



# **Bathymetry from Space**

**Mapping ocean depths  
with  
satellite altimetry**

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**Silver Spring, Maryland**



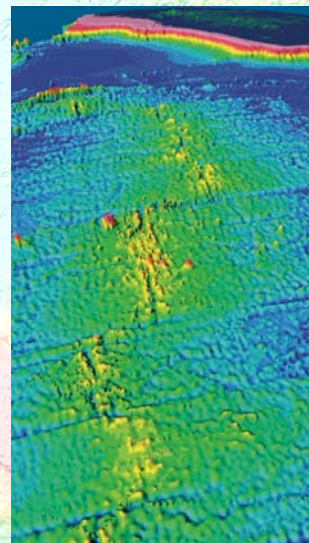
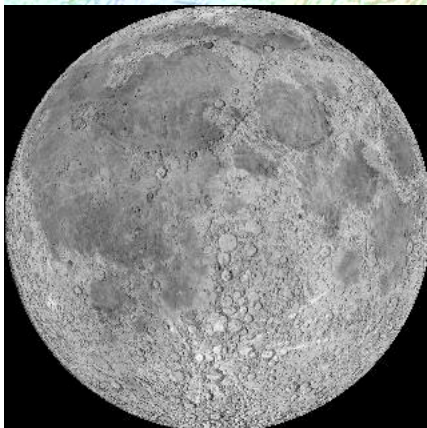
# Earth's depths are mostly unmeasured

"...an ocean less charted than the surface of the moon", H. Sverdrup, *California Monthly*, December 1940.

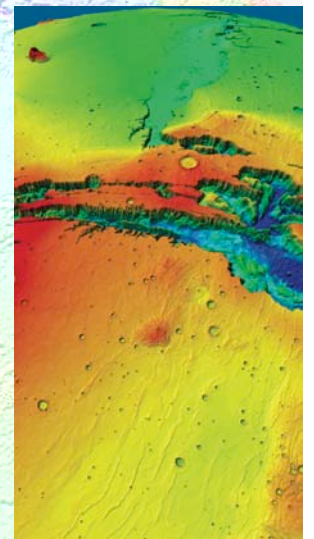
"We know less about the ocean's bottom than the moon's behind", A. F Spilhaus Sr. (?), Apollo era.

Today, Mars, Venus, Moon and some asteroids are better mapped than Earth's ocean floors.

Moon

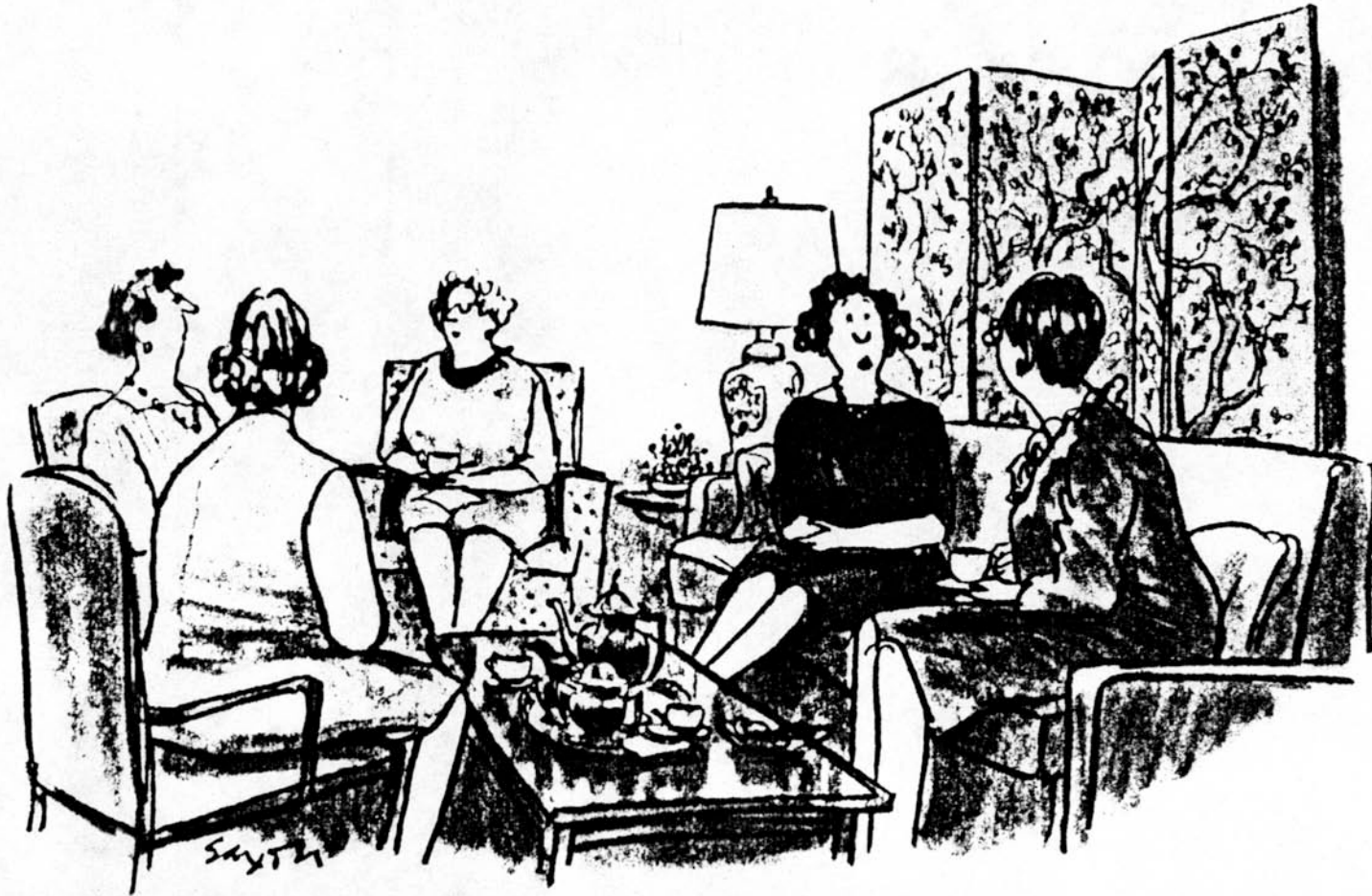


Mars (right) is 15x better horizontally and 250x better vertically than Earth's ocean (left).

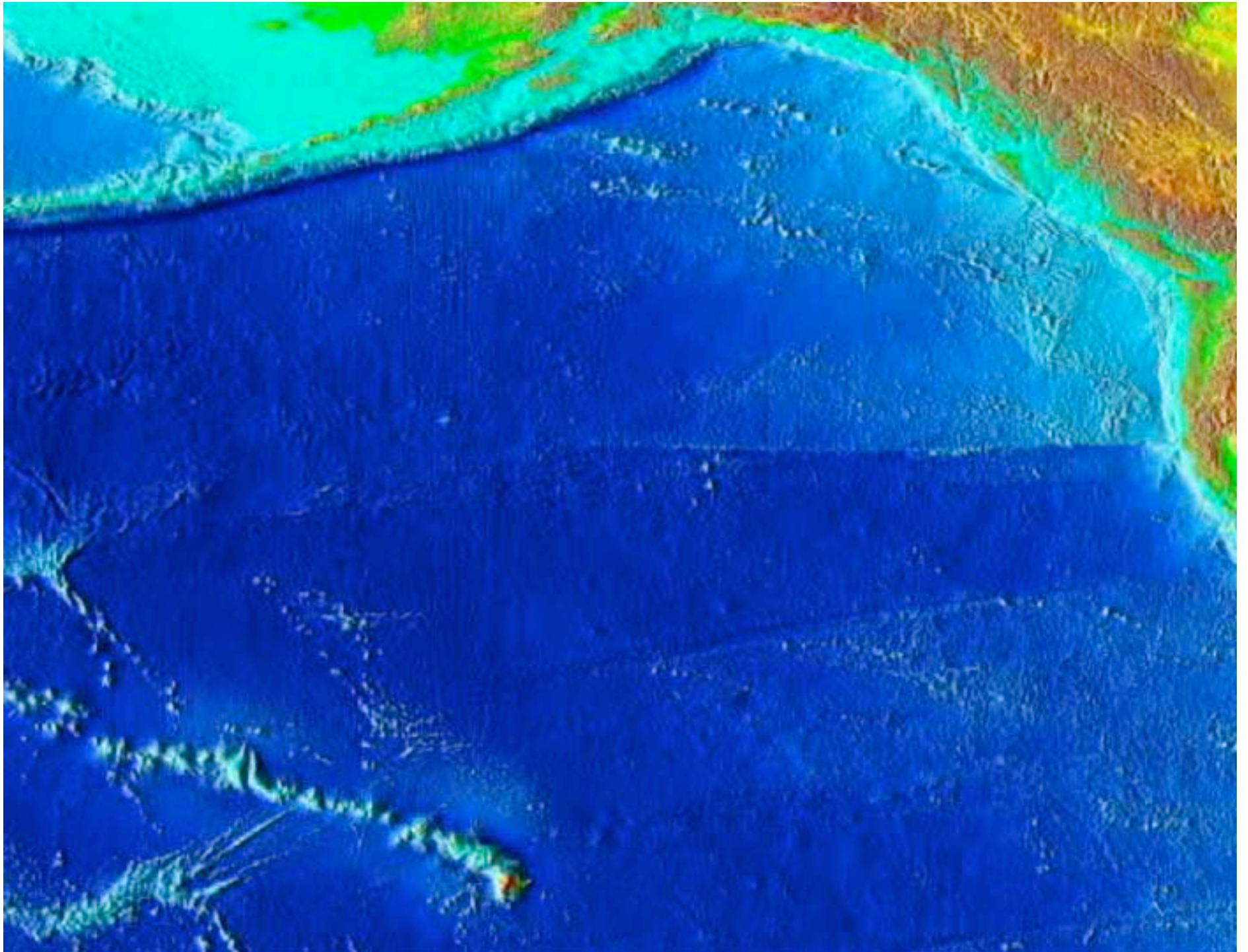




# Why care about the ocean's bottom?



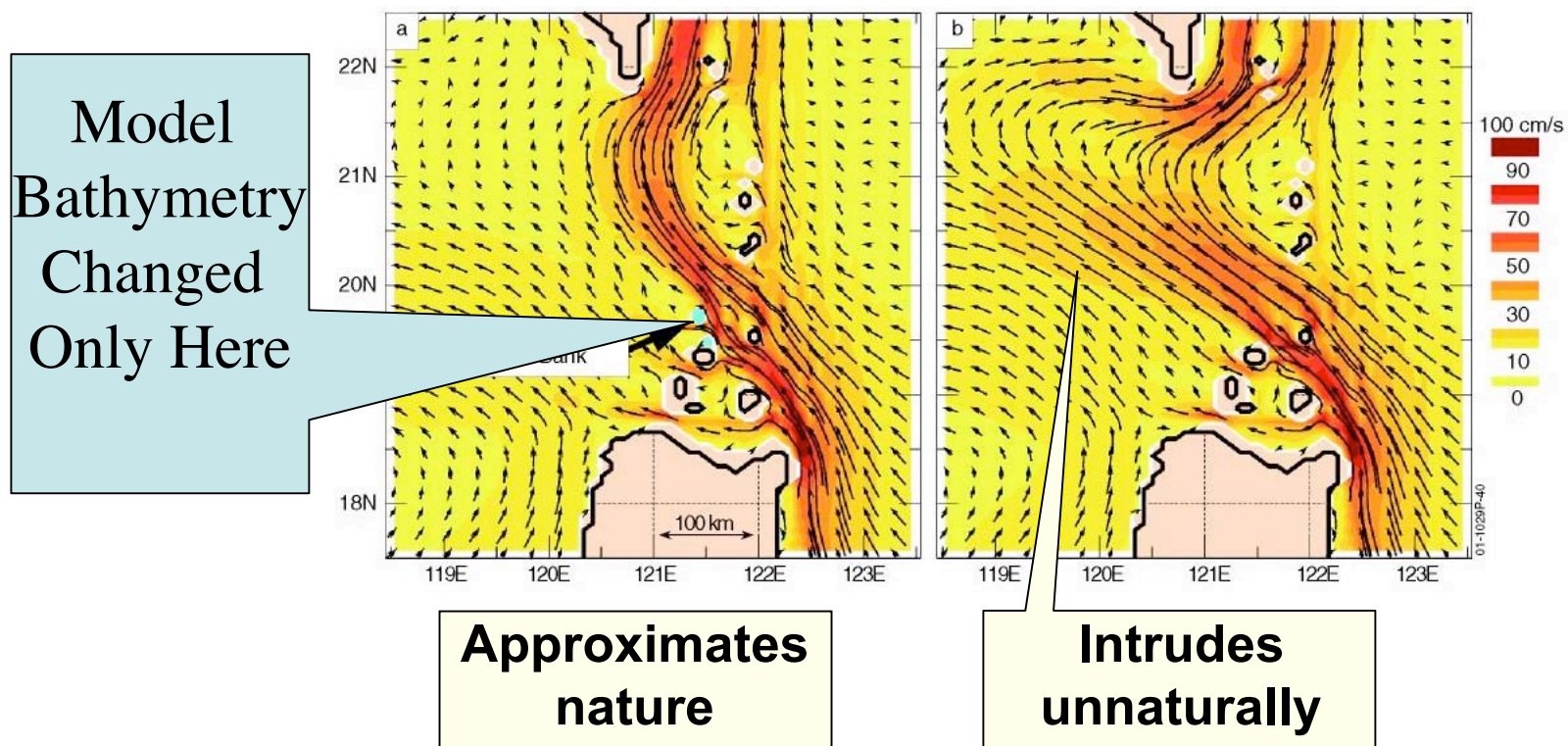
*"I don't know why I don't care about the bottom  
of the ocean, but I don't."*





# Fine-scale bathymetry steers currents

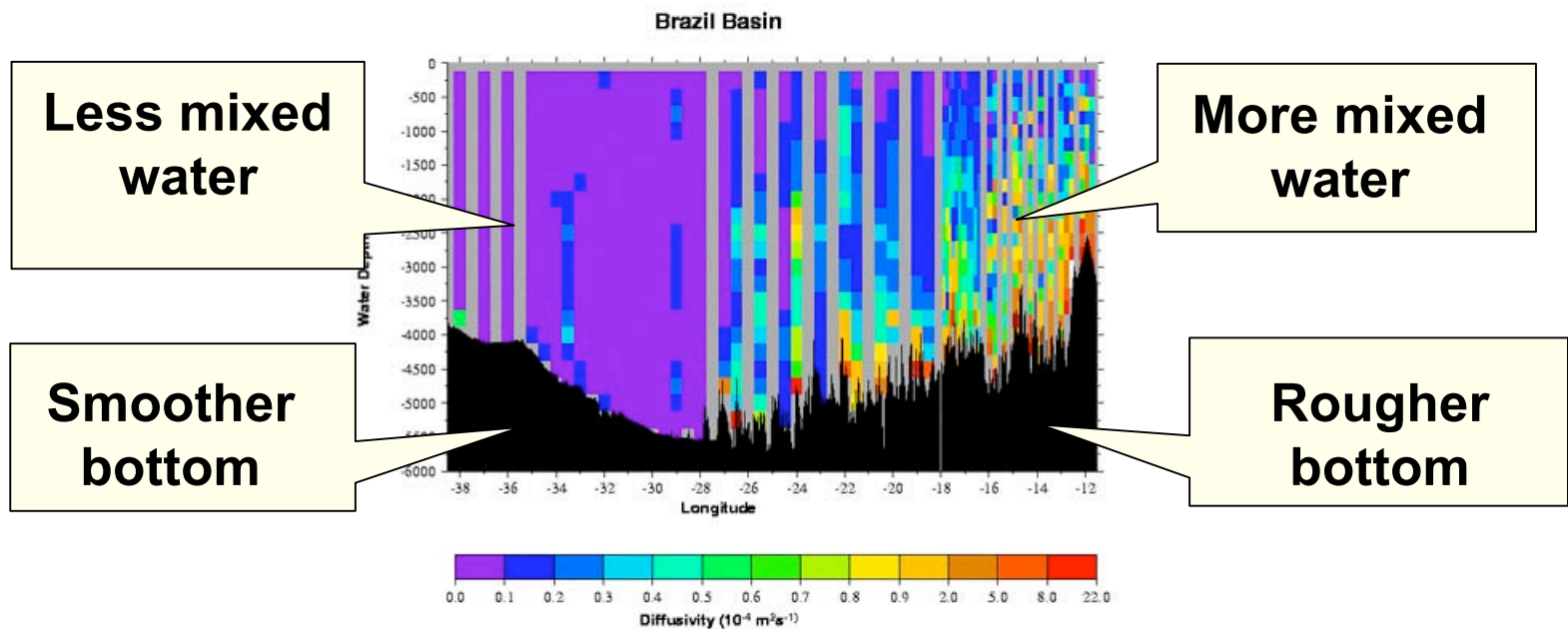
Forecast models require correct global bathymetry



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



# Bottom Roughness Controls Mixing

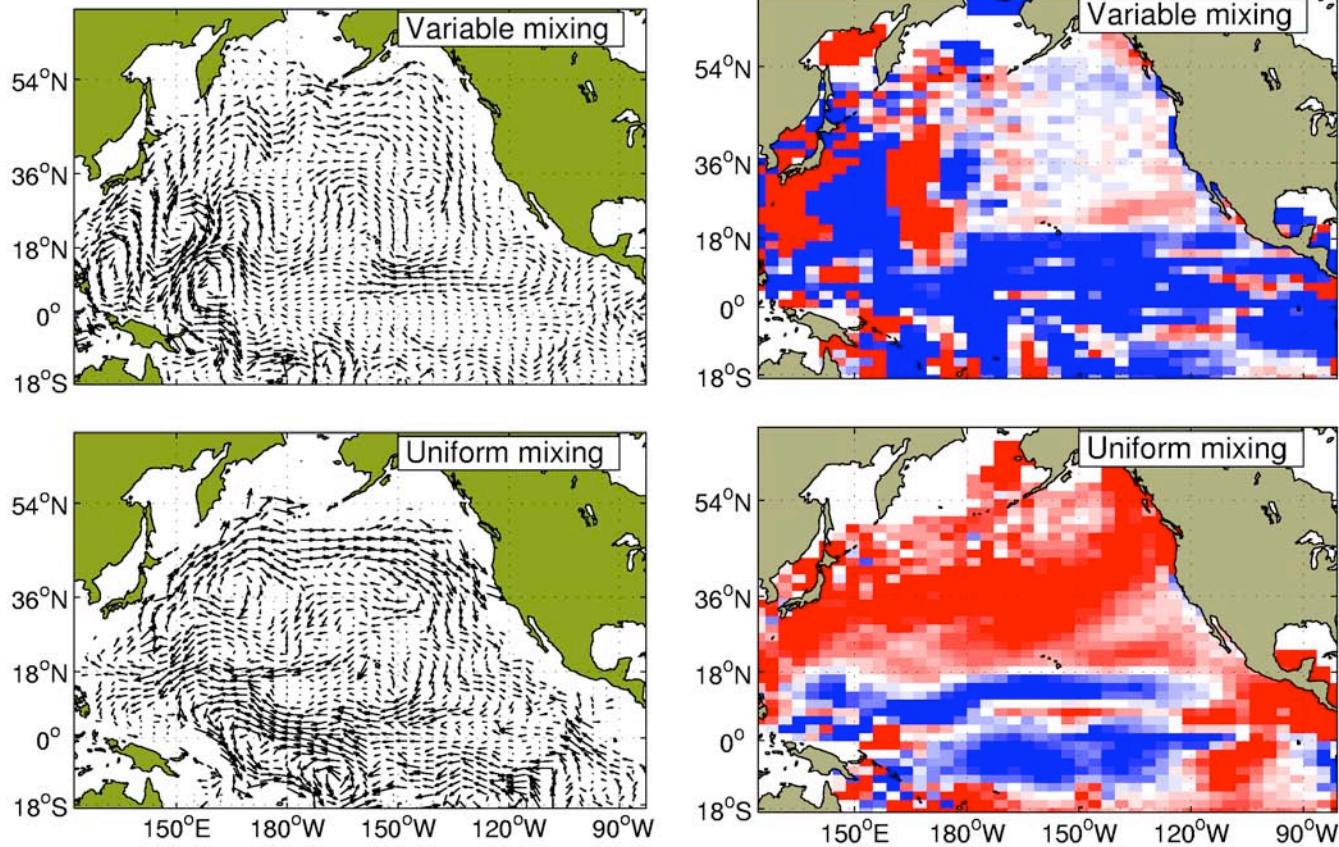


**Spatial variations in bottom roughness change mixing rates by order of magnitude (vertical diffusivity  $< 10^{-5}$  at left and  $> 10^{-4}$  at right; [Polzin et al., *Science*, 1997]).**

