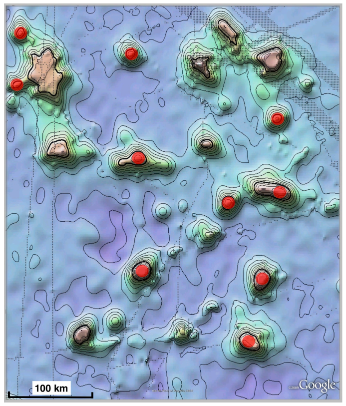
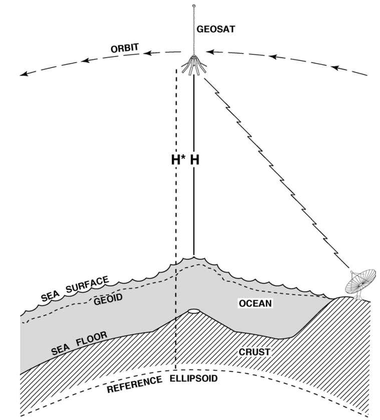
Sixth GMTSAR Course
UCAS, June, 2017



Predicting Bathymetry from Satellite Altimetry: The Good, The Bad, and the Ugly



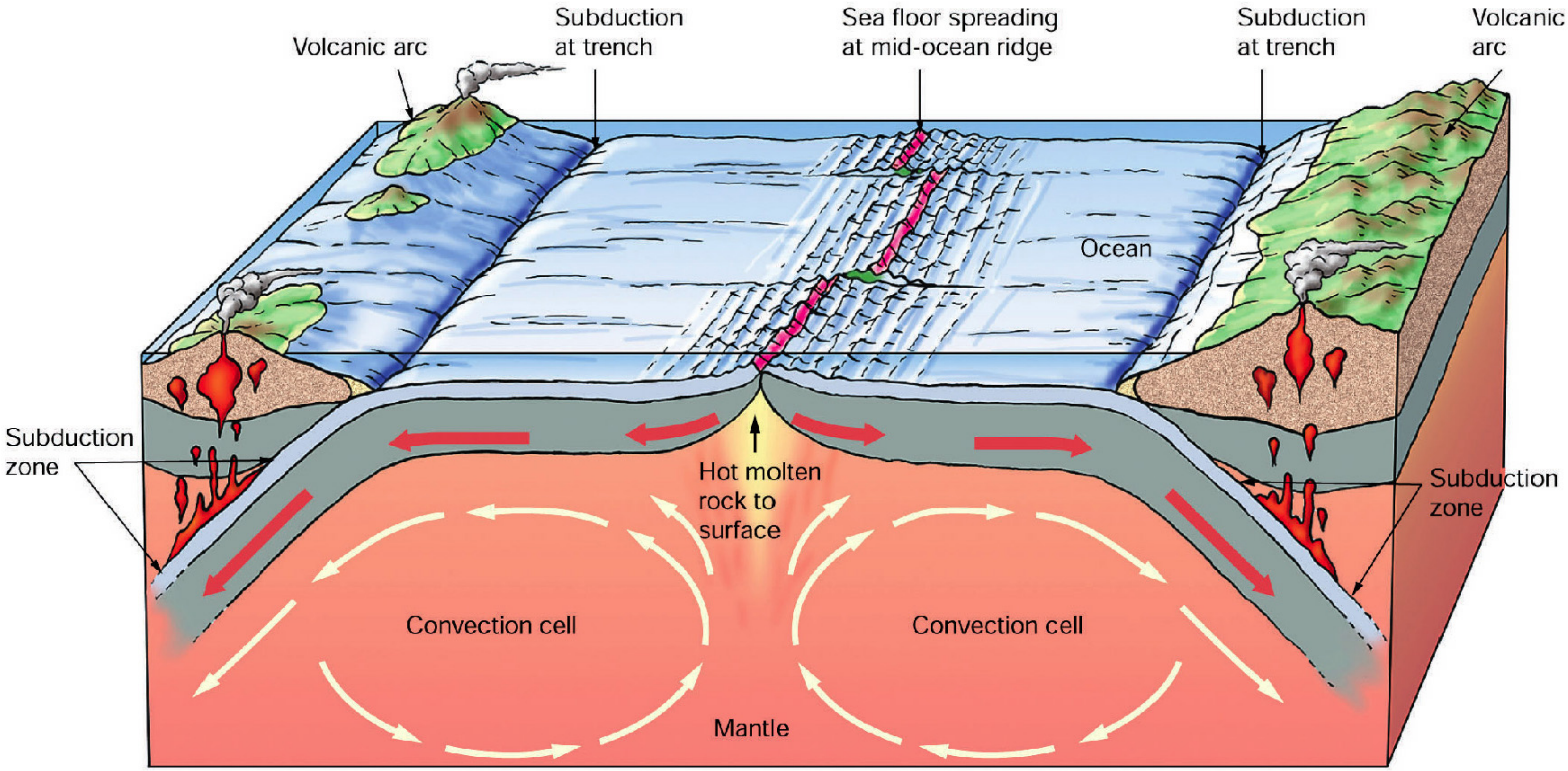
David T. Sandwell - Scripps Institution of Oceanography
Walter H. F. Smith - Laboratory for Satellite Altimetry, NOAA
Shengjun Zhang – Northeastern University, China
Joseph J. Becker - Naval Research Laboratory
Christopher Olson - Scripps Institution of Oceanography

Objective – construct the best possible global map of the deep ocean floor for science, public outreach, and applications.

- Tectonics and topography of the deep ocean
- Mapping by ships - what is missing?
- Mapping by satellites

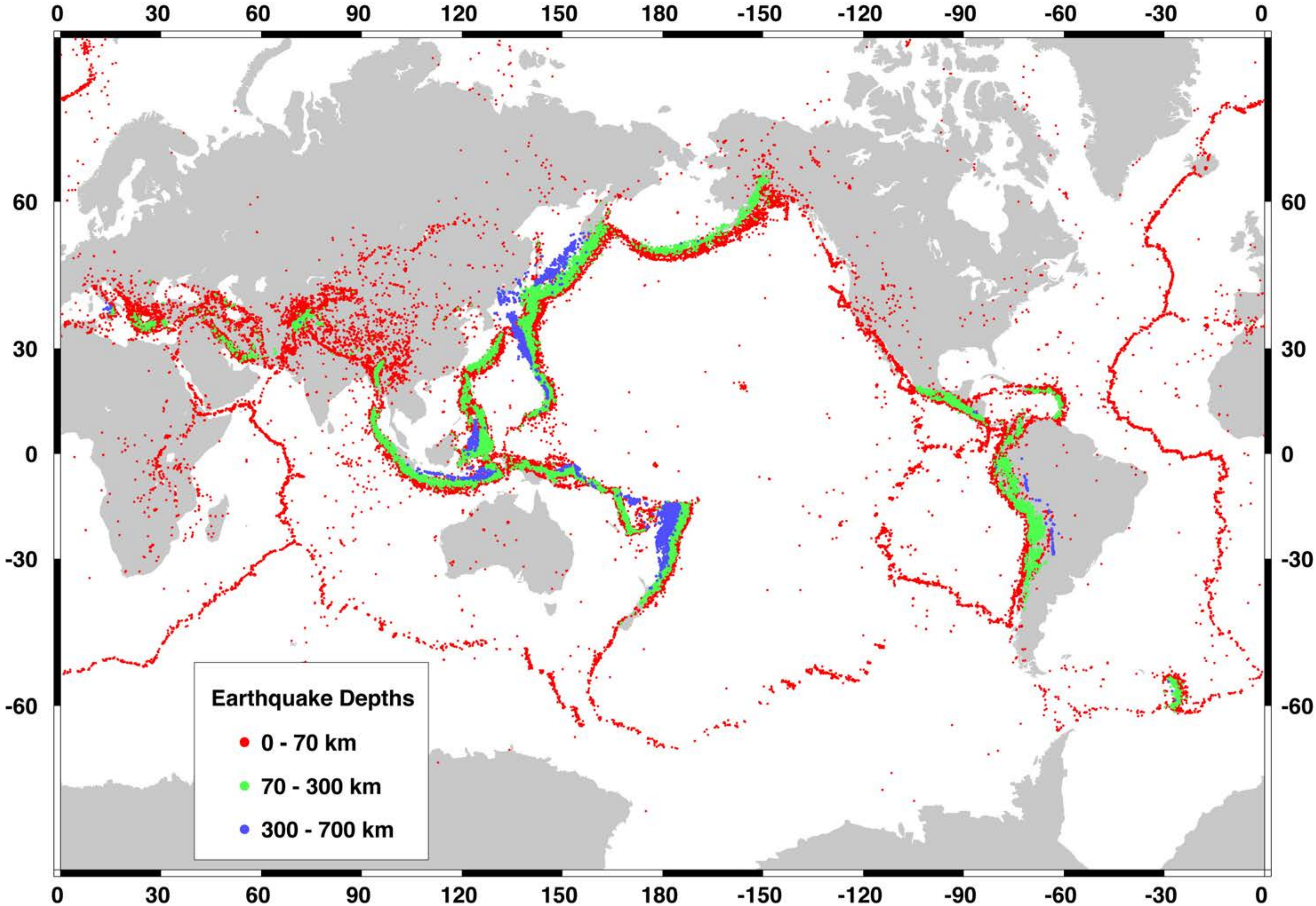
Funding:
Google Inc.
National Science Foundation
Office of Naval Research
National Geospatial Agency

plate tectonics

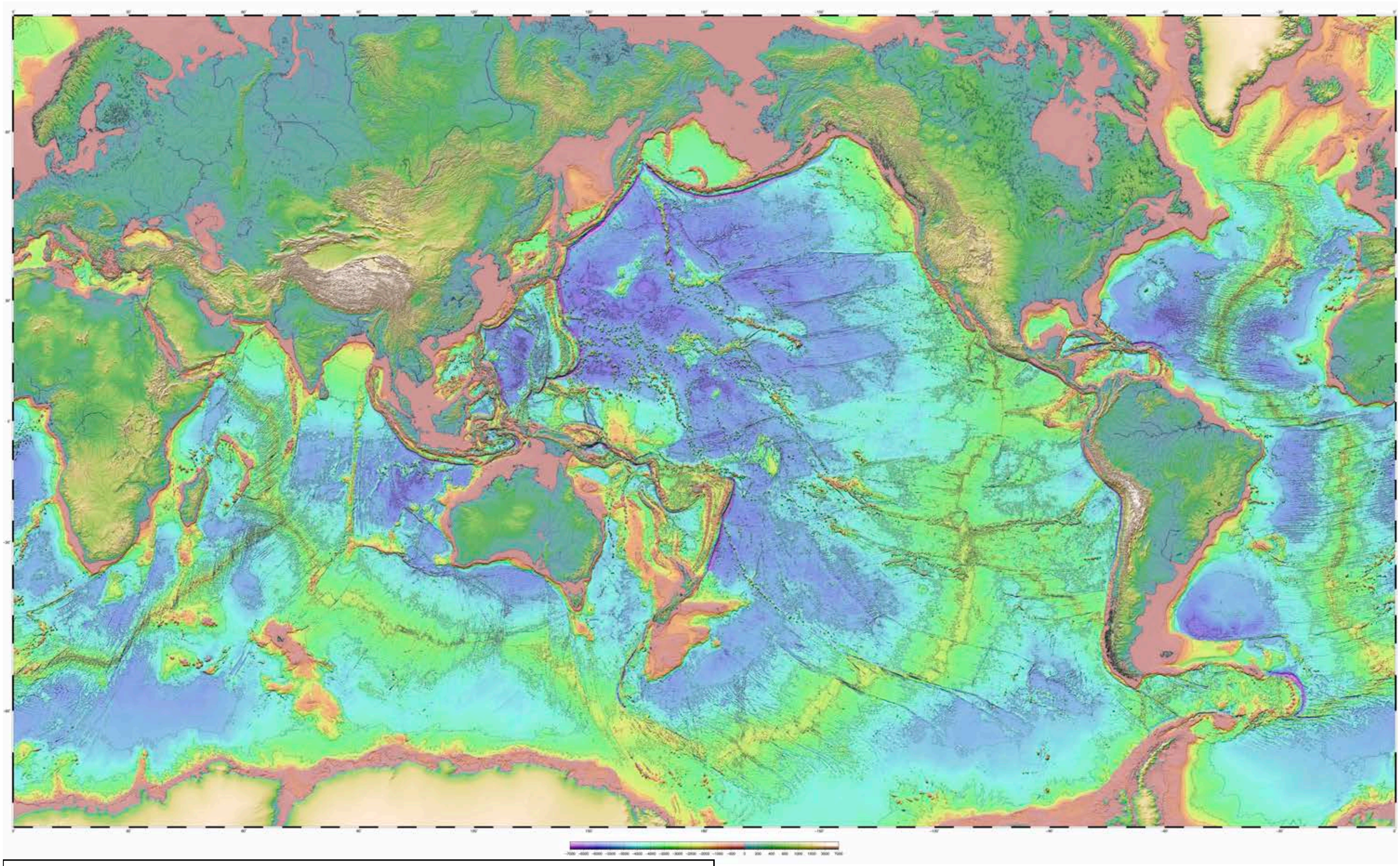


(Trujillo A. P. and H. V. Thurman, Essentials of Oceanography, Prentice Hall, New Jersey, 2004)

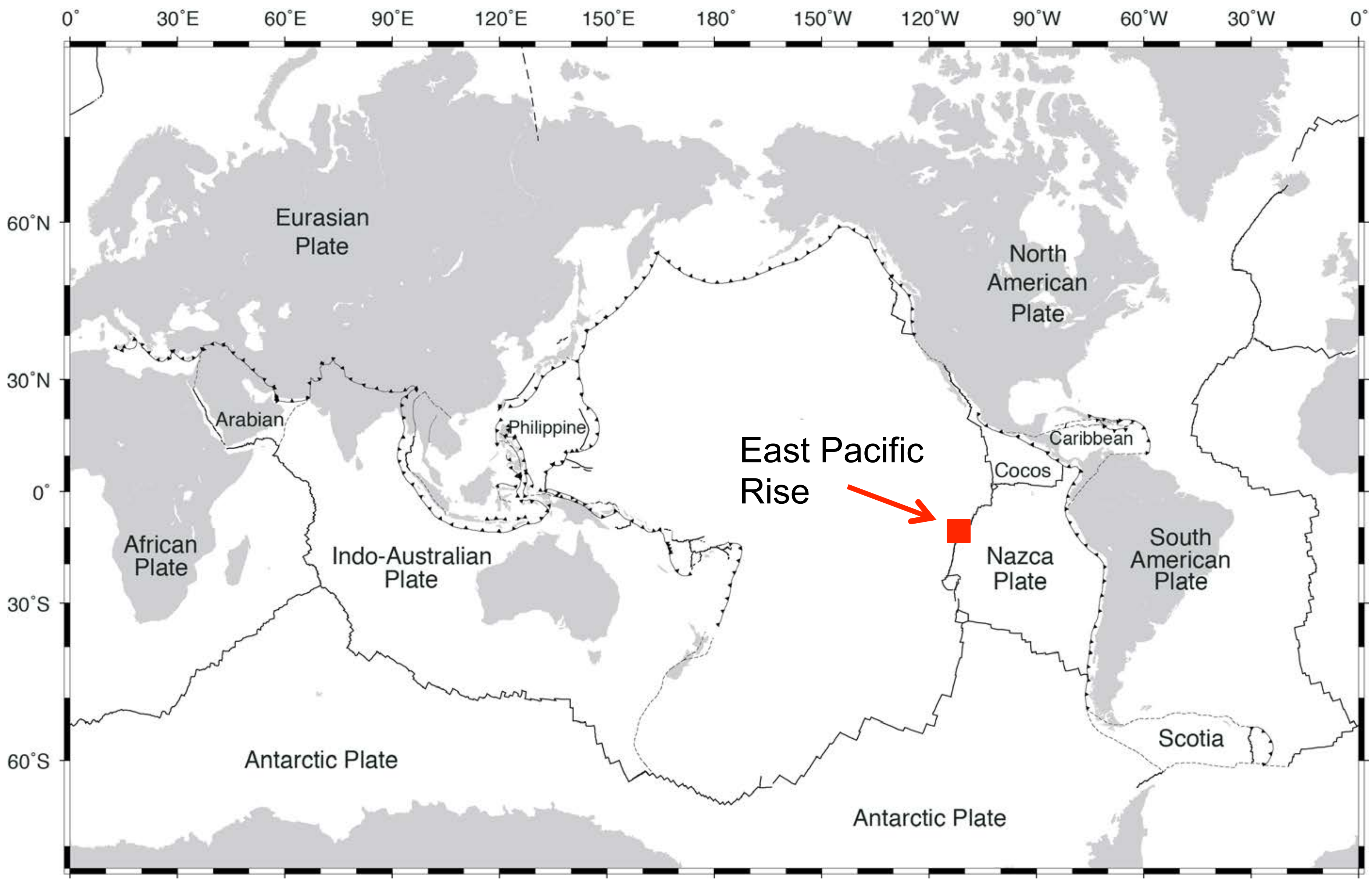
global seismicity



topography and bathymetry



Google Earth version at http://topex.ucsd.edu or
ftp://topex.ucsd.edu/pub/srtm30_plus/SRTM30_PLUS.kmz



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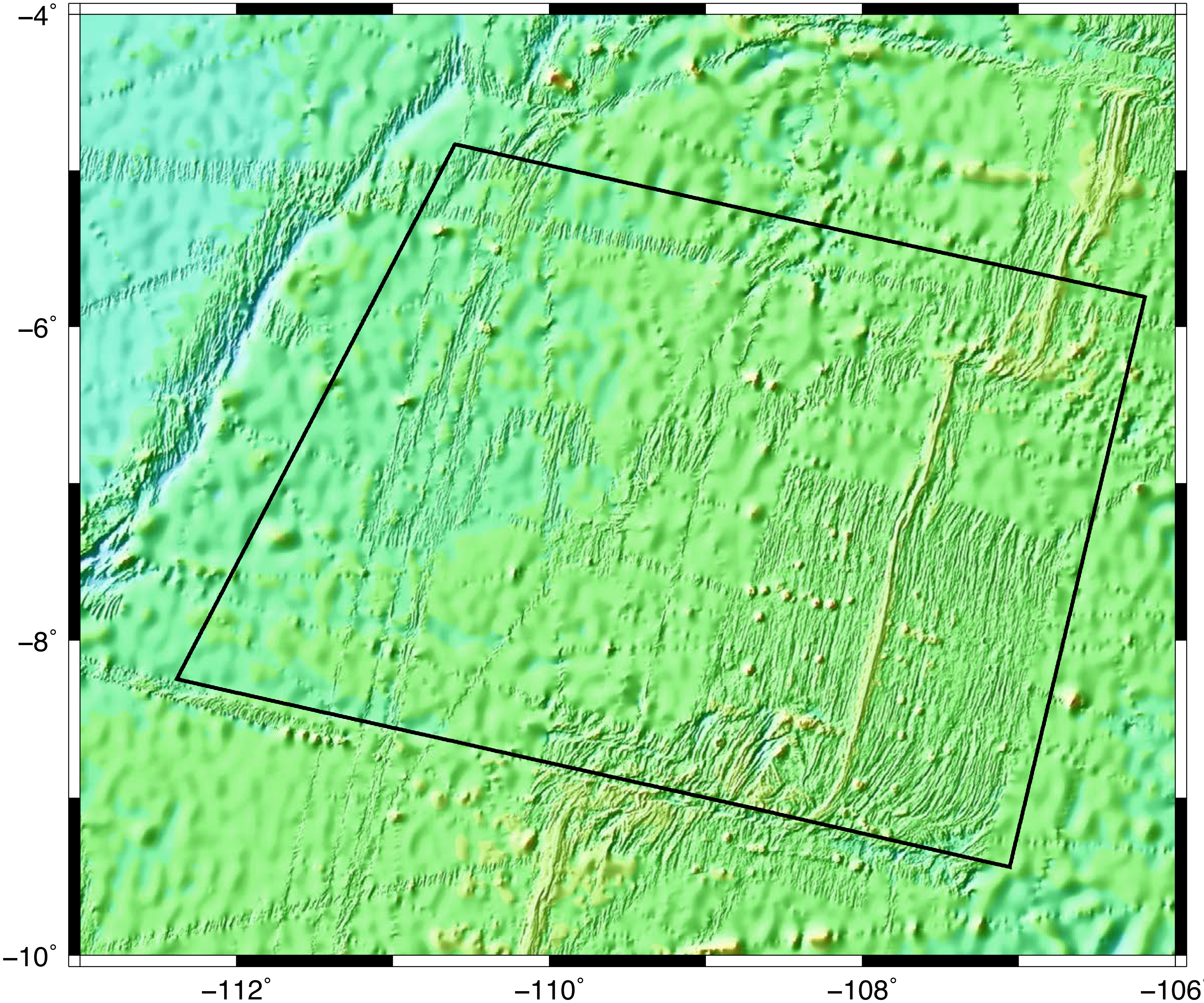
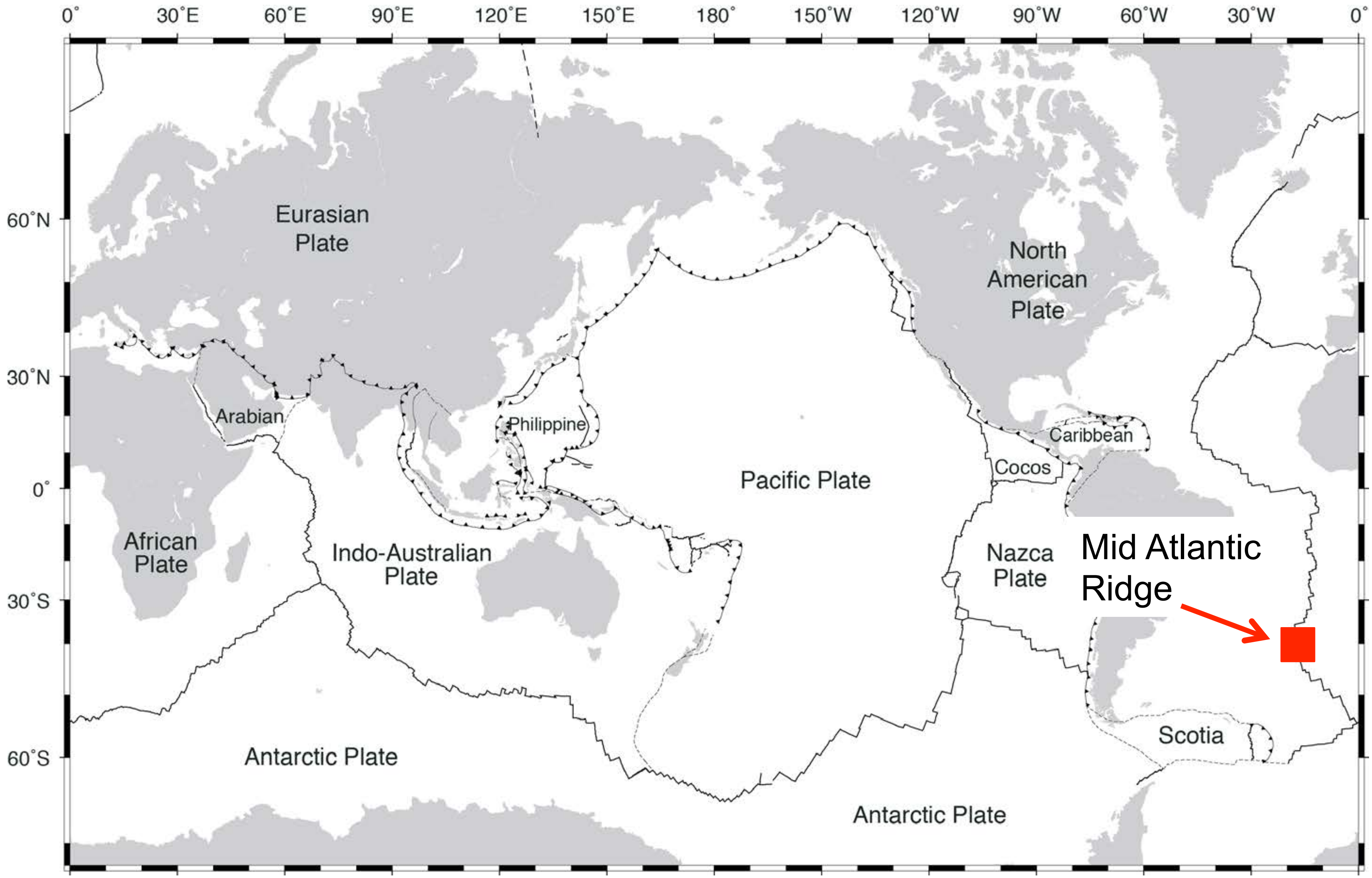
60°S
Eurasian Plate
North American Plate
Arabian
Philippine
Caribbean
Cocos
East Pacific Rise
African Plate
Indo-Australian Plate
Nazca Plate
South American Plate
Scotia
Antarctic Plate
Antarctic Plate



EPR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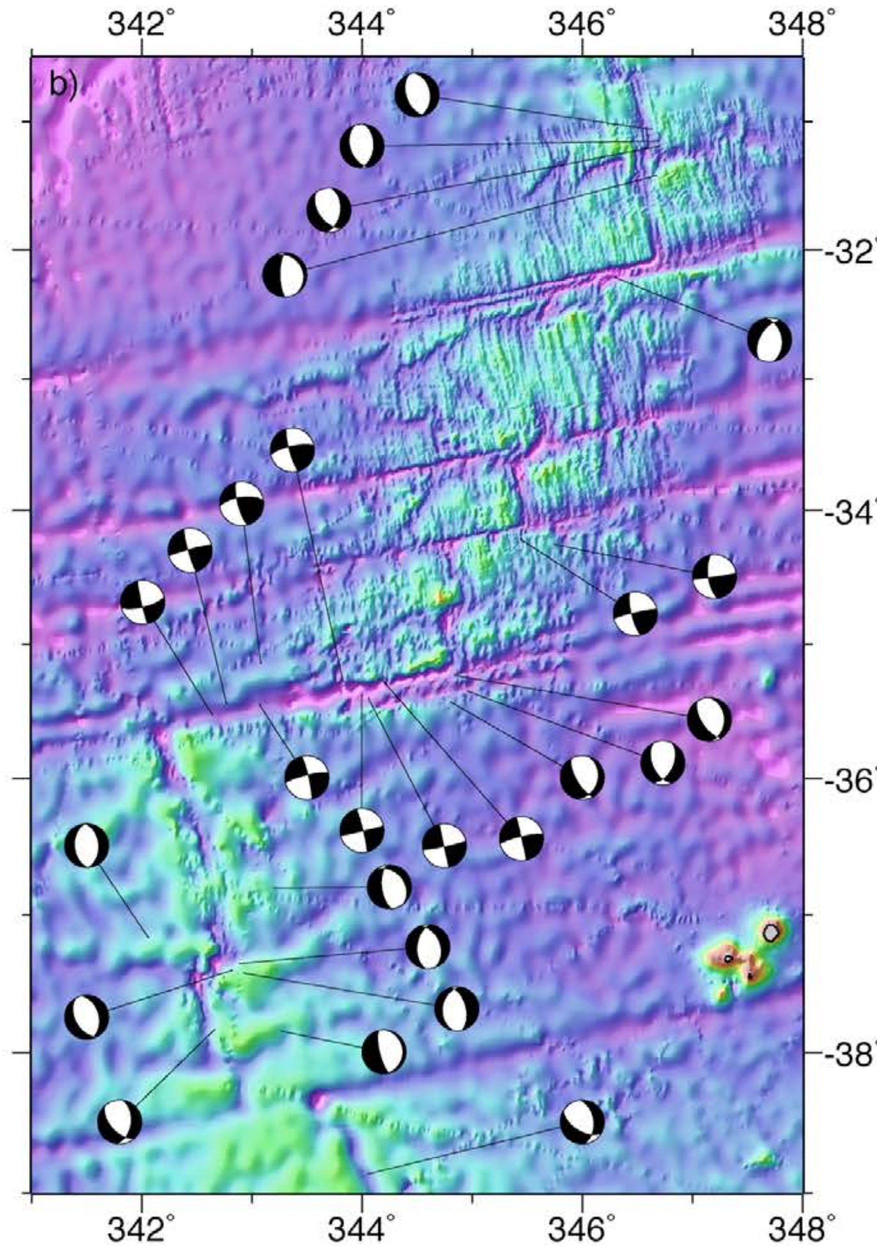
Eurasian Plate
North American Plate
Arabian
Philippine
Caribbean
Cocos
Pacific Plate
African Plate
Indo-Australian Plate
Nazca Plate
Mid Atlantic Ridge
Scotia
Antarctic Plate
Antarctic Plate

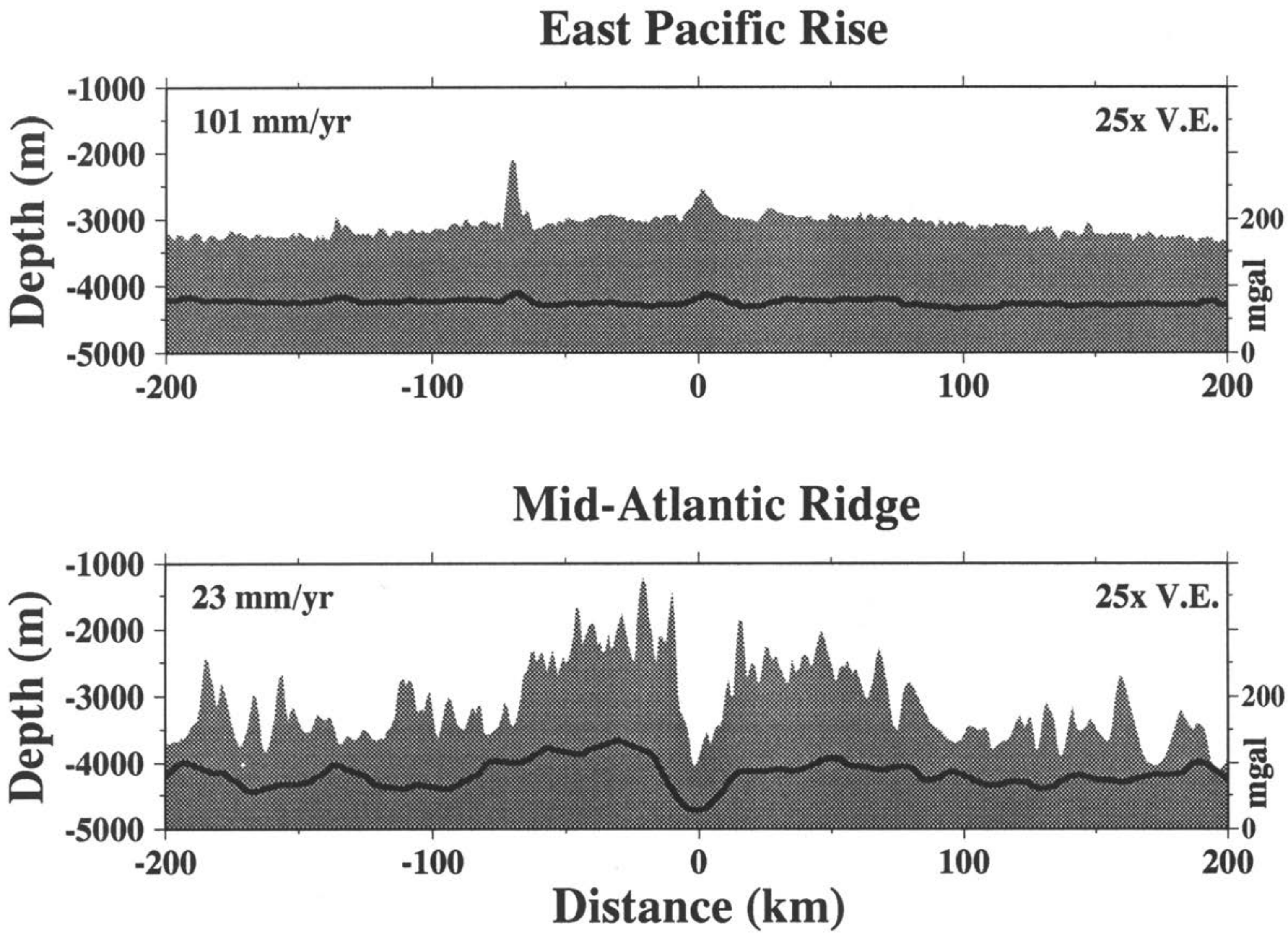
Mid Atlantic Ridge

- alternating spreading ridge and transform offset segments
- ridge earthquakes have normal focal mechanism
- transform earthquakes have strike-slip focal mechanism

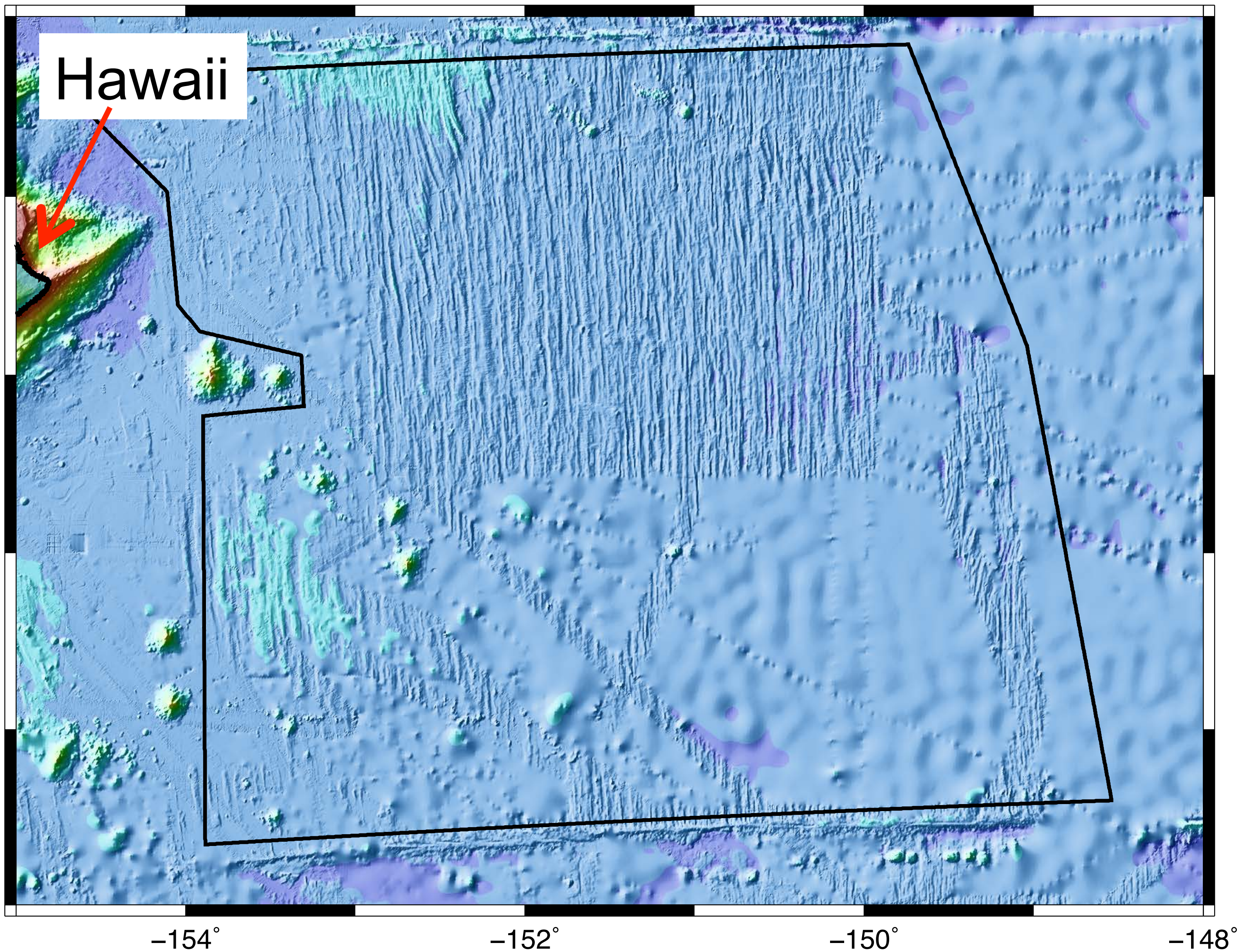


[Luttrell and Sandwell, JGR, 2011]

