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Main Stages and Geodynamic Regimes of the Earth's Crust Formation in East Antarctica in the Proterozoic and Early Paleozoic

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Abstract—Geological, geochemical, and isotopic data (U–Pb for zircon and Sm–Nd for whole-rock samples) are summarized for Proterozoic and Early Paleozoic geological complexes known from various regions of East Antarctica. The main events of tectonothermal and magmatic activity are outlined and correlated in space and time. The Paleoproterozoic is characterized as a period of rifting in Archean blocks, their partial mobilization, and formation of a new crustal material over a vast area occupied by present-day East Antarctica. In most areas, this material was repeatedly reworked at the subsequent stages of evolution (1800–1700, 1100–1000, 550–500 Ma). Complexes of Mesoproterozoic juvenile rocks (1500, 1400–1200, 1150–1100 Ma) arising in convergent supra-subduction geodynamic settings are established in some areas (basalt–andesite and tonalite–granodiorite associations with characteristic geochemical signatures). The evolution of the Proterozoic regions in East Antarctica may be interpreted as a Wilson cycle with the destruction of the Archean megacontinent 2250 Ma ago and the ultimate closure of the secondary oceanic basins by 1000 Ma ago. The Mesoproterozoic regions make up a marginal volcanic–plutonic belt that combines three provinces of different ages corresponding to consecutive accretion of terranes 1500–1150, 1400–950, and 1150–1050 Ma ago. The Neoproterozoic and Early Paleozoic tectonomagmatic activity developed nonuniformly. In some regions, it is expressed in ductile deformation, granulite-facies metamorphism, and postcollision magmatism; in other regions, a weak thermal effect and anorogenic magmatism are noted. The evolution of metamorphic complexes in the regime of isothermal decompression and the intraplate character of granitoids testify to the collision nature of the Early Paleozoic tectonomagmatic activity.

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INTRODUCTION

East Antarctica was traditionally regarded as an ancient platform composed of largely Archean metamorphic complexes which underwent recurrent tectonomagmatic activation in the Proterozoic [1]. Outcrops almost completely demonstrate lithotectonic complexes of the lower structural stage of basement, whereas the complexes of the upper structural stage (Meso- and Neoproterozoic fill of troughs) crop out only locally [2, 20]. Therefore, the exposed portion of East Antarctica may be regarded as a crystalline shield. It is suggested that rocks of pre-Riphean, Riphean, and Phanerozoic platform cover occupy some under-ice territories [2], so that the term *Antarctic Shield* applied below, first of all, to the near-shore exposed areas, is, to a great extent, nominal.

Rb–Sr and U–Pb dating have shown that the Antarctic Shield consists of relatively small cores of Archean stabilization (cratons) and vast areas of Proterozoic tectogenesis, which underwent Grenville (~1000 Ma) granulite-facies metamorphism, anatexis, and vigorous ductile deformation [3 and references therein]. Some authors consider these areas as a polycyclic mobile belt [1]. Thereby, the material of the mobile belt is regarded as deeply and repeatedly reworked Archean crust. Structural and numerous U–Pb geochronological studies performed in the 1990s showed that granulite-facies metamorphism, ductile deformation, and emplacement of granitoids occurred in the Vendian–Cambrian (570–500 Ma ago) [53, 73]. In line with the concept of Precambrian supercontinents, the orogenic (accretionary–collisional) nature of both Late Mesoproterozoic (Grenville) [32] and Neoproterozoic–Early Paleozoic (Pan-African) [73] tectonic processes in Antarctica became predominant. The eventual formation of East Antarctica at the Proterozoic–Paleozoic boundary is suggested as a result of collision of several lithospheric blocks [27, 38]. However, in most cases, geological bodies and rock associations were regarded merely as metamorphic complexes [19]; the composition of their protolith was not studied specially, and geodynamic analysis was not carried out. Main attention was focused on the Archean rocks, especially on the Napier high-temperature complex of the Enderby Land [5, 19],

whereas Proterozoic rocks and processes fell back into the shadow.

The objective of this paper is to fill, to a certain extent, this gap on the basis of integral consideration of geological, geochronological, and geochemical data, which makes it possible to reconstruct the formation conditions of lithotectonic complexes, to determine particular events of tectonomagmatic activity, and to develop a new model describing the formation and evolution of the Earth's crust of East Antarctica in the Proterozoic and Early Paleozoic. The Archean complexes require a special discussion and are out of the scope of this study. The same should be said about the Neoproterozoic and Early Paleozoic complexes of the Transantarctic Mountains, which are situated in East Antarctica but in terms of tectonics are related to the Ross Fold System that frames the Antarctic Shield on the Pacific side [1, 2].

The dataset used in this study comprises more than 250 U–Pb zircon dates, more than 500 Sm–Nd isotopic analyses, more than 2000 major element chemical compositions of rocks, and about 1000 trace element compositions. Most of these data were taken from the literature and obtained through exchange of information with foreign specialists.

MAIN GEOLOGICAL FEATURES AND STAGES OF THE EARTH'S CRUST FORMATION

The isotopic geochronological data available at present (see [12] for a review) have made a substantial contribution to the timing of the main tectonomagmatic events and have been used for compilation of the tectonic scheme shown in Fig. 1. The age was established by numerous U–Pb datings of zircon (mainly with SIMS SHRIMP) carried out in foreign and Russian laboratories. The recent results of U–Pb study of detrital zircon from metamorphic rocks remain insufficient for recognition of sedimentary sequences of different age and composition. The bar chart (Fig. 2) characterizes the distribution of U–Pb ages of volcanic rocks, gabbroids, pre- and synkinematics granitoids, and metamorphic events accompanying emplacement of granitic plutons and ductile deformation. The dates of post-tectonic granitoids and basic dike suites were omitted. Because particular areas of East Antarctica are studied in terms of geochronology extremely nonuniformly, this bar chart does not reflect the real manifestation of geologic events of certain ages but clearly demonstrates the chronological boundaries of tectonomagmatic activity. In most cases, the dated rocks and processes pertain to the final structure-forming stages of tectogenesis because the early phases are commonly not recorded in U–Pb systematics. To estimate the oldest age of tectonomagmatic activity and early generation of crustal material, the model Nd age (t_{DM}) is used as a measure of separation of the primordial crustal material from the depleted mantle [35]. The data available for East Antarctica are summarized in [16]. As was shown in this publication, the model Nd age, as a rule, is much older than the age of magmatic activity determined with the U–Pb method on accessory minerals. The discrepancy between the U–Pb zircon and model Nd ages indicates that juvenile lithotectonic complexes are rare in the crystalline shield of East Antarctica or the mantle and lower crustal protoliths were composed of material somewhat enriched in lithophile elements, including LREE, in the preceding evolution. The bar chart of model Nd age is shown in Fig. 3. On compilation of this chart, only 5–10 samples from each studied area were taken into account; as a result, a uniform sampling is reached at a first approximation. The peaks of crust volume increase in East Antarctica are the periods 3000–2700 and 1900–1600 Ma ago [17].

Taking into account the age of the main phases of tectonomagmatic activity predated by sedimentation, volcanism, and granite formation, regions of Archean stabilization (cratons), of Paleo- and Mesoproterozoic stabilization, and of superimposed tectonomagmatic reactivation are distinguished (Fig. 1). The regions of Mesoarchean (3100–2800 Ma) stabilization in western Dronning Maud Land, Enderby Land (Napier Terrane)[1] and the southern Prince Charles Mountains, as well as regions of Neoarchean stabilization (2650–2450 Ma) in the Vestfold Hills (Ruker Terrane), Queen Mary Land, and the George V Coast are relatively small cores. The rocks from all these regions and some Proterozoic regions have model Nd age in a wide range from 2.5 to 4.0 Ga [17], testifying to prolonged crust formation. The regions of Proterozoic evolution embrace the vast territories of the exposed Antarctic Shield. Numerous episodes of tectonomagmatic activities accompanied by ductile deformation and/or metamorphism and emplacement of mafic and felsic intrusions are established throughout the Proterozoic, making arbitrary the chronological boundaries of particular phases: 2650–2450, 2150–2000, 1800–1700, 1500, 1400–1200, 1100–950, 700, 650–570, 550–500, and 480 Ma ago. The composition and geodynamic setting of coeval geological complexes differ substantially between separate areas. The scheme of spatiotemporal correlation of the lithotectonic complexes and tectonomagmatic and thermal events in particular regions of East Antarctica that developed and stabilized in the Proterozoic (Fig. 4) allows recognition of major events of tectonomagmatic activity. Tectonomagmatic and metamorphic events within intervals 2650–2450, 1800–1700, 1400–950, and 550–500 Ma ago are especially widespread and may be regarded as the main stages of crystalline shield formation in East Antarctica. The interval from 900 to 700 Ma is characterized by relatively quiet evolution without indications of orogenic processes.

[1] In the opinion of some researchers, the high-temperature metamorphism in the Napier Terrane dated at 2600–2450 Ma was not accompanied by deformation [48].

