internal−wave drag



c Change in dissipation between cases



Mixing affects flow



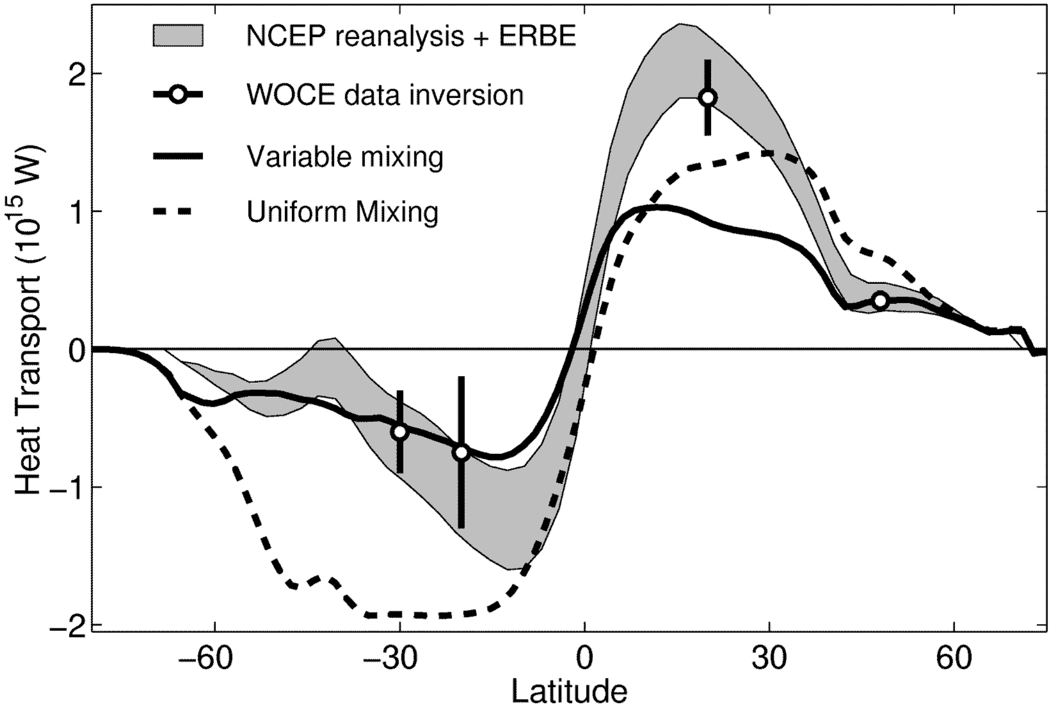
Including spatially variable deep mixing in an ocean model changes its circulation & upwelling…

[Simmons et al., 2004]