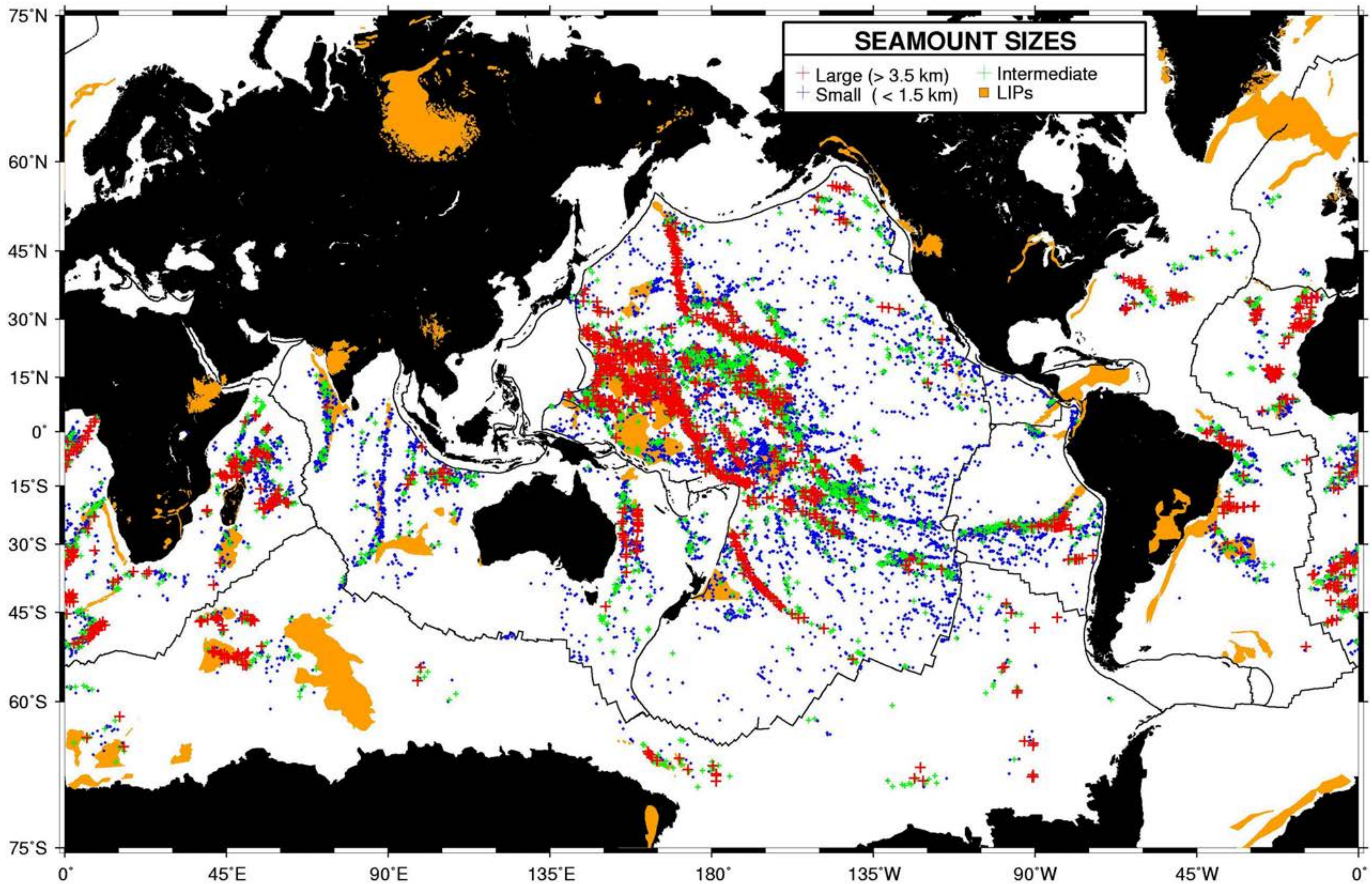
fast vs. slow spreading



abyssal hills are the most common landform on the Earth

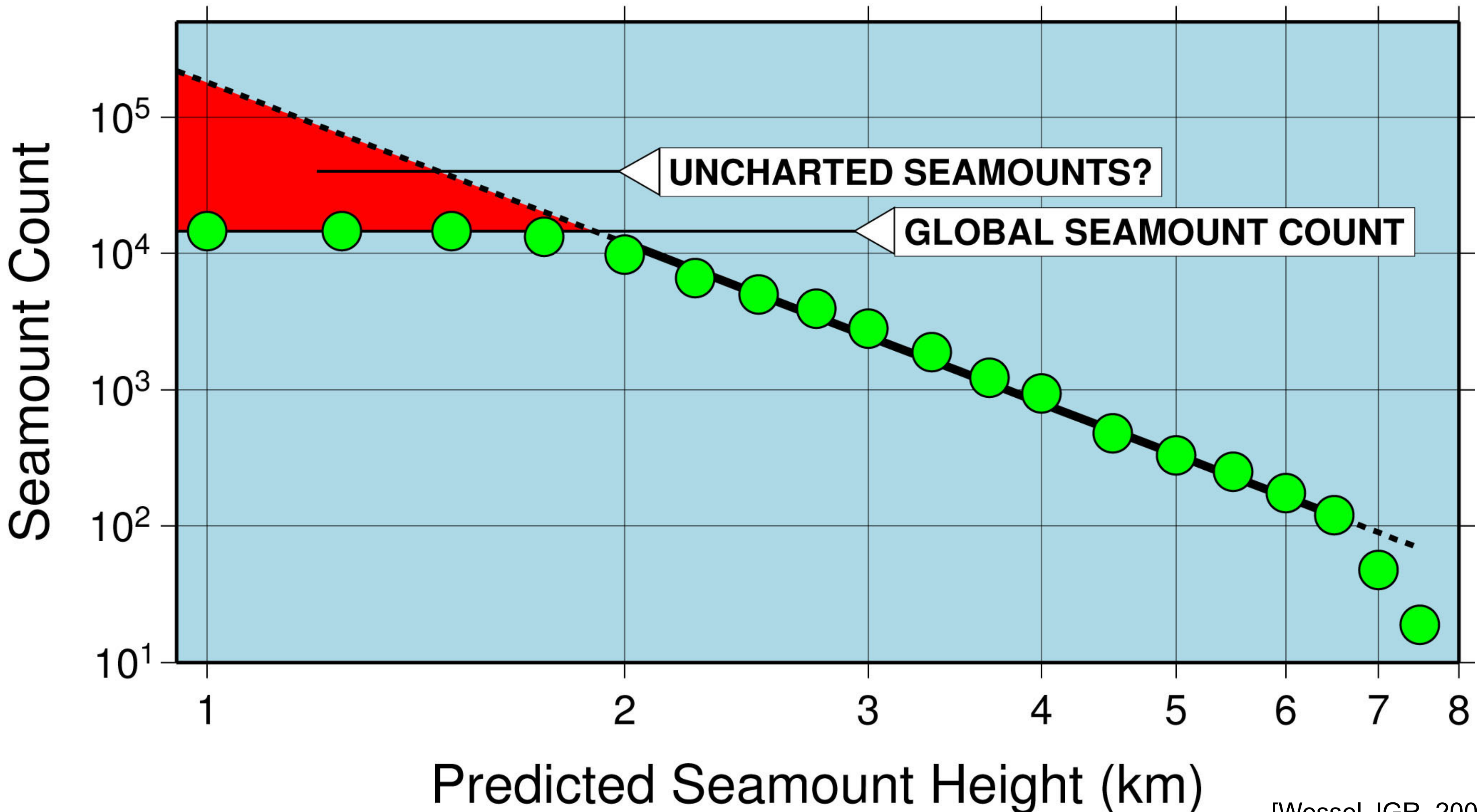


seamounts or undersea volcanoes



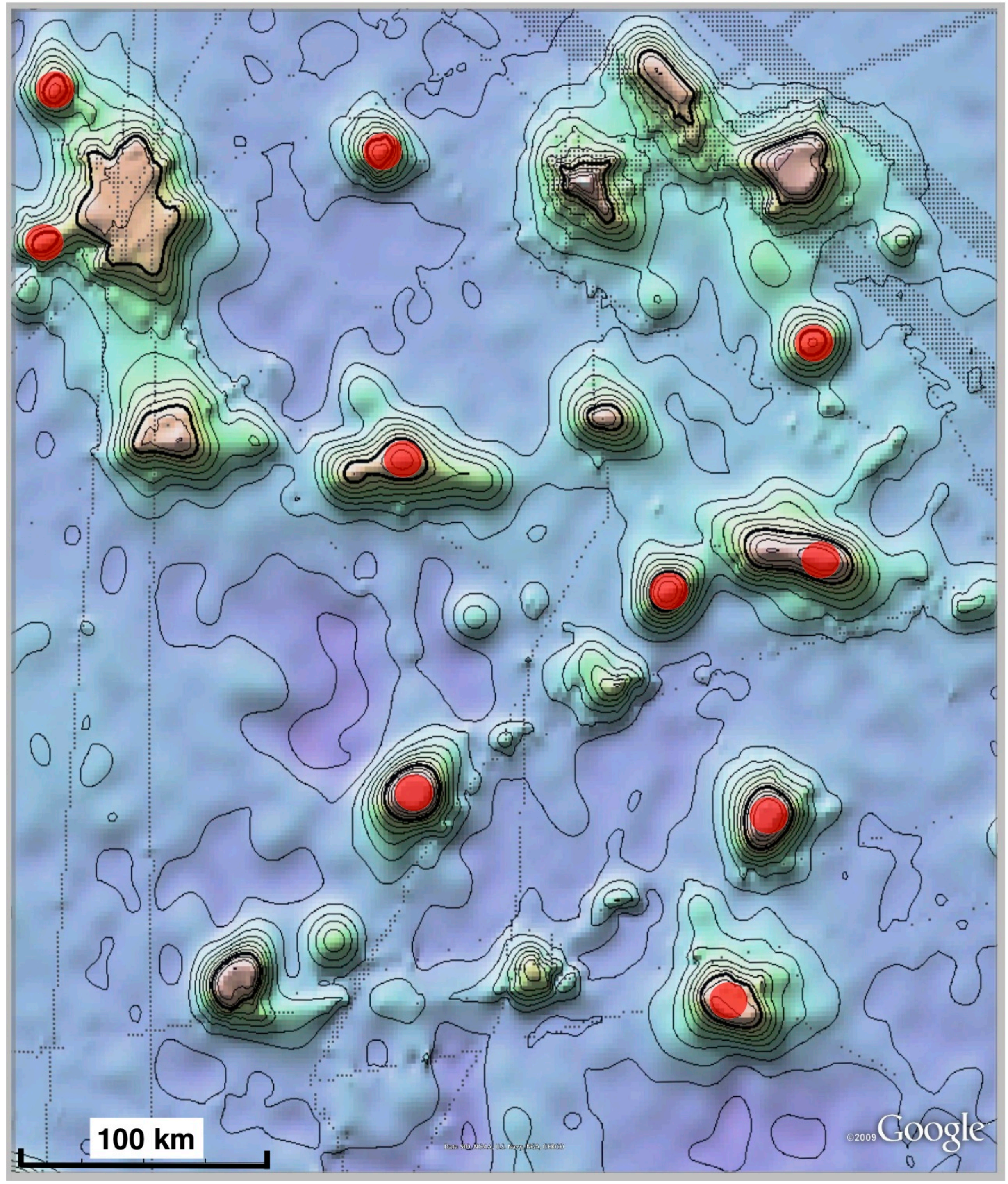
[Wessel JGR, 2001]

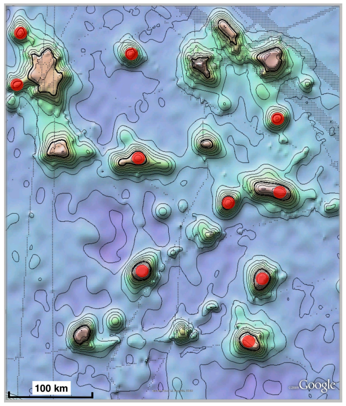
size distribution of seamounts



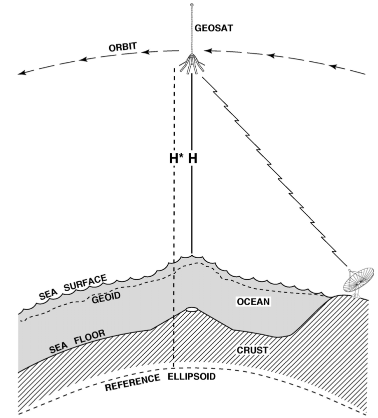
[Wessel JGR, 2001]

uncharted seamounts > 3 km tall



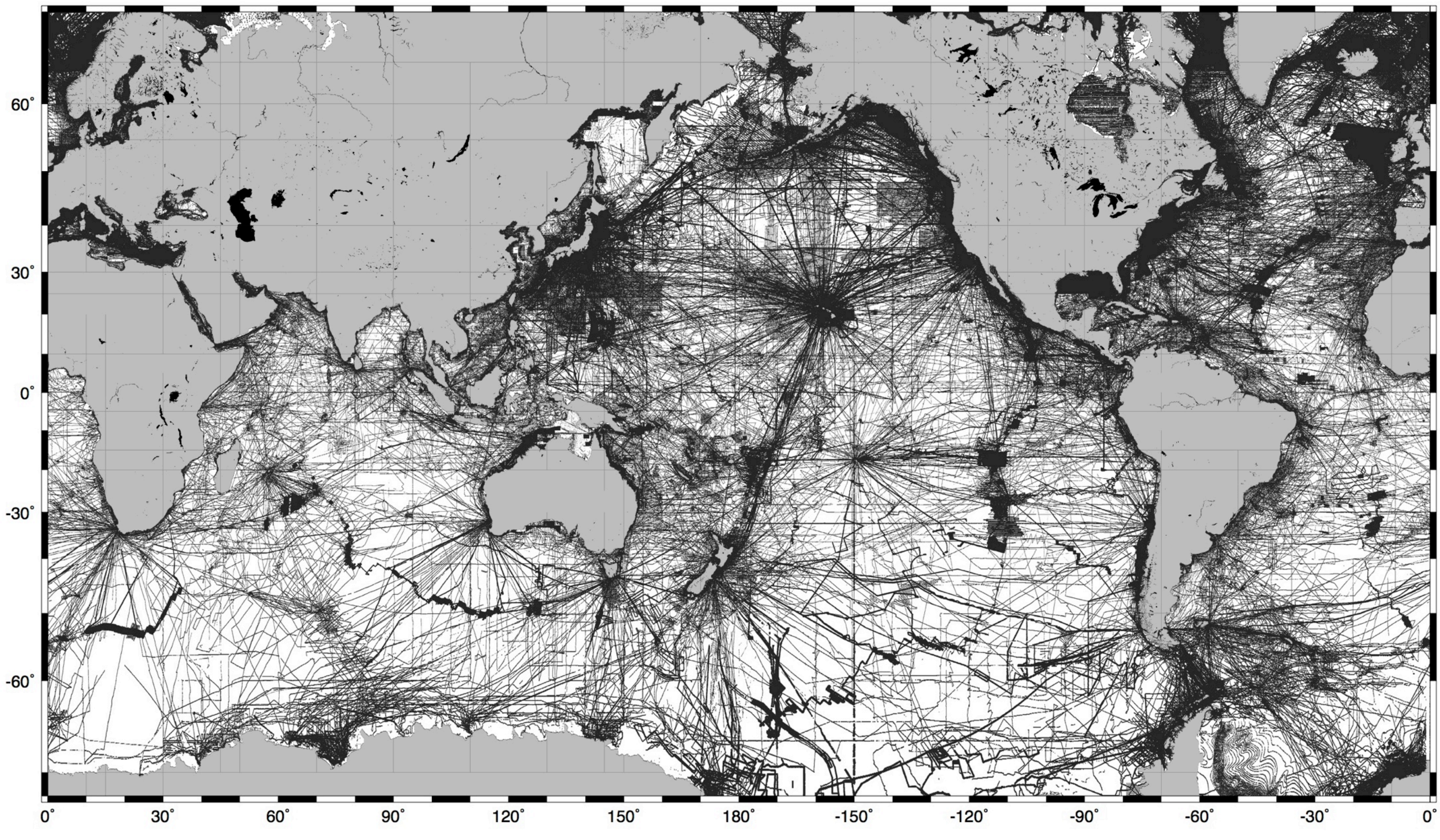


Exploring the Deep Ocean Basins with Ships and Satellites

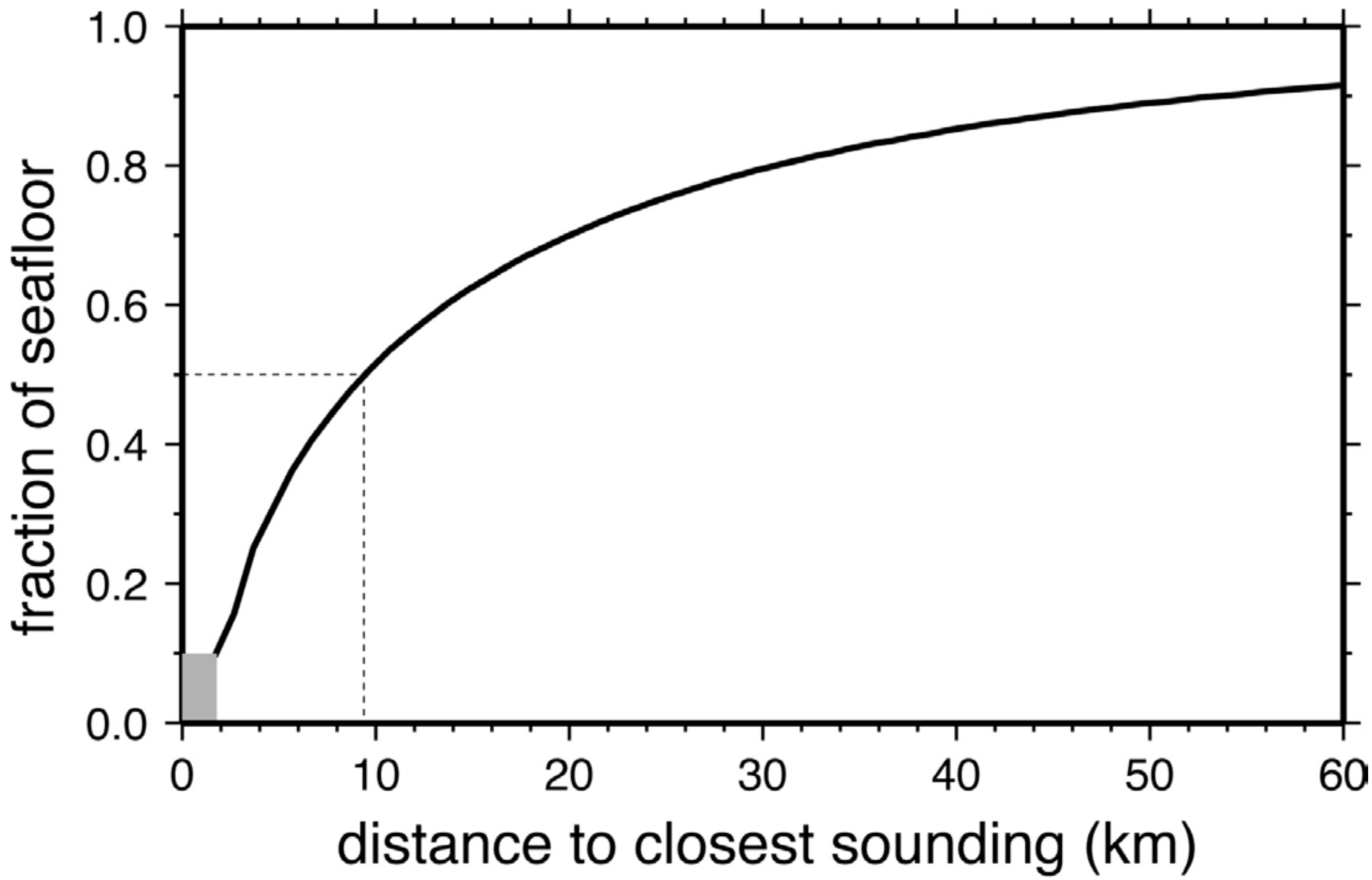


- Tectonics and topography of the deep ocean
- **Mapping by ships - what is missing?**
- Mapping by satellites

Soundings used in SRTM15/30_PLUS
multibeam, singlebeam, grids, . . .



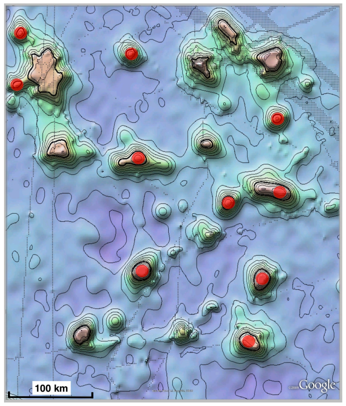
1/2 of global seafloor bathymetry not resolved at 10 km



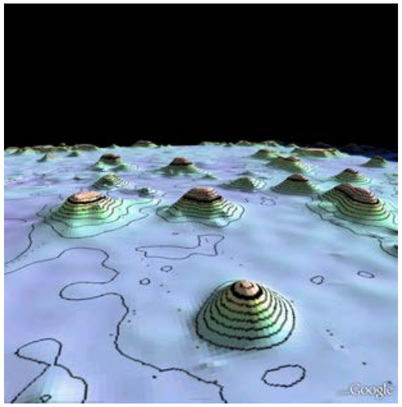
[Smith and Marks, 2009]

source	# points (500 m)	% flagged	% seafloor @ 1 km
NGDC_multi	127901083	4.75	5.134
NOAA_geodas	40897565	11.06	2.506
US_multi	51187020	5.32	2.219
JAMSTEC_multi	79103040	0.62	2.04
SIO_various	40754645	13.93	1.325
IBCAO_various	18302390	0.03	0.773
GEBCO_various	8950614	0.17	0.523
AGSO_grid	12875795	2.62	0.503
DNC_points	5878651	1.23	0.49
CCOM_grid	10023471	0.08	0.195
GEOMAR_grid	18138868	0.06	0.181
NGA_single	4415125	19.44	0.179
NOAA_grids	6748376	0.49	0.162
IFREMER_single	7653537	10.62	0.151
3DGBR_various	5523560	11.36	0.112
NAVO_multi	422089	0.06	0.009
total	**438,775,829**		**16.5 % in V11**

percentage of seafloor mapped at 1 km resolution



Needs for Improved Bathymetry in the Deep Oceans



Science

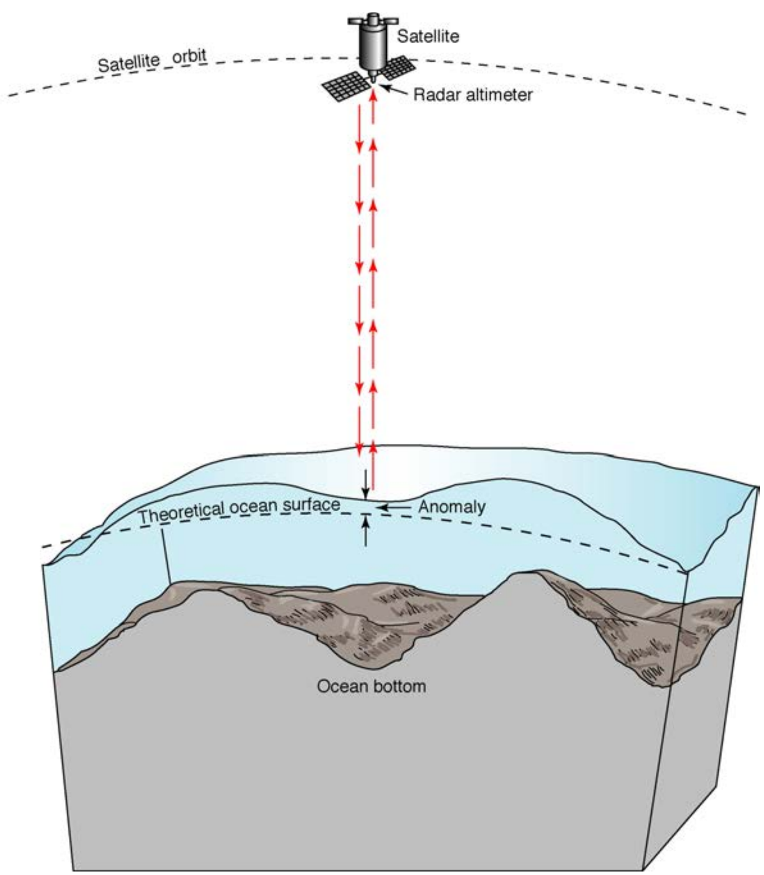
- global tectonics, seafloor roughness
- seamounts
- tsunami models
- ocean circulation and tides
- marine ecosystems
- planning tool

Outreach and applications

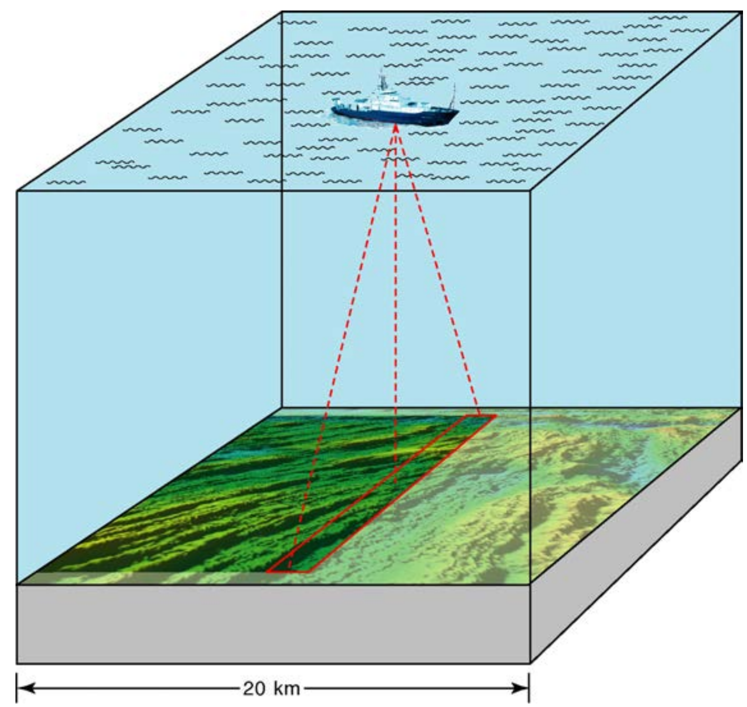
- education and outreach
- military applications
- Industry applications

modern mapping tools

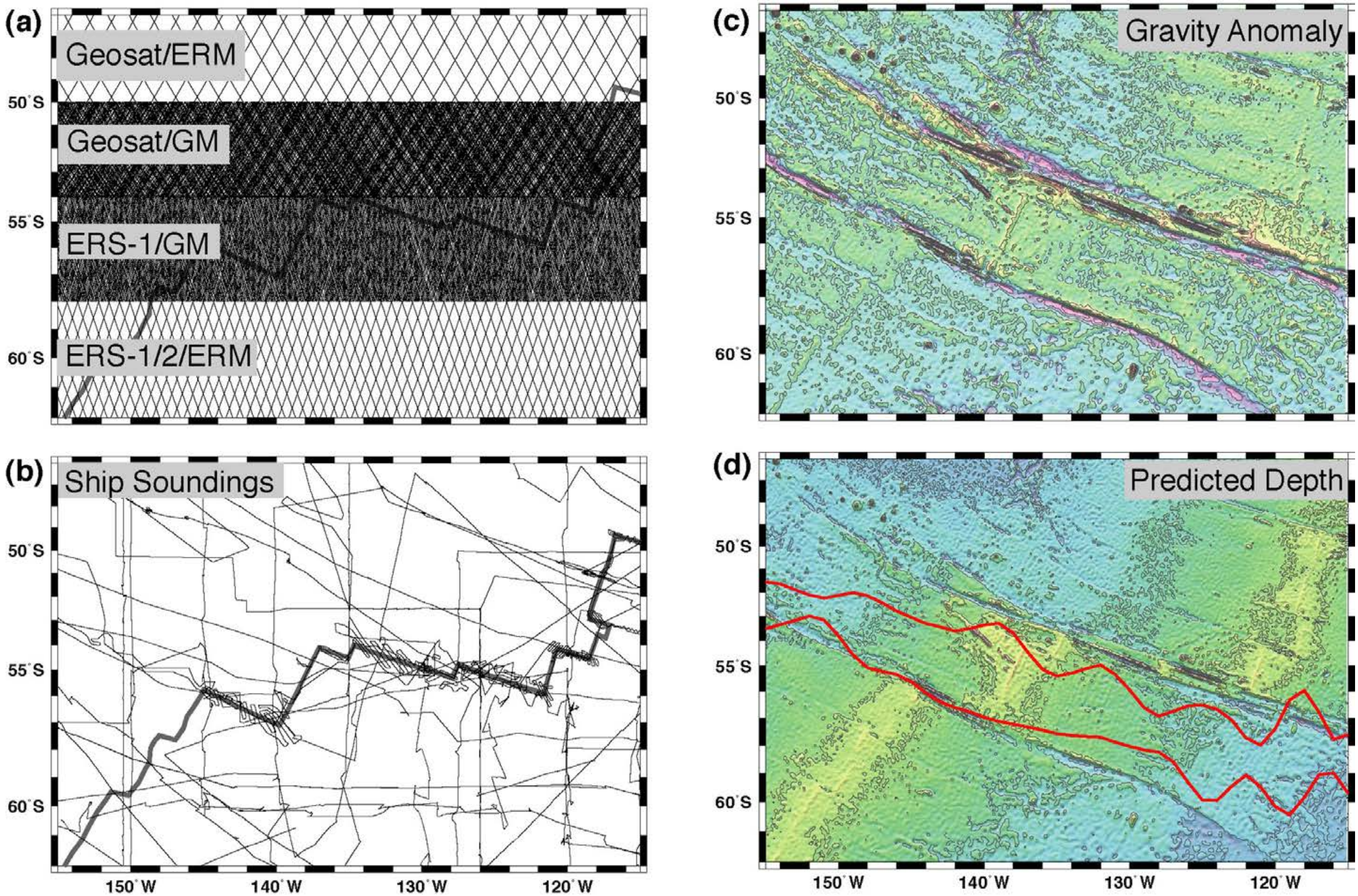
satellite altimeter



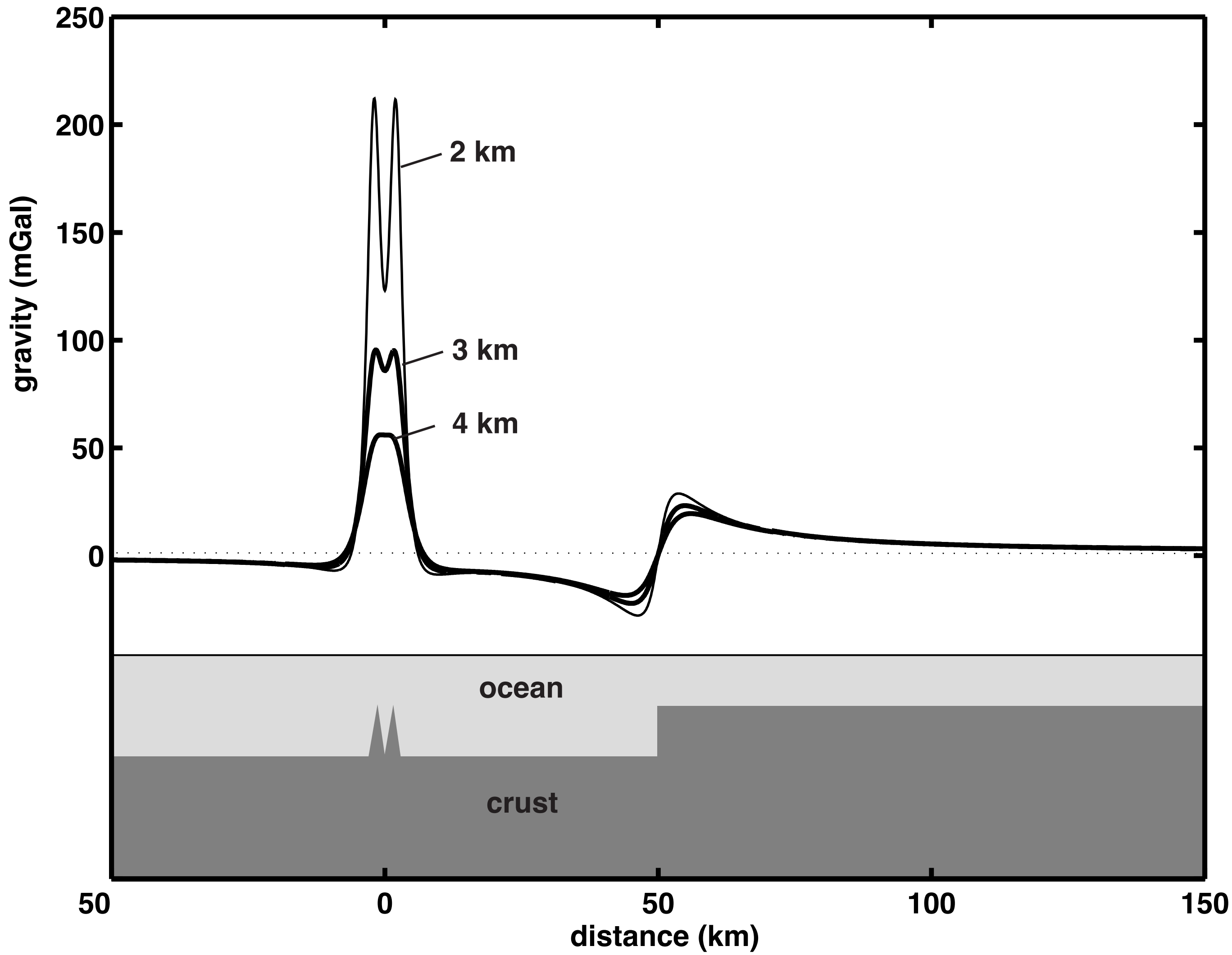
multibeam echo sounder



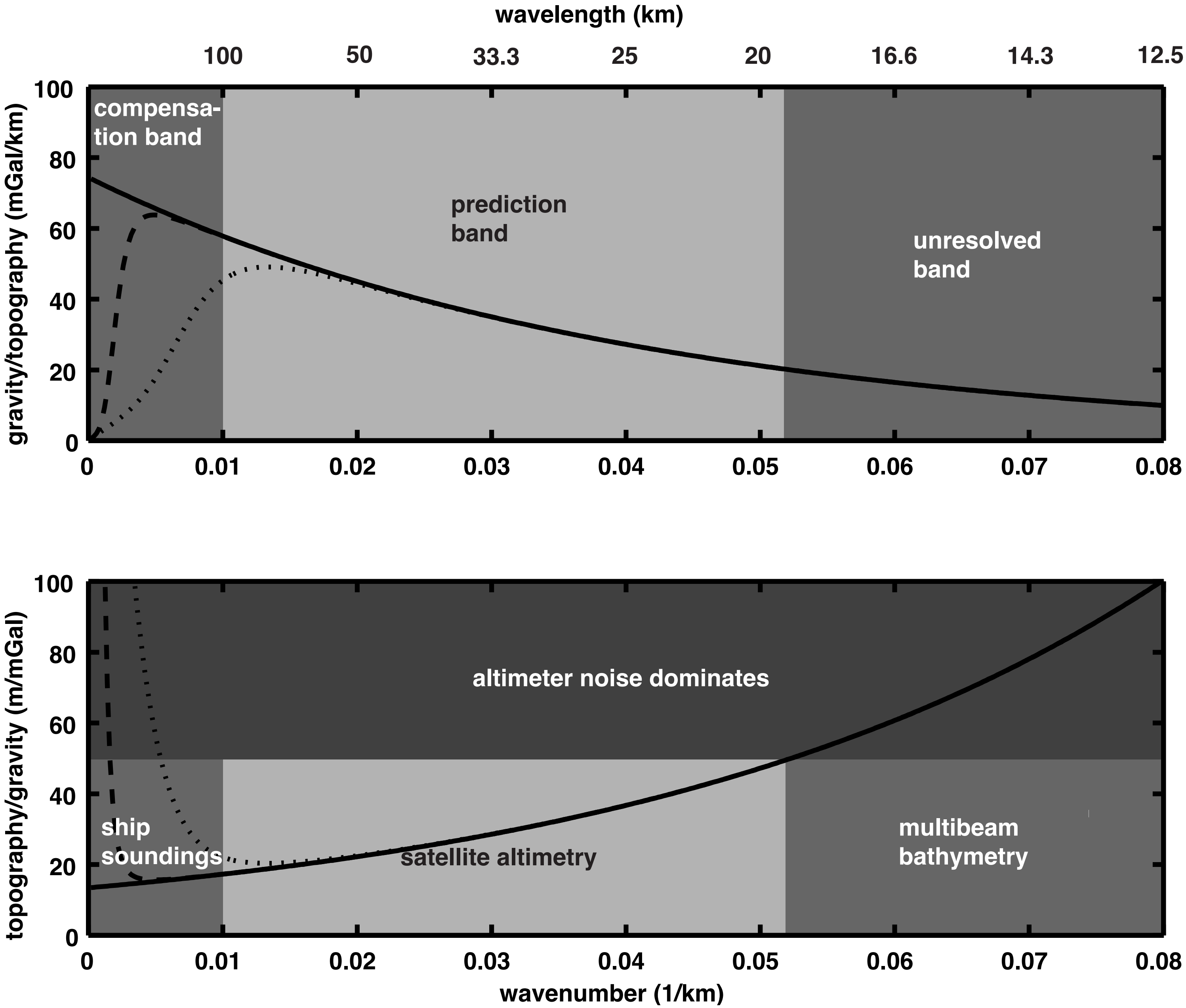
sparse soundings + gravity anomaly = global bathymetry



