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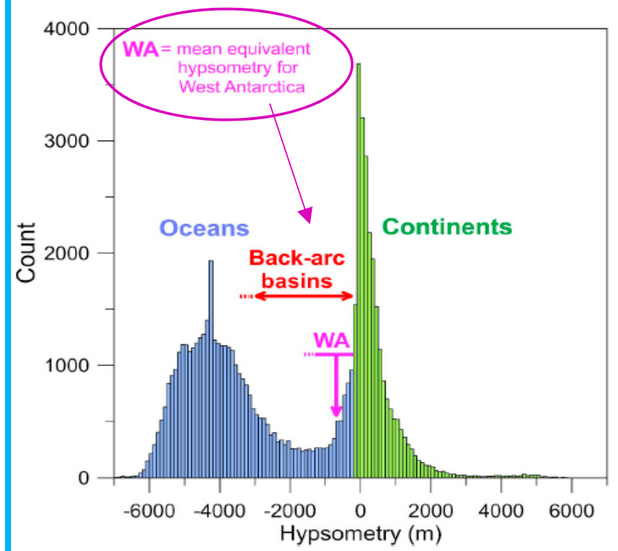
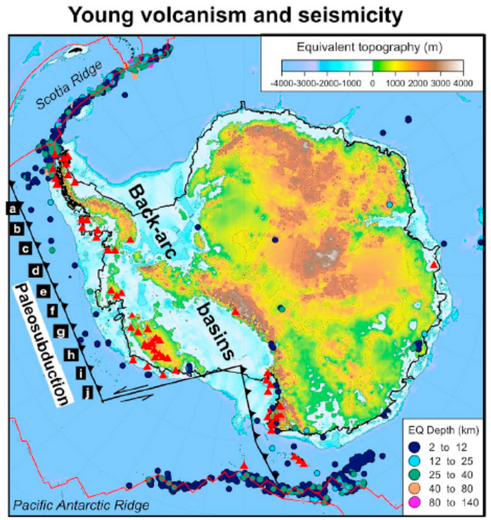
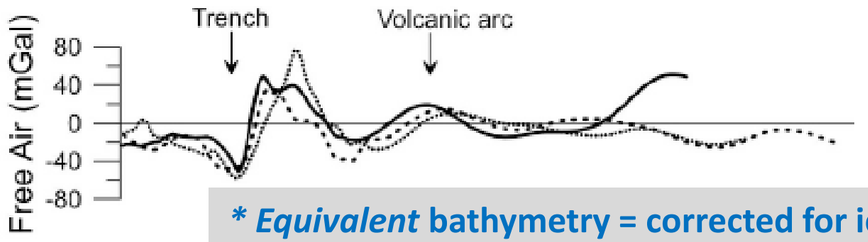
1/3 of Antarctica is not continental: Geophysical evidence for West Antarctica as a backarc system

Geophysical observations that support our interpretation:

- **extremely deep *equivalent** bathymetry not observed in continental regions** (it is 400 m deeper than on the shelves!)
- **the volcanic arc** along the Pacific margin of WA;
- **a linear belt of seismicity** sub-parallel to the arc;
- **gravity anomalies** typical of subduction systems;
- extremely thin crystalline **crust typical of back-arcs**.





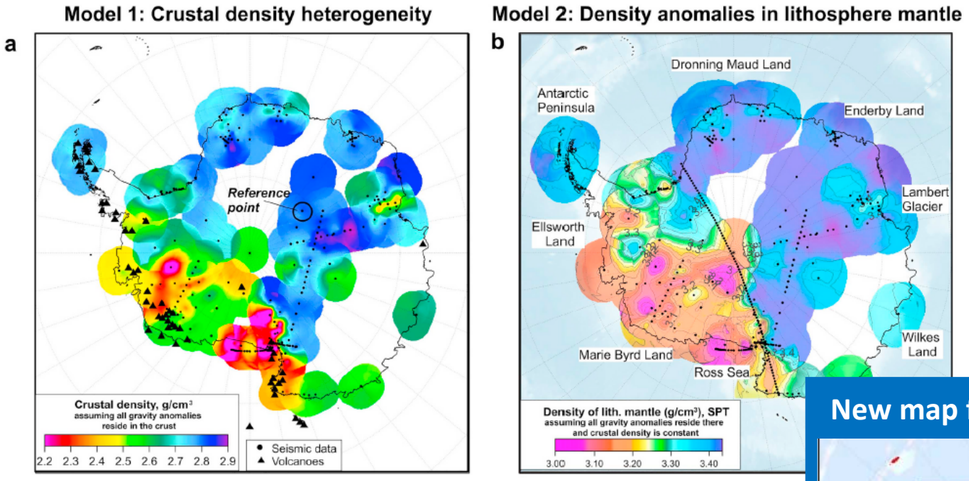


** Equivalent* bathymetry = corrected for ice and water**

We calculate lithosphere density for two end-member scenarios:

✓ Model 1 requires that the crystalline basement is only 12-15 km thick.
Such thickness is not observed in continental crust.

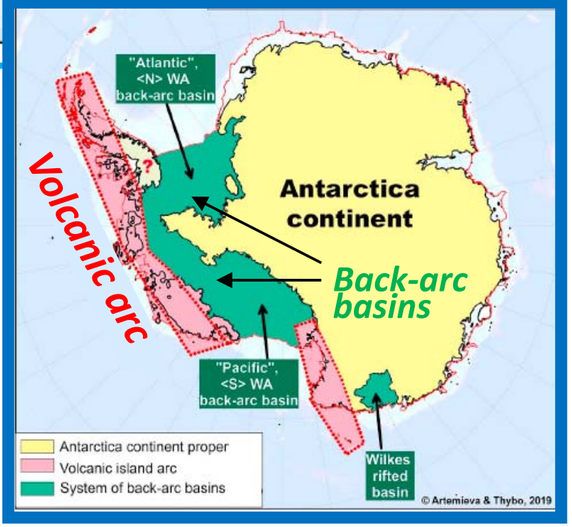
✓ Model 2 requires the presence of exceptionally hot mantle below the entire WA.
Such a size is much larger than around continental rifts.



These results favor the presence of oceanic or transitional crust in most of West Antarctica.

We propose, by analogy with back-arc basins in the Western Pacific, the existence of rotated back-arc basins caused by differential slab roll-back during subduction of the Phoenix plate under the West Antarctica margin.

New map for the Antarctica continent



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Continent size revisited: Geophysical evidence for West Antarctica as a back-arc system

Irina M. Artemieva[a,b,c,*], Hans Thybo[a,d,e]

New map for the Antarctica continent

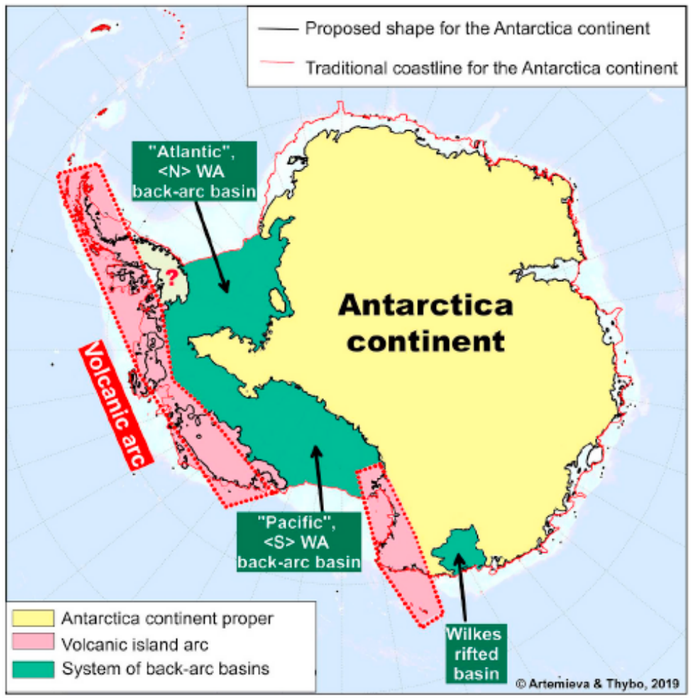


Fig. 16. New model of the Antarctica continent and the West Antarctica back-arc system behind the volcanic arc formed by Mesozoic subduction. The possible < S > volcanic arc is proposed to explain the Wilkes basin within the framework of the "Atlantic" and "Pacific" back-arc basins, although less constrained by our geophysical data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Abstract

Antarctica has traditionally been considered continental inside the coastline of ice and bedrock since Press and Dewart (1959). Sixty years later, we reconsider the conventional extent of this sixth continent (Artemieva and Thybo, Earth-Science Reviews, 2020, https://doi.org/10.1016/j.earscirev.2020.103106).

We present geophysical observation in support of our geodynamic interpretation that the entire West Antarctica formed as a back-arc basin system, similar to the Japan Sea. This includes:

- the presence of the volcanic arc along the entire Pacific margin of West Antarctica associated with subduction of the Phoenix plate until the mid-Cretaceous;
- a linear belt of seismicity sub-parallel to this volcanic arc;
- a very specific pattern of free air gravity anomalies typical of subduction systems;
- extremely thin crystalline crust typical of back-arc basins;
- extremely deep equivalent bathymetry, which is not observed anywhere on continents, including even the shelves. However, such deep bathymetry is typical of back-arc basins and oceans proper. This first order observation questions the conventional interpretation of West Antarctica as continental.

We use seismic data on crustal thickness and calculate lithosphere density for two end-member models. We demonstrate that mantle residual gravity anomalies may be fit only in 2 cases.

- Case 1 requires that sediments make up to 1/2 of the total crustal thickness, so that the crystalline basement is <15 km thick. Such thickness is not observed anywhere on continents.
- Case 2 requires the presence of anomalously hot low-density mantle below the entire West Antarctica. The amplitude of the anomaly and its size are much larger than around any known continental rifts.

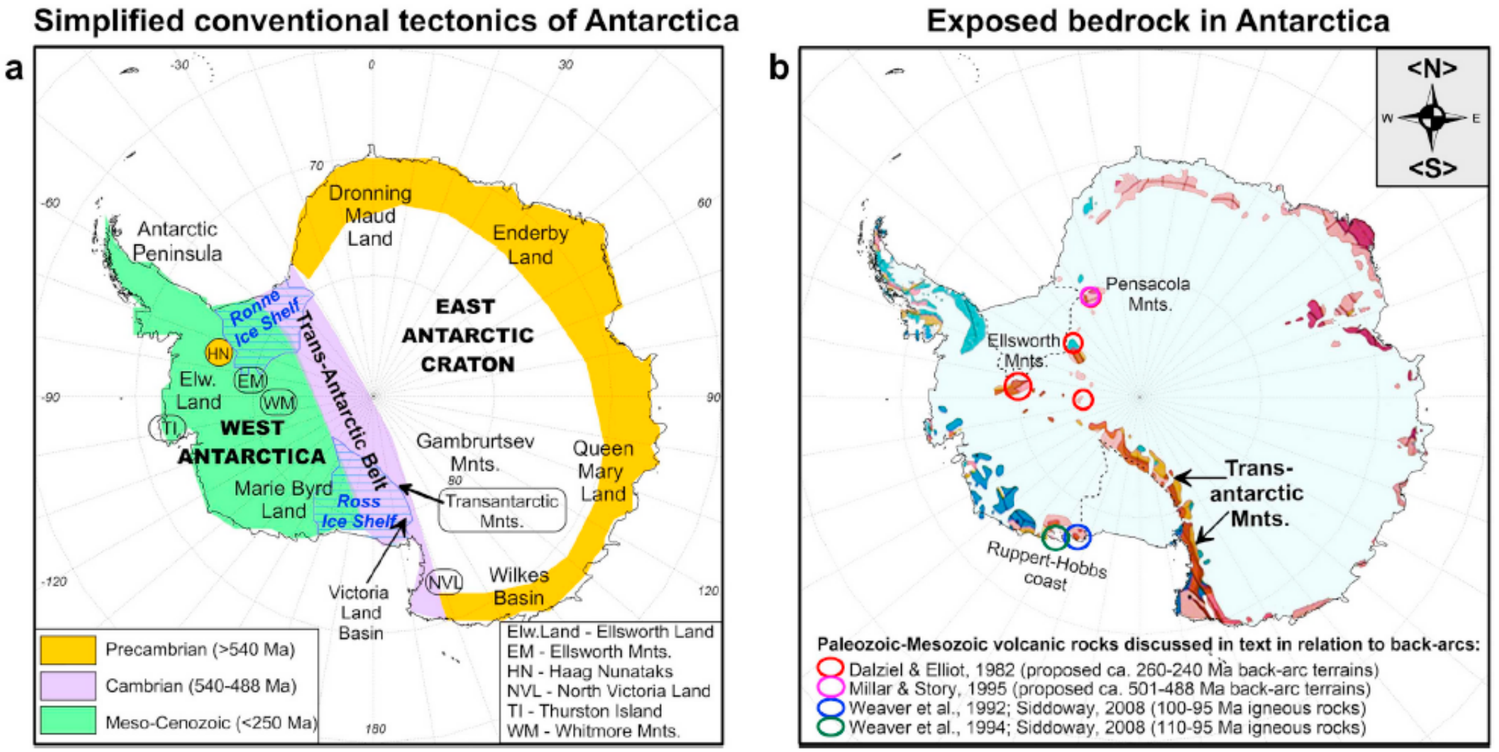
Our results favor the presence of oceanic or transitional crust in most of West Antarctica and possibly beneath the Ronne Ice Shelf.