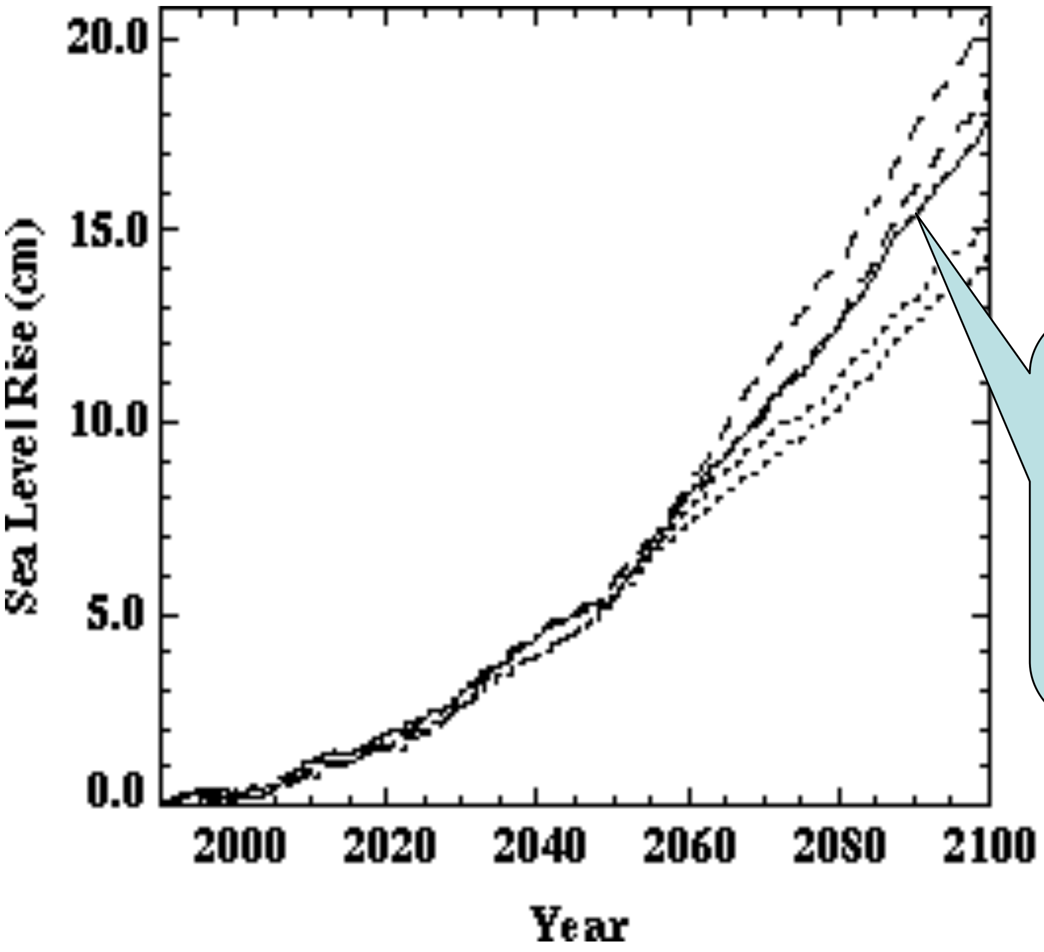
Mixing affects heat transport

…which changes the modeled meridional heat transport

[Simmons et al., 2004]