upward continuation and isostatic compensation
space domain



upward continuation and isostatic compensation wavenumber domain



Bathymetry from Gravity and Ship Soundings: Inverse Nettleton Method

1. Grid available depth soundings.

2. Separate into low-pass and high-pass filtered components (~160 km).

3. High-pass filter gravity and downward continue to low-pass filtered depths.

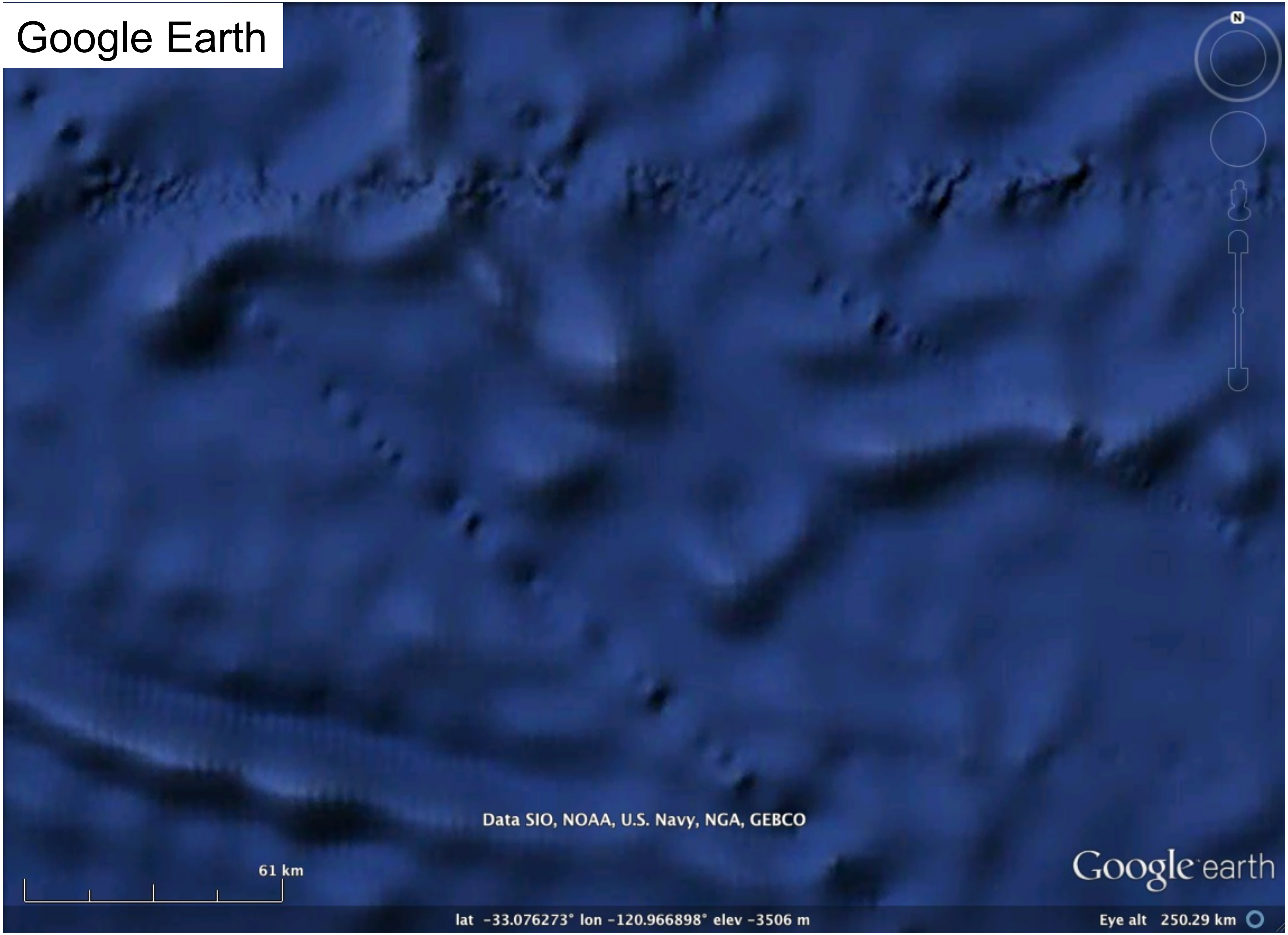
4. Perform a robust linear regression of high-pass topography and high-pass, downward-continued gravity in small regions.

5. Multiply gravity by topography/gravity slope to predict topography in pass band.

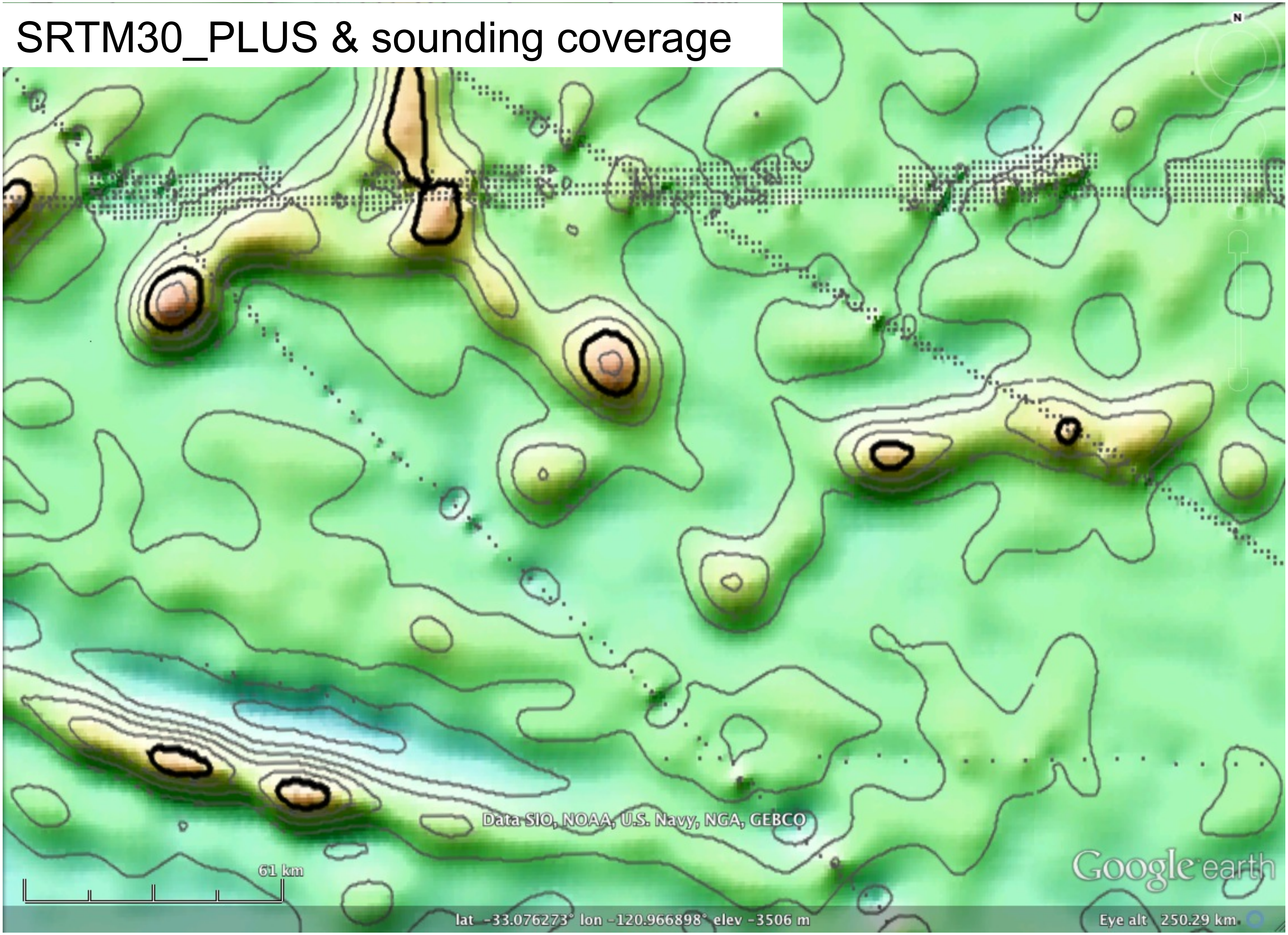
6. Add original low-pass filtered depth.

7. Force agreement with soundings. **(Warning this last step can create anomalies on the ocean floor.)**

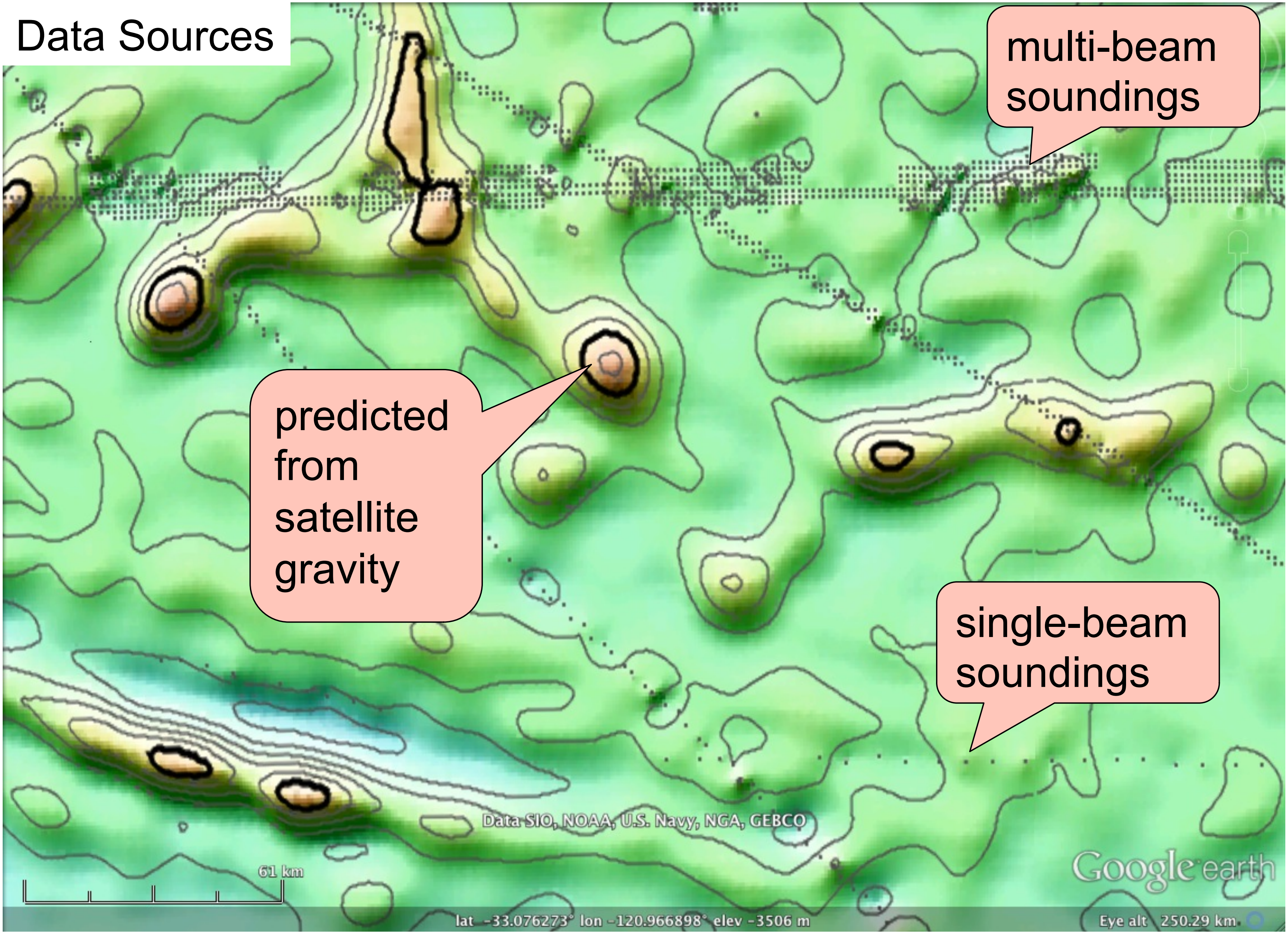
Google Earth



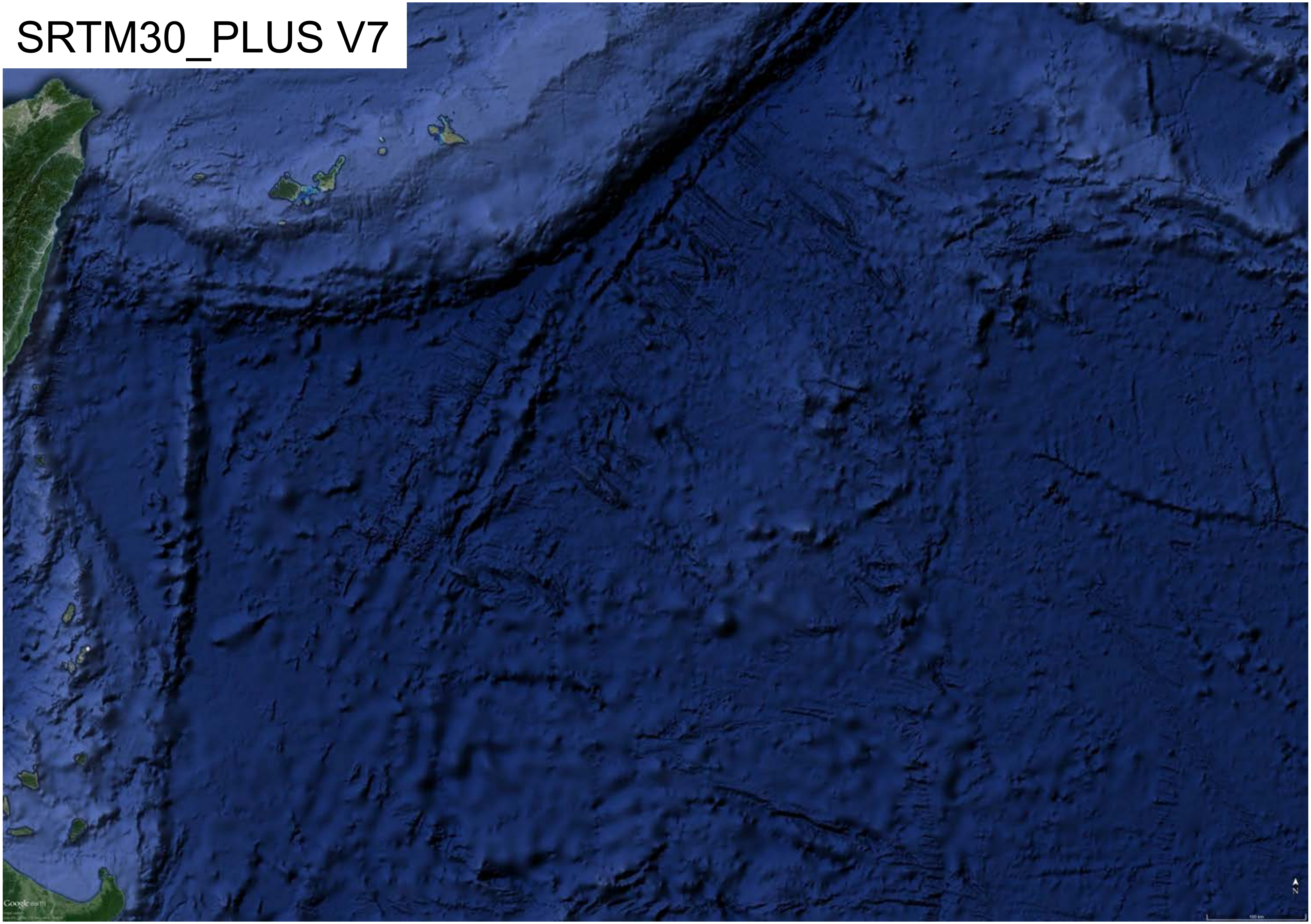
SRTM30_PLUS & sounding coverage



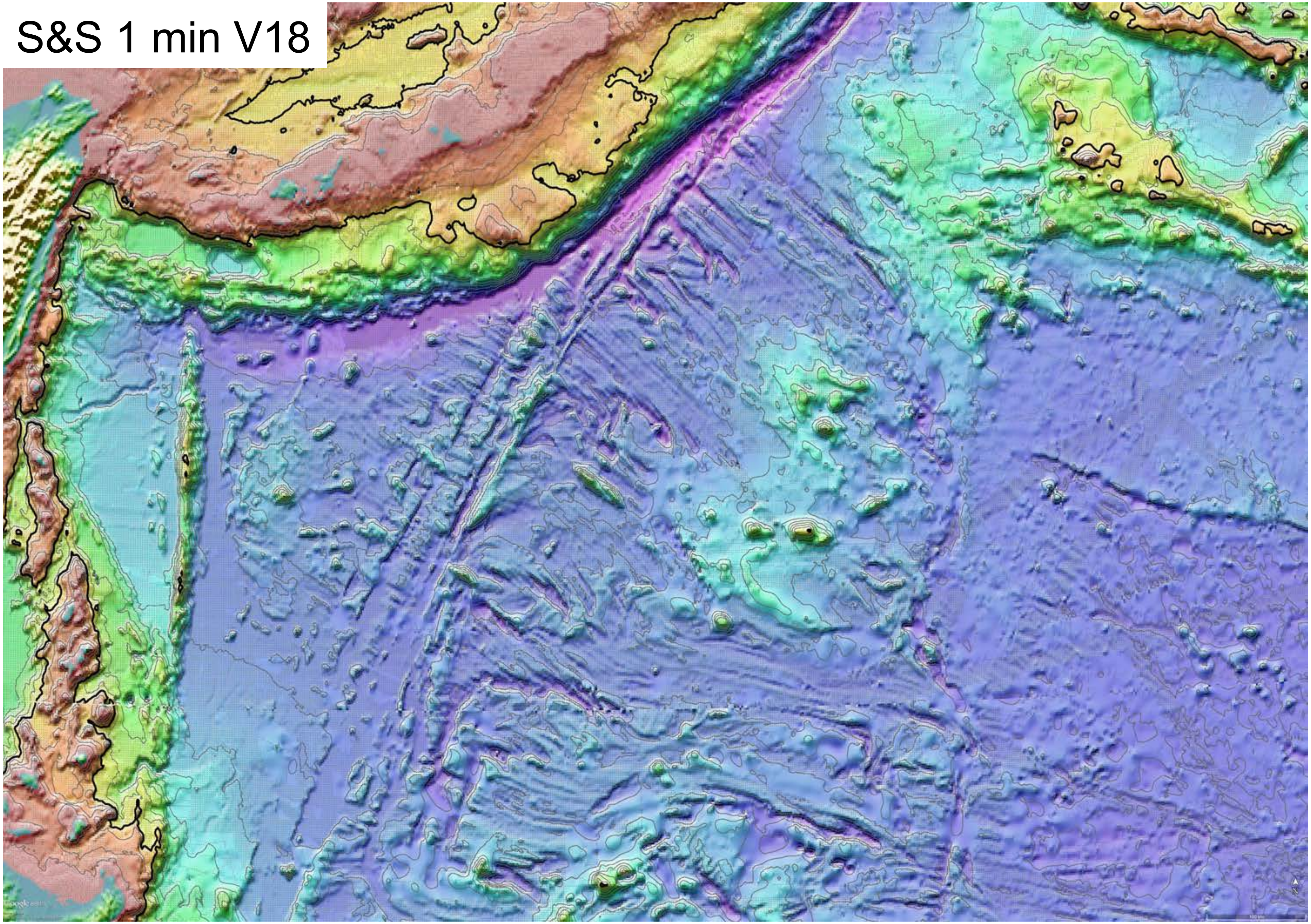
Data Sources

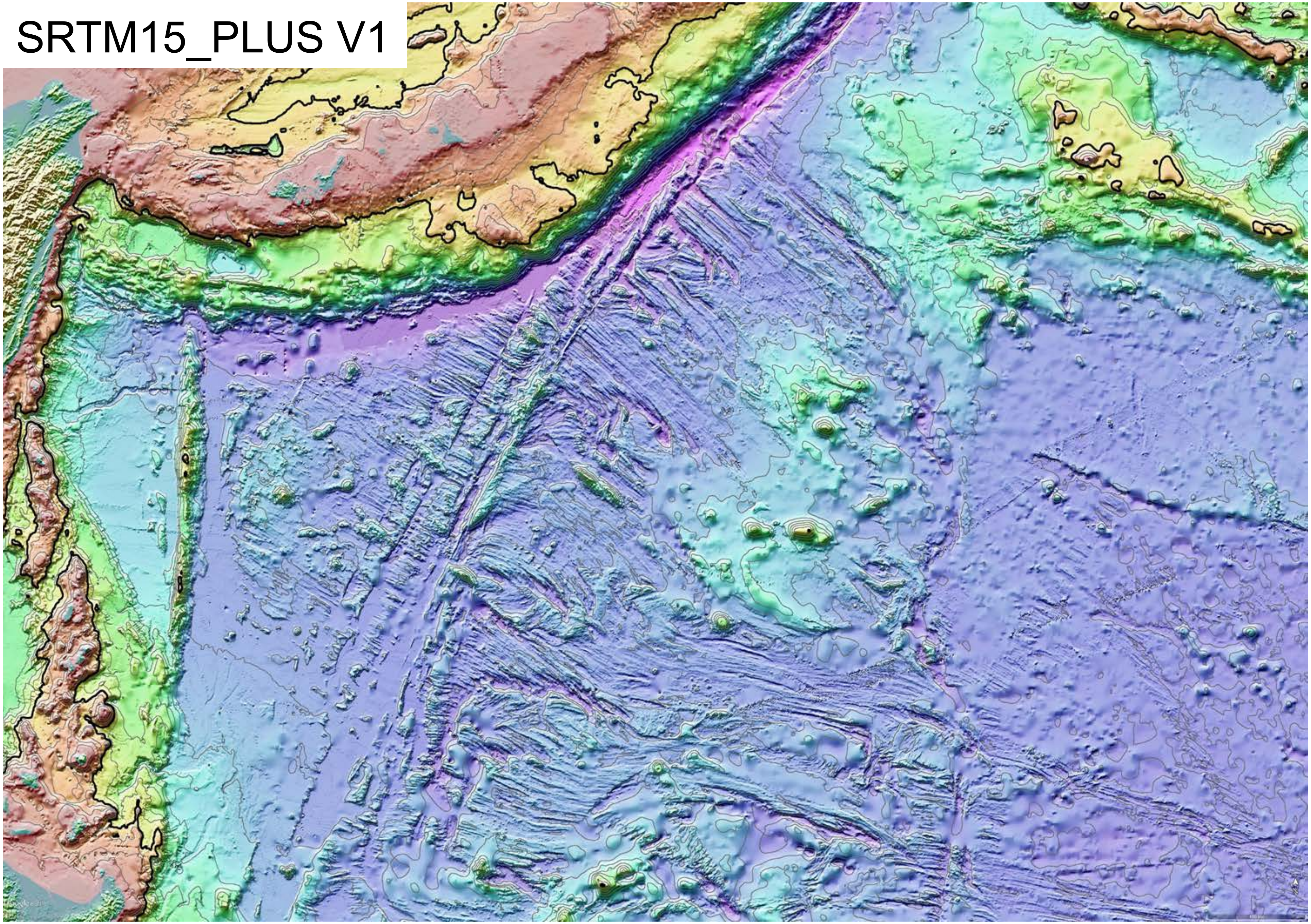


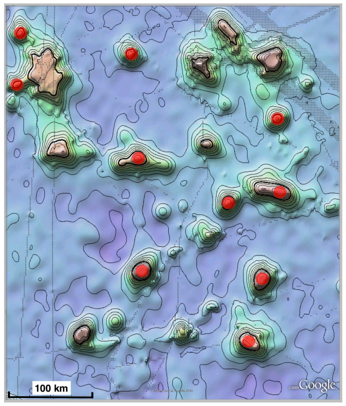
SRTM30_PLUS V7



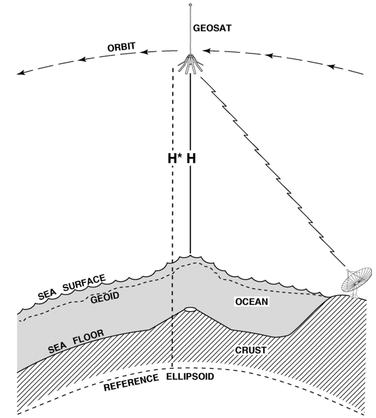
S&S 1 min V18




SRTM15_PLUS V1

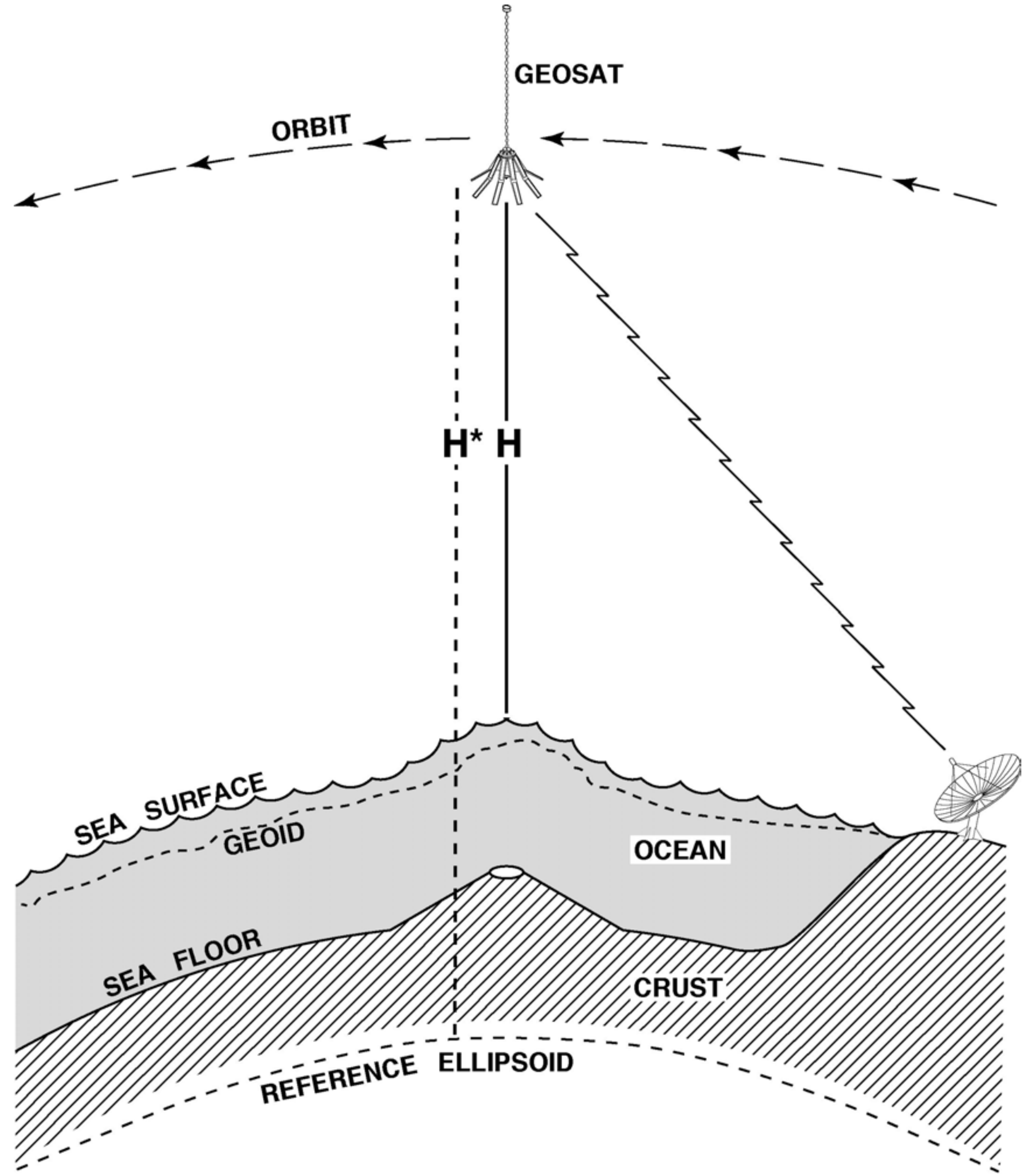


Exploring the Deep Ocean Basins with Ships and Satellites

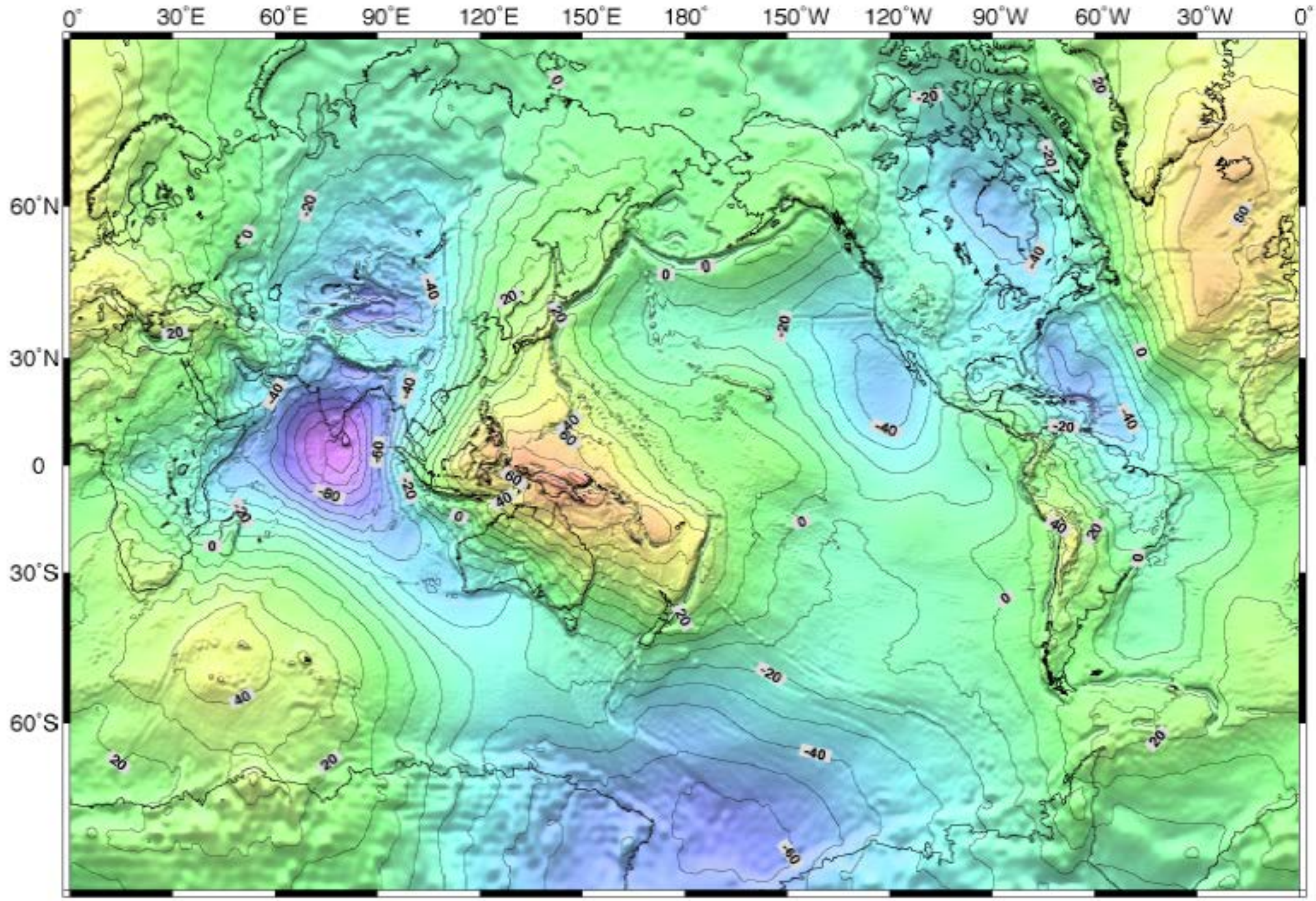


- Tectonics and topography of the deep ocean
- Mapping by ships - what is missing?
- **Mapping by satellites**
- How can we do better?