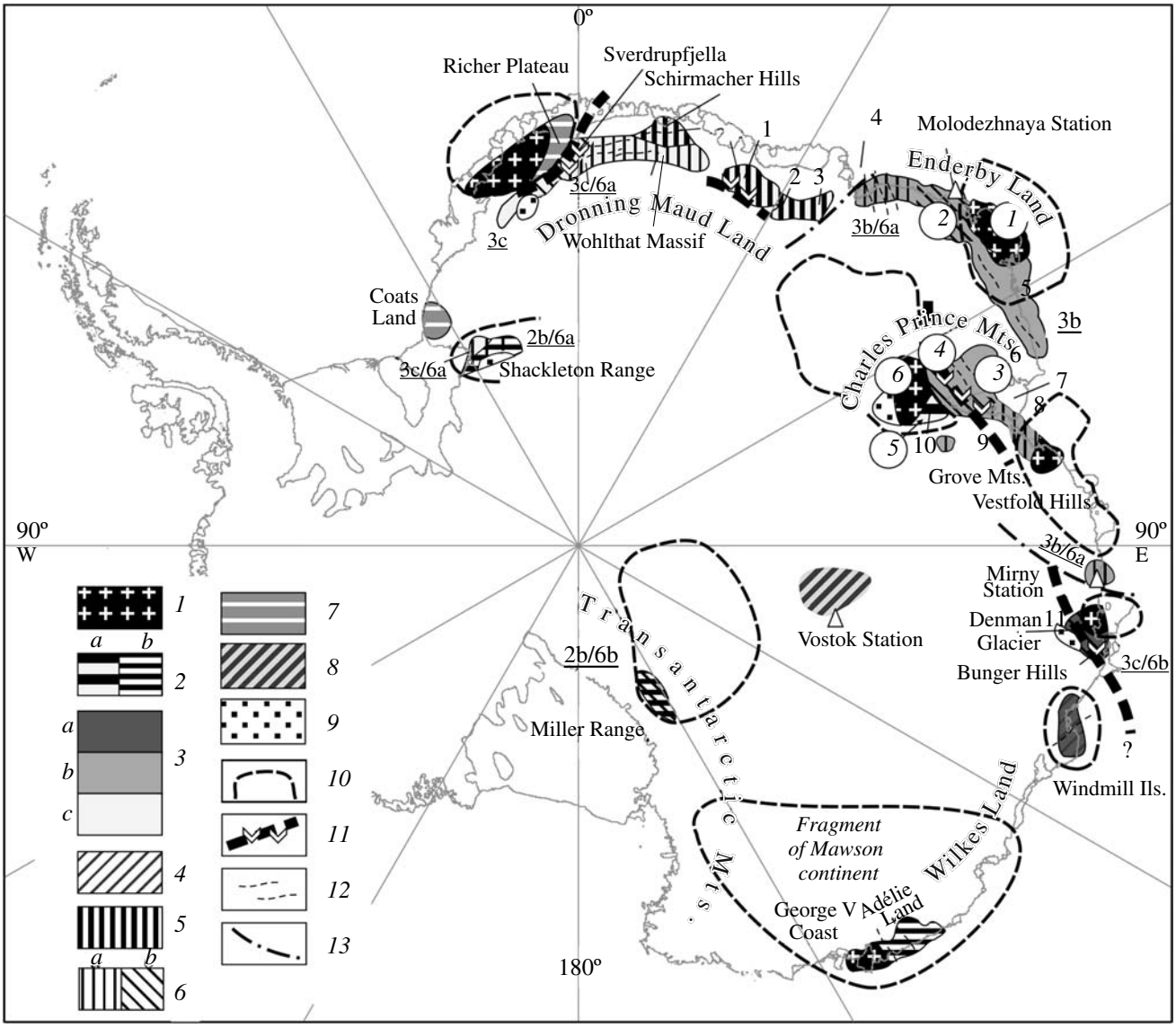


Fig. 1. Tectonic scheme of East Antarctica. (*1–8*) Lower structural stage: (*1*) region of Archean stabilization (craton); (*2*) region of Paleoproterozoic stabilization: (a) 2100 Ma and (b) 1700–1800 Ma ago; (*3*) region of Mesoproterozoic evolution: (a) 1500–1150, (b) 1400–950, and (c) 1150–1050 Ma ago; (*4–6*) regions of tectonomagmatic reworking: (*4*) Mesoproterozoic, (*5*) Neoproterozoic, (*6*) Early Paleozoic: (a) granulite-facies metamorphism, ductile deformation, and anatexis; (b) greenschist- and amphibolite-facies metamorphism and/or emplacement of granitoids; (*7*) undeformed Late Mesoproterozoic volcanic and sedimentary rocks (rifting in foreland of Mesoproterozoic mobile belt); (*8*) under-ice territory (2.2–0.6 Ga); (*9*) region of Neoproterozoic sedimentary complexes of the upper structural stage; (*10*) contours of under-ice blocks with Archean age of primary crustal material on the basis of model Nd age and with account of anomalous magnetic field in interpretation by R.G. Kurinin (unpublished data); (*11*) inferred paleosuture and areas occupied by juvenile complexes; (*12*) regional structural trend; (*13*) arbitrary boundary between Mesoproterozoic tectonic provinces. Geographic localities (numerals in figure): (1) Sor Rondane Mountains, (2) Belgica Mountains, (3) Yamato Mountains, (4) Lützov-Holm Bay, (*5*) Kemp Land, (6) MacRobertson Land, (7) Eimery Glacier, (8) Prueds Bay, (9) Princess Elizabeth Land, (10) Mawson Escarpment, (11) Queen Mary Land. terranes (numerals in circles): (1) Napier, (2) Rayner, (3) Beaver, (4) Fisher, (5) Lambert, (6) Ruker.

The Late Archean–Paleoproterozoic (2650–2450 Ma) and the Late Paleoproterozoic (1800–1700 Ma) events are distinctly correlated between various areas of the Antarctic Shield. It should be noted that manifestations of the Paleoproterozoic processes concentrate in the eastern (east of the Mirny Station) and Pacific sectors. The Mesoproterozoic tectonomagmatic events in some regions of East Antarctica are coeval, for example, the emplacement of charnockite in western Dronning Maud Land, MacRobertson Land, the Prince Charles Mountains, the Bunger Hills, and the Windmill Islands, or the formation of dolerite dike suites in the Vestfold Hills, Enderby Land, and the Prince Charles Mountains. At the same time, a certain rejuvenation of Meso-

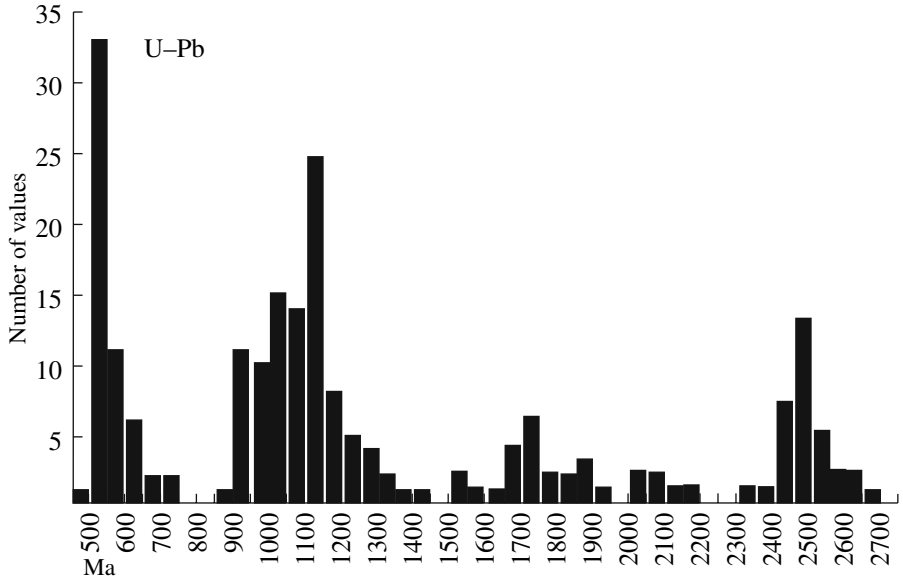


Fig. 2. Bar chart of U–Pb zircon dates indicating the age of volcanic rocks, gabbroids, pre- and syntectonic granitoids, and metamorphic events. The age values divisible by 100 (500, 600, etc.) are included in the right intervals.

