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1/3 of Antarctica is Not a Continent: Geophysical Evidence for West Antarctica as a Backarc System

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Antarctica has traditionally been considered continental inside the coastline of ice and bedrock. In our recent study (Artemieva and Thybo, 2020) we reconsider the conventional extent of this continent and demonstrate that 1/3 of Antarctica is not a continent. Here we present a brief summary of our results.

Most of the Antarctica continent is covered by a 0.5–3.0 km thick ice sheet, and the only direct information on its geology and geodynamic evolution comes from tiny outcrops of bedrock exposed mostly along the edge of the ice sheet and in the Trans-Antarctic Mountains that separate tectonically stable cratonic East Antarctica from a much younger West Antarctica. Based on existing geophysical data, East Antarctica shows all characteristics of a normal cratonic lithosphere, with a 38–55 km thick crust, fast seismic velocities in the upper mantle, and thicker than 150–250 km lithosphere (Baranov and Morelli, 2013; Hansen et al., 2014; An et al., 2015). Sparse geochemical data indicate Archean-Proterozoic ages for basement outcrops along the edges of the ice sheet in EA.

The only Precambrian (Grenvillian age) rocks known in West Antarctica are in the Ellsworth-Whitmore mountains (Tingey, 1991). This basement high separates two large and broad depressions in equivalent topography, the Ross and the Ronne Ice Shelves. The Ross Ice Shelf with a size of ca 2000 km × 1000 km is one of the world's largest crustal extension areas and continues into West Antarctica. Historically West Antarctica is interpreted as the West Antarctica Rift System (WARS) (Behrendt, 1999), and until present it is referred as WARS in all regional publications. The proposed tectonic analogues include the North Sea Rift, the Newfoundland-Iberia passive margin, the East African Rift, and the Basin and Range Province in western USA (LeMasurier, 2008). All of these analogues assume continental rifting as a major tectonic process, with localized deformation of continental lithosphere due to either deep thermal anomalies or far-field tectonic stresses. However, West Antarctica does not have linear zones of extension as in continental rifts and does not have broad areas of homogeneous extension as in the Basin and Range Province. Instead, West Antarctica represents a huge extensional area with series of basins with an extremely deep equivalent topography. Equivalent topography is used in ice- and water-covered areas, and it is topography calculated by compressing ice and water masses to density of near-surface rocks, 2.67 g/cc here.

Topography is controlled by lithosphere buoyancy and dynamic component from intra-lithospheric stresses and sublithospheric dynamic processes. In continental lithosphere it ranges from high elevations in young mountain belts, to 300–500 m elevation in the cratons, and to 0 to −200 m of equivalent topography in extended lithosphere of continental shelves. Here we interpret an unusually deep equivalent topography (−580 ± 335 m on average and down to −1.6 km) in West Antarctica as back-arc basin system, flanked by a volcanic arc. Such deep bathymetry is not observed on submerged continental lithosphere (e.g., shelves do not extend deeper than −200 m in equivalent hypsometry), but it is common in other back-arc basins. This first order observation questions the conventional interpretation of West Antarctica as continental.

Geophysical observations in support of our interpretation

We report a set of geophysical observations in support of our geodynamic interpretation. This includes:

(a) A linear belt of seismicity sub-parallel to the volcanic arc along the Pacific Arctic margin of West Antarctica,

(b) The presence of a volcanic arc along the West Antarctica margin,

(c) A pattern of free air gravity anomalies typical of subduction systems,

(d) Extremely thin crystalline crust typical of back-arc basins.

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 (Fig. 1), instead of a continental rift system as conventionally interpreted.

(a) We recognize a linear belt of shallow magnitude 4.2

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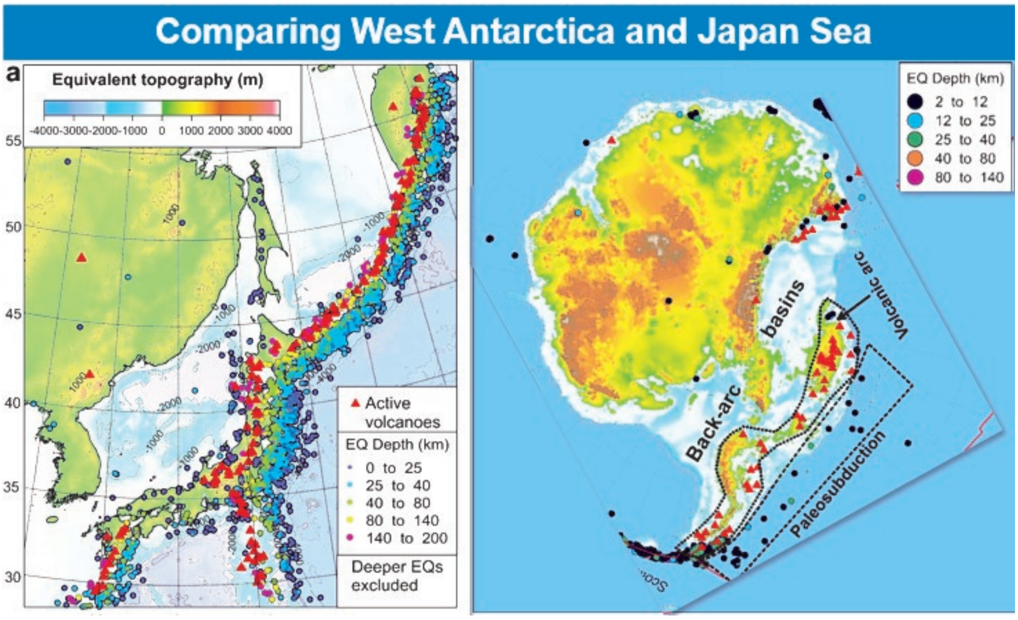

Fig. 1. Comparison of equivalent topography and seismicity style in West Antarctica and the Japan Sea. Antarctica continent is rotated by 120 deg counterclockwise to demonstrate the similarity between the two regions.