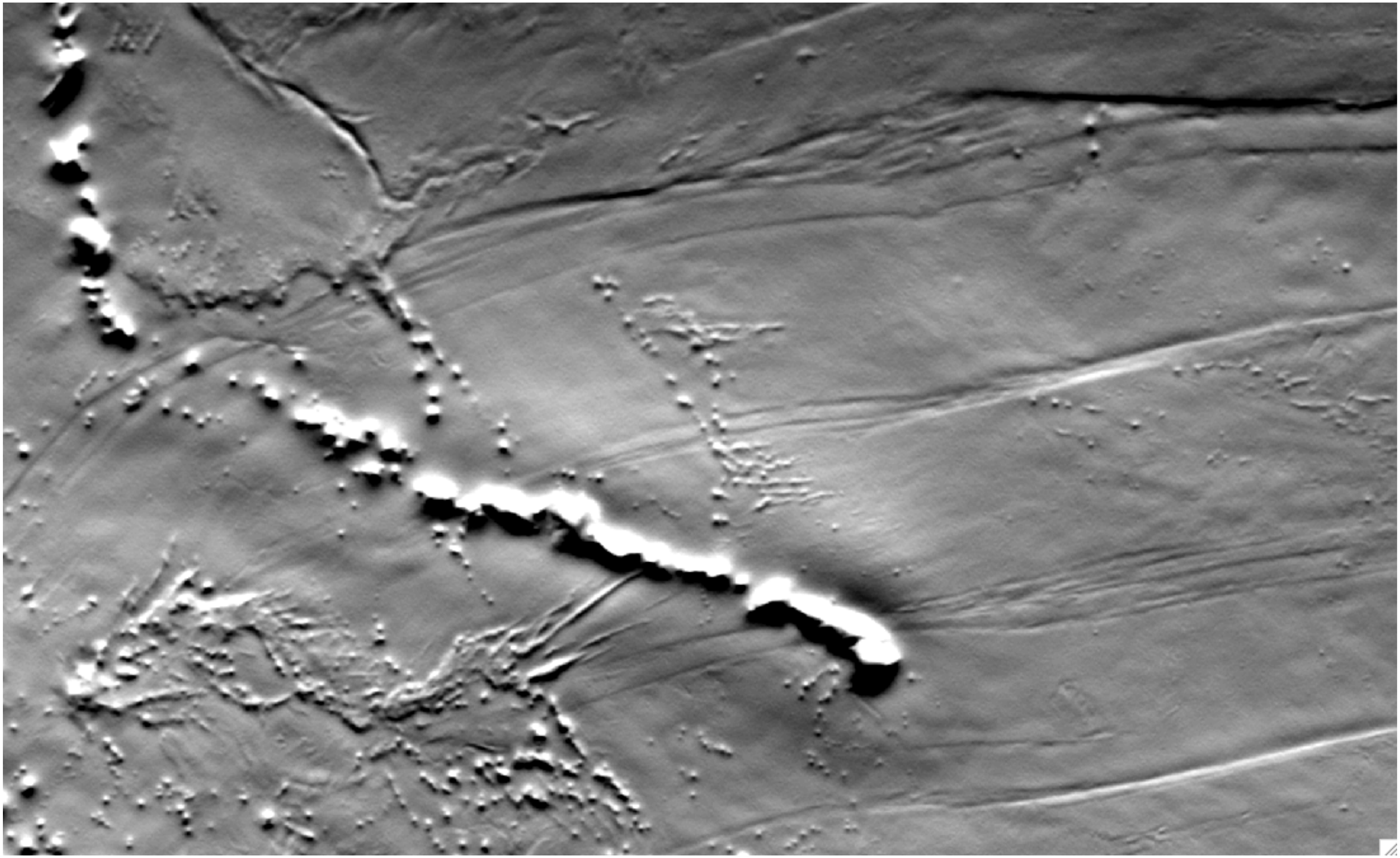
radar altimetry



geoid height ~ sea surface topography



slope of ocean surface



slope requirement

Φ disturbing potential

$N = \dfrac{1}{g_o}\Phi$ geoid height

$\Delta g = -\dfrac{\partial \Phi}{\partial z}$ gravity anomaly

$\eta = -\dfrac{\partial N}{\partial x}$ slope of ocean surface

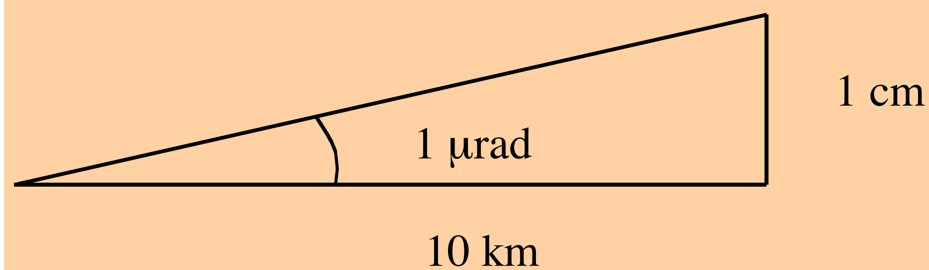
Laplace's equation, assume 2-D anomaly

$$\nabla^2 \Phi = 0 \quad \Rightarrow \quad g_o \frac{\partial \eta}{\partial x} + \frac{\partial g}{\partial z} = 0$$

take fourier transform w.r.t. x

$$\Delta g(k) = i g_o \frac{k}{|k|} \eta(k)$$

1 μrad of slope error ⇔ 1 mGal gravity error



Achieving 1 mGal Gravity Accuracy

- Improved range precision -- A factor of 2 or more improvement in altimeter range precision, with respect to Geosat and ERS-1, is needed to reduce the noise due to ocean waves.

- Fine cross-track spacing and long mission duration -- A ground track spacing of 6 km or less is required.

- Moderate inclination -- Current non-repeat-orbit altimeter data have high inclination and thus poor accuracy of the E-W slope at the equator.

- Near-shore tracking -- For applications near coastlines, the ability to track the ocean surface close to shore is desirable.

MARINE GEODESY
http://dx.doi.org/10.1080/01490419.2016.1265032

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Retracking of SARAL/AltiKa Radar Altimetry Waveforms for Optimal Gravity Field Recovery

Shengjun Zhang[a] and David T. Sandwell[b]

[a]School of Geodesy and Geomatics, Wuhan University, Wuhan, China; [b]Scripps Institution of Oceanography, University of California at San Diego, La Jolla, California, USA

ABSTRACT

The accuracy of the marine gravity field derived from satellite altimetry depends on dense track spacing as well as high range precision. Here, we investigate the range precision that can be achieved using a new shorter wavelength Ka-band altimeter AltiKa aboard the SARAL spacecraft. We agree with a previous study that found that the range precision given in the SARAL/AltiKa Geophysical Data Records is more precise than that of Ku-band altimeter by a factor of two. Moreover, we show that two-pass retracking can further improve the range precision by a factor of 1.7 with respect to the 40 Hz-retracked data (item of range_40 hz) provided in the Geophysical Data Records. The important conclusion is that a dedicated Ka-band altimeter-mapping mission could substantially improve the global accuracy of the marine gravity field with complete coverage and a track spacing of <6 km achievable in ~ 1.3 years. This would reveal thousands of uncharted seamounts on the ocean floor as well as important tectonic features such as microplates and abyssal hill fabric.

ARTICLE HISTORY

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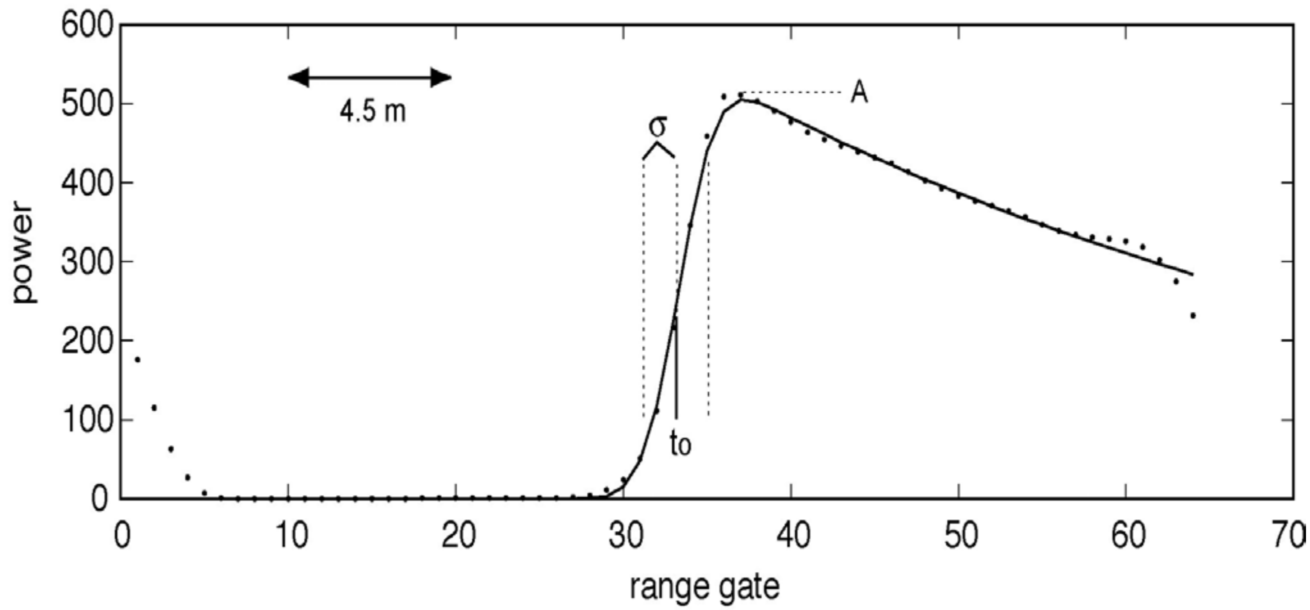
KEYWORDS

Gravity field; noise level; SARAL/AltiKa; waveform retracking

2-pass waveform retracking improves range precision



1) retrack waveforms with standard 3-parameter model

2) smooth rise time over 45-km

3) retrack waveforms with 2-parameter model

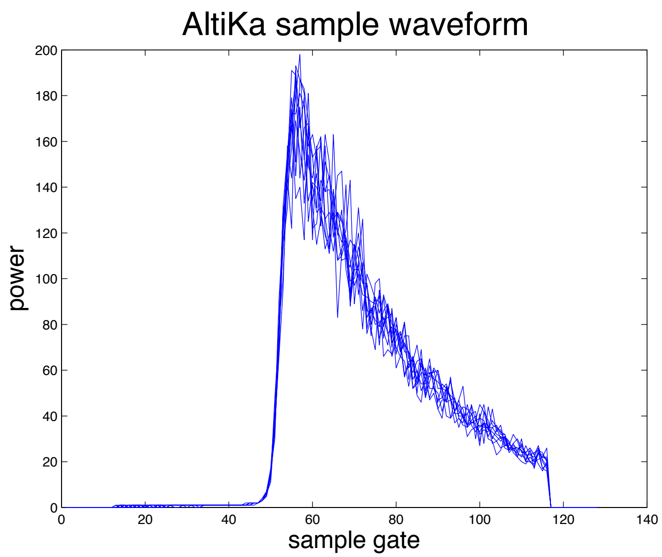
Note: this assumes wave height varies smoothly along track.

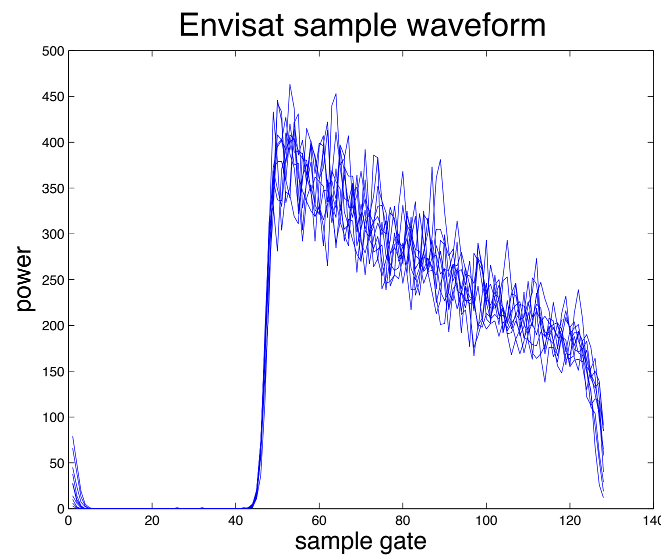
Estimate 3 parameters: arrival time (t_o), rise time (σ), and power (A).

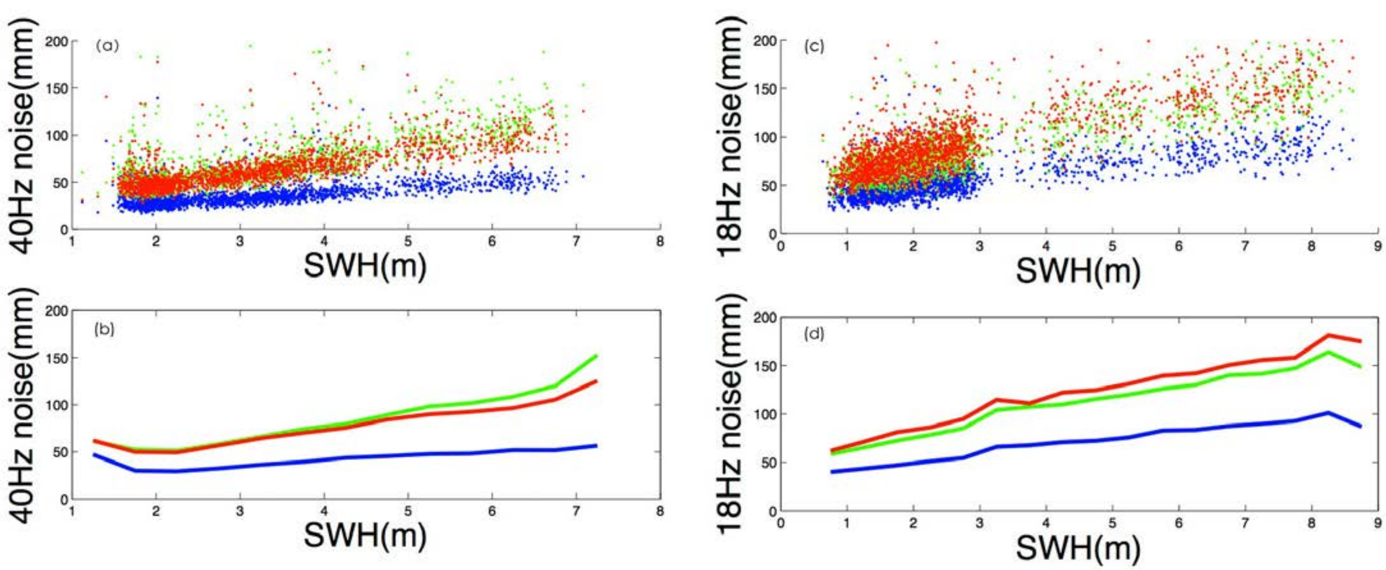
$$M(t) = \frac{A}{2}\{1 + erf(\eta)\}; \qquad \eta = \frac{t - t_o}{\sqrt{2}\sigma}$$

[*Sandwell and Smith*, 2005; *Zhang and Sandwell*, 2016]]

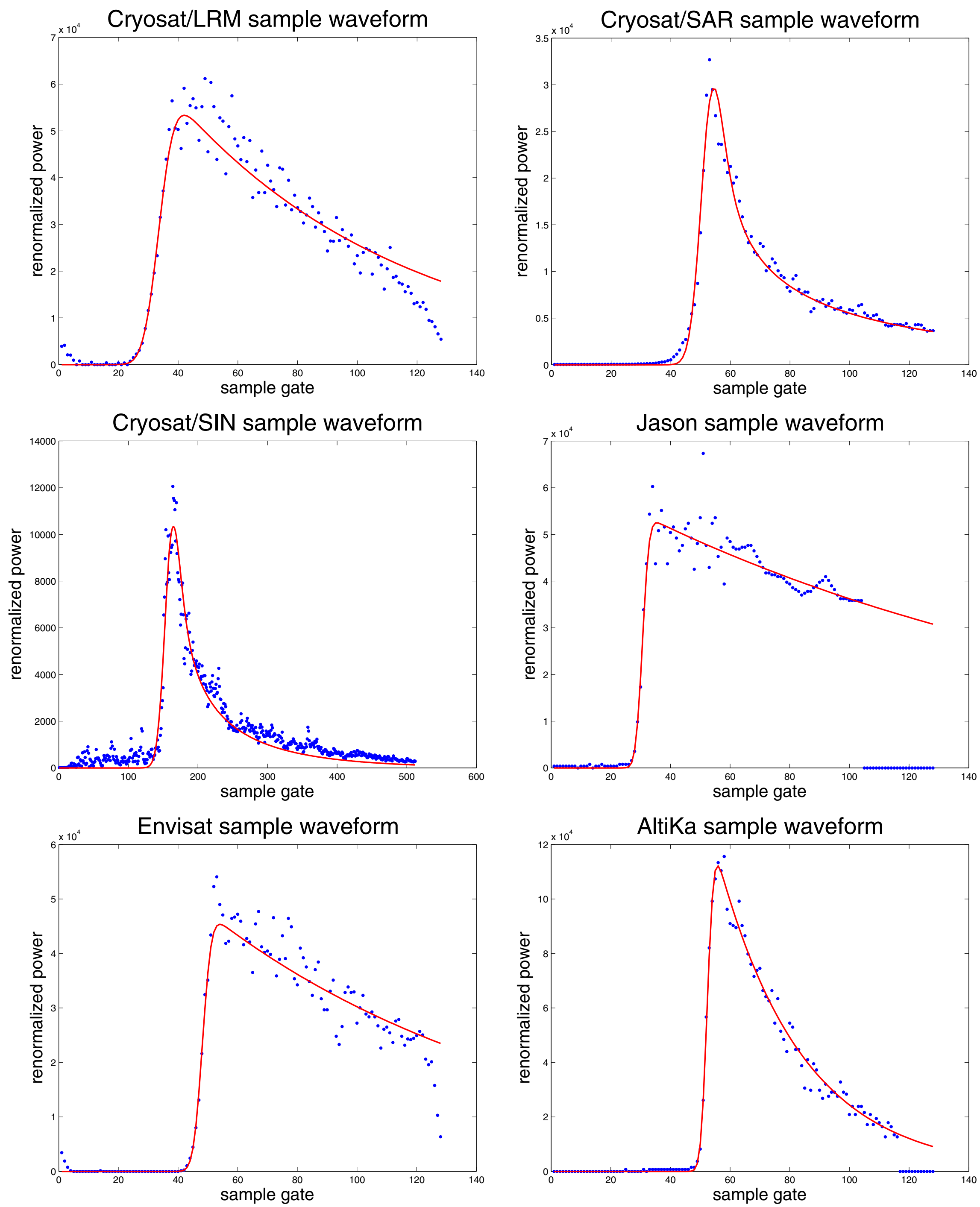
AltiKa and Envisat waveforms







[Zhang and Sandwell, 2016]



Fitting results of available waveforms

[Zhang et al., 2017]

AltiKa is 2 times more precise than all previous altimeters

Altimeter	3-PAR @ 2 m	2-PAR @ 2 m
Geosat	88.0	57.0
ERS-1	93.6	61.8
Envisat	78.9	51.8
Jason-1	75.9	46.4
CryoSat-2 LRM	64.7	42.7
CryoSat-2 SAR	49.5	49.7
AltiKa	**34.3**	**20.5**

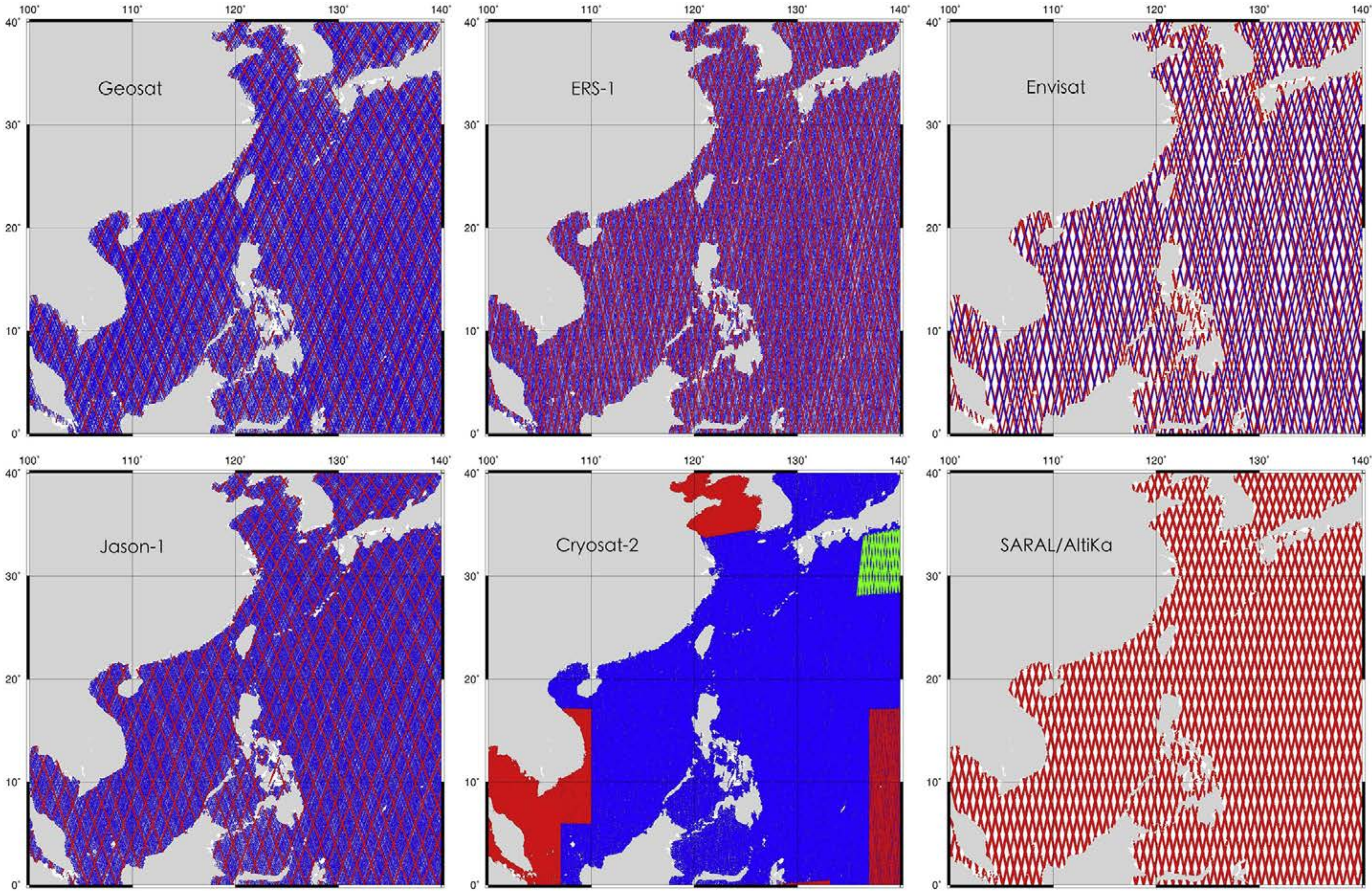
Smith [2015] showed standard GDR of AltiKa is 2 X more precise than Envisat

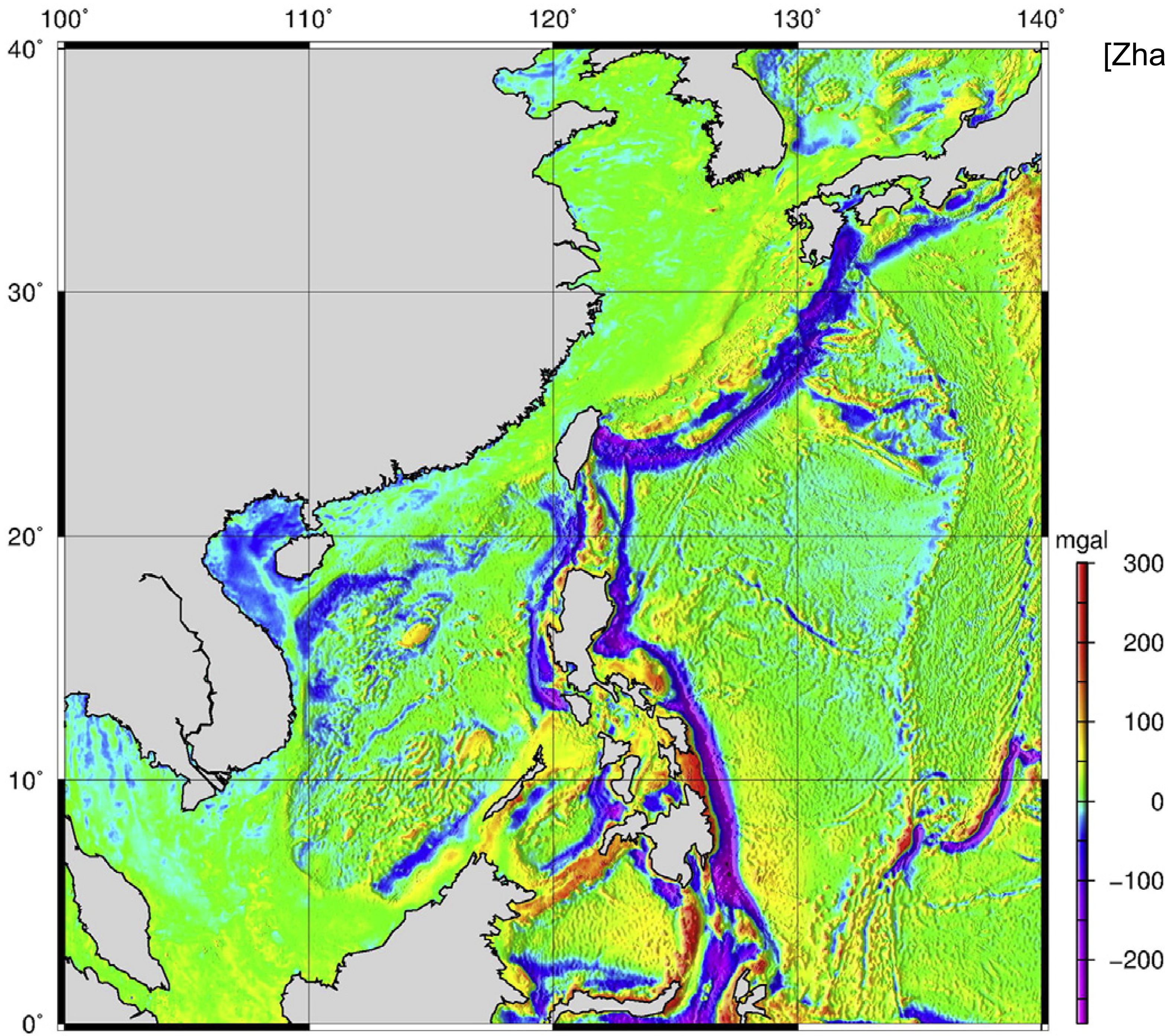
Zhang and Sandwell [2016] showed that AltiKa also benefits from 2-pass retracking.

In July 2016 AltiKa began geodetic mapping. Could achieve 1 mGal global marine gravity.

AltiKa 4.5 mm @ 1 Hz

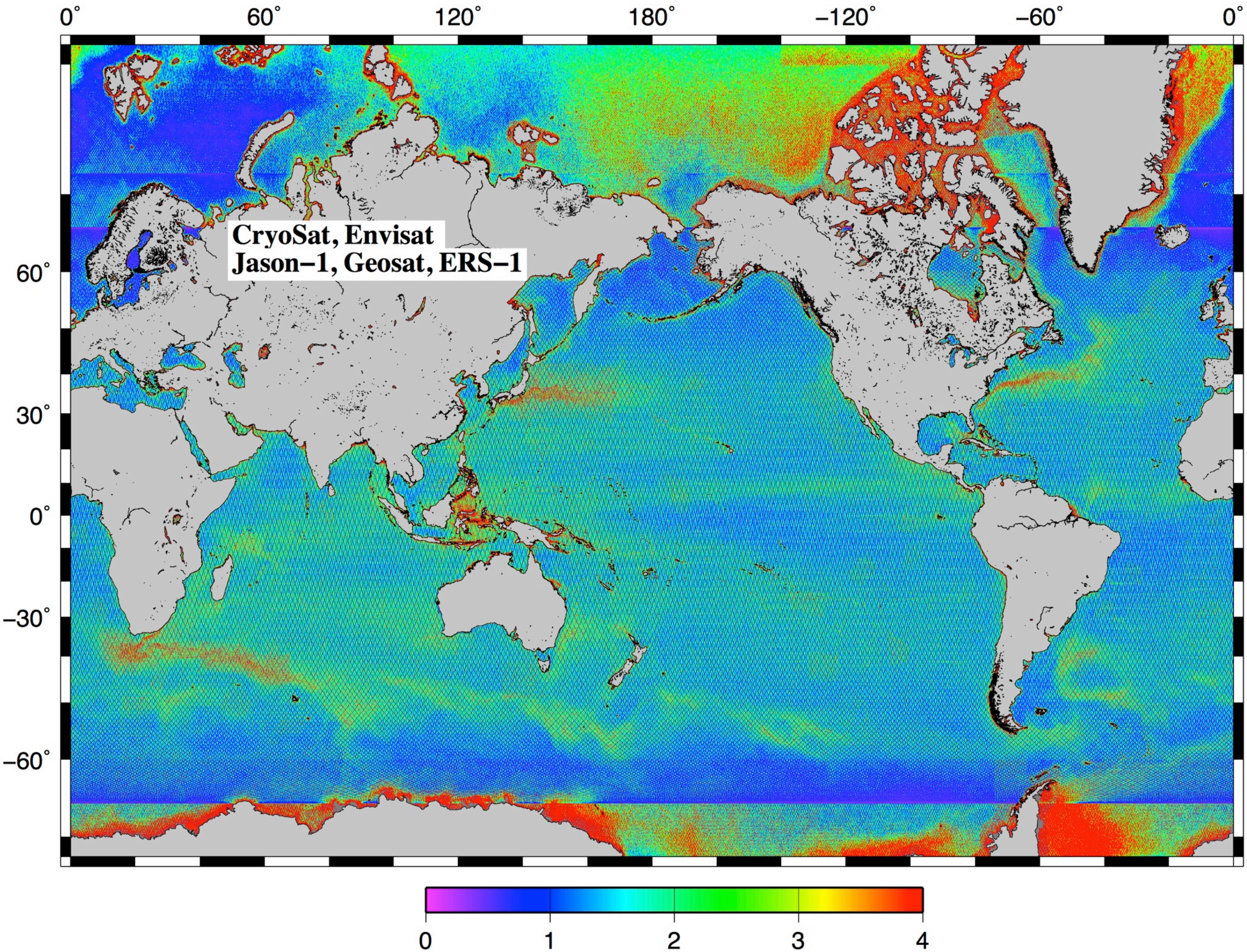
Altimeter Tracks for Southeastern China Seas



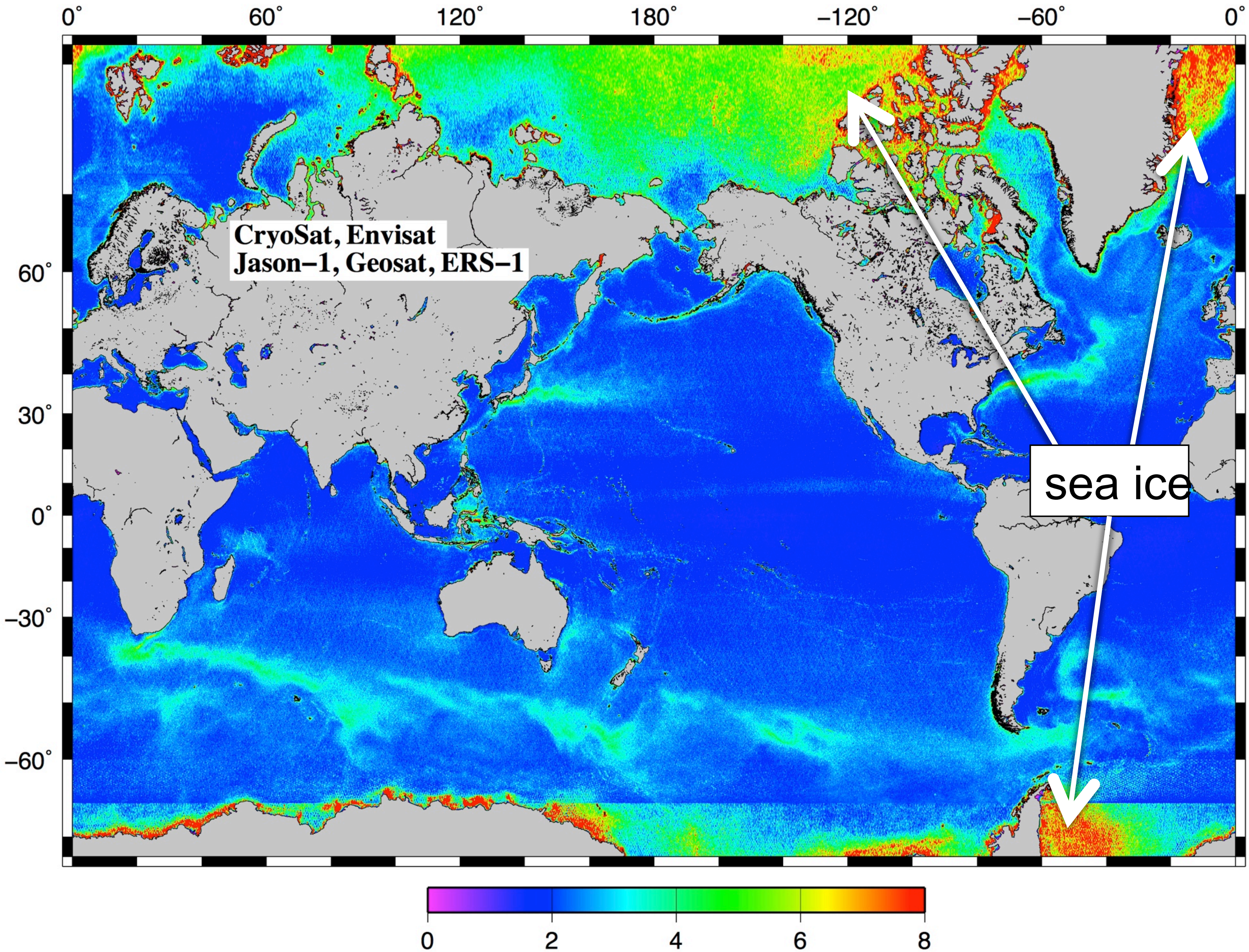


[Zhang et al., 2017]

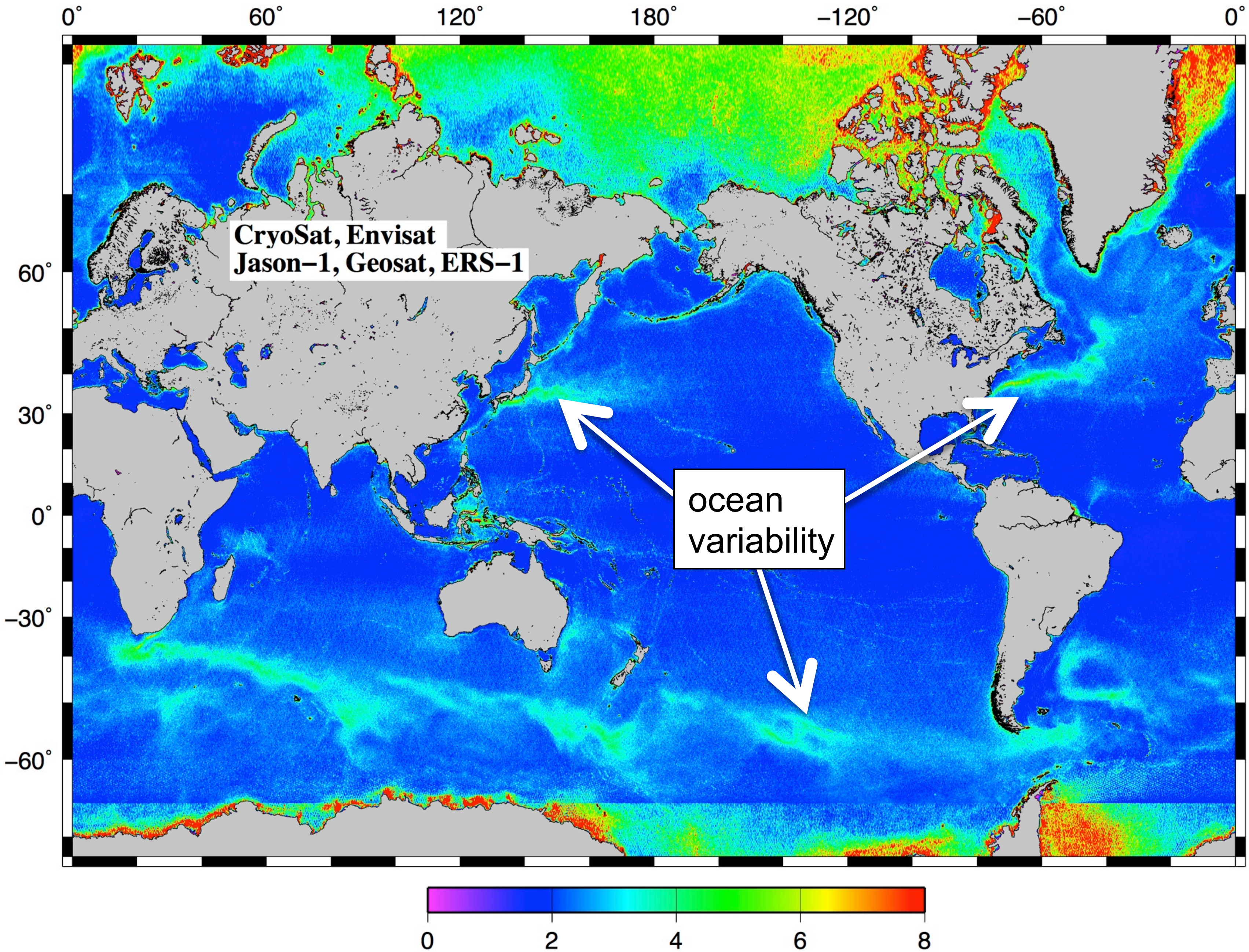
gravity anomaly error (mGal) calibrated using NGA analysis