**$\lambda < 100$  km bathymetry controls mixing**  
**Seafloor spreading shapes bathymetry at these scales.**



# Mixing affects flow



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

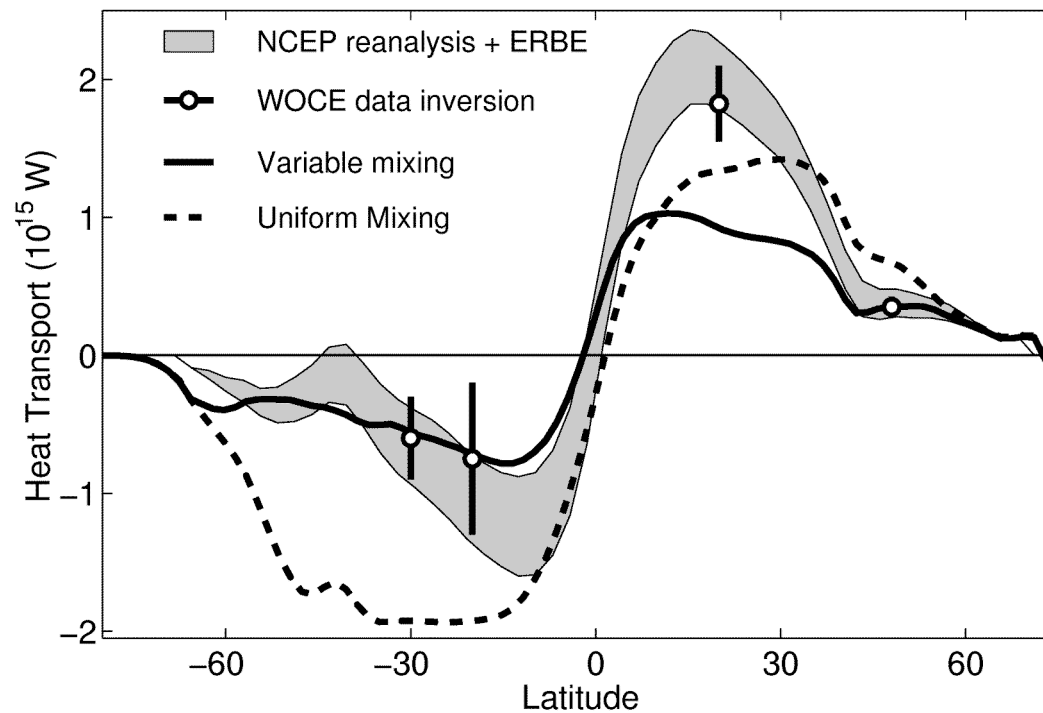
**[Simmons et al., 2004]**



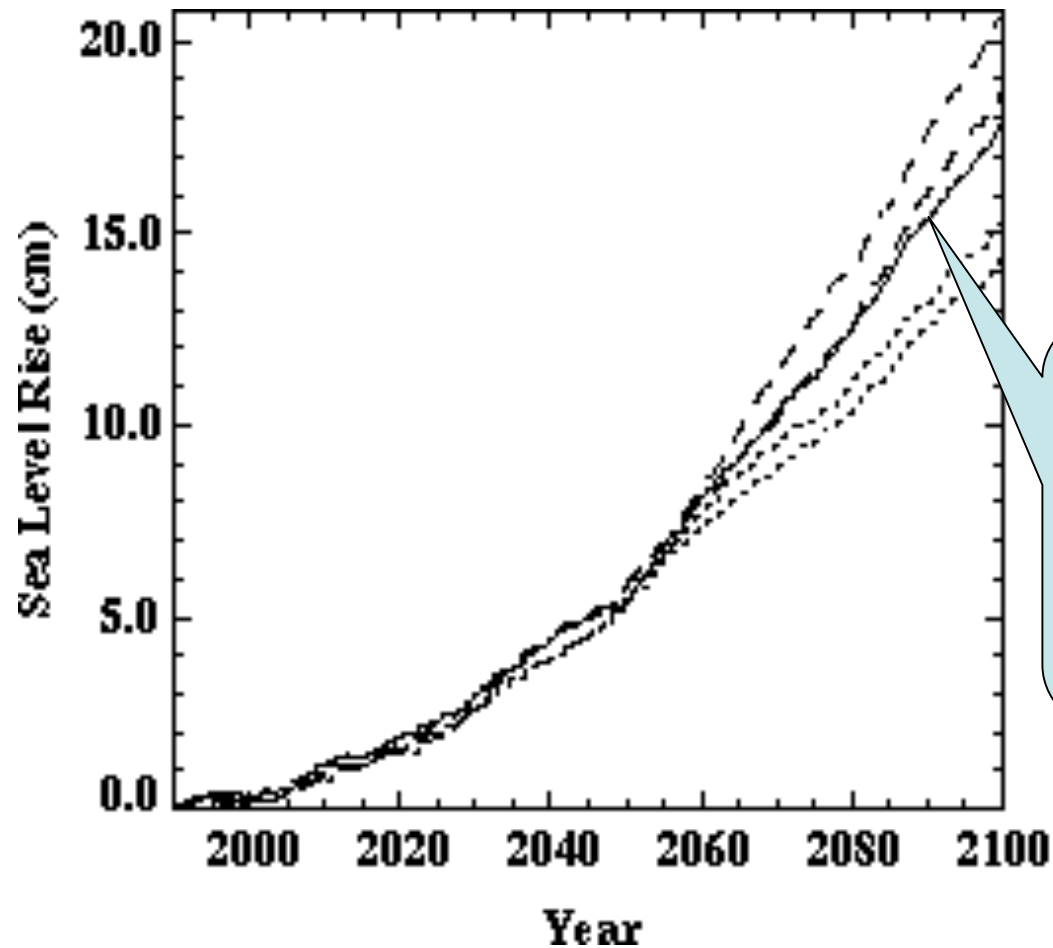
# Mixing affects heat transport

...which changes the modeled meridional heat transport

[Simmons et al., 2004]



# Mixing influences sea level rise

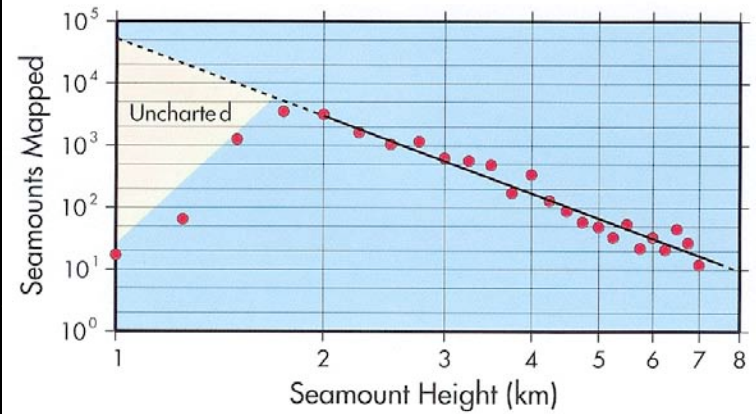
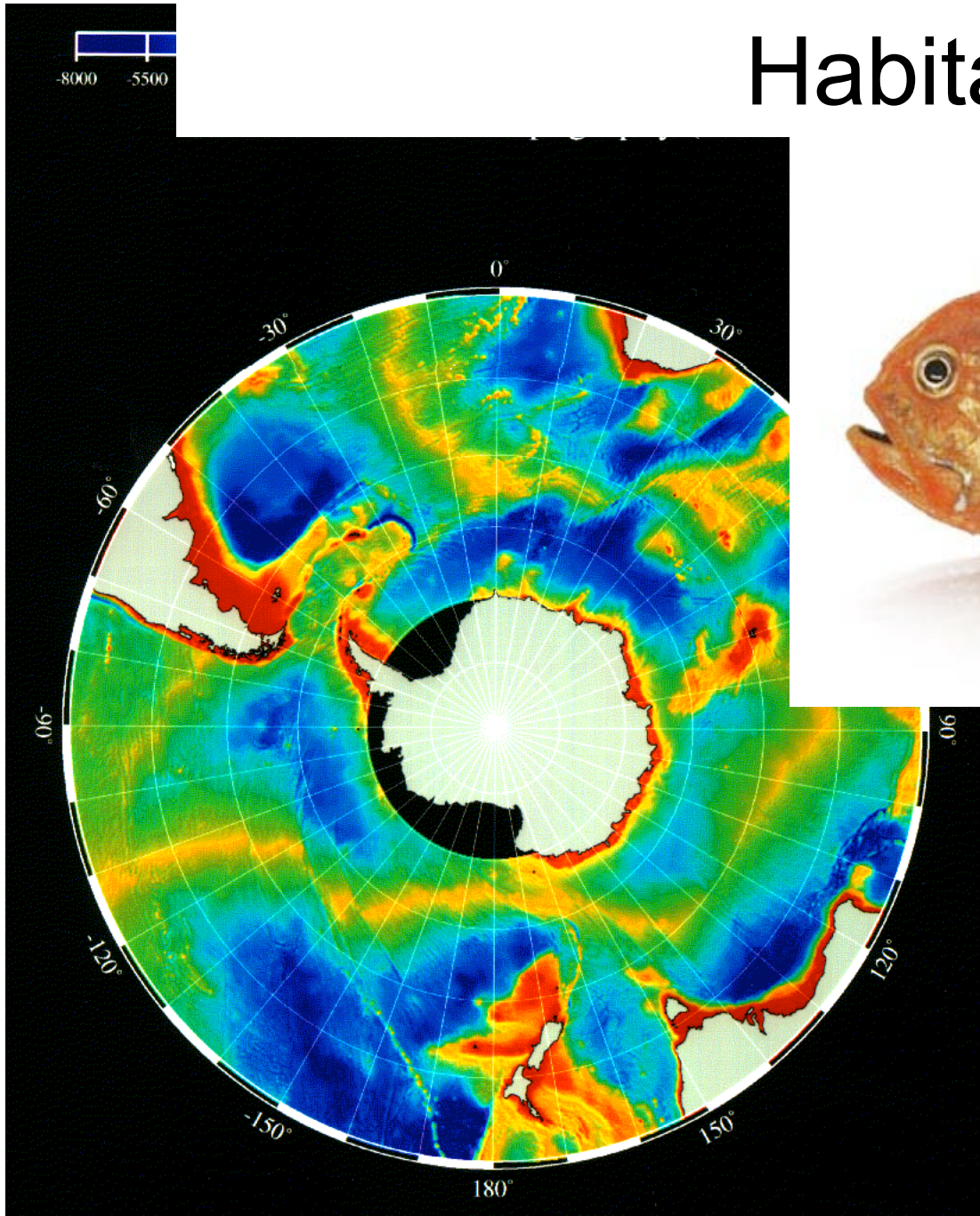


**SL rise forecasts depend on models of vertical mixing in the oceans**

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



# Habitat



# Hazards to Navigation

Before 8 Jan 2005



After 8 January 2005



## USS *San Francisco* in Drydock



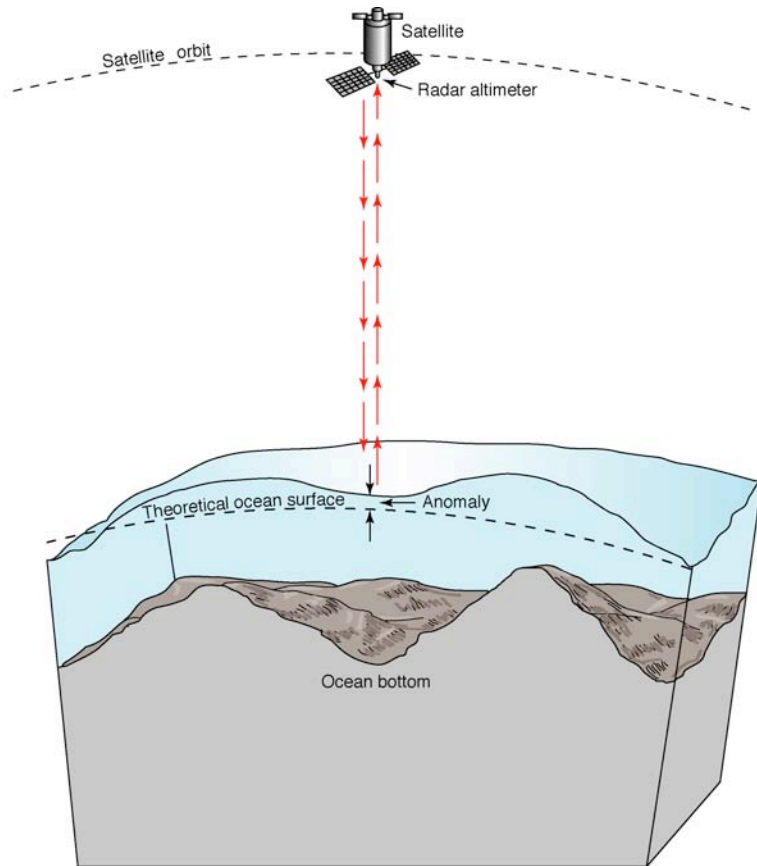
A bathymetric map of the ocean floor, showing various depths and features. The map uses a color scale where red and orange represent shallow depths, yellow and green represent intermediate depths, and blue and purple represent deep depths. The map shows a complex network of ridges, trenches, and seamounts, with a prominent mid-ocean ridge running diagonally across the center. The text "How can we map the oceans?" is overlaid in the center of the map.