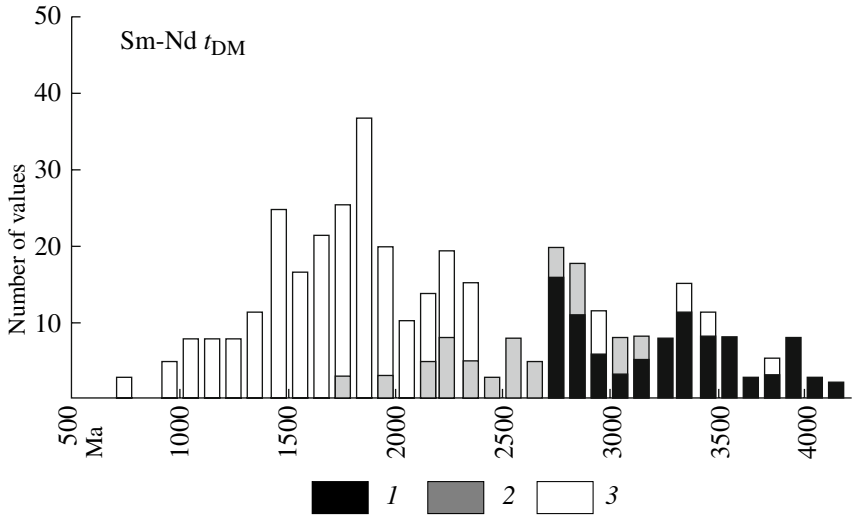
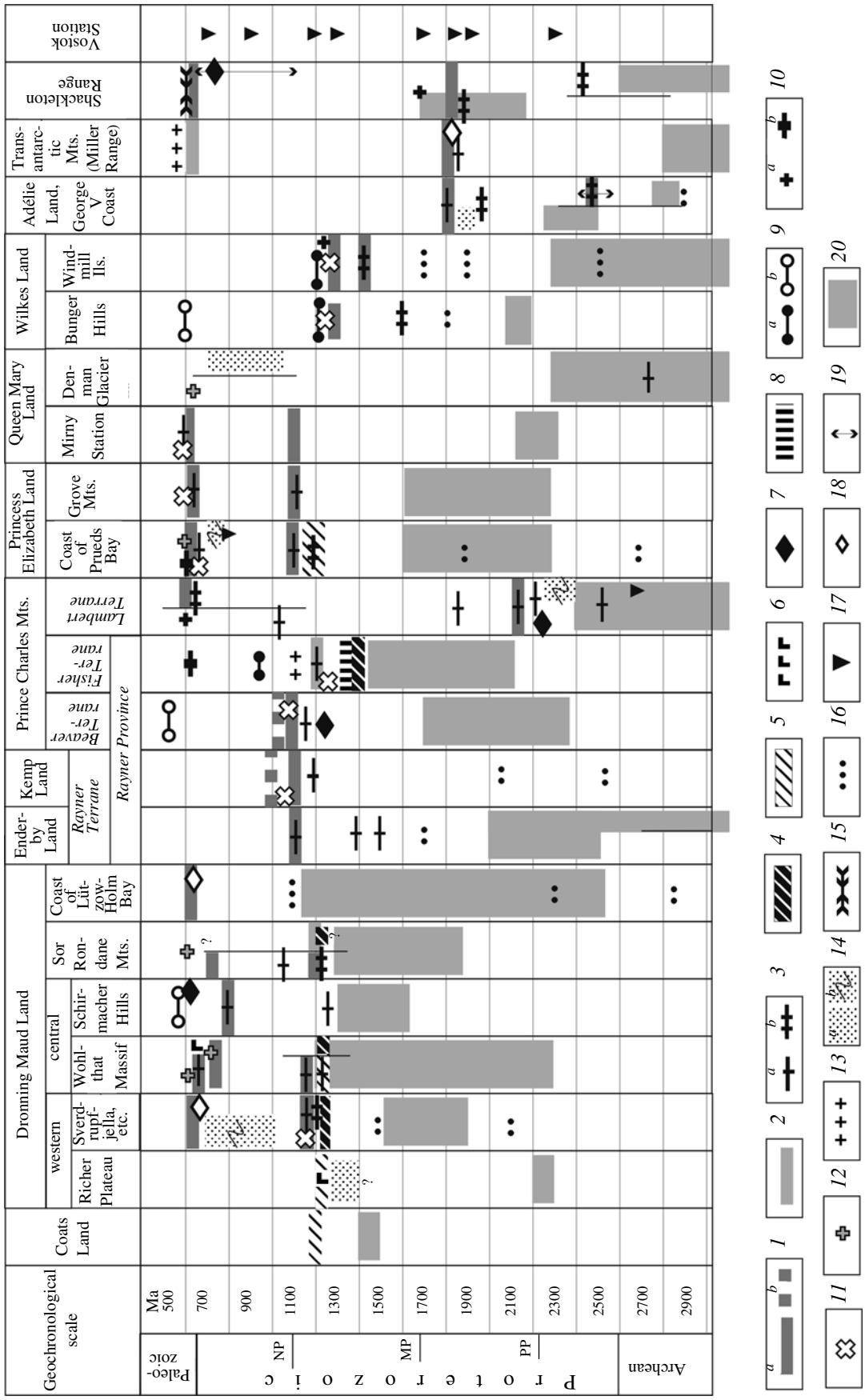


Fig. 3. Bar chart of model Nd ages of rocks (t_{DM}). (*1*) Archean cratons, (*2*) regions of Paleoproterozoic stabilization, (*3*) regions of Mesoproterozoic evolution.

Fig. 4. Spatiotemporal correlation of tectonomagmatic and thermal events in regions of East Antarctica that evolved and stabilized in the Proterozoic. (*1*) Granulite- and amphibolite-facies metamorphism and accompanied ductile deformation: (a) regional metamorphism and (b) dynamometamorphism in zones of viscoplastic flow; (*2*) regional greenschist- and epidote-amphibolite-facies metamorphism; (*3*) emplacement of pre- and syntectonic granitic (a) and tonalitic–granodioritic (b) plutons; (*4*) eruption of basic and intermediate lavas; (*5*) eruption of felsic and bimodal lavas; (*6*) crystallization of mafic intrusions, including layered plutons; (*7*) crystallization or tectonic emplacement of ultramafic and mafic complexes; (*8*) emplacement of gabbro–diorite–plagiogranite plutons; (*9*) emplacement of basic dikes of (a) normal and (b) high alkalinity; (*10*) emplacement of peraluminous leucogranites: (a) postkinematic and (b) synkinematic; (*11*) emplacement of charnockites; (*12*) emplacement of anorthosite–mangerite–charnockite association or A-type granitic plutons; (*13*) emplacement of postkinematic calc-alkaline granitoids; (*14*) period of sedimentation: (a) slightly metamorphosed and deformed sequences and (b) folded sequences; (*15*) thrusting; (*16*) zircon crystallization (relict material in cores of grains in orthogneisses); (*17*) zircon crystallization (detrital grains in sedimentary rocks), (*18*) crystallization of high-pressure parageneses, including eclogitic assemblage; (*19*) interval of uncertainty; (*20*) interval of model Nd age. The vertical line indicates the local development of lithotectonic complexes. The areas of tectonic stabilization at ~1000 Ma in Enderby Land and Kemp Land are named Rayner Terrane [4], and the larger tectonic unit, which also includes MacRobertson Land and Princess Elizabeth Land, is designated as Rayner Province.


Geochronological scale
Coats Land
Dronning Maud Land
western
central
Richer Plateau
Sverdrupfjella, etc.
Wohlthat Massif
Schirmacher Hills
Sor Rondane Mts.
Coast of Lützow-Holm Bay
Enderby Land
Kemp Land
Rayner Terrane
Rayner Province
Prince Charles Mts.
Beaver Terrane
Fisher Terrane
Lambert Terrane
Princess Elizabeth Land
Coast of Prueds Bay
Grove Mts.
Queen Mary Land
Mirny Station
Denman Glacier
Wilkes Land
Bunger Hills
Windmill Ils.
Adélie Land, George V Coast
Transantarctic Mts. (Miller Range)
Shackleton Range
Vostok Station
Ma
500
700
900
1100
1300
1500
1700
1900
2100
2300
2500
2700
2900
Paleozoic
NP
MP
PP
Proterozoic
Archean

proterozoic tectonic processes is established from the east westward along the coast of the Antarctic Shield. On the basis of correlation links, three large Mesoproterozoic provinces are recognized: (1) Wilkes Province (Bunger Hills, Windmill Islands), 1500–1150 Ma; (2) Rayner Province (Enderby Land, Kemp Land, MacRobertson Land, including the Prince Charles Mountains, and Princess Elizabeth Land), 1400–950 Ma; and (3) Maud Province (Dronning Maud Land, including Lützow-Holm Coast), 1150–1050 Ma.

GEODYNAMIC REGIMES OF THE FORMATION OF GEOLOGICAL COMPLEXES

Due to orographic and geological features, the reconstruction of geodynamic regimes in East Antarctica is based on the data of metamorphic petrology, which ascertain the *PT* conditions of metamorphism and the character of endogenetic evolution, and on geochemical and isotopic data, which determine the paleotectonic settings of the formation of geological complexes. The metamorphic conditions of Antarctic rocks are considered in many publications [19, 47, 48, and references therein]; therefore, the detailed characteristics of mineral parageneses are omitted in this paper. The geochemistry of igneous complexes and protoliths of metamorphic rocks is studied to a lesser extent. These data are available in [10, 11, 13, and references therein].

Paleoproterozoic. The particular geodynamic settings of the formation and evolution of the Earth's crust of East Antarctica in the Paleoproterozoic can be determined only with considerable uncertainty due to the insufficient study of geological complexes. Three types of geodynamic settings can be distinguished: (1) extension and related destruction of the Archean crust, (2) collision characterized by substantial reworking of the previously existing crust and local formation of a new crustal material, and (3) accretion related to the formation of a considerable body of new crust.

The blocks of Archean stabilization in the central sector of the Antarctic Shield (Enderby Land, the southern Prince Charles Mountains, the Vestfold Hills) developed in the ***setting of extension*** (rifting). In the interval 2400–2250 Ma ago[2], almost identical dike suites of high-Mg gabbronorite-dolerites were formed here [14]. The specific composition of these rocks was determined by the character of mantle plume at the first stage of rifting. The metamorphosed dunite–orthopyroxenite–gabbro complex at the Mawson Escarpment (see below) probably pertains to the advanced stage of rifting [15, 63]. It should be noted that high-Fe dolerite dikes occur in the Early Precambrian blocks; in the Vestfold Hills they are dated at 1750 Ma [58].

[2] Here and below, unless otherwise specified, the U–Pb age (SIMS SHRIMP) of zircon or monazite is concordant or corresponds to the upper intersect with concordia for a slightly discordant group of 5–10 measurements.