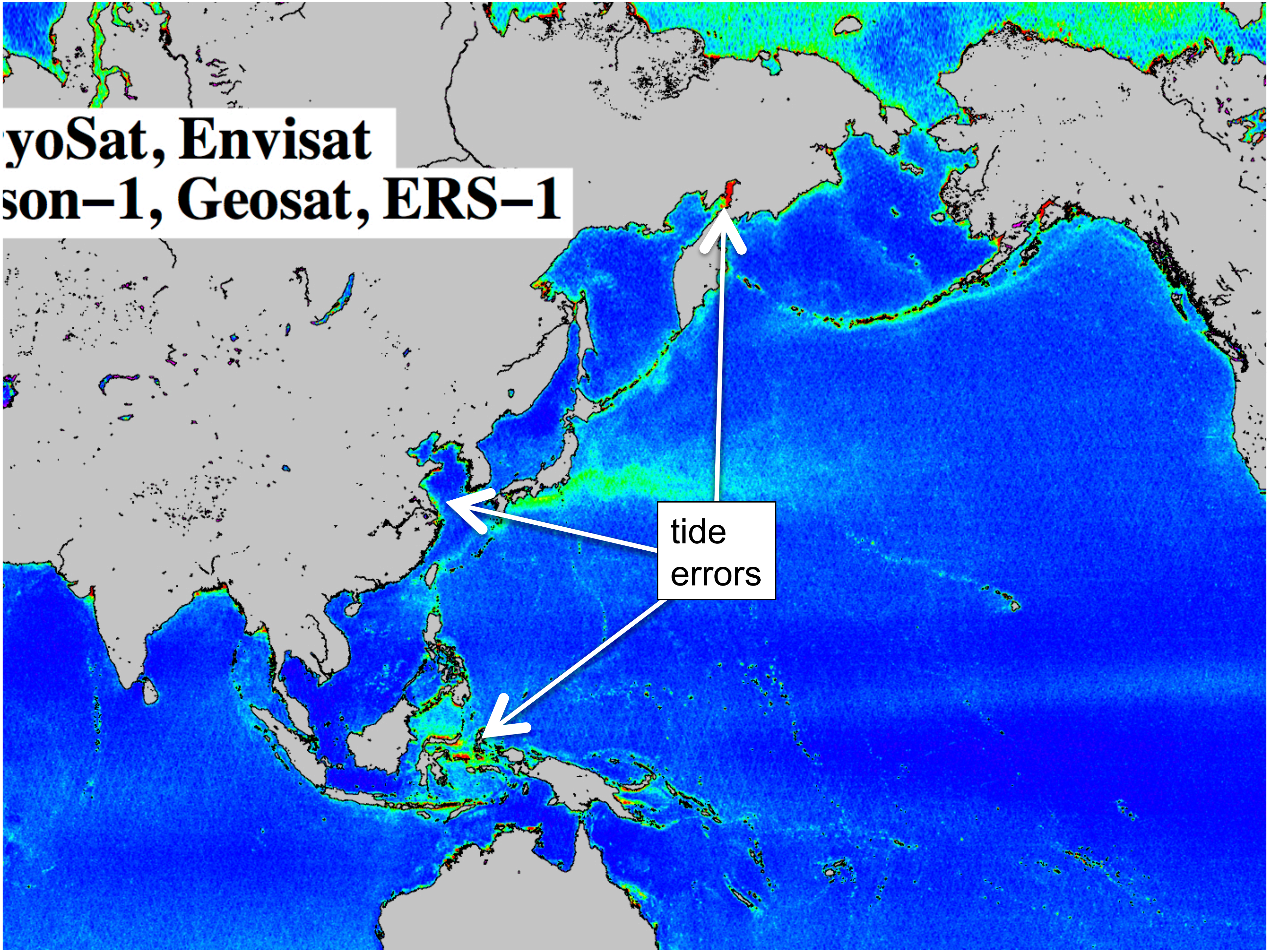


remaining sources of error

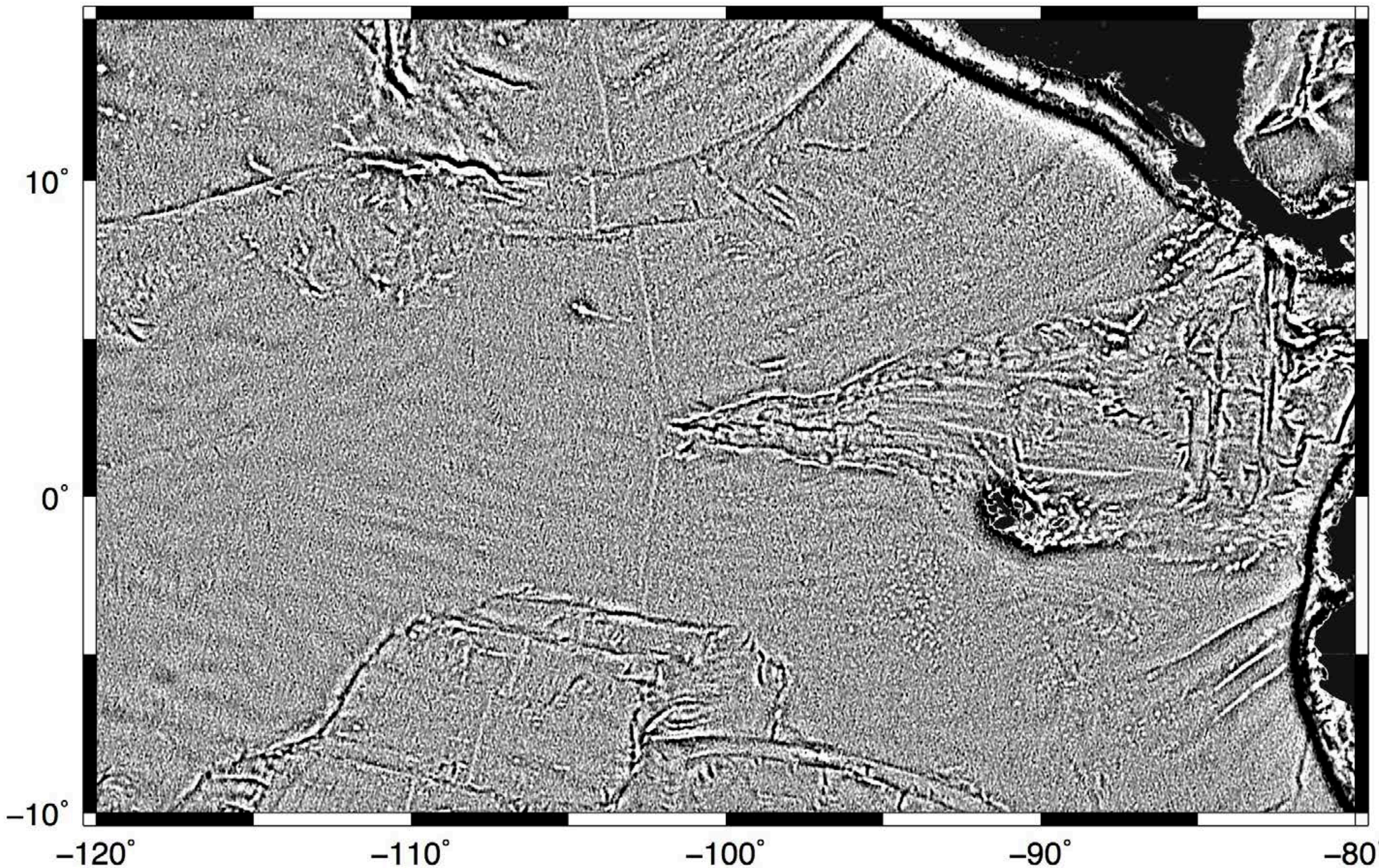


remaining sources of error

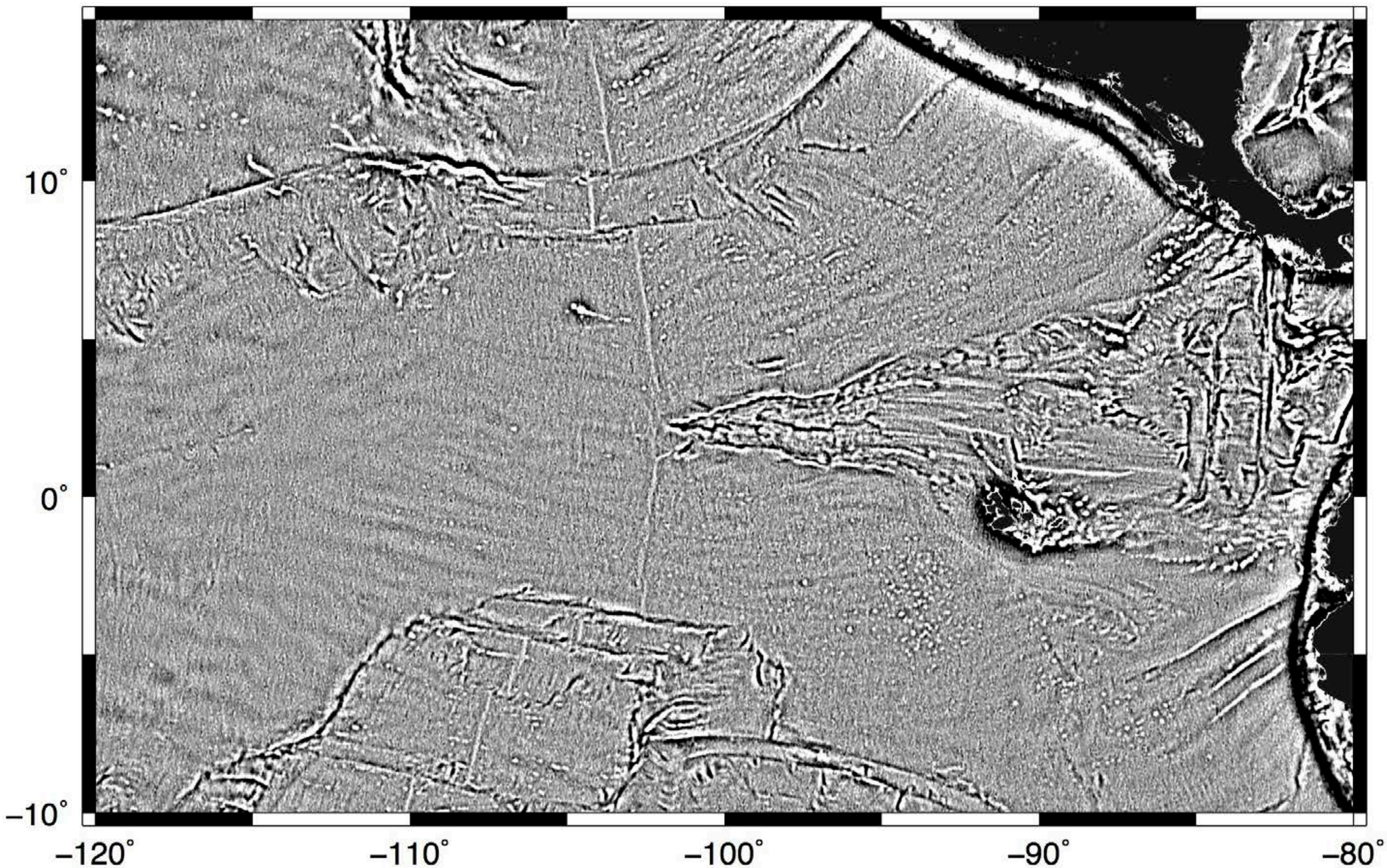



yoSat, Envisat
son–1, Geosat, ERS–1
tide
errors

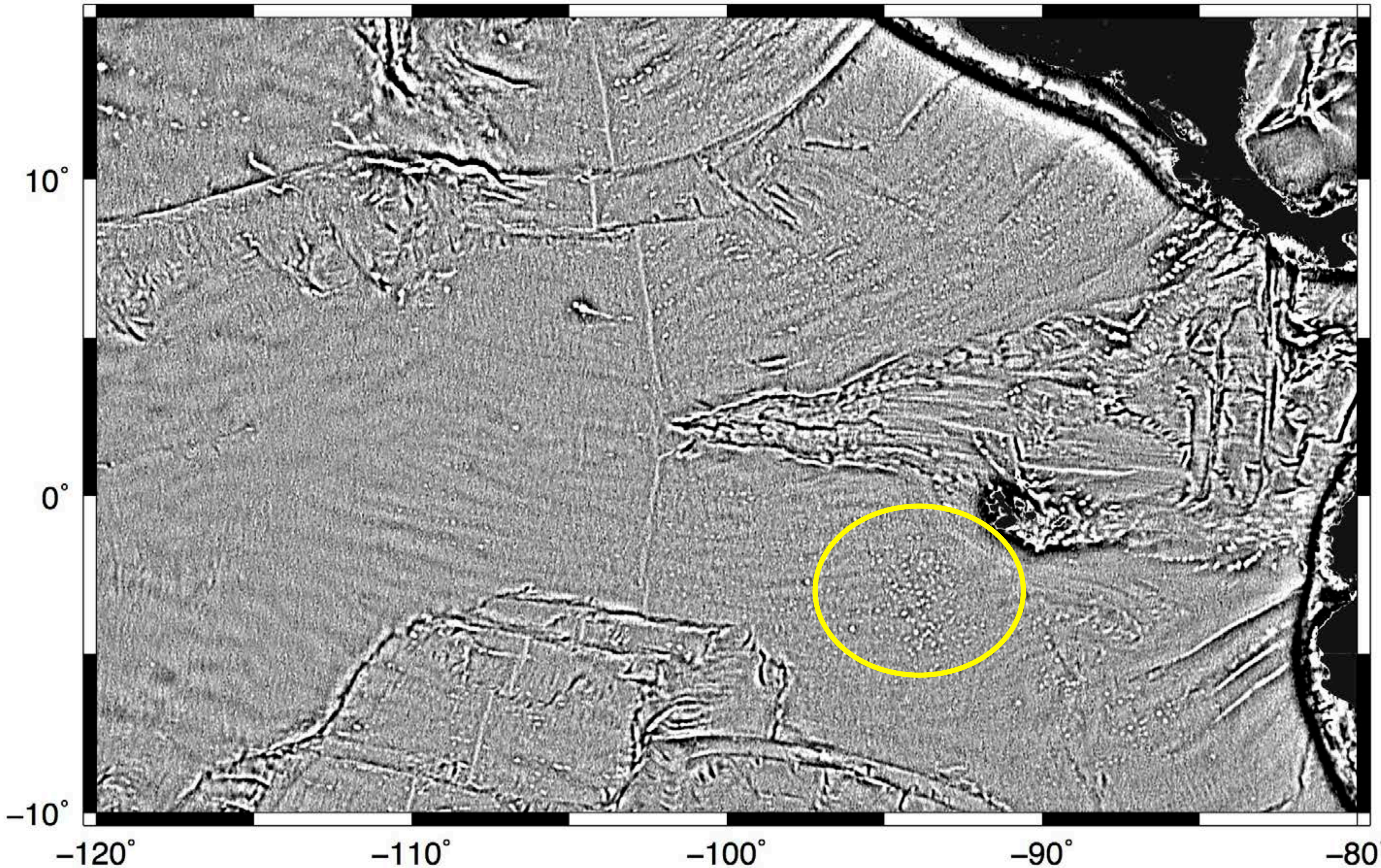
VGG (V18) Geosat + ERS



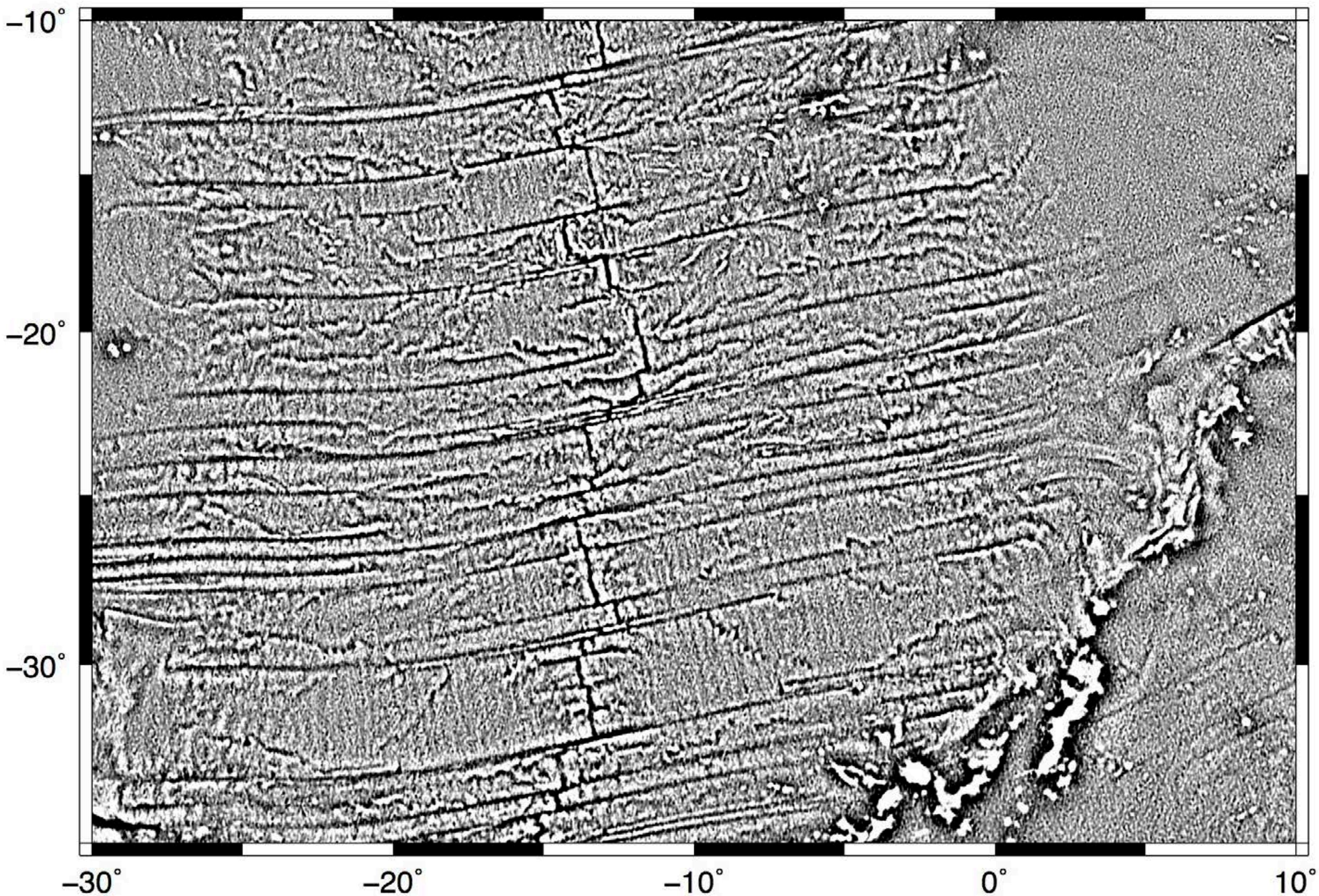
VGG (V24) + CryoSat + AltiKa + Jason-1



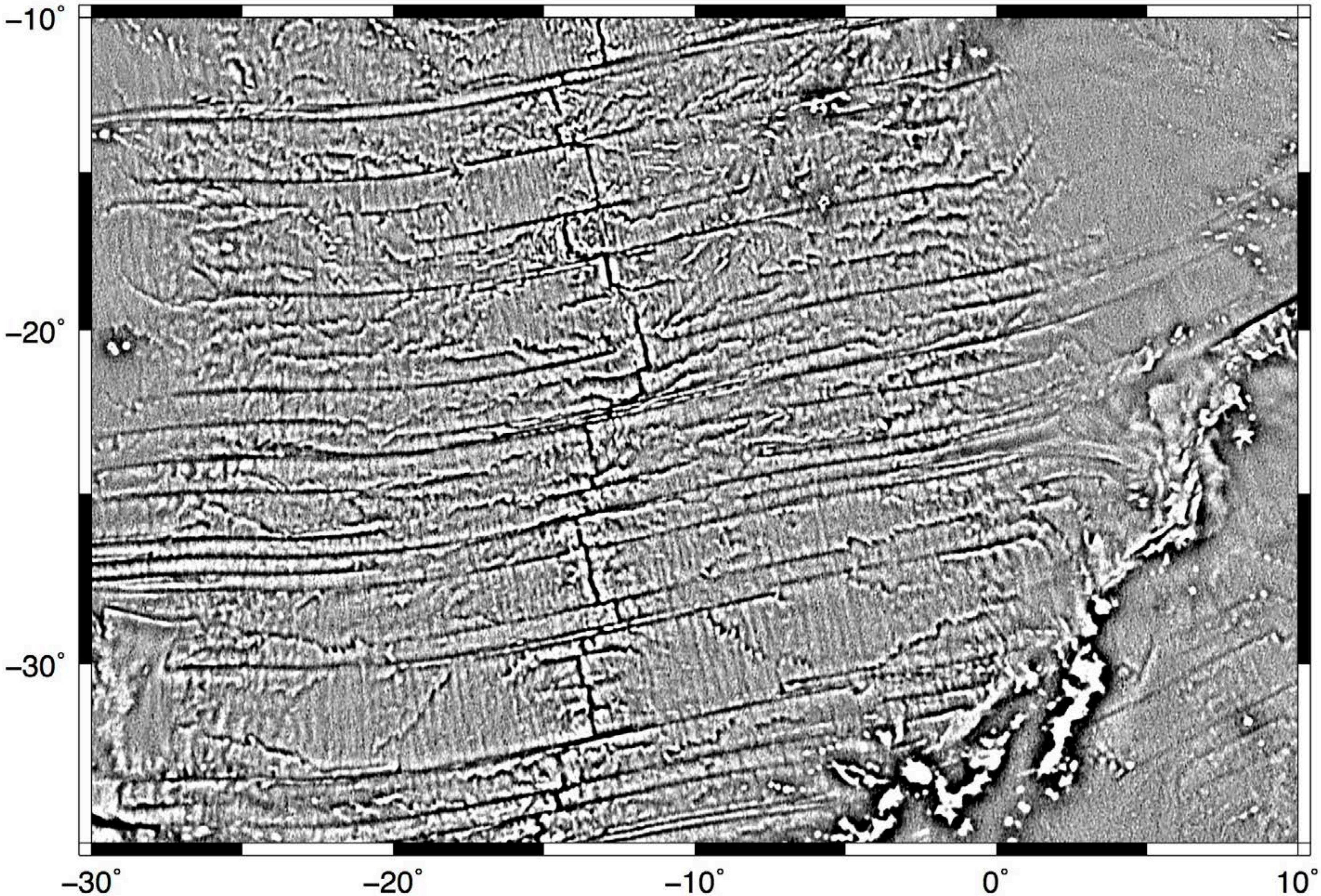
Discovery of small seamounts



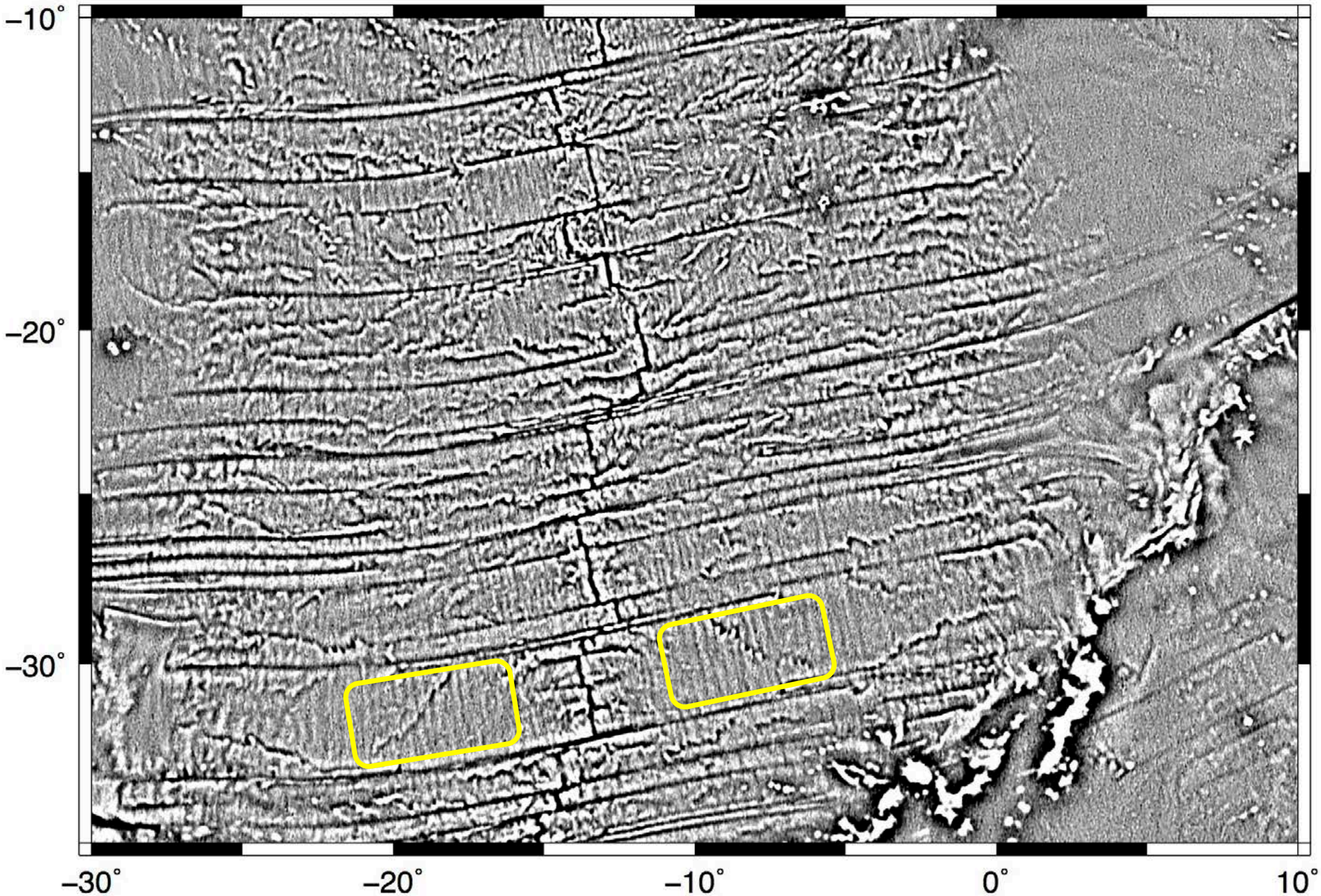
VGG (V18) Geosat + ERS



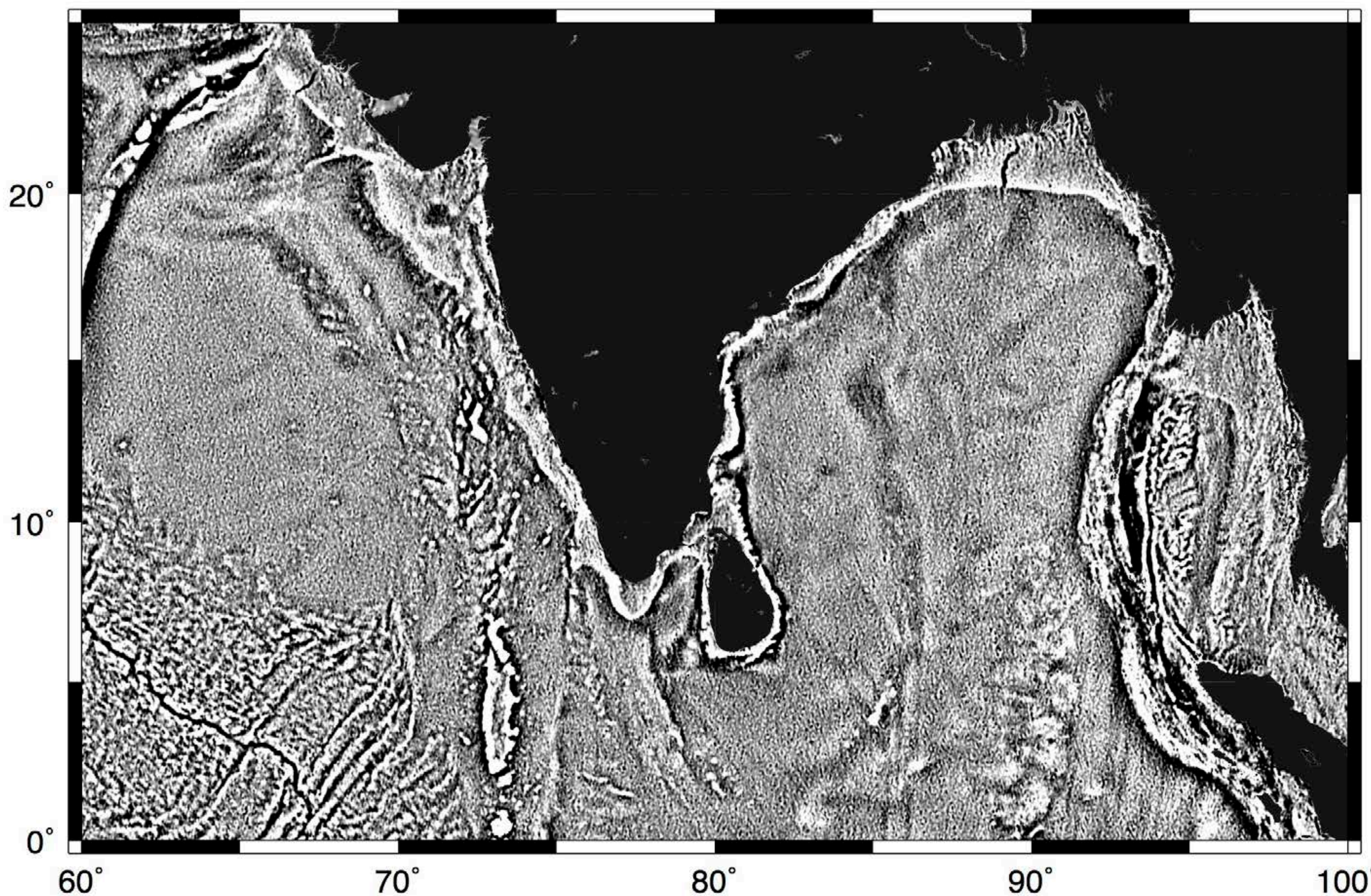
VGG (V24) + CryoSAT + AltiKa + Jason-1



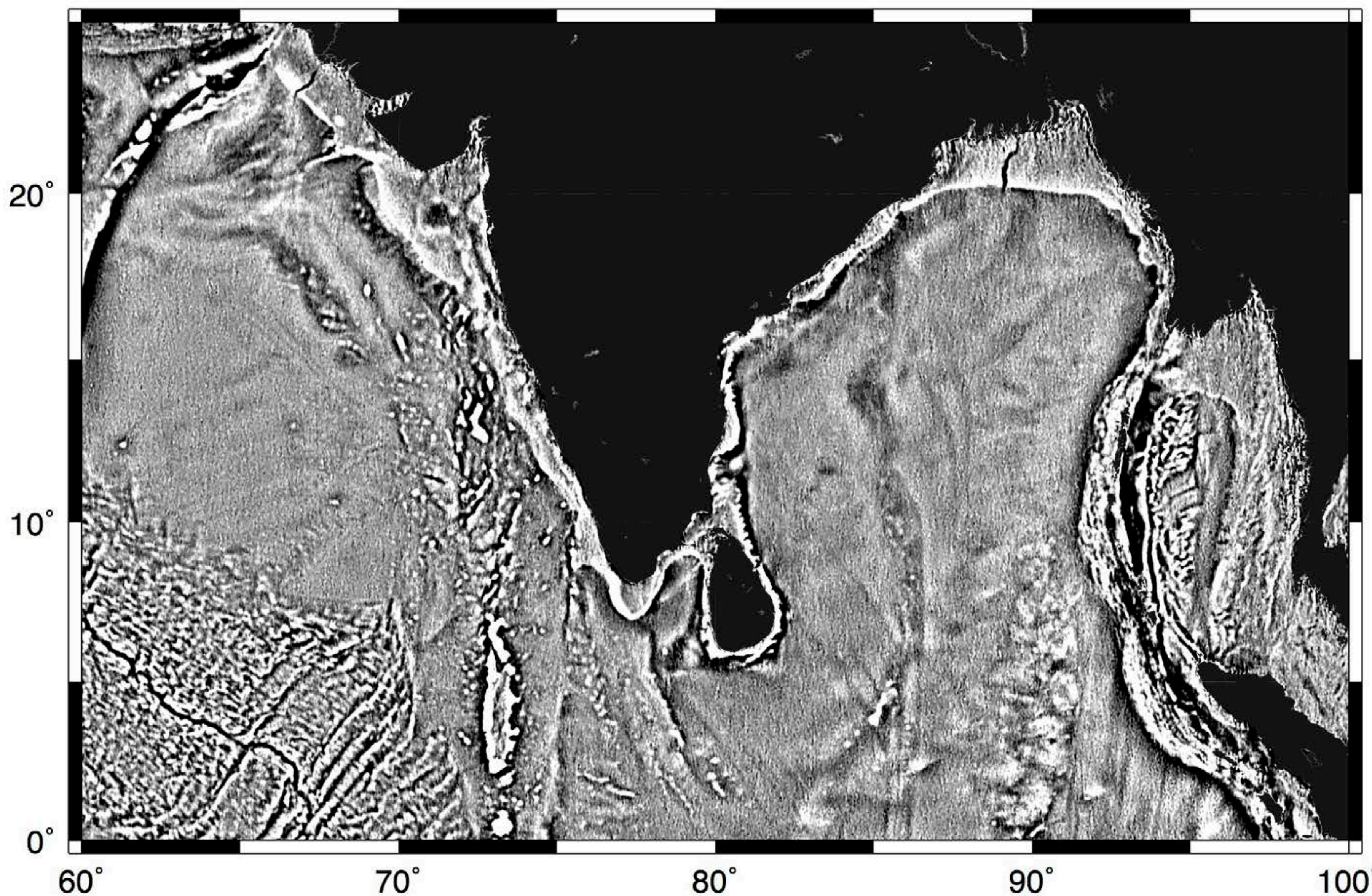
Resolution of uncharted abyssal hills



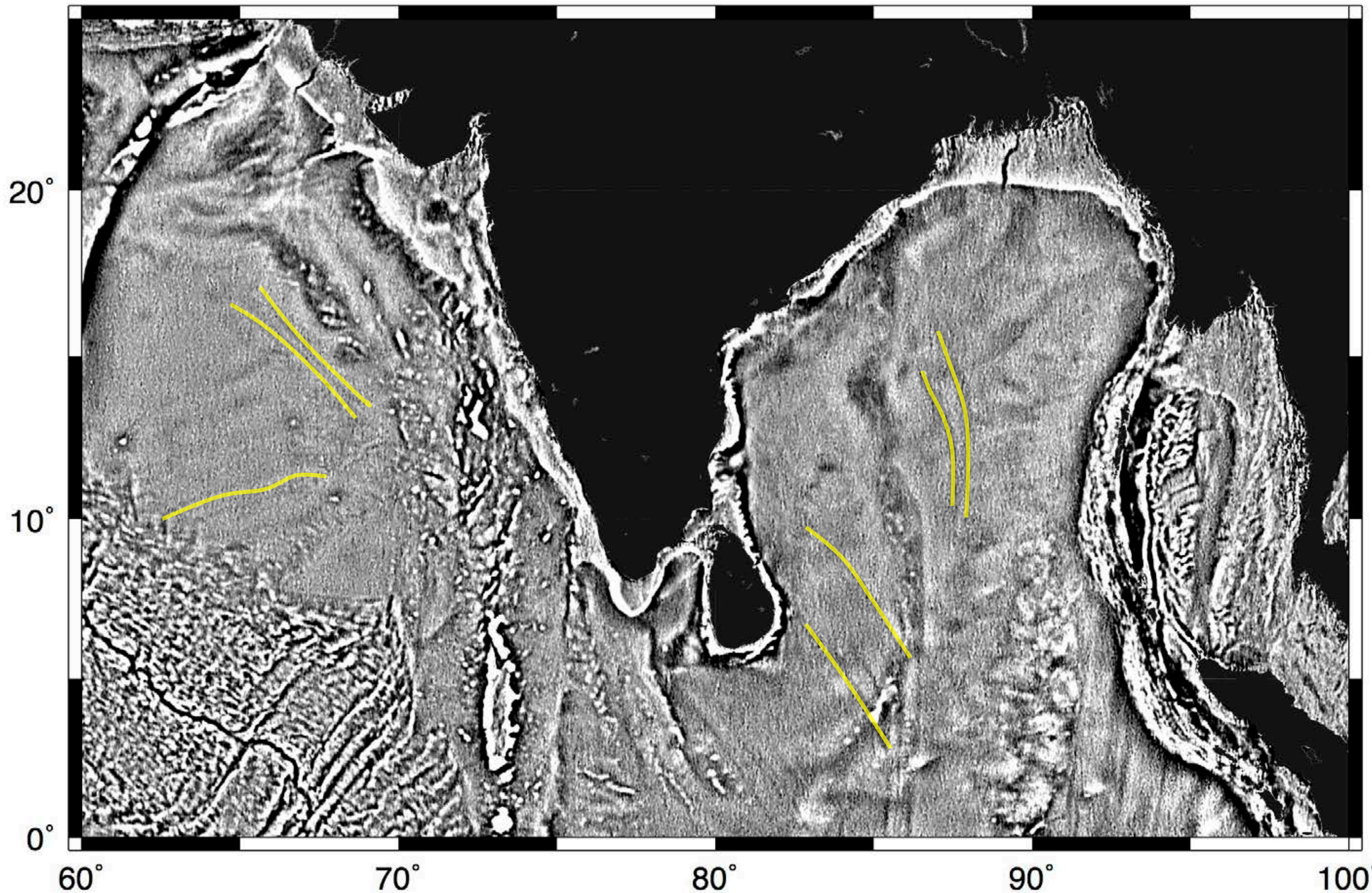
VGG (V18) Geosat + ERS



VGG (V24) + CryoSAT + AltiKa + Jason-1

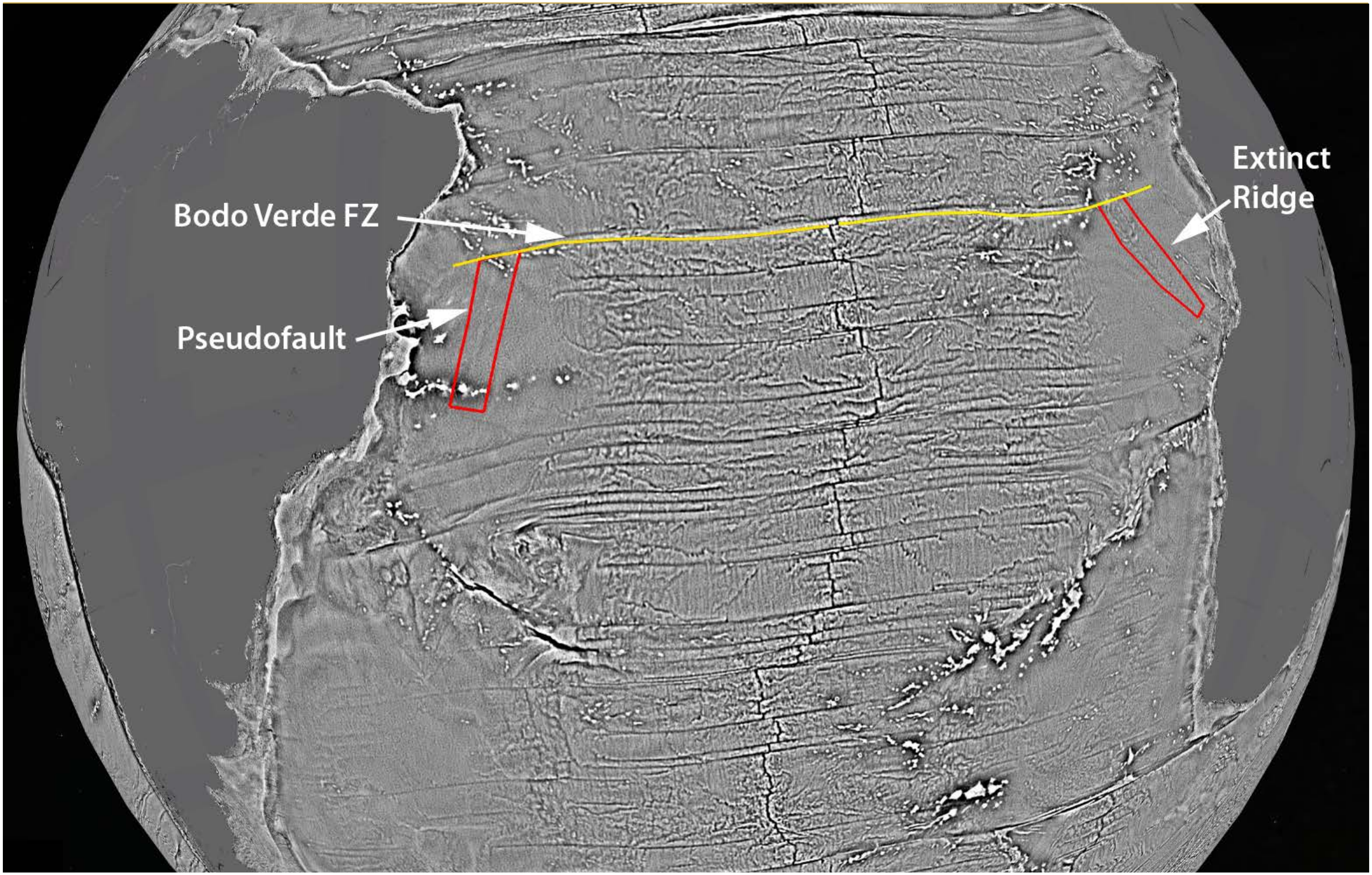


Resolution buried tectonic structures



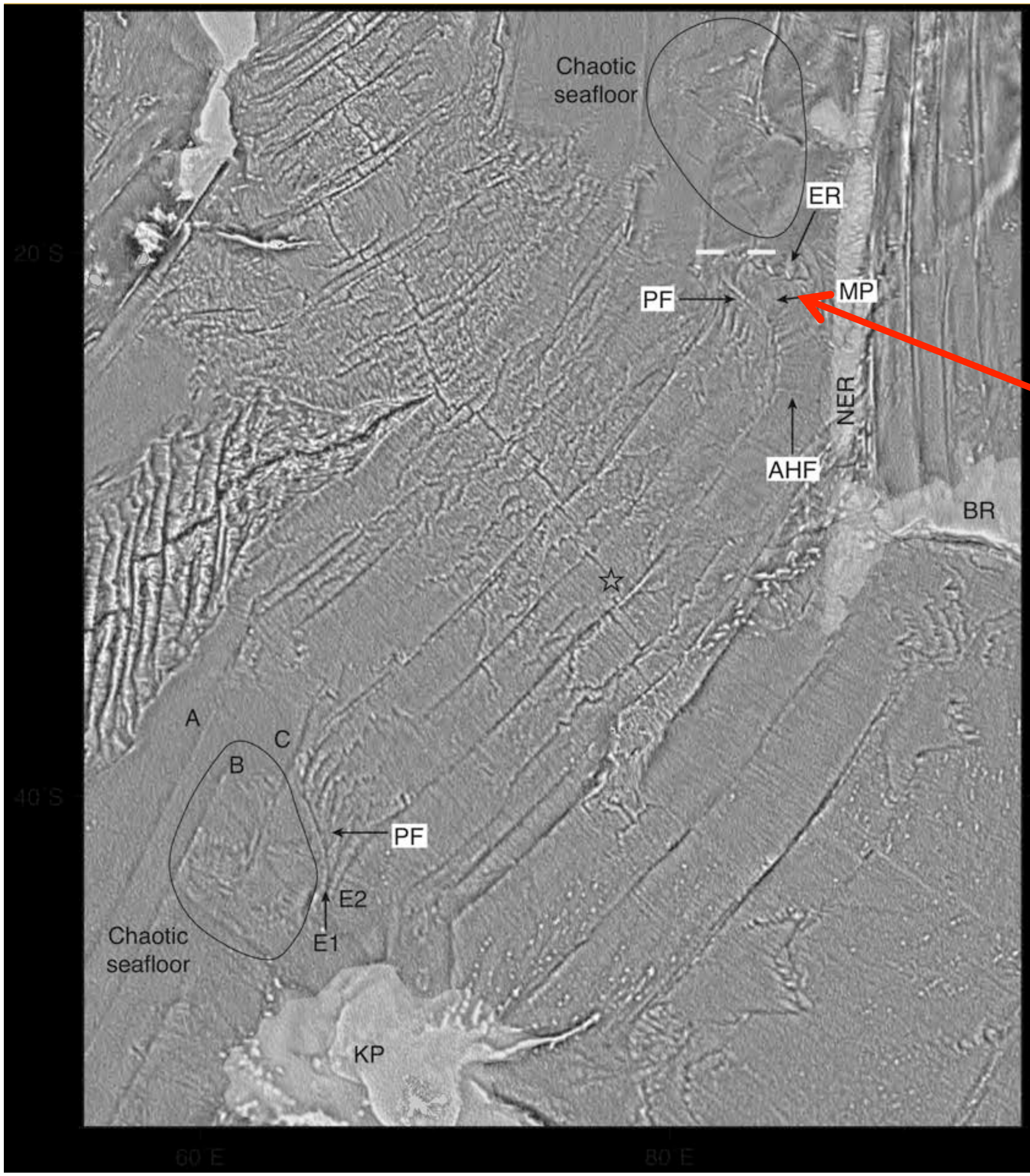
Propagating Ridge, South Atlantic

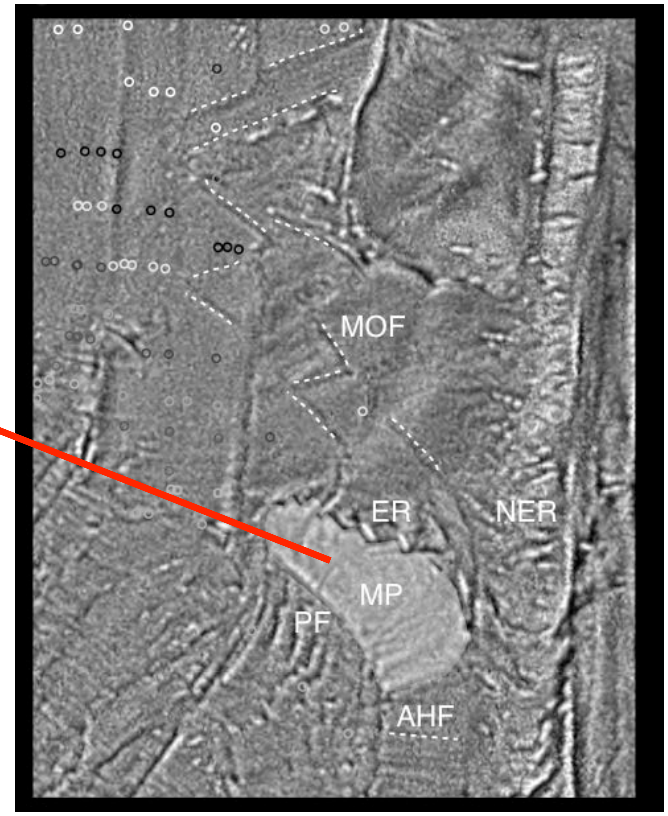
[Sandwell et al., Science, 2016]



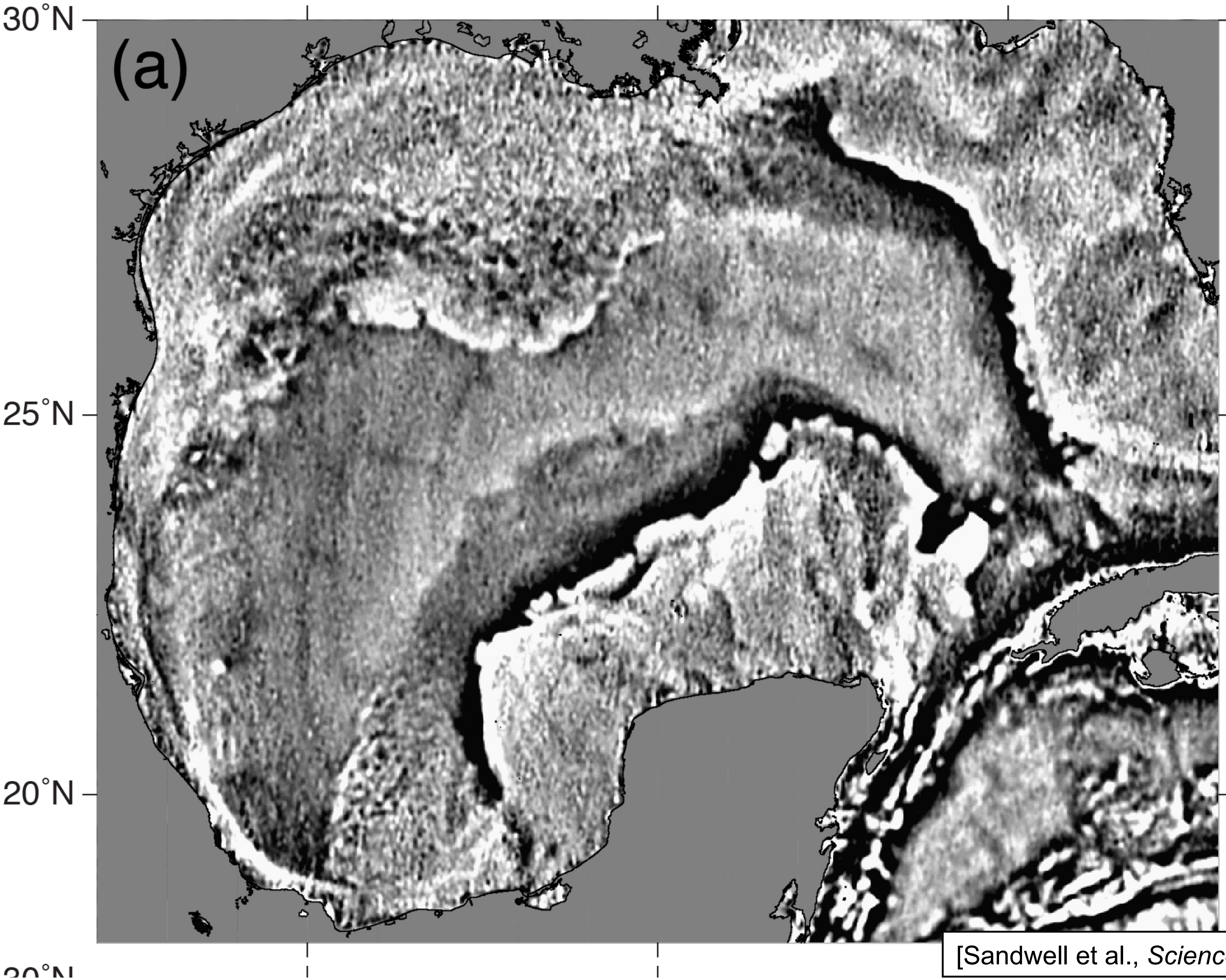
Mammerickx Microplate, Indian Ocean

[Matthews et al. , EPSL, 2015]

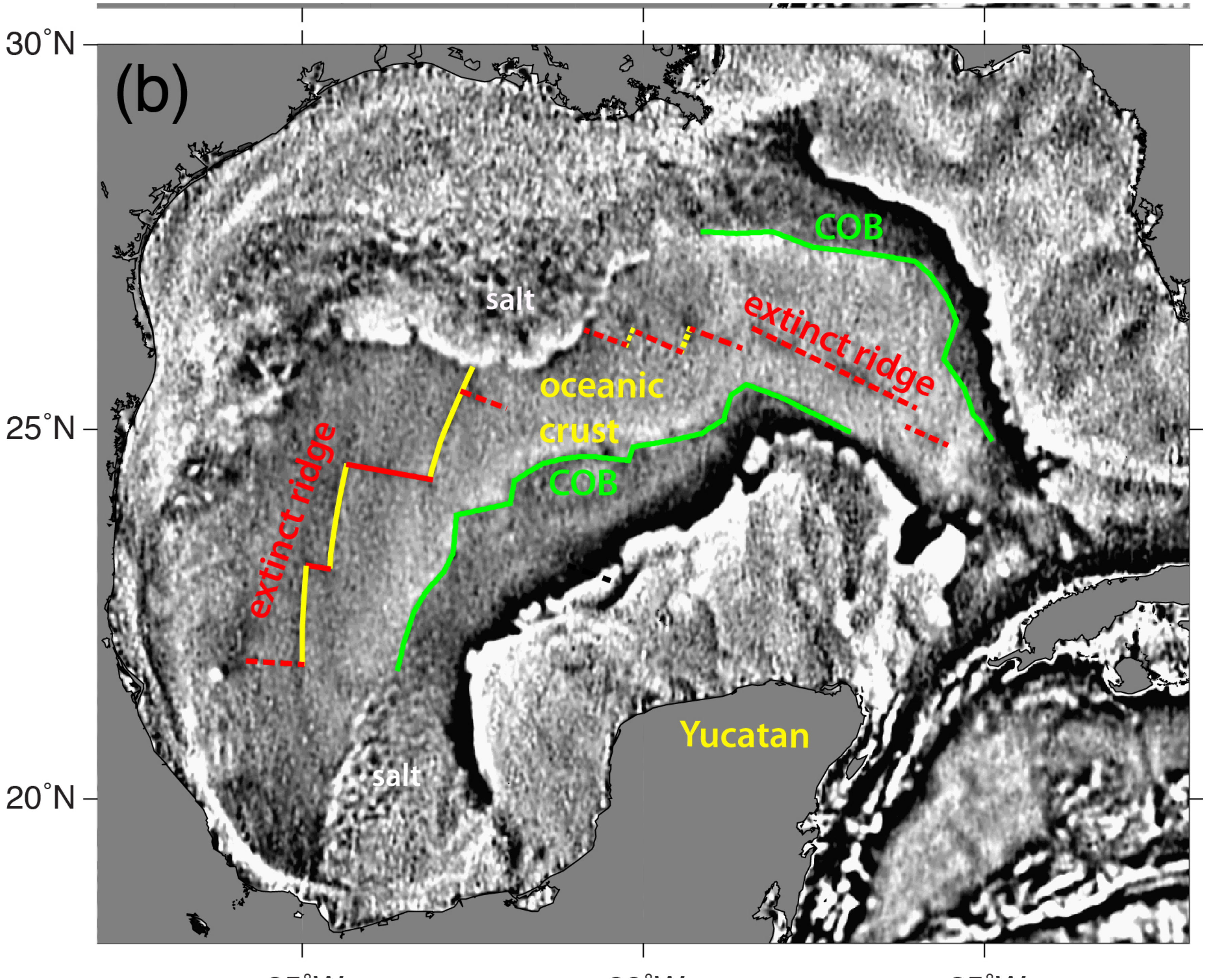


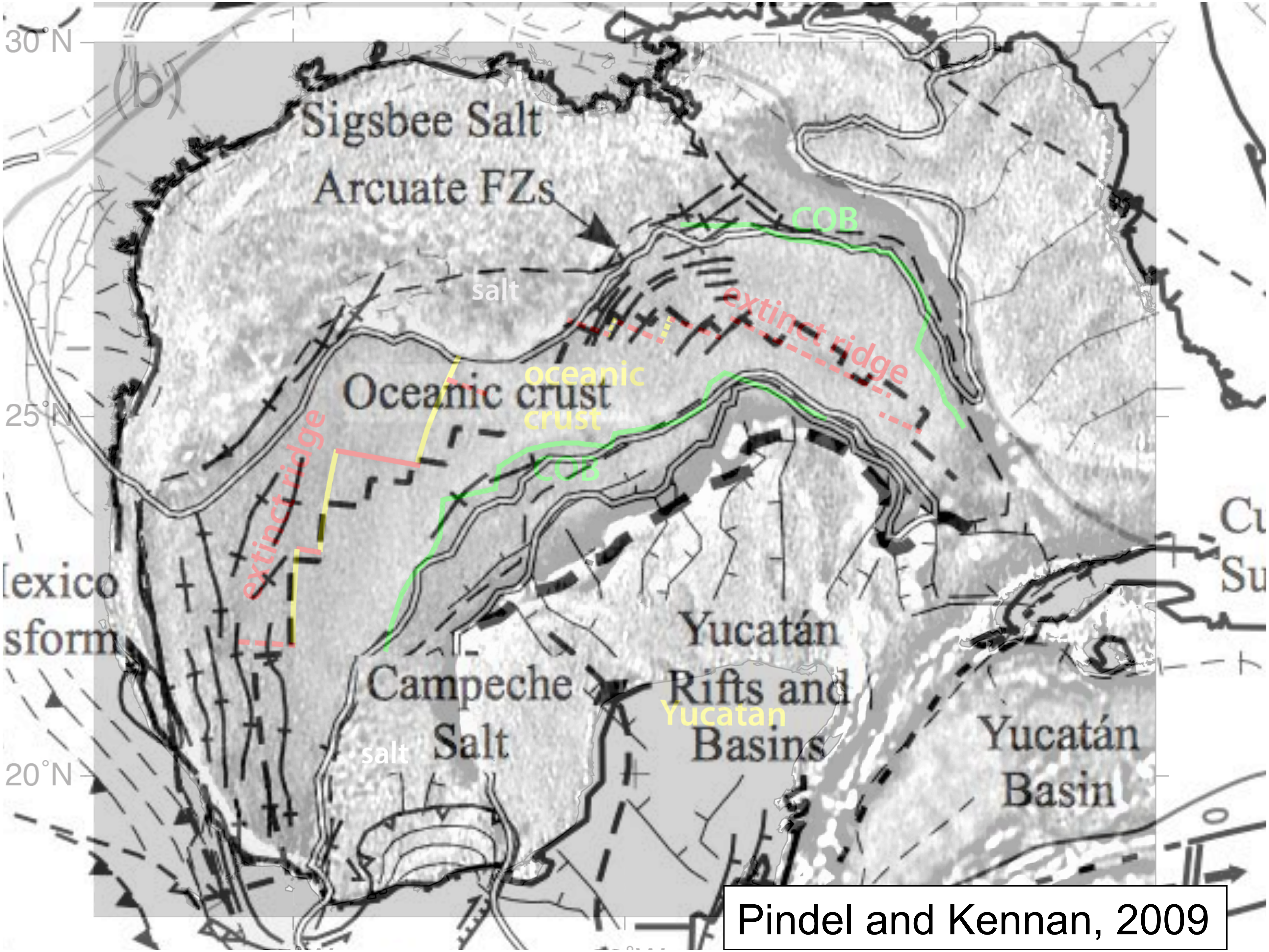


previously uncharted microplate the size of West Virginia

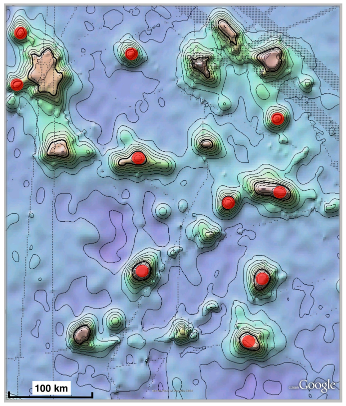


[Sandwell et al., *Science*, 2014]

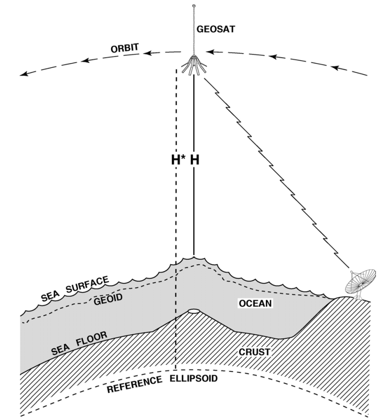

30°N
25°N
20°N
(b)
salt
COB
extinct ridge
oceanic
crust
COB
extinct ridge
Yucatan
salt