Our finding reduces the continental lithosphere in Antarctica to 2/3 of its traditional area.

Our model predicts that a granitic crustal layer with a high radiogenic heat production is almost absent in most of West Antarctica, which may affect heat flux at the base of the ice with potential important implications for models of ice melting.

GEOLOGICAL DATA:
Classic concept of Antarctica and exposed bedrock

Nunataks (exposed rocks)



(a) Classic concept of Antarctica consisting of three domains: West Antarctica made of several amalgamated continental terranes, East Antarctica craton, and the Trans-Antarctic belt (Harley, 2003).

(b) Exposed bedrock in Antarctica (based on CGMW Geological Map of the World, 2002). Colors show rock ages based on conventional colors of geological timescale.

This map is quite important – it clearly illustrates how little is available for geological studies.

Artemieva and Thybo: West Antarctica as a backarc system. *Earth-Science Reviews, 2020; https://doi.org/10.1016/j.earscirev.2020.103106*

GEOLOGICAL DATA:
Gondwana breakup and Panthalassic subduction

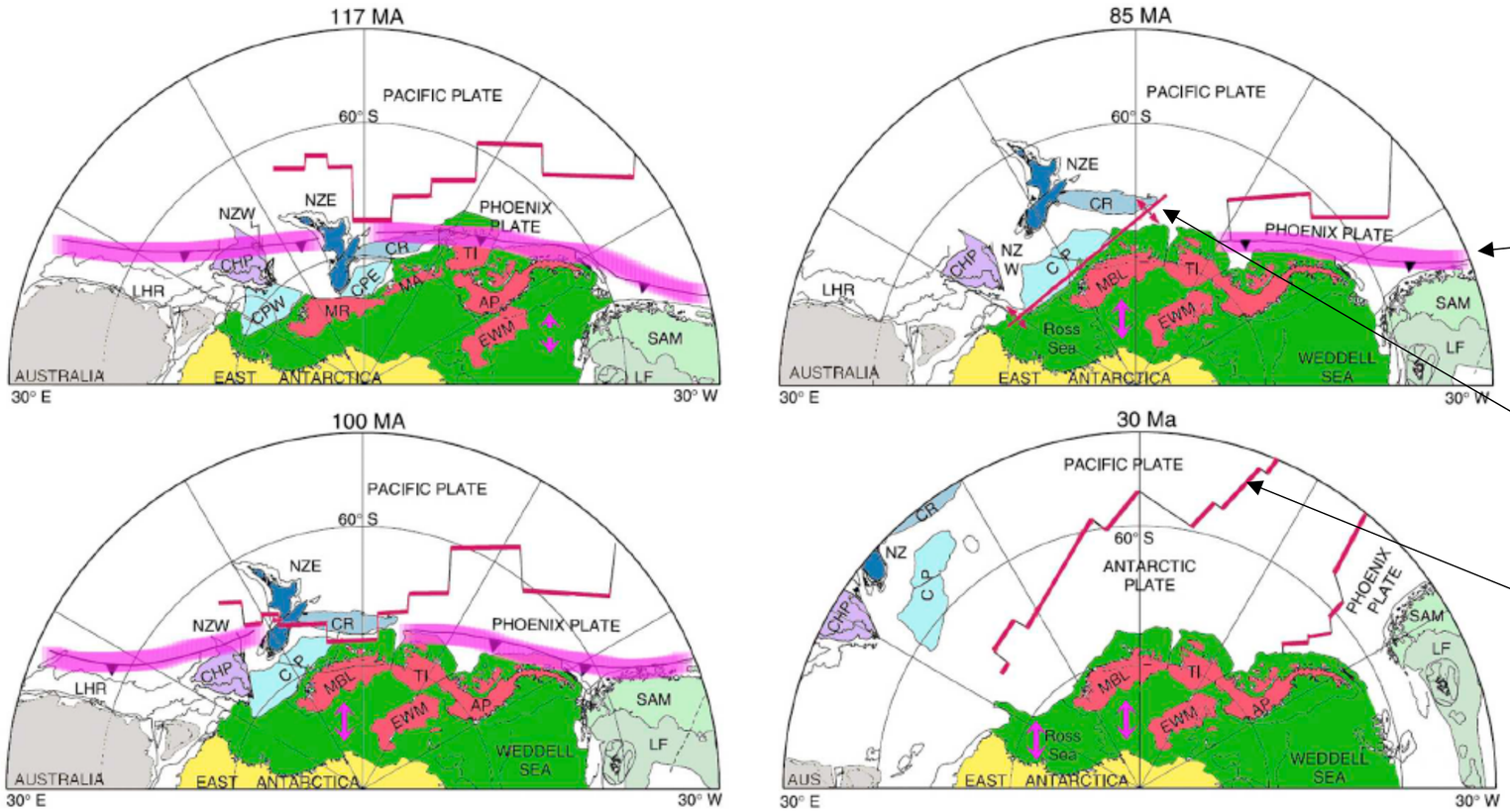


Plate reconstructions of the region around West Antarctica illustrating the Mesozoic subduction of the Phoenix Plate in paleo-reconstructions between 117 and 30 Ma.

Location of the subduction trench is emphasized by a purple line and purple arrows illustrate locations of back-arc spreading and extension.

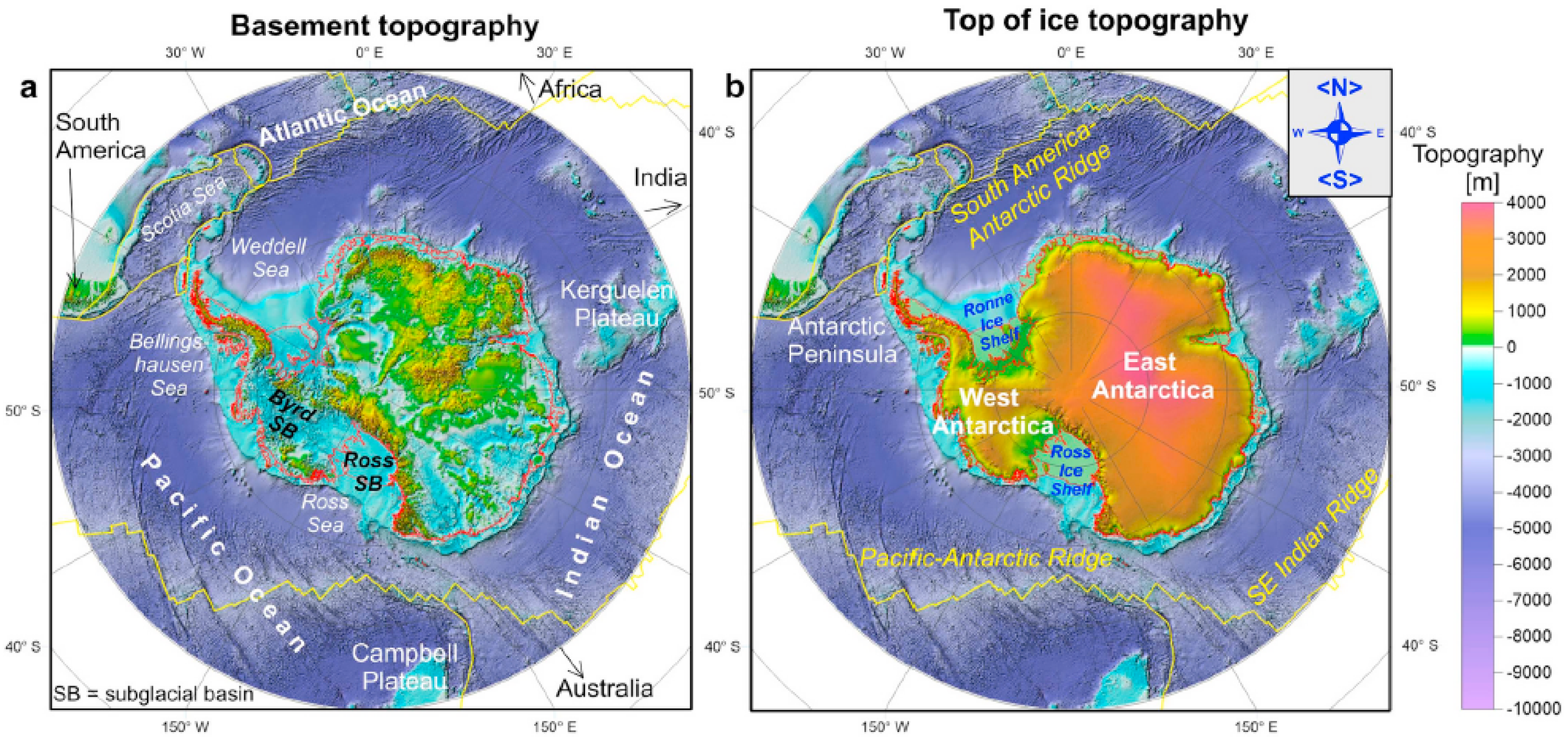
Red-arrowed line in 85 Ma reconstruction is incipient Pacific-Antarctic spreading center between the Marie Byrd Land crustal block and the New Zealand microcontinent;
Dark red lines - spreading ridges.

Abbreviations:
West Antarctica crustal blocks (red): *AP - Antarctic Peninsula; EWM - Ellsworth-Whitmore Mountains; MBL - Marie Byrd Land; TI - Thurston Island;*
Other blocks*: AUS - Australia; CHP - Challenger Plateau; CP - Campbell Plateau (east and west); CR—Chatham Rise; LF—Lafonian microplate; LHR—Lord Howe Rise; NZ - New Zealand (east and west); SAM - South America.*

After Musaka and Dalziel, 2000

Artemieva and Thybo: West Antarctica as a backarc system. *Earth-Science Reviews, 2020; https://doi.org/10.1016/j.earscirev.2020.103106*