The collision setting is recognized at the Mawson Escarpment in the Prince Charles Mountains (Lambert Terrane) and in the Miller Range of the central Transantarctic Mountains. The Lambert Terrane is located in the northern and central Mawson Escarpment. Felsic orthogneiss, paragneiss, and marble of amphibolite–granulite metamorphic facies and a tectonically separated complex of metamorphosed mafic and ultramafic rocks (metagabbro, orthopyroxenite, dunite, peridotite) incorporated into felsic ortho- and paragneisses occur here. The age of gabbroic rocks is 2250–2150 Ma (A. Corvino, personal communication). Orthogneisses of the Lambert Terrane make up a calc–alkaline association. As suggested in [62], this association was formed under convergent tectonic conditions. The Early Paleoproterozoic orogen of the Lambert Terrane is a result of ensialic collision, because the model Nd age of 2.3–3.3 Ga indicates a long crustal prehistory of the material. As was established recently, orthogneisses were emplaced 3520 ± 20, 2420 ± 20, and 2120 ± 12 Ma ago [28, 62]. Thus, it is necessary to consider the geochemistry of each chronological group; however, the available data are insufficient for this purpose. According to the study of detrital zircon [67], the time of sedimentation is limited by an interval of 2500 to 2000 Ma. The sedimentation probably occurred under conditions of rifting at a passive margin. The high-temperature metamorphism is dated at 2060 ± 20 [62] and 508 ± 11 Ma [28]; small bodies of synkinematic granitoid were emplaced 1800–1750 and 920 Ma ago. The structure of this region was probably formed 2150–2050 Ma ago, and the subsequent tectonomagmatic processes bore the character of reactivation. It should be noted that the Lambert Terrane is the single known example of the Early Paleoproterozoic orogen in Antarctica. Sporadic sheetlike granitoid bodies with a relatively young model Nd age (1900 Ma) indicate that juvenile Paleoproterozoic rocks occur in the Lambert Terrane [28, 63], but their role seems to be insignificant.

The banded para- and orthogneisses of amphibolite facies occur in the Miller Range. The earliest intrusive phases of orthogneiss protoliths are dated at 3150 and 2980 Ma. The metamorphic sequence is cut through by synkinematic and synmetamorphic granitoids dated at 1730 ± 10 Ma [44 and references therein]. The relict eclogitic mineral assemblage close in age (~1720 Ma) testifies to the collision nature of this Late Paleoproterozoic orogen. The model Nd age within the range 2700–3100 Ma indicates the Neoarchean crust in this region and activation character of Paleoproterozoic processes.

The rocks in the Shackleton Range and on Adélie Land pertain to the category of *accretionary complexes*. In the Shackleton Range, the Paleoproterozoic complex of metamorphic rocks and allochthonous metasedimentary complexes are combined with Neoproterozoic or Early Paleozoic ophiolites. Protoliths of plagiogneisses (felsic volcanic and intrusive rocks) were formed 2328 ± 7 and 1810 ± 2 Ma ago. Metamorphism of

amphibolite facies is dated at ~1700 Ma; post-tectonic granitoids were emplaced 1590 ± 5 Ma ago [75 and references therein]. The conditions of Paleoproterozoic metamorphism are estimated at P = 5–7 kbar and T = 700–800°C. The retrograde evolution was not determined reliably due to the intense reworking in the Early Paleozoic; a slow cooling at a great depth is suggested [74, 75]. The model Nd age is 2500–3000 Ma.

On Adélie Land, basement and tectonically (?) overlying metasedimentary rocks of the upper structural stage are recognized. The formation of basement structural elements and metamorphism are dated at 2500–2400 Ma [66]; protoliths of tonalitic orthogneisses were emplaced 2440 and 1850 Ma ago [36]; model Nd ages are 2700–2800 Ma. The upper structural stage is composed of intensely deformed and migmatized metapelites and metagraywackes, felsic metavolcanics and metabasic sills [34]. The metamorphic conditions are estimated at P = 4–6 kbar and T = 700–750°C and characterized by slow isobaric cooling [66]. It is suggested that sedimentation and the main tectonothermal activity covered a narrow time span from 1720 to 1690 Ma. The model Nd age of 2200–2400 Ma [34] indicates the juvenile character of rocks from the upper structural stage, but this inference does not hinder the authors to refer them to the category of rift-related complexes. The HT–LP metamorphism on Adélie Land and in the Shackleton Range probably marks a thermal anomaly caused by deep underplating.

Thus, the model Nd ages of rocks from regions of Paleoproterozoic stabilization vary from 2300 to 3300 Ma, and this range overlaps, to a great extent, the range of model ages of rocks from Archean blocks (Fig. 3). This circumstance allows recognition of areas that evolved in the Early Precambrian (Archean–Paleoproterozoic) as a certain geological integrity—the blocks (cores) of the Archean crust. At a first approximation, the localization of these blocks in under-ice territories may be established from anomalous magnetic field [37, 41, 42]. The regions of Early Precambrian evolution are characterized by specific features of the anomalous magnetic field (R.G. Kurinin, unpublished data), which are traceable under ice (Fig. 1). It should be emphasized that the magnetic field of the central and eastern inland parts of East Antarctica remains practically unstudied, and therefore it cannot be ruled out that such regions are rather widespread. In the vicinity of the Russian Vostok Station, a borehole drilled through the ice cover reached a bottom ice layer that contains small particles of sedimentary rocks with zircon grains dated at 2200–1600, 1200–800, and 600 Ma [8]. This finding confirms the occurrence of Paleoproterozoic rocks in under-ice territories.

In the areas of the Mesoproterozoic stabilization, the convergent settings that generated a new crustal material were predominant in the Paleoproterozoic. This is confirmed by abundant rocks of model Nd ages corresponding to Paleoproterozoic with a peak at 1600–1900 Ma [17]. The Earth's crust was formed actively in volcanic arcs and at the margins of the Archean cores. However, geological evidence of these processes was not retained because of vigorous Mesoproterozoic tectonothermal reworking. Only locally, e.g., on the Windmill Islands, was the Paleoproterozoic age determined in cores of zircon grains.

Mesoproterozoic. The composition of Mesoproterozoic rocks shows that lithotectonic complexes of this age were formed in convergent or extensional geodynamic settings [15]. The category of convergent setting comprises (1) accretionary setting related to the juvenile crust formation under suprasubduction conditions at active continental margin or volcanic arc; (2) accretionary–collisional setting related largely to collision with reworking of already existing crustal material and a limited contribution of newly formed material of the mantle origin. The extensional conditions are characterized by development of mafic dikes in regions of Archean stabilization (rifting) or in Mesoproterozoic orogenic zones (postorogenic regime), as well as by the occurrence of volcanic and sedimentary sequences and mafic intrusions in ancient cratons (regime of epiplatform troughs).

Accretionary settings are reconstructed from the characteristic set of rock associations (sodic basalts, basalt–andesite, gabbro–diorite–plagiogranite, and tonalite–trondhjemite–granodiorite complexes) and geochemical signature of rocks. Such settings are recognized in the central Prince Charles Mountains (Fisher Terrane), on western Dronning Maud Land, in the Sor Rondane Mountains, and in the Bunger Hills (Fig. 1). Some of the rocks pertaining to the Rayner Complex on Enderby Land were formed in this setting as well.

The Fisher Terrane comprises several mountainous massifs in the central Prince Charles Mountains (71°00′–72°30′ S) composed of felsic and mafic crystalline schists of epidote-amphibolite and amphibolite facies (Fisher Complex) and deformed plutons of metagabbro, diorite, tonalite, granodiorite, and granite [13, 61 and references therein]. Crystalline schists occasionally retain primary magmatic texture and structure testifying to their volcanic origin; layering is observed in metagabbro. Metasedimentary rocks (psammites, tuffites, carbonate rocks) are of very subordinate importance. Basic and intermediate volcanic rocks are dated at 1300 Ma [13 and references therein]. The age of plutonic rocks (gabbro, tonalite) is 1290–1220 Ma [6, 7]. Metamorphism and deformation occurred 1150–1100 Ma ago. The protolith of granitic ortogneisses was emplaced 1105 ± 5 Ma ago, whereas post-tectonic granitoids are dated at 1120 or 1020 Ma. In chemical composition, the rocks of the Fisher Complex correspond to basalt, basaltic andesite, andesite, dacite, and rhyodacite with predominance of basalt and are correlated with associations of sodic basalts and basalts and andesites. The rocks are slightly enriched in LILE and characterized by a distinct Nb anomaly and low HFSE

(P, Ti, Y, Zr, Nb, Hf) contents. Some basalts are close to E-MORB and may be accreted rocks of oceanic plateau. These volcanic rocks belong to the calc-alkaline series. Plotted on discriminant diagrams, the rock compositions of the Fisher Terrane fall into the field of volcanic arcs and active continental margins. The rocks of the Fisher Complex are identical in composition to gabbro and plagiogranite. Comparable Ti/P, K/Rb, Zr/Nb, and Ce/Y ratios and similar $\varepsilon_{Nd}(1300)$ = 2.0–4.0 and low Sr_i = 0.703–0.706 indicate their common origin. Other rocks (felsic orthogneisses and paragneisses) differ in low ε_{Nd} (down to –5). Model Nd age varies from 1300 to 2000 Ma.

In western Dronning Maud Land (Sverdrupfjella district and the areas located southwesterly), the predominant metasedimentary rocks are associated with orthogneisses and mafic crystalline schists of amphibolite facies. The oldest dated rocks are andesitic and basaltic andesitic metavolcanics (1170–1130 Ma) and tonalite–granodiorite–plagiogranite gneiss (1150–1130 Ma). The cores of zircon grains from some rocks are dated at 1400 and 2000 Ma [51, 54 and references therein]. Metamorphism and penetrative schistosity are dated by the same authors at 1100–1030 Ma. Synkinematic granitoids, including charnockite, were emplaced 1110–1050 Ma ago and postkinematic S-granites 1080–1050 Ma ago, testifying to nonuniform and asynchronous development of Grenville deformations. The metamorphic framework is a sequence of intercalating gray felsic plagiognesses and amphibolites. Intermediate rocks are predominant; the distribution of SiO_2 is unimodal and symmetric with a mode at 60–62 wt % SiO_2 [46]. The isotopic data testify to the juvenile origin of most rocks related to Mesoproterozoic sources: t_{DM} = 1400–1800 Ma; $\varepsilon_{Nd}(t)$ = +6 to –2; Sr_i = 0.702–0.708 [13 and references therein].

