Tectonics of the Antarctic

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Introduction

The Antarctic region extends from 60°S to the South Pole and includes the Antarctic continent surrounded by the southern parts of Atlantic, Indian and Pacific Oceans (Fig. 1). At 14 million km², the continent is almost completely (by 99%) covered with ice that averages 1.9 km in thickness. However, even rare rock outcrops visited by scientists at the early stage of Antarctic exploration provided exiting basic information about geological structure of Antarctica which appeared a missing link of Gondwanaland that had utmost importance for reconstructing global tectonic history.

As a consequence, after the entry in force in 1961 of the Antarctic Treaty, IUGS recommended that Antarctica should be taken into account by CGMW as one of the regions of the World, and respective action was taken at the CGMW meeting in December in 1962 by establishing Sub-commission for Antarctica.

Since then CGMW consistently encouraged publication of overview geoscience maps of the continent compiled both under international projects and in individual counties. A few geological and tectonic maps of Antarctic mainland at 1:5,000,000 and 1:10,000,000 scale were produced in the last decades of the past century mainly in Russia, USA and Australia, and various geological and structural images of the Antarctic region also appeared in global compilations made under CGMW auspices. In early

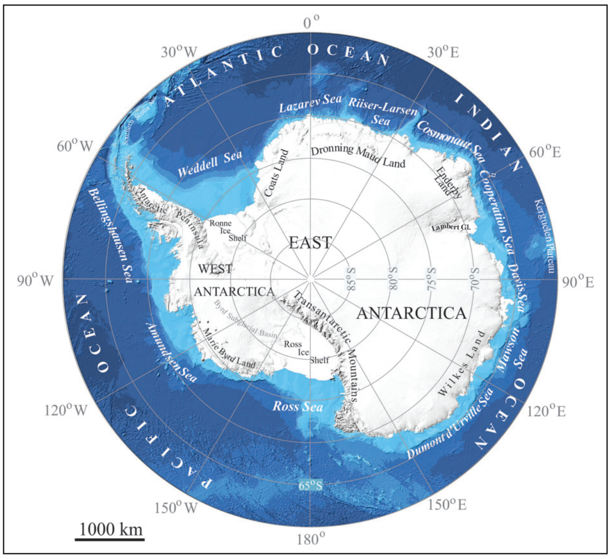

Figure 1. Antarctic physiography and selected place names referred to in the text. Source: Geographic background from Arndt et al., 2013.