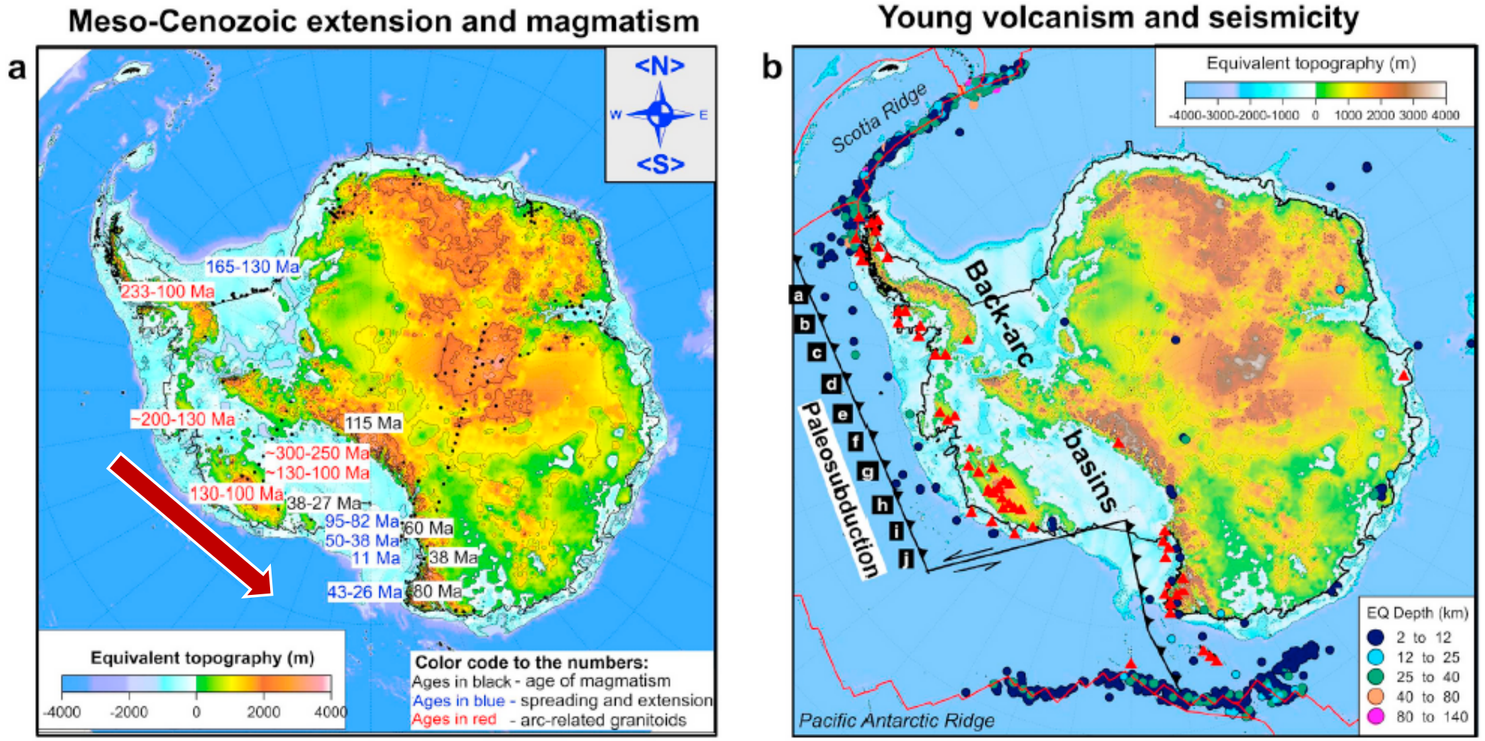
OBSERVATIONS:
TOPOGRAPHY



Artemieva and Thybo: West Antarctica as a backarc system. *Earth-Science Reviews, 2020; https://doi.org/10.1016/j.earscirev.2020.103106*

OBSERVATIONS:
Equivalent topography

Equivalent topography is calculated by correcting density of ice 0.92 g/cm3 and of water 1.02 g/cm3 to rock density of 2.67 g/cm3.



Color-coded numbers - age of volcanism (*Kyle and Muncy, 1989; Collinson et al., 1994; Mukasa and Dalziel, 2000; Harley, 2003*).

Note age progression of volcanism !

Color dots - seismicity by depth since 1916 from USGS catalogue (*https://earthquake.usgs.gov/earthquakes/search/*).

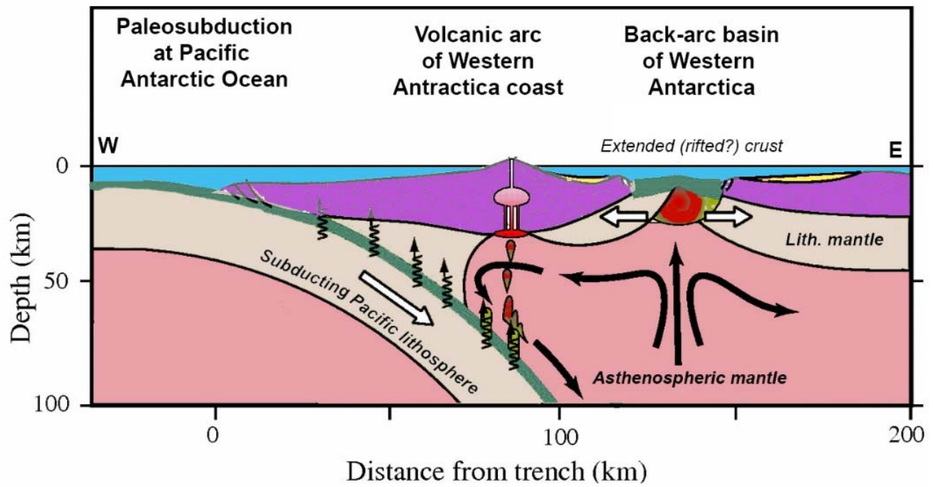
Red triangles - Cenozoic volcanoes.
Black lines – paleosubduction system with proposed subduction jump.
Labels a-j mark the western end of profiles in slide 12.

This map forms basis for our new tectonic model of West Antarctica

- **with subduction-related volcanic arc**
- **and back-arc basins.**

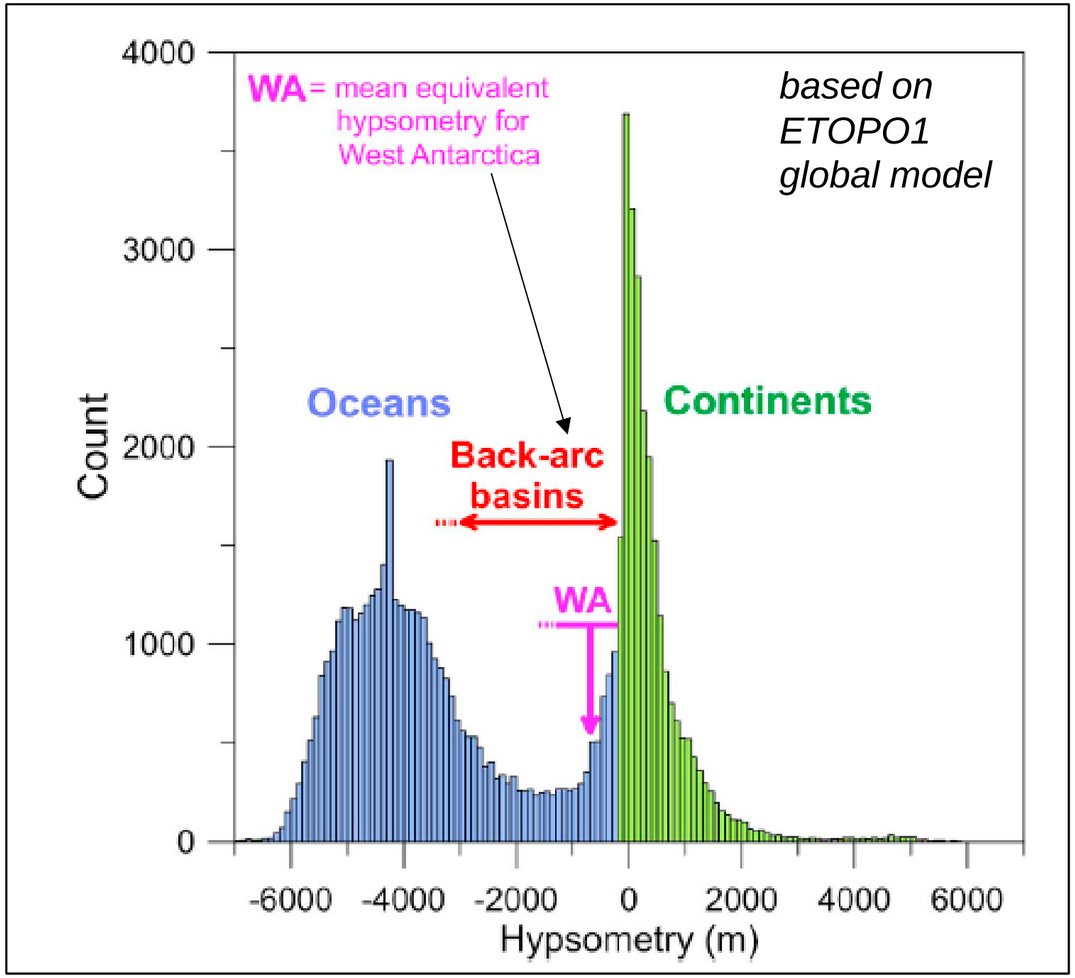
West Antarctica is marked by:

- **the volcanic arc along the Pacific margin;**
- **a linear belt of seismicity sub-parallel to the arc**



Artemieva and Thybo: West Antarctica as a backarc system. *Earth-Science Reviews, 2020; https://doi.org/10.1016/j.earscirev.2020.103106*

OBSERVATIONS:
Bathymetry & topography globally



Globally, the fundamental difference between oceanic and continental lithosphere is reflected in hypsometry (= topography & bathymetry), largely controlled by lithosphere buoyancy.

The equivalent (corrected for ice and water) hypsometry in West Antarctica is −580 ± 335 m on average, extending down to −1580 m.

It is much deeper than in any continent, since even continental shelves do not extend deeper than −200 m in equivalent hypsometry.

An unusually deep equivalent hypsometry in West Antarctica corresponds to back-arc basins (with average values of equivalent hypsometry between ca −3000 m and −300 m) and oceans proper.

This first order observation questions the conventional interpretation of West Antarctica as continental.

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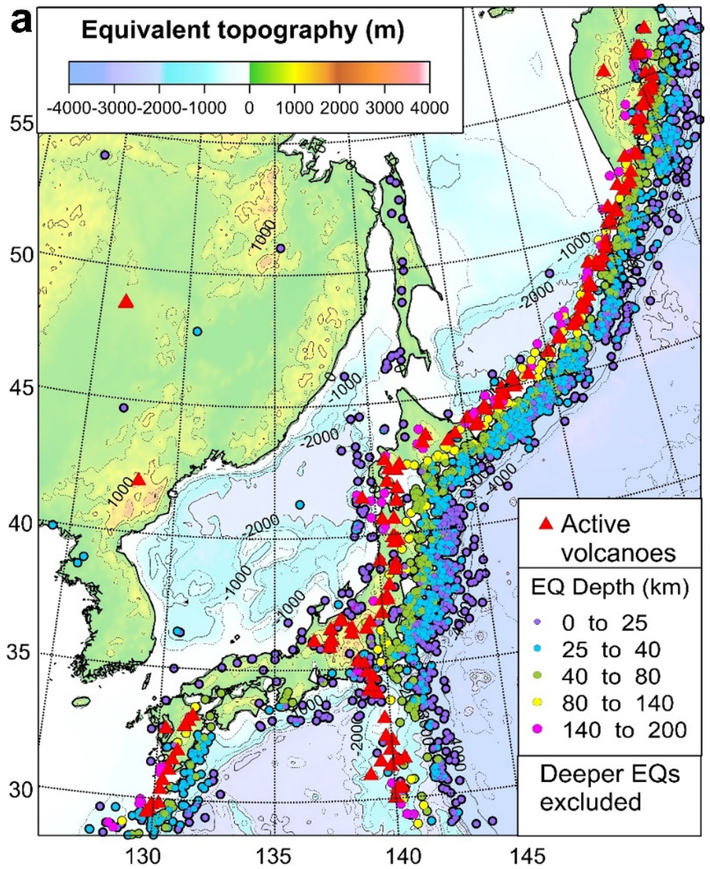
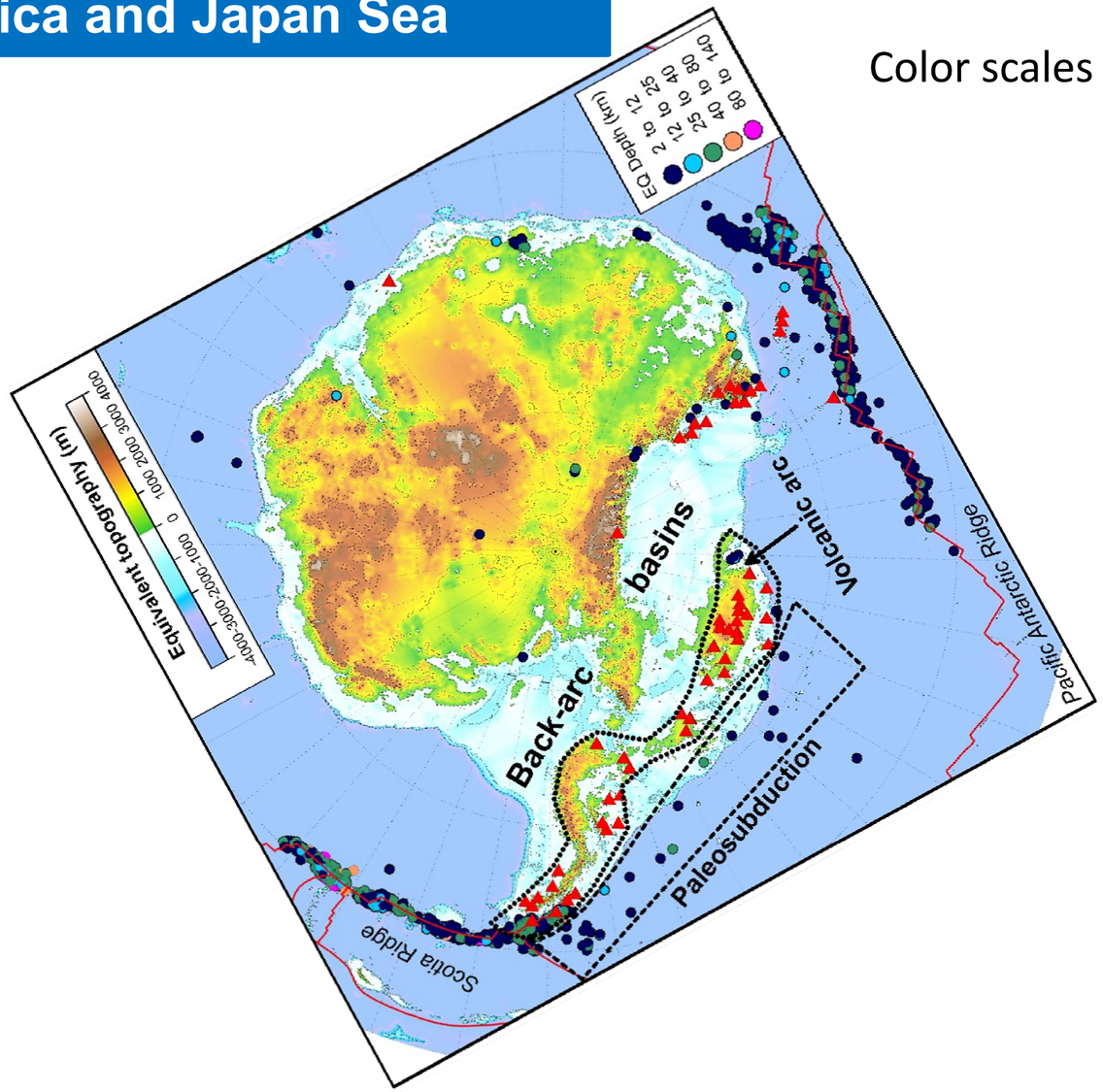
GEOPHYSICAL DATA:
Comparing West Antarctica and Japan Sea