**How can we map the oceans?**

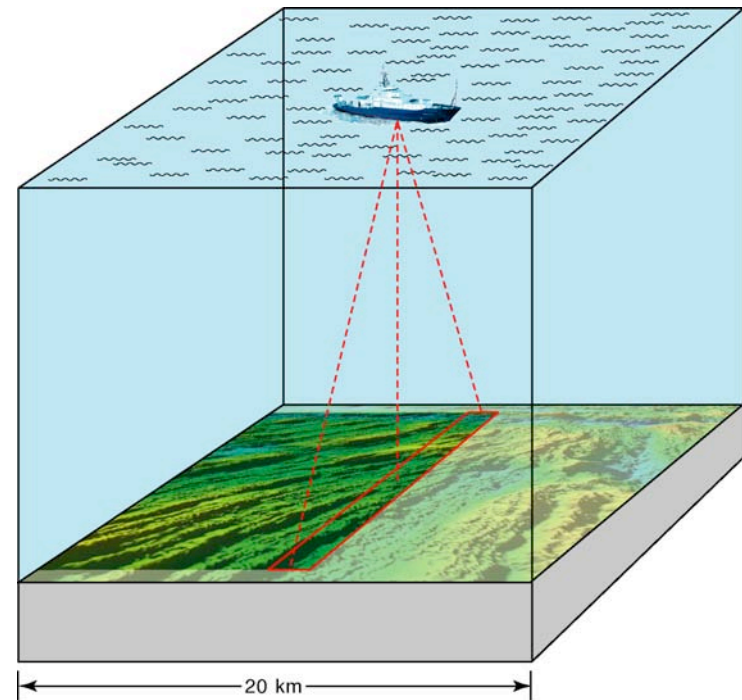


# Modern ocean mapping tools

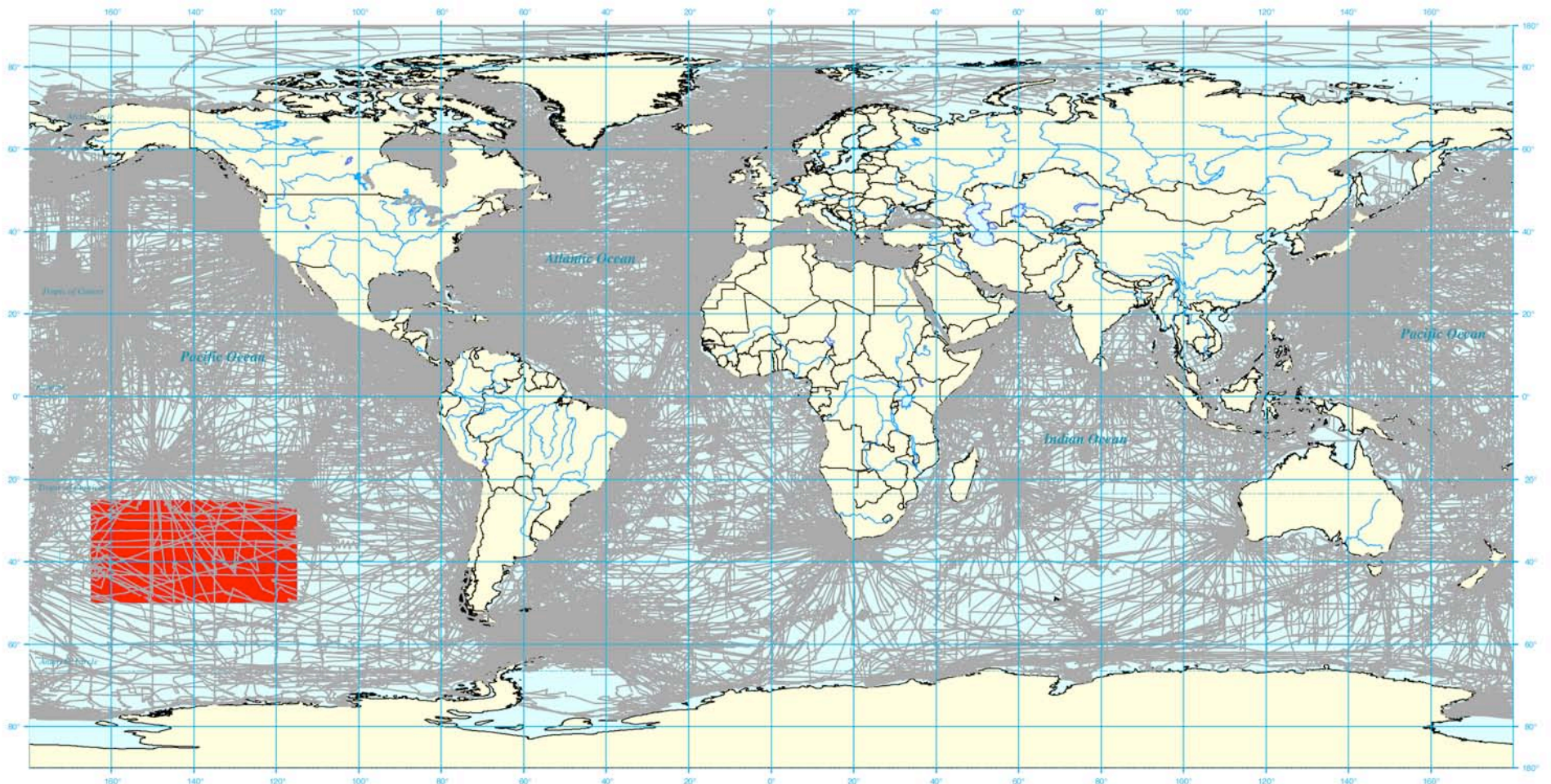
satellite altimeter



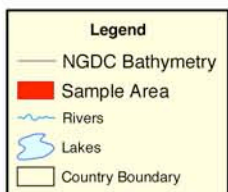
multibeam  
echo sounder





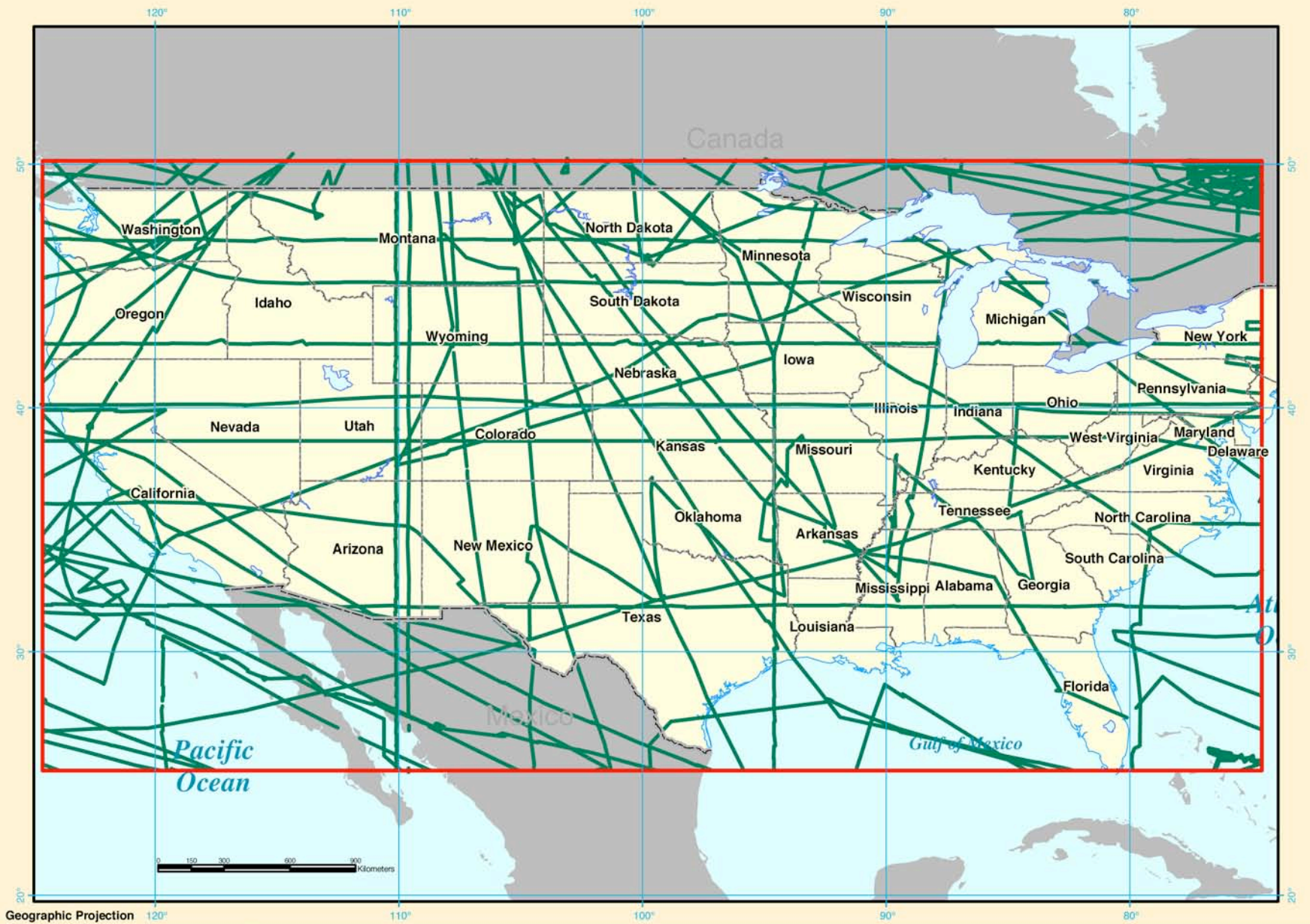


Geographic Projection



# NGDC Global Bathymetry



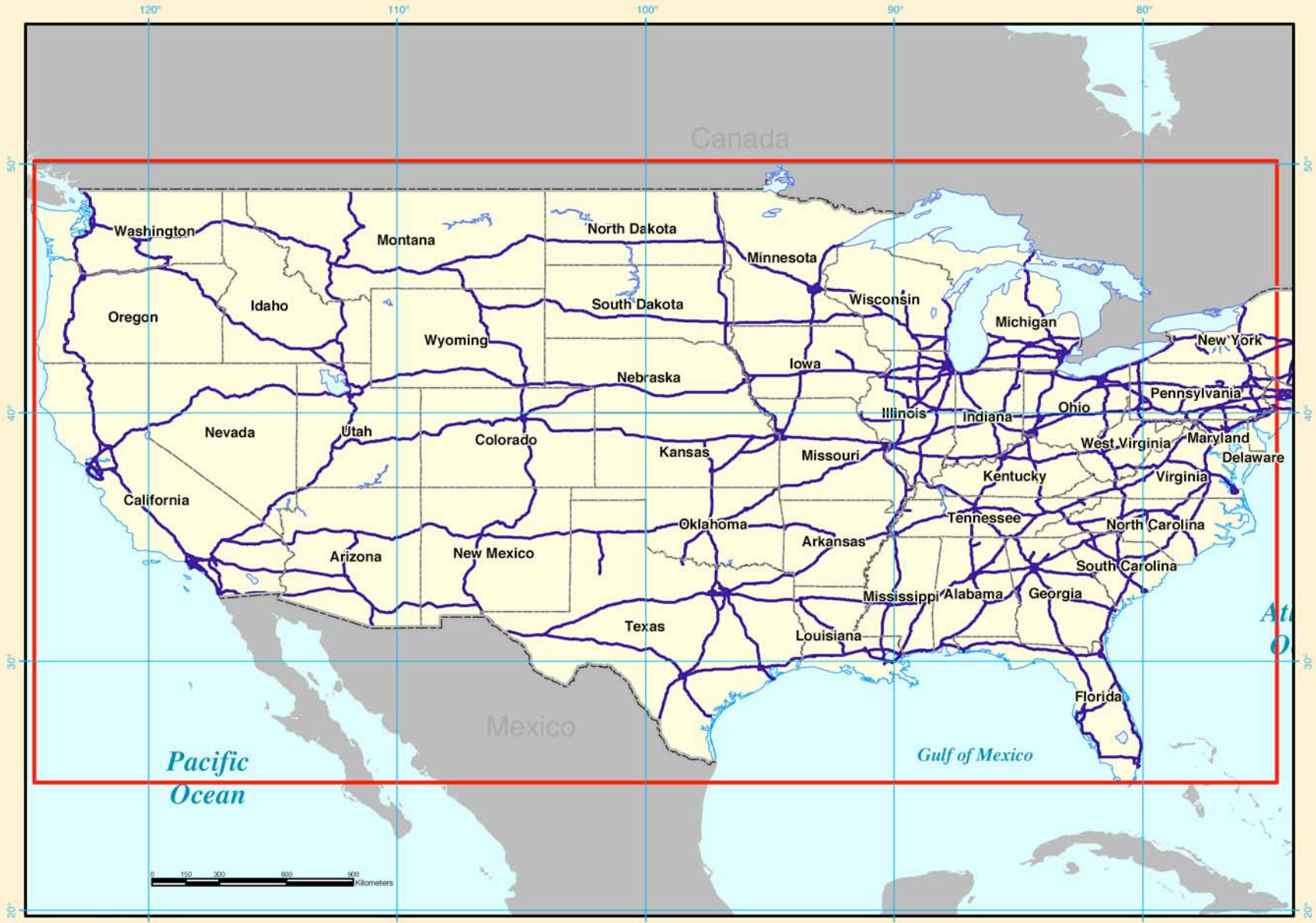


**Legend**

- South Pacific Ship Tracks
- State Bnd
- Lakes

# South Pacific Tracklines





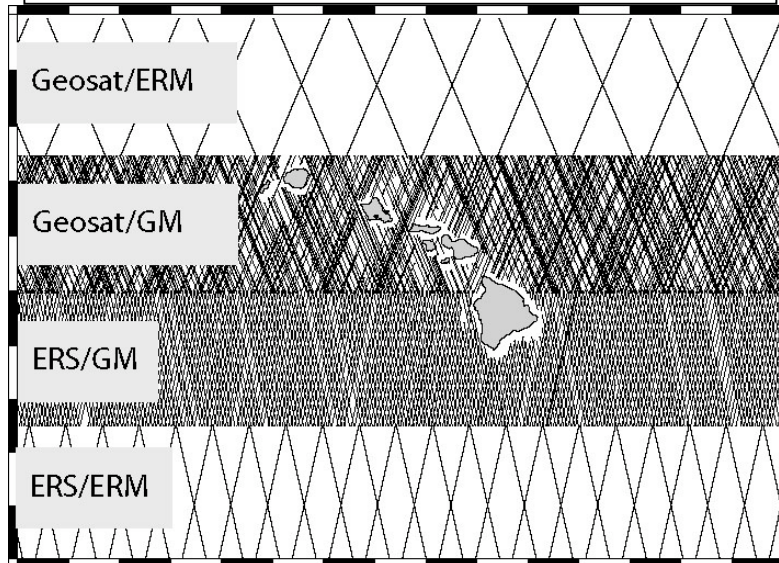
- Legend**
- Interstate Highways
  - State Bnd
  - Lakes

# U.S. Interstate Highway System

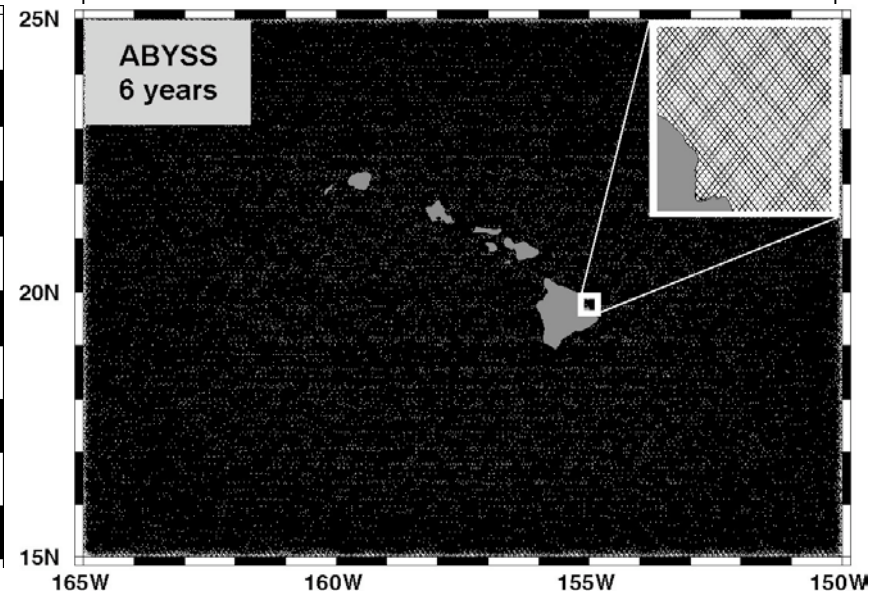
# Satellite track coverage

- **Dense network (~5 km spacing)**
- **Fast (few years) and cheap (\$60M)**

Current altimeters have poor E-W control, high noise (ERS/GM), and uneven track spacing (Geosat/GM).

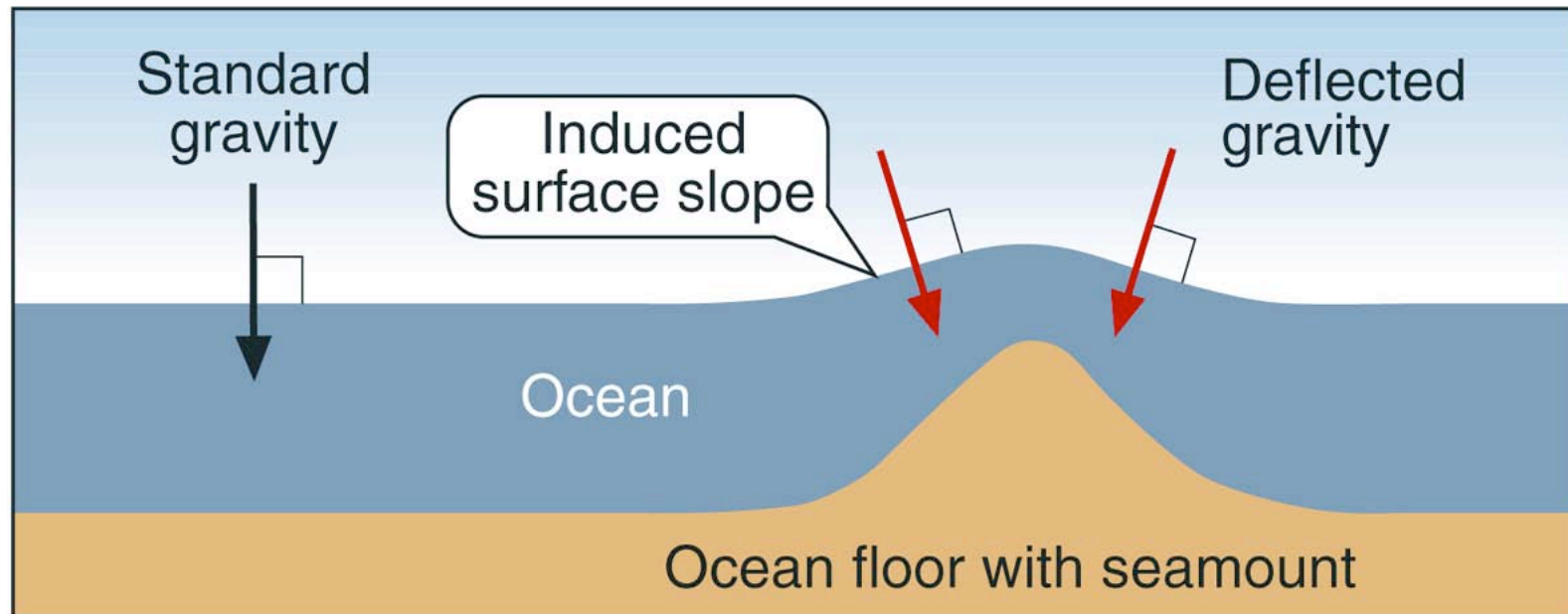


**ABYSS will have good E-W control, low noise, and very dense track spacing.**



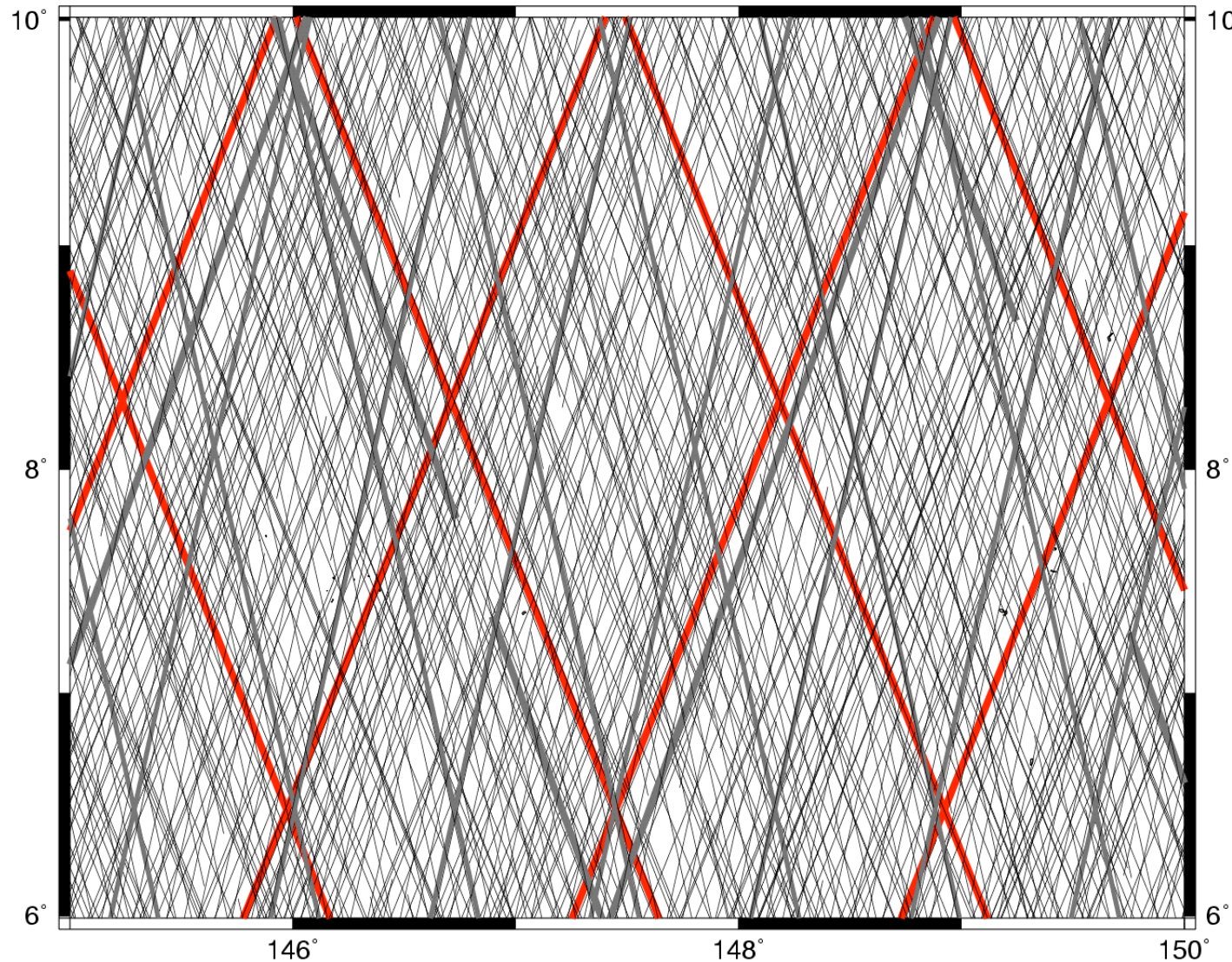


# Satellite bathymetry is via gravity



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.

# Altimeter tracks near SSN711 site



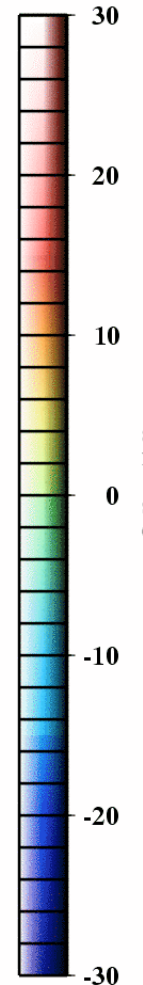
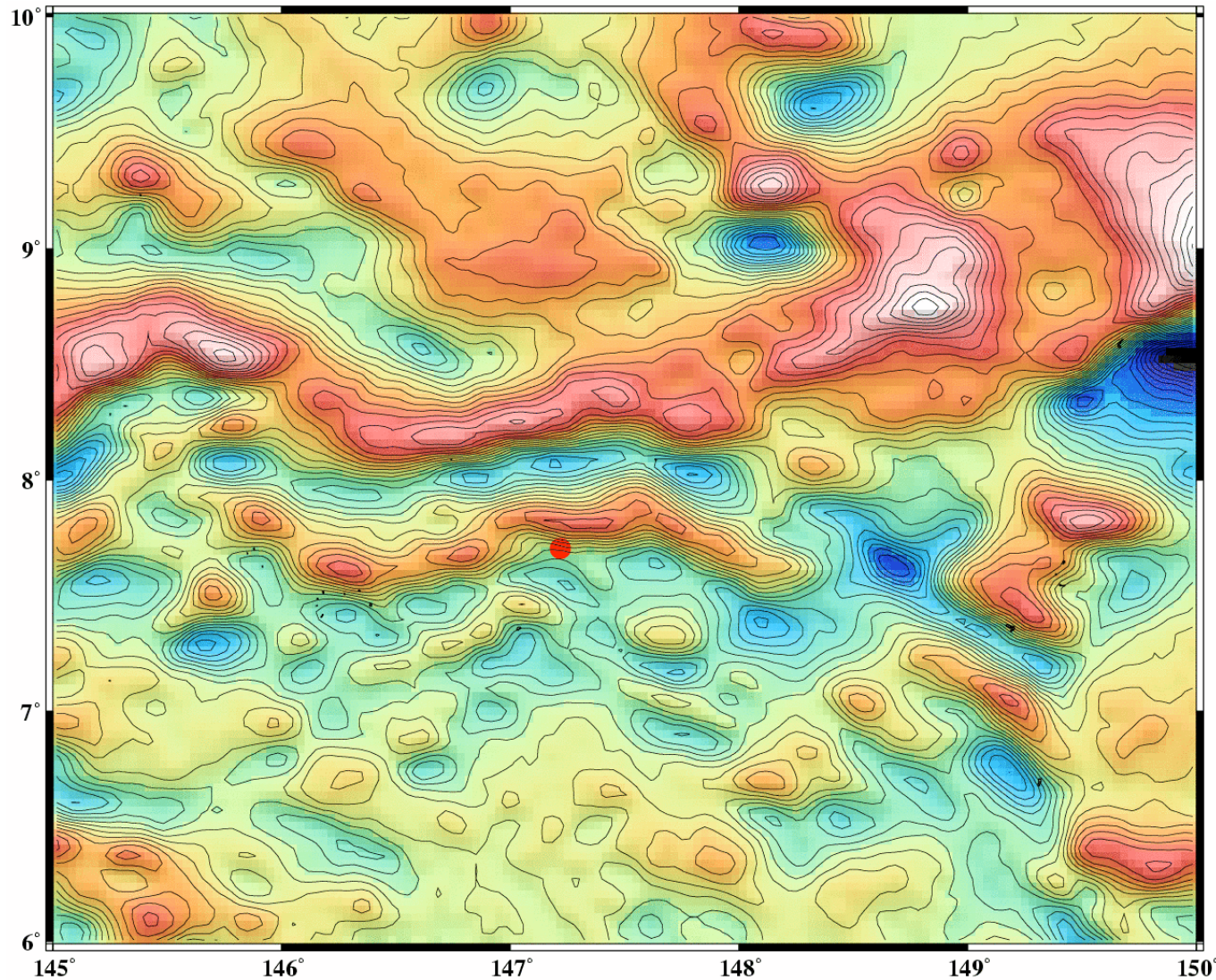
Geosat ERM  
& GFO in red.

Other exact-  
repeats grey.

Geodetic  
Mission tracks  
are single  
lines.



# VD in N-S plane, “ $\xi$ ”, positive south



+15 arc-  
sec near  
“discol.  
water”  
site (red  
dot).

