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Neoproterozoic and Early Paleozoic Geological Complexes of Eastern Antarctica: Composition and Origin

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Abstract—Geological and geochemical data on Neoproterozoic and Early Paleozoic metamorphic and igneous complexes of East Antarctica are considered. Sedimentation and formation of mafic dikes in the Neoproterozoic point to dominant extension through most of the Antarctic Shield, although no indications of advanced rifting and opening of deep basins have been established so far. As well, no distinct evidence for large-scale Early Paleozoic convergence accompanied by closure of oceanic basins, which would be reflected in particular geological complexes of East Antarctica, has been recorded. The Early Paleozoic development peak is related to thermal and intrusive consequences of tectonic activation that determined structural reworking and repeated metamorphism of host Grenvillian complexes. The main phase of the Early Paleozoic tectogenesis may be interpreted as an intraplate response to the oblique collision of large continental blocks that occurred beyond present-day Antarctica and was accompanied by underplating of mantle material at the base of the crust.

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INTRODUCTION

For a long time, the standpoint of Russian geologists on geological evolution of East Antarctica was based on assumptions of (1) primary continental crust, (2) its ensialic growth due to granitization, and (3) sharp prevalence and determining role of vertical tectonic movements. The Early Precambrian age obtained for rocks from the Enderby Land was extrapolated practically onto all the lithotectonic complexes of East Antarctica [5, 20]. Manifestations of Proterozoic and Neoproterozoic–Early Paleozoic processes substantiated by many K–Ar and Rb–Sr dates (1600–500 Ma) were interpreted by most researchers as indicating exclusively tectonothermal activation of Early Precambrian structures. It was assumed that Late Neoproterozoic–Early Paleozoic (600–500 Ma ago) geological processes resulted only in regional heating and intrusion of anorogenic granitoids and were of a “geosynclinal” nature. The geochronologic data obtained by the U–Pb method on zircons during the last 15 years suggest, however, more active Late Neoproterozoic–Early Paleozoic (Pan-African) tectogenesis that was accompanied by high-grade metamorphism, plastic deformations, and formation of penetrative schistosity in some areas [14, 24, 29, and others]. Most researchers interpreted these processes as a response to the collision of lithospheric plates, which resulted in amalgamation of eastern Gondwana from isolated blocks [1, 3]. These concepts were, however, based primarily on isotopic–geochronologic data, while composition of Neoproterozoic and Early Paleozoic geological complexes was insufficiently known.

The purpose of this work is the generalization of available data on the composition of the Neoproterozoic and Early Paleozoic geological complexes and a thorough analysis of geodynamic models of the development of East Antarctica.

COMPOSITION OF GEOLOGICAL COMPLEXES

East Antarctica represents a Precambrian platform [20]. Judging from outcrops, it is largely composed of crystalline basement rocks, which allows the largest part of East Antarctica to be considered as an ancient shield. The shield comprises several Archean or Archean–Paleoproterozoic protocratonic blocks and an extended Proterozoic mobile belt of polycyclic development (Fig. 1) [8, and references therein]. Peaks of endogenic activity within the belt correspond to periods of 1850–1700, 1400–1250, 1200–920, and 600–500 Ma ago. The crystalline basement consists largely of strongly metamorphosed rocks and igneous complexes variable in lithology (mainly granitoids) and tectonic position. Many areas composed of Archean complexes host swarms of mafic dikes.

Metamorphic Complexes

Rock complexes with metamorphism dated back to 570–500 Ma ago developed in the extended coastal areas of the Antarctic Shield in the central and eastern parts of Queen Maud Land and Princess Elizabeth Land