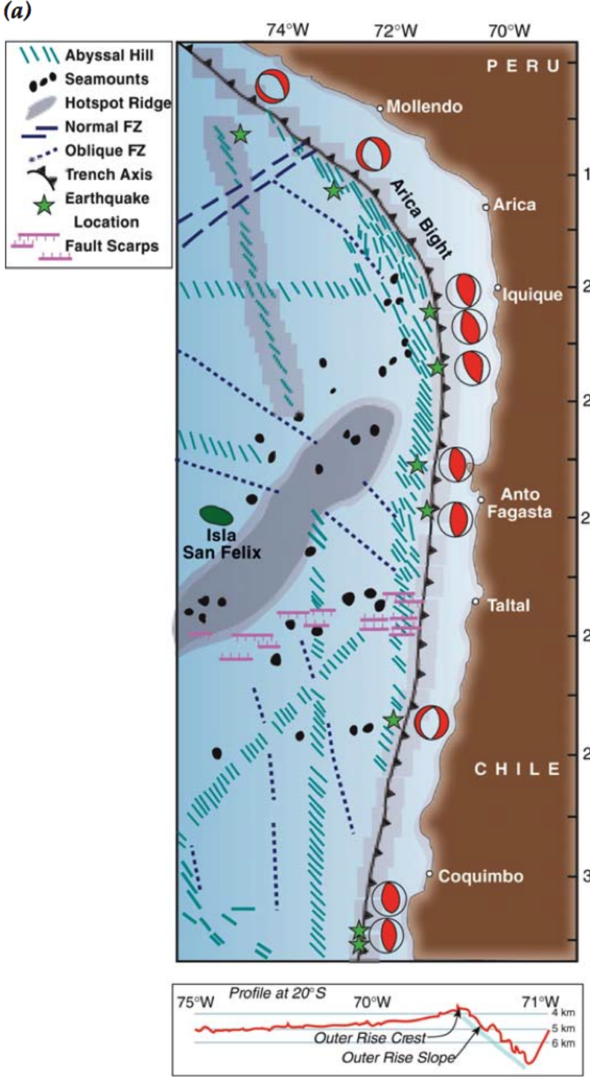
Mixing influences sea level rise

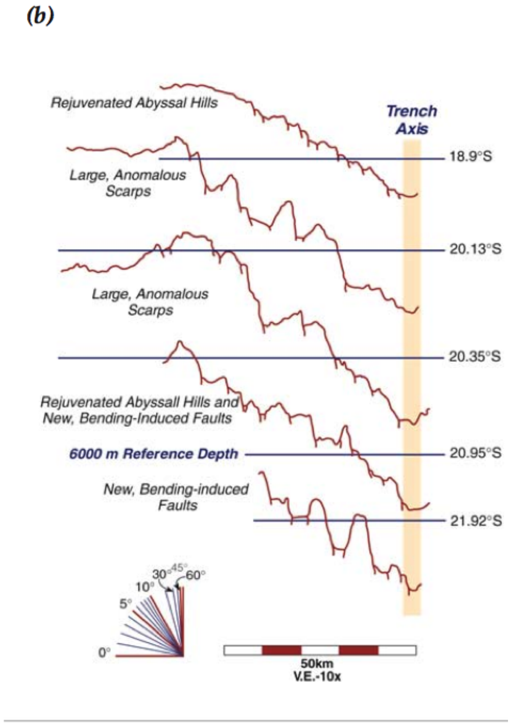


SL rise forecasts depend on models of vertical mixing in the oceans

Mixing determines rate of heat uptake, and where in the water column heat & salt go. [Sokolov et al., 1997; 1998]

Abyssal hills & tsunami hazard





When an ocean plate subducts, it bends.

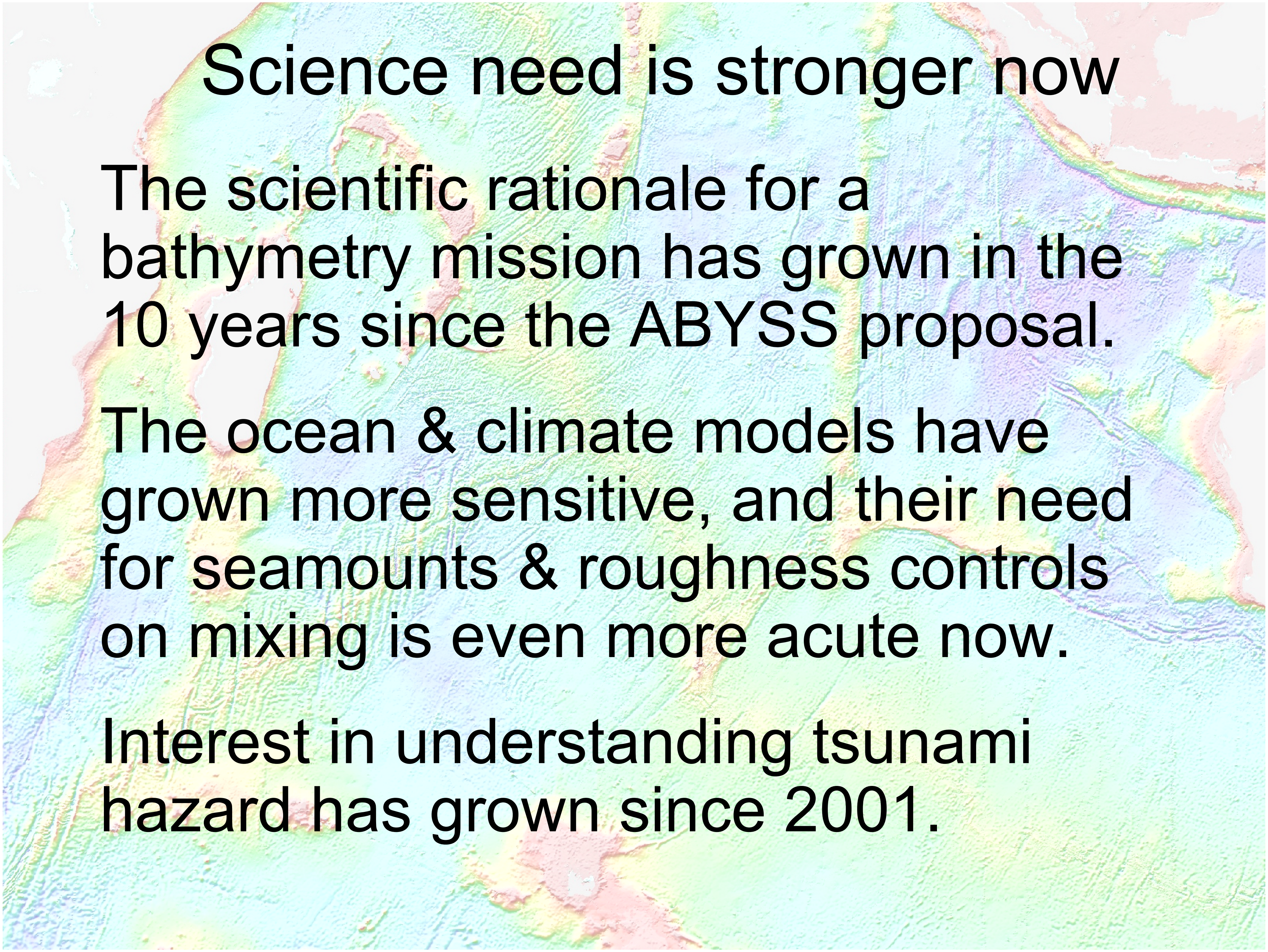
Abyssal hills hold old faults.

