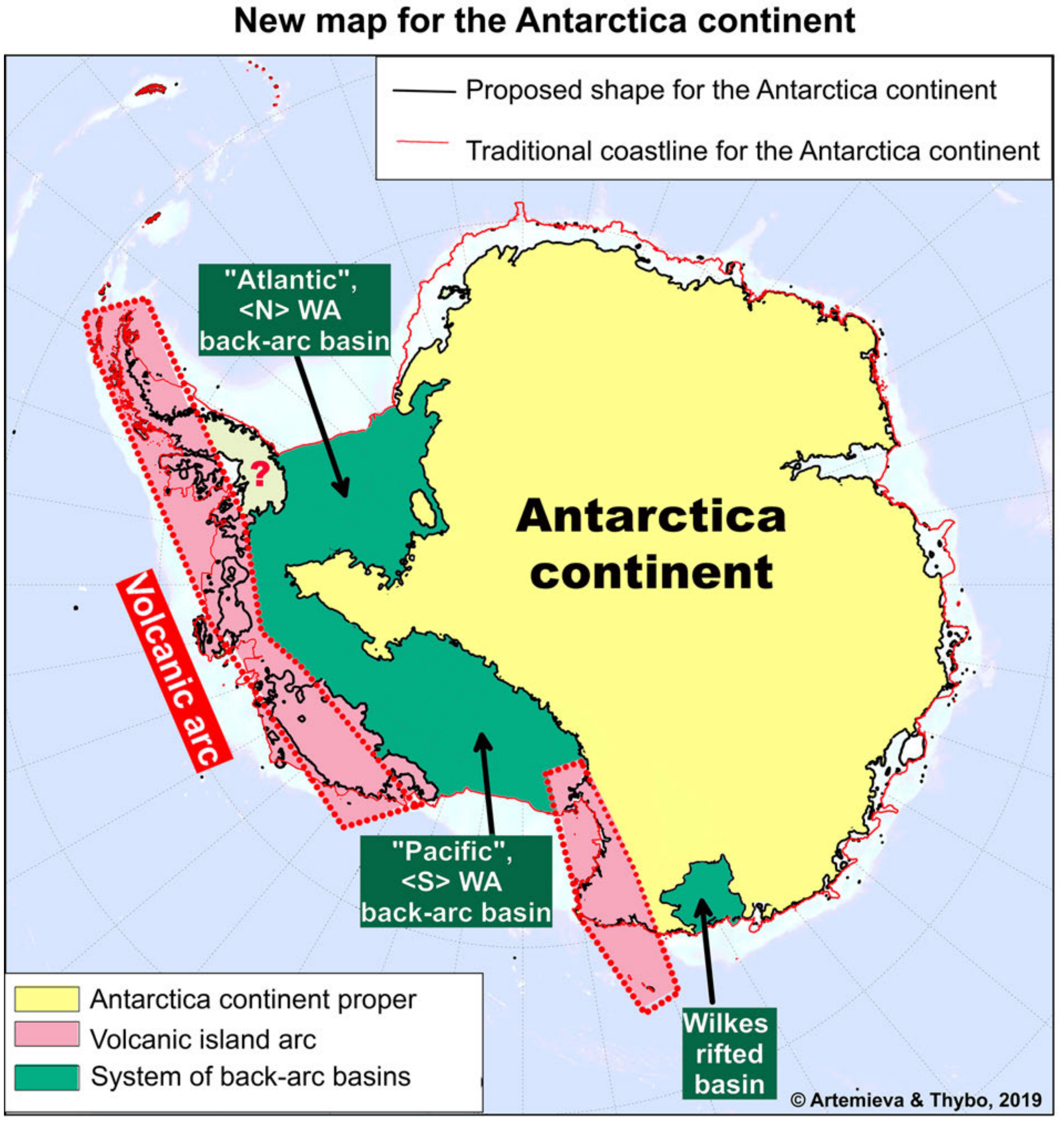
Graphical abstract



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

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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. Geochemical observations show that subduction was active along the whole western coast of West Antarctica until the mid-Cretaceous after which it gradually ceased towards the tip of the Antarctic Peninsula. We propose that the entire West Antarctica formed as a back-arc basin system flanked by a volcanic arc, similar to e.g. the Japan Sea, instead of a continental rift system as conventionally interpreted. Globally, the fundamental difference between oceanic and continental lithosphere is reflected in hypsometry, largely controlled by lithosphere buoyancy. The equivalent hypsometry in West Antarctica (-580±335 m on average, extending down to -1.6 km) is much deeper than in any continent, but corresponds to back-arc basins and oceans proper. This first order observation questions the conventional interpretation of West Antarctica as continental, since even continental shelves do not extend deeper than -200 m in equivalent hypsometry.

We present a suite of geophysical observations that supports our geodynamic interpretation: a linear belt of seismicity sub-parallel to the volcanic arc along the Pacific margin of West Antarctica; a pattern of free air gravity anomalies typical of subduction systems; and extremely thin crystalline crust typical of back-arc basins. We calculate residual mantle gravity anomalies and demonstrate that they require the presence of (1) a thick sedimentary sequence of up to ca. 50% of the total crustal thickness or (2) extremely low density mantle below the deep basins of West Antarctica and, possibly, the Wilkes Basin in East Antarctica. Case (2) requires the presence of anomalously hot mantle below the entire West Antarctica with a size much larger than around continental rifts. 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. Our finding reduces the continental lithosphere in Antarctica to 2/3 of its traditional area. It has significant implications for global models of lithosphere-mantle dynamics and models of the ice sheet evolution.

Keywords: Continental crust, lithosphere, upper mantle, paleosubduction, back-arc extension

1. General tectonic framework

The geology of Antarctica is largely unknown due to the cover by the up-to 3.5 km thick ice sheet (Fig. 1) (*Tingey, 1991; Fretwell et al., 2013*), with only sparse outcrops of bedrock (Fig. 2b). The continent traditionally includes 3 major tectonic units (Fig. 2a): the stable cratonic East Antarctica which is separated by the Transantarctic Mountain belt (a 2.1-1.8 Ga orogen (*Zhao et al., 2002*) reactivated in Cambrian during the time of the Pan-African orogenic event) from the younger, extended lithosphere of West Antarctica. Since the focus of this study is on West Antarctica, we omit details on tectonic evolution of the East Antarctica craton and the Transantarctic Mountains (see e.g. *Dalziel, 1992; Fitzsimons, 2000; Ferraccioli et al., 2011*).

West Antarctica consists of several tectonic terranes that acted individually during the break-up of Gondwana (*Storey et al., 1988; Storey & Alabaster, 1991*). The only dated Precambrian rocks (of Grenvillian age) in West Antarctica are from the Haag Nunataks at the Antarctic Peninsula end of the Ellsworth-Whitmore mountains (*Wareham et al., 1998*), which form a topographic basement high across West Antarctica (Fig. 1a, 2ab). This basement high, possibly also Precambrian in age (*Dalziel and Elliot, 1982),* separates two large, broad and unusually deep depressions in equivalent topography, to which we refer as the “southern” (<S>) and “northern” (<N>) West Antarctica basins (Fig. 3), although strictly speaking such geographical terms are meaningless around the pole.

- The southern domain, that extends from the Ross Ice Shelf to the Antarctic Peninsula and includes Marie Byrd and Ellsworth Land, has long been recognized as one of the world’s largest crustal extensional areas with a size of ca. 3000 km x 1000 km (*Stock and Molnar, 1987; Bradshaw, 1989; Lawver et al., 1991; Behrendt, 1991; 2013; Cande et al., 2000; Harley, 2003; Siddoway, 2008; Ramirez et al., 2016*).
- The northern domain, which includes the Ronne Ice Shelf, has been interpreted as formed by extension during the Mesozoic breakup of Gondwana and possibly caused by rotations during the opening of the Weddell Sea between South America and Antarctica at ca. 165-130 Ma (*Behrendt, 1999; Konig and Jokat, 2006)* (Fig. 3a).

Geological and geophysical studies indicate that the crust (possibly the entire lithosphere) of West Antarctica has been subject to a significant extension and magmatism (Fig. 3) since late Paleozoic, although the timing may be controversial (*Stock and Molnar, 1987; Bradshaw, 1989; Cande et al., 2000; Granot et al., 2010)*. Geodynamic mechanisms of the extension are also controversial, and plate reconfigurations during the Gondwana breakup possibly played an important role in lithosphere extension (see section 3 below).

The southern domain is traditionally interpreted in the extensive literature as a continental rift system. We next review various geodynamic hypotheses on the origin of lithosphere extension in West Antarctica and propose an alternative explanation, based on the available geophysical data and supported by our model for the upper mantle density structure.

2. Traditional geodynamic view on West Antarctica

2.1. West Antarctica Rift System

Traditionally <S> West Antarctica is perceived as the West Antarctica Rift System (*LeMasurier and Rex, 1989; Behrendt et al., 1991; Hart et al., 1997; Behrendt, 1999; 2013; Cande et al., 2000; Ritzwoller et al., 2001; Harley, 2003; Siddoway et al., 2004; Huerta and Harry, 2007; Siddoway, 2008; Busetti et al., 2009; Granot et al., 2010; Bingham et al., 2012; Darniani et al., 2014; An et al., 2015ab; Davey et al., 2016; Ramirez et al., 2016; Jordan et al., 2017; Fei et al., 2018; Granot and Dyment, 2018; White-Gaynor et al., 2019).* It is also often mentioned as "one of the largest active continental rift systems on Earth" (*Cande et al., 2000*), "comparable in area to the Basin and Range and the East African rift system" (*Behrendt et al., 1991*), and with geodynamic development similar to the East African rift and other continental analogues (*LeMasurier and Rex, 1989; LeMasurier, 2008*). The mountain ranges that extend from the Ellsworth-Whitmore mountains in the north to the Transantarctic Mountains in the south have been interpreted as rift shoulders (*Behrendt, 1991; Fitzgerald, 1992; van Wijk et al., 2008*), with the opposing poorly defined rift shoulder at coastal outcrops of Marie Byrd Land (Fig. 2a).

Geological and geophysical observations for interpreting <S> West Antarctica as a wide continental rift system include (1) crustal extension and crustal thinning, (2) intensive volcanism and (3) hot mantle. We briefly summarize these observations below.

2.1.1. Crustal extension

West Antarctica is recognized as a broad zone of episodic crustal extension from geological (*Dalziel and Elliot, 1982; Cooper and Davey, 1985; Lawver and Gahagan, 1994; Fitzgerald and Baldwin, 1997; Salvini et al., 1997*) and high-resolution geophysical mapping (*Houtz and Davey, 1973; Cooper et al. 1995; Studinger et al., 2002*). In particular, aeromagnetic surveys and seismic reflection profiles established the presence of two subparallel grabens under the Ross Ice Shelf, filled with 7-8 km and 14 km of sediments, correspondingly (cf. *Behrendt et al., 1991*). The presence of a thin crust in West Antarctica, recognized from early seismic and gravity surveys of 1960-80'ies, has been confirmed by recent seismic experiments (cf. *Baranov and Morelli, 2013; Chaput et al., 2014; An et al., 2015*), which show crustal thickness of 20-30 km in West Antarctica with an average value of ca. 20 km in the Ross Sea, ca. 25 km in Marie Byrd Land and ca. 34 km in Ellsworth Land (Fig. 4). These values are significantly lower than typical thickness of continental crust (*Christensen and Mooney, 1995; Artemieva and Shulgin, 2019*) and indicate strong crustal extension.

The estimated maximum crustal extension in <S> West Antarctica since late Cretaceous until present ranges from 250 km to 350 km (cf *Behrendt*, *1999)*, with ca. 150 km of extension between 68 Ma and 46 Ma at the Ross Sea segment (*Cande and Stock, 2004*), ca. 180 km extension in its northwestern part between 43 Ma and 26 Ma (*Cande et al., 2000*), and another extensional episode at the Ross Sea at ca. 11 Ma (*Granot and Dyment, 2018*). Estimates of the whole crust stretching factor for the Ross Subglacial Basin based on gravity modeling yield extremely high values of $\beta \sim 3$ on average with local maximum of $\beta > 4$ (*Fei et al., 2018*), which are not observed in any continental rift zones (*McKenzie, 1978; Thybo and Nielsen, 2009*). These values are in contrast to $\beta \sim 2$ estimated for stretching of the entire lithosphere beneath the West Antarctica Rift System (*Behrendt et al., 1991*). However, the latter may be strongly underestimated in the absence of reliable models on the lithosphere structure in Antarctica in 1990ies. Since late Paleogene, extension slowed down and became restricted to the Ross Subglacial Basin (*Huerta and Harry, 2007*), with no present-day extension resolved by GPS measurements in West Antarctica (*Wilson et al., 2015*).