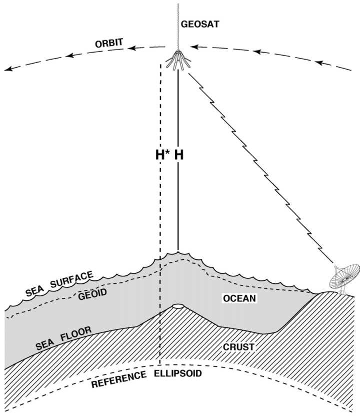
Pindel and Kennan, 2009



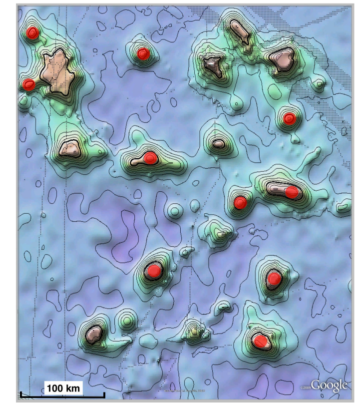
Conclusions – 1



- Topography and tectonics of the deep ocean are VERY different from the continents.
- Abyssal hills, created at seafloor spreading ridges, are the most common landform on the planet.
- There could be 100,000 seamounts taller than 1000 m that are uncharted.
- Mapping by ships provides ~100 m spatial resolution but it would take 125 ship years to map the oceans.
- Mapping by satellites (gravity) has ~6000 m spatial resolution and is improving.



Conclusions - 2



- **GOOD**

  Global marine gravity from satellite altimetry will reach 1-mGal accuracy with AltiKa and SWOT.

  It may be possible to locate all seamounts > 1 km tall and resolve abyssal hill fabric.

- **BAD**

  Only 17% of the seafloor has been mapped by sonar at < 1 km resolution.

  Depths predicted from gravity have 6 km resolution and an accuracy of only 250 – 400 m.

- **UGLY**

  Bathymetric prediction fails on continental margins because sediment masks original topography.

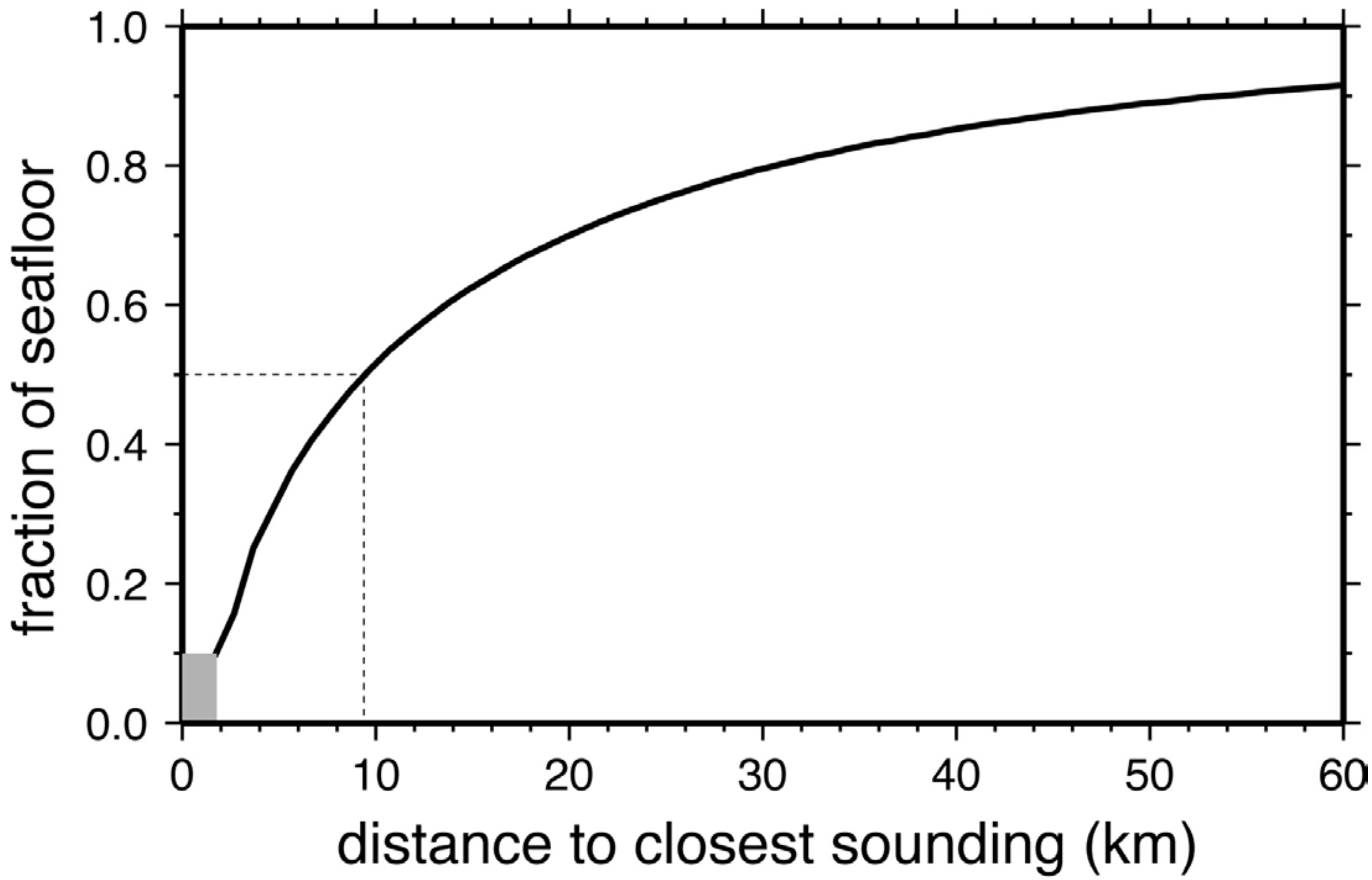
  The rate of seafloor mapping has decreased since the end of the Cold War, especially in the southern hemisphere.

Questions?

How can we do better?

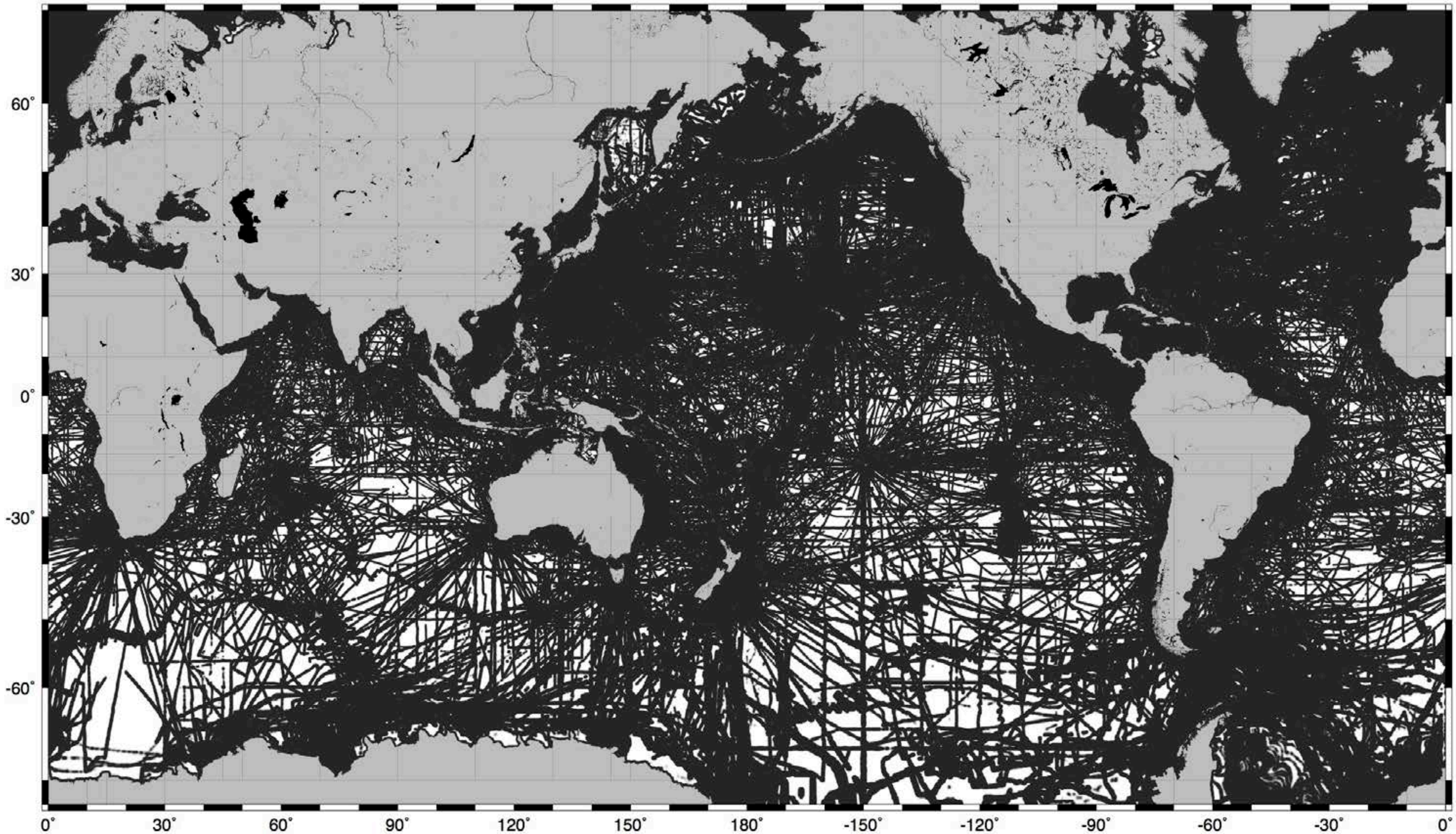
- Improve public archives of bathymetry.
- Map the oceans with multibeam echosounders - ships of opportunity.
- Acquire new satellite altimeter data.
- Declassify US Navy bathymetry data.