If the hills parallel the trench, subduction bending can use the hills' existing faults, resulting in many small earthquakes.

If the hills are at an angle to the trench, the bending must cut new faults, resulting in fewer but much larger earthquakes.

Mofjeld et al. [2004]

Science need is stronger now

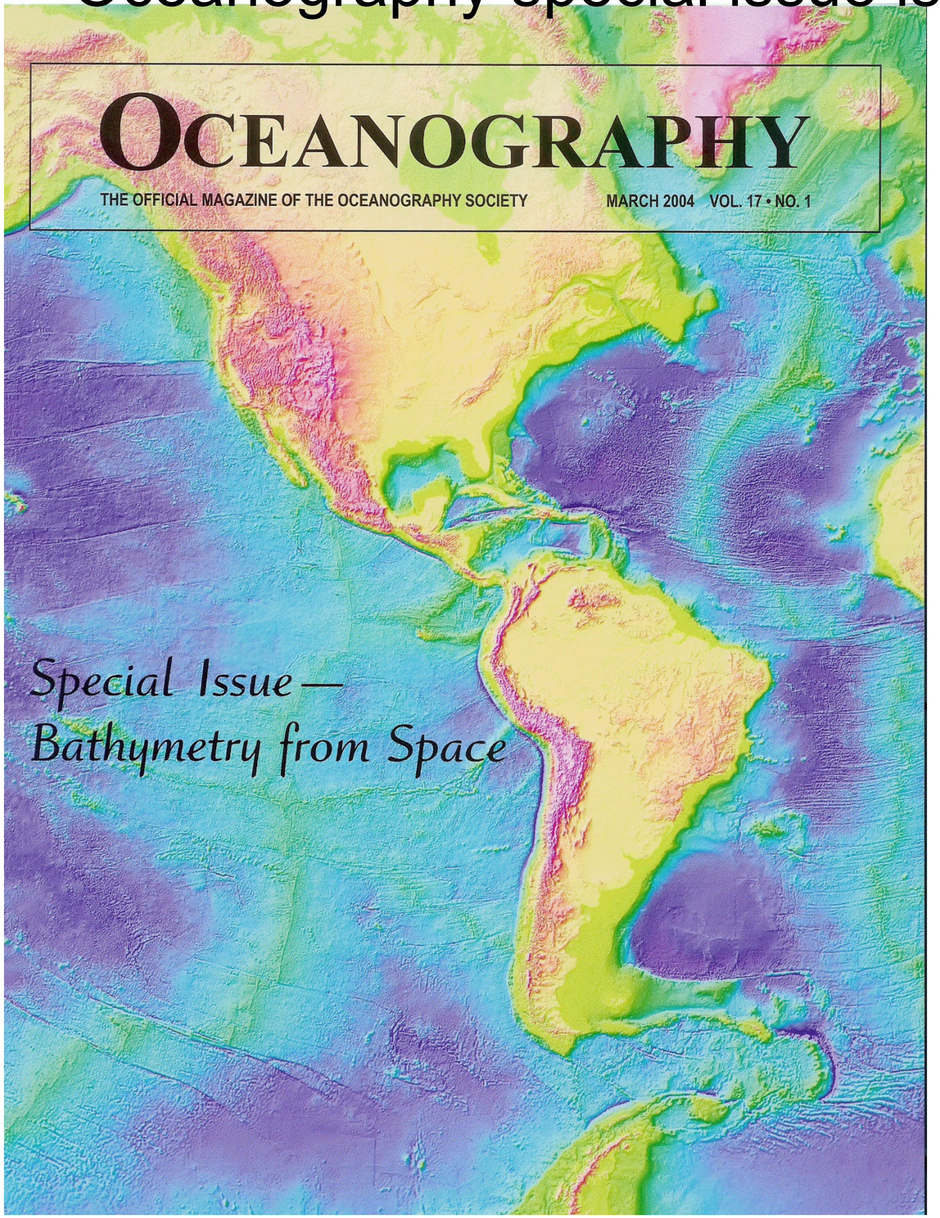


The scientific rationale for a bathymetry mission has grown in the 10 years since the ABYSS proposal.