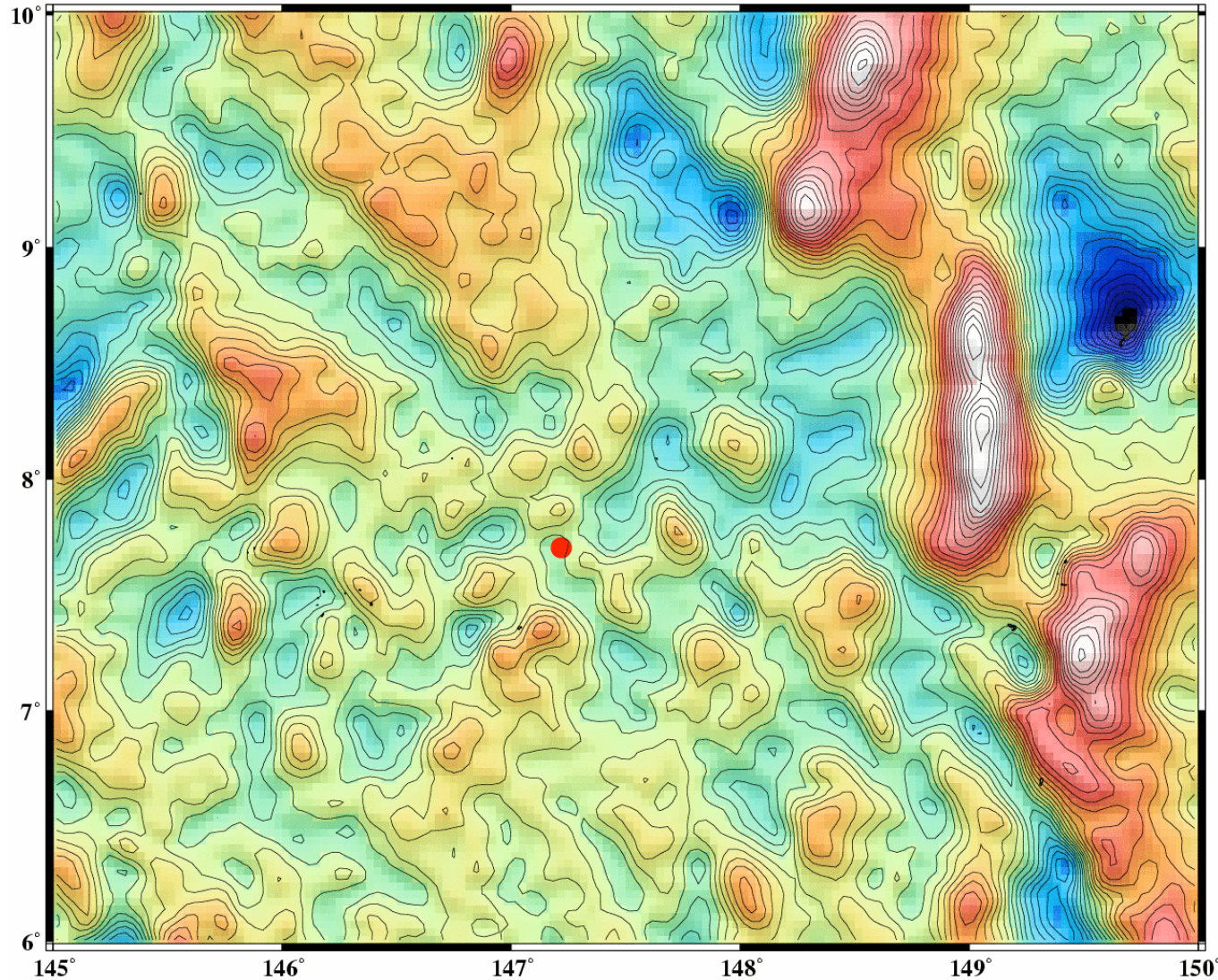
+/- 34 in  
area.

$\xi$  is <10  
over  
most  
(95% ?)  
of Earth.

North Vertical Deflections, Version 14.2 C.I.=2 arcsec



# VD in E-W plane, $\eta$

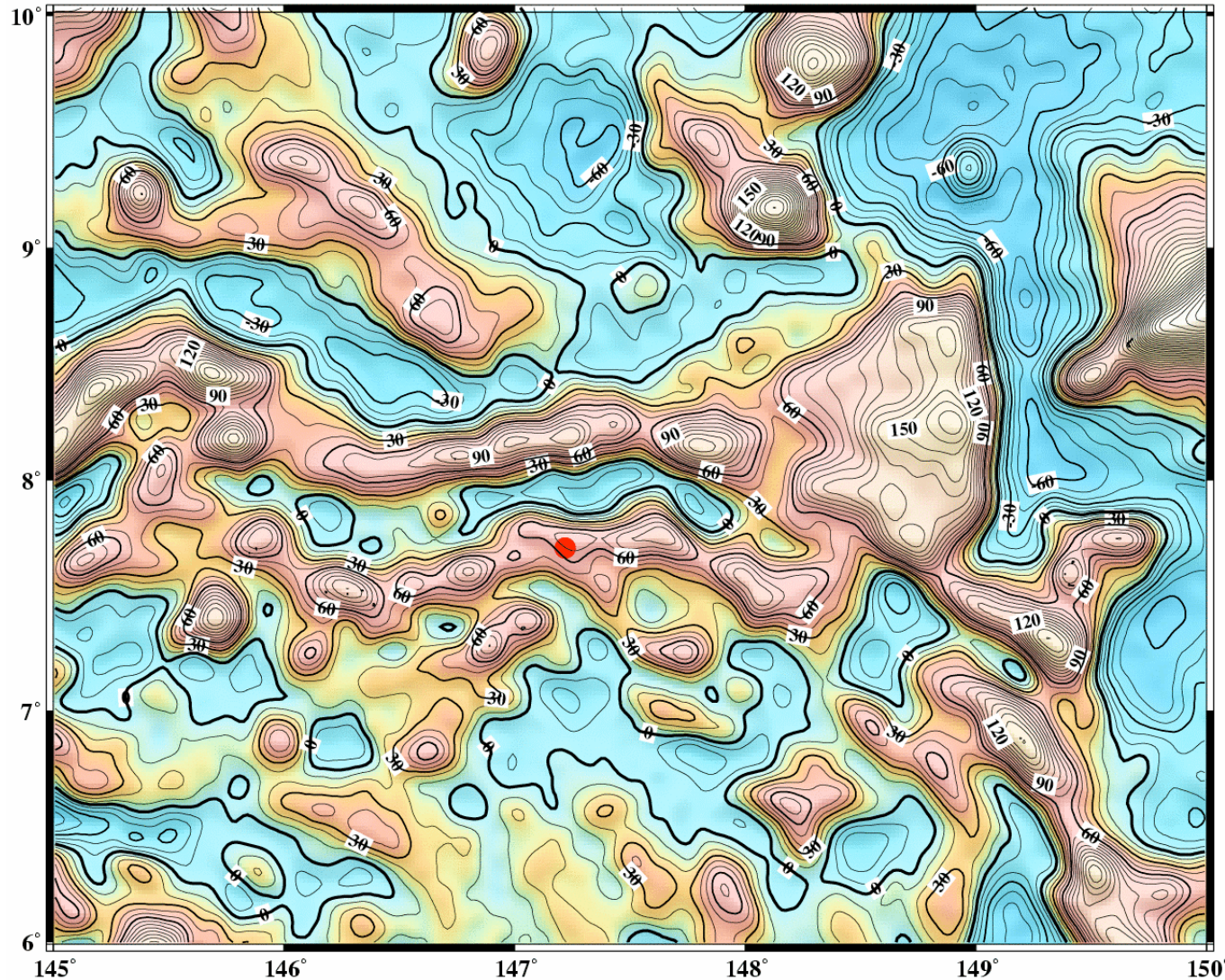


We can combine north and east VD to estimate gravity anomalies. (next slide) These can be checked against shipborne gravimetry.

East Vertical Deflections, Version 14.2 C.I.=2 arcsec



# Gravity anomaly from VD



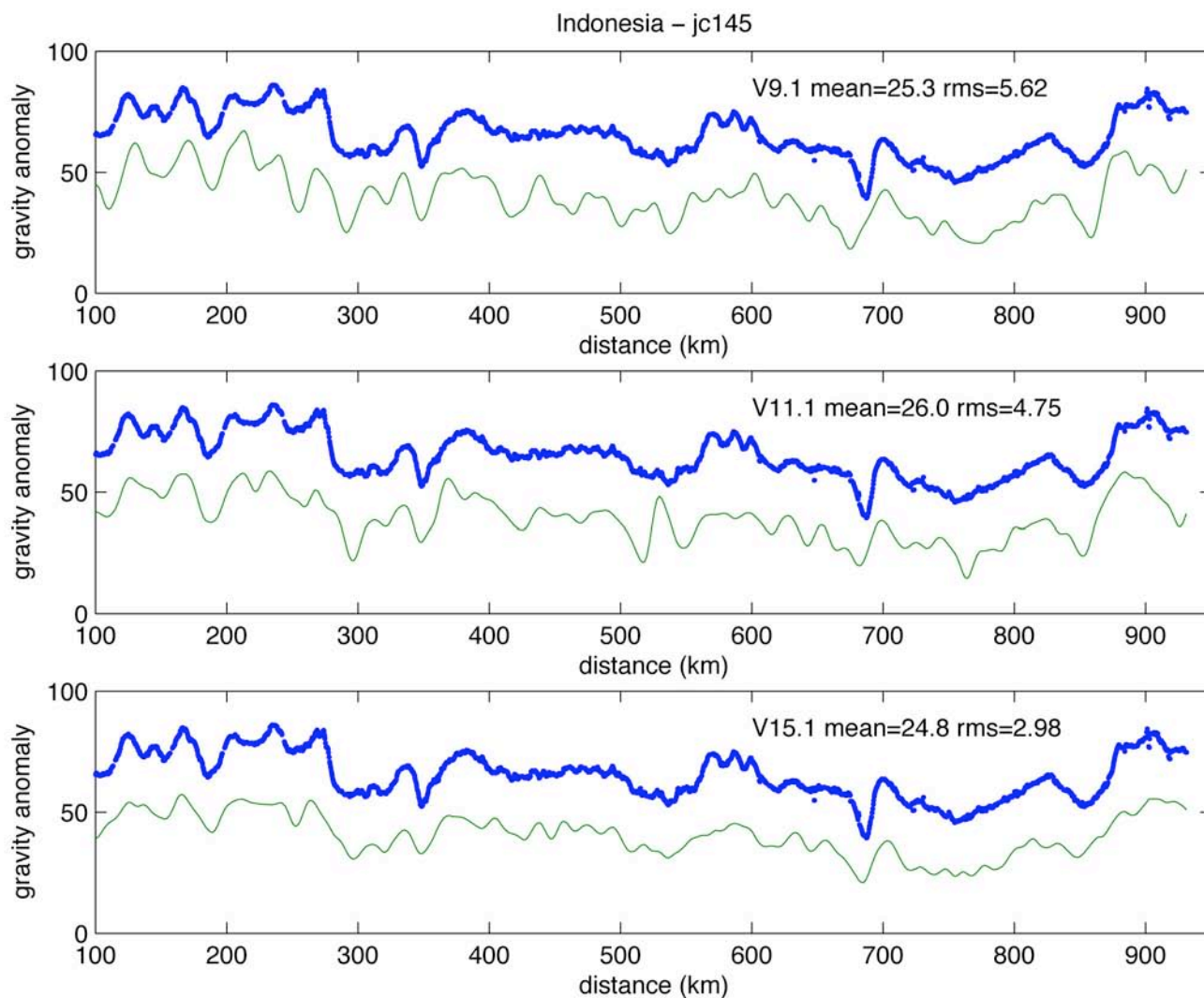
Local max.  
~+79 mGal  
at site. E-W  
trending  
features w/  
>100 mGal  
relief in the  
area of site.

Expect to  
find ~ 2 km  
of relief on  
sea floor at  
these ridges.

mGal

Gravity, Version 14.1 C.I.=10 mGal

# Verify altimetric $g$ with ship gravimetry

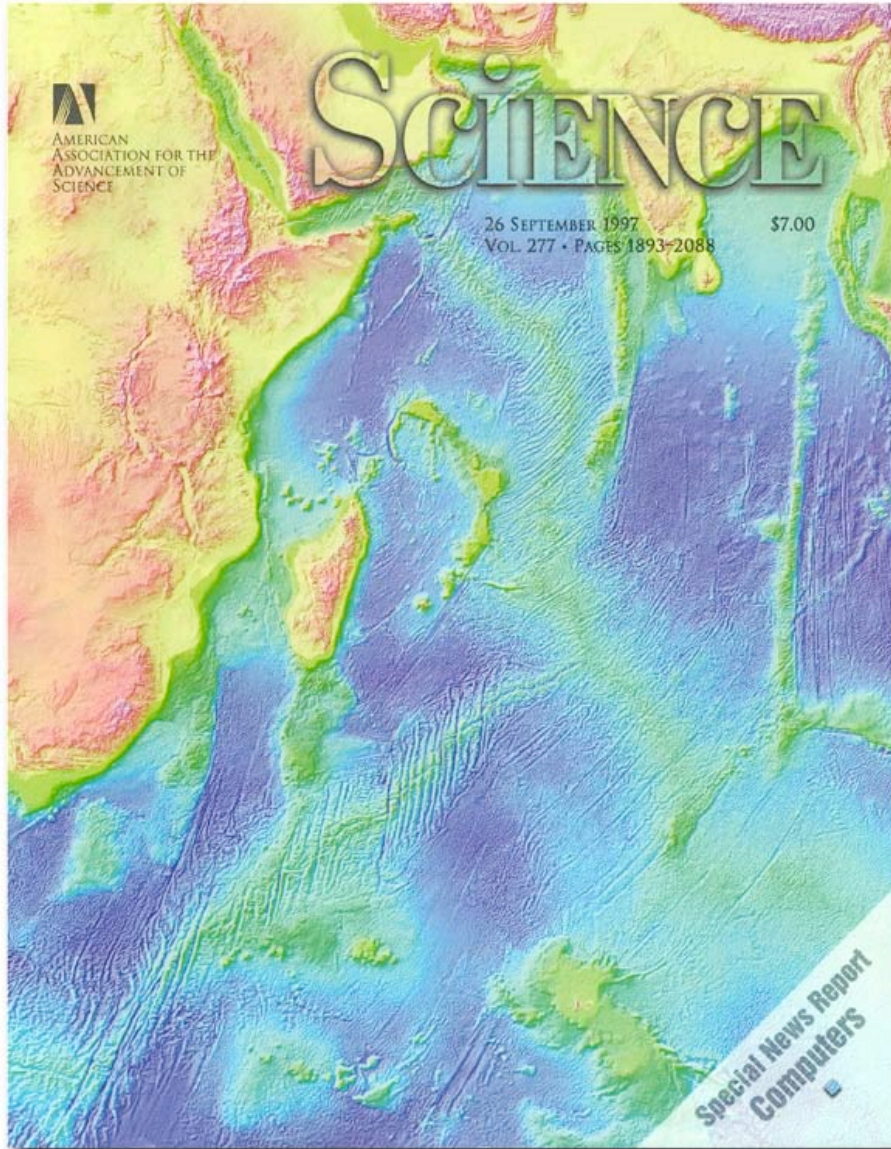


Comparing our altimetric gravity with  $g$  measured by ships gives us a sense of the r.m.s. error, spatial resolution, and signal-to-noise ratio as a function of spatial wavelength, assuming that the ship's data are good enough.

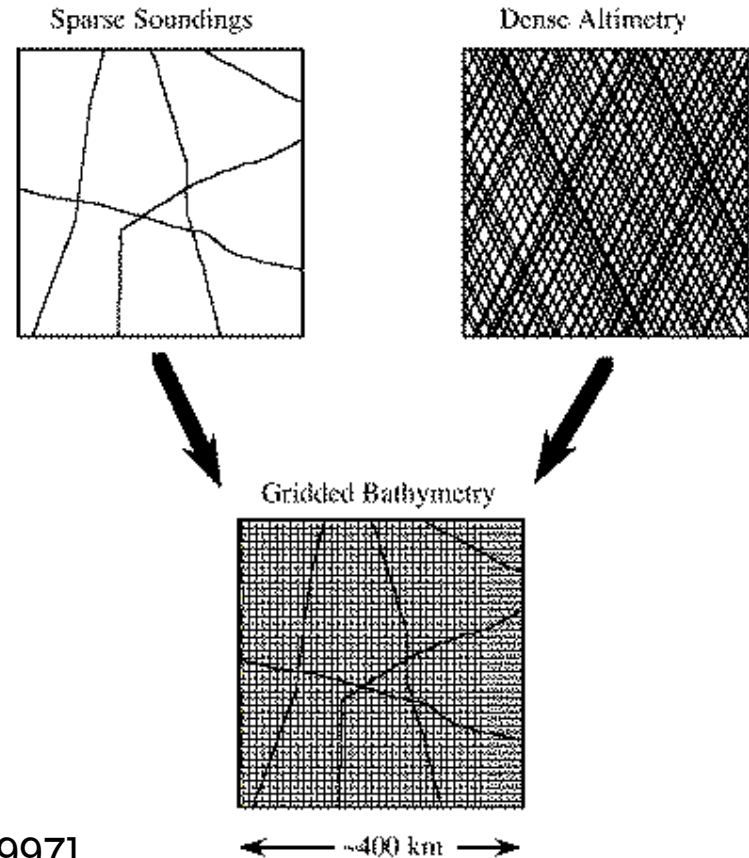
Most ship  $g$  is not good enough to beat our altimetry.



# “Bathymetry from Space” concept:

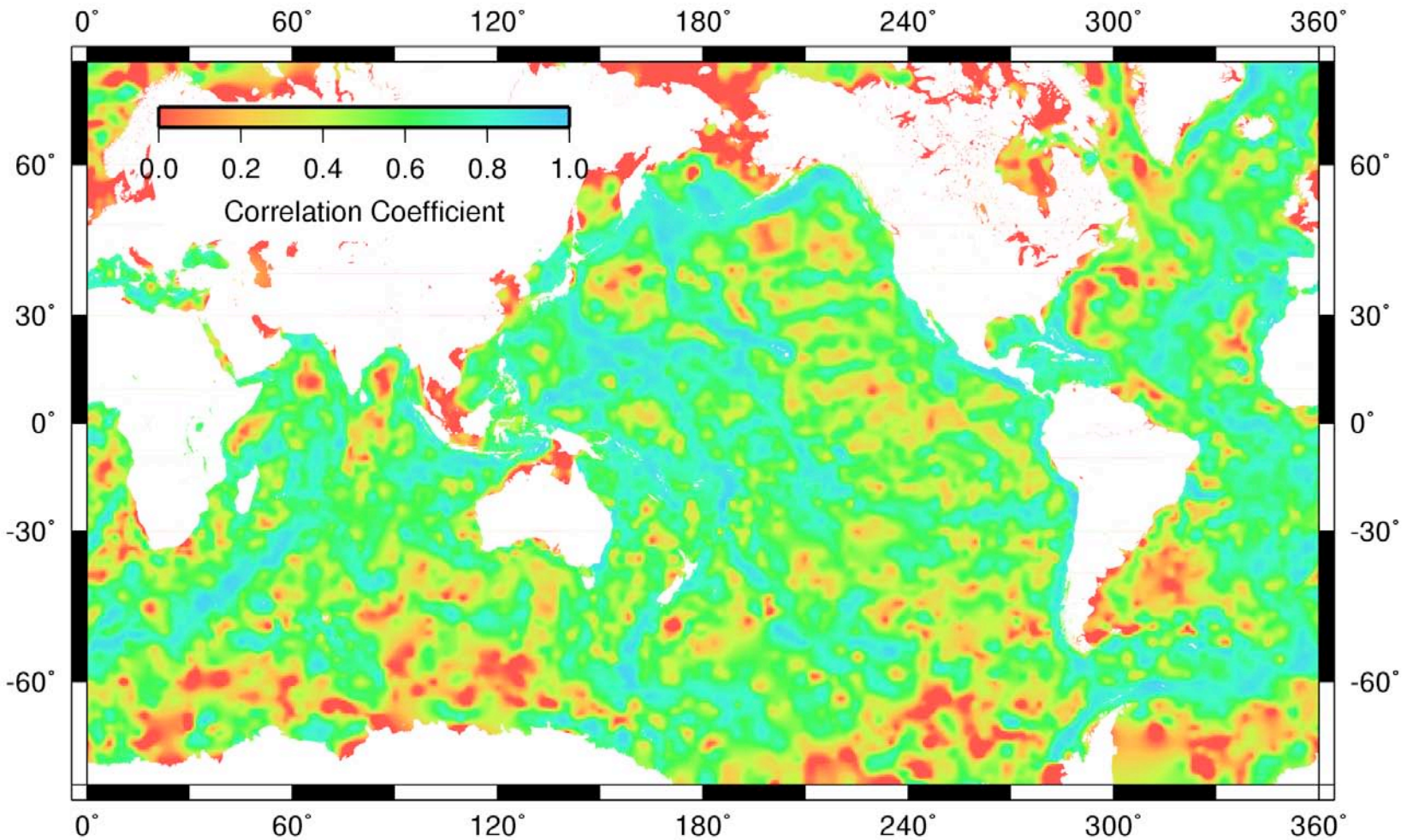


Exploit correlation between  $g$  and depth so that altimetry can guide the interpolation between ship surveys.