Color scales for eq. topo are the same

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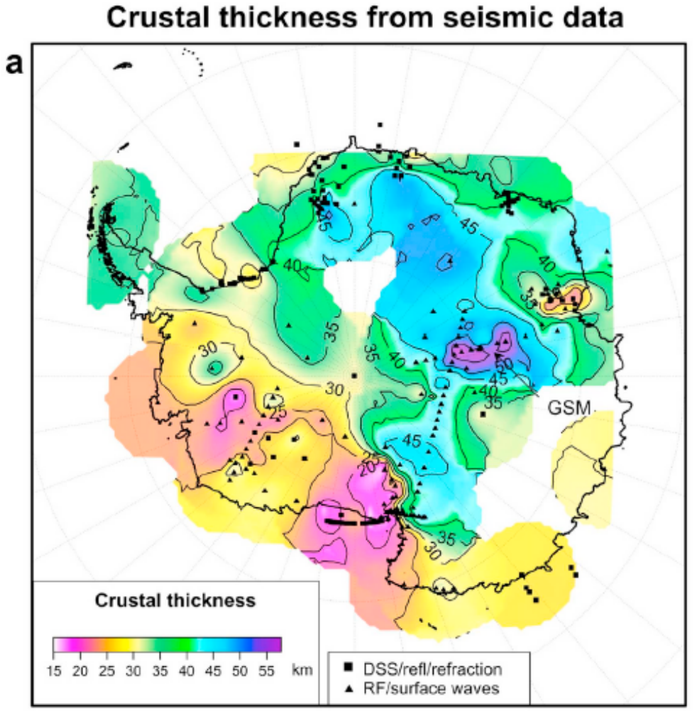
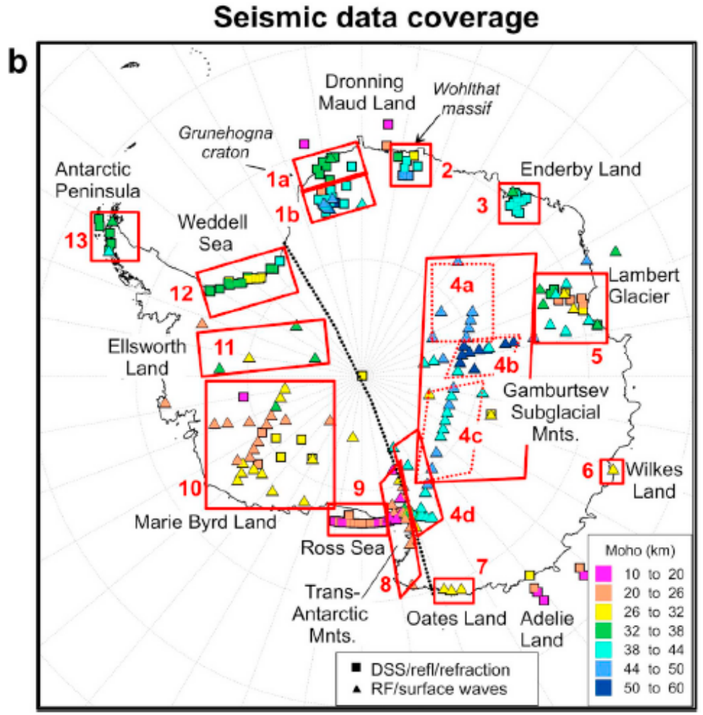
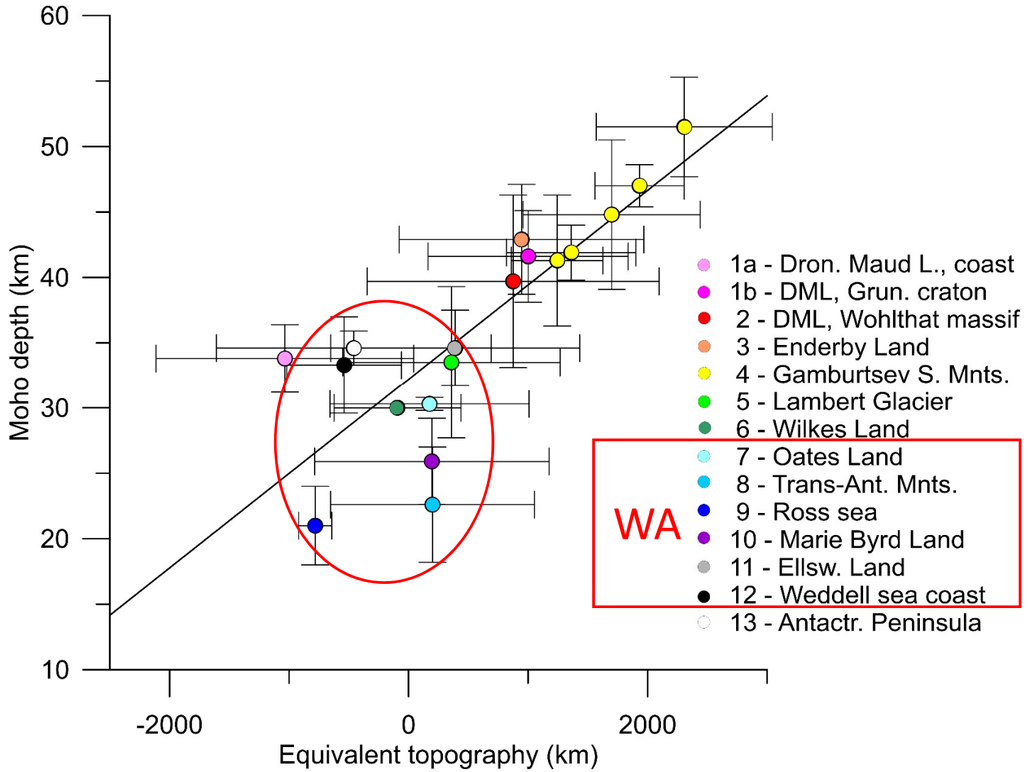
GEOPHYSICAL DATA:
Crustal thickness from seismic data

We do not use gravity constraints on crustal thickness, because we use the Moho depth data in gravity modeling







Compiled from *Baranov and Morelli, 2013; updated by results from Chaput et al., 2014; Feng et al., 2014; An et al., 2015b; Hansen et al., 2016; Ramirez et al., 2016*.

Seismic Moho depths (from sea level) grouped into classes by tectonic setting. Average values for each tectonic group are used in correlation analysis (right plot).

Crustal thickness in West Antarctica ~20-30 km

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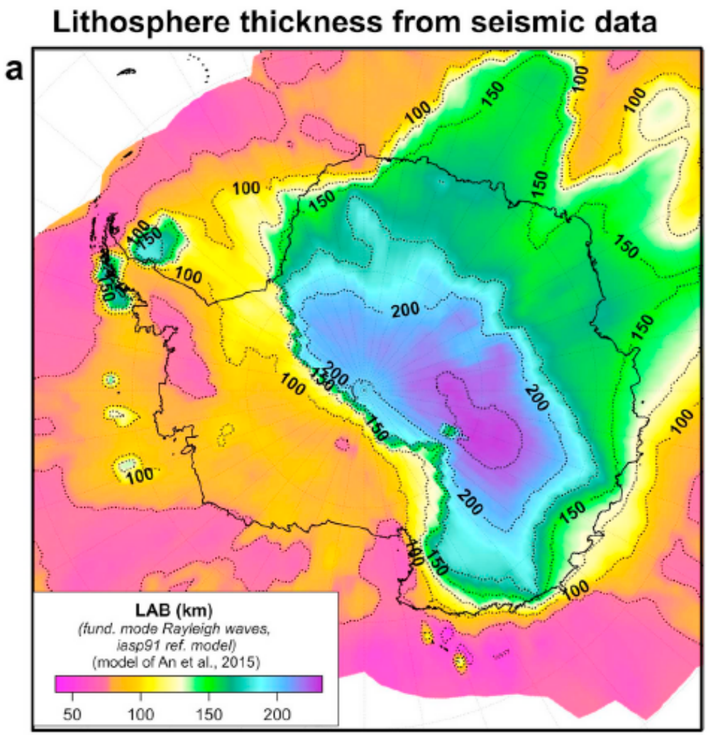
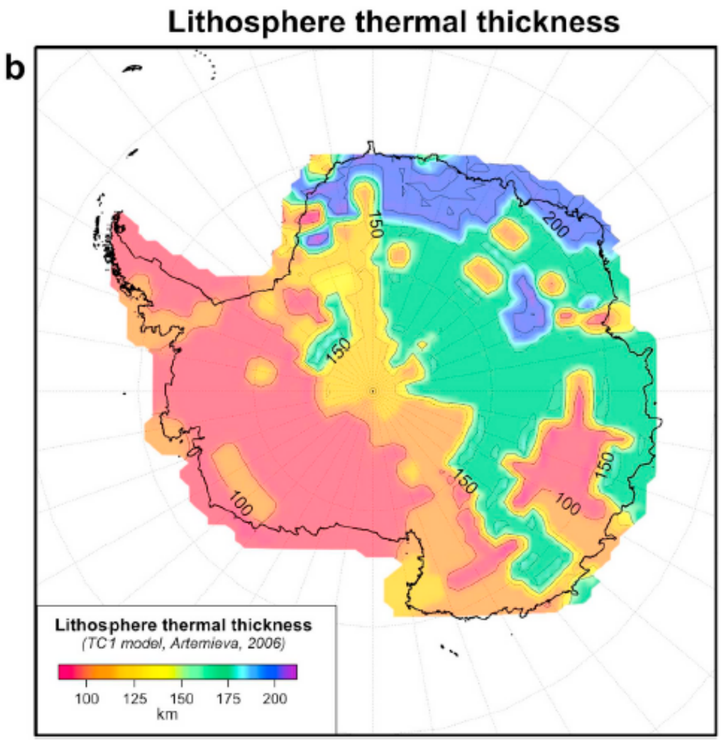
GEOPHYSICAL DATA:
Lithosphere thickness and thermal state





Lithosphere thickness in West Antarctica <100 km

Based on a seismic tomography model (An et al., 2015b), with the LAB defined by a 1% velocity perturbation

Based on thermal TC1 model (Artemieva, 2006).