2.1.2. Meso-Cenozoic basaltic volcanism

Volcanic activity in West Antarctica began in the Mesozoic (Fig. 3a) and continued in the Cenozoic along the coast of Marie Byrd Land, in the southern part of West Antarctica along the Transantarctic mountains, and possibly in the interior of the West Antarctica domain (*Behrendt et al., 1997; Fitzgerald and Baldwin, 1997; Hart et al., 1997; Siddoway, 2008*). Since most volcanic rocks are under ice, the information on their volume and the age of volcanism remains incomplete *(Blankenship et al., 1993)*. An estimated volume of volcanic rocks in West Antarctica interpreted from magnetic anomalies exceeds 1 mln km^3 (*Behrendt et al., 1994*).

Later Mesozoic volcanism has been explained by reorganization of lithosphere blocks (*Dalziel and Elliot, 1982; Cande et al., 2000*), such as Late Cretaceous rifting and separation of the New Zealand-Campbell Plateau from Antarctica (*Weaver et al., 1994; Luyendyk et al., 1996*), or intraplate deformation and plate dynamics (*Rocchi et al., 2002, 2003, 2005*). The geochemical composition of Cenozoic volcanic rocks is compatible with deep mantle melting (*Behrendt , 1999; Worner, 1999; Rocchi et al., 2002)* and is similar to ocean plateau basalts *(Hart et al., 1997*), suggesting a mantle plume as an alternative or additional mechanism to lithosphere stretching (*Dalziel, 1992; Winberry and Anandakrishnan, 2004)*. Late Cenozoic volcanic activity is attributed to adiabatic mantle melting during continental rifting in West Antarctica (*LeMasurier, 1990*). We further discuss the origin of Meso-Cenozoic volcanism in section 3.

2.1.3. Hot mantle?

Overall, the resolution of regional seismic tomography models for Antarctica is limited due to insufficient ray path coverage: although seismicity at the ring of mid-ocean ridges around the Antarctic plate provides a good azimuthal coverage, the distribution of seismic stations remains sparse. As a result, details of the upper mantle structure beneath West Antarctica are controversial. Regional seismic tomography models show slow seismic velocities in the upper mantle of West Antarctica, in contrast to a typical cold and thick cratonic lithosphere of the East Antarctic craton (*Danesi and Morelli, 2001; Ritzwoller et al., 2001; Sieminski et al., 2003; Morelli and Danesi, 2004; Hansen et al., 2014; An et al., 2015b*). All geodynamic interpretations of slow seismic velocity anomalies favor lithosphere rifting in case of shallow (above a 200 km depth) anomalies and a possible role of mantle plumes for deep-seated velocity anomalies imaged beneath Marie Byrd Land (*Hansen et al., 2014; Lloyd et al., 2015)* and the Ross Embayment *(Bannister et al., 2000; Danesi and Morelli, 2001)*. Slow seismic velocity anomalies are interpreted in terms of high upper mantle temperatures and thin lithosphere in West Antarctica (*Shapiro and Ritzwoller, 2004; An et al., 2015a*) (Fig. 5a).

Flexural modeling also suggests a sharp transition across the Ross Embayment at the Transantarctic Mountains with a thin (<100 km) elastic lithosphere beneath West Antarctica and a 250 km thick lithosphere beneath the East Antarctic craton (*Stern and ten Brink, 1989*). The same model assumes that at 100 km depth the upper mantle beneath the Ross Subglacial Basin is ca. 600 ^{o}C hotter than beneath the craton (*ten Brink et al., 1997*), whereas a thermal model suggests a temperature difference of ca. 300 ^{o}C between the Ross Subglacial Basin and the East Antarctic craton at a 100 km depth (*Artemieva, 2006)*.

A high resolution seismic transect across Marie Byrd Land and Byrd Subglacial Basin reveal significant velocity heterogeneity of the West Antarctic upper mantle (*Lloyd et al., 2015*). Relatively fast P- and S- velocities beneath the Ellsworth-Whitmore mountains and most of the West Antarctic Rift System are interpreted to represent a possible Precambrian lithosphere fragment, while slow velocity anomalies beneath a deep narrow subglacial basin (the Bentley Subglacial Trench) and the central coast in Marie Byrd Land are interpreted as consistent with a plume-related warm upper mantle (*Lloyd et al., 2015*).

One of the peculiar features imaged in a surface wave tomography model is a high velocity anomaly in the upper mantle beneath the Antarctic Peninsula, which has been interpreted as a slab associated with an Eocene subduction along the coast of the Antarctic Peninsula, Marie Byrd Land, and Ellsworth Land (*An et al., 2015a)*. Despite this observation, no inference was made to explain the slow velocity anomaly beneath the whole of West Antarctica by backarc spreading, which the authors conventionally interpreted as the West Antarctic Rift System, and their comparison of the West Antarctica Pacific margin with the active Pacific margin in Asia focuses on the thin crust and lithosphere in onshore China, but not on back-arc spreading in the Japan Sea (*An et al., 2015a*).

In general, there is a significant controversy in mantle temperature anomalies constrained by different seismic tomography models and magnetic methods, both in the amplitudes and the locations. Targeted magnetotelluric profiling across the Byrd Subglacial Basin of central West Antarctica did not image a strong conductivity anomaly as expected for active rift zones (*Wannamaker et al., 1996*). In contrast, the presence of a hot upper mantle with a shallow Curie depth beneath the Byrd Subglacial Basin is suggested from the analysis of airborne magnetic data *(Martos et al., 2017*), although satellite magnetic data suggests that the strongest anomaly is located beneath <N> West Antarctica, and not beneath <S> West Antarctica (*Fox Maule et al., 2005)*.

2.2. Alternative geodynamic models : Plumes and plates

Until present, West Antarctica is tagged in the literature as “West Antarctica Rift System”, and most interpretations maintain this geodynamic model (*LeMasurier and Rex, 1989; Behrendt et al., 1991; Hart et al., 1997; Behrendt, 1999; 2013; Cande et al., 2000; Ritzwoller et al., 2001; Harley, 2003; Siddoway et al., 2004; Huerta and Harry, 2007; Siddoway, 2008; Busetti et al., 2009; Eagles et al., 2009; Faure and Mensing, 2010; Granot et al., 2010; Jordan et al., 2010, 2013; Bingham et al., 2012; Darniani et al., 2014; An et al., 2015ab; Lloyd et al., 2015; Davey et al., 2016; Ramirez et al., 2016; Jordan et al., 2017; Fei et al., 2018)*. Importantly, the geodynamic processes behind the continental rifting analogues are based on rifting in long linear zones of continental lithospheric plates (*Olsen, 1995*) due to either deep thermal anomalies (*Ritzwoller et al., 2001*) or far-field tectonic stresses (*Sengör and Burke, 1978*).

These extensional systems above sea level must have a different geodynamic origin than the West Antarctica basins, which are submerged deep below sea level and are neither localized linear zones of extension (*McKenzie, 1978*), as in continental rift zones, nor broad areas of homogeneous extension, as in the Basin and Range Province (*Wernicke, 1981*). Instead, they represent broad depressions with a superimposed series of basins at extremely deep equivalent hypsometry (corrected by compressing ice and water masses to the density 2.67 g/cm^3 of near-surface rocks), on average 580 m below sea level (Fig. 3a) which is much deeper than observed anywhere else in continental rift zones or other tectonic provinces on continental lithosphere (Fig. 6). Although the existence of deep submerged basins in West Antarctica has been known for decades, they were traditionally explained by lithosphere stretching of continental lithosphere; a possible contribution of phase transition and thermal subsidence (*Podladchikov et al., 1994*) as an alternative or an additional mechanism was estimated to be too low to explain large subsidence of the West Antarctic Rift System (*Behrendt, 1999*).

A brief overview in section 2.1 indicates that the original perception from the 70-90’ies on the West Antarctica as a wide zone of continental rifting has been challenged by several authors, who emphasized the role of other mechanisms in Mesozoic – early Cenozoic extension and volcanism of West Antarctica:

- the Gondwana plate reconfiguration, Gondwana breakup and late Cretaceous rifting of the New Zealand-Campbell Plateau from Marie Byrd Land (*Jankowski and Drewry, 1981; Dalziel and Elliot, 1982; Stock and Molnar, 1987; Bradshaw, 1989; Lawver et al., 1991; Weaver et al., 1994; Luyendyk , 1995; Luyendyk et al., 1996; Cande et al., 2000; Siddoway, 2008; Veevers, 2012*);
- mantle plumes and convective instabilities (*Behrendt et al., 1991; Dalziel, 1992; Storey, 1996; Hart et al., 1997; Rocci et al., 2002; Winberry and Anandakrishnan, 2004; Finn et al., 2005; Hansen et al., 2014; Lloyd et al., 2015; Seroussi et al., 2017; Ebbing et al., 2019*);
- intraplate deformation (*Rocchi et al., 2003, 2005*) and lithosphere flexure (*Stern and ten Brink, 1989; ten Brink et al., 1997*), also due to sediment (*Karner et al., 2005*) and magmatic loading (*Jordan et al., 2010; Karner et al., 2005; Trey et al., 1999*);

- possible dynamic topography associated with mantle flow and subduction (e.g. *Spasocevic et al., 2010; Sutherland et al., 2010*).

Here we propose an alternative hypothesis, that the entire West Antarctica formed by back-arc extension in Mesozoic subduction settings along the Panthalassic (paleo-Pacific) margin. Although this mechanism is related to the Gondwana plate reconfiguration and back-arc extension has been mentioned by several authors in relation to tectonics of West Antarctica, the role of this process has been severely underestimated. We next present a brief overview for West Antarctica tectonic models during the Gondwana breakup.

3. Gondwana breakup and Panthalassic subduction

The amalgamation of the pre-Gondwana cratons accreted continental fragments and arc material to the Panthalassic (paleo-Pacific) margin of Gondwana in late Cambrian - Cretaceous. An overview of West Antarctica's position in Gondwana can be found in the extensive literature on the subject (e.g. *Dalziel and Elliot, 1982; Vaughan and Pankhurst, 2008; Boger, 2011; Veevers, 2012; Dalziel et al., 2013*). Here we mention only major tectonic events important for further discussion of the Meso-Cenozoic extension in West Antarctica (Fig. 7), and in particular refer to the studies where back-arc extension is mentioned in various context.

3.1. Mid-Jurassic/early Cretaceous Gondwana breakup

The breakup of Gondwana, which started in the mid-Jurassic, led to the opening of the Weddell Sea between South America and Antarctica at ca. 165-130 Ma (*Behrendt, 1999; Konig and Jokat, 2006).* Possible rotations of the Ellsworth-Whitmore mountains lithosphere block in West Antarctica during the opening of the Weddell Sea (although questioned recently, *Jordan et al., 2017*) may have been caused by slab rollback associated with subduction beneath southern Africa at ca. 185-180 Ma (*Dalziel et al., 2013; Jordan et al., 2017*).

Early Paleozoic to early Mesozoic back-arc terrains identified in regional geological observations in outcrops around the Ronne Ice Shelf (*Dalziel and Elliot, 1982; Millar and Storey, 1995)* (Fig. 2b) predate the opening of the Weddell Sea. Pillow-basalt flows of late Cambrian to early Ordovician age in the Pensacola mountains were interpreted as rift-related, with a possibility of a back-arc basin development (*Millar and Storey, 1995; cited in Faure and Mensing, 2010*). Based on sparse outcrop of locally exposed volcanic detritus in the Ellsworth mountains (*Dalziel and Elliot, 1982)*, there were early speculations about possible existence of a late Early Permian back-arc basin along the Panthalassic margin with an undefined areal extent (*Collinson et al., 1994*) (see Fig. 2b for locations).

3.2. Early-mid Cretaceous subduction at the Panthalassic (paleo-Pacific) margin

The early Cretaceous separation of Australia coincided broadly with the collisional events along the West Antarctica margin (*Boger, 2011*), which included the collision of the Amundsen and Ross provinces of Marie Byrd Land by 107 Ma (*Mukasa and Dalziel, 2000; Vaughan et al., 2002*). Marie Byrd Land, Thurston Island block, and the Antarctic Peninsula are interpreted as fore-arc and magmatic arc terranes associated with the Cretaceous subduction of the Phoenix plate at the Panthalassic margin of Gondwana *(Dalziel and Elliot, 1982; Mukasa and Dalziel, 2000; Boger, 2011*) (Fig. 7), which terminated at 110-105 Ma (*Bradshaw, 1989*). Note that paleo-reconstructions fail to match the coast lines of the Antarctica Peninsular and the Gondwana continents in the Gondwana reconstructions (*Dalziel and Elliot, 1992*), and therefore it has long been proposed that the Antarctic Peninsula can be a "Mesozoic accretionary belt" (*Dietz and Sproll, 1970)*.