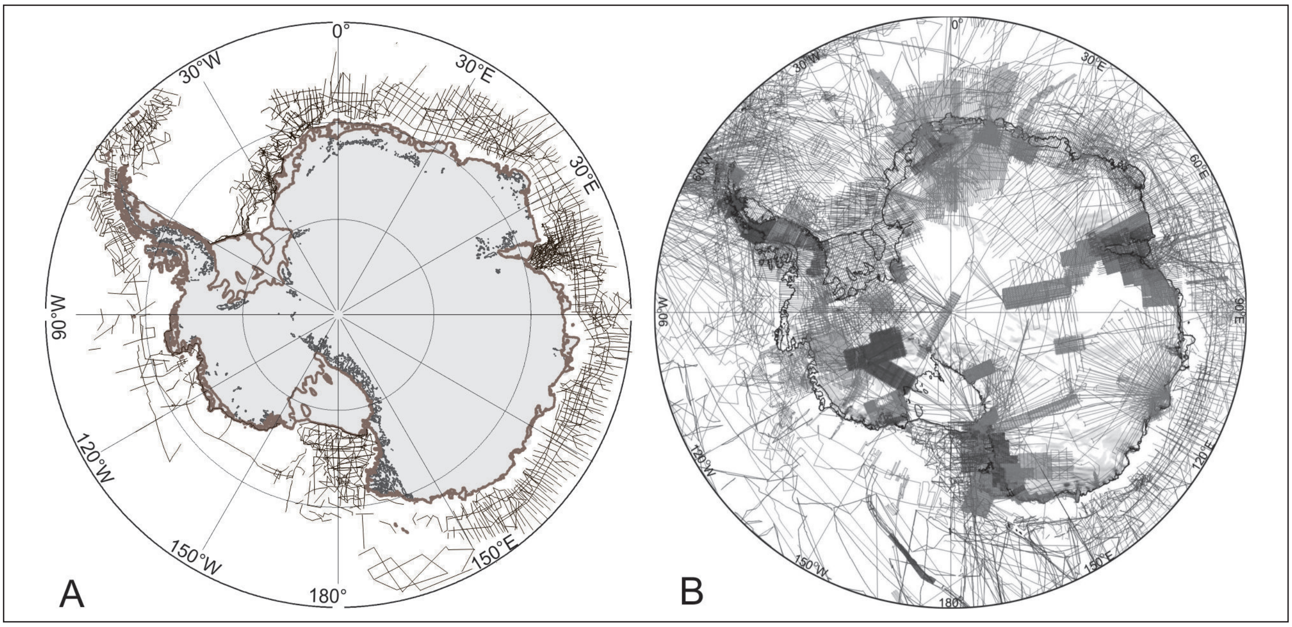

Figure 2. Geophysical research in the Antarctic. A – location of multichannel seismic lines. Source: https://sdls.ogs.trieste.it. B – location of air-borne and ship-born magnetic lines. Source: Golynsky et al., 2017.

1. INERIS, Parc technologique Alata, 60550 Verneuil-en-Halatte. Courriel : philippe.gombert@ineris.fr
2. Stations de Transfert d'Energie par Pompage.

2000-s CGMW contributed to IPY 2007-2009 scientific program by launching special projects for preparation of Arctic and Antarctic tectonic maps, and the map encompassing both the Antarctic continent and the surrounding Southern Ocean south of 600 S was first published at 1:10,000,000 scale (Grikurov and Leitchenkov, 2012). A considerable progress was made about the same time by several independent Antarctic projects relevant to tectonic interpretations, such as mapping of Antarctic subglacial bedrock (Fretwell *et al.*, 2013) and Circum-Antarctic bathymetry (Arndt *et al.*, 2013), synthesizing marine seismic data (Fig. 2A; Cooper *et al.*, 2011) and the results of magnetic surveys (Fig. 2B; Golynsky *et al.*, 2017). New findings provided by these initiatives, as well as continued massive employment of state-of-the-art isotopic and geochemical studies of the Antarctic rocks enabled improved understanding of tectonic structure and geodynamic history of the Antarctic region and prompted compilation of the updated 2-nd edition of earlier printed 1:10,000,000 tectonic map. Generalized version of currently prepared draft of the new is presented and briefly discussed in this paper.

Outline of Antarctic structural and tectonic history (Fig. 3)

The bulk of East Antarctic landmass is an essentially unaltered remnant of ancient continental crust that was amalgamated into primeval Gondwana supercontinent close to Precambrian/Phanerozoic time boundary. The Transantarctic Mountains and West Antarctica with southern Scotia Arc belong to Panthalassic-Pacific active margin of Gondwana affected in Phanerozoic by both accretional crustal buildups and strong crustal stretching. Post-breakup Gondwana disintegration led to opening and expansion of Atlantic and Indian sectors of the Southern Ocean.

Antarctic landmass

East Antarctica is underlain by Archean nuclei (cratons) and Proterozoic structures, the latter displayed as orogenic belts, supracrustal intraplate fold systems and platform covers (Harley *et al.*, 2013; Mikhalsky and Leitchenkov, 2018). The occurrence of these units is verified in scattered outcrops beyond which their extent is traced, where possible, by remote sensing data. The sub-ice structure of a vast interior of East Antarctica remains virtually unknown and is tentatively shown on the map as undifferentiated Precambrian basement.

Tectonic history recorded in basement exposures of Antarctic cratons spans all the Archean eon with the oldest events dated in Enderby Land at almost 4000 Ma. Recurrent generation, high-grade metamorphism and repeated tectono-thermal reworking of juvenile protoliths were the most typical Archean events, as well as the appearance of earliest clastic products and their merging with the primeval crust into integrated plutonic-metamorphic infrastructure.