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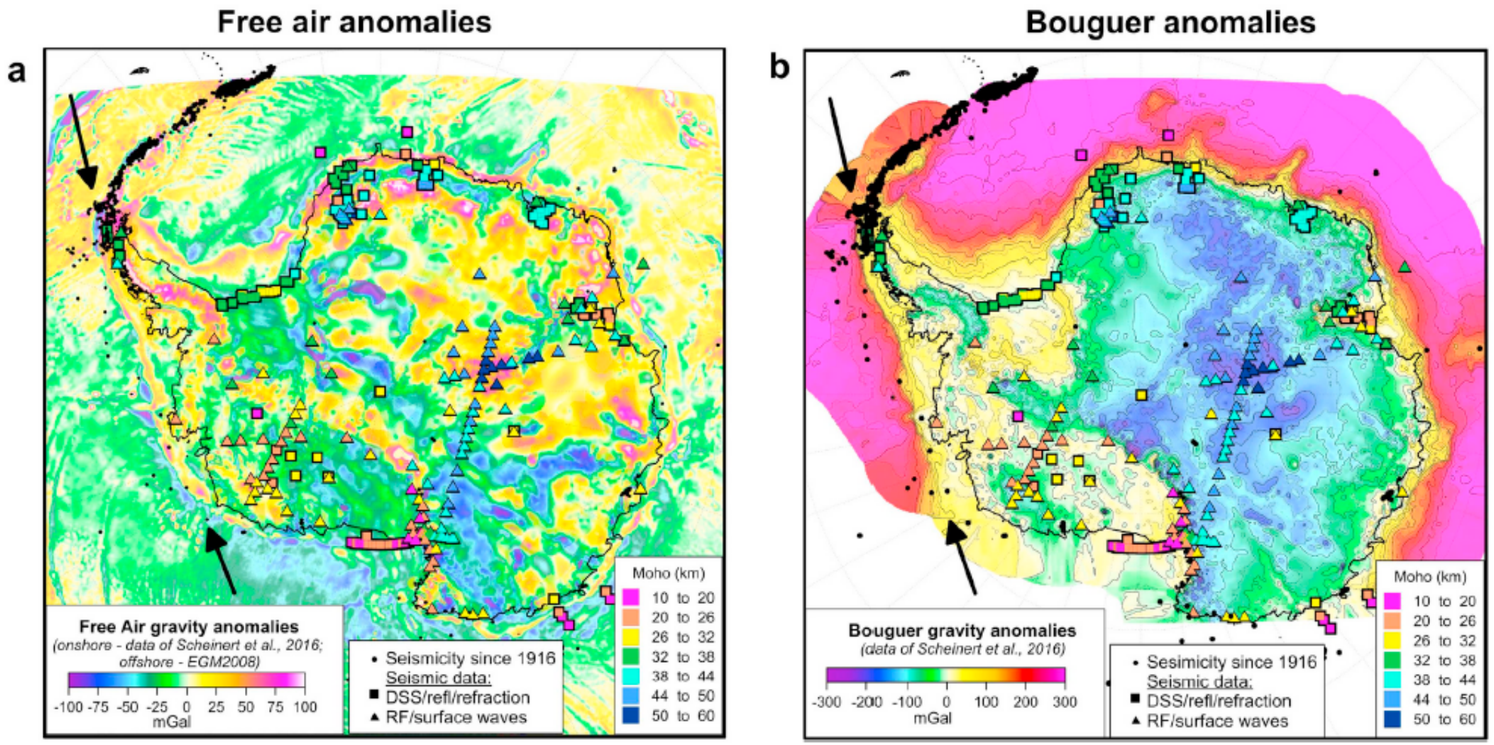
GEOPHYSICAL DATA:
Gravity anomalies



Gravity anomalies across the Pacific margin of West Antarctica are **similar to active subduction systems with the trench** (located between the two black arrows).

Sources: onshore (Scheinert et al., 2016); offshore (Pavlis et al., 2012).

Colored symbols - depth to Moho from sea level based on reflection/refraction (boxes) and seismic RF (triangles).

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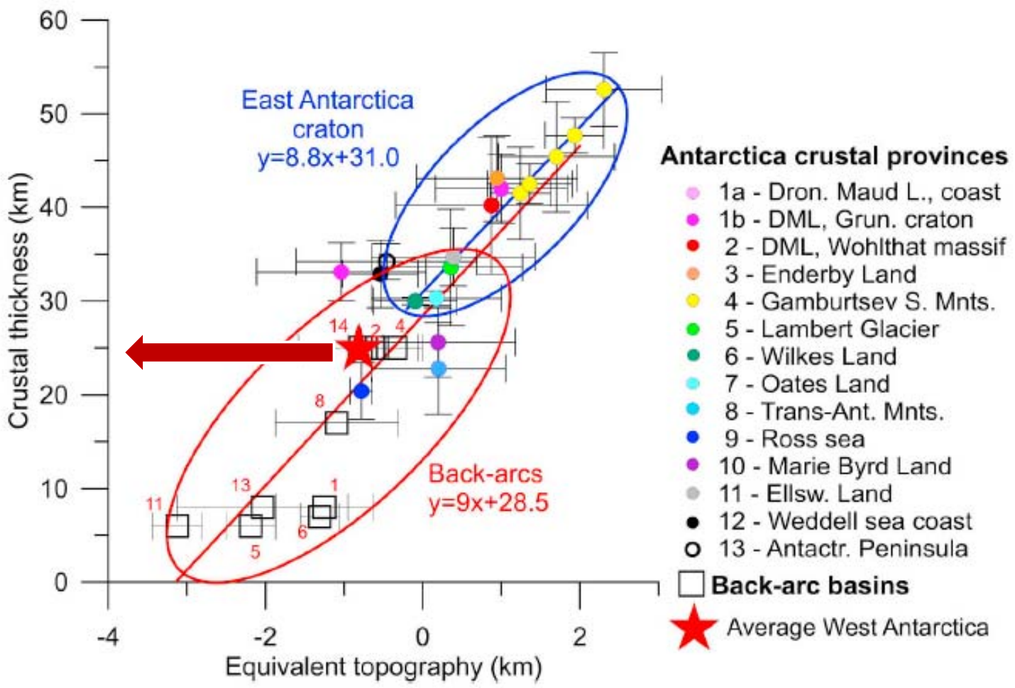
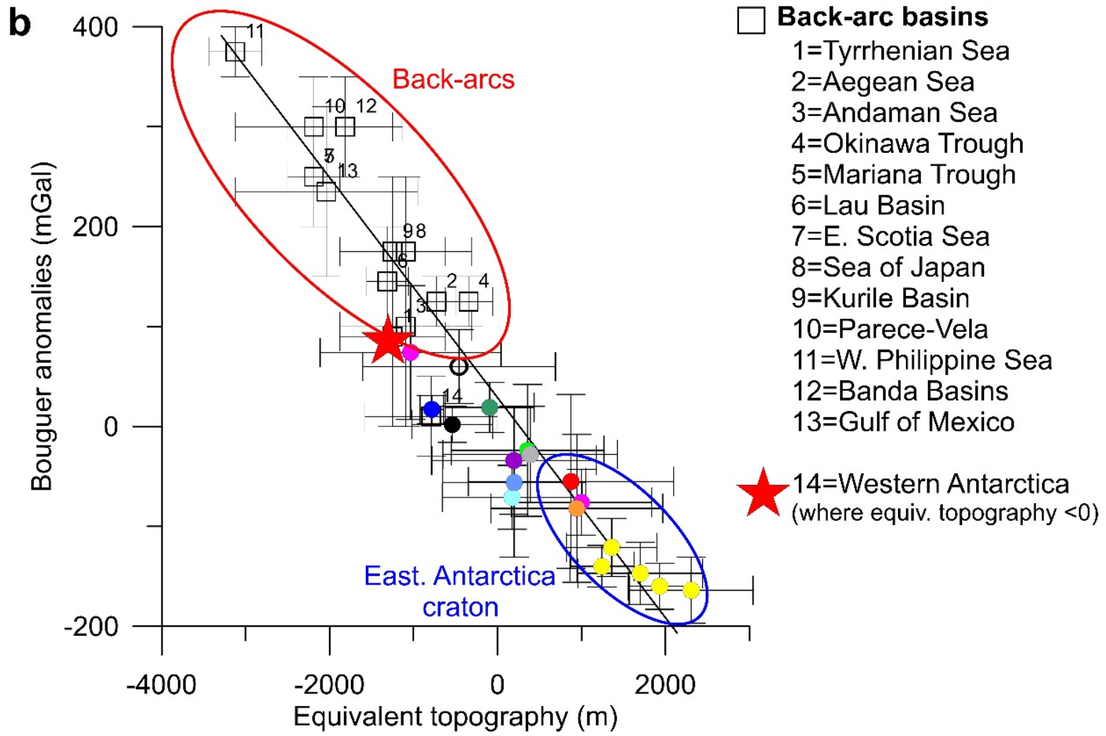
GEOPHYSICAL DATA:
Crustal thickness and gravity anomalies vs equivalent topography

West Antarctica plots with back-arc basins of the world





Crustal thickness in West Antarctica ~20-30 km

For further discussion see slide 15.

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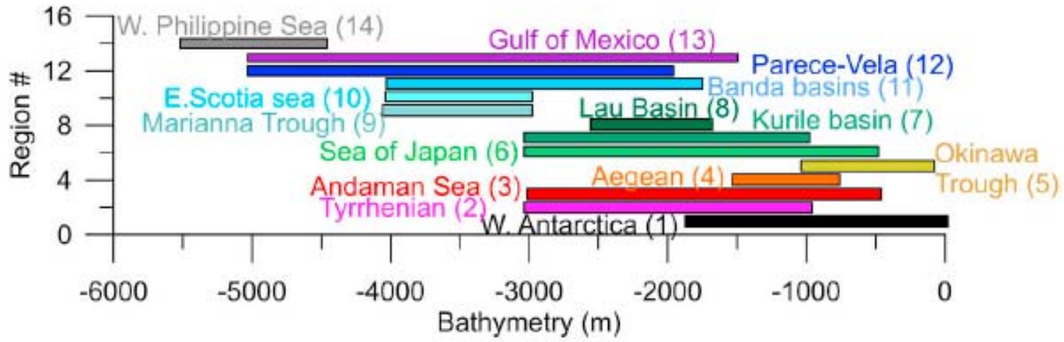
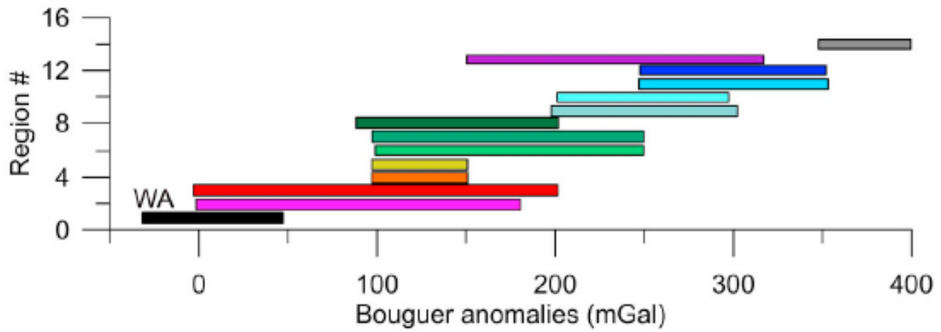
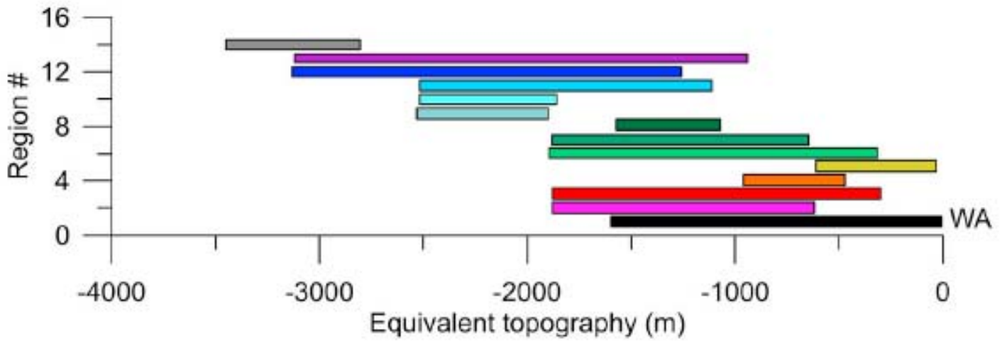
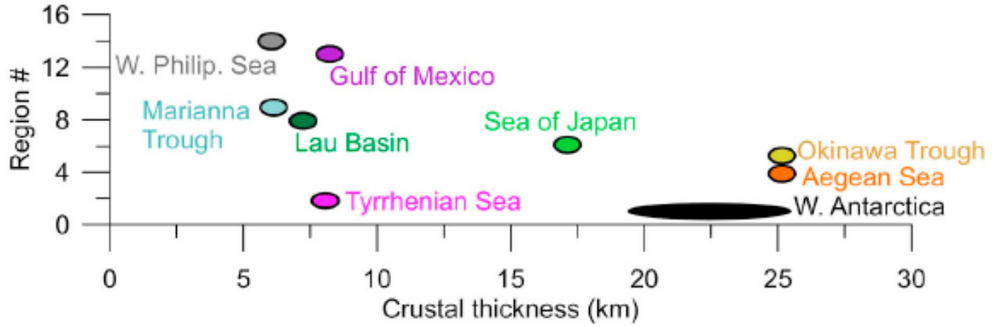
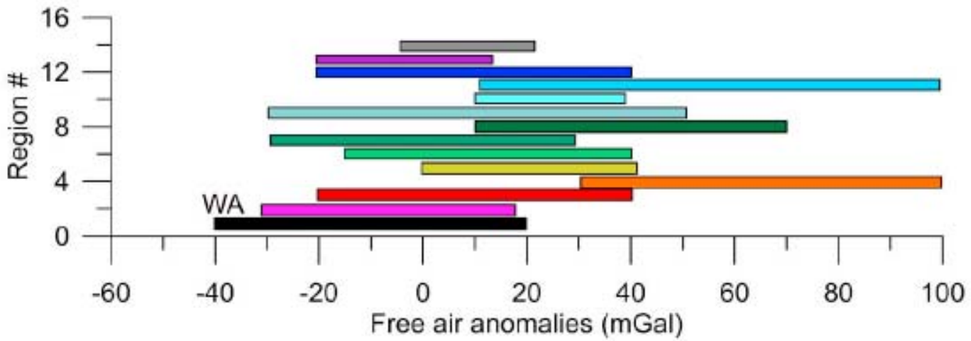
GEOPHYSICAL DATA:
Comparison of West Antarctica with other back-arc basins