Subduction related, calc-alkaline magmatism has been observed in Marie Byrd Land from ca. 320 Ma (the oldest granodiorite rocks) until ca. 110 Ma (the age of the youngest I-type granites) (*Mukasa and Dalziel, 2000*). I-type granitoids (124-108 Ma) of central Marie Byrd Land (the Ruppert-Hobbs coast, Fig. 2b) are interpreted as typical subduction-related magmas (*Weaver et al., 1994)*. These authors find evidence that subduction of the Phoenix Plate below Marie Byrd Land ceased gradually from <S> to <N> between 108 and 95 Ma (Fig. 7). Mafic rocks with ages of 110-95 Ma from central Marie Byrd Land (the Ruppert-Hobbs coast, Fig. 2b) have composition of continental flood-basalt affinity typical of rift magmatism in the presence of plume-head (*Weaver et al., 1992, 1994)*. Slightly younger wide-spread A-type granitoids with age of 102-95 Ma from eastern Marie Byrd Land (Edward VII Peninsula on the Ross Sea margin, Fig. 2b) are interpreted as associated with intracontinental rifting that later led to the separation of the Zealandia block from West Antarctica (*Weaver et al., 1992, 1994)*.

Later, with reference to the same interpretations (*Weaver et al., 1992; 1994)*, back-arc extension has been mentioned as a possible source of the mid-Cretaceous alkaline plutonism in eastern Marie Byrd Land for a short period of 105-102 Ma (*Siddoway, 2008; Damiani et al., 2014*), although the overall regional evolution was explained traditionally - by continental break-up and intracontinental rifting in the presence of a postulated mantle plume (*Siddoway, 2008*). A speculation on a possible existence of a back-arc basin in Byrd Subglacial Basin and in the far-eastern sector of the Transantarctic Mountains has been later repeated without new evidence (e.g. *Faure and Mensing, 2010*) and with reference to a study, where Neogene extension in West Antarctica rifts was inferred from comparisons with the East African rift system and the entire region was interpreted as the West Antarctica Rift System (*LeMasurier, 2008*).

3.3. Mid-/late-Cretaceous extension

In mid-Cretaceous (ca. 100 Ma) the composition of igneous rocks in central Marie Byrd Land changed from subduction-related to rift-related, indicating the change in stress regime from transpressional to transtensional (*Weaver et al., 1994*). At this time, Australia separated from Antarctica with the first seafloor formed in-between by 96 Ma (*Veevers et al., 1991*); the Zealandia block (including the New Zealand-Campbell Plateau) rifted away from Antarctica with the formation of the first seafloor by ca. 83 Ma (*Weaver et al., 1994; Luyendyk et al., 1996; Larter et al., 2002*). This separation formed the western margin of Antarctica as it is seen today (*Boger, 2011*) (Fig. 7).

Thereafter subduction ceased sequentially along the West Antarctica margin (*Dalziel, 1992*). A capture of the subducted Phoenix plate by the Pacific plate was proposed as a mechanism for extension (*Luyendyk, 1995*) based on geochemical data on magmatic rocks and ocean floor magnetic anomalies. Further <N> along the Antarctic Peninsula, subduction also gradually ceased from <S> to <N> after 94 Ma, and today the only remaining subduction is presently active at the South Shetlands Trench at the northern tip of the Antarctic Peninsula (*Storey and Garrett, 1984; Barker, 1982*).

4. Continent revisited: Equivalent topography - a first order observation

We conclude that not a single publication argue for the back-arc origin of the entire West Antarctica, including both <S> (Ross and Byrd Subglacial Basins) and <N> (Ronne Ice Sheet) domains. Geological interpretations consider late Cretaceous-Cenozoic intracontinental extension, possibly in the presence of a mantle plume, as the major tectonic process in <S> West Antarctica, and mostly without even mentioning back-arc extension as a possible mechanism (*Finn et al., 2005; Ferraccioli et al., 2006; Eagles et al., 2009; Jordan et al., 2010, 2013; Bingham et al., 2012*). The Meso-Cenozoic evolution of the ice-covered Ronne Ice Sheet is not discussed in literature, possibly due to lack of geological data. We next present geophysical evidence in support of our hypothesis for a back-arc origin of the entire West Antarctica and propose a geodynamic model for its Meso-Cenozoic evolution.

Hypsometry on Earth is largely controlled by lithosphere buoyancy and dynamic processes related to plate tectonics and mantle convection. Its bimodal distribution reflects the existence of two principally different lithosphere types, oceanic and continental (Fig. 6). On continental lithosphere hypsometry globally ranges from high elevations in young mountain belts and stable regions with dynamic topography, to 300-500 m elevation in cratons, and down to -200 m of equivalent hypsometry on continental shelves.

East Antarctica and the Transantarctic Mountain belt have high equivalent hypsometry typical of continental landmass (+1050±650 m on average, up to +3.5 km, Fig. 3) and East Antarctica shows all characteristics of normal cratonic lithosphere, with a 38-55 km thick crust (*Baranov & Morelli, 2013; Feng et al., 2014; An et al., 2015b; Ramirez et al., 2016*) (Fig. 4), high seismic velocities in the upper mantle (*Ritzwoller et al., 2001; An et al., 2015a*), and thicker than 150-250 km lithosphere (*An et al., 2015a*) (Fig. 5b).

In contrast, West Antarctica is characterized by unusually deep equivalent hypsometry (-580±335 m on average, down to -1.6 km) (Figs. 3, 6). Such deep bathymetry as in West Antarctica is globally observed nowhere in continents, while oceans proper usually are much deeper (4-6 km for bathymetry and ca. 2.5-3.5 km for equivalent hypsometry). This first order observation shows that West Antarctica consists of neither continental nor oceanic lithosphere, while such hypsometry is common in many back-arc basins flanked by a volcanic arc on the ocean side (*Dickinson, 1978; Uyeda & Kanamori, 1979; Brooks et al., 1984; Waschbusch & Beaumont, 1996*) (Figs. 6, 8-10).

5. Continent revisited: Geophysical observations in support of back-arc tectonics

We present geophysical evidence that most of West Antarctica represents a Mesozoic to Cenozoic back-arc system with two main basins separated by the Ellsworth-Whitmore mountains, in contrast to conventional interpretations of West Antarctica as a continental rift system. We recognize the following features typical of back-arc systems worldwide (*Wernicke, 1981*) (Fig. 9):

1) the presence of a volcanic arc along the Pacific margin of West Antarctica (Fig. 3b, 8),
2) the presence of a sub-parallel, linear belt of seismicity deepening towards the volcanic arc (Fig. 3b, 8),
3) a linear pattern of free air gravity anomalies along the Pacific margin of West Antarctica typical of subduction systems (Fig. 11a),
4) the presence of an extremely thin crystalline crust over broad basins of West Antarctica (Fig. 4) typical of back-arc basins, in contrast to typically linear belts of thin crust in continental rift zones (*Olsen, 1995*),
5) the presence of a thin and hot lithosphere over broad basins of West Antarctica (Fig. 5ab).

We briefly review these features below and then support our interpretation by a new density model of the West Antarctica lithosphere.

5.1. Volcanism

The West Antarctica basin system is flanked in the west by the (partly extinct) volcanic arc along the Pacific-Antarctic paleosubduction zone (Fig. 3b), with volcanic age decreasing <S-ward> (*Jordan et al., 2017)* (Fig. 3a) from Triassic-Cretaceous in the Antarctic Peninsula (*Collinson et al., 1994; Riley & Leat, 1999; Vaughan & Storey, 2000; Harley, 2003),* to Cretaceous arc-related granitoids (*Weaver et al., 1992; 1994; Mukasa & Dalziel, 2000*) and recent volcanic activity (*Lemasurier & Rex, 1989; Hart et al., 1997*) in Marie Byrd Land, and to the active volcanoes at the end of the Transantarctic Mountains at the Ross Sea (*Kyle &*

Muncy, 1989), although a few recently active volcanoes also exist at the tip of the Antarctic Peninsula (*Larter & Barker, 1991*). This volcanic belt forms a narrow elongated zone with positive equivalent topography between the Pacific Ocean and the West Antarctica basin system (Fig. 3b).

5.2. Seismicity

We interpret a linear belt of shallow (<40 km and mostly crustal) magnitude 4.2-6.3 seismicity (Fig. 3b, 8), as well as aligned mantle earthquakes parallel to the volcanic arc, as related to paleosubduction of the Phoenix plate below West Antarctica (Fig. 3b). We emphasize that the seismicity does not reflect present day subduction (which ceased along the Marie Byrd margin in late Cretaceous), but instead follows the weakness zones created during paleo-subduction. The pattern of arc-related volcanism between a parallel belt of seismicity on the ocean side and deep basins on the continental side is similar to the volcanic arcs in the subduction systems of the NW Pacific Ocean which have back-arc basins (*Van Horne et al., 2015*) (e.g. Japan and the Aleutians, Fig. 8).

5.3. Gravity anomalies

Subduction systems have a unique pattern of free air gravity anomalies across strike with strong negative anomalies above trenches followed by weak positive anomalies towards the volcanic arc (*Artemieva et al., 2016*). We observe a similar pattern of free air gravity anomalies along the Pacific margin of West Antarctica with a linear belt of negative (-100-40 mGal) anomalies as the gravity signal from the trench, which today has been isostatically readjusted and filled with sediments, and a parallel narrow belt of positive (+10+70 mGal) free air anomalies on the side of the volcanic arc (Fig. 8a, 11a). Seismicity is restricted to the belt of negative free air anomalies and its ocean-ward vicinity (Fig. 3b, 8b), and it may be related to stress relaxation, equilibration, and isostatic readjustment after the cease of subduction.

Antarctica is to a large degree in isostatic equilibrium, although the large basins in West Antarctica are slightly undercompensated, and the <S> Transantarctic Mountains and the Wilkes Basin are highly undercompensated (Fig. 11a). In West Antarctica, free air anomalies are slightly positive (+25 mGal) in topographic highs, including the volcanic arc (Fig. 8a, 11a). The generally slightly negative (-23±20 mGal) free air anomalies in the <N> and <S> West Antarctica back-arc basins are superimposed by three NW-SE linear strong negative (ca. -70-100 mGal) anomalies within the Ross Ice Shelf that have been interpreted earlier as continental rift grabens (*Cooper et al., 1991*). These features do not show up as prominent Bouguer anomalies (Fig. 11b), and we propose that they are caused by extinct spreading zones in the back-arc system.

Bouguer anomalies also follow the pattern expected for active margins (*Artemieva et al., 2016*). The transition from oceanic lithosphere to the volcanic arc is marked by a sharp change in Bouguer anomalies from >+250 mGal to <+100 mGal (Fig. 11b) which coincides with the linear belt of negative free air anomalies and the zone of seismicity. There is a sharp contrast in Bouguer anomalies between strongly negative values (-100-250 mGal) in the East Antarctica craton and near-zero (-30 to +40 mGal) values in basins of the Ross Ice Shelf and Marie Byrd Land, up to ca. +100 mGal in the Ronne Ice Shelf, and ca. -50 mGal in the volcanic arc and in the Ellsworth mountains (Fig. 11b). Typically, back-arc basins of the world have stronger positive Bouguer anomalies, >+100 mGal, than in West Antarctica (Fig. 9), but some back-arc basins, like the Tyrrhenian and the Andaman seas, have Bouguer anomalies in the same range of 0-200 mGal as in West Antarctica (Fig. 9; Table 1). We speculate that the amplitude of the anomaly reflects the amount of oceanic-type crust that has been produced (that is the maturity of back-arc spreading), as well as later compensation by deposited sediments, which form a much thicker sequence in West Antarctica than in most other back-arc systems and, therefore, reduces the amplitude of the Bouguer gravity anomalies.

5.4. Crustal structure

A characteristics of back-arc basins is the presence of zones where oceanic-type crust is, or is close to, being produced. The West Antarctica basins have thin (25±5.7 km) crust (Fig. 4) similar to the back-arc basins of the Aegean Sea, the Okinawa Trough and, possibly, the Sea of Japan (Fig. 9). Such widely occurring thin crust is atypical for continental lithosphere except for much more localized rift zones (*Christensen & Mooney, 1995*) and subduction-related back-arc basins (Table 1).

We observe a strong linear correlation between the equivalent topography and crustal thickness (Fig. 12), with the best correlation for the cratonic East Antarctica where Airy-type isostatic compensation clearly dominates. The slope of the line determines the average density contrast between the crust and the upper mantle (Fig. 13), which is therefore very uniform for different tectonic provinces, with compositional variations in crustal density apparently compensated by temperature-induced mantle density variations. The predicted density contrast between the crust and the upper mantle is ca. 0.35 g/cm^3 (Fig. 13). This value is similar to the best fit estimates of Moho density contrast (0.23-0.40 g/cm^3) for both East Antarctica craton and West Antarctica based on fitting gravity and seismic data on crustal thickness (*O'Donnell and Nyblade, 2014*).