In eastern Dronning Maud Land, in the Sor Rondane Mountains, the rocks of granulite–amphibolite facies (mafic granulites, gneisses, tonalitic orthogneisses, and crystalline schists) occur in the northeast and extreme west of this territory, whereas crystalline schists of epidote-amphibolite and greenschist facies crop out in the southwest of this mountain system [4]. The emplacement of tonalite orthogneiss protolith is dated at 1100 Ma (U–Pb method, TIMS). Synkinematic granite is dated at 1050–950 Ma with the Rb–Sr method [13 and references therein]. In chemical composition, amphibolites correspond to normal basalt and some varieties to picrobasalt [4]; felsic rocks vary in composition from andesitic dacite to rhyolite. The abundant intermediate rocks (plagiogneisses) are mentioned in [4, 65]. The chemical composition shows that protoliths of these rocks were derived from mantle sources and underwent advanced fractionation and mixing with crustal components. The formation of protoliths in oceanic setting, island arcs, and at the continental margin is suggested on the basis of discriminant paleotectonic diagrams [65]. The model Nd age ranges from 1000 to 1700 Ma; $\varepsilon_{Nd}(1000)$ = +7 to –1; Sr_i = 0.704.

The Bunger Hills are composed of banded felsic orthogneisses (orthopyroxene-bearing quartz–feldspar gneisses and plagiogneisses), biotite–garnet paragneisses and metapelites, and subordinate mafic granulites and metapsammites. The orthogneisses correspond to the tonalite–trondhjemite–granodiorite (TTG) association. The overwhelming majority of samples are distinguished by a low Y content (<30 ppm), indicating partial melting of a deep mafic source with retention of hornblende or garnet as restitic phases. The rocks are moderately enriched in Pb, Ba, U, K, and LREE and marked by a distinct Nb minimum [13 and references therein]. They are depleted in HFSE and characterized by a low Rb/Sr ratio (~0.03 on average). The age of this series is estimated at 1521 ± 29 Ma; metamorphism is dated at 1190 ± 15 Ma; and relict zircon cores yield 1700 ± 20 Ma [72]. Charnockites of granodiorite–granite composition were emplaced contemporaneously with the final phase of tectonic activity 1170–1150 Ma ago. Dolerite dikes are dated at 1100 Ma. The model Nd age is 2000–2100 Ma.

Thus, rocks in the areas considered above bear characteristic geochemical attributes (negative Nb anomaly, high LILE/HFSE ratio, Sr_i < 0.710, and ε_{Nd} > 0) that testify to their juvenile origin under suprasubduction conditions. Metamorphism in these areas is relatively low-grade (epidote–amphibolite and amphibolite facies) in comparison with the rest of the territory of East Antarctica. Both volcanic and plutonic rocks are characterized by a distinct calc-alkaline trend in the AFM diagram [13, 15]. Plotted on discriminant diagrams, the compositions of these rocks correspond to calc-alkaline basaltoids and tholeiites and mostly fall into the fields of volcanic (magmatic) arcs, orogenic regions, and active continental margins. Some basalts correspond to E-MORB in composition and are interpreted as indicators of oceanic plateau. Granitoids are comparable with orogenic I-type granites. It may be suggested that metavolcanics and comagmatic intrusive rocks are related to geodynamic settings of volcanic arcs at different stages of their evolution. The Fisher Complex in the central Prince Charles Mountains was formed at a more primitive arc than the rocks from western Dronning Maud Land.

Accretionary–collisional settings are identified in Beaver Terrane of the northern Prince Charles Mountains, central Dronning Maud Land, and in the Rayner Terrane of Enderby Land. The Beaver Terrane to the north of 71°S is composed of granulite-facies metamorphic rocks (Beaver metamorphic complex after [4]), large charnockite plutons, and sporadic conformable bodies of mantle-derived mafic and ultramafic rocks. These bodies are dated at 1160 Ma [61]. A peak of thermal metamorphism and emplacement of synkinematic and late kinematic granites and charnokite fall on 1050–950 Ma ago [57 and author's unpublished data].

Metamorphic conditions reached P = 5–7 kbar and T = 700–830°C [48]. The endogenetic regime corresponds to isobaric cooling with insignificant locally developed decompression. Felsic orthogneisses (tonalitic and plagiogranitic plagiogneisses, granodioritic and granitic gneisses with variable amounts of pyroxene and hornblende) are the most abundant rocks in this locality. Biotite–garnet gneisses, most likely metasedimentary in origin, are widespread as well. Many massive gneisses are considered to be metamorphosed intrusive rocks, whereas the gneisses intercalating with metasedimentary rocks have volcanic protoliths; judging from the chemical composition, both are comagmatic [61]. Orthogneisses contain 60–74 wt % SiO_2 and 1–7 wt % K_2O and are characterized by low K/Rb (235) and high Rb/Sr (1.12) and K/U (22000) ratios (arithmetic mean is given here and hereafter). The chondrite-normalized La/Yb ratio (6–10) is relatively low in comparison with granulite complexes elsewhere. These parameters strictly fit the composition of post-Archean granulites [70]. Mafic rocks correspond to gabbroids formed at a volcanic arc characteristic of convergent continental margins or ocean–continent transitional zones, but the volume of these rocks is insignificant; bimodal metamorphic sequences are distinguished by sharp prevalence of felsic rocks (dacite–rhyolite and diorite–granodiorite associations). These rocks are enriched in LILE and LREE, have a high initial $^{87}Sr/^{86}Sr_i$ ratio (0.710–0.730) and low $\varepsilon_{Nd}(1300)$ = –10 to 0; t_{DM} = 1600–2300 Ma. These parameters testify to the Paleoproterozoic crustal material as a source of these rocks.

The late kinematic charnockite complexes (980–950 Ma) widespread in the Beaver Terrane in fact occupy the tectonic setting of calc-alkaline I-type granites. The origin of charnockites probably is related to relatively dry conditions of partial melting in syncollision regime.

Central Dronning Maud Land (2°–15°E) is composed of high-grade metasedimentary sequences, bimodal granulitic series, and felsic orthogneisses. In the Wohlthat massif, pre- and synkinematic granitoids were emplaced 1150–1115 Ma ago; felsic volcanics were formed about 1130 Ma ago, and granulite-facies metamorphism developed 1090–1050 Ma ago, accompanied by ductile deformation and emplacements of synkinematic granitoids [53, 55]. $\varepsilon_{Nd}(1300)$ of orthogneiss varies from +5.0 to –1.5 and t_{DM} from 1100 to 1800 Ma, indicating heterogeneity of this rock group. Chemical composition shows that the rocks of this region were formed in intraplate setting with limited involvement of deep mantle material [60] 1150 Ma ago. These orthogneisses differ in trace element geochemistry from typical granitoids in convergent setting and to a greater extent correspond to A_1-granites [23].

In the Rayner Terrane of Enderby Land, the granulite-facies rocks of moderate pressure were formed at P = 6–8 kbar and T = 750–800°C [48]; locally, pressure increased to 13 kbar and temperature to 900°C [4]. Tonalitic (in subordinate amount), granodioritic and granitic orthogneisses, banded paragneisses, and mafic granulites make up the Rayner metamorphic complex [19]. Structure and mineral assemblages of this complex were formed at the Grenville stage of tectonomagmatic activity 1000 Ma ago. Granitic orthogneiss in the vicinity of the Molodezhnaya Station has a Rb–Sr isochron age at 1022 ± 62 Ma; however, similar rocks from other portions of the Rayner Complex have U–Pb zircon ages of 1425 ± 30, 1465 ± 25, and 1290 ± 25 Ma [25]. These dates probably represent the time of protolith emplacement, and the Rb–Sr age is the time of metamorphism. Migmatized metasedimentary rocks and granite gneisses are predominant in the Rayner Complex. The latter, however, often replace melanocratic crystalline schists and plagiogneisses. Mafic and mafic–felsic igneous series of the mantle origin are not abundant. The Nye Group of the Rayner Complex [4] consisting of migmatized hypersthene plagiogneisses and pyroxene–plagioclase crystalline schists serves as an example. The rocks of the Rayner Complex cover a wide compositional range with predominance of basic and silicic rocks and subordinate contribution of intermediate rocks. Felsic rocks are commonly distinguished by a distinct Nb minimum, enrichment in LILE, and saw-shaped HFSE distribution with positive Zr anomaly. The rocks have model Nd age in a range of 1900 to 2400 Ma; $\varepsilon_{Nd}(1000)$ = –4 to –13; Sr_i = 0.706–0.712.

The regions developed in the accretionary–collisional regime are characterized by granulite-facies metamorphism at the final stage of their evolution. Kinematic indicators testify to prevalent compression with thrusting [29]. Granitoid para- and orthogneisses are predominant; granites and granodiorites are most abundant. In geochemistry, these rocks are close to A-granite, although calc-alkaline granitoids occur as well. Low ε_{Nd} = 0 to –10, and Sr_i > 0.706 (commonly, >0.710) are typical. The mantle derivatives are very subordinate in abundance, but their contribution probably remains underestimated.