Color-coded boxes show typical range of values.
Black boxes – typical values for regions of West Antarctica with negative equivalent topography.

West Antarctica is particularly similar to back-arc basins of the Tyrrhenian, Andaman, Okinawa and Aegean systems.

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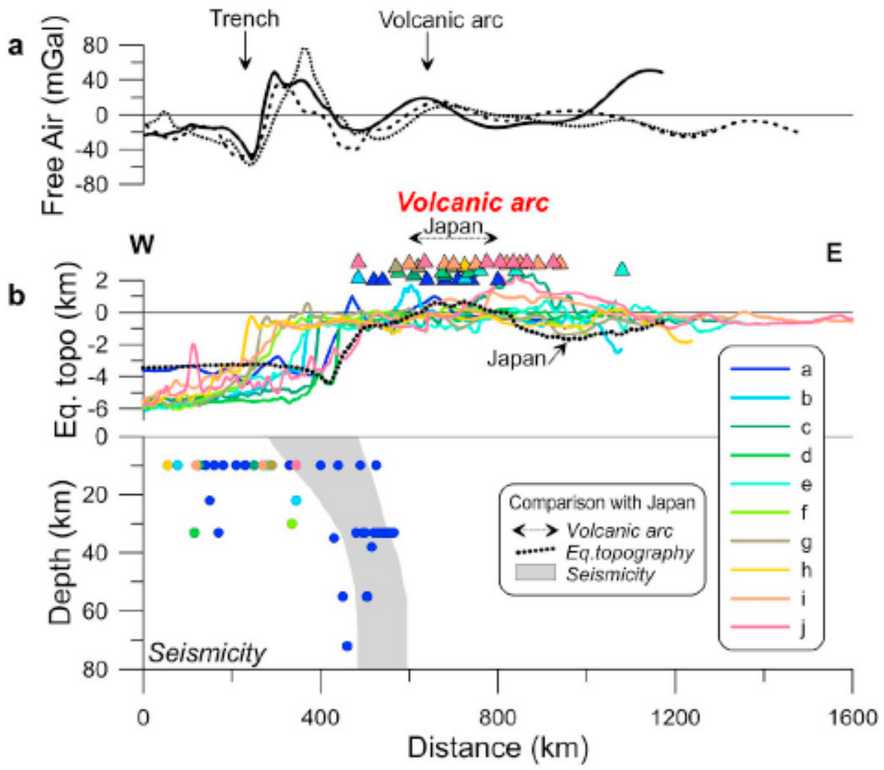
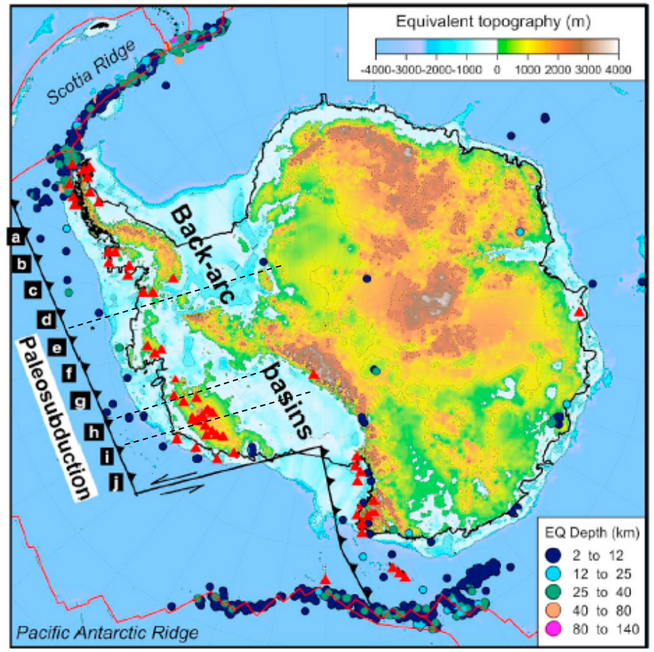
GEOPHYSICAL DATA:
Gravity anomalies, seismicity & equiv. topography

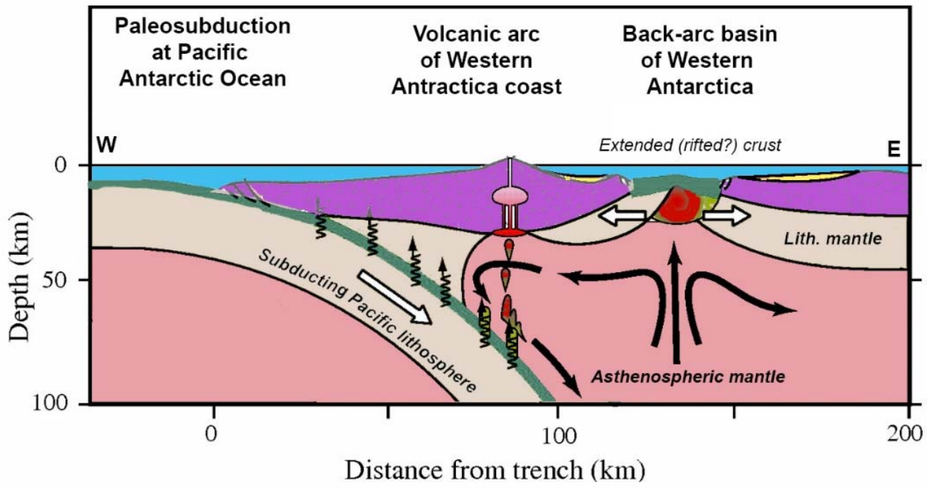
A series of profiles perpendicular to the paleosubduction trench at the Pacific margin of West Antarctica (see insert map for locations).





Similar to other subduction systems, the trench has negative and the volcanic arc has slightly positive free air anomalies.

The volcanic arc along West Antarctica is similar to Japan volcanic arc.



(a) *Three profiles are aligned to start at the trench (e – solid line; h – dashed line; I – dotted line).*
(b) *Equivalent hypsometry (top, lines), volcanoes (top, triangles) and seismicity (bottom, circles) profiles. Color codes for lines and symbols refer to profiles in the insert map.*
For comparison - data for the Japan subduction and volcanic arc at 40°N

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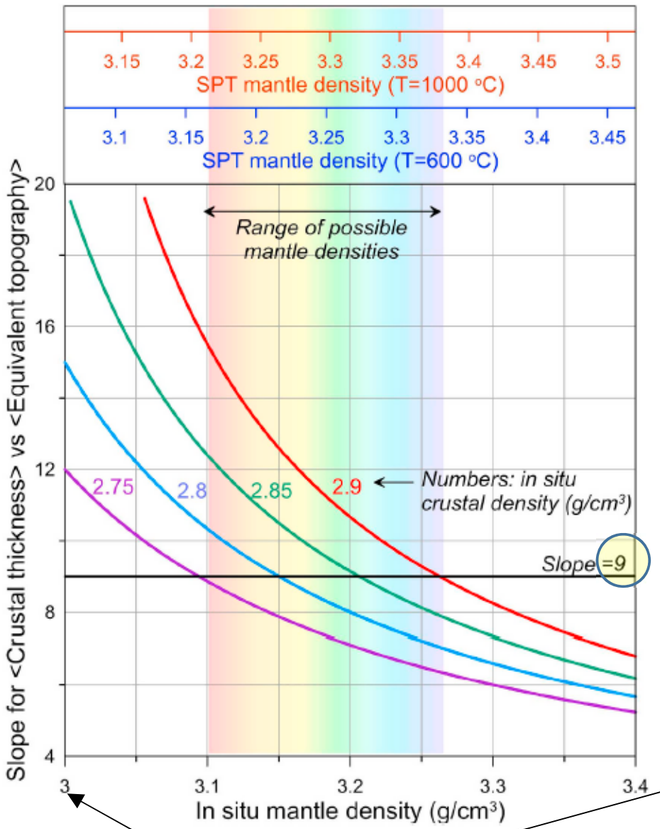
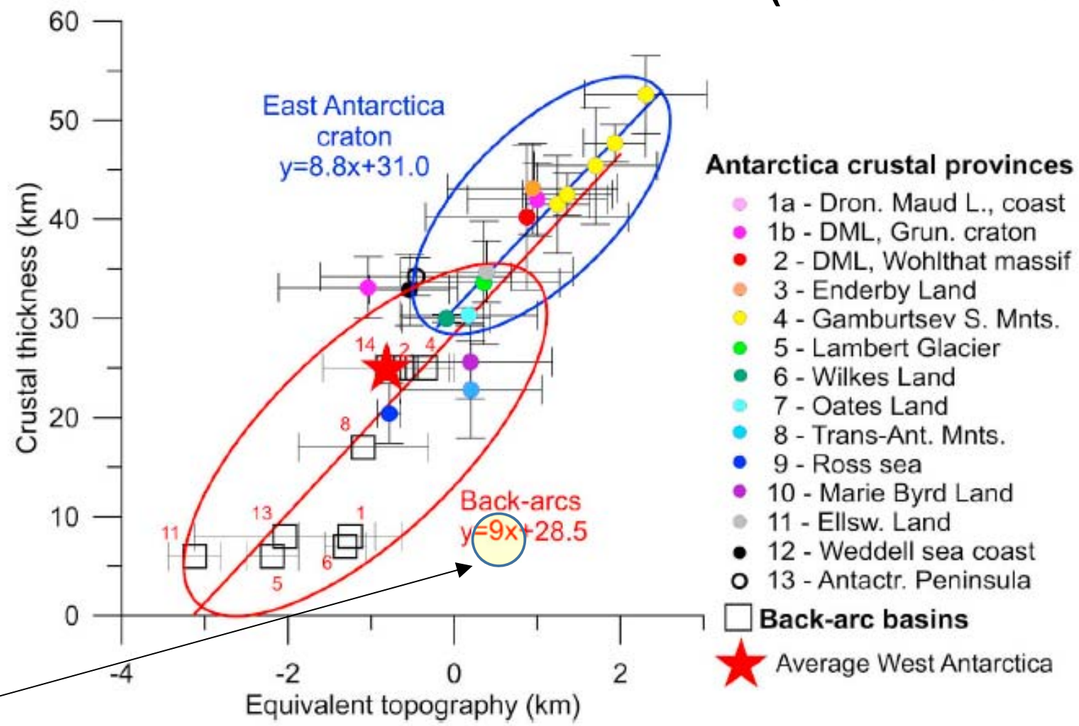
GEOPHYSICAL MODELING:
Permitted mantle density range

Density contrast between the crust and the upper mantle assuming Airy-type isostasy.