Back-arc basins of the world follow the same general trend but with a large scatter (Table 1, Fig. 9), as also the West Antarctica domain. We attribute this scatter to crustal density heterogeneity associated with extension, magmatism (in form of sills, diapirs and underplating), and metamorphism which are common for back-arc basins, as well as to mantle density heterogeneity associated with different stages of back-arc extension.

6. Continent revisited: West Antarctica lithosphere density model

We support our interpretation of West Antarctica as a system of back-arc basins by a new regional density model of the lithosphere, which shows the presence of a hot low-density mantle (Fig. 14a) below most of the West Antarctica. The pattern is in overall agreement with lithosphere thermal structure as constrained by airborne magnetic anomalies (*Martos et al., 2017*) (Fig. 14b).

Residual mantle gravity anomalies (Fig. 14a) calculated under the assumption of 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 examine the relative roles of crustal and mantle heterogeneities and a possible range of in situ mantle density values for two end-member scenarios discussed below (Fig. 15). In the absence of high-resolution models on the internal velocity and density structure of the crust of most of Antarctica (Fig. 4) other approaches are not justified.

6.1. Model 1: variable crustal density

Assuming only crustal thickness and density heterogeneity, isostatic compensation at the Moho, and an average crustal density of 2.8 g/cm^3 at a reference cratonic station, we calculate the average crustal density (Fig. 15a) required to explain the Bouguer anomalies (Fig. 11b) for the known equivalent topography (Fig. 3) and seismic crustal thickness (Fig. 4). In this scenario, we find crustal density in the East Antarctica craton within the normal range for shield crust, around 2.8-2.9 g/cm^3 (*Artemieva and Shulgin, 2019*). However, the crust of West Antarctica has extremely low predicted average density, between 2.1 and 2.6 g/cm^3.

Average crustal density values of 2.4-2.6 g/cm^3 (crystalline basement plus the sedimentary cover) are only possible if the sedimentary cover (with average density of ~2.2 g/cm^3) forms ca. 40-60% of the total crustal thickness as in the Peri-Caspian depression (*Artemieva and Thybo, 2013*). For the West Antarctica 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, which is in agreement with seismic observations in the Victoria Land Basin of the Ross Subglacial Basin (*Cooper et al., 1991*), but nearly double of the reported 8 km thickness of Mesozoic sediments in other grabens of the Ross Sea (*Cooper et al., 1991; Harley, 2003*).

Unrealistically low average crustal density values of <2.4 g/cm^3 required by the model for Ellsworth Land, the Ross Ice Shelf and the Ross Sea are directly correlated with thin crust (Fig. 4). Furthermore, the regions with very low predicted average crustal density are all associated with young volcanoes (Fig. 15a), with thin lithosphere as constrained by seismic tomography (*An et al., 2015a*) (Fig. 5a), and with very small Curie depth (*Martos et al., 2017*) (Fig. 14b). We therefore conclude that 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.

6.2. Model 2: variable density of lithosphere mantle

As another end-member scenario, we assume that no density heterogeneity exists in the crust with an average density of 2.8 g/cm^3 and that all mantle density anomaly resides in the layer between the Moho and the LAB as defined from a recent regional seismic tomography model (*An et al., 2015b*) (Fig. 5a). In this scenario, we find lithospheric mantle densities at room (SPT) conditions between 3.3 and 3.4 g/cm^3 in the East Antarctic craton and less than 3.1 g/cm^3 in West Antarctica (Fig. 15b) (recalculated from in situ to room temperatures assuming that the seismic LAB corresponds to 1300 ^{o}C). The values for East Antarctica are within the range expected for continental lithosphere mantle (*Griffin et al., 2003*) and in agreement with other results (*Lloyd et al., 2015*) that the Ellsworth-Whitmore mountains have cratonic density values, thus supporting a Precambrian age of these mountains (*Wareham et al., 1998*). The West Antarctica values are extremely low, implying that either average crustal density should also be low, or that lithospheric mantle has very high temperatures with possible presence of fluids and melts. We interpret these low-density mantle anomalies as 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.

The assumption of a constant average crustal density of 2.8 g/cm^3 (crystalline basement plus sediments) in this end-member scenario, together with seismic data on the presence of ca 8 km thick layer of Mesozoic sediments in grabens of the Ross Subglacial Basin (*Cooper et al., 1991; Harley, 2003*) require an average density of ~ 3.0 g/cm^3 of ca. 12-15 km thick crystalline crust. Such high density requires the presence of high-density underplated material in the lower crust (*Thybo & Artemieva, 2013*) and the absence of a low-density radiogenic 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.

Our results indicate that the most recent back-arc spreading in West Antarctica appears to be concentrated over most of central and <S> West Antarctica, where low-density anomalies indicative of the presence of a hot mantle are located (Fig. 15b). For the Ronne Ice Shelf, the knowledge of crustal structure is insufficient for definite conclusions on the origin of the basin. It also hampers determination of mantle density structure. However, anomalously deep equivalent hypsometry (including the deepest values in West Antarctica, down to >-1.5 km) together with the results of regional seismic tomography (*Ritzwoller et al., 2001; An et al., 2015a*) indicate a common geodynamic origin of the Ronne Ice Shelf and the Marie Byrd Land - Ross Ice Shelf lithospheric regions.

By analogy between mantle density anomalies beneath West Antarctica and the Wilkes basin in East Antarctica, we propose that the latter may be another back-arc basin that developed when subduction jumped eastwards (*Harley, 2003*) (ca. 86 Ma), to the present day <S> Transantarctic Mountains (Fig. 3b, 16). This conclusion agrees with interpretation of regional aeromagnetic signatures (*Ferraccioli et al., 2001; 2009; Ferraccioli and Bozzo, 2003*) and with flexural models of lithosphere deformation (*Stern & ten Brink 1989; van Wijk et al., 2008*).

6.3. Summary

We conclude, that residual mantle gravity anomalies require the combined effect of:

(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, and

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

Based on geophysical data on crustal thickness, equivalent topography, mantle residual gravity anomalies, lithosphere thickness, and the spatial-temporal patterns of the volcanic belt, seismicity and free air gravity anomalies, we propose that the basins in West Antarctica developed in back-arc systems (Fig. 16) due to subduction roll-back at various stages. The early formation of the Ronne Ice Shelf basin explains the relatively high lithospheric mantle densities (Fig. 15b) because low temperatures have re-equilibrated after a long cooling history.

7. Continent revisited: Geodynamic setting of the back-arc system

Based on a variety of geophysical evidence and our new lithosphere density model, we have demonstrated that West Antarctica cannot be made of normal continental crust, even if modified by extension to form a large rift system as proposed in early models and commonly accepted until present. The extraordinary deep equivalent hypsometry in West Antarctica is atypical for any continental lithosphere setting (Fig. 6). This first order observation, despite known for more than a decade, demonstrates on its own that a major part of West Antarctica cannot be continental. Our density modelling results, together with regional seismic, geochemical and geological evidence for crustal extension and magmatism, require that West Antarctica instead formed in a back-arc setting, as also further supported by the patterns of seismicity and gravity anomalies (Figs. 3b, 8, 11).

Geochemical data for early- to mid-Cretaceous magmatic rocks from West Antarctica have long been interpreted as subduction-related (sections 3.1-3.3), although with some controversy. Active subduction of the Phoenix Plate along the <W> margin of West Antarctica is generally recognized from plate reconstructions and sampling of subduction-related volcanic rocks (*Mukasa and Dalziel, 2000; Weaver et al., 1994*). Along Marie Byrd Land, subduction ceased from 108 to 95 Ma (*Weaver et al., 1994)*, while a nearly simultaneous break-up between West Antarctica and Zealandia in Marie Byrd Land initiated rifting-related volcanism as demonstrated by the occurrence of A-type granites (*Weaver et al., 1994*). However, subduction at the Panthallasic/Pacific margin, gradually ceasing from <S> to <N>, continued along the Antarctic Peninsula so that presently the only remaining active subduction is at the northern tip of the Antarctic Peninsula (at the South Shetland Islands).

These paleo-subduction events formed a magmatic arc along the West Antarctica margin, which includes the Antarctic Peninsula, Ellsworth Land and Marie Byrd Land. However, the exact timing of subduction is uncertain due to sparse geochemical sampling in this inaccessible, ice-covered region (Fig. 2b). A compilation of the age progression of volcanic rocks based on the available limited sampling is summarized in Fig. 3. The uncertainties related to the geochemical studies in the region may be illustrated by the difference between an anonymous reviewer's comment to our manuscript: *"the Marie Byrd Land volcanic rocks contain no evidence of a subduction input in their geochemistry*", whereas *Weaver et al. (1994)* and *Mukasa & Dalziel (2000)* provide geochemical evidence for the presence of subduction-related volcanic rocks between 320 and 108 Ma in Marie Byrd Land. The uncertainties appear further evident from another reviewer's comment: "*Along the entire length of the Antarctic Peninsula, post-subduction alkaline volcanic rocks occur in scattered locations and these are unusual in having no subduction signature*", despite it appears clear from other evidence, including seismicity (Fig. 3b), that subduction existed.

With sparse geochemical sampling, leading to controversy regarding geodynamic interpretations, our results based on geophysical evidence and first order observation of the non-continental deep hypsometry of the West Antarctic basins, contribute to constraining geodynamic models for the formation and evolution of West Antarctica. Two earlier studies are further important for our new interpretation of West Antarctica geodynamics.

(1) Plate reconstructions of relative movements between East and West Antarctica indicate relative rotation that may amount to ca. 180 km of separation in the Eocene and Oligocene (*Cande et al., 2000*).

(2) Sparse outcrops of locally exposed volcanic rocks in the Ellsworth and Pencasola mountains around the edge of the Ronne Ice Shelf (Fig. 2b) formed basis for speculations about late Paleozoic – early Mesozoic back-arc basin(s) with an undefined areal extent (*Dalziel and Elliot, 1982; Collinson et al., 1994*).

Based on our geophysical observations and interpretations, taking into account plate reconstructions and the age progression of magmatism and extension in West Antarctica (Fig. 3a) 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 (Fig. 7). 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.

Given the limitations involved in the sampling of volcanic rocks and plate reconstructions in the region, we stress that the timing of these events remains uncertain. However, all geophysical evidence requires that the basin system in West Antarctica originates from Mesozoic back-arc systems. It is possible that the Cenozoic subduction below the Antarctica Peninsula contributed by further back-arc extension in the <N> basins around the Ronne Ice Sheet and the Weddell Sea. Although the back-arc formation has ceased, West Antarctica, which makes one third of the traditionally considered continent, still preserves geophysical and hypsometric characteristics of back-arc systems.

8. Conclusions

We review geophysical and geological observations for West Antarctica and 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.

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Figure Captions

Fig. 1. Basement topography (a) and topography of the ice sheet (b) in the Antarctic region.

Fig. 2. **(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). Locations marked on the map are discussed in text. Colors show rock ages.

Fig. 3. Equivalent topography map (for density of ice 0.92 g/cm^3 and of water 1.02 g/cm^3 corrected to density 2.67 g/cm^3). This map forms basis for our new tectonic model of West Antarctica with subduction-related volcanic arc and back-arc basins.

Also shown are: (a) Color-coded numbers - age of volcanism (*Kyle & Muncy, 1989; Collinson et al., 1994; Mukasa & Dalziel, 2000; Harley, 2003*). **(b)** 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 Fig. 8.

Fig. 4. (a) Crustal thickness in Antarctica compiled from various sources (*Baranov & 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*). In our compilation, we do not use gravity constraints on crustal thickness (e.g. *Block et al., 2009*). **Symbols** – locations of seismic stations.

(b) Seismic Moho depths (from sea level) grouped into classes by tectonic setting. Average values for each tectonic group are used in correlation analysis (Fig. 12).

Fig. 5. Lithosphere thickness in Antarctica (a) based on a seismic tomography model (*An et al., 2015b*), with the LAB defined by a 1% velocity perturbation;

(b) based on thermal TC1 model (*Artemieva, 2006*).

Fig. 6. Hypsometry based on ETOPO1 global model. WA – equivalent hypsometry in West Antarctica (corrected for water and ice) extends down to -1580 m with an average value of -580±335 m. In other back-arc basins average values of equivalent hypsometry are between ca. -3000 m and -300 m (Table 1).

Fig. 7. Plate reconstructions of the region around West Antarctica (after *Musaka and Dalziel, 2000*) illustrating the Mesozoic subduction of the Phoenix Plate in paleo-reconstuctions 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. 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. 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 are spreading ridges.

Fig. 8. Topography, seismicity and gravity anomalies across the Pacific margin of West Antarctica along a series of profiles perpendicular to the paleosubduction trench (see Fig. 3b for locations)**.**

(a) Free air anomalies across the central part of the West Antarctica Pacific margin along three profiles aligned to start at the trench (e - solid line; h – dashed line; I – dotted line). Similar to other subduction systems, the trench has negative and the volcanic arc has slightly positive free air anomalies.