Smith & Sandwell [1997]

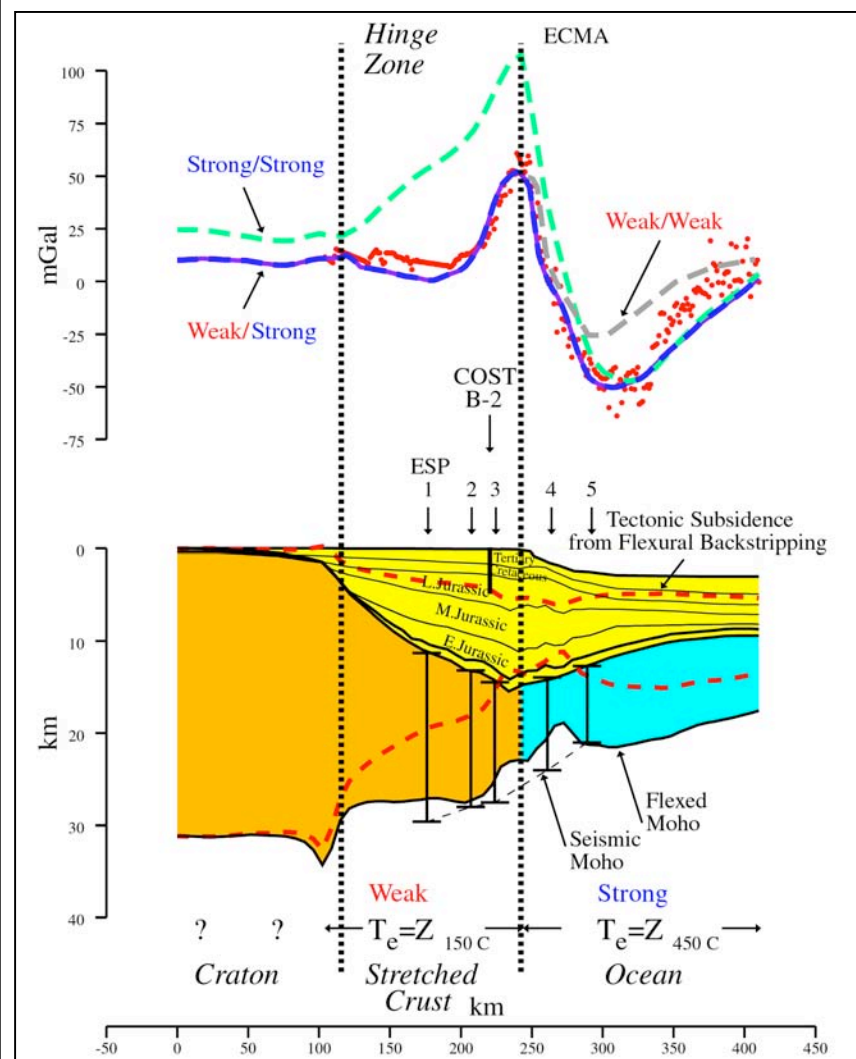
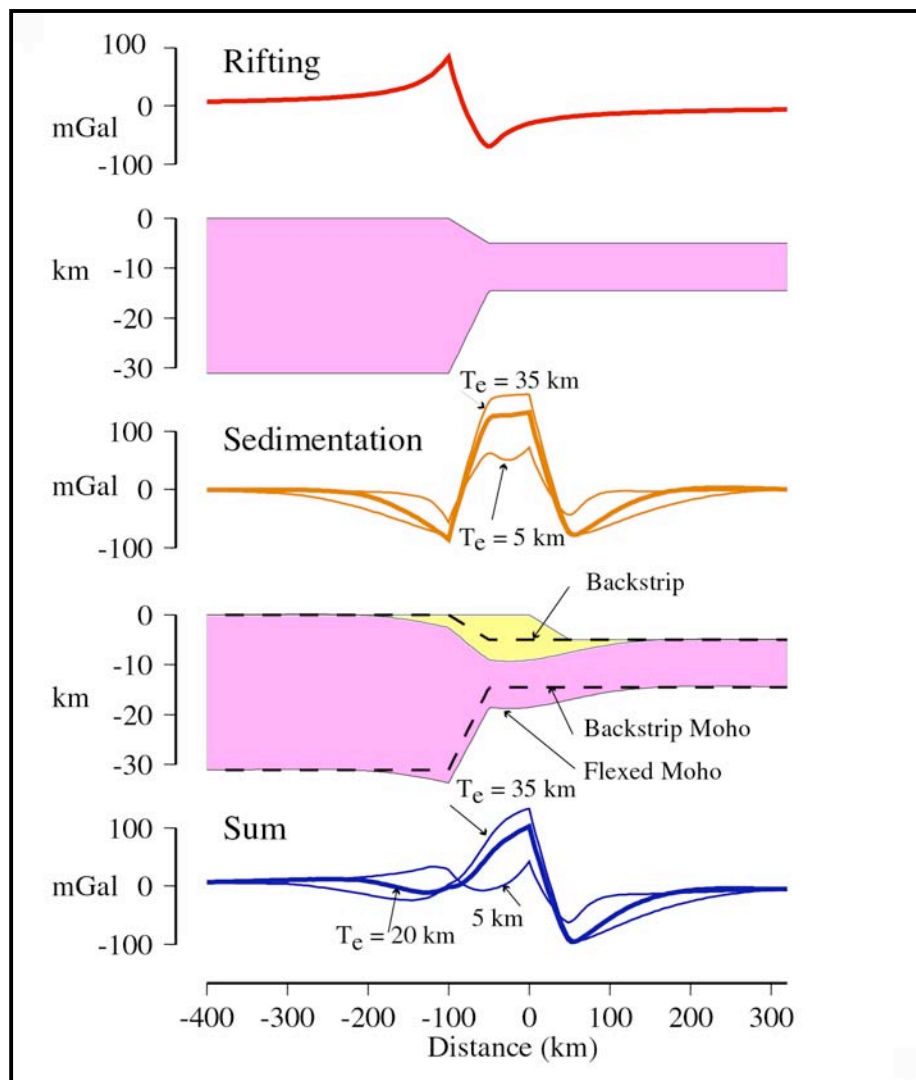
# Gravity-Bathymetry Correlation



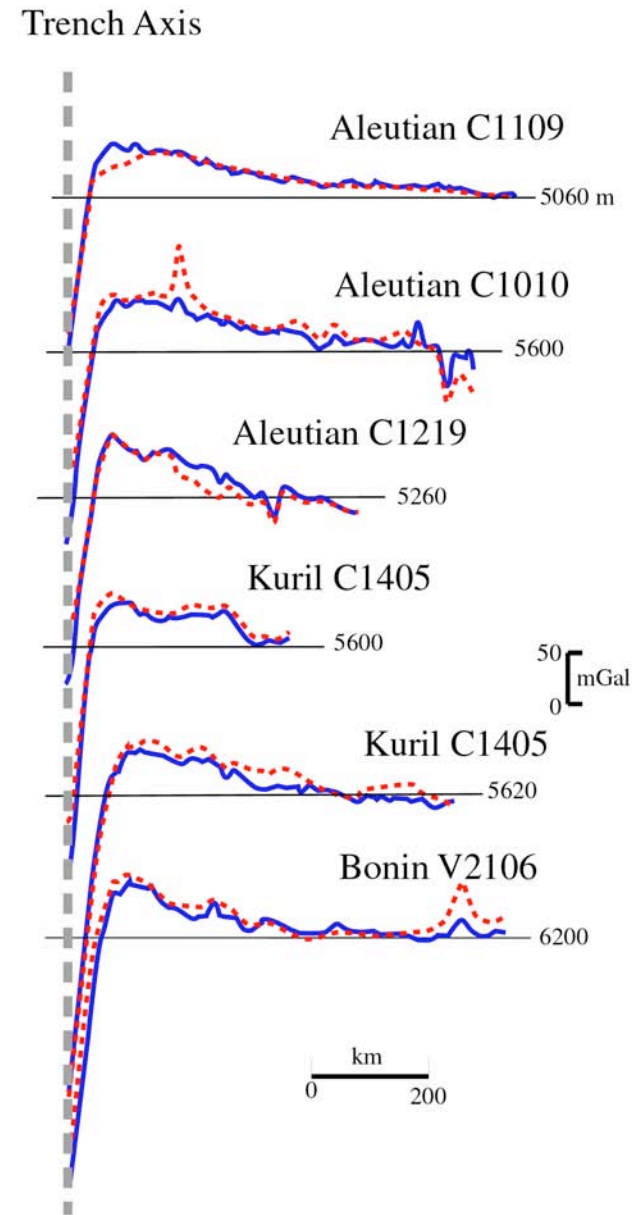
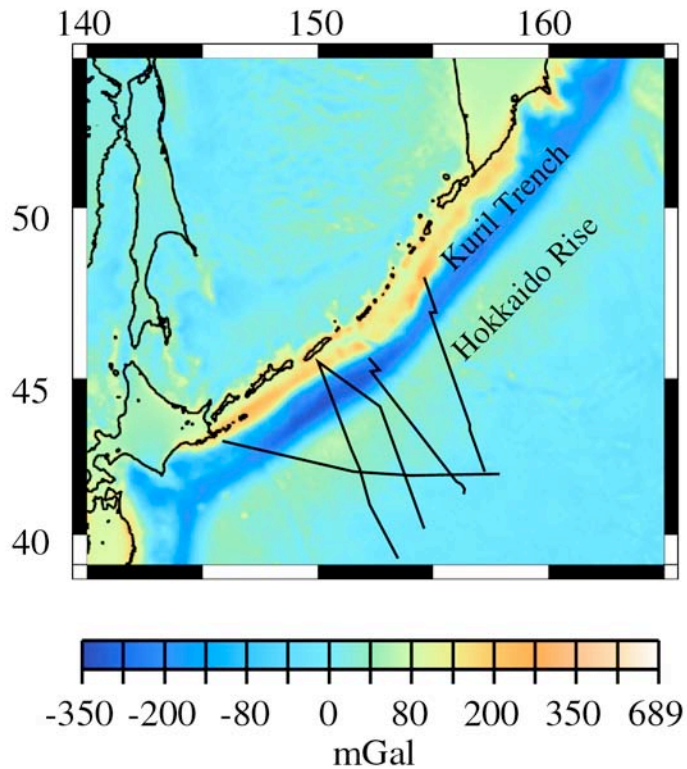
Strong over rough topography in the deep ocean where sediment is thin. Weak on continental margins and abyssal plains.



# Continental margin gravity anomalies are the net result of several processes

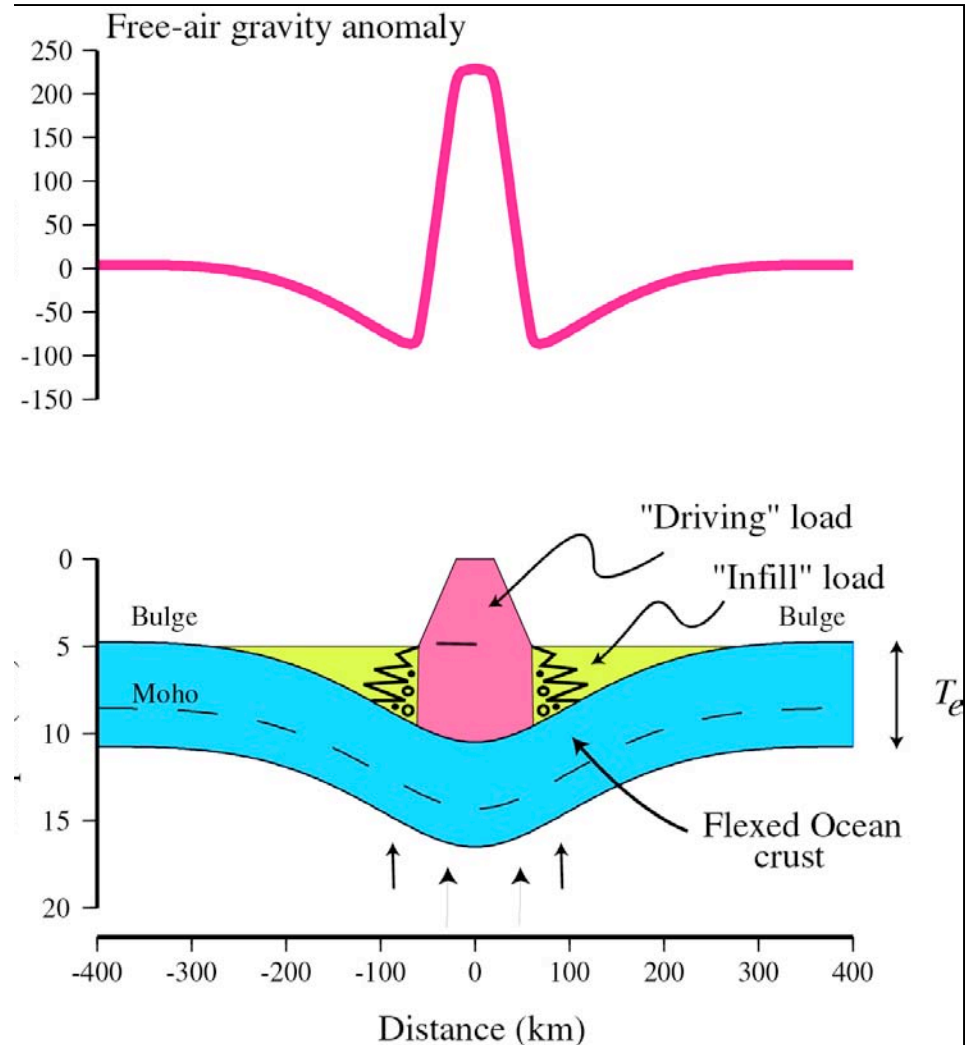
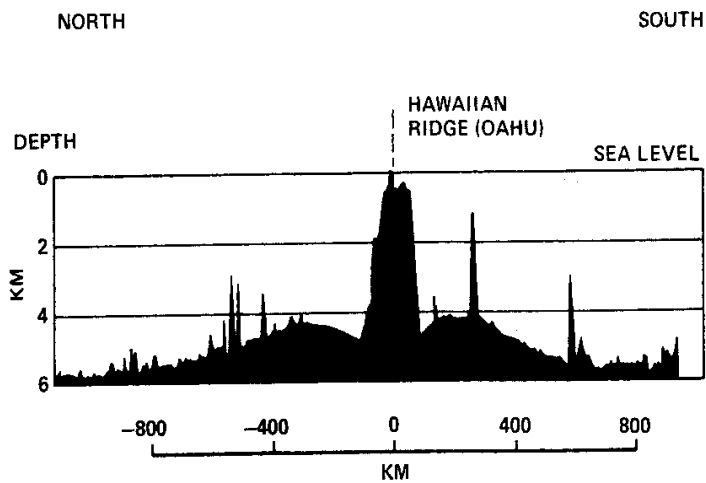
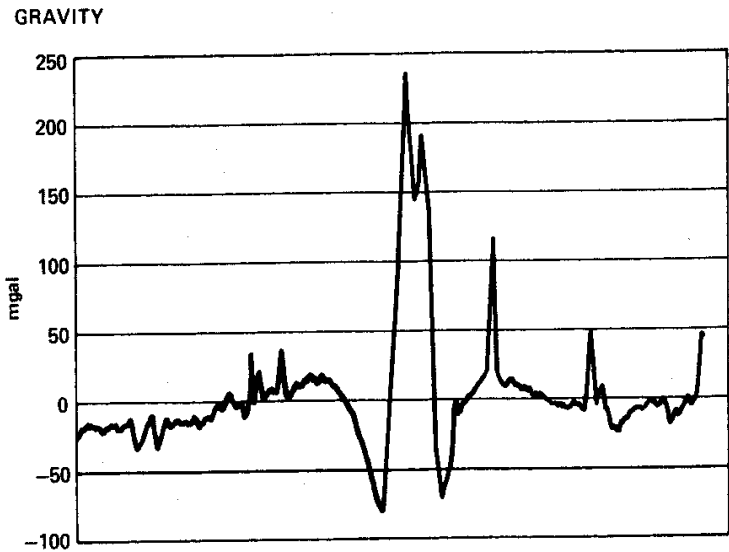


Gravity in the deep oceans is simple, 1: trenches.

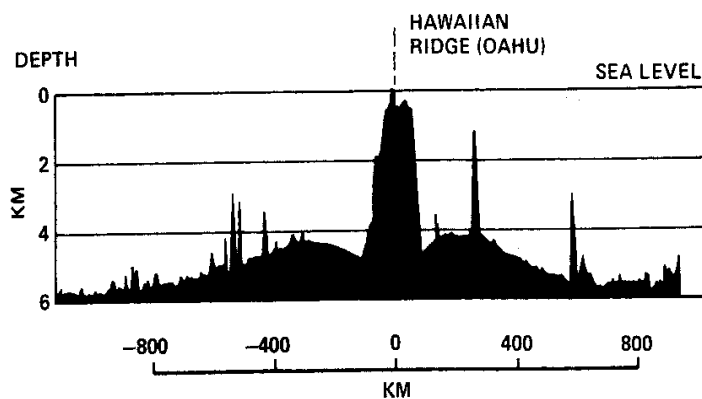
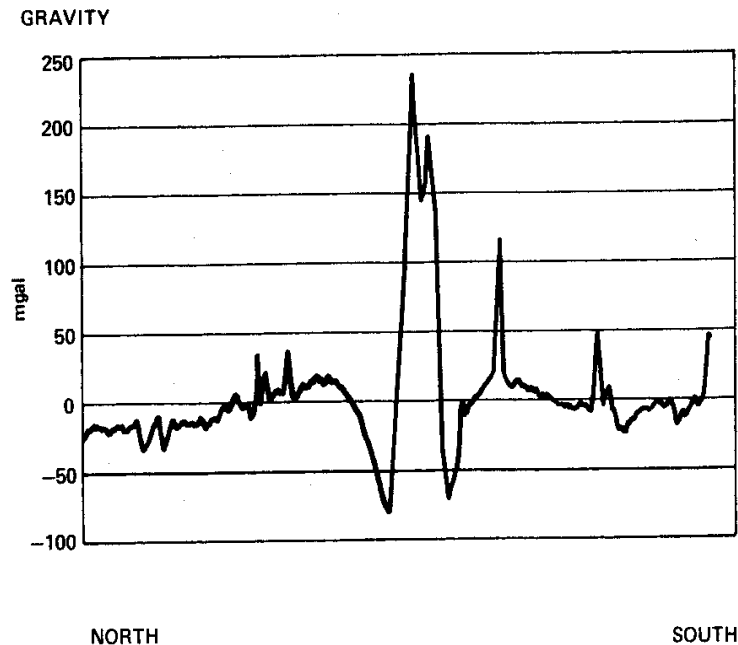




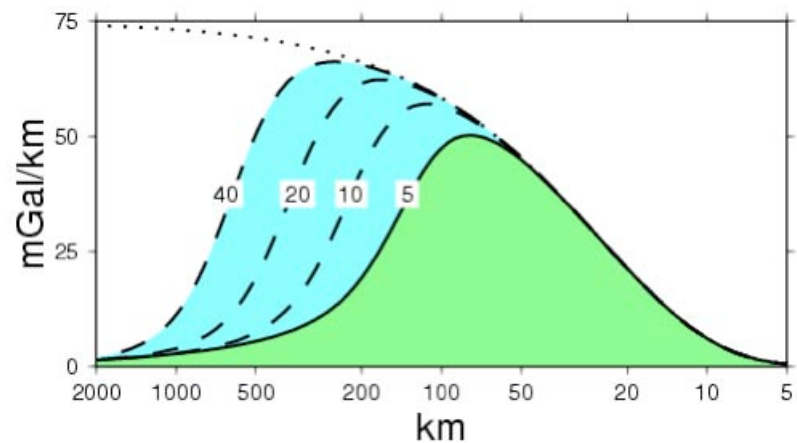
# Gravity in the deep oceans is simple, 2: seamounts



# Gravity and bathymetry can be correlated



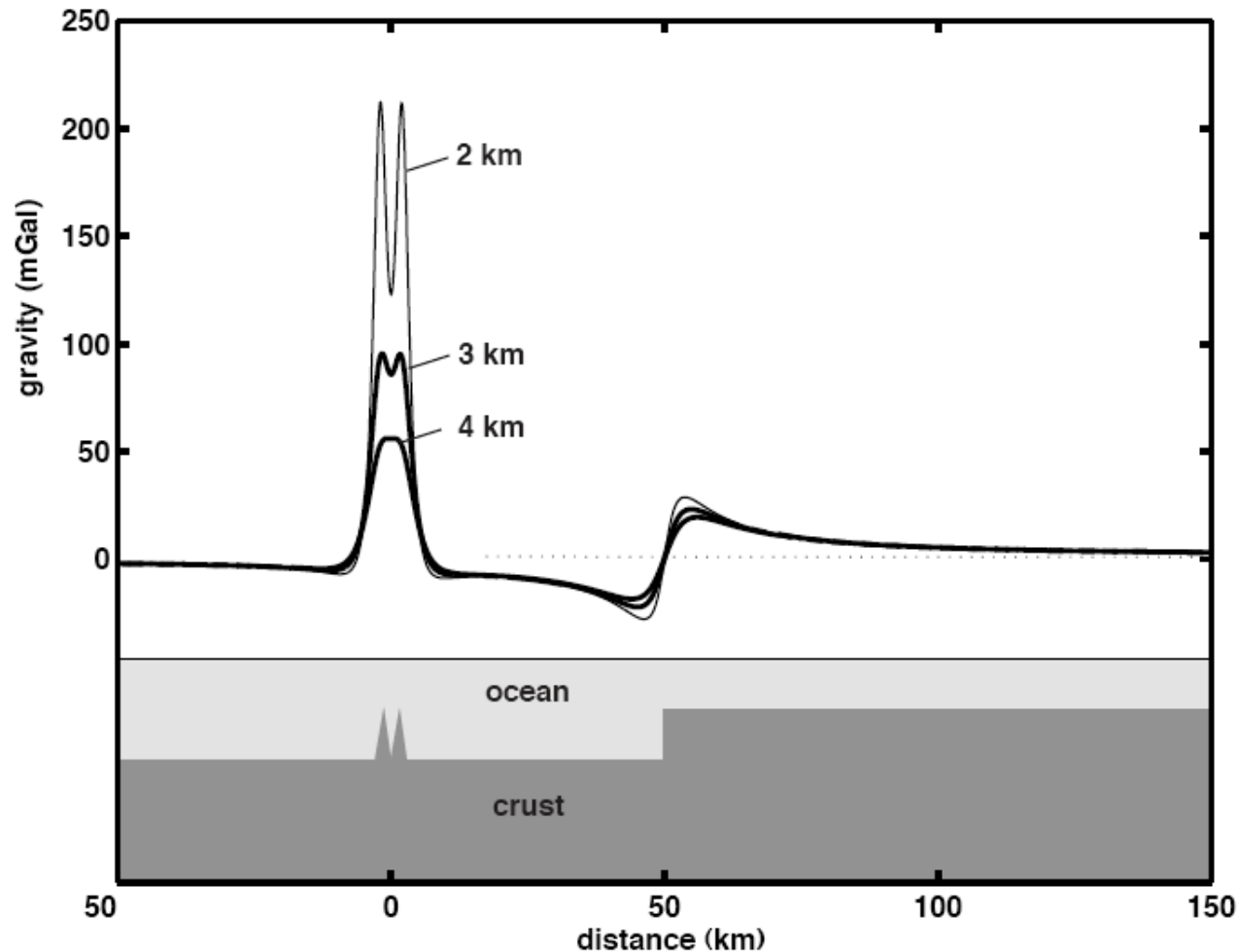
Theory and observation yield a topography in, gravity out, band-pass filter.