The ocean & climate models have grown more sensitive, and their need for seamounts & roughness controls on mixing is even more acute now.

Interest in understanding tsunami hazard has grown since 2001.

A change since 2001: the science is further documented.
Oceanography special issue is free at www.tos.org

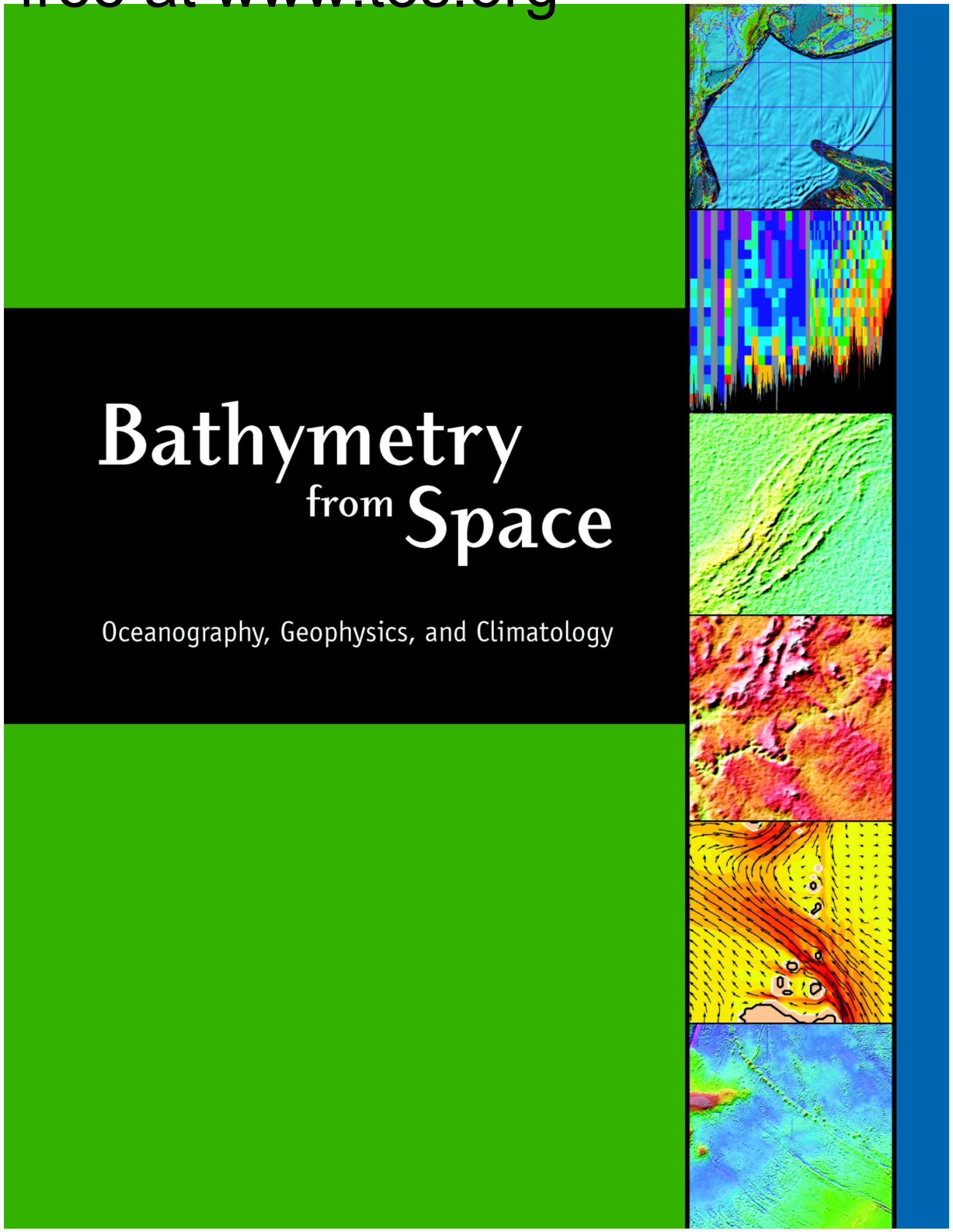


OCEANOGRAPHY

THE OFFICIAL MAGAZINE OF THE OCEANOGRAPHY SOCIETY

MARCH 2004 VOL. 17 • NO. 1

Special Issue —
Bathymetry from Space



Bathymetry
from Space

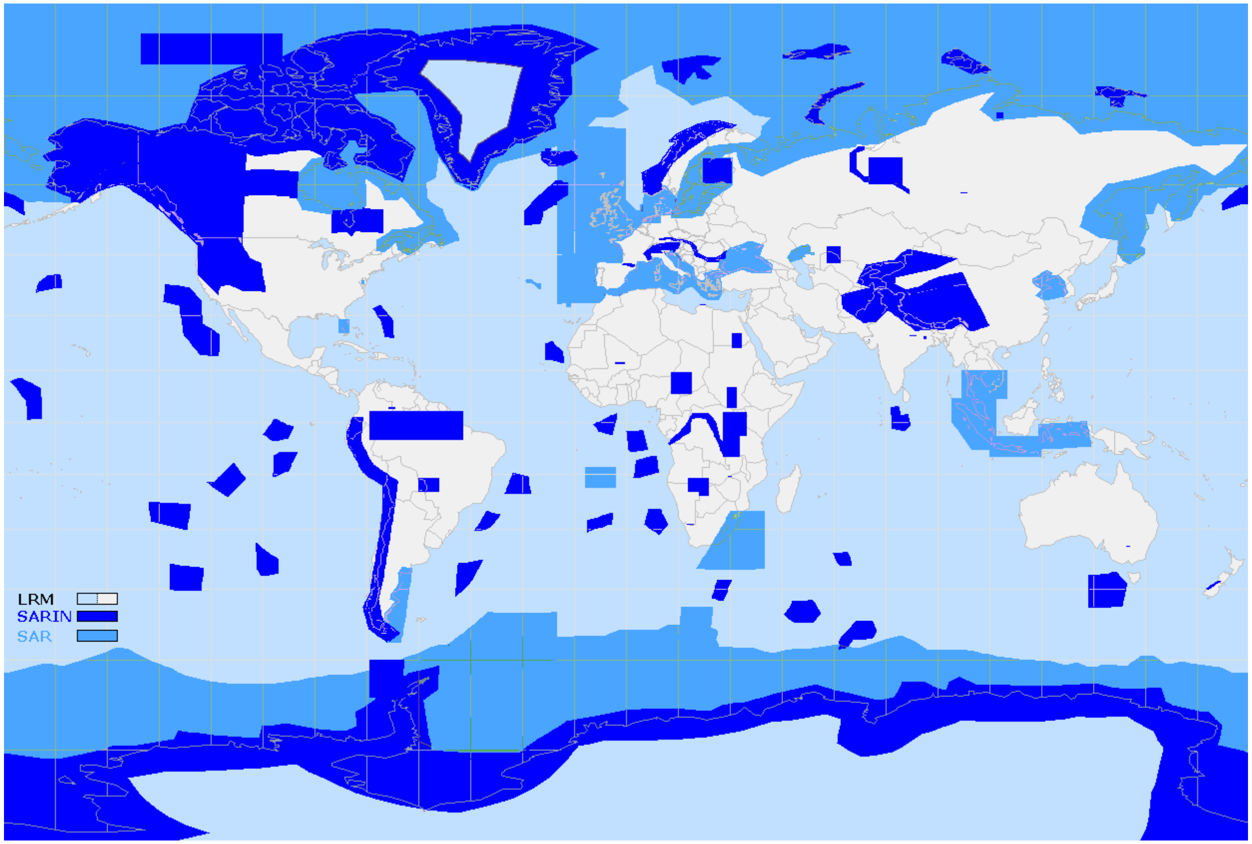
Oceanography, Geophysics, and Climatology

Measurement requirements?

- Improved range precision by a factor of 3 to 4 (or more, if possible).
  - Slope to 1 μrad (ideally $1/\sqrt{2}$) at $\lambda = 12$ km
- Fine track spacing (5 km or less).
  - 1 km tall seamounts are ~5 km wide. Orbit non-repeat for 1.5 years or more. (Six year mission cuts range error by 2x via avging.)
- Moderate inclination ($I = 125^\circ$ retrograde or $I = 50^\circ$ prograde is optimal).
  - Minimize slope error anisotropy over ocean. (80% of ocean, more of ice-free, covered.)

Requirements are essentially unchanged since ABYSS

CryoSat-2: launched 2010



Polar inclination won't resolve east-west slope.

7.5 km track spacing, compared to 5 km from Geosat.