The regime of ***rifting*** existed in the Mesoproterozoic within Archean blocks. The magmatic activity in these regions were reduced to the formation of swarms of basic dikes of normal alkalinity 1400–1200 Ma ago (dated largely with the Rb–Sr method) in the Vestfold Hills, the Napier Terrane in Enderby Land, and in the Ruker Terrane of the Prince Charles Mountains [71]. The practically complete compositional identity of dikes in all regions with respect to major and minor elements and isotope ratios [13] indicates their derivation from the same mantle source. The origin of dike swarms, whose age is close to the early phases of tectonomagmatic processes in the adjacent mobile belts, may be related to the rifting in their forelands. However, the age of the dike suites has been determined only at a first approximation, and it cannot be ruled out that their emplacement marks the early stage of a Ber-

trand cycle with opening of a secondary oceanic basin limited in size.

In some regions of Mesoproterozoic tectogenesis (Bunger Hills, Windmill Islands), suites of basic dikes were formed in the ***postorogenic regime.*** These dikes appreciably differ in composition from the coeval dike suites in Archean cratons, in particular, in enrichment in HFSE and appearance of alkaline varieties [13].

Regime of epiplatform troughs is recognized on Coats Land and the Richer Plateau in western Dronning Maud Land. Undeformed and unmetamorphosed felsic volcanics crop out in some nunataks on Coats Land. The rocks are dated at 1112 ± 4 Ma [45]; $\varepsilon_{Nd}(1100)$ = 5.4–4.5 indicates their mantle origin. The K–Ar age of 830 Ma shows that the thermal processes completed in the Neoproterozoic. The weakly metamorphosed volcanic–sedimentary sequence up to 3000 m thick cut through by mafic sills is exposed on the Richer Plateau. The sills are dated at 1130 Ma [68], and this estimate coincides with the age of tectonomagmatic processes in the mobile belt. The great thickness of rocks inconsistent along the strike and the substantial contribution of silicic and intermediate rocks [4] may be regarded as evidence for geodynamic setting of epiplatform orogeny passing to the stage of rifting marked by basic sills. This region likely was a pericratonic trough in the foreland of a mobile belt.

Neoproterozoic. The geological complexes of East Antarctica show that *extension* dominated here in the Neoproterozoic (900–600 Ma). At that time, shallow-water basins were formed within inland territories of western Dronning Maud Land, the southern Prince Charles Mountains, and the head of the Denman Glacier. Variegated sequences consisting largely of psammitic and psephitic sediments were deposited in these basins. The age of these rocks was determined roughly with Rb–Sr and U–Pb methods with account of palinological data [10 and references therein]. The structures of rocks testify to shallow-water sedimentation. The rocks are slightly metamorphosed and deformed only locally. These basins, probably, were intracontinental pull-apart basins. In the opinion of many researchers, the Neoproterozoic sedimentation proceeded in some near-shore areas (coasts of the Lützow-Holm and Prueds bays) as well. The rocks in these areas are highly metamorphosed and intensely deformed; their age and primary composition are not established reliably.

At the same time, basic intrusions of elevated alkalinity were formed in some places. According to the unpublished data of A.A. Laiba, the Sm–Nd age of low-alkaline dikes in the central Prince Charles Mountains is 850 Ma. Hypabyssal high-Ti intrusive rocks cut through Neoproterozoic sedimentary rocks in the southern Prince Charles Mountains.

Collisison conditions in the Neoproterozoic are suggested only in the near-shore tract of Dronning Maud Land (the Schirmacher Hills), where granitoids emplaced about 700 Ma ago are related to the orogenic event of this age. The composition of granitic rocks and model Nd age do not indicate the presence of Neoproterozoic juvenile material [10]. The conditions of Late Neoproterozoic metamorphism in the Schirmacher Hills are estimated at P = 6 kbar and T = 600–650°C [34].

Late Neoproterozoic and Early Paleozoic. The Late Neoproterozoic–Early Paleozoic stage of tectonothermal activity (Kuung Orogeny, 600–500 Ma after [59]) developed to various extents over most of East Antarctica [12 and references therein]. Wilkes Land, Adélie Land, and some areas in the extreme west of Dronning Maud Land, which completed their evolution earlier and were not reactivated afterward, are the only exceptions. Two phases of the Late Neoproterozoic–Early Paleozoic tectonothermal activity are recognized. The early phase (650–600 Ma, probably, up to 570 Ma) developed in central Dronning Maud Land, including the Sor Rondane, Yamato, and Belgica Mountains. This time was characterized by ductile deformation, metamorphism, and emplacement of charnockites and anorthosites found as xenoliths in younger intrusive rocks. The late Kuung phase (550–500 Ma) was the most intense in some areas of central and eastern Dronning Maud Land, in particular, on the coast of the Lützow-Holm Bay, and in Princess Elizabeth Land (coast of Prueds Bay and the Grove Mountains). Ductile deformation, high-grade metamorphism, and crustal anatexis with formation of granitoids are related to this phase.

The characteristic feature of the Early Paleozoic tectonomagmatic activity in the Wohlthat massif of central Dronning Maud Land was granulite-facies metamorphism and the subsequent endogenetic activity under conditions close to isothermal decompression [31] and partial melting 600–570 and 550–510 Ma ago. Some heating of the crust in the course of decompression is suggested. The peak conditions likely attained at the younger interval were not accompanied by deformation. The metamorphic conditions were estimated at P = 7–8 kbar and T = 700–800°C with subsequent decompression to P = 3–4 kbar and cooling to 650°C [48]. Mafic intrusions (525 ± 5 Ma) and large plutons of anorthosites and charnockitoids of monzonitic–syenitic series (A_2-type after [23]) were emplaced 600 and 510–500 Ma ago [18, 53]. A tectonic block of metaperidotite crossed by synkinematic felsic veins dated at 517 ± 8 Ma (author's unpublished data) is exposed in an isolated nunatak to the south of the Schirmacher Hills. This block is the single outcrop of the Early Paleozoic Alpine-type peridotite in Antarctica.

The Early Paleozoic endogenetic regime with a substantial contribution of isothermal decompression established on Dronning Maud Land is adequately described by the model of ***collision*** of continental blocks with doubling thickness and subsequent delamination of the lithosphere that gave rise to the emergence (exhumation) of the territory and the following

collapse of the orogen with passage into the regime of extension. These processes are reconstructed in the East African Orogen [69], which reveals some geological features similar to those of Dronning Maud Land [53]. In particular, these regions are characterized by the development of left-lateral transcurrent zones of viscoplastic flow formed by oblique collision during closure of the Mozambique ocean. Large plutons of charnockitoids and anorthosites may be referred to a ***postcollision*** (rift-related) event.

The coast of Prueds Bay is occupied by paragneisses of granulite facies and relatively rare orthogneiss bodies, numerous pre- and synkinematic granitoid veins, and relatively large post-tectonic granitoid plutons. The synkinematic granitoids are dated at 547 ± 9 to 514 ± 7 Ma; the latter episode was accompanied by repeated granulite-facies metamorphism [49 and references therein]. The peak conditions were P = 6–7 kbar and T = 850°C with subsequent decompression to 4–5 kbar [48]. Early Paleozoic post-tectonic peraluminous leucogranites and granites of A_1-type dated at 516–500 Ma are widespread in this area [13 and references therein]. Thus, metamorphism in this region was not so high-grade as on Dronning Maud Land and decompression was not so deep and developed only locally. Rift-related rocks characteristic of postcollision collapse of the orogen are unknown here, and igneous rocks comprise only peraluminous leucogranite and A1-type granites. To a great extent, these phenomena can be caused by ***unedrplating*** of the crust by mantle-derived material.

Early Paleozoic alkaline dikes formed throughout East Antarctica under ***intraplate conditions*** [13 and references therein]. These rocks (alkali dolerites, lamproites, and lamprophyres) are widespread but are exposed only as sporadic thin dikes (Bunger Hills, Prince Charles Mountains, Enderby Land, Dronning Maud Land).

EVOLUTION OF THE EARTH'S CRUST IN EAST ANTARCTICA

The blocks of the Archean crust contoured on the basis of geological and geophysical data (Fig. 1) are cores surrounded by material formed in the course of Proterozoic tectogenesis. The Archean cores underwent substantial tectonomagmatic reworking at the Proterozoic stages of evolution. Beyond the Archean cores, the exposed territory of East Antarctica is occupied by rocks with model Nd ages largely falling into the interval from 1400 to 2400 Ma [17], testifying to the active formation of the primary crust in the Proterozoic. The occasionally detected rocks with Archean model Nd age, e.g., on the shelf of Eimery Glacier, indicate the occurrence of reworked Archean material. Dates of metamorphism, emplacement of pre- and synkinematic granitoids, and ductile deformation obtained with U–Pb method cover a long time interval from 2400 to 950 Ma ago. The oldest Paleoproterozoic dates correspond to one of the phases pertaining to the formation of the most ancient supercontinent Pangea-0 [22]. It may be suggested that the Napier Terrane of Enderby Land, as well as the Vestfold Hills and Ruker Terrane in the Prince Charles Mountains were constituents of this supercontinent or made up a separate megacontinent EVER (Fig. 5). All these blocks are crossed by dikes of high-Mg basic rocks dated at 2400–2250 Ma, which are related to the first phases of rifting. A hypothetical Mawson paleocontinent may be regarded as another constituent of the megacontinent. The Mawson paleocontinent comprised the Gawler Craton of South Australia and block of Adélie Land in Antarctica [35]. Apparently, rifting reached the advanced stage with formation of a secondary oceanic basin [21] because the space between Early Precambrian blocks is filled with relatively young Proterozoic crust. While the oceanic basin was being formed, the tectonic regime once underwent inversion, which could have been caused by exceeding of the width of the convective mantle cell due to extension of the lithosphere [9]. The inversion acquired an active form [21] with development of subduction zones migrating toward the continent and generating sialic crust, as supported by model Nd ages with a peak at 1600–1900 Ma. In the southern Prince Charles Mountains, the main tectonic activity was completed by the Middle Paleoproterozoic about 2100 Ma ago, whereas on Adélie Land and in the Miller and Shackleton ranges this happened about 1700 Ma ago. The juvenile origin of the rock complexes having this age is validated only on Adélie Land and in the Shackelton Range, where the difference between model Nd age and the time of the final stage of tectogenesis is relatively small.