We want to do the reverse: gravity in, bathymetry out. We are limited to a band of wavelengths. Resolution is increasingly limited by noise as horizontal scale decreases.



# Band-pass filter consequences



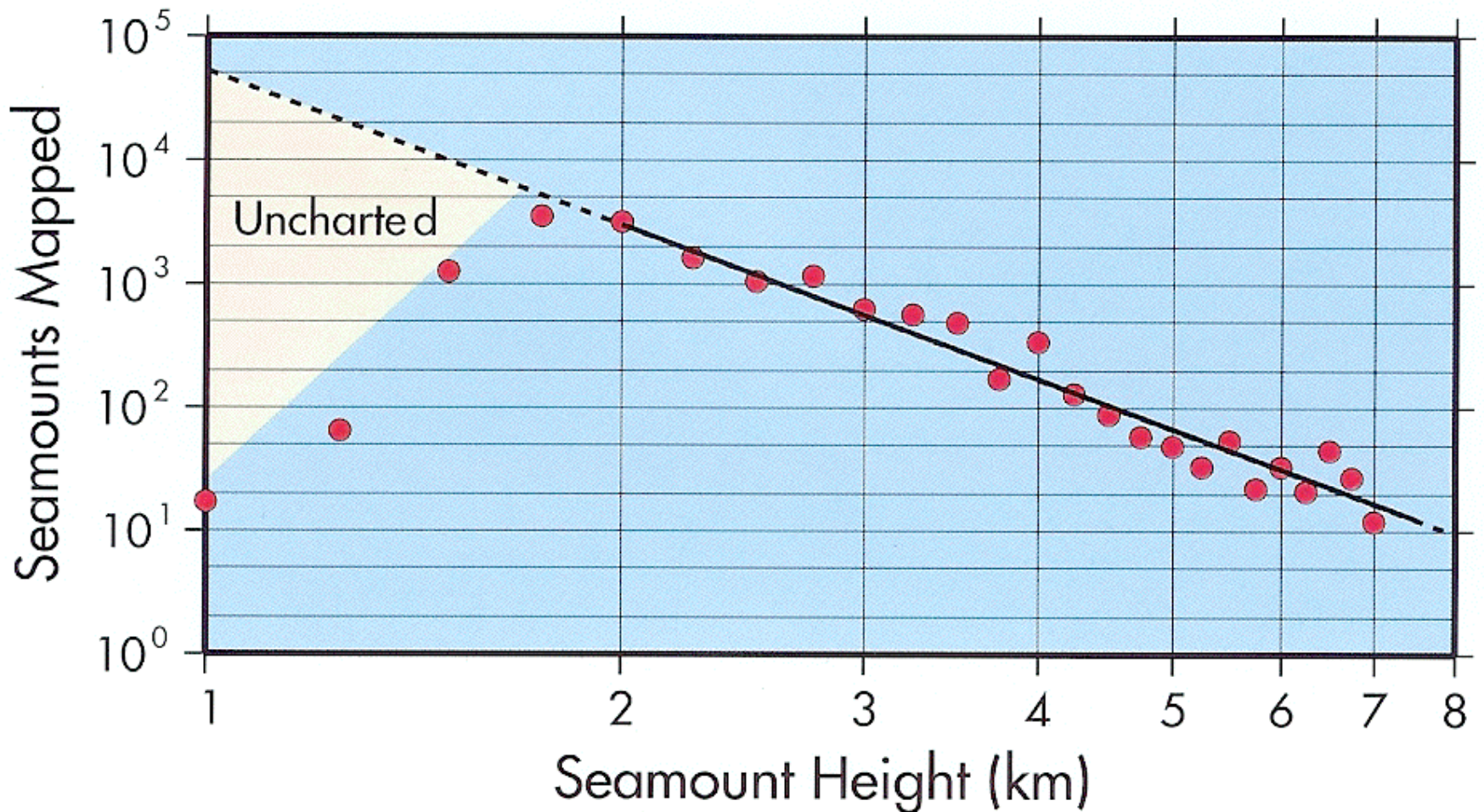
Horizontal resolution and signal amplitude (hence, sensitivity to noise) are a function of regional water depth.

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

# How well are seamounts found?

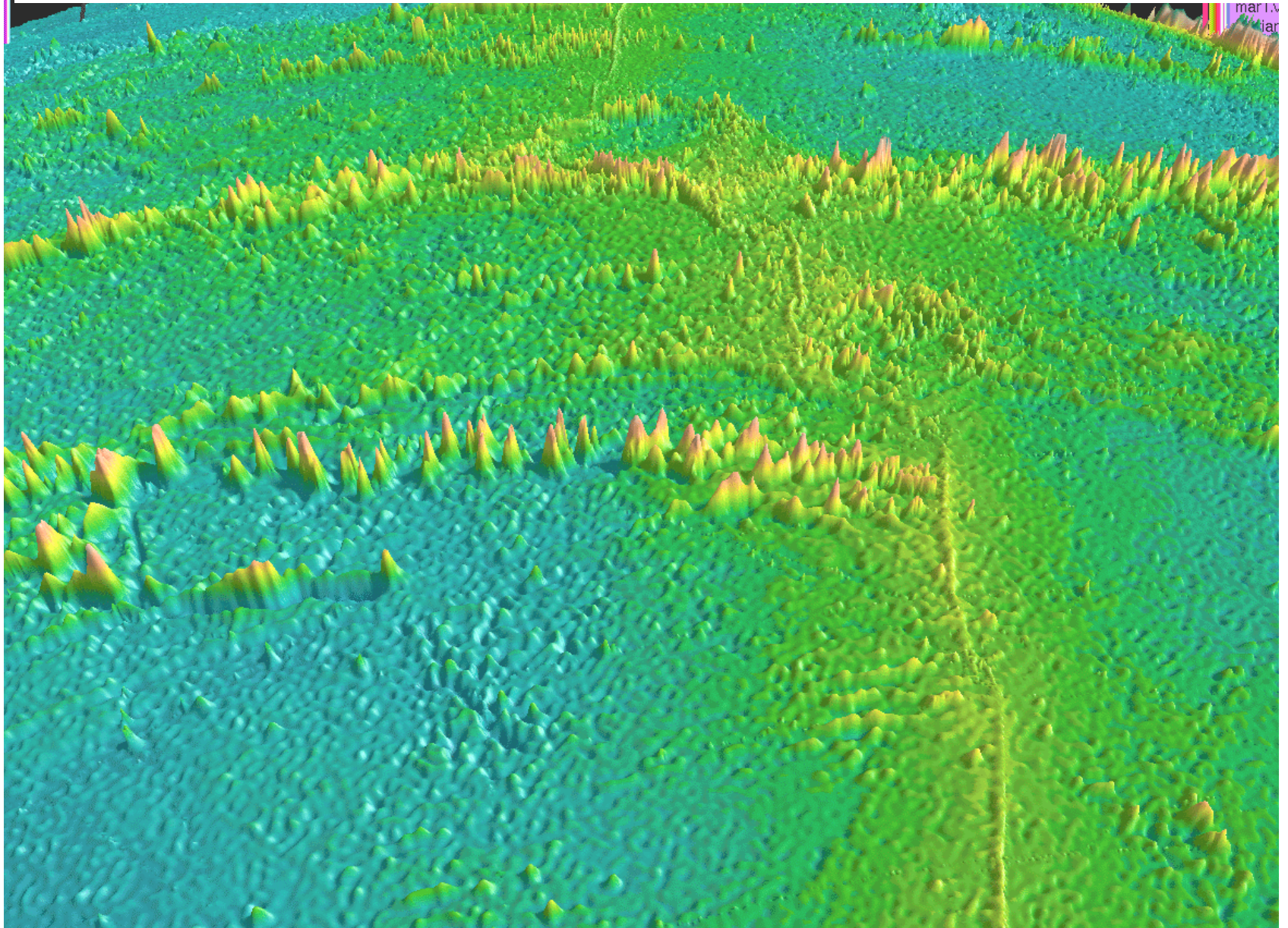
Probably 50,000 seamounts 1 km tall remain undetected.

A 2x better resolving power may find 17x more seamounts.

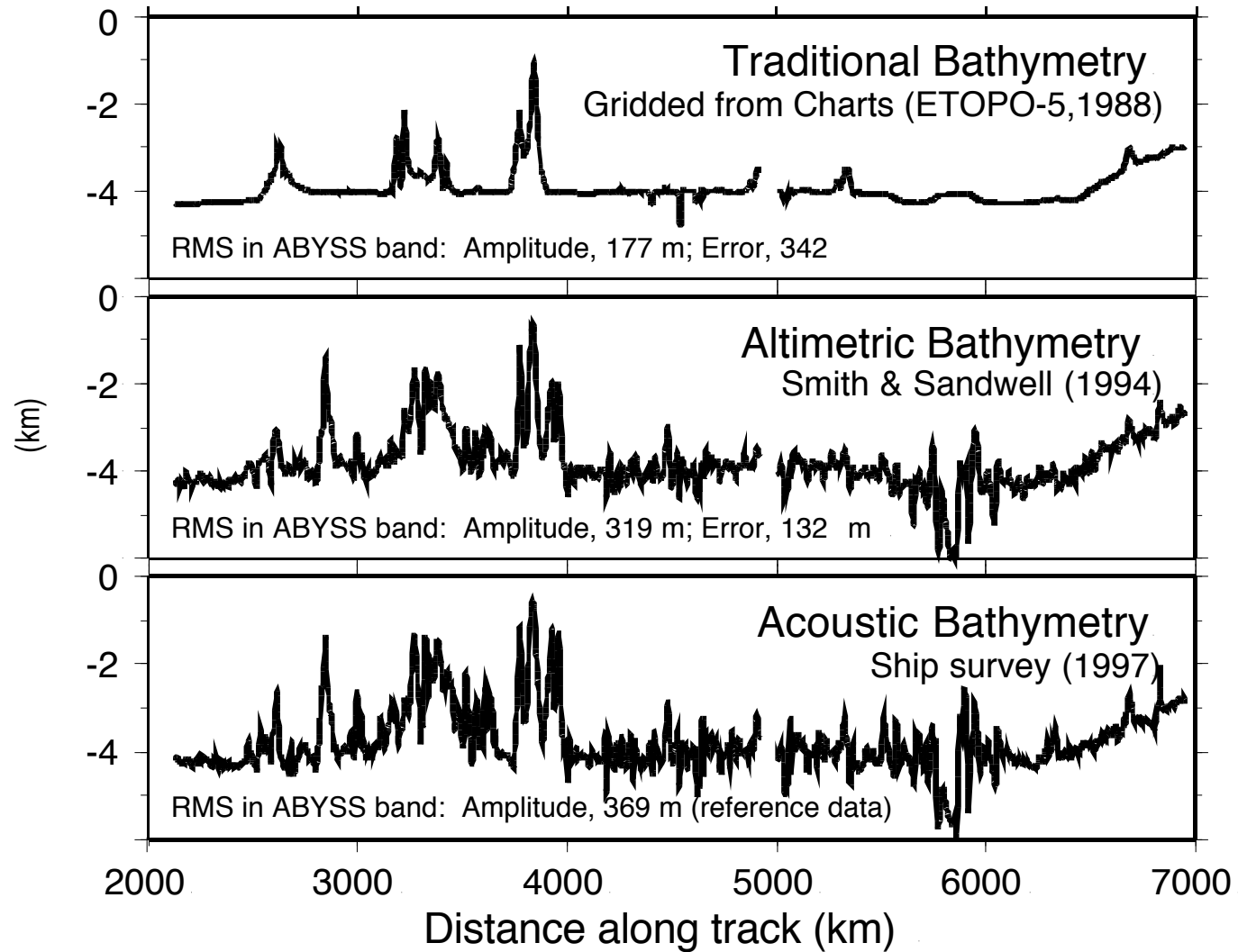




# “Foundations” Seamounts: Ground Truth

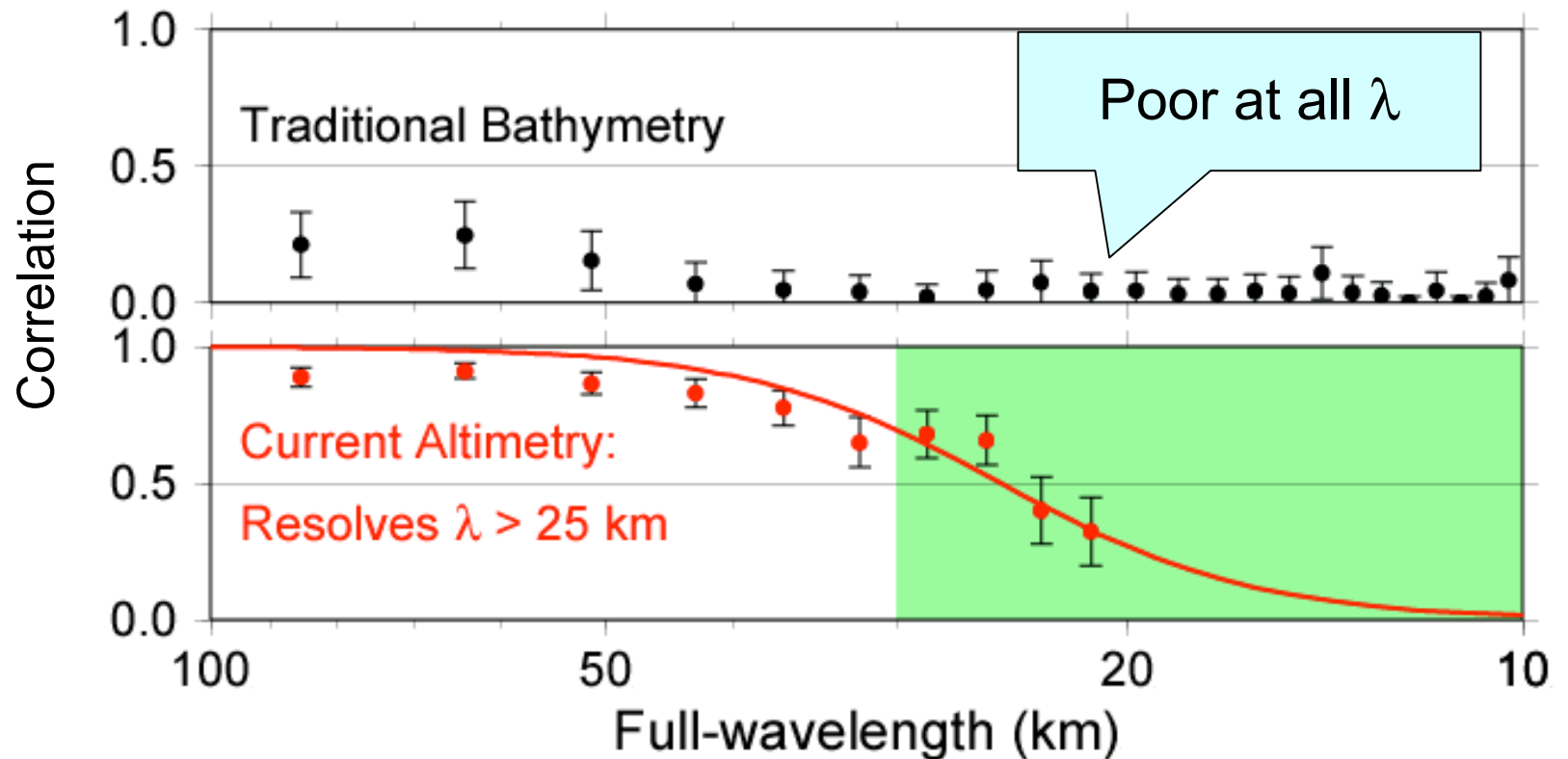


# “Foundations” Bathymetry Profile



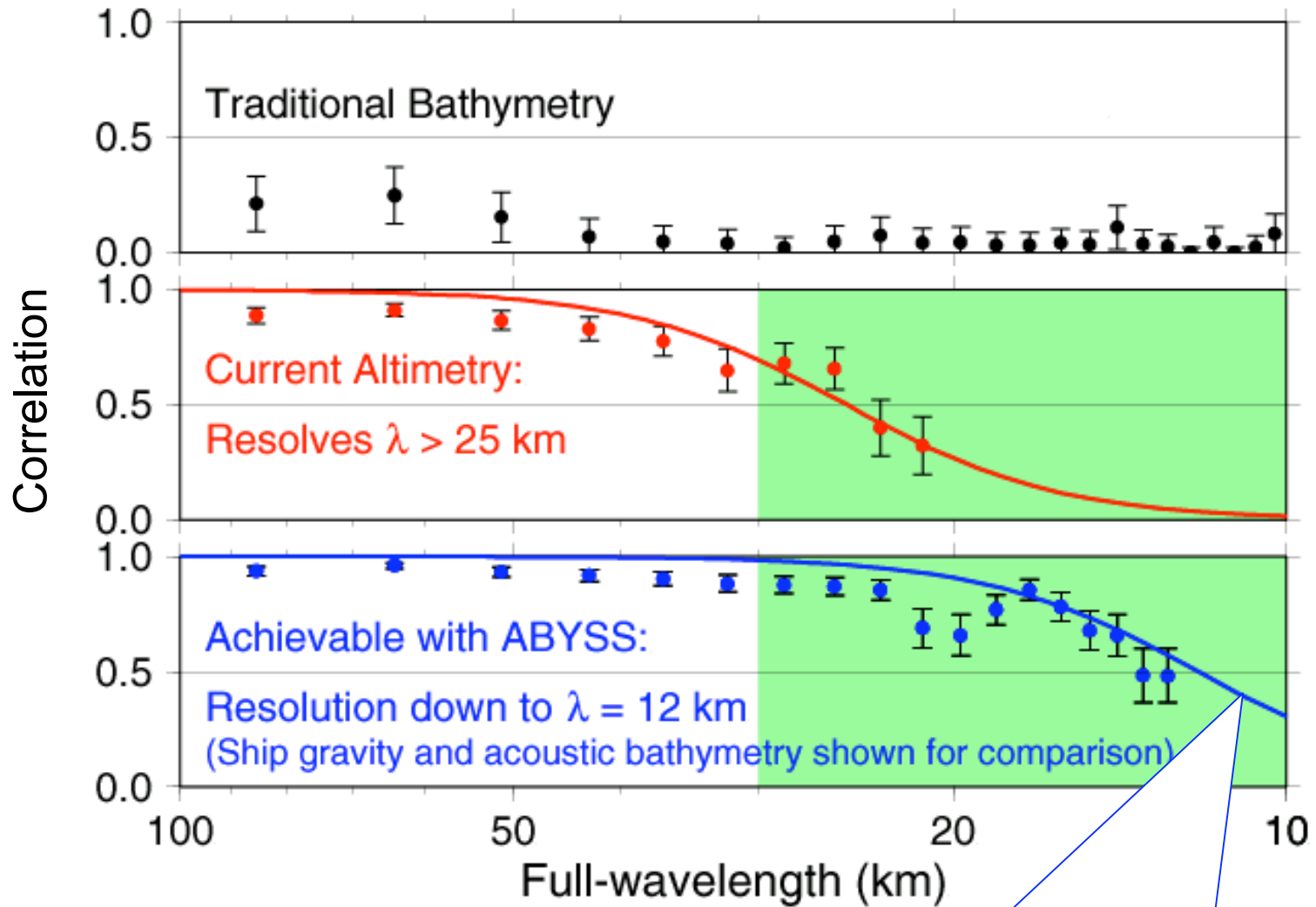


# Profile Correlation by Wavelength



**This band was not resolved in 1997 with our then ~5 mGal noise level, but we believe it could be within reach. Resolving this band is the key to finding seamounts and controls on mixing.**

# Best Possible Resolution: Measure Gravity as Well as a Ship Can (to $\sim 1$ mGal, or $1 \mu\text{rad}$ of sea surface slope)



**This limit is physical, not instrumental**





# How can we do better?

Improve altimetry signal-to-noise ratio:

- Fly a new mission with a better altimeter ("ABYSS")

- Reprocess ("retrack") existing data

Improve algorithms

- Can optimization theory help? (My UNH CCOM visit.)