(b) Equivalent hypsometry (top, lines), volcanoes (top, triangles) and seismicity (bottom, circles) profiles. Color codes for lines and symbols refer to profiles in Fig. 3b. Data for the Japan subduction and volcanic arc at 40ºN are shown for comparison.

Fig. 9. Comparison of back-arc basins of the world (see Fig. 10 for locations and Table 1 for details). 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.

Fig. 10. Location of back-arc basins of the world listed in Table 1. The proposed system of back-arc basins of West Antarctica is mostly outside the map.

Fig. 11. Gravity anomalies.

(a) Free air anomaly for onshore (*Scheinert et al., 2016*) and offshore (*Pavlis et al., 2012*) area. Gravity anomalies across the Pacific margin of West Antarctica are similar to active subduction systems with the trench between the two arrows (*Artemieva et al., 2016*). **Dots** - seismicity since 1916 (based on USGS catalogue). **Colored symbols** - depth to Moho from sea level based on reflection/refraction data (boxes) and seismic receiver functions (triangles).

(b) Bouguer anomaly (reduction density 2.67 g/cm^3). Colored symbols - depth to Moho from sea level based on reflection/refraction data (boxes) and seismic receiver functions (triangles).

Fig. 12. Equivalent topography versus crustal thickness for back-arc basins in the world and for tectonic provinces in Antarctica. Tectonic locations for Antarctica are shown in Fig. 4b. Other back-arc basins are described in Table 1 and shown in Fig. 10. Horizontal and vertical bars: standard deviations for locations in Antarctica and the span of values for back-arc basins in the world. Star – average values for areas of West Antarctica below sea level. Best fit lines are based on locations 1b-7 for East Antarctica craton and for locations 8-13 and back-arc basins in the world for back-arcs. For some back-arc basins crustal thickness is unknown.

Fig. 13. Density contrast between the crust and the upper mantle assuming Airy-type isostasy. 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.

Fig. 14. (a) Residual mantle gravity anomalies calculated by subtracting the crustal contribution based on crustal thickness (Fig. 4a) for constant density of 2.8 g/cm^3. Reference model: 40 km thick crust with density 2.8 g/cm^3 above 30 km thick mantle layer with density 3.35 g/cm^3.

(b) Depth to Curie point based on airborne magnetic data (*Martos et al., 2017*).

Fig. 15. Lithosphere density calculated for two end-member scenarios to fit mantle residual gravity anomaly (Fig. 14a) and seismic data on crustal thickness (Fig. 4).

(a) Crustal density assuming that all mantle residual gravity anomaly is caused solely by density variations in the crust. The model is calibrated by seismic data at the reference point in East Antarctica, where crustal density is assumed 2.8 g/cm^3.

(b) Lithospheric mantle density at standard P-T conditions (room temperature and pressure) for the lithospheric layer between the Moho and the seismic LAB (*An et al., 2015a*) (Fig. S2b), assuming constant crustal density of 2.8 g/cm^3.

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.

Table 1. Geophysical characteristics of back-arcs of the world

No.	Back-arcs	Bathymetry (m)	Equivalent topography (m)	Free air anomalies (mGal)	Bouguer anomalies (mGal)	Crustal thickness from seismic data (km)
	Active					
2	Tyrrhenian Sea	-3000 to -1000	-1875 to -625	-30 to +20	+20 to +180	Ca. 8 km (*Sartori et al., 2004*)
3	Andaman Sea	-3000 to -500	-1875 to -310	-20 to +40	0 to +200	N/A
4	Aegean Sea	-1500 to -800	-950 to -500	+30 to +100	+100 to +150	Ca. 25 km (*Zhu et al., 2006*)
5	Okinawa Trough	-1000 to -100	-625 to -60	0 to +40	+100 to +150	23-27 km (*Nakamura & Umedu, 2009*)
8	Lau Basin	-2500 to -1700	-1560 to -1060	+10 to +70	+90 to +200	5-10 km (*Crawford et al., 2003*)
9	Mariana Trough	-4000 to -3000	-2500 to -1875	-30 to +50	+200 to +300	5-7 km (*Takahashi et al., 2007*)
10	E. Scotia Sea	-4000 to -3000	-2500 to -1875	+10 to +40	+200 to +300	N/A
	Extinct					
6	Sea of Japan	-3000 to -500	-1875 to -310	-15 to +40	+100 to +250	15-20 km (*Iwasaki et al., 2003*)
7	Kurile Basin	-3000 to -1000	-1875 to -625	-30 to +30	+100 to +250	N/A
11	Banda Basins	-4000 to -1800	-2500 to -1130	+10 to +100	+250 to +350	N/A
12	Parece-Vela	-5000 to -2000	-3125 to -1250	-20 to +40	+250 to +350	N/A
13	Gulf of Mexico	-5000 to -1500	-3125 to -950	-20 to +15	+150 to +320	7-10 km (*Christeson et al., 2014*)
14	W. Philippine Sea	-5500 to -4500	-3440 to -2810	-5 to +20	+350 to +400	3-5 km (*Goodman et al., 1989*)
1	West Antarctica (only regions with negative equivalent topography)	-675±350 (-1850 to 0)	-580±335 (-1580 to 0)	-23±20 (-40 to +20)	5±23 (-30 to +50)	25±5.7 km (14 km to 40 km) (*Baranov & Morelli, 2013; Feng et al., 2014; An et al., 2015b; Ramirez et al., 2016*)

Figures

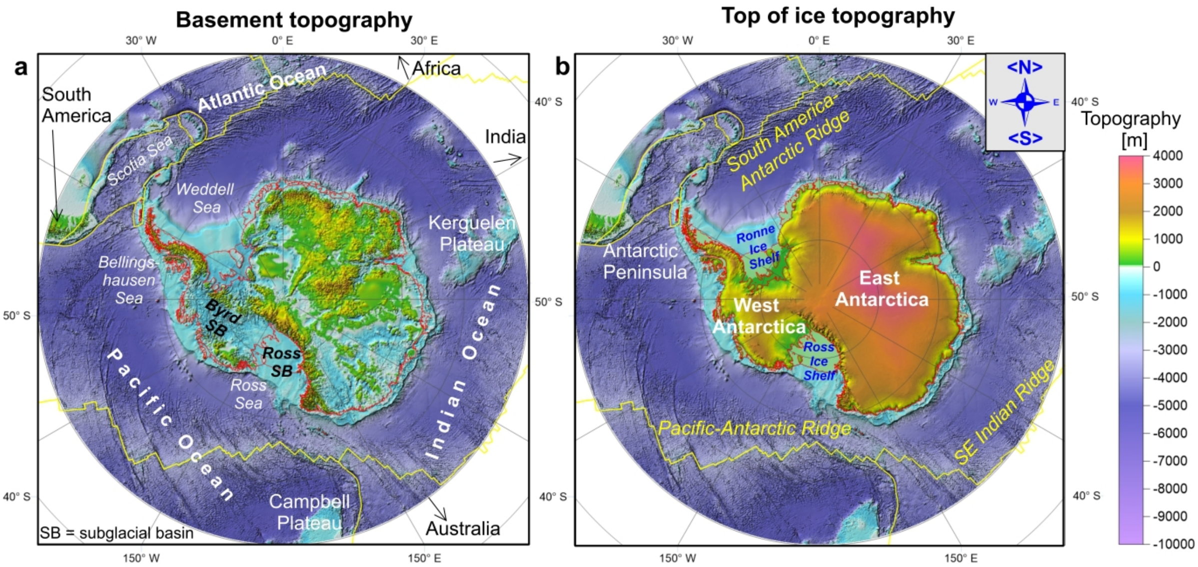

Fig. 1. Basement topography (a) and topography of the ice sheet (b) in the Antarctic region.

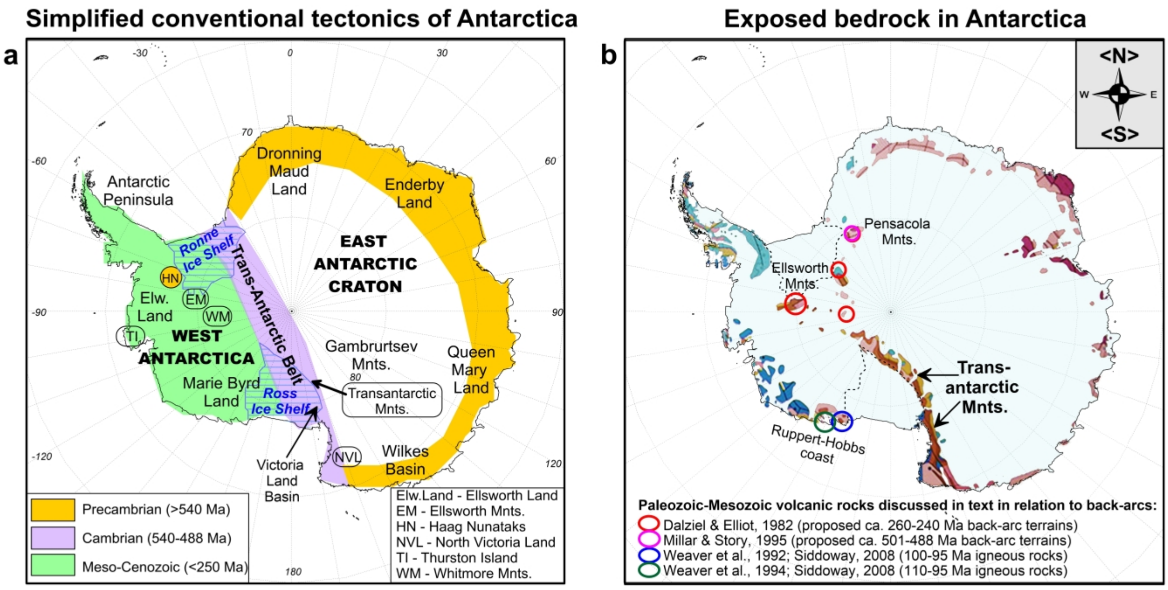

Fig. 2. **(a)** Classic concept of Antarctica consisting of three domains: West Antarctica made of several amalgamated continental terranes, East Antarctica craton, and the Trans-Antarctic belt (*Harley, 2003*).

(b) Exposed bedrock in Antarctica (based on CGMW Geological Map of the World, 2002). Locations marked on the map are discussed in text. Colors show rock ages.

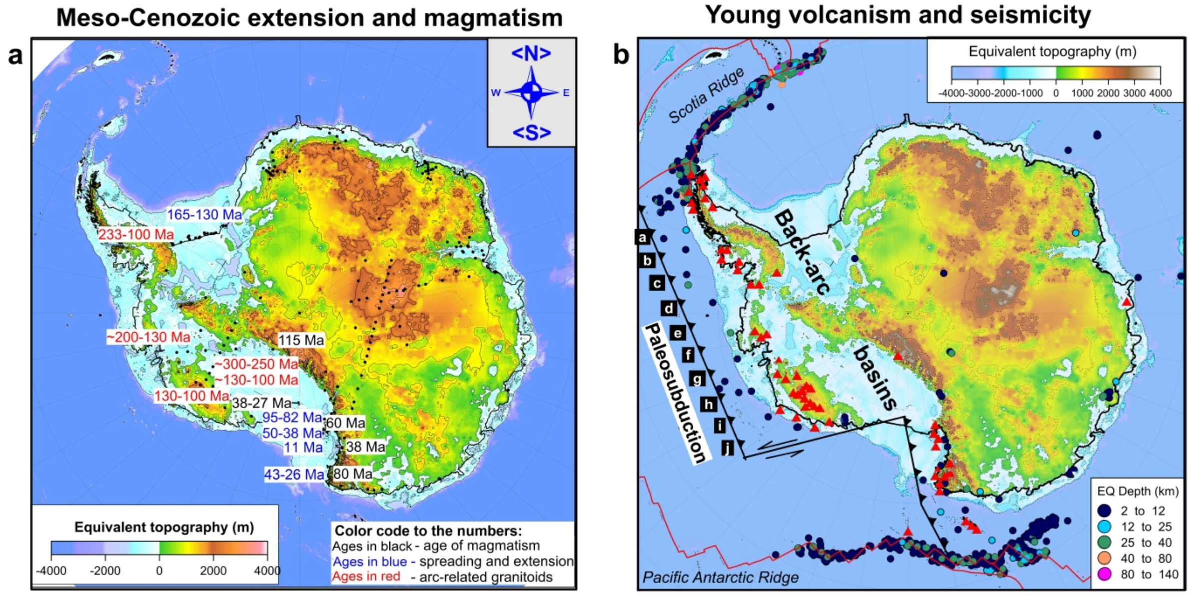

Fig. 3. Equivalent topography map (for density of ice 0.92 g/cm^3 and of water 1.02 g/cm^3, corrected to density 2.67 g/cm^3). This map forms basis for our new tectonic model of West Antarctica with subduction-related volcanic arc and back-arc basins. **Also shown are: (a)** Color-coded numbers - age of volcanism (*Kyle & Muncy, 1989; Collinson et al., 1994; Mukasa & Dalziel, 2000; Harley, 2003*). **(b)** 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 Fig. 8.