The range of permitted mantle densities at in situ P-T is between 3.10-3.26 g/cm3 (rainbow zone in left plot).





Vertical axis – slope of the equivalent topography versus crustal thickness trend.

Horizontal axes – mantle density at in situ conditions (bottom) and recalculated to room (SPT) conditions for two different in situ temperatures (top).

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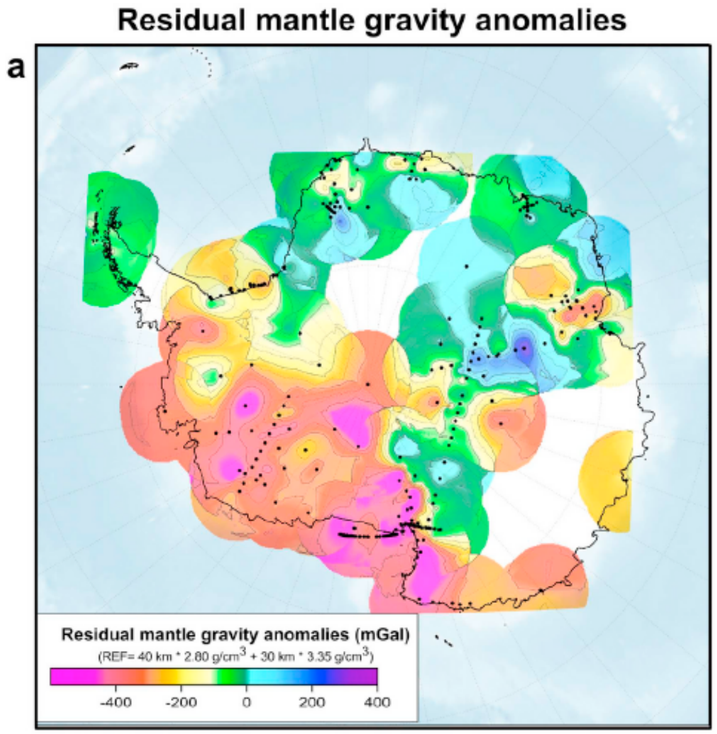
GEOPHYSICAL MODELING:
RMGA, crustal and mantle density



Calculated by subtracting the crustal contribution from free air anomalies based on crustal thickness for density of 2.8 g/cm3. Reference model: 40 km thick crust with density 2.8 g/cm3 above 30 km thick mantle layer with density 3.35 g/cm3.

Residual mantle gravity anomalies (RMGA):

- ❑ are calculated assuming a constant crustal density for all of Antarctica;
- ❑ show a sharp distinction between East and West Antarctica,
  - with extremely low (< −300 mGal) values in West Antarctica
  - and intermediate to high values in the East Antarctic craton.

These anomalies require strong thermo-chemical heterogeneity of the mantle that may be enhanced by crustal density heterogeneity.

We next examine:

- the relative roles of crustal and mantle heterogeneities and
- a possible range of in situ mantle density values for two end-member models.

In the absence of high-resolution models on the internal velocity and density structure of the crust of most of Antarctica other approaches are not justified.

RMGA reflect density anomalies below the Moho

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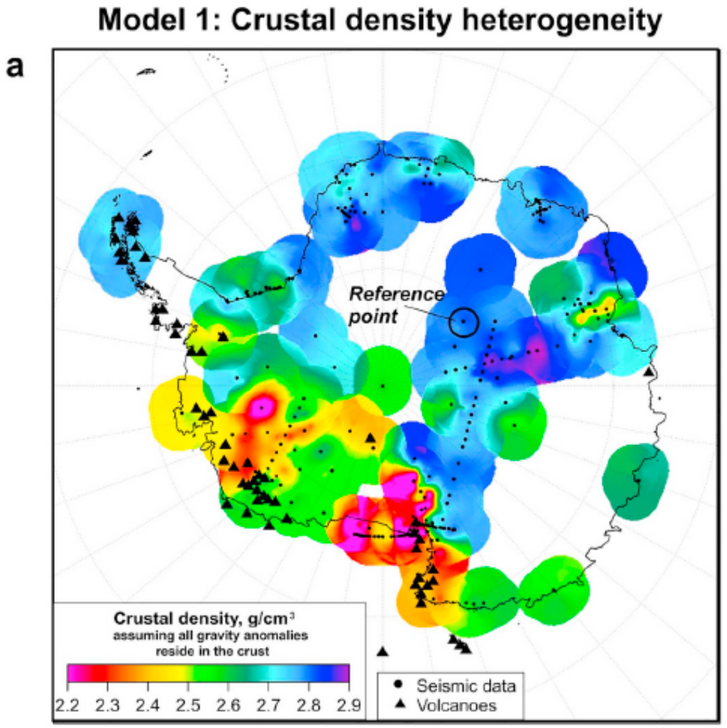
GEOPHYSICAL MODELING:
Crustal and mantle density

Model 1: Variable crustal density



We calculate the average crustal density required to explain the Bouguer anomalies for the known equivalent topography and known seismic crustal thickness.

Results for predicted average crustal density **:**

East Antarctic craton:

- 2.8–2.9 g/cm3 - within the normal range for shield crust;

West Antarctica:

- **extremely low, between 2.1 and 2.6 g/cm3.**

Artemieva and Thybo: West Antarctica as a backarc system. *Earth-Science Reviews, 2020; https://doi.org/10.1016/j.earscirev.2020.103106*

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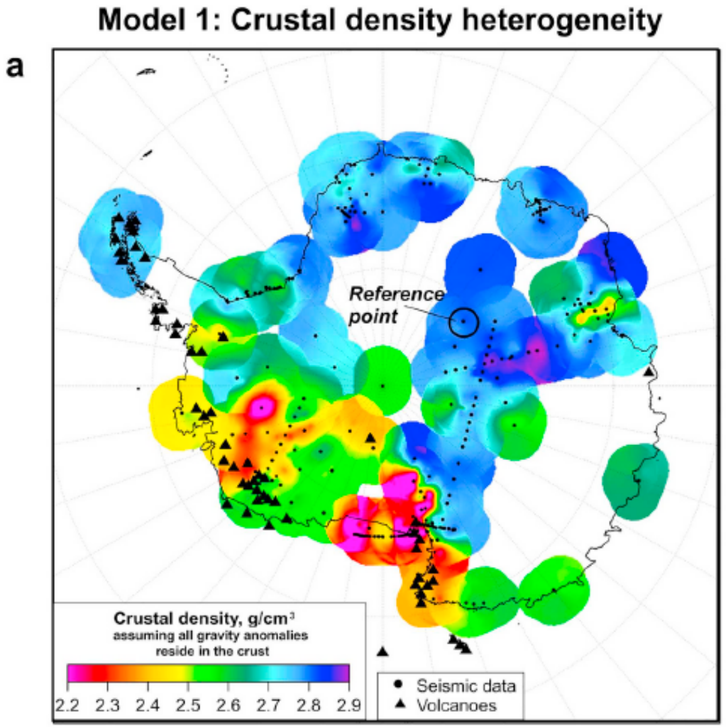

Interpretation:

- Average crustal density values of 2.4–2.6 g/cm3 (crystalline basement plus the sedimentary cover) are only possible if sediments make 40–60% of the total crustal thickness.
- **For the WA basins, it would imply that the crystalline basement is only ca. 10–12 km thick and the sedimentary cover is ca. 12–15 km thick**.
- **Such thin crystalline crust does not exist in continents;**
- Seismic observations of thick sediments in WA:
  - 12+ km in the Victoria Land Basin of the Ross Subglacial Basin,
  - only 8 km in the Ross Sea grabens (Cooper et al., 1991; Harley, 2003)

Alternative interpretation:

The regions with very low average crustal density are all associated with:

- young volcanoes,
- thin lithosphere,
- very small Curie depth.

→ **A significant contribution from the mantle is required to explain the Bouguer anomalies in West Antarctica,**

→ **for example through high mantle temperatures, such as expected in back-arc basins.**

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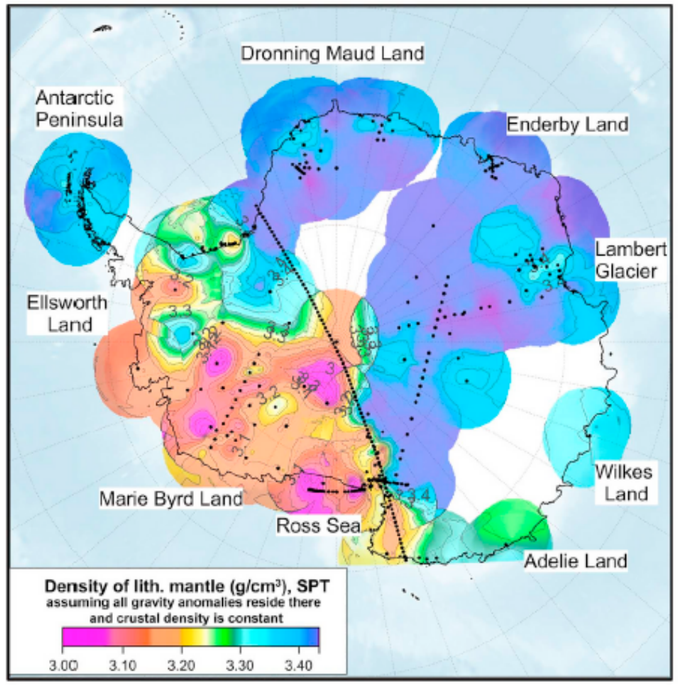
GEOPHYSICAL MODELING:
Crustal and mantle density

Model 2: Variable density of lithosphere mantle (LM)

Model 2: Density anomalies in lithosphere mantle

b



Assumptions:

- no density heterogeneity in the crust;
- all mantle density anomaly resides in the layer between the Moho and the LAB.

Results: LM densities at room (SPT) conditions (recalculated from in situ to room temperatures)

East Antarctic craton:

- 3.3-3.4 g/cm3 - within the range expected for continental LM;

West Antarctica:

- <3.1 g/cm3 - extremely low,

→ LM has very high temperatures with possible presence of fluids and melts.

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Model 2: Variable density of lithosphere mantle (LM)

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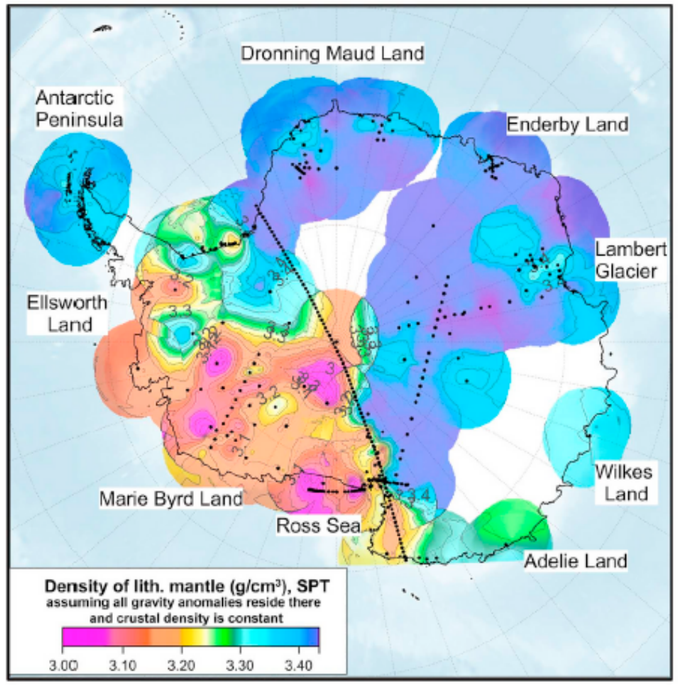

Interpretation:

1) Low-density mantle anomalies are related to the back-arc spreading, including a possible mid-ocean ridge formation (Talwani et al., 1965), which has later ceased as in the Sea of Japan.

2) Our model assumes average crustal density of 2.8 g/cm3 (crystalline basement plus sediments).