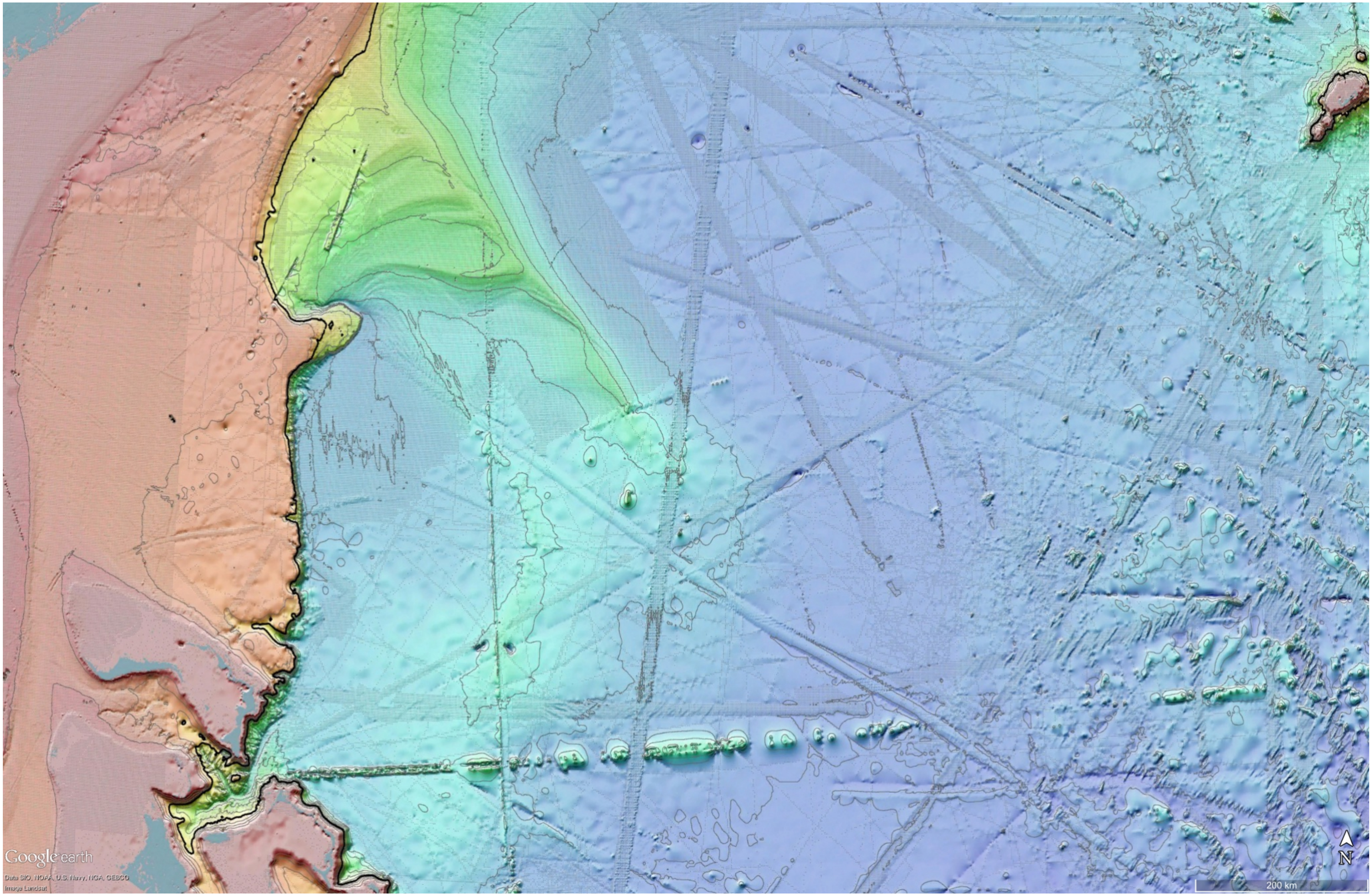
1/2 of global seafloor is more than 10 km from a depth sounding

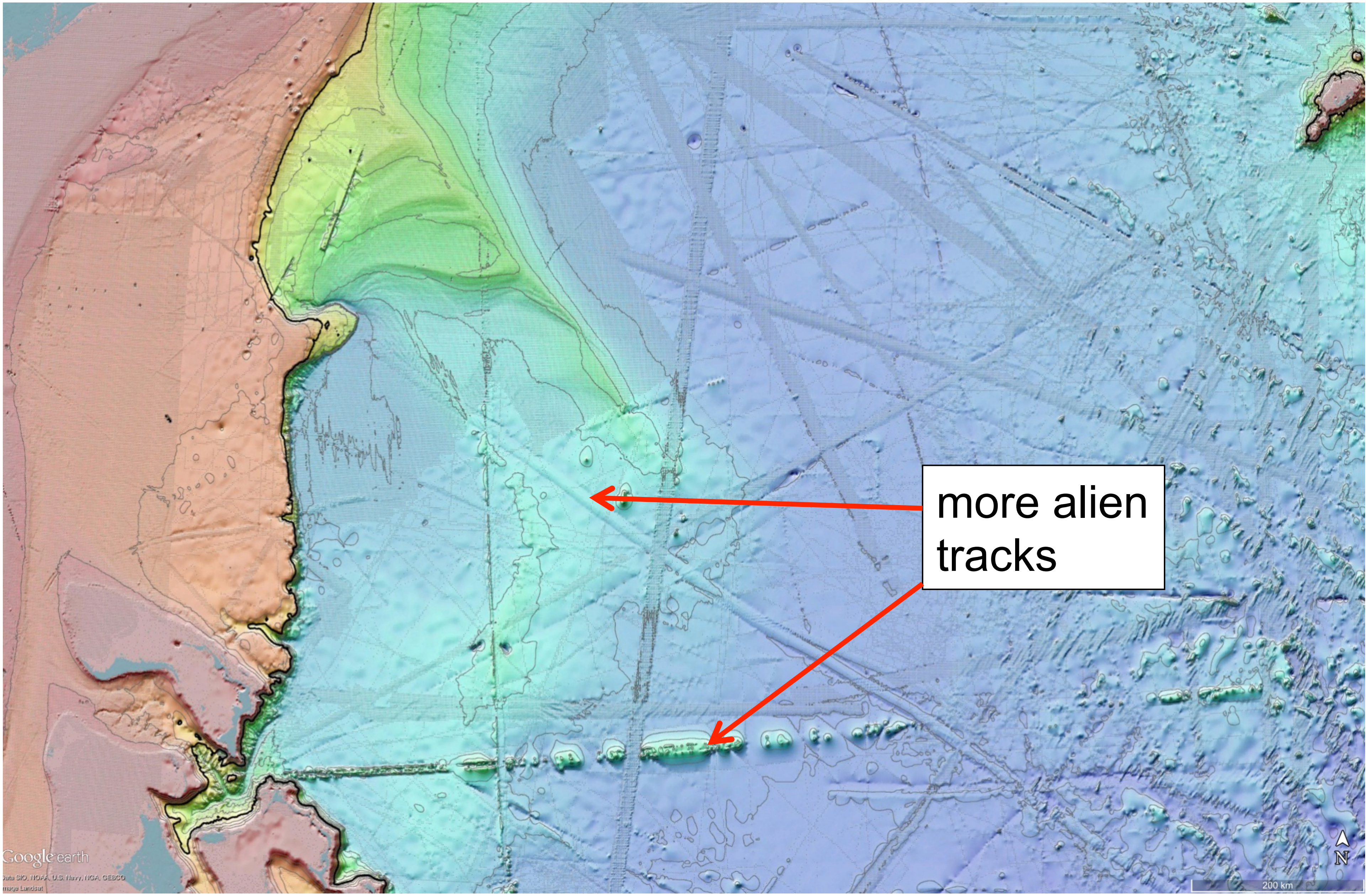


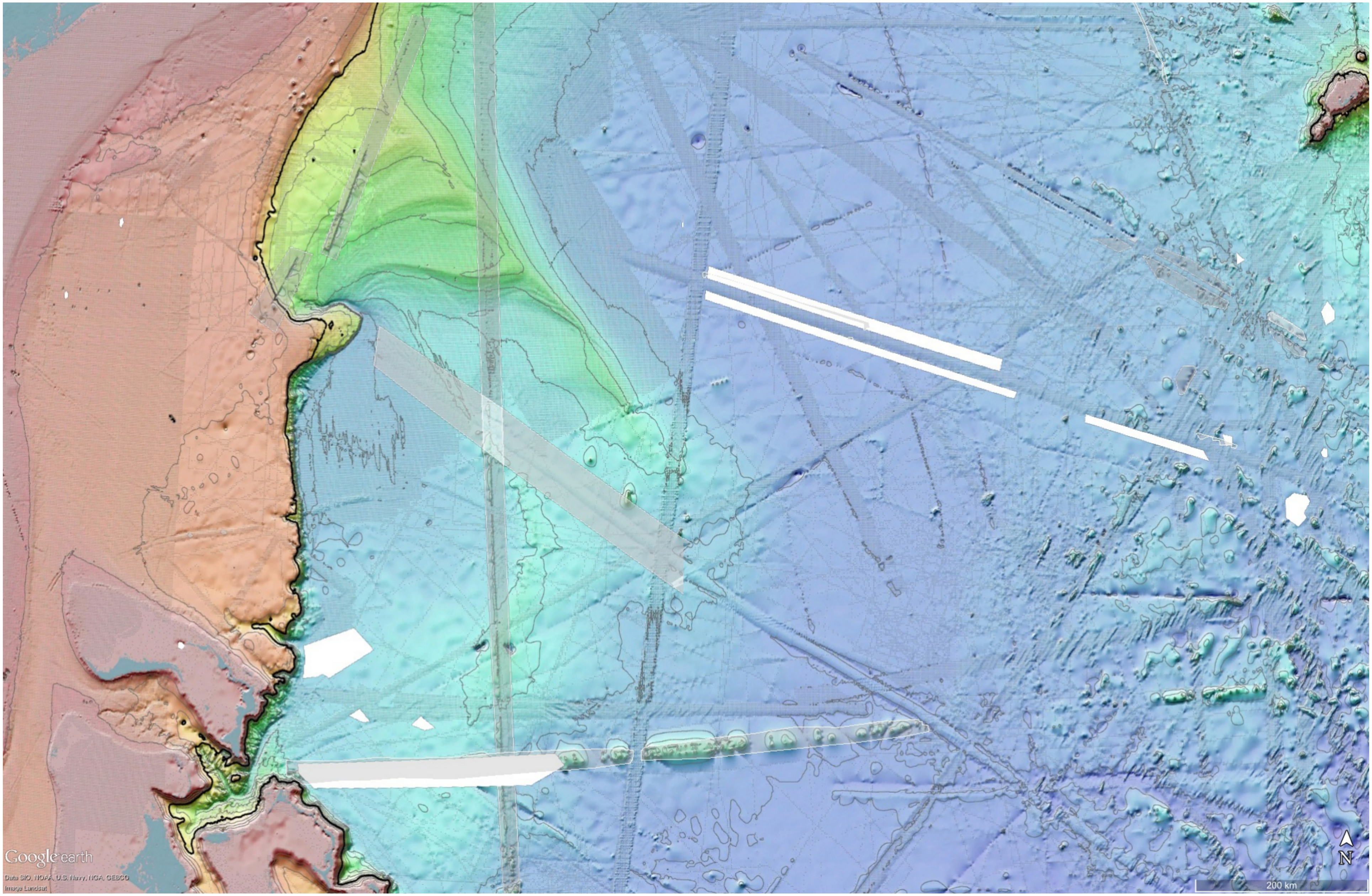
[Smith and Marks, 2009]

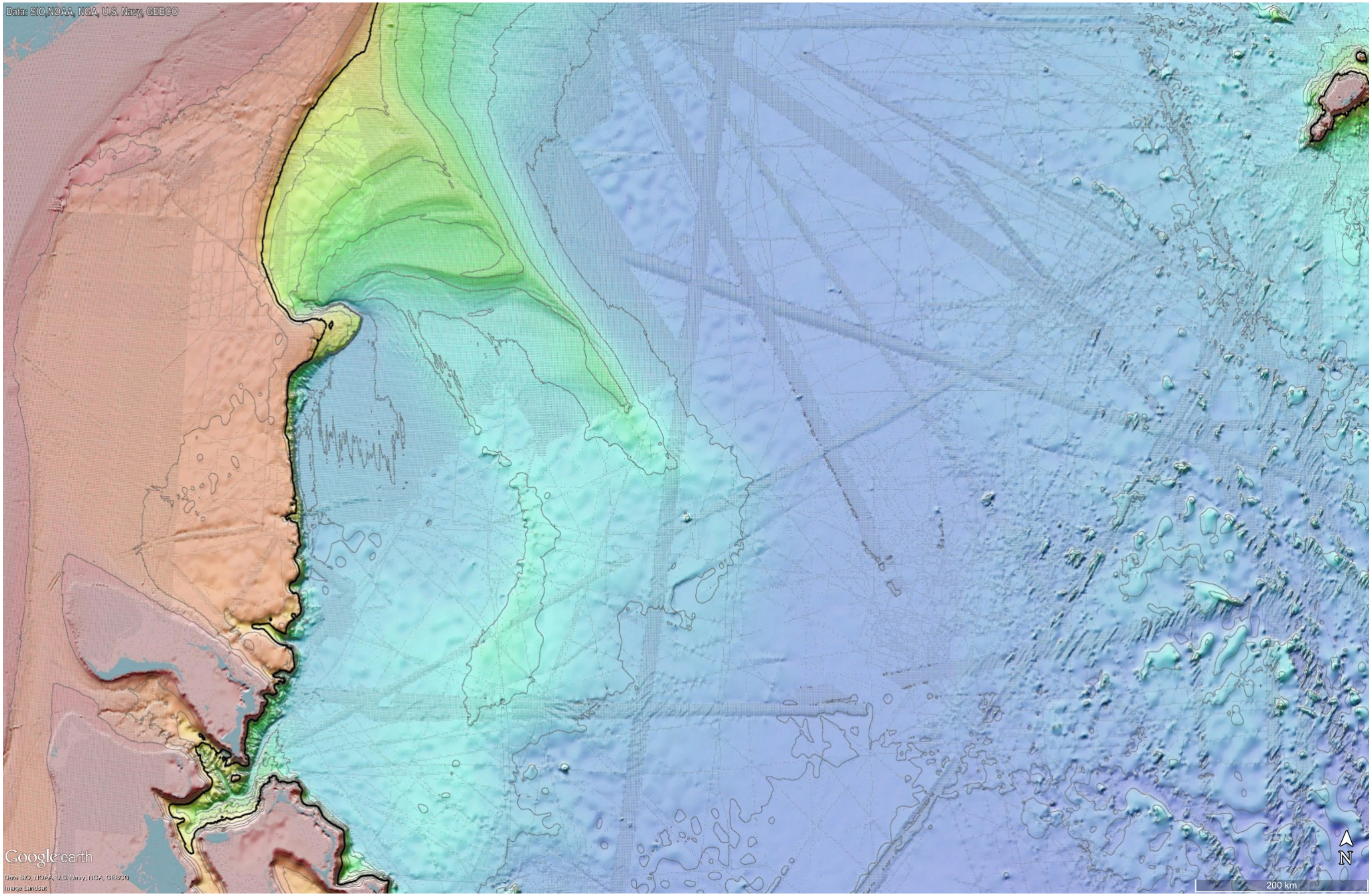
areas of seafloor more than 10 km from a sounding




Google earth
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat
N
200 km


more alien tracks
Google earth
200 km
N


Google earth
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat
N
200 km


Data: SIO,NOAA, NGA, U.S. Navy, GEBCO
Google earth
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat
N
200 km

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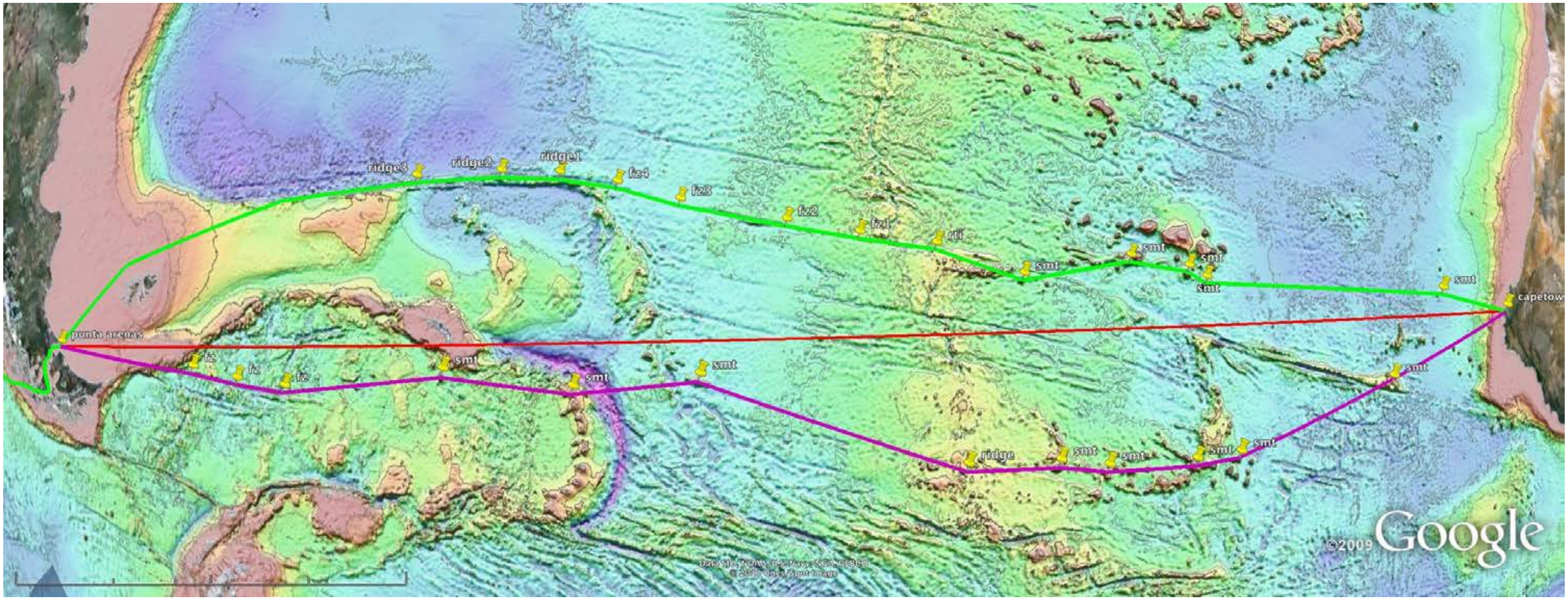
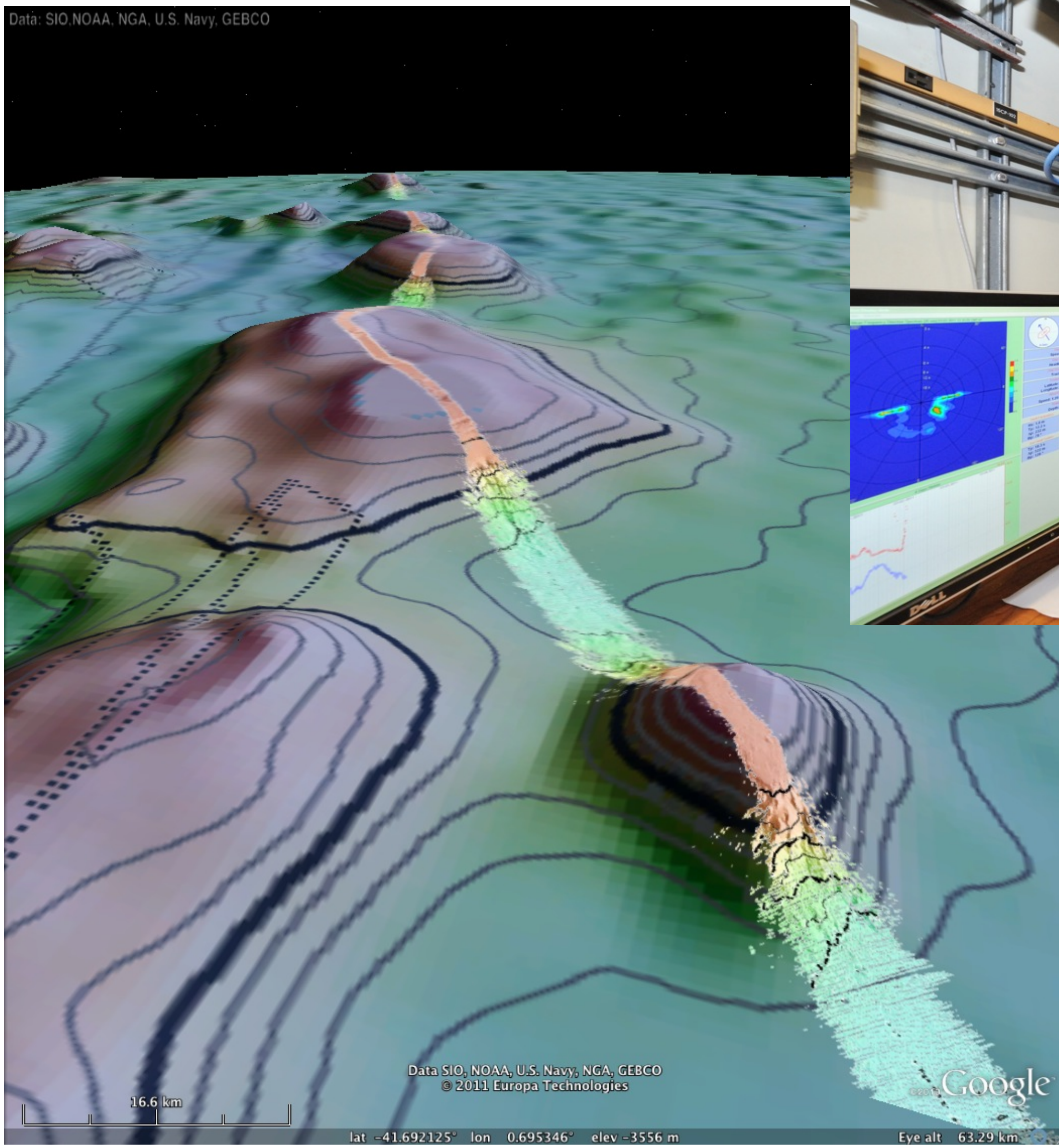
Cape Town to Punta Arenas - Melville - Feb, 2011

red - great circle = 6896 km
green - 10 new seamounts = 7130 km (1.034)
violet - 11 new seamounts = 7069 km (1.025)

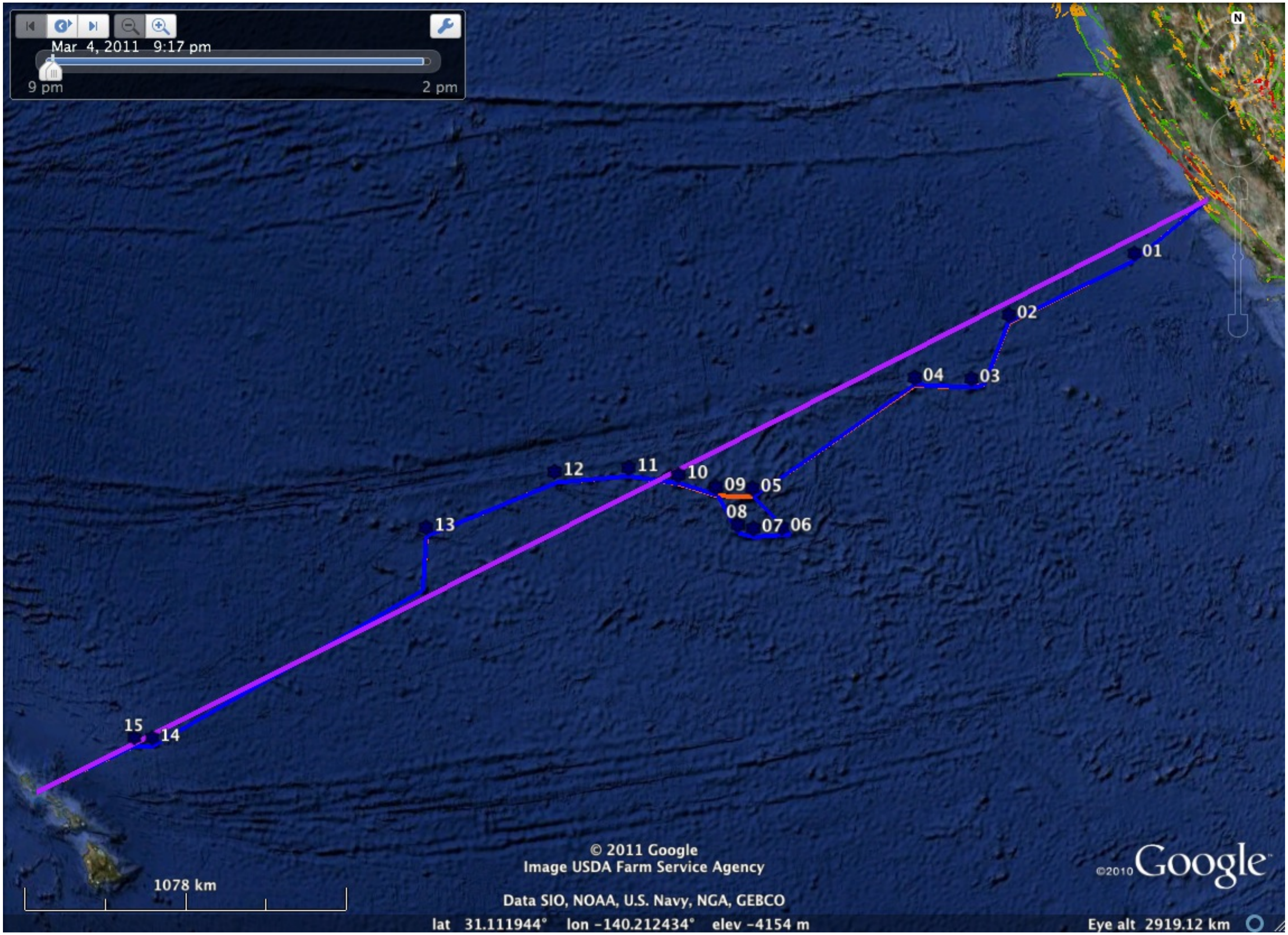


Cape Town to Punta Arenas - Melville - Feb, 2011

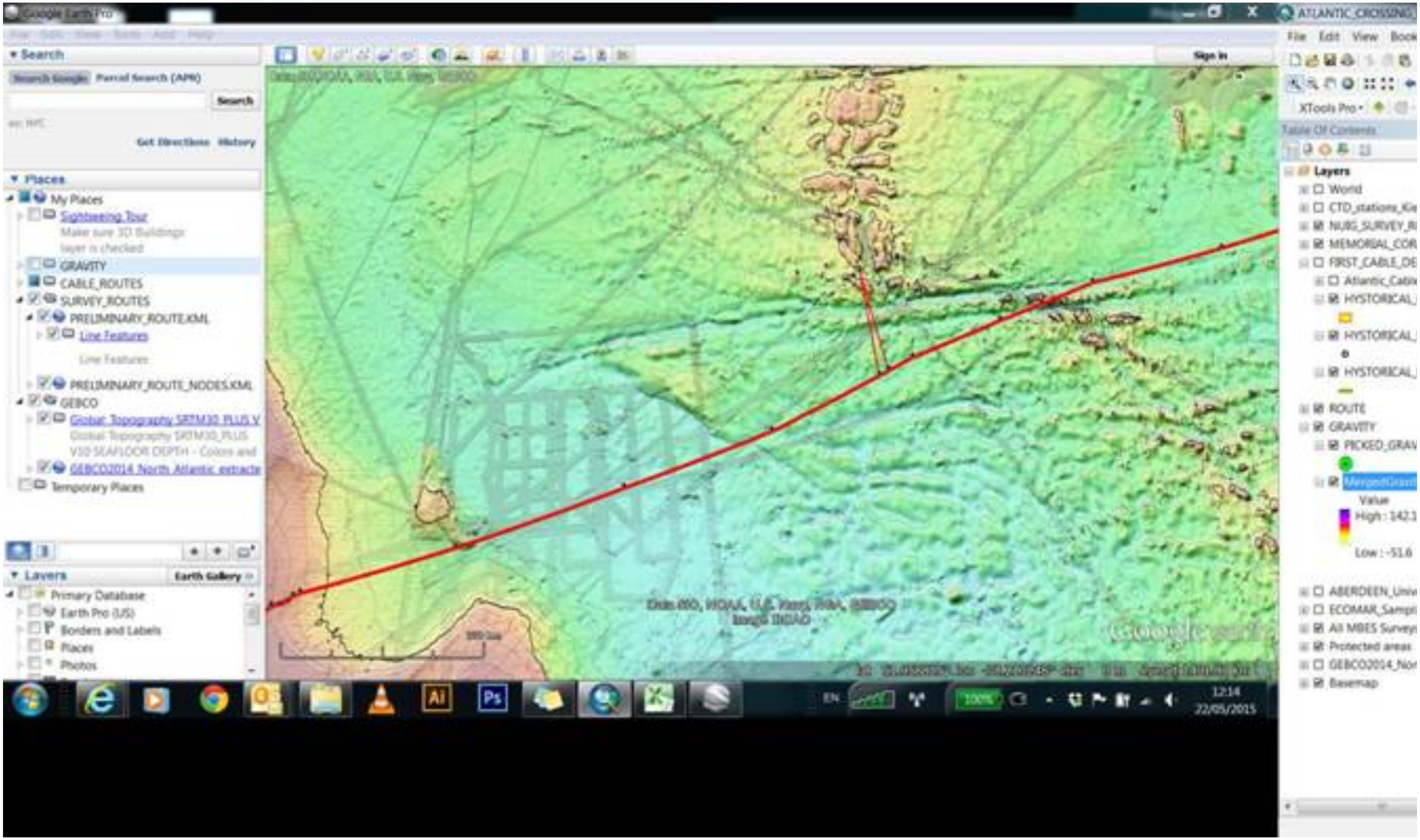


Okeanos Explorer - Monterey Bay to Honolulu – 2013

Elizabeth Lobecker



Irish National Seabed Mapping Programme – Thomas Furey - 2015



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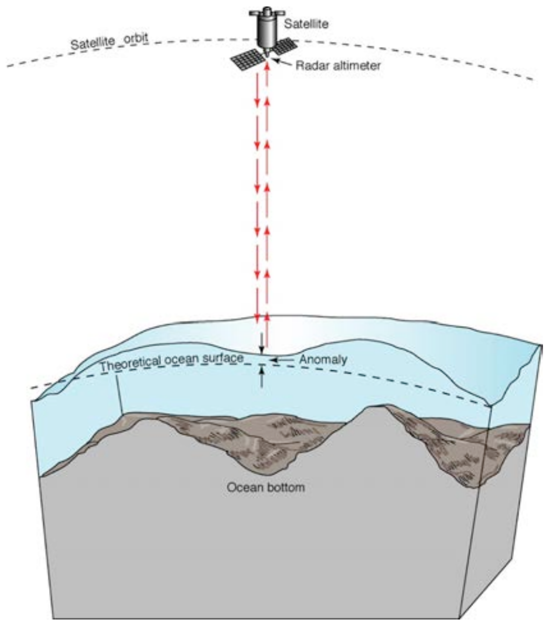
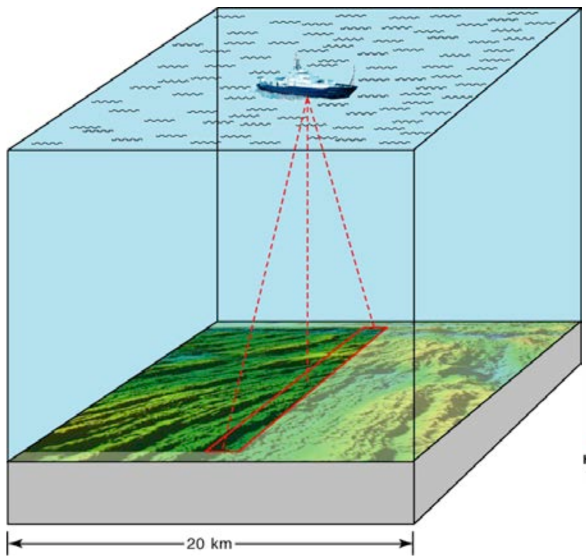
~~Modern~~ Seafloor Mapping Tools
Future

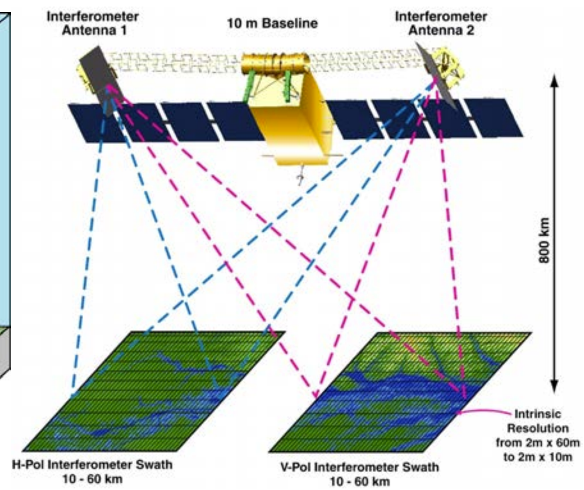
nadir-looking satellite altimeter



shipboard echo sounder



interferometric swath altimeter



schematic: *SWOT mission website* (https://swot.jpl.nasa.gov/)

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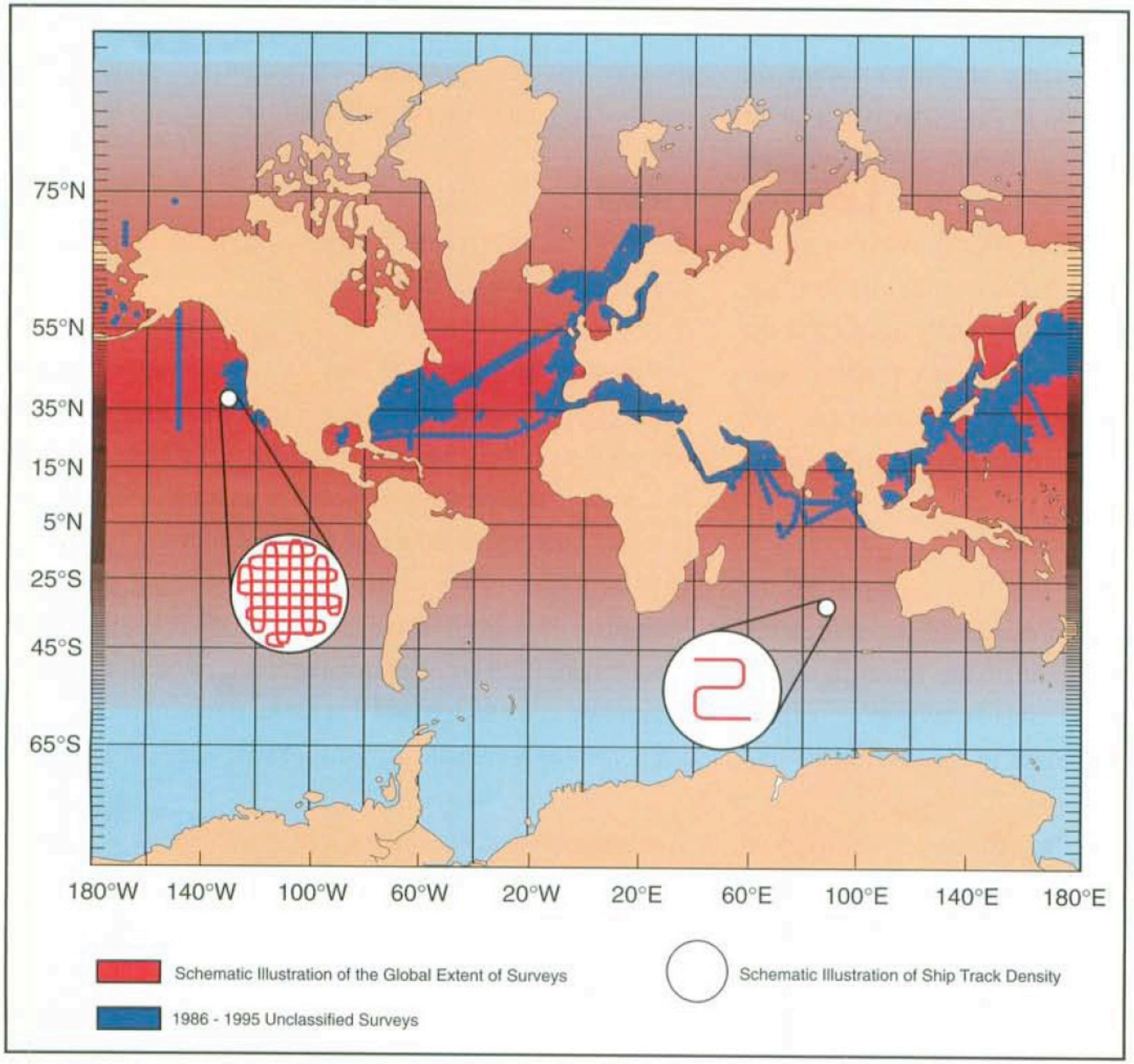
MEDEA: Scientific Utility of Naval Environmental Data,
(Mitre, Co., June, 1995)

FIGURE 2. WORLDWIDE SURVEY OPERATIONS



The red shaded area illustrates the global scope of the Navy's oceanographic survey and measurement program. As the tapered shading suggests, there has been a greater concentration of resources in the Northern Hemisphere than the Southern Hemisphere.