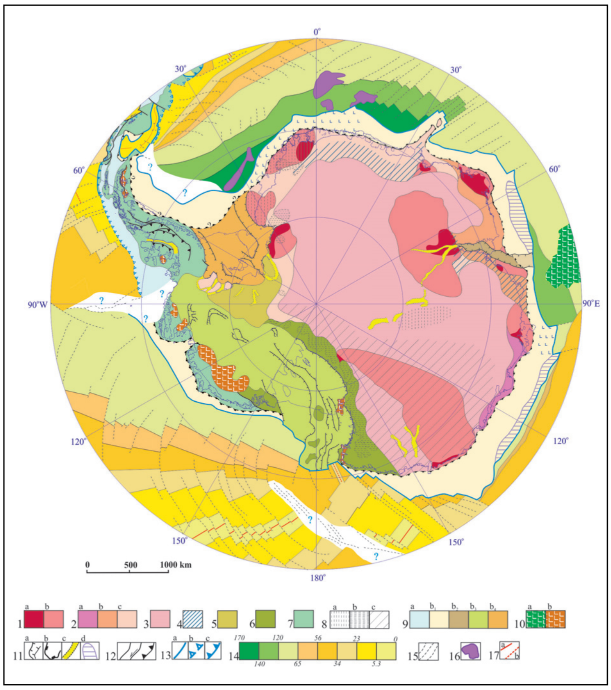

Figure 3. Tectonic structure of the Antarctic region. Continental crust: 1 – Archean cratonic nuclei (a) documented by outcrop evidence, (b) predicted under ice and/or sub-bottom by remote sensing data; 2 – Proterozoic orogens evolved during (a) ca. 1800-1150 Ma, (b) ca. 1400-900 Ma, (c) ca. 1150-900 Ma intervals; 3 – undifferentiated Precambrian basement; 4 – zones affected by ca. 600-500 Ma (Pan-African) orogenic reactivation conceivably ascribed to collisional events during Gondwana amalgamation; 5 – Paleozoic intraplate fold zone; 6 – ca. 600-500 Ma suprasubduction Ross Orogen dismembered within Early Cretaceous to recent West Antarctic Rift System (WARS); 7 – Antarctandes (Antarctic continuation of Andean Belt) – polyphase orogenic system comprised of diachronous Phanerozoic magmatic arcs; 8 – platform covers (a) Late Mesoproterozoic, (b) Middle Paleozoic to early Mesozoic, (c) undifferentiated; 9 – sedimentary basins (a) Late Cenozoic forearc basins, (b) rift-related basins: b1 –controlled by Lower Jurassic-Cretaceous marginal rifts (magma-rich areas are L-patterned), b2 – confined to Permian-Early Cretaceous Lambert Glacier Rift Zone (light colored where overlapped by marginal rift basin), b3 – associated with WARS, b4 – attributed to Paleozoic (?)-Mesozoic rifting in the southern Weddell Sea; 10 – volcanic provinces (a) Early Cretaceous basalts of Kerguelen microcontinent, (b) Late Cenozoic alkaline basalts; 11 – extensional features (a) boundaries of intracontinental rifts (mainly inferred in the Weddell Sea Basin and in the central WARS), (b) inboard boundaries of marginal rifts (dashed where poorly defined), queried where purely hypothetical), (c) graben-like bedrock depressions probably associated with rifting, (d) areas of exposure of serpentinized mantle at the base of post-rift unit; 12 – faults, strike-slip faults, thrust; 13 - Continent-ocean boundary: delineated by (a) rifted and/or transform margin, (b) paleosubduction zone, (c) active subduction zone. Oceanic crust: 14 – age scale (Ma); 15 – oceanic plateaus; 17 – spreading axes (a) active, (b) extinct. Source: Compilation within our work at CGMW (Tectonic Map of Antarctica, 2-nd revision), unpublished.

Cratons are partly overlapped by Proterozoic supracrustals, both tightly folded and flat-lying. The former usually occur in narrow zones of limited size which are not shown on the map. Undeformed Late Mesoproterozoic cover units are thought to occupy the greater part of Coats Land; their stratigraphic equivalents and younger cover units may also be present under ice in the south-eastern sector of the continent (Frederick *et al*., 2016).