Get more/better/cleaner in situ control data

- NOAA/NGA/Navy "MOA Annex" project.



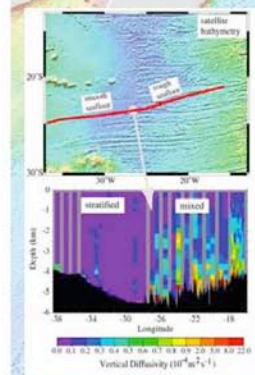
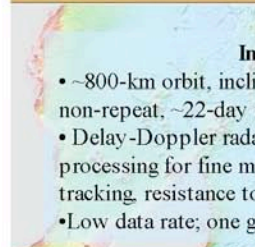
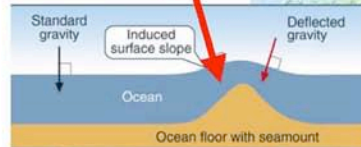
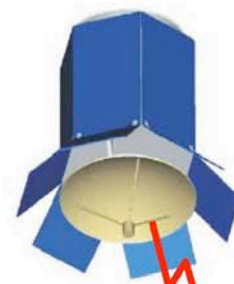
# ABYSS Proposal Status

"ABYSS" proposal to NASA ESSP-3 for ISS, circa 2001. (4 fed agcys & 12 univs partnered, top peer reviews.)

"ABYSS-Lite" free-flyer design study, June 2003.

Invited NRC Concept Paper (May 2005) (~100 signatories).

Navy is studying a similar mission now, and looking for partners. NGA has expressed strong interest in meeting ABYSS goals.



Fact Sheet

## Abyss-Lite\*

### An altimeter for geodesy and mesoscale oceanography

#### Method

- Radar measurement of sea surface slope reveals gravity anomalies & ocean flows

#### Themes

- The fine-scale (200-km to 5-km) ocean shape yields bathymetry, gravity anomalies, and deflections of the vertical (VD) unavailable by other means
- The non-repeat orbit monitors ocean currents and eddies unseen by other missions

#### Complements Related Missions

- GRACE, Champ and GOCE sense gravity at orbital altitude, where resolution is limited to ~200 km; Abyss-Lite measures gravity at sea level, where resolution down to ~5 km is available.
- Abyss-Lite's drifting orbit fills holes in the exact-repeat orbits covered by TOPEX/Poseidon, GFO, Envisat, and Jason-1, enabling fine-scale geodesy and detailed recovery of mesoscale eddies.

#### Implementation

- ~800-km orbit, inclination ~120° (preferred) or ~60°, non-repeat, ~22-day near-repeat, 6-y mission, small s/c
- Delay-Doppler radar altimeter w/ on-board processing for fine measurement precision, near-shore tracking, resistance to "wave noise"
- Low data rate; one ground station

#### Science

- Ocean bottom shape and roughness control tsunami propagation, steering of flows, mixing rates, heat transport, global climate & sea level.
- Ocean floor structure answers fundamental science questions about Earth's magma budget, volcanism tectonics, and seismic hazards.

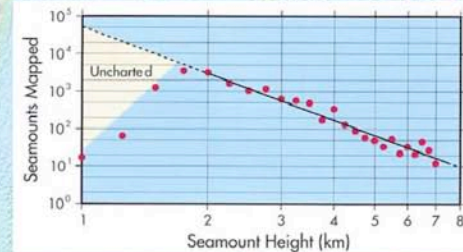
#### Applications

- Bathymetry aids habitat management, ecology, cable and pipeline routing, & Law of the Sea.
- Gravity field details enable precision inertial navigation and resource exploration.
- Real-time sea level anomaly observations enable operational oceanography.

#### Cost and Schedule

\$75M (2-string altimeter, WVR, bus, integration and test)  
Phase A/B FY 2006, Phase C/D FY 2007-9, Launch CY 2009

\* A White Paper submitted to the NRC Decadal Survey



**A new Bathymetry from Space mission should find 50,000 unmapped seamounts** (yellow area). A 2-fold improvement in seamount height precision should increase the total number of seamounts mapped by 18-fold. The proposed mission will yield a 20-fold improvement in areal resolution of the marine gravity field and bathymetry.

#### Participants and Endorsers

National Oceanic and Atmospheric Administration  
University of California (San Diego)-Scripps  
Johns Hopkins University Applied Physics Laboratory  
~100 signatories from academia, civilian and military operational agencies, and international organizations

#### Points of Contact

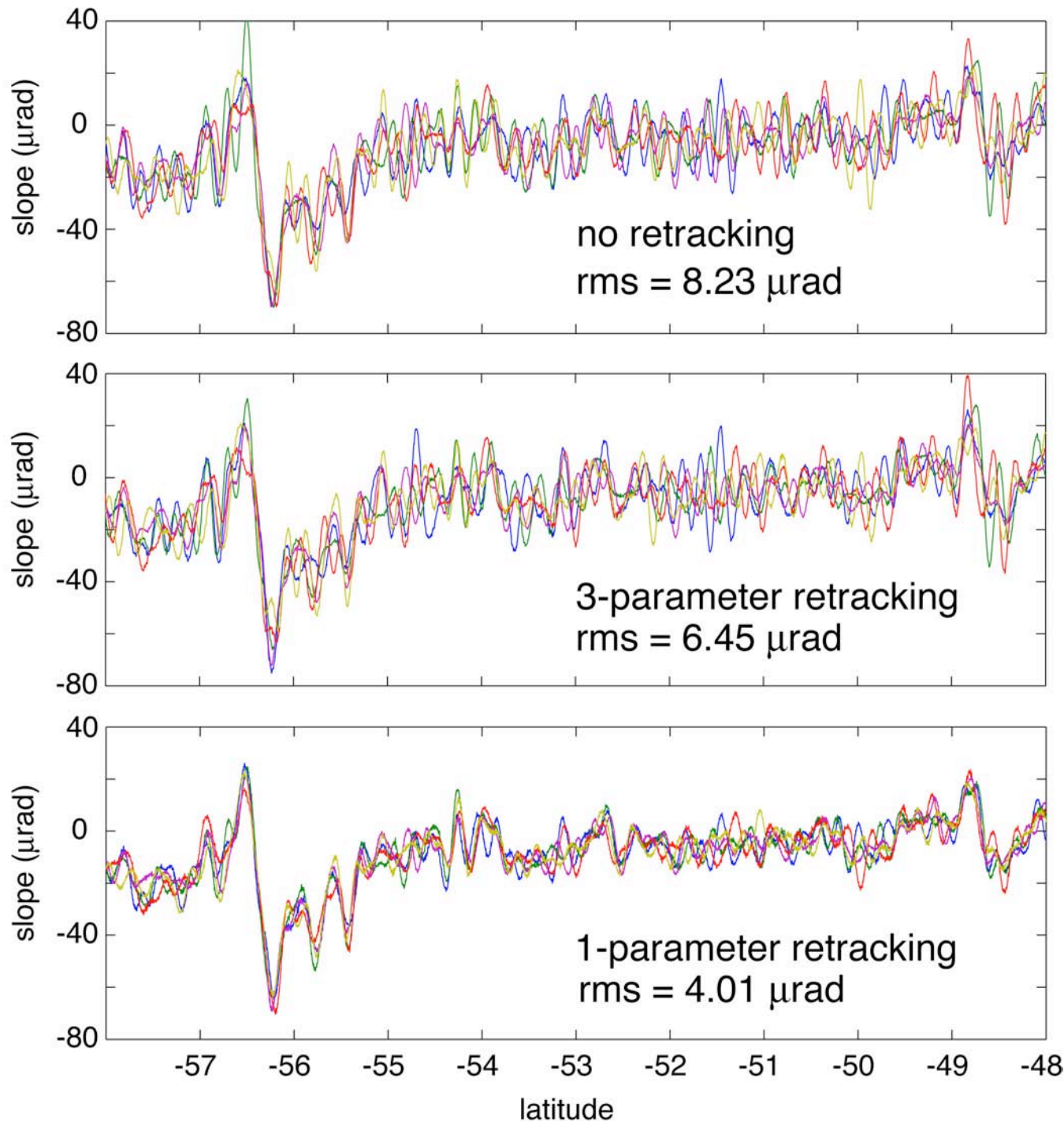
Dr. Walter Smith, NOAA  
Walter.HF.Smith@NOAA.gov

Prof. David Sandwell, UCSD-SIO  
dsandwell@ucsd.edu

Dr. Keith Raney, JHU/APL  
Keith.Raney@jhuapl.edu

May 2005





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.



# Optimization?

After the sub crash, Dan Donnell of NGA Maritime asked me, "Is this all just a big least squares number crunch?". The answer was "not so far", but he got me thinking:

If we had DoD's computing power available, would we gain anything by formulating the estimation as a  $g$ -to-depth cross-covariance weighted scheme, analogous to those known as "objective analysis", "kriging", "geostatistics"?

I visited the NOAA NOS / University of New Hampshire joint Center for Coastal and Ocean Mapping and developed a course for PhD students called "optimal mapping", to review the theory of these methods and test algorithms.



# Optimal predictor formulation

If the optimal predictor is linear, spatially invariant, and isotropic, then it must have the form:

$$z(\vec{x}) = \iint p(|\vec{x} - \vec{y}|) g(\vec{y}) d\vec{y}^2$$

The optimization problem can be put in standard form if we say "optimization" means minimizing the squared misfit,  $E^2$ , between the predicted depth and the observed depth,  $d_i$ , at points where we have data:

$$E^2 = \sum_i \left[ d_i - z(\vec{x}_i) \right]^2$$

Then given an altimetric gravity map and some scattered depth soundings, we have a linear inverse problem for  $p(r)$ .

# Optimal predictor expansion

If we expand the Hankel transform of the optimal predictor in some finite set of basis functions we may write:

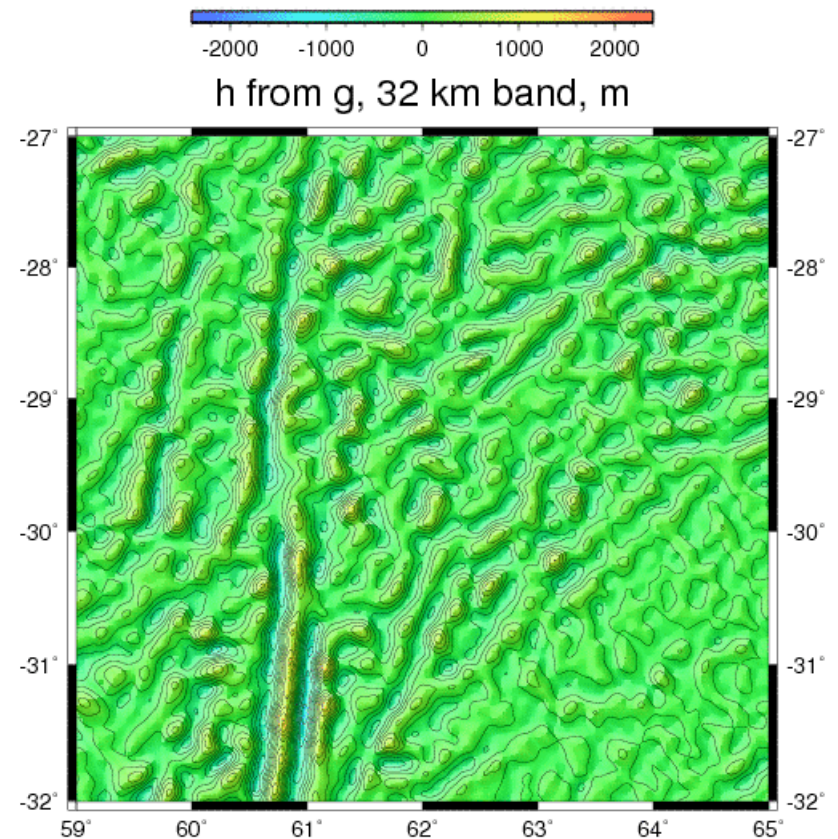
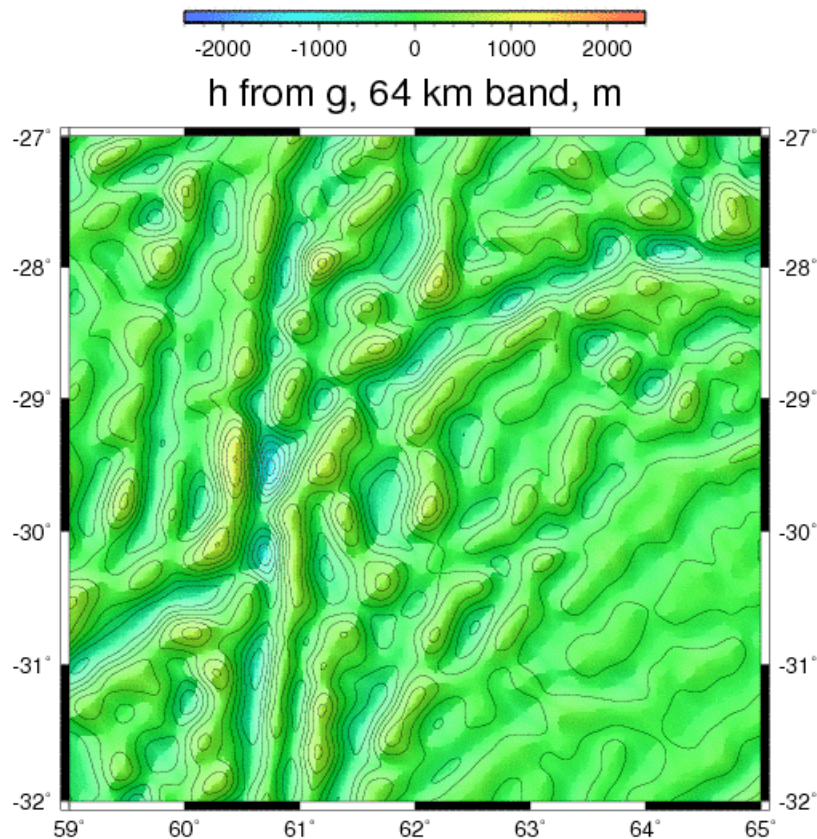
$$p(r) = 2\pi \int_0^{\infty} J_0(2\pi qr) \sum_{k=1}^K \alpha_k P_k(q) q dq$$

Then the problem boils down to least squares fitting of the coefficients  $\alpha_k$  that give the best fit to the data. The predicted depth map is a linear combination of  $K$  filtered gravity maps, where the  $k$ 'th map has been filtered with the filter  $P_k$ . I used a  $\beta$ -spline basis for the  $P_k$ , so that each filtered gravity map was a narrow-band-pass centered on a different wavelength.

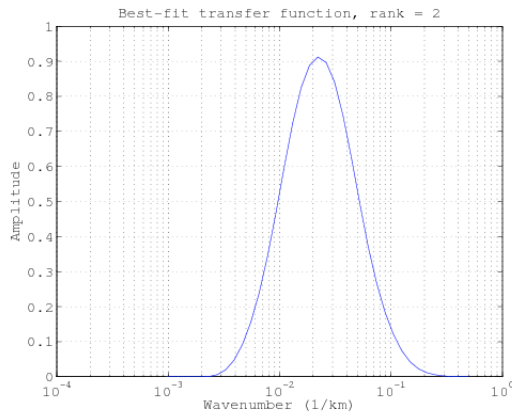
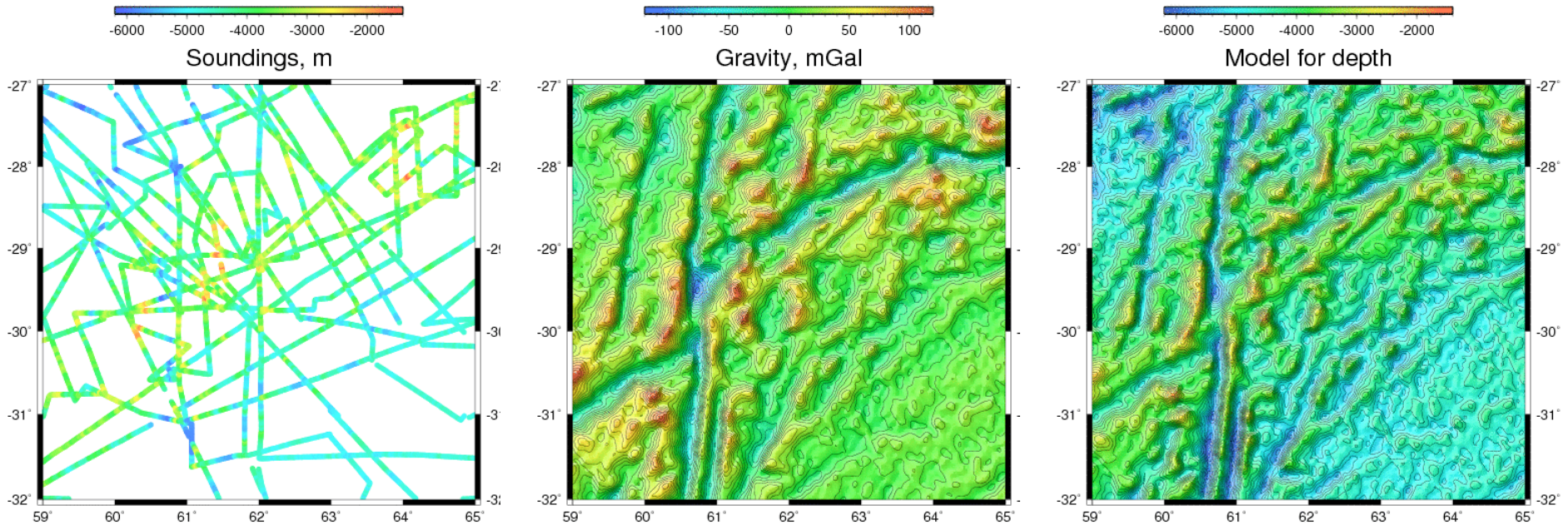


# Examples of filtered basis maps

The problem boils down to fitting, by least squares, the best linear combination of a set of maps like the two shown here.



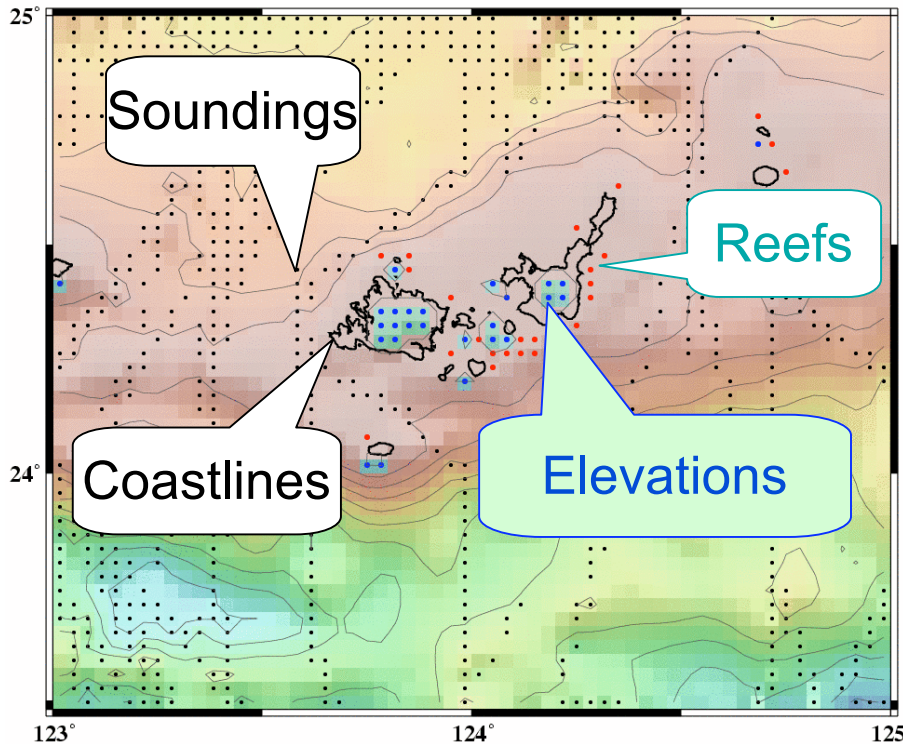
# Resulting "optimal" prediction



Not surprisingly, the "optimal" predictor turns out to be a band-pass filter. So all this computation may not have bought us very much. These ideas need further development and test.