–6.3 seismicity (USGS catalogue) parallel to the volcanic belt which we interpret as related to paleosubduction of the Pacific plate below West Antarctica. 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 (e.g., Japan and the Aleutians).

(b) West Antarctica is flanked in the west by the (largely extinct) volcanic arc along the Pacific-Antarctic paleosubduction zone. Apparently the age of volcanics decreases from Triassic-Cretaceous in the Antarctic Peninsula to Cretaceous arc-related granitoids in the western Marie Byrd Land (MBL) to the active volcanoes at the Ross Sea, although few recently active volcanoes exist at the tip of the Antarctic Peninsula. The volcanic belt forms a narrows elongated zone with positive equivalent topography between the Pacific Ocean and the West Antarctica basin.

(c) Subduction systems have a unique pattern of free air gravity anomalies across the strike with strong negative anomalies above trenches followed by weak positive anomalies towards the volcanic arc. We observe a similar pattern of gravity anomalies along the Pacific Arctic margin of West Antarctica. We interpret a linear belt of weakly negative (–100 to 40 mGal) free air anomalies as gravity signal from the trench, which has been isostatically readjusted and filled with sediments such that there is no bathymetric expression of the trench. A parallel belt of weakly positive (+10+70 mGal) free air anomalies exists on the side of the volcanic arc.

(d) Characteristics of back-arc basins is the presence (existence) of zones where oceanic-type crust is being produced or the stretching has developed close to the production of a new oceanic-type crust. The West Antarctic basin has thin (25 ± 5.7 km) crust similar to crustal thickness in the back-arc basins of the Aegean Sea, Okinawa Trough and the Sea of Japan. Such widely occurring thin crust is atypical for continental lithosphere except for in a localized rift zones.

Testing the new geodynamic model

We calculate residual mantle gravity anomalies which show principally different patterns in East and West Antarctica with extremely low values (< –300 mGal) in West Antarctica. These anomalies originate either from crustal density heterogeneity or from thermo-chemical heterogeneity of the mantle, or a combination of both.

(1) As one end-member scenario, we investigate a possible role of crustal heterogeneity in WA, using seismic models on regional variations in crustal thickness and assuming isostasy is satisfied at the Moho. Under these assumptions, West Antarctica has extremely low average crustal density, between 2.1 and 2.6 g/cc. The values of 2.4–2.6 g/cc for average crustal density are possible in case sedimentary cover makes up to 50–60% of the total crustal thickness. For a 25 km deep Moho, it means that the crustal basement is only ca. 12 km thick, and such continental crust is not observed anywhere.

(2) As another end-member scenario, we calculate the density distribution in the lithospheric mantle under the assumption that no density heterogeneity exists in the crust which has an average density of 2.8 g/cc. Making the reasonable assumption that all mantle density contrast resides in the layer between the Moho and the LAB (with LAB defined from a recent regional seismic tomography model (An et al., 2015)), we find in situ lithospheric mantle densities of less than 3.1 g/cc in West Antarctica. These values are too low to be realistic, having in mind a huge size of the region. The very low densities in the lithospheric mantle require very high temperatures and, possibly, the presence of fluids and melts below the entire

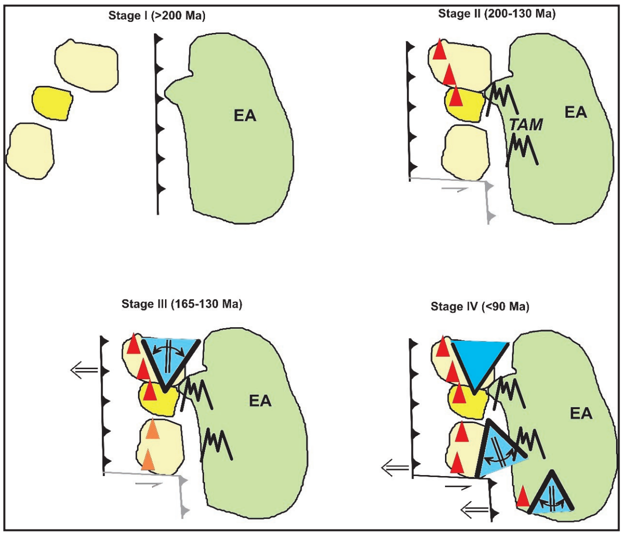

Fig. 2. Geodynamic interpretation. We propose that the basins in West Antarctica developed in back-arc systems due to subduction roll-back at various stages. EA=East Antarctica craton; TAM=Trans-Antarctic mountains. Black line on the left – paleo-Pacific subduction; blue colors – back-arc basins.

Fig. 3. New map for the Antarctica continent (Artemieva and Thybo, 2020), where West Antarctica is not continental but represents series of back-arc basins (green) flanked by volcanic arcs (red).

West Antarctica with a size much larger than around continental rifts. We interpret these low-density mantle anomalies as related to the back-arc spreading with a possible mid-ocean ridge formation, which has later ceased.

Geodynamic evolution

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 (Fig. 2). Our geodynamic model involves four stages:

• Stage I (> 200 Ma): 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 (200–130 Ma): 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 (165–130 Ma): 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 (< 90 Ma): 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.

Our finding reduces the continental lithosphere in Antarctica to 2/3 of its traditional area (Fig. 3). This result has significant implications for global models of lithosphere-mantle dynamics and models of the ice sheet evolution. 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.

Key words: paleosubduction, back-arc extension, continental crust, lithosphere, upper mantle

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