- For 8 km of Mesozoic sediments in grabens of the Ross Subglacial Basin, an average density of ca. 12–15 km thick crystalline crust is ~3.0 g/cm3 .
- **Such high density requires the presence of high-density underplated material in the lower crust and the absence of a low-density granitic layer, which is characteristic of the continental crust.**

This conclusion again supports our interpretation that a significant part of West Antarctica may have oceanic or transitional crust.

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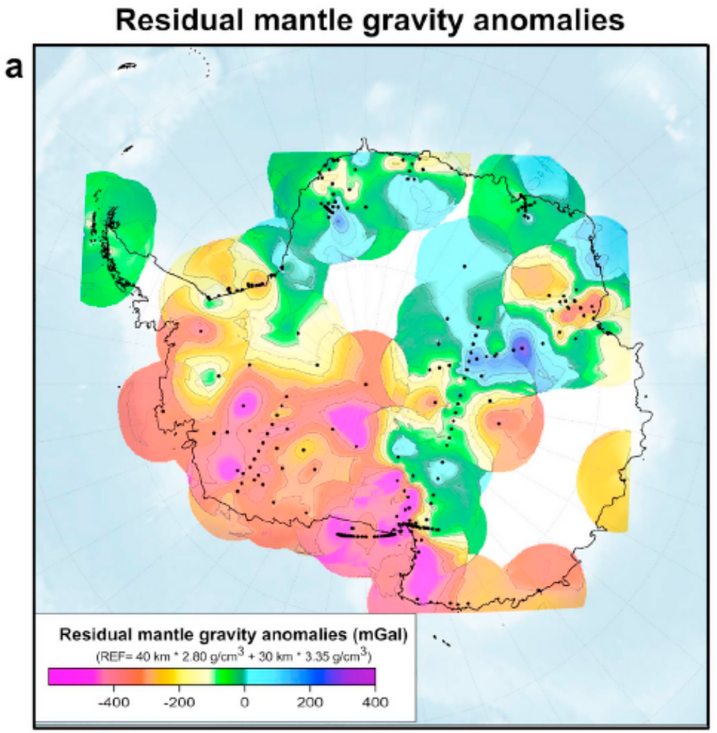
GEOPHYSICAL DATA & MODELING:
Interpretation & Conclusions



Residual mantle gravity anomalies require the combined effect of (1) anomalous crust <u>and</u> (2) anomalous mantle:

(1) the absence of a granitic crustal layer,
- and the presence of high density crustal material
- below a thick sedimentary sequence
- which makes up to ca. 30–50% of the total crustal thickness,

<u>and</u>

(2) the presence of **extremely low-density mantle** below the basins of West Antarctica and, possibly, below the Wilkes Basin in East Antarctica.

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GEOPHYSICAL DATA & MODELING:
Interpretation & Conclusions

We propose that the basins in WA developed in back-arc systems due to subduction roll-back at various stages.

The early formation of the Ronne Ice Shelf basin explains the relatively high lithospheric mantle densities because low temperatures have re-equilibrated after a long cooling history.

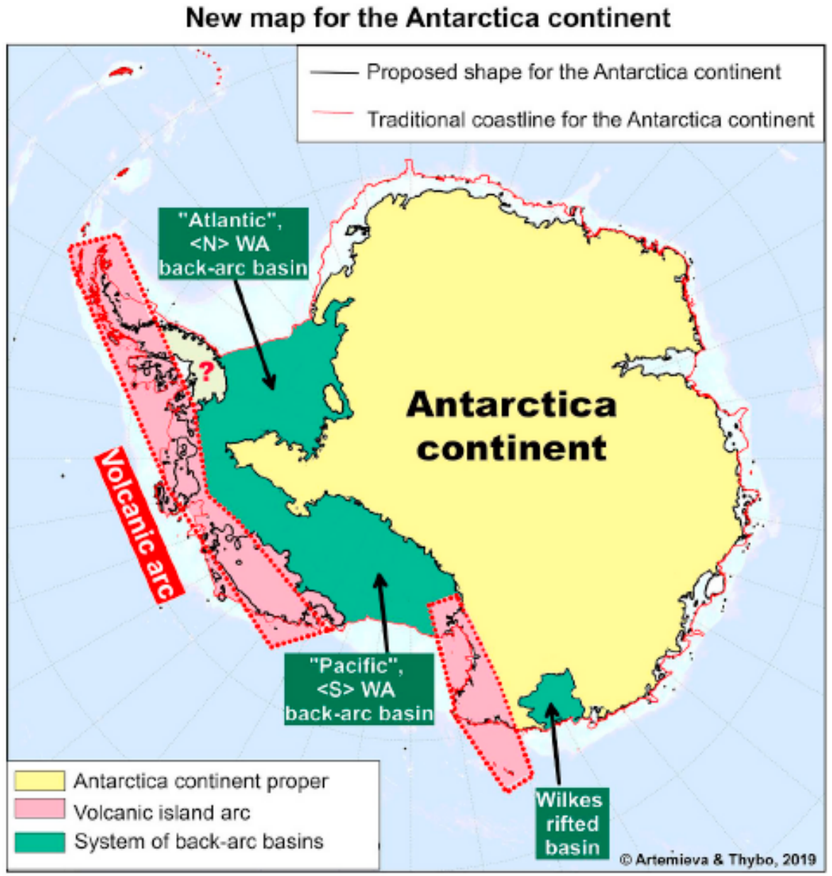

Fig. 16. New model of the Antarctica continent and the West Antarctica back-arc system behind the volcanic arc formed by Mesozoic subduction. The possible < S > volcanic arc is proposed to explain the Wilkes basin within the framework of the "Atlantic" and "Pacific" back-arc basins, although less constrained by our geophysical data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Based on our geophysical observations and interpretations, taking into account

- plate reconstructions
- and the age progression of magmatism
- and extension in West Antarctica

and by analogy with back-arc basins in the Western Pacific (Van Horne et al., 2015),

we propose the existence of three rotated back-arc basins caused by differential slab roll-back in the Mesozoic associated with subduction of the Phoenix plate under the West Antarctica margin.

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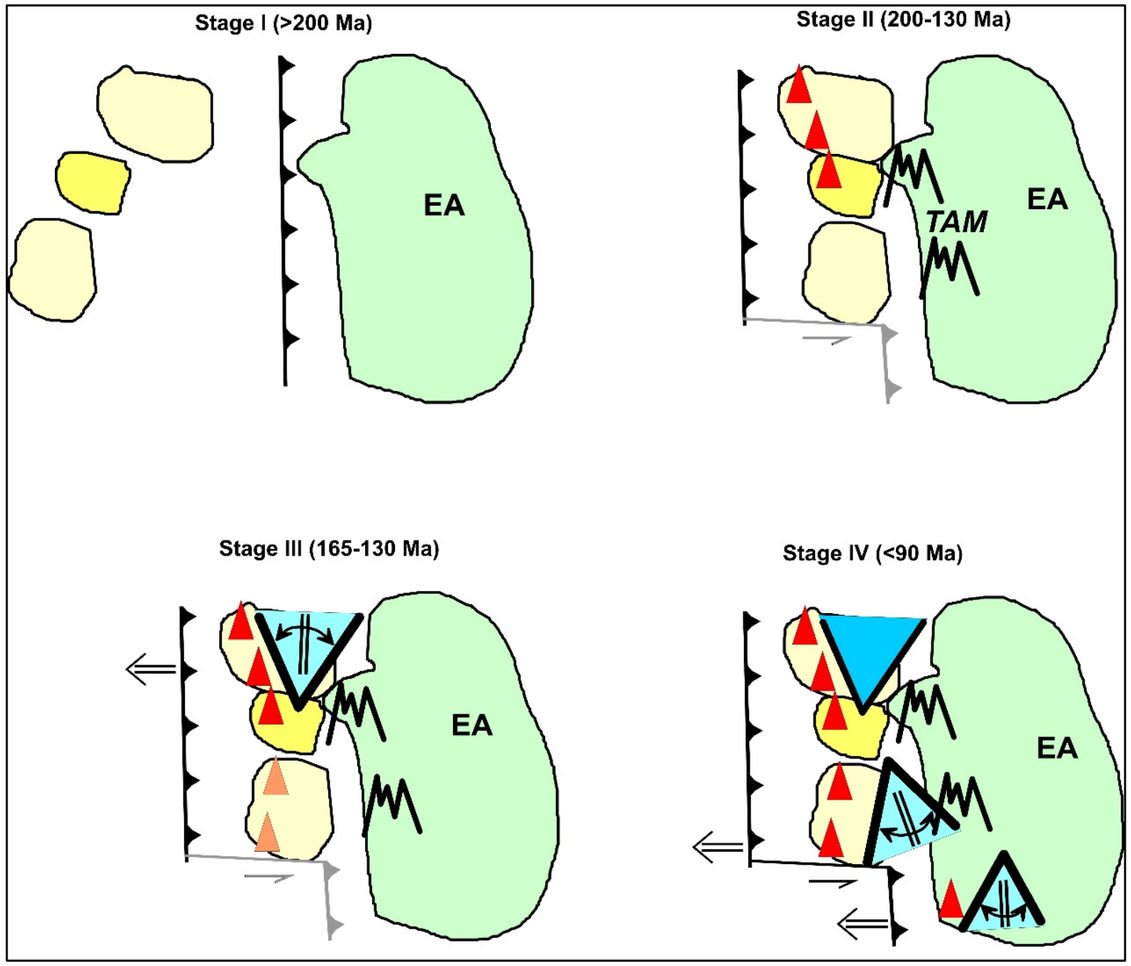
GEOPHYSICAL DATA & MODELING:
Conceptual model

We propose that the basins in WA developed in back-arc systems due to subduction roll-back at various stages.



Our geodynamic model involves four stages:

- **Stage I:** Eastward subduction of the Phoenix plate under what presently makes East Antarctica and eastwards movement of lithospheric terranes that later form West Antarctica.
- **Stage II:** Collision between the terranes and East Antarctica, leading to subduction jump to the western side of the colliding terranes, probable development of a transform fault in the Ross Sea region, reactivation of the Transantarctic mountains, and development of subduction-related volcanism at the Antarctic Peninsula and along the margin of Ellsworth Land.
- **Stage III:** Slab roll-back and rotational opening of the Ronne Ice Shelf back-arc basin with<S>ward progression of arc-related volcanism along the western margin of West Antarctica, while further<S>ward back-arc opening is prevented by the Precambrian block of the Ellsworth-Whitmore mountains.
- **Stage IV:** Slab roll-back in the central West Antarctica (Marie Byrd Land), leading to rotational opening of the Ross Ice Shelf back-arc basin on the accreted lithosphere and active subduction-related volcanism in the<S>, with further<S>slab roll-back causing extension in the Victoria Land and *possible* formation of the Wilkes back-arc basin on the cratonic lithosphere of East Antarctica.

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Conclusions

We propose that the region traditionally interpreted as the "West Antarctic Rift System", together with the Ronne Ice Shelf formed as a system of back-arc basins.

1. **Our proposed model explains within the same framework** the unusually deep equivalent hypsometry of the lithosphere in the West Antarctica superdeep basins, the subduction-related volcanic arc flanking these basins on the ocean side, and the seismicity pattern along the volcanic arc of West Antarctica.

2. **The calculated mantle residual gravity anomalies and lithosphere mantle density show a strong contrast between the East Antarctic craton and West Antarctica**. They require the absence of a granitic crustal layer and the presence of high-density crustal material below a thick sedimentary sequence and the presence of extremely low density mantle below the basins of West Antarctica and the Wilkes Basin in East Antarctica. **These results favor the presence of oceanic or transitional crust in most of West Antarctica and possibly beneath the Ronne Ice Shelf.**

3. **Our model predicts that a granitic crustal layer with a high radiogenic heat production is almost absent** in most of West Antarctica, which may affect heat flux at the base of the ice with potential important implications for models of ice melting.

4. Importantly, **the new geodynamic model reduces the size of the Antarctica continent proper**, as 1/3 of its perceived area should be regarded as a back-arc system including deep basins and the volcanic arc instead of extended continental lithosphere.

- **Clearly this new model will open new perspectives for understanding the ice sheet dynamics in Antarctica, which is affected by basal ice melting.**

- **It also has significant implications for global models of lithosphere-mantle interaction and lithosphere plate dynamics.**

The controversial comments of five anonymous reviewers on our manuscript clearly demonstrated substantial controversy in the opinions on geodynamic evolution of West Antarctica.

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