The convergence of some Archean cores in the Late Paleoproterozoic probably resulted in collision of Mawson continent and block of the Miller Range with development of high-pressure rock associations. It may be suggested that the block of the Shackleton Range underwent coeval orogenesis (Fig. 4) and made up a single massif with the block of the Miller Range and Mawson continent. At the current state of knowledge, it is difficult to establish whether this massif, whose fragments now occupy the Pacific sector of East Antarctica, was connected at the end of the Paleoproterozoic with ancient cores in its central sector (Enderby Land, Prince Charles Mountains, Vestfold Hills). Most likely, the answer to this question should be negative, because the "Pacific" Paleoproterozoic massif was characterized by convergent geodynamic conditions, whereas the "central" sector was distinguished by divergent conditions (sedimentary basins, basic dikes, tectonomagmatic reactivation) and somewhat older age. The different characters of tectogenesis in the "Pacific" and "central" sectors probably were determined by localization of these lithospheric blocks above differently directed cells of mantle convection.

The active evolution of the geodynamic system continued in the Mesoproterozoic and was accompanied by formation of the juvenile crust. However, the area of

proved juvenile Mesoproterozoic rocks was not so large as the area with Paleoproterozoic model Nd age of crustal protoliths. At the same time, it should be emphasized that the mantle material could have been enriched in lithophile elements, including LREE, at the preceding stages. In this case, the calculated model Nd age serves only as the upper limit of the time of the primary crust origination, and the true contribution of such crust may be much greater. On the other hand, partially reworked fragments of Archean material could have been left in the crust with Paleo- and Mesoproterozoic model ages. Furthermore, it is evident that, like the crust of other Precambrian cratons, the crust of East Antarctica has a layered structure, and the lower units could have been composed of Early Precambrian complexes overlain by younger units in the process of collision. In particular, the discovery of xenogenic Early Precambrian zircon in basic dikes of the Schirmacher Hills [24] composed of Mesoproterozoic rocks confirms this suggestion.

The structure of the Antarctic Shield was largely formed by progressive accretion and collision with blocks of the Archean and Paleoproterozoic volcanic arcs and, probably, oceanic plateaus and microcontinents from the east westward (in present-day coordinates) 1500–1050 Ma ago. In total, the Mesoproterozoic structural elements have formed a vast marginal volcanic–plutonic belt, whose cyclic evolution [56] may be interpreted in terms of Bertrand cycles [21] from 1700–1800 to 1000–1050 Ma ago. In different areas, the endogenetic activity developed asynchronously (early phases are dated at 1500, 1400–1300, and 1150 Ma, see above). Therefore, it may be suggested that several Mesoproterozoic mobile belts participated in the structure of the Antarctic Shield. Some fragments of the Antarctic Shield underwent special tectonomagmatic evolution 1500–1150, 1400–950, or 1150–1050 Ma ago and may be regarded as separate Wilkes, Rayner, and Maud tectonic provinces (terranes), respectively. The established period of evolution of the latter province was incomparably short; the early stages of tectonomagmatic activity therein probably remain unknown. Soft arc–arc or arc–continent collision brought about tectonomagmatic reworking of Paleoproterozoic and partly Archean rocks, and only the youngest complexes avoided deep reworking. Particular phases of tectonomagmatic activity were separated by relatively quiet periods. For example, in the Fisher Terrane of the Prince Charles Mountains, the orogenic events dated at ~1300 and ~1100 Ma were separated by a stage of relative stabilization under extensional conditions, when a complex of layered gabbro was formed. It should be noted that the final phase of Mesoproterozoic tectogenesis was practically synchronous (1050–950 Ma) throughout East Antarctica except the Bunger Hills and Windmill Islands, where tectonomagmatic activity was completed by 1150 Ma ago.

The Mesoproterozoic tectonothermal processes found their reflection in some blocks in western Dronning Maud Land and Kemp Land, probably the most rigid Archean and Paleoproterozoic blocks. Volcanic–sedimentary and volcanic sequences were formed here in the Mesoproterozoic practically synchronously with the main orogenic phase in the adjacent mobile belt but did not undergo substantial deformation and metamorphism. These rocks were referred to by many authors as a platform cover [2], however the composition and geological setting of these rocks testify to their formation under conditions of rifting in the foreland of the mobile belt.

A vast megacontinent apparently formed by 1000 Ma ago (Fig. 5), embracing the central and eastern sectors of the Antarctic Shield and southern and western Australia. It cannot be ruled out that Dronning Maud Land along with the Kalahari Craton were constituents of this block, however it is commonly suggested that Dronning Maud Land was a part of the African continent separated from Antarctica by the Mozambique Ocean [26, 29, 52]. It is supposed that the aforementioned block was a part of Rodinia supercontinent.

According to the commonly adopted viewpoint, the post-Grenville Rodinia underwent complete disintegration in the Neoproterozoic to form several isolated continents and vast separating oceans. In the Early Paleozoic, the landmasses were amalgamated into a new Gondwana megacontinent [69]. However, the data on Antarctica do not corroborate this hypothesis. The Neoproterozoic sedimentation and formation of basic dikes testify to extension of the Earth's crust in the Antarctic Shield, but no indications of a rift-to-drift stage with opening of deepwater spreading basins have been established in East Antarctica to date. The Neoproterozoic tectogenesis with formation of sialic crust in magmatic arcs, metamorphism, and orogeny, widespread on other continents, was ascertained in Antarctica only in the coastal Schirmacher Hills. The Nd and Sr isotope ratios of the Neoproterozoic and Early Paleozoic metamorphic and igneous complexes argue against the substantial participation of juvenile material of this age in the structure of East Antarctica. It may be noted that some charnockitoids bear attributes of juvenile matter [18]. As follows from the overall occurrence of relict zircons dated at ~1000 Ma and older, this stage was characterized by reworking of ancient geological complexes.

In spite of this circumstance, it has to be admitted that the Neoproterozoic and Early Paleozoic tectonomagmatic processes in East Antarctica with a culmination 550–500 Ma ago are related in one way or another to continental collision, and are characterized by ***collision and postcollision regimes.*** This is supported by the character of postpeak isothermal decompression and the composition of late kinematic and postkinematic granitic rocks (charnockites, peraluminous leucogranites, and A-type granites). The Neoproterozoic and Early Paleozoic tectonomagmatic events in East Antarctica are likely related to the formation of

Gondwana, however, the location of a suture of this age remains a matter of search and discussion. Many authors suppose that the Shackleton Range with ophiolites and the coast of the Lützov-Holm Bay with high-pressure parageneses are the sites of the exposed Early Paleozoic suture. However, the regional structure in the latter region is oriented perpendicular to the suggested direction of the suture (Fig. 1); the magnetic anomalies are oriented in the same direction as well [40]. In addition, rocks that escaped Early Paleozoic granulite-facies metamorphism are known from Dronning Maud Land and the Sor Rondane Mountains, and this circumstance comes into conflict with the model assuming doubling of the crust thickness over the entire Dronning Maud Land. It is evident that nonuniform metamorphism was brought about by heating rather than by subsidence. It is probable that the collision zone was not wide, and the suture was localized beyond the present-day contours of Antarctica, or (most probably) extended at a tangent to the near-shore zone of central and western Dronning Maud Land, where the relict eclogites are dated at 565 Ma, i.e., 40 Ma older than the peridotite in the Schirmacher Hills. Thus, these rocks are related to different orogenic phases. At the same time, it is known that the effect of collision can spread inland for a great distance, and therefore it is possible that the Mozambique ocean closed in the central Mozambique Belt and did not spread over Antarctica. In this case, tectonomagmatic activity in Antarctica was controlled by underplating of the crust by deep mantle material that replaced the lithosphere, which experienced postcollision delamination far beyond the collision zone proper. The additional factors that determined tectonomagmatic activity probably were tectonic processes in the western African continent, the closure of the hypothetical Adamastor paleoocean [50], and the formation of western Gondwana.

According to the reconstruction of Gondwana, the zone of the Lützow-Holm Bay extends westward to the Damara–Zambezi Belt (560–510 Ma) [30], while its eastern continuation may be the area of Princess Elizabeth Land; this, however, is not supported by the structure of the anomalous magnetic field [42]. The Early Paleozoic tectonomagmatic processes on Princess Elizabeth Land developed under compression and were probably caused by mantle underplating of the crust without preliminary thickening and delamination of the lithosphere. Underplating could have been induced by collision of the India–Madagascar Block with Antarctica, but the geological consequences of these events on Princess Elizabeth Land were different than on Dronning Maud Land. Probably, this was caused by the sliding character of collision or the soft, not completely consolidated, state of the Antarctic massif, which prevented doubling of the crust and the subsequent fast exhumation of lower units. In central Dronning Maud Land, transtension and extension were predominant. The present-day thickness of the lithosphere in central Antarctica is 30 km (on average) greater than the lithosphere thickness beneath Dronning Maud Land [64], reflecting the different geological evolution of these regions.