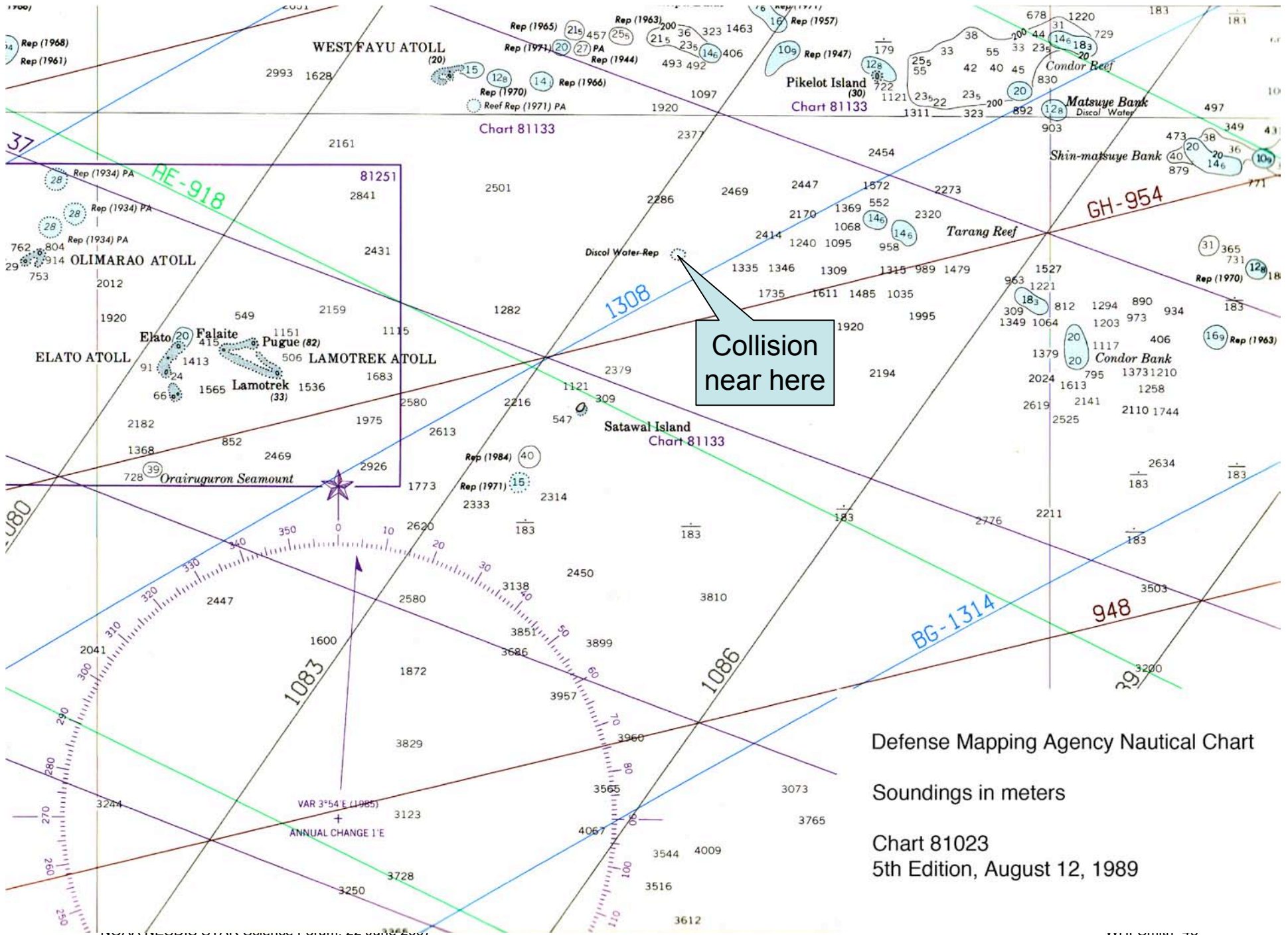
# NOAA-NGA-Navy MOA Annex Bathymetry Project



After the *USS SF* accident, NGA asked me to lead a tri-agency project to build a better global bathymetry model.

NOAA ORA & NGDC supply altimetry, soundings, land elevations, shorelines, algorithms and expertise.

NGA and NOO supply additional shoreline, hazard and obstruction data, and labor. Their classified data are used for verification and algorithm improvement. The final products will have both secret and public versions.



Collision near here

Defense Mapping Agency Nautical Chart

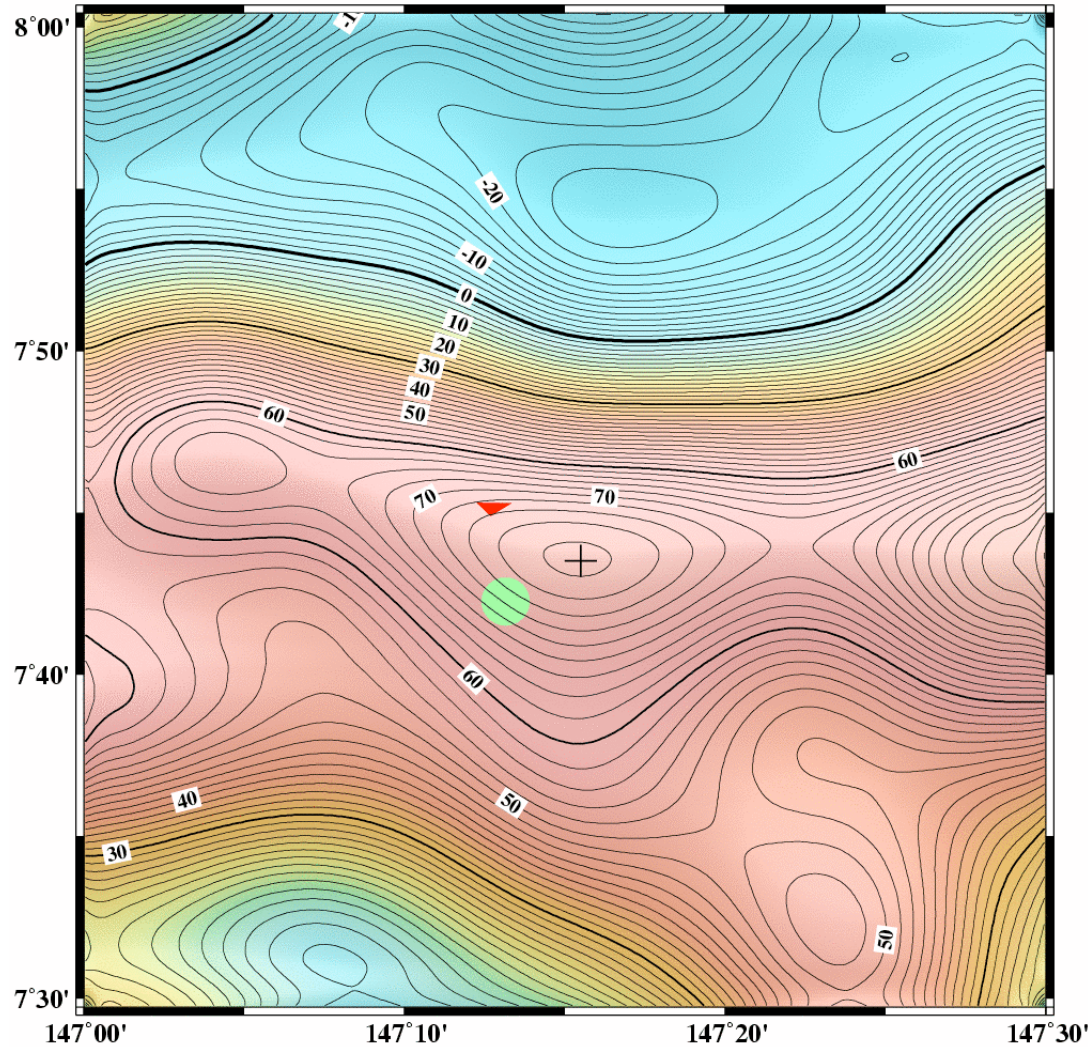
Soundings in meters

Chart 81023  
5th Edition, August 12, 1989





# Gravity maximum near collision



Gravity, Version 14.1 C.I.=2 mGal

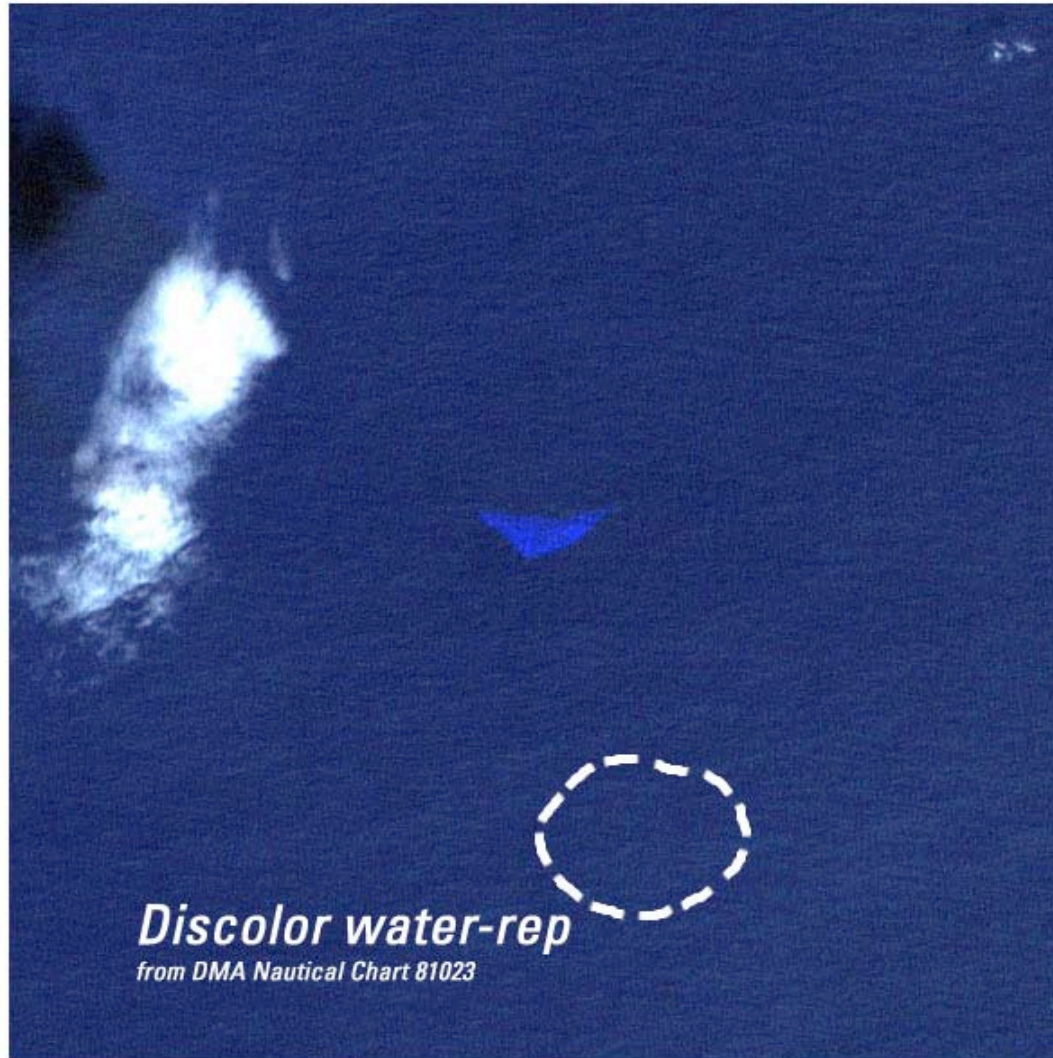
+79mGal @ 7°43'30"N,  
147°15'30"E. Gravity  
maximum may be  
skewed toward  
resolved center of  
mass of seamount;  
not shallowest point.

3 n.m. from Landsat  
shoal (triangle, actual  
size); and DMA chart  
81023 discolored  
water report (circle,  
actual size).

Note large gravity  
gradient in area: 100  
mGal in 10 n.m.



# "Discolored Water"



Landsat 7 data acquired 1/21/2004  
shows an area of discolored water approx. 350 miles south of Guam  
centered at 7°45' 5.34" N 147°12' 39.41" E.

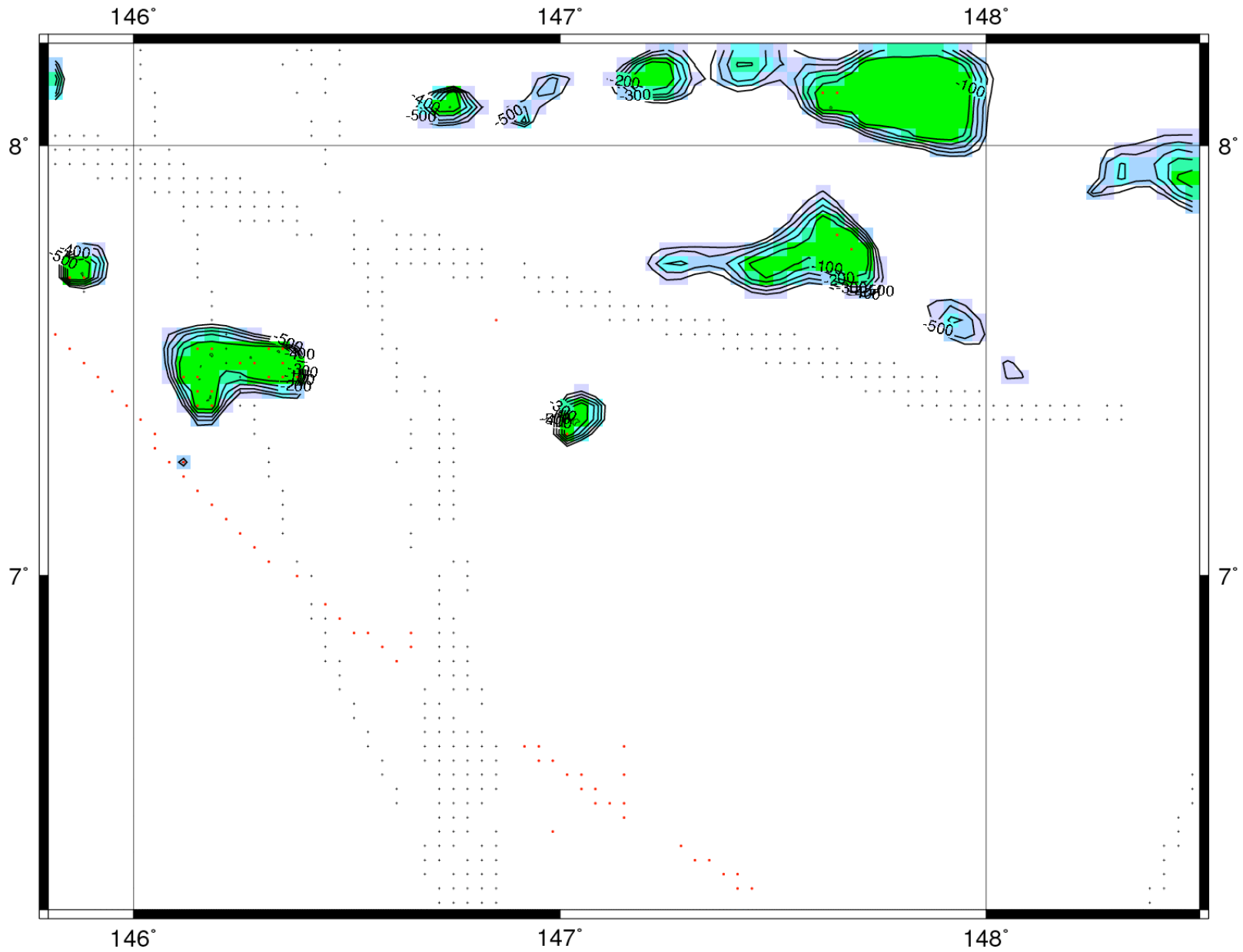


# MOA project status

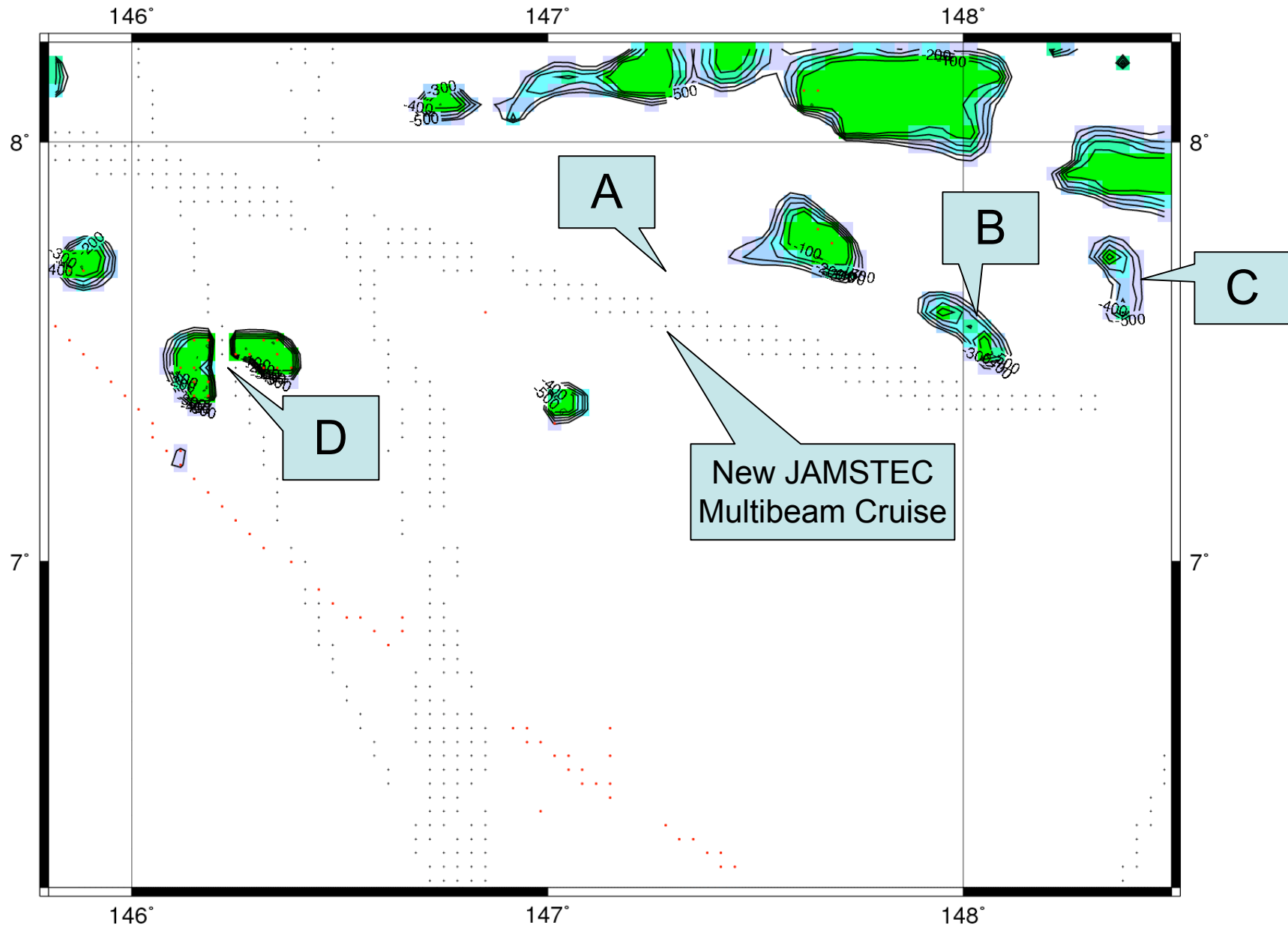
- MOA Annex Agreement signed
- Initial data & algorithm exchange completed
- Telecons ~monthly and face-to-face meetings about every 6 months.
- Draft bathymetry estimated completed in May and currently under review. A pair of slides from our last telecon follows.



# Topo 8.2



# Topo 9.2







**Thank you!**