Also shown schematically are inset illustrations of how different the densities of ship tracks might be in different ocean areas. Tracks of naval oceanographic surveys (blue) from just the unclassified cruises covering the years from 1986 to 1995 show the worldwide nature of the sources of data.

Examination of all survey ship tracks from the entire cold war history of naval survey operations would show both a global breadth of coverage and a scientifically well founded spatial sampling of ocean processes.

MEDEA: Scientific Utility of Naval Environmental Data,
(Mitre, Co., June, 1995)

TABLE 2. FINDINGS RELATED TO SPECIFIC DATA SETS

- ***Scientific Utility***

  We have singled out 10 data sets whose potential for supporting important science is so significant that our first recommendation to the Navy is to "...consider prompt declassification of the high priority environmental data sets identified here." Four of these data sets are in the domain of geology and geophysics (Marine Gravity, Geomagnetics, Geosat Altimetry, and Seafloor Sediment Properties), two are concerned with sea ice (Ice Keel Depth Acoustic Data and Historical Ice Morphology), and four are concerned with the volume and boundary properties of the ocean (Marine Bathymetry, Realtime Salinity and Temperature Fields [GOODS], Archival Salinity and Temperature Fields [MOODS], and Ocean Optics and Bioluminescence).

- ***Prioritization of Data Sets***

  The listing below shows a twofold prioritization of the probable scientific importance and uniqueness of the data, should they be made publicly available.

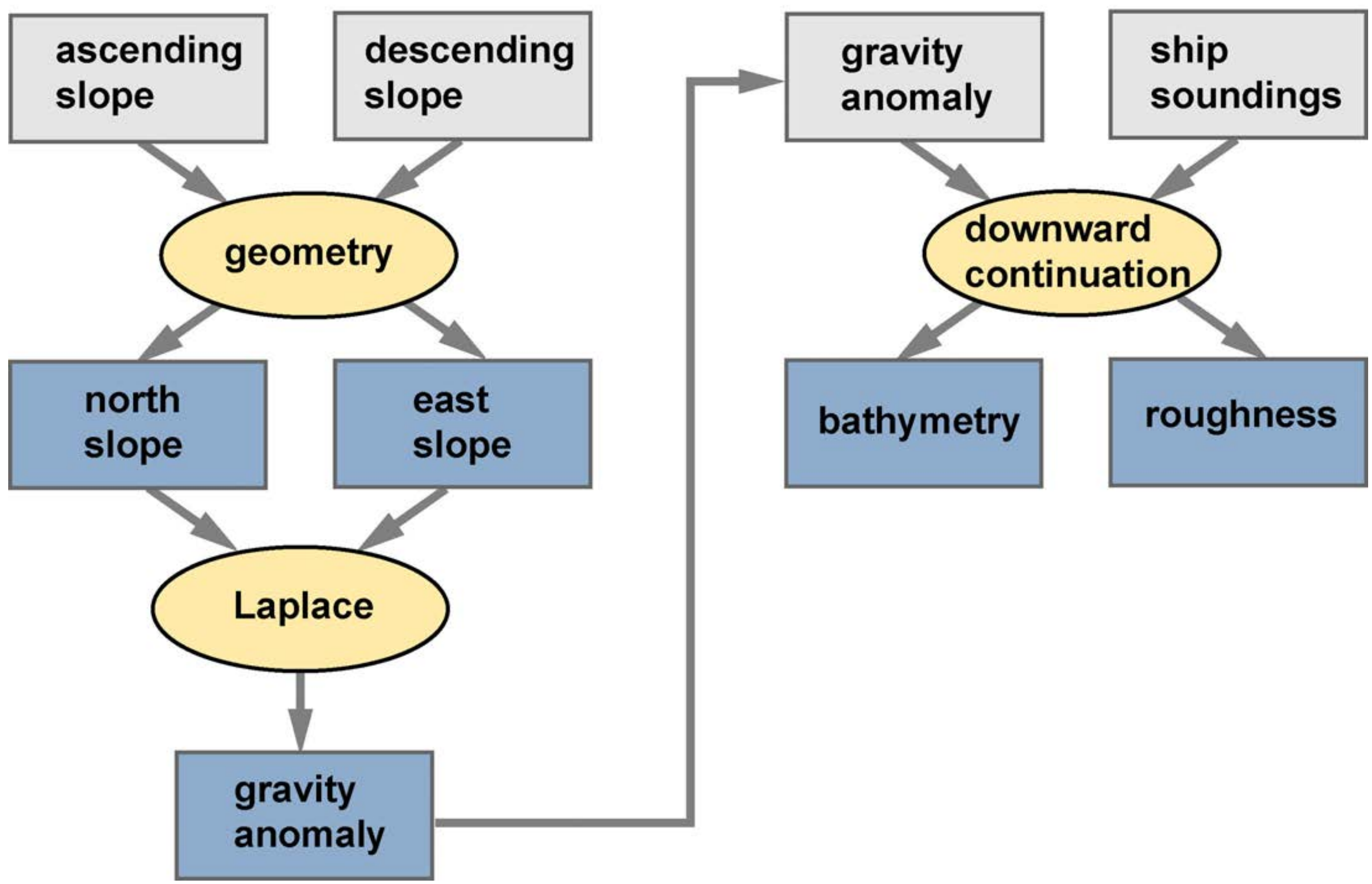
First Tier

- Marine Gravity
- Geomagnetics
- Ice Keel Depth Acoustic Data
- Marine Bathymetry
- Geosat Altimetry

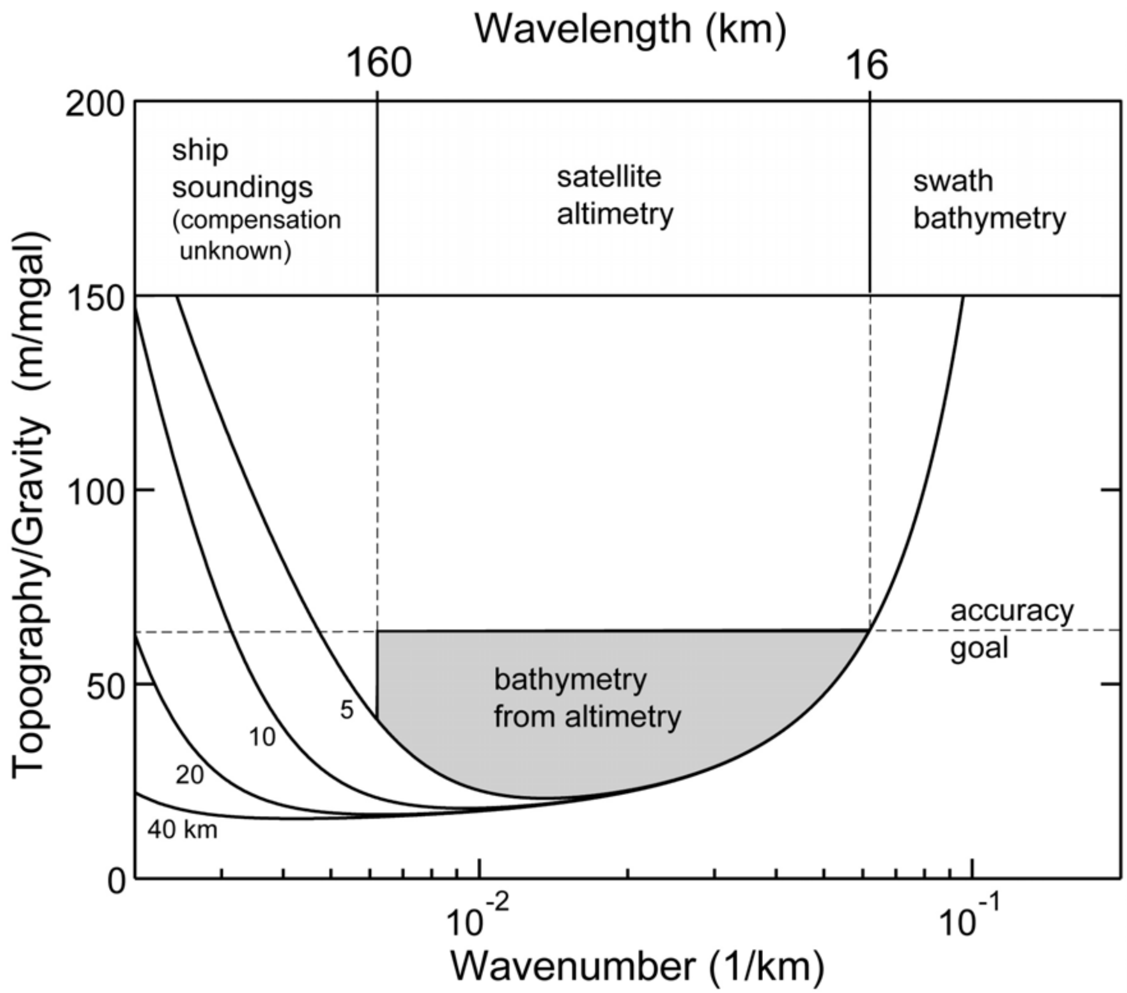
Second Tier

- Historical Ice Morphology
- Seafloor Sediment Properties
- Realtime Salinity and Temperature Fields (GOODS)
- Archival Salinity and Temperature Fields (MOODS)
- Ocean Optics and Bioluminescence

gridded map products — flow chart



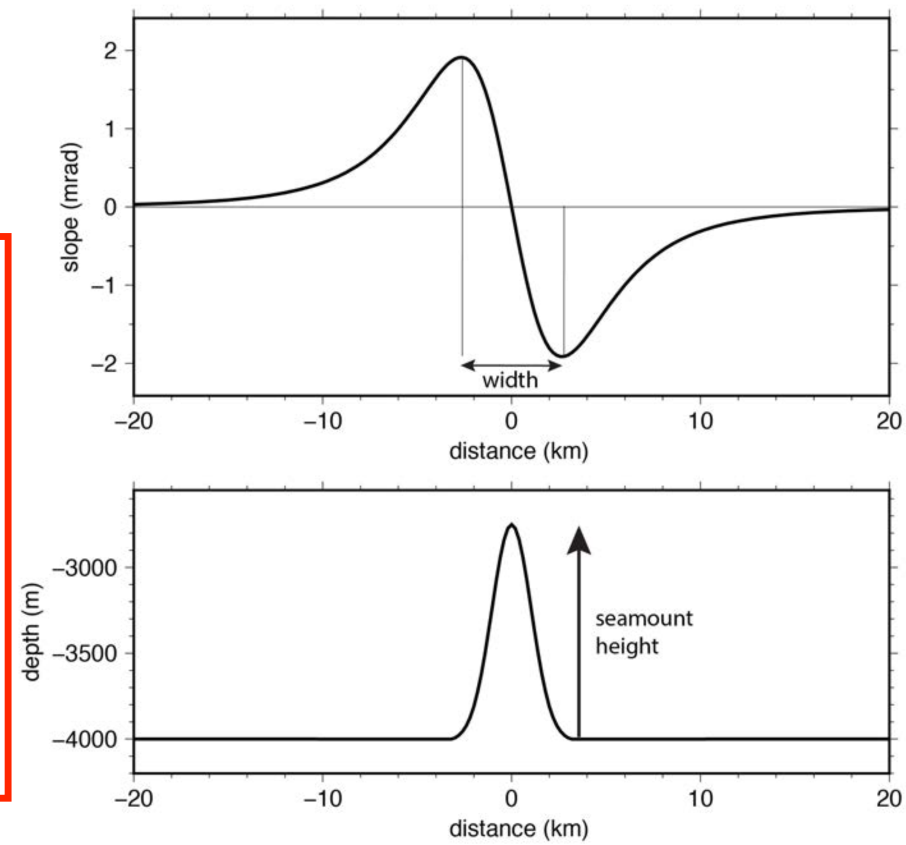
inverse model



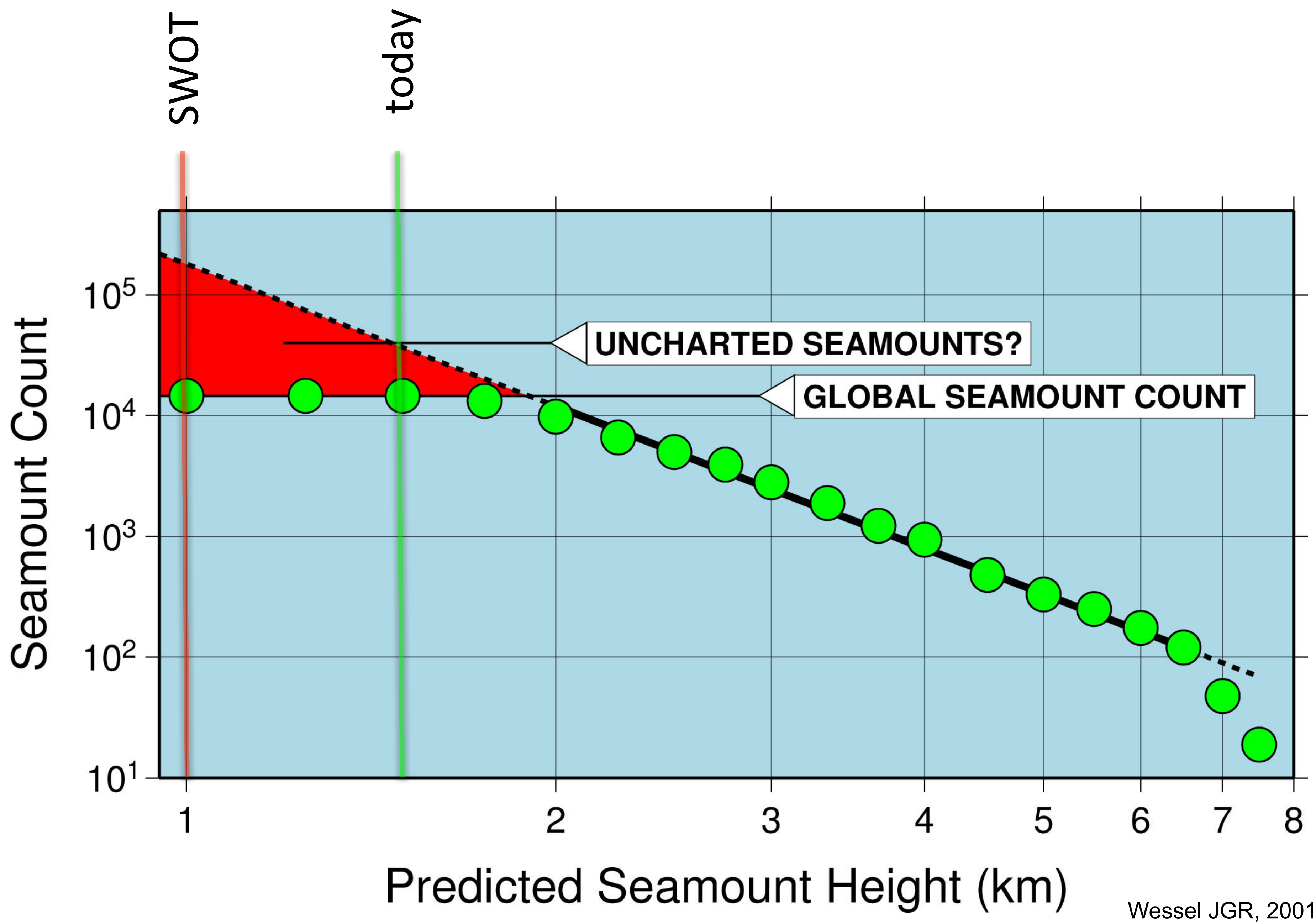
Signal of Gaussian Seamount

SWOT could resolve
all seamounts if slope noise
is less than 1 μrad at ~6 km
resolution or 3 μrad at ~2 km
resolution.

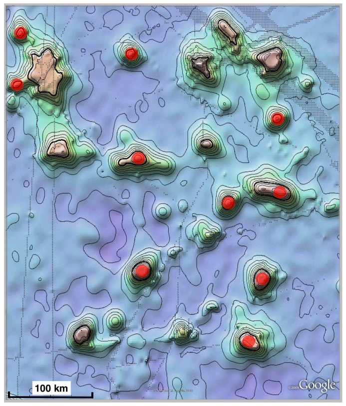
Need <500 m postings



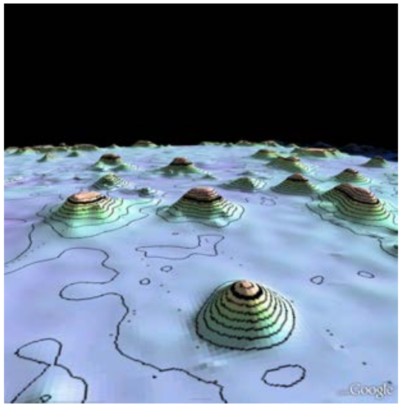
	seamount		sea surface		
	height (km)	radius (km)	slope (μrad)	width (km)	Δheight (mm)
after SWOT	**1.00**	**2.50**	**1.0**	**5.2**	**5.2**
	1.25	3.13	1.9	5.3	10.1
today	**1.50**	**3.75**	**3.2**	**5.4**	**17.3**
	2.00	5.00	7.3	5.6	40.9
	2.50	6.25	13.3	5.7	75.8
	3.00	7.50	21.7	5.8	125.9



SWOT
today
UNCHARTED SEAMOUNTS?
GLOBAL SEAMOUNT COUNT
Seamount Count
10^5
10^4
10^3
10^2
10^1
1
2
3
4
5
6
7
8
Predicted Seamount Height (km)
Wessel JGR, 2001



Seamount Discovery Tool



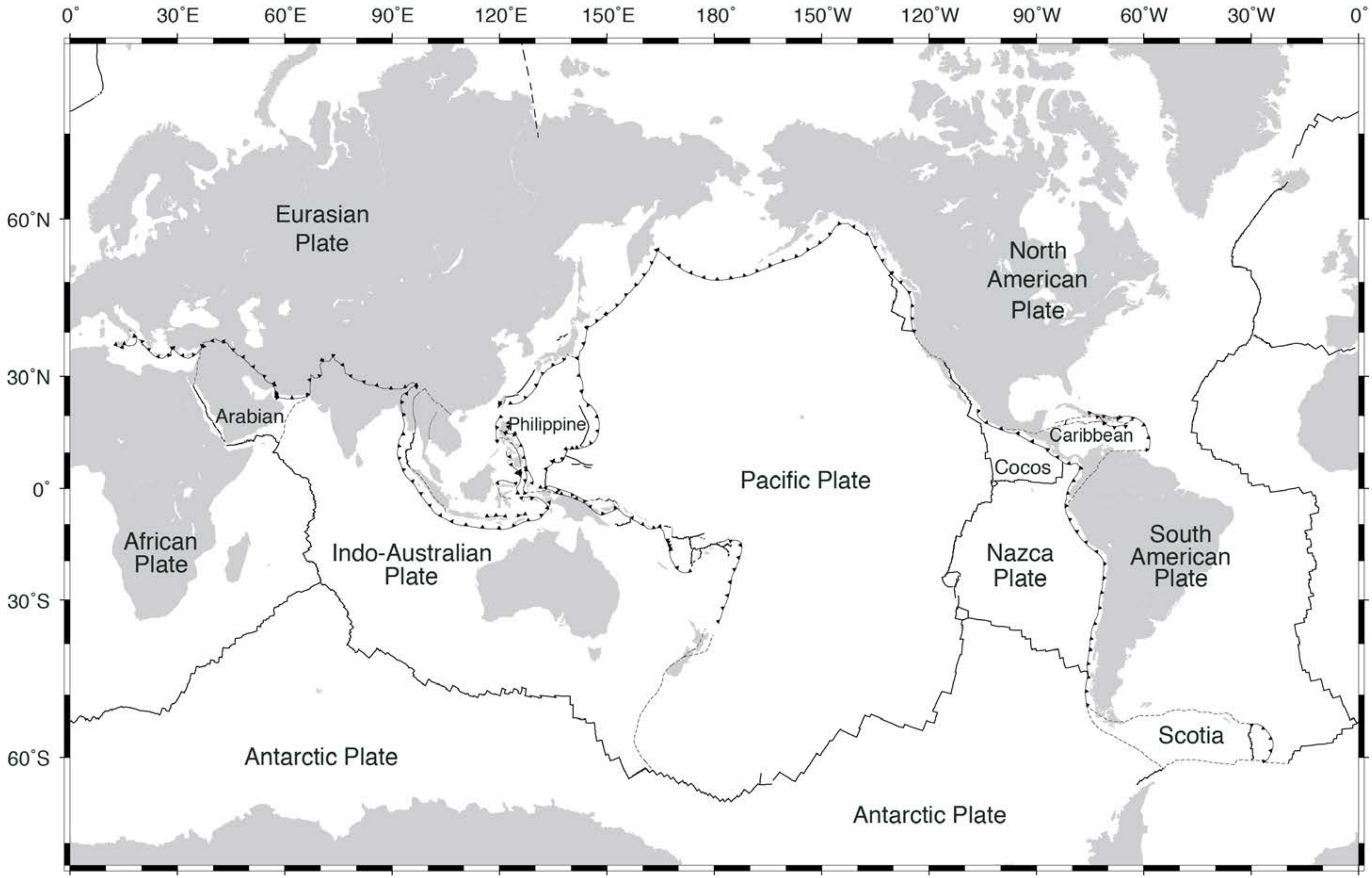
- Created as an efficient way for ships of opportunity to plan routes that travel over uncharted seamounts.

- Discovery tool uses Google Earth and a GPS

Wessel, P., D. T. Sandwell and S-S. Kim, The global seamount census,
Oceanography, 23:1 p. 24-33, 2010.

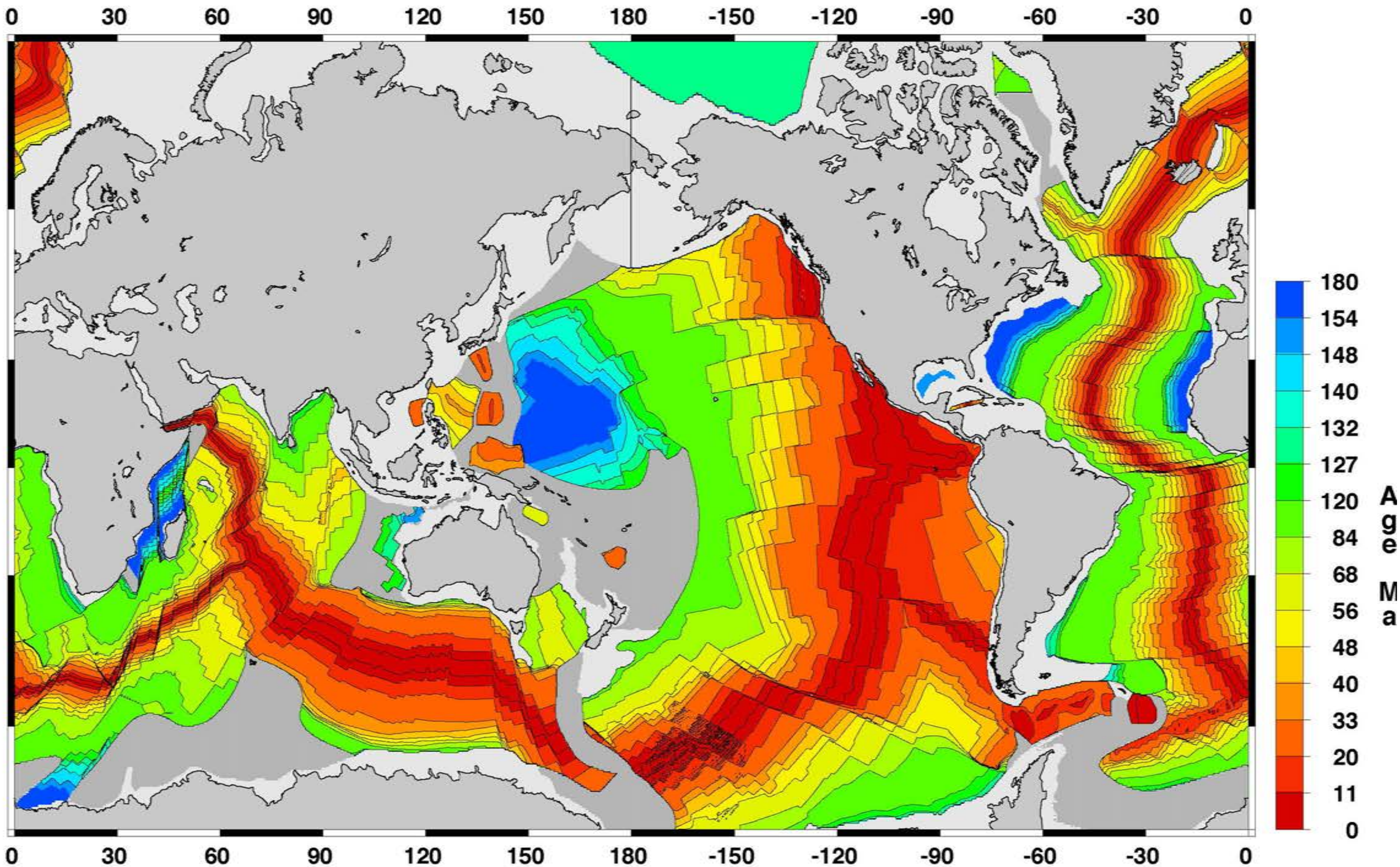
Sandwell, D. T., and P. Wessel, Seamount discovery tool aids navigation to uncharted seafloor features,
Oceanography, 23:1 , p. 24-26, 2010.

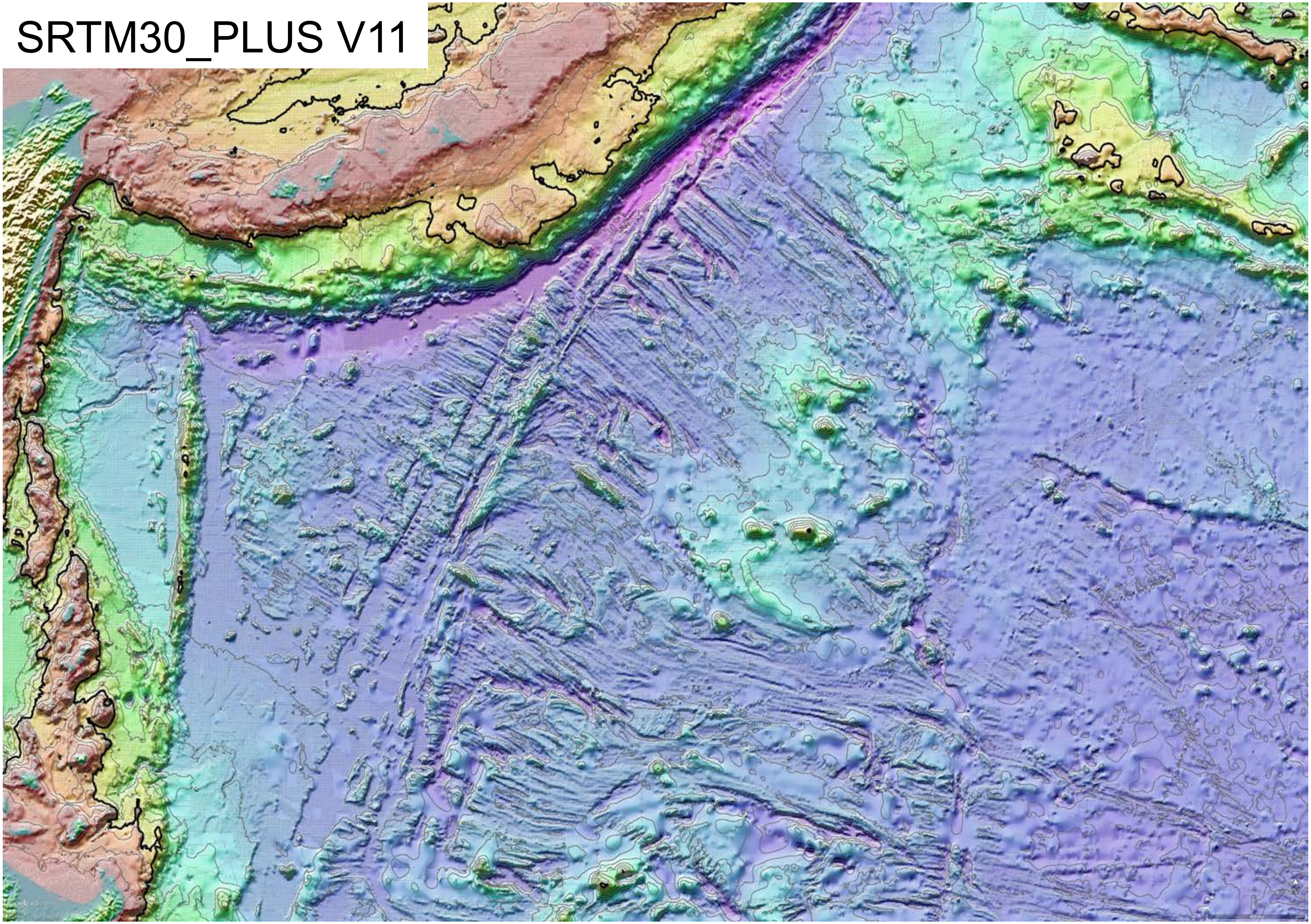
plates


0˚
30˚E
60˚E
90˚E
120˚E
150˚E
180˚
150˚W
120˚W
90˚W
60˚W
30˚W
0˚
60˚N
30˚N
0˚
30˚S
60˚S
Eurasian Plate
North American Plate
Arabian
Philippine
Caribbean
Cocos
Pacific Plate
African Plate
Indo-Australian Plate
Nazca Plate
South American Plate
Scotia
Antarctic Plate
Antarctic Plate

FZ direction + magnetic anomalies = seafloor age

[*Mueller et al.,* 1997]



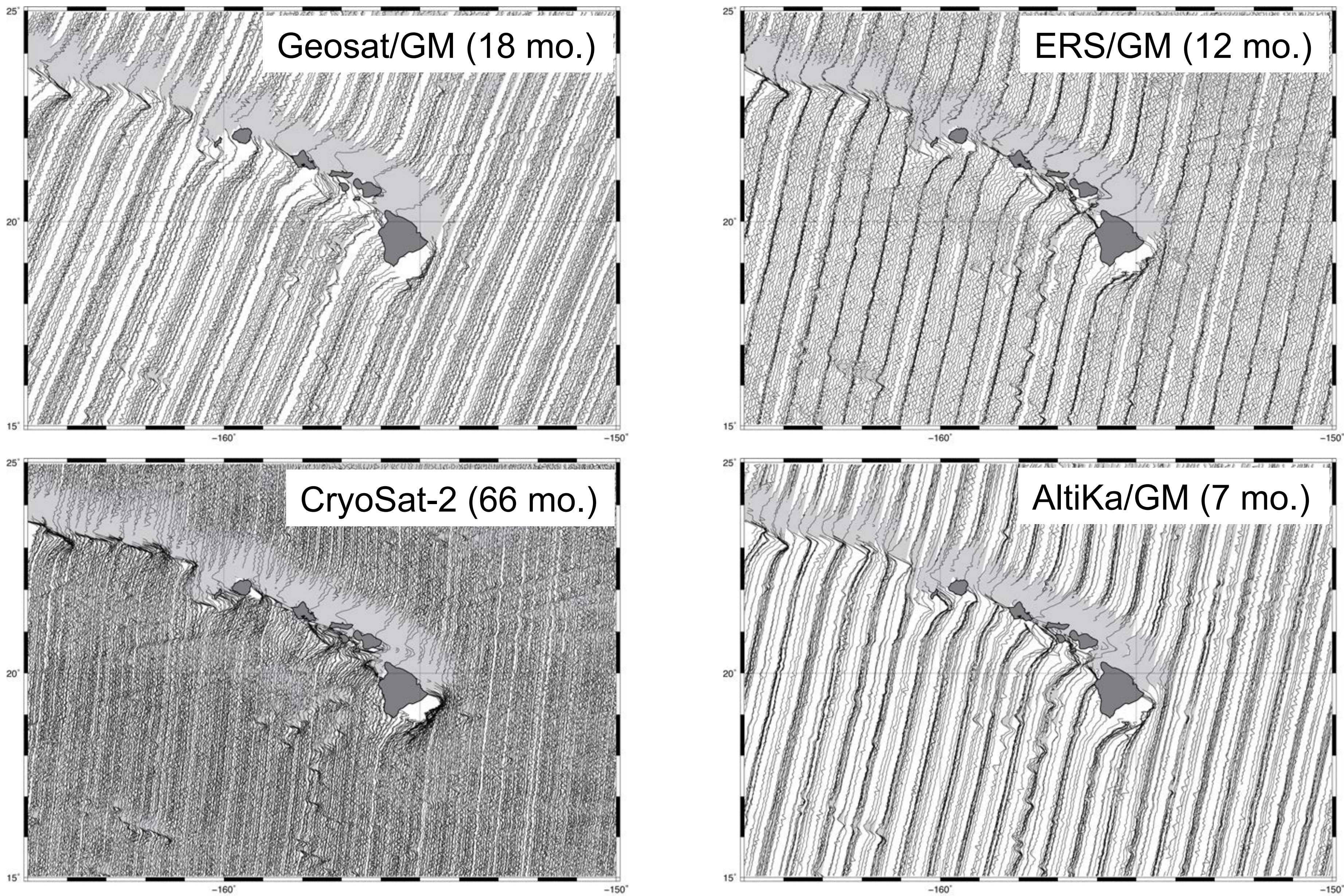

SRTM30_PLUS V11

20 Hz range precision

Altimeter	3-PAR @ 2 m	2-PAR @ 2 m	3-PAR/2-PAR
Geosat	88.0	57.0	1.54
ERS-1	93.6	61.8	1.51
Envisat	78.9	51.8	1.52
Jason-1	75.9	46.4	1.63
CryoSat-2 LRM	**64.7**	**42.7**	**1.51**
CryoSat-2 SAR	49.5	49.7	.996
CryoSat-2 SARIN	138.5	138.7	.998

[*Garcia et al.*, 2014]

along-track sea surface slope over Hawaii



gravity anomaly

– use Laplace equation to convert slopes to gravity anomaly.
– restore long-λ gravity model.