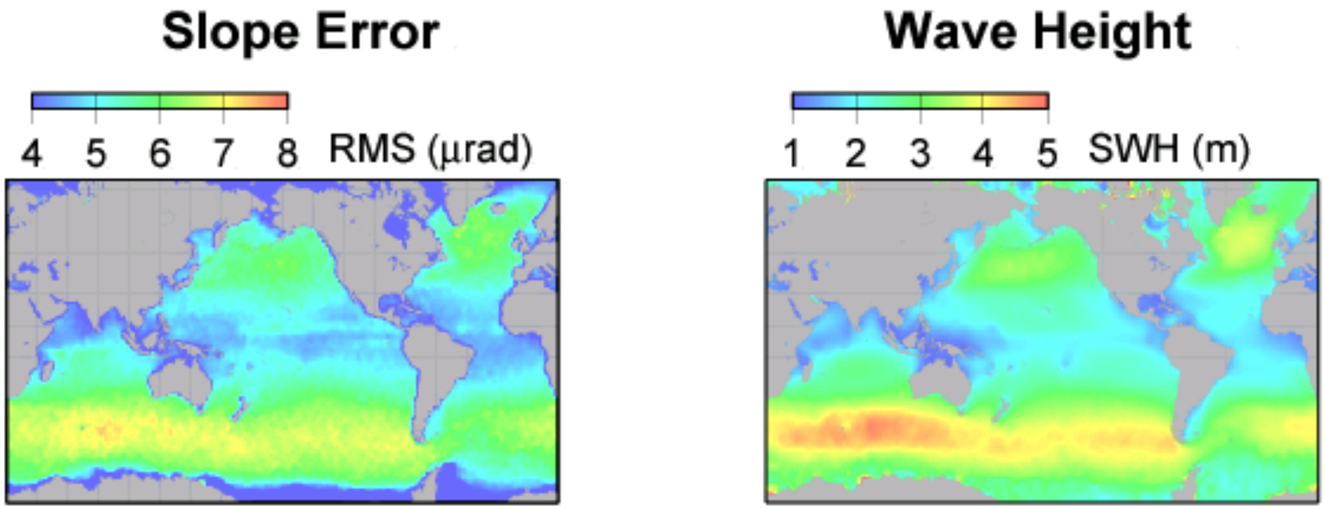
3 operating modes: LRM, SAR, SARIn

LRM (conventional) covers most of ocean; PRF=1920 Hz should reduce north-south slope noise to 0.72 of Geosat.

We are using SAR mode to space test delay-Doppler.

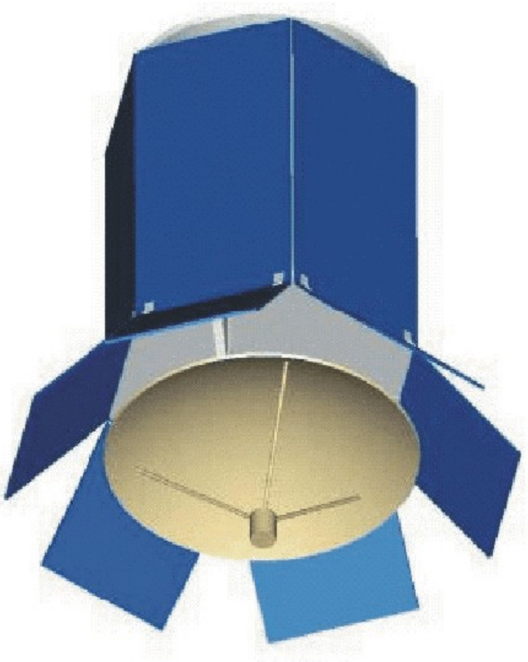
Another change since 2001: noise sensitivity to wave height?

In the ABYSS proposal we said that slope error increases as wave height increases. This was a secondary driver of the selection of the delay-Doppler altimeter. (Figure from ABYSS proposal shown here.)



With the two-step retracking of Sandwell & Smith [2005], this effect is greatly reduced. We still need an advanced altimeter, but wave height isn't a big problem.