Proterozoic orogens are mostly composed of high-grade metamorphic complexes showing progressive eastward increase in time of their formation within the Proterozoic eon. In Dronning Maud Land, Proterozoic orogenic events lasted for ca. 250 Ma from Late Stenian to Early Tonian, in the Lambert Glacier area they continued for at least ca. 500 Ma from the beginning of Ectasian, and in Wilkes Land they appeared to occur mainly during the Statherian to Ectasian interval.

Proterozoic orogens are commonly regarded as juvenile lateral additions extending the nuclei of Archean crust. However, growing discoveries of Archean isotopic marks in Proterozoic rocks may indicate their generation partly at the expense of recycling primeval continental protocrust rather than exclusively from juvenile additions. This would, by implication, suggest a much wider extent of Archean infrastructure than shown by distribution of presently known cratons.

Intense orogenic reactivation at ca. 600-500 Ma is recorded in Middle Proterozoic to Earliest Neoproterozoic crustal assemblages between 00 and 900 E and attributed to collisional events during Gondwana amalgamation. Broadly at the same time subduction of oceanic crust commenced beneath the Paleo-Pacific continental margin of East Antarctica and resulted in emergence here of Ross Orogen of the Transantarctic Mountains.

Important subsequent events in East Antarctica were marked by accumulation of undeformed Middle Paleozoic – Early Mesozoic platform cover followed by emplacement of widespread intraplate Early Jurassic tholeiites. Exposures of these complexes are most abundant on the peneplained surface of the Ross Orogen and also sporadically occur along the south-eastern rim of the Weddell Sea. Elsewhere they could have been eroded in the areas of basement elevations but preserved in sub-ice bedrock lows, as may be the case between 1200 and 1500 E.

A 600-km long rift underlying Lambert Glacier is the only major intracontinental extensional zone in East Antarctica. It is confidently traced offshore beneath continental margin of the southern Cooperation Sea and probably continues far inland, as suggested by a chain of graben-like bedrock morphologies extending into sub-ice interior. The rift valley is expressed by a 50 - 80 km wide trough in bedrock topography with up to 10 km of sedimentary fill which makes the upper layer of thinned (20-25 km) continental crust. Beginning of rifting in Late Carboniferous was followed by a sag phase documented by more than 2.5 km of Permian - Triassic coal-bearing molasses outcropped on the western flank of the Lambert Glacier. After a period of post-Triassic tectonic quiescence the second phase of rifting commenced and lasted until break-up of India and Antarctic in the middle Early Cretaceous.

West Antarctica was affected by crustal stretching to a much greater extent most clearly manifested by formation of two vast sedimentary basins. The south-western extensional basin occupies both the open and ice shelves of the Ross Sea and extends via Byrd Subglacial Basin to the base of Antarctic Peninsula. This 750–1000-km-wide area entirely belongs to intracontinental West Antarctic Rift System (WARS) which is one of the largest regions of extended continental crust on the Earth. Rift structures which are best studied in the Ross Sea open shelf suggest that broadly distributed extension began in the Cretaceous and progressed to a more focused stress during Cenozoic time; recent tectonic activity is indicated by emplacement of abundant Late Cenozoic to Recent alkaline basalts. Geological similarity of basement highs in the central Ross Sea horst and westernmost Marie Byrd Land with the northern termination of Transantarctic Mountains implies that incipient rifting affected the outboard flank of the Ross Orogen and eventually led to distal separation of its unaltered fragments by zones of hyper-stretched Ross crust.