It seems reasonable to suggest that the rheological and structural heterogeneities that arose in the Mesoproterozoic are retained in Antarctica, being reactivated as a result of shearing. The shear zones might have developed due to oblique collision of the Tanzanian Craton with the Antarctic Block at the early Kuung stage (assuming that an oceanic basin existed on the place of the Damara–Zambezi Belt, though this is not evident) and collision of the India–Madagascar and Antarctic blocks at the late Kuung stage (Fig. 5). An additional geodynamic factor determining the evolution of the Antarctic Shield was related to the convergence at the Pacific margin, where accretionary and collisional events pertaining to longitudinal subduction and collision of microcontinents entering into West Antarctica were pivotal in the formation of the Ross Fold System [43]. The sedimentary basins that arose at the early Kuung stage (Lützow-Holm and Prueds coasts) were apparently closed at the late stage and underwent inversion accompanied by advanced tectonomagmatic reworking of the material under compression. No reliable indications that these basins reached the oceanic stage of evolution are known at present.

CONCLUSIONS

At the current state of geological knowledge, East Antarctica is regarded as an area of the Early Precambrian crust consisting of Archean blocks and Paleo- and Mesoproterozoic provinces. The Mesoproterozoic tectonic units are subdivided into high-grade paragneissic belts (central Dronning Maud Land, the Beaver Terrane in the Prince Charles Mountains) and relatively low-grade orthogneissic belts (Fisher Terrane in the Prince Charles Mountains, western Dronning Maud Land). Three provinces are distinguished by age ranges of the main tectonomagmatic and thermal processes from formation of the juvenile igneous complexes under suprasubduction conditions to post-tectonic granite formation in combination with regions of Neoproterozoic and Early Paleozoic superimposed tectonomagmatic impact, which is manifested in intense tectonothermal reworking (granulite-facies metamorphism, ductile deformation, syntectonic granites) or relatively weak reactivation (thermal effect expressed in isotopic rejuvenation, anorogenic igneous rocks). The Mesoproterozoic massif of East Antarctica was not an absolutely rigid lithospheric block but retained certain mobility, ability to rheid deformation, and susceptibility to tectonothermal perturbances. The ultimate stabilization of the lithosphere and cratonization of the Antarctic Shield occurred only in the Early Paleozoic and is marked by the formation of alkaline igneous rocks unknown previously.

The performed study leads to the conclusion that none of the existing hypotheses on the tectonic evolution of East Antarctica is quite adequate. It casts no

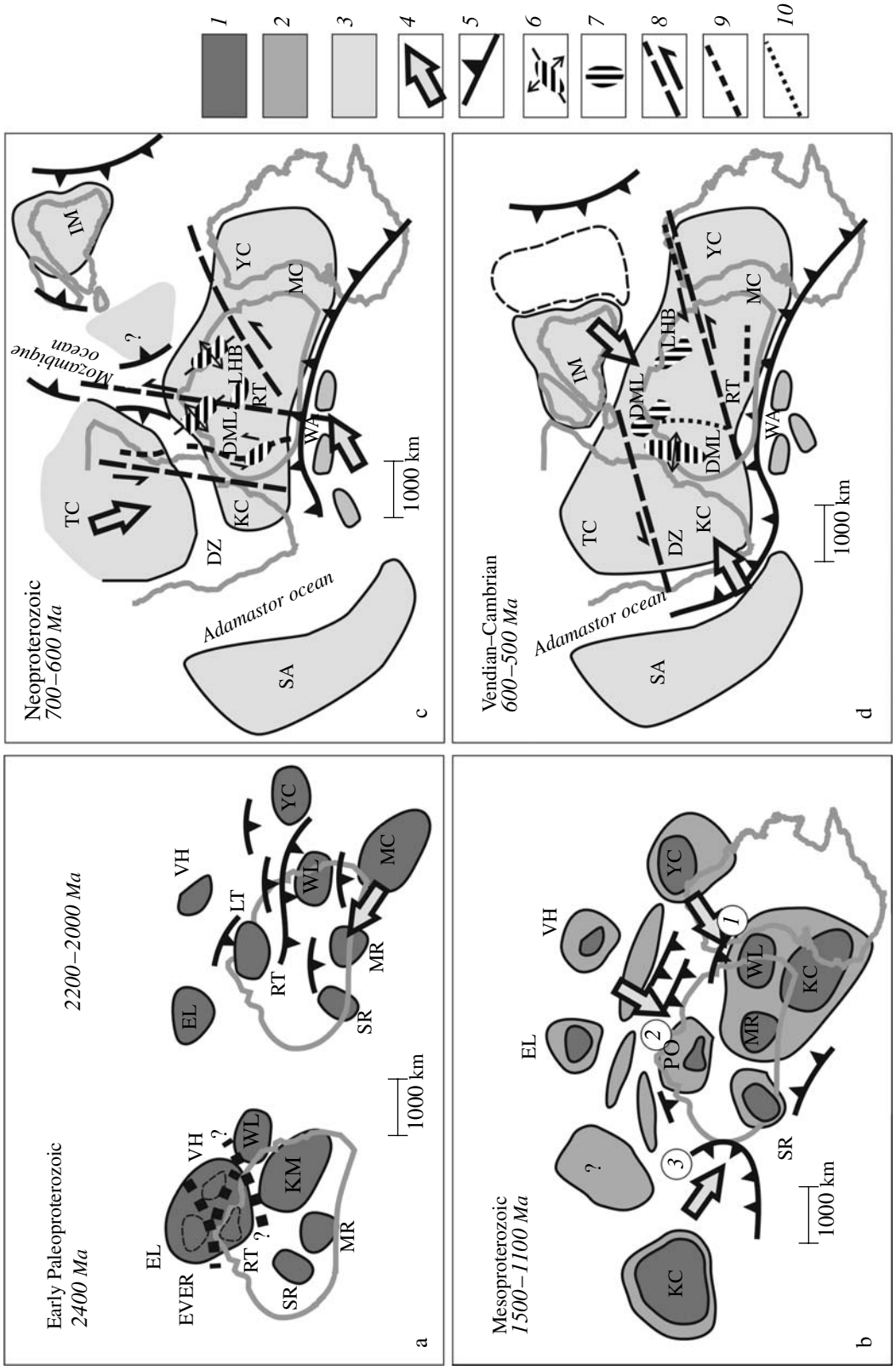


Fig. 5. Geodynamic schemes of the formation of the Antarctic continent at the main stages of its evolution: (a) Early Paleoproterozoic, (b) Mesoproterozoic, (c) Neoproterozoic, and (d) Vendian–Cambrian. (*1*) Crustal cores of Archean age; (*2*) continental blocks formed by the end of the Paleoproterozoic and Paleoproterozoic juvenile crust in system of volcanic arcs; (*3*) continental blocks formed by the end of the Mesoproterozoic; (*4*) inferred direction of relative motion of continental blocks as constituents of lithospheric plates; (*5*) paleosubduction; (*6*) region of extension, inferred direction and axis; (*7*) region of compression on the place of intracontinental sedimentary basin; (*8*) main direction of strike-slip dislocations; (*9*) transpressional zone of viscoplastic flow; (*10*) hypothetical suture, after [54]. Tectonic provinces (terranes) (numerals in circles): (1) Wilkes, (2) Rayner, (3) Maud. Localities and tectonic units (abbreviations in figure): (DZ) Damara–Zambezi Belt; (WA) microcontinents of West Antarctica; (DML) Dronning Maud Land; (LHB) Lützow-Holm Bay; (PEL) Princess Elizabeth Land; (EL) Enderby Land; (WL) Wilkes Land; (IM) India, Madagascar; (YC) Yilgarn Craton; (KC) Kalahari Craton; (MK) Mawson Craton (continent); (LT) Lambert Terrane; (VH) block of Vestfold Hills; (RT) Ruker Terrane; (TC) Tanzanian Craton; (SR) block of Shackleton Range; (MR) block of Miller Range; (EVER) hypothetical Enderby–Vestfold–Ruker continent; (SA) South Africa.

doubt that extensive areas of Proterozoic tectogenesis are not occupied by reworked Archean crystalline complexes, as was assumed before. At the same time, the hypothesis of the Early Paleozoic amalgamation of Antarctica does not find its substantiation, because juvenile igneous rocks of this age are unknown. The documented Early Paleozoic tectonothermal and magmatic processes are teleorogenic and should be regarded as distal manifestations of collision developed beyond Antarctica.

Summarizing, the following conclusions may be drawn: (1) The evolution of the Proterozoic regions of East Antarctica may be interpreted as a Wilson cycle that started with the destruction of a megacontinent 2250 Ma ago and finished by the closure of secondary oceanic basins 1050 Ma ago. These regions make up a marginal volcanic–plutonic belt, whose structure embodies accretion of several Mesoproterozoic terranes that developed 1500–1150, 1400–950, and 1150 (?)–1050 Ma ago.

(2) Antarctica is a landmass that has experienced coherent tectonic evolution as a single whole since the end of the Mesoproterozoic (1000–950 Ma ago). No evidence for complete disintegration of the landmass in the Neoproterozoic is established. It cannot be ruled out that Antarctica was not completely cratonized and was a paraplatform. Its lithosphere did not acquire significant rigidity and continued to retain a certain mobility in the Neoproterozoic.

(3) The Vendian–Cambrian tectonomagmatic processes mainly reflected oblique collision of various continental blocks in the course of the formation of Gondwana and vigorous reworking of Proterozoic structures. The eventual cratonization of East Antarctica was reached by the Ordovician and fixed by the formation of alkaline igneous rocks.

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