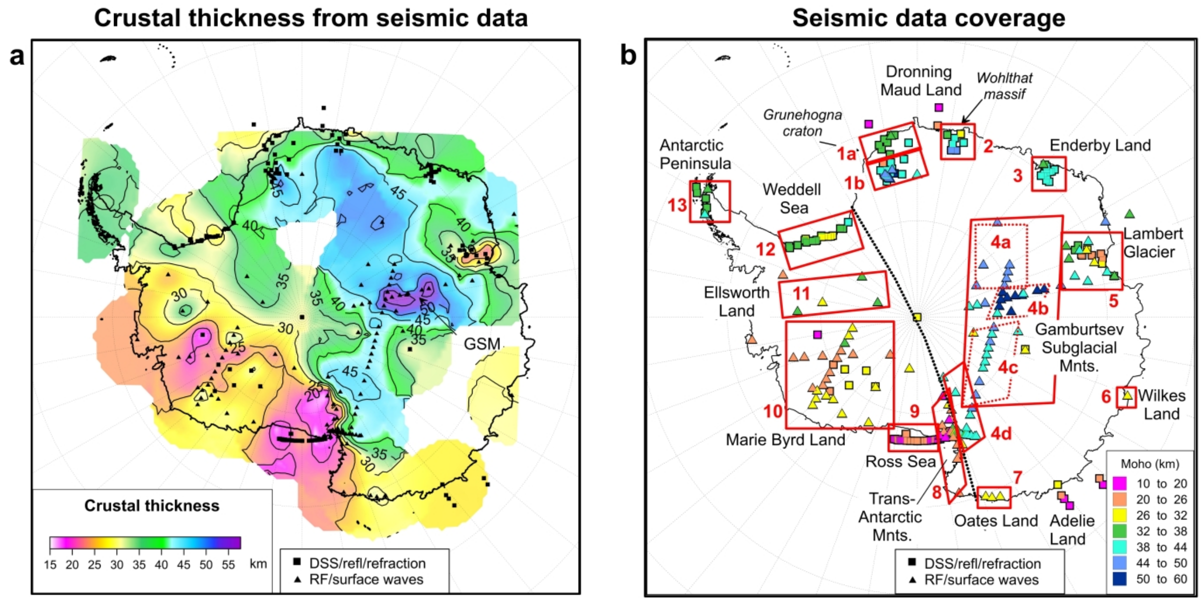

Fig. 4. (a) Crustal thickness in Antarctica compiled from various sources (*Baranov & Morelli, 2013;* updated by results from *Chaput et al., 2014; Feng et al., 2014; An et al., 2015b; Hansen et al., 2016; Ramirez et al., 2016*). In our compilation, we do not use gravity constraints on crustal thickness (e.g. *Block et al., 2009*). **Symbols** – locations of seismic stations.

(b) Seismic Moho depths (from sea level) grouped into classes by tectonic setting. Average values for each tectonic group are used in correlation analysis (Fig. 12).

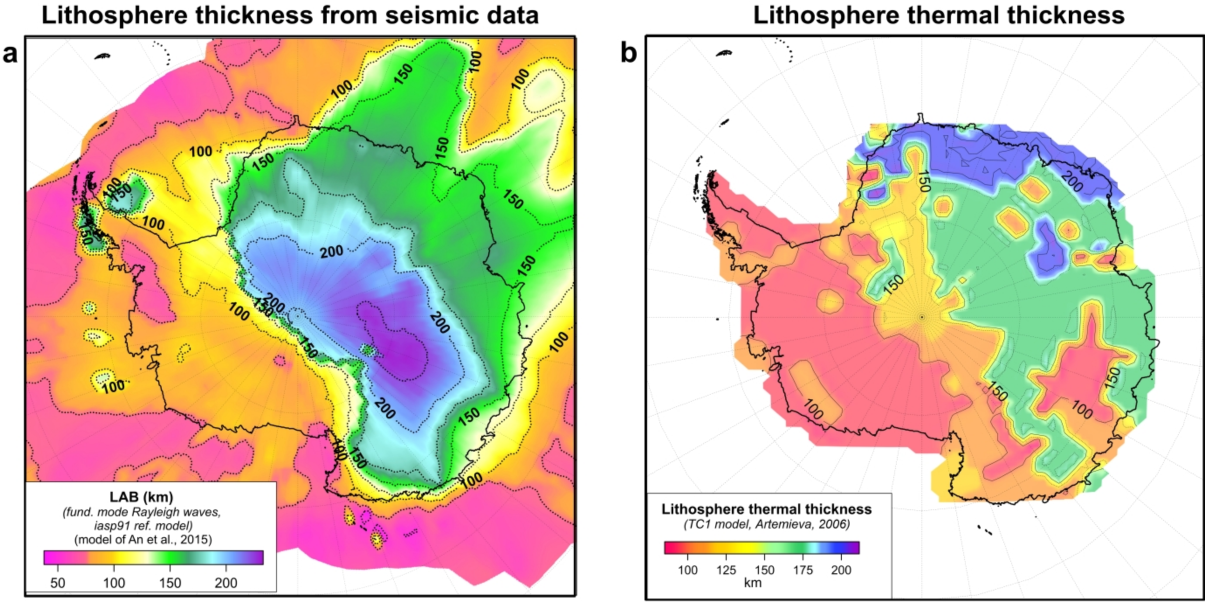

Fig. 5. Lithosphere thickness in Antarctica (a) based on a seismic tomography model (*An et al., 2015b*), with the LAB defined by a 1% velocity perturbation;

(b) based on thermal TC1 model (*Artemieva, 2006*).

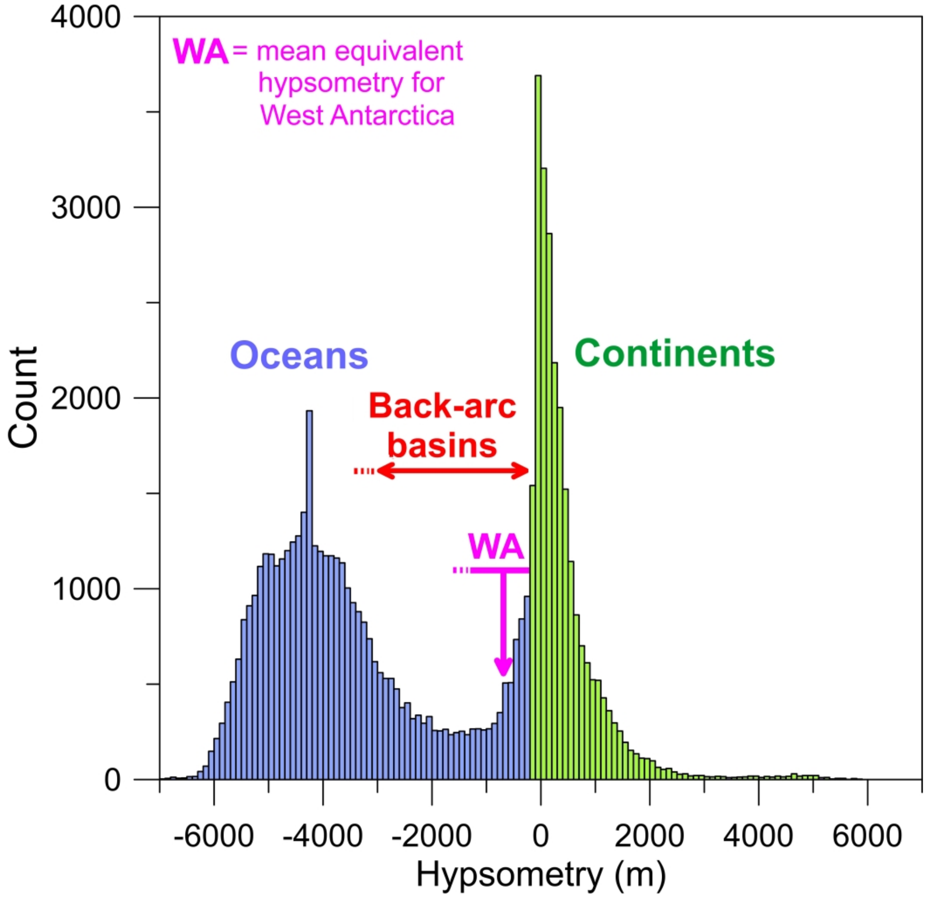

Fig. 6. Hypsometry based on ETOPO1 global model. WA – equivalent hypsometry in West Antarctica (corrected for water and ice) extends down to -1580 m with an average value of -580±335 m. In other back-arc basins average values of equivalent hypsometry are between ca. -3000 m and -300 m (Table 1).

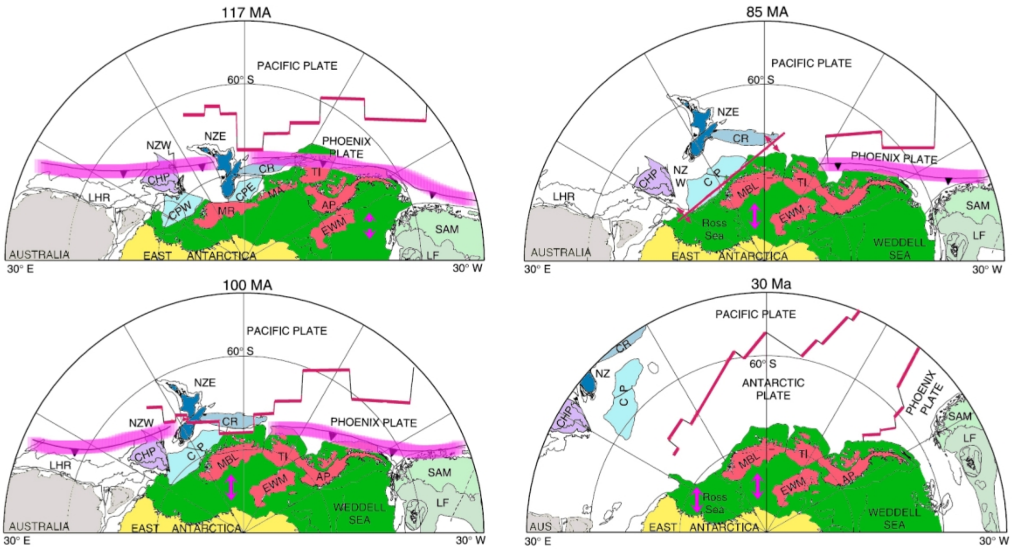

Fig. 7. Plate reconstructions of the region around West Antarctica (after *Musaka and Dalziel, 2000*) illustrating the Mesozoic subduction of the Phoenix Plate in paleoreconstuctions between 117 and 30 Ma. Location of the subduction trench is emphasized by a purple line and purple arrows illustrate locations of back-arc spreading and extension. 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. 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 are spreading ridges.

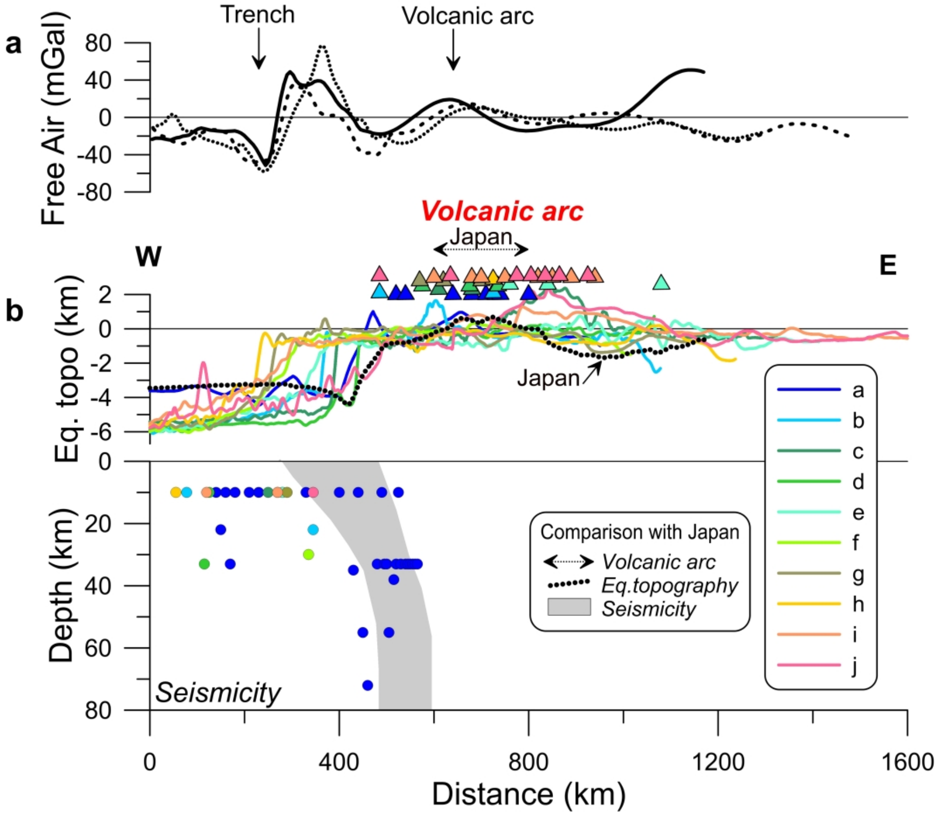

Fig. 8. Topography, seismicity and gravity anomalies across the Pacific margin of West Antarctica along a series of profiles perpendicular to the paleosubduction trench (see Fig. 3b for locations)**.**

(a) Free air anomalies across the central part of the West Antarctica Pacific margin along three profiles aligned to start at the trench (e - solid line; h – dashed line; I – dotted line). Similar to other subduction systems, the trench has negative and the volcanic arc has slightly positive free air anomalies.