In the north-west sector of the Antarctic region there is another vast intracontinental extensional basin underlying the southern Weddell Sea and its shelf. It is separated from WARS by westward protrusion of essentially unstretched crust that extends from East Antarctica along 900 W. This wedge comprises Paleozoic intraplate fold system (mildly to intensely deformed Cambrian to Permian mainly sedimentary successions locally underlain by latest Neoproterozoic strata) and ca. 1000 Ma fault-broken crystalline block similar to widespread East Antarctic Proterozoic basement. Remote position of this block relative to its supposed conjugate equivalents is commonly attributed to anticlockwise crustal stretching responsible for formation of the Weddell Sea Basin. There is no agreement, however, on whether this process culminated in oceanic opening underlying the southern Weddell Sea (Jokat and Herter, 2016) or was limited to formation here of hyper-stretched rifted crust, as is assumed in Fig. 3. Available evidence indicates anomalous structural features whose tectonic history remains unclear. In central part of the basin presumably Late Mesozoic to Cenozoic low-velocity strata appear to overly a 8-10 km thick medium-velocity (5.5 - 5.6 km/s) layer provisionally interpreted as metamorphosed Paleozoic deposits which, in turn, rest directly on the lower « mafic » crust with velocities 6.9 - 7.3 km/s. On western and eastern margins of the basin potential field modeling predicts emplacement of basaltic magmas presumably associated with pre- and/or syn-breakup rifting.

The southern Scotia Arc, Antarctic Peninsula and the larger part of Marie Byrd Land are collectively called Antarctandes, or Andean Orogen of Antarctica seen as a continuation of the South American Andean Belt. Antarctandes evolved as Middle Paleozoic – Cenozoic subduction-related magmatic arcs accreted to East Antarctica (with already formed Ross Orogen) at the Panthalassic-Pacific active margin of Gondwana prior and subsequent to its breakup. Except for random allochthonous Cenozoic(?) blueschist-like assemblages on Pacific flanks of southern Scotia Arc and southern Antarctic Peninsula, as well as some oceanic scrape-offs mixed with accretional prisms sediments, the bulk of the Andean province is made of magmatic products derived from juvenile melts that were significantly contaminated by crustal component (Burton-Johnson and Riley, 2015). Only on the eastern side of Antarctic Peninsula there are intraplate felsic volcanics and associated granitoids coeval with East Antarctic Early Jurassic traps and silicic large igneous province of Patagonia. This notable exception from dominating magmatic arc history of the Andean Orogen apparently coincides with a major stretching episode in formation of the Weddell Sea Basin.

Very complex internal structure of the Antarctandes is caused by tectonic interference of individual orogenic zones which emerged from diachronous episodes of arc magmatism and were displaced relatively each other by transpressional and transtensional deformations accompanied by shearing, thrusting, strike-slip dislocations, etc. Where individual members of this polyphase orogenic system are preserved in their original position, synkinematic magmatism in younger outboard orogenic zone appears broadly coeval with emplacement of late- to post-kinematic igneous complexes in older inboard zone.

Antarctic Seas

Antarctic seas encompass continental margins and oceanic basins formed at different stages of Gondwana breakup. Most margins had rift origin and became passive after rifting ceased, and only along the Pacific side of Antarctic Peninsula there is a fossil active margin with abandoned subduction zone. Among passive margins, magma-poor margins dominate. The Earth's crust of Antarctic seas contains unique geological information about the history of degradation of Gondwana supercontinent with successive clockwise separation from Antarctica of South America (with Falkland Plateau), Africa, India, Australia, and New Zealand. Disintegration of Gondwanaland commenced at the end of Early Jurassic (c. 185-180 Ma) due to lithospheric extension between Africa, Antarctica and Falkland Plateau. This time coincides with peak of plume-related igneous activity recorded in South Africa and Antarctica which clearly points to emplacement under the lithosphere of the southern supercontinent of a mantle plume (known as Karoo Plume) as the cause of rifting and initial Gondwana break-up. Abundant volcanic activity was responsible for formation in the eastern Weddell Sea and Lazarev Sea of 150-200 km wide magma-rich passive margins. In the conjugate margins presently occupied by Riiser-Larsen Sea and Mozambique Basin the earliest lithospheric breakup and ocean growth occurred at about 160-155 Ma. From that time to about 140 Ma incipient Lazarev Sea and eastern Weddell Sea represented a transtensional strike-slip margin. At 140 Ma or slightly later a triple junction appeared with formation of Antarctic, South American and African plates.