ABYSS-Lite Baseline Design



Target cost*: less than $60 M

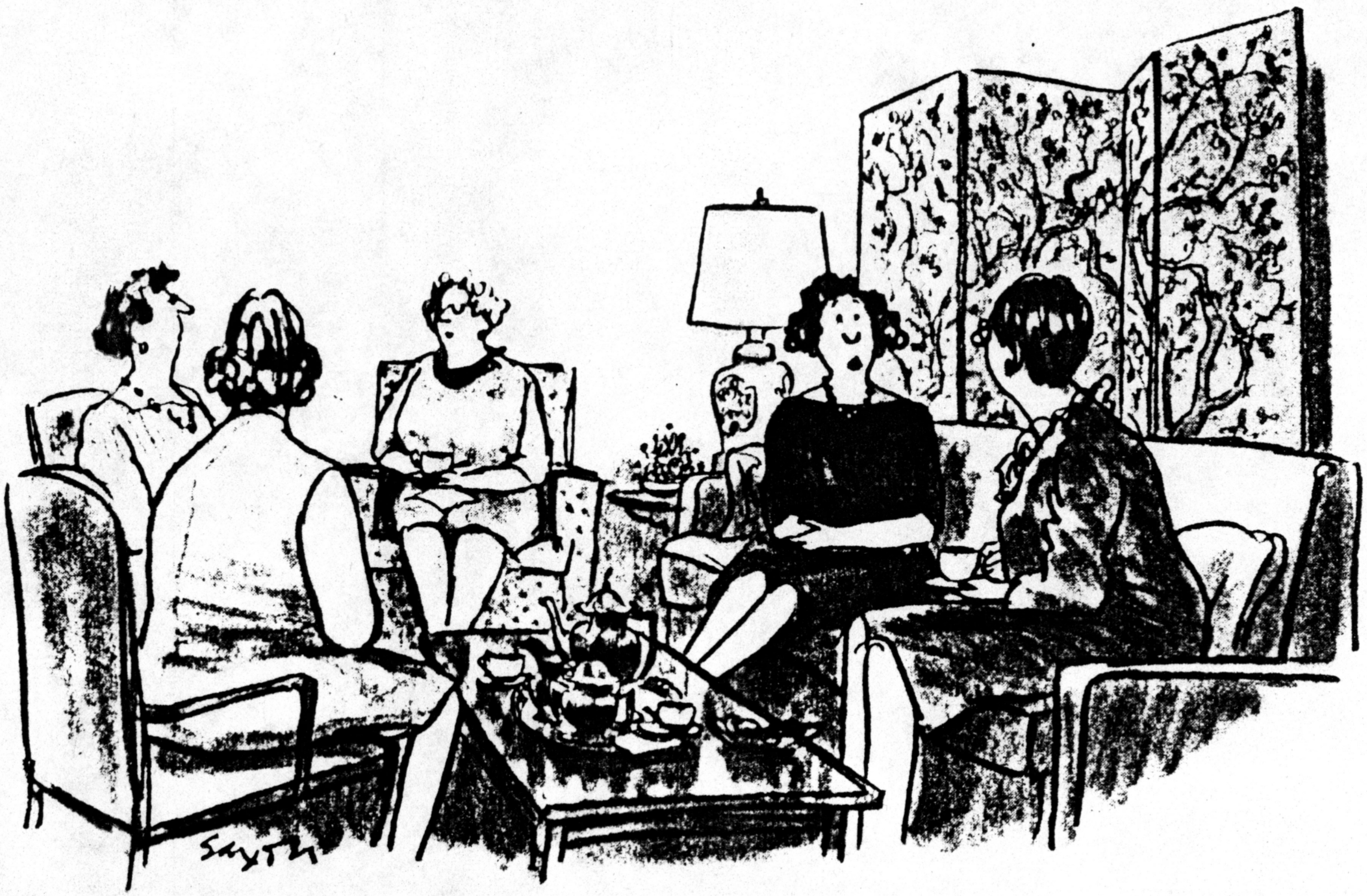
Radar mass (kG)	~ 28
Spacecraft mass (kG)	148
Antenna diameter (m)	1.0
Science data rate (Kb/s)	25 (average)
Radar power (W)	< 75 (fixed solar arrays)
D/L data rate (Mb/s)	4 (two days of data, 10 min)
Navigation	Star-trackers & GPS
Attitude control	Pitch wheel and torque rods
Launch	Pegasus (60 degrees#)

**Excluding reserves and launch vehicle*

#*Additional cost of retrograde orbit TBD*

What's in a name?

- GANDALF
  - Gravity Anomaly Detection from Space Station Alpha
- ABYSS
  - Altimetric Bathymetry from Surface Slopes
- DEPTHSat
  - Deep Environment Probe - Tsunami Hazard Satellite
- ?????



"I don't know why I don't care about the bottom of the ocean, but I don't."