(b) Equivalent hypsometry (top, lines), volcanoes (top, triangles) and seismicity (bottom, circles) profiles. Color codes for lines and symbols refer to profiles in Fig. 3b. Data for the Japan subduction and volcanic arc at 40ºN are shown for comparison.

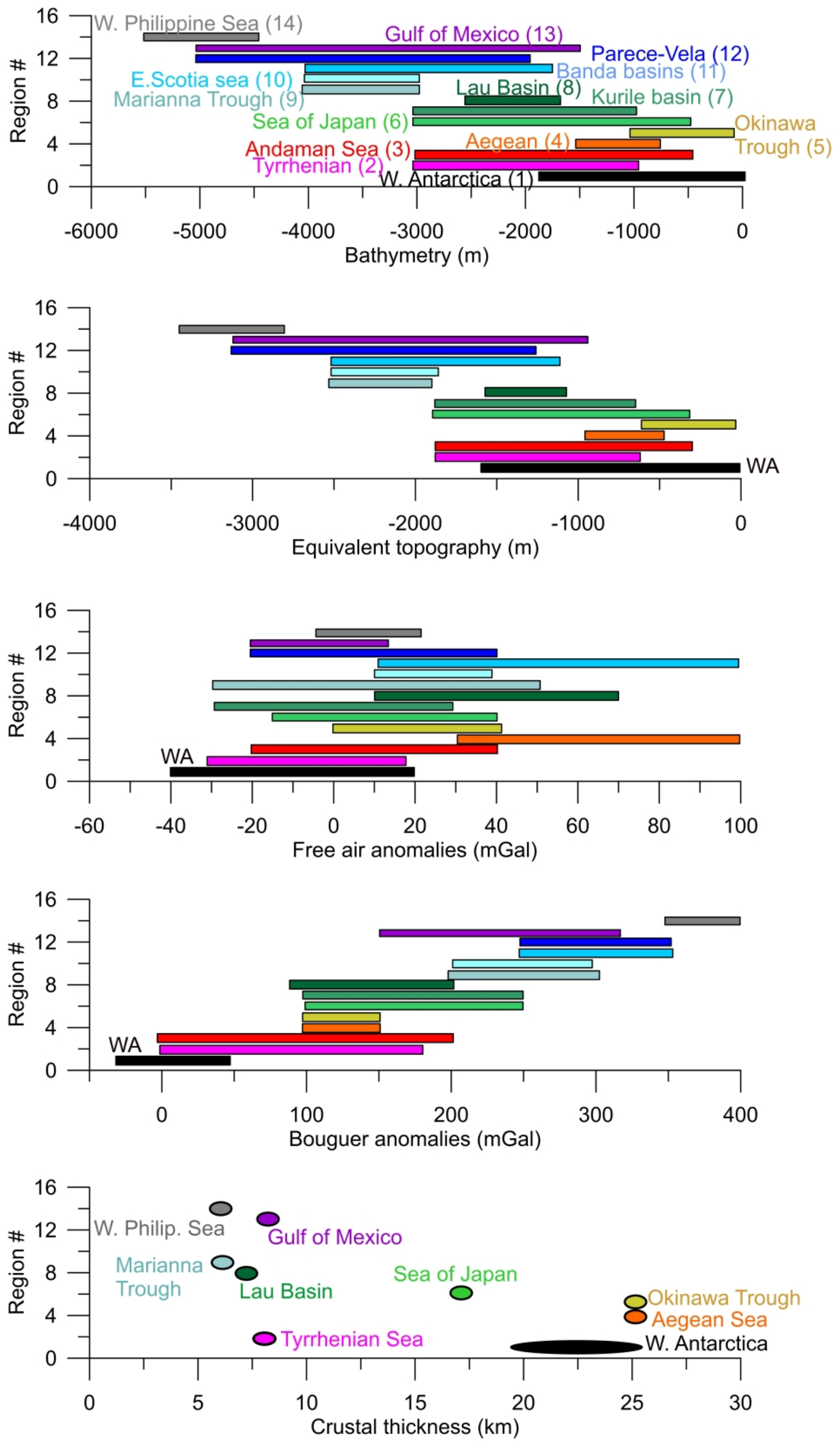

Fig. 9. Comparison of back-arc basins of the world (see Fig. 10 for locations and Table 1 for details). Color-coded boxes show typical range of values. Black boxes – typical values for regions of West Antarctica with negative equivalent topography. West Antarctica is particularly similar to back-arc basins of the Tyrrhenian, Andaman, Okinawa and Aegean systems.

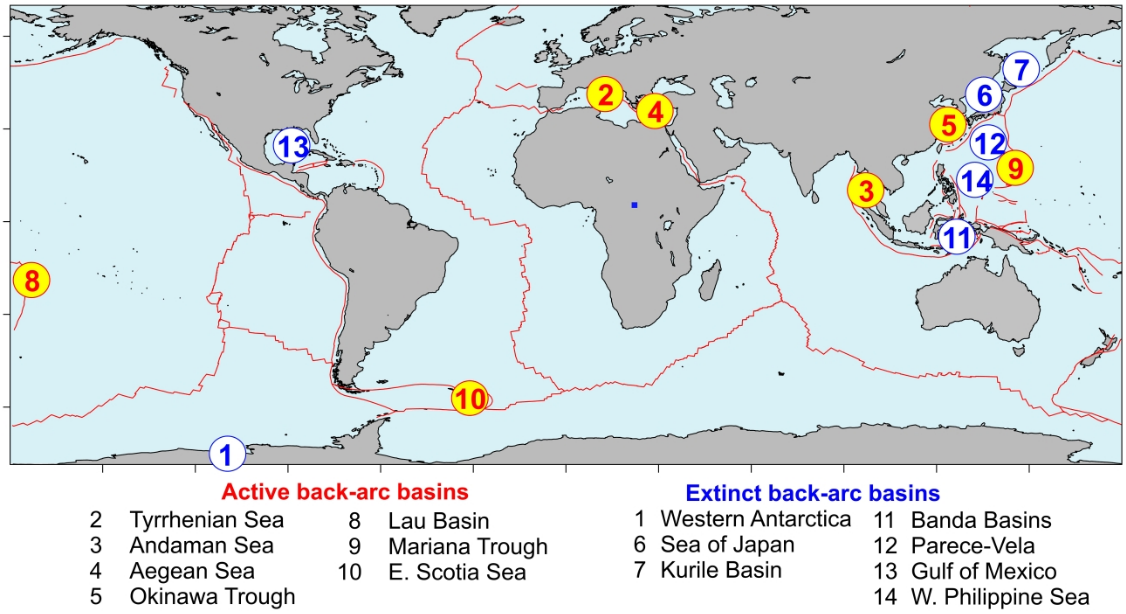

Fig. 10. Location of back-arc basins of the world listed in Table 1. The proposed system of back-arc basins of West Antarctica is mostly outside the map.

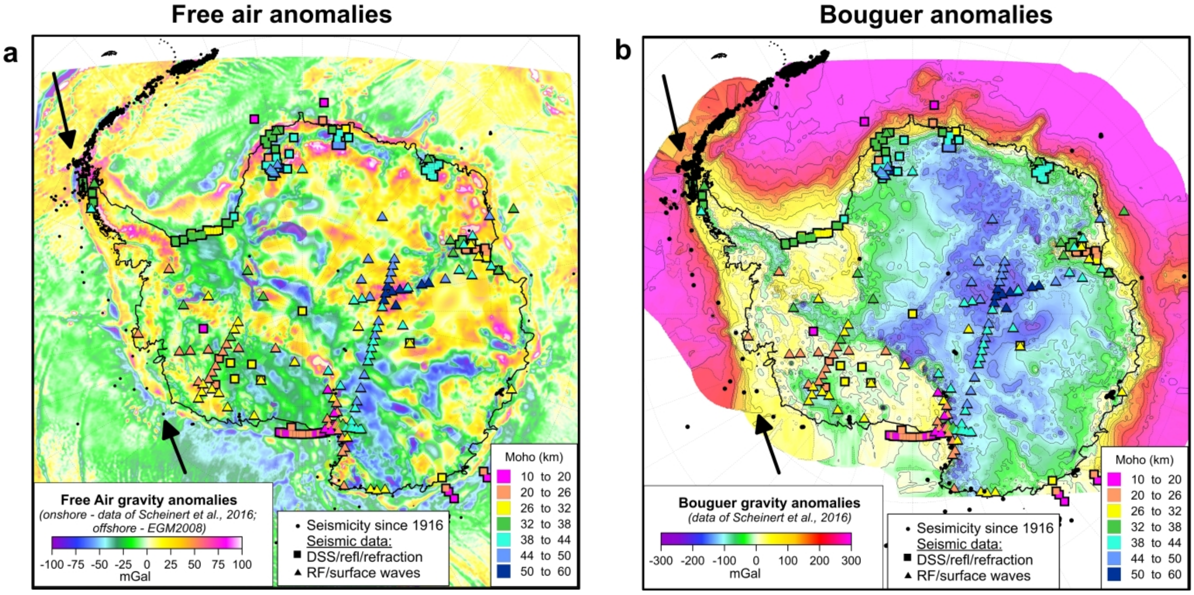

Fig. 11. Gravity anomalies.

(a) Free air anomaly for onshore (*Scheinert et al., 2016*) and offshore (*Pavlis et al., 2012*) area. Gravity anomalies across the Pacific margin of West Antarctica are similar to active subduction systems with the trench between the two arrows (*Artemieva et al., 2016*). **Dots** - seismicity since 1916 (based on USGS catalogue). **Colored symbols** - depth to Moho from sea level based on reflection/refraction data (boxes) and seismic receiver functions (triangles).

(b) Bouguer anomaly (reduction density 2.67 g/cm^3). Colored symbols - depth to Moho from sea level based on reflection/refraction data (boxes) and seismic receiver functions (triangles).

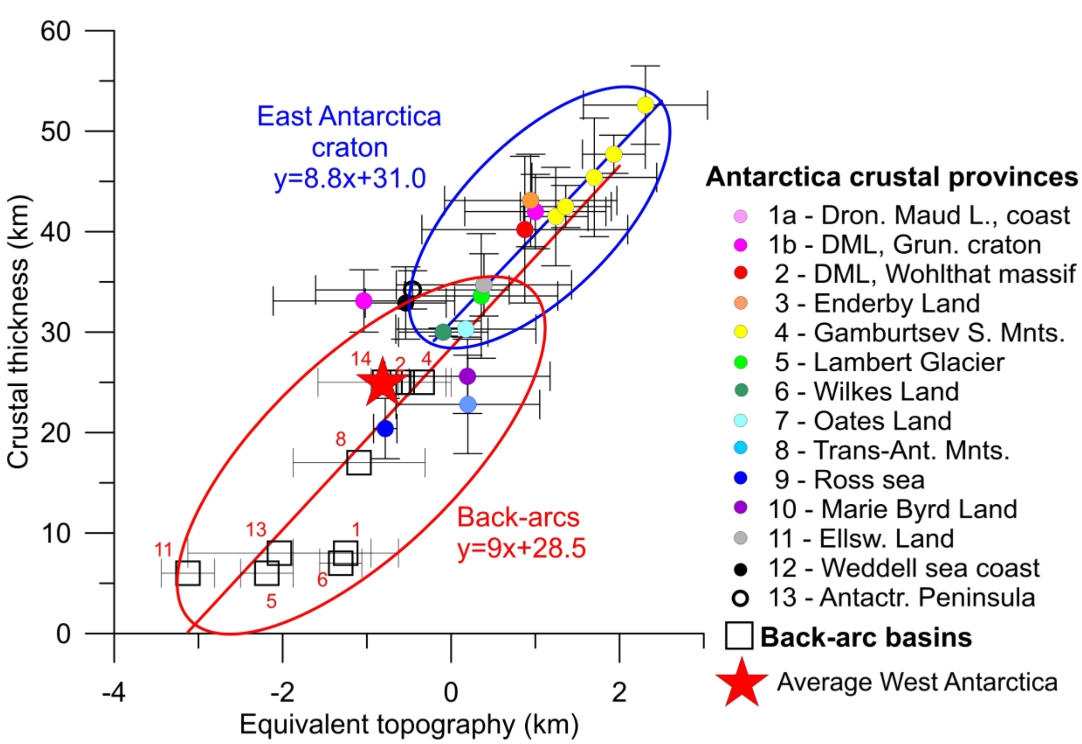

Fig. 12. Equivalent topography versus crustal thickness for back-arc basins in the world and for tectonic provinces in Antarctica. Tectonic locations for Antarctica are shown in Fig. 4b. Other back-arc basins are described in Table 1 and shown in Fig. 10. Horizontal and vertical bars: standard deviations for locations in Antarctica and the span of values for back-arc basins in the world. Star – average values for areas of West Antarctica below sea level. Best fit lines are based on locations 1b-7 for East Antarctica craton and for locations 8-13 and back-arc basins in the world for back-arcs. For some back-arc basins crustal thickness is unknown.