The offshore region of East Antarctica from the western Cosmonaut Sea to eastern Davis Sea evolved due to separation of India and Antarctica. Rifting between these continents began in Middle Jurassic (c. 170 Ma). The Antarctic rifted margin shows variable crustal characteristics. In the Cooperation Sea, it ranges in width from 300 to 400 km and includes a 100-km-wide continent-ocean transition zone (COZT) characterized by exposure of exhumed mantle at the base of post-rift units. The margins in the Cosmonaut and Davis Seas are narrower and varying between 50 and 200 km. Sea-floor spreading propagated from east to west (Fig. 3). Well identified magnetic ?nomalies in the Perth Basin (West Australia margin) show that the earliest opening between Great India and Australia/Antarctica occurred at about 130 Ma. Vague magnetic lineations in the Davis Sea suggest that oceanic basin probably evolved here at the same time, whereas farther west the spreading was compensated by extreme lithospheric stretching accompanied by mantle unroofing. Transition from rifting to drifting in the Cooperation Sea is marked by linear high-amplitude magnetic anomaly which was generated at about 120 Ma, namely, just the time when the Kerguelen Plume was emplaced into the lithosphere of the incipient Indian Ocean to form the southern part of the volcanic Kerguelen Plateau (Leitchenkov et al., 2018). The latter is thought to be underlain by the continental crust which was transferred from the Indian margin and isolated on the Antarctic plate via ridge jumps associated with the Kerguelen Plume.

Rifting between Australia and Antarctica was characterized by long history and hyperextension of lithosphere also accompanied by exhumation of the mantle. On the Wilkes Land margin COZT is more than 1000 km long and 100-150 km wide (Fig. 3). To the east of 1300 E, the margin is distinguished by the extended crustal block with uplifted and deformed syn-rift unit and abundant magmatic emplacements. The deformation is thought to be caused by shearing along the prominent fracture zones developed between Indian and Pacific Oceans. The oceanic crust of this area is dated by linear magnetic anomalies from C33 to C17 and characterized by half-spreading rate ranging between 1 and 17 mm/yr. Extremely slow sea-floor spreading (less than 1 mm/yr) is documented in the eastern part of region which shows development of the chain of high basement ridges. These ridges are interpreted to be oceanic core complexes with exhumed mantle. On the conjugate Australian margin this chain has a counterpart known as the Diamantina Zone.

Identification of magnetic anomalies suggests that opening of oceanic basin between Australia and Antarctica began close to C33 polarity chron (about 79-81 Ma ago), while east of roughly 1340 E it happened even later (60-65Ma ago). On the west the Wilkes Land magma-poor margin borders with the marginal volcanic plateau (Fig. 3).

Continental margin and oceanic basins in the Pacific Ocean have complicated structure with variety of tectonic settings including modern mid-ocean ridge (Fig. 3). Between c. 1700 W and 900 W, the margin evolved as a result of lithospheric extension between New Zealand continental blocks and West Antarctica in Late Cretaceous, while east of 900 W one of the Pacific Ocean microplates (the Phoenix Plate) was at the same time subducted beneath the Antarctic Peninsula. The breakup began at 83-85 Ma with the separation of Chatham Rise from Marie Byrd Land and then propagated westward with final oceanic opening between continental blocks underlying the Ross Sea and Campbell Plateau at 75-80 Ma (Eagles *et al*., 2004). Subduction beneath the Antarctic Peninsula margin continued concurrently with plate divergence but ceased successively eastward due to ridge-crest-trench collision between c. 50 to 4 Ma (Fig. 3). A short fragment of COB at the tip of Antarctic Peninsula is shown on the map as Recent subduction zone may in reality be not active since the extinction of Phoenix Ridge at 3.3 Ma, although deep trench and inertial slab submergence are still present (Eagles *et al*., 2004).

The eastern Antarctic Peninsula margin is poorly studied but magnetic surveys suggest more than 10 km of sedimentary infill. This margin developed from Jurassic to at least Eocene time in response to back-arc extension caused by subducting Pacific crust but its structure and interrelation with the rest of Weddell Sea Basin remain ambiguous. A complex region in the north-western Weddell Sea is represented by continental blocks, active and extinct plate boundaries and small Oligocene-Miocene back-arc basins (see figure 3).

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