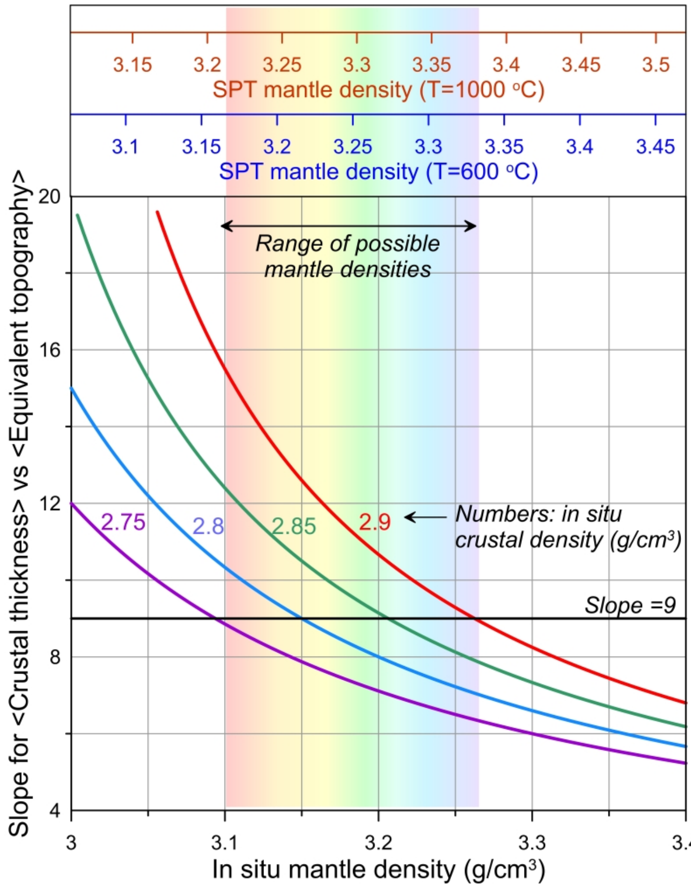

Fig. 13. Density contrast between the crust and the upper mantle assuming Airy-type isostasy. Vertical axis – slope of the equivalent topography versus crustal thickness trend. Horizontal axes – mantle density at in situ conditions (bottom) and recalculated to room (SPT) conditions for two different in situ temperatures.

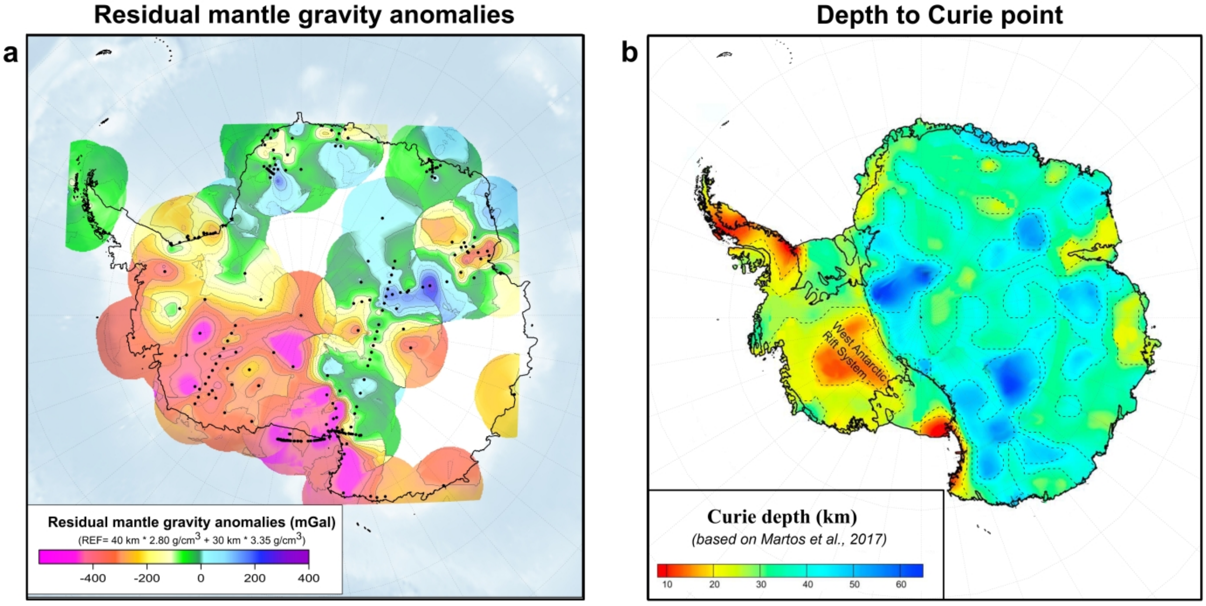

Fig. 14. (a) Residual mantle gravity anomalies calculated by subtracting the crustal contribution based on crustal thickness (Fig. 4a) for constant density of 2.8 g/cm^3. Reference model: 40 km thick crust with density 2.8 g/cm^3 above 30 km thick mantle layer with density 3.35 g/cm^3. **(b)** Depth to Curie point based on airborne magnetic data (*Martos et al., 2017*).

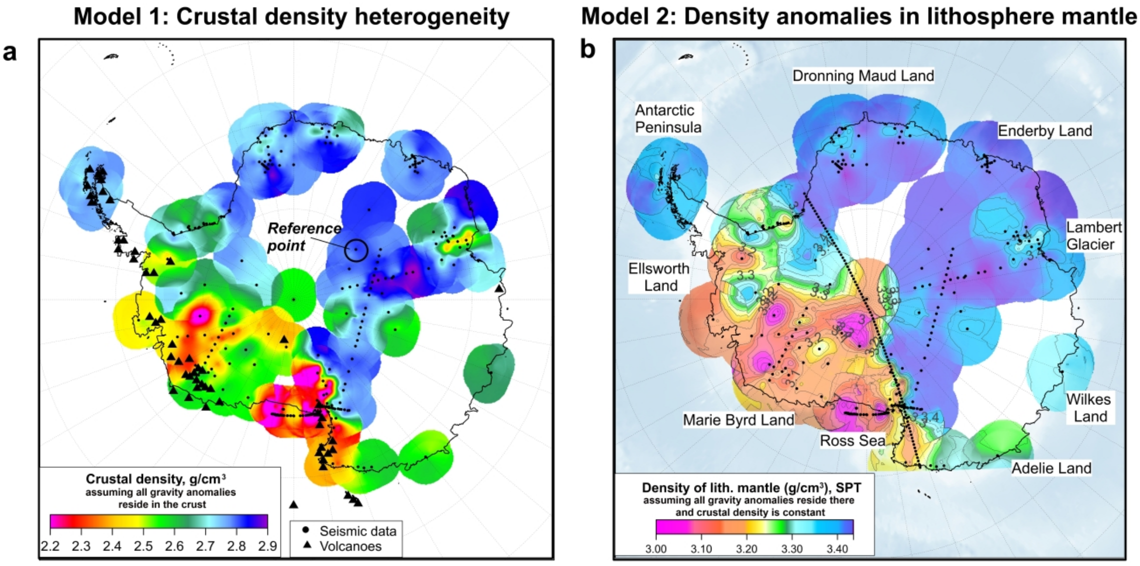

Fig. 15. Lithosphere density calculated for two end-member scenarios to fit mantle residual gravity anomaly (Fig. 14a) and seismic data on crustal thickness (Fig. 4).

(a) Crustal density assuming that all mantle residual gravity anomaly is caused solely by density variations in the crust. The model is calibrated by seismic data at the reference point in East Antarctica, where crustal density is assumed 2.8 g/cm^3.

(b) Lithospheric mantle density at standard P-T conditions (room temperature and pressure) for the lithospheric layer between the Moho and the seismic LAB (*An et al., 2015a*) (Fig. S2b), assuming constant crustal density of 2.8 g/cm^3.

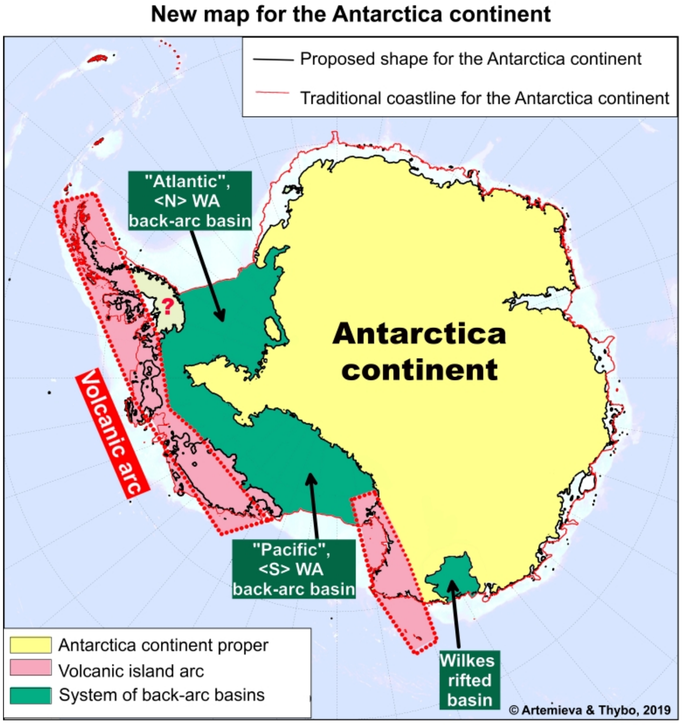

Fig. 16. New model of the Antarctica continent and the West Antarctica back-arc system behind the volcanic arc formed by Mesozoic subduction. The possible <S> volcanic arc is proposed to explain the Wilkes basin within the framework of the “Atlantic” and “Pacific” back-arc basins, although less constrained by our geophysical data.

Table 1. Geophysical characteristics of back-arcs of the world

No.	Back-arcs	Bathymetry (m)	Equivalent topography (m)	Free air anomalies (mGal)	Bouguer anomalies (mGal)	Crustal thickness from seismic data (km)
	Active					
2	Tyrrhenian Sea	-3000 to -1000	-1875 to -625	-30 to +20	+20 to +180	Ca. 8 km (*Sartori et al., 2004*)
3	Andaman Sea	-3000 to -500	-1875 to -310	-20 to +40	0 to +200	N/A
4	Aegean Sea	-1500 to -800	-950 to -500	+30 to +100	+100 to +150	Ca. 25 km (*Zhu et al., 2006*)
5	Okinawa Trough	-1000 to -100	-625 to -60	0 to +40	+100 to +150	23-27 km (*Nakamura & Umedu, 2009*)
8	Lau Basin	-2500 to -1700	-1560 to -1060	+10 to +70	+90 to +200	5-10 km (*Crawford et al., 2003*)
9	Mariana Trough	-4000 to -3000	-2500 to -1875	-30 to +50	+200 to +300	5-7 km (*Takahashi et al., 2007*)
10	E. Scotia Sea	-4000 to -3000	-2500 to -1875	+10 to +40	+200 to +300	N/A
	Extinct					
6	Sea of Japan	-3000 to -500	-1875 to -310	-15 to +40	+100 to +250	15-20 km (*Iwasaki et al., 2003*)
7	Kurile Basin	-3000 to -1000	-1875 to -625	-30 to +30	+100 to +250	N/A
11	Banda Basins	-4000 to -1800	-2500 to -1130	+10 to +100	+250 to +350	N/A
12	Parece-Vela	-5000 to -2000	-3125 to -1250	-20 to +40	+250 to +350	N/A
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The authors declare no conflict of interest

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