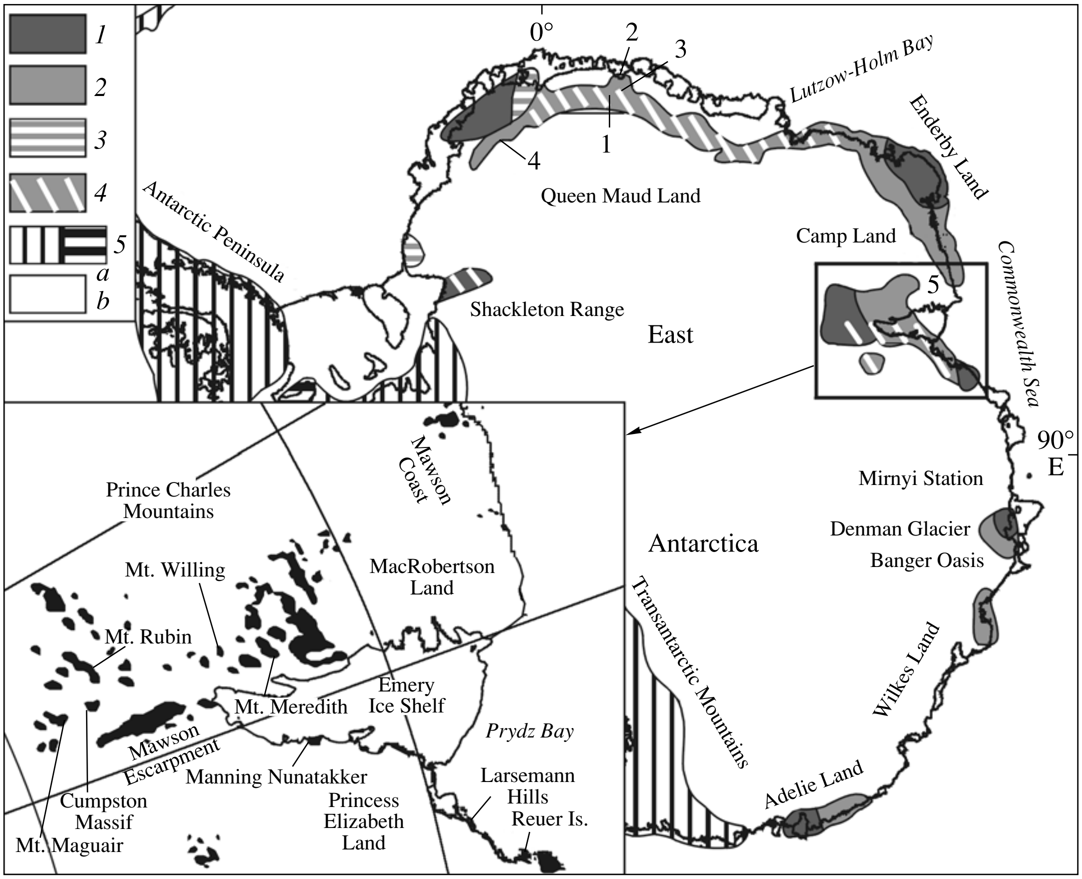

Fig. 1. Schematic tectonic structure of Antarctica. (*1–4*) East Antarctic Platform: (*1*) Archean or Archean–Paleoproterozoic protocratons, (*2*) areas of Mesoproterozoic consolidation, (*3*) Mesoproterozoic cover, (*4*) areas of Neoproterozoic–Early Paleozoic activation; (*5*) Phanerozoic mobile belt of West Antarctica and the Transantarctic Mountains: (*a*) Precambrian basement inliers, (*b*) areas covered by continuous ice shield. Numbers in the map: (1) Voltat Massif, (2) Schirmacher Oasis, (3) Inzel Mountains, (4) Kirvanweggen Range, (5) Mawson Coast. The inset demonstrates schematic location of outcrops in the Prince Charles Mountains area and tectonic provinces.

(Fig. 1). These complexes are largely composed of paragneisses (pelites, semipelites, pasmmites) and subordinate felsic gneisses, migmatites, mafic granulites or amphibolites, and rare ultramafic rocks.

In the central part of Queen Maud Land, maximal pressure and temperature values of 8 kbar and 830°C, respectively [18], were characteristic of the period from 570 to 550 Ma ago [10, 14]. The terminal stages of metamorphism with respective PT parameters of 3–4 kbar and 650°C were accompanied by intrusion of syncinematic granitoids 530–510 Ma old. Structural features inherent to this stage include tectonic nappes, dragging folds, and lateral milonitization zones.

In the eastern part of Queen Maud Land (Lutzow-Holm Bay coast), metamorphic complexes demonstrate significant gradient with development of amphibolite facies parageneses in the easternmost areas and granulite facies indicating moderate pressures (6–8 kbar) in western areas. Mineral of garnet–sillimanie–orthopyroxene association include relicts of kyanite and staurolite, which implies "clockwise" development of endogenic regime (Motoioshi and Isikawa, 1997).The peak of metamorphism has been dated back to 517 ± 9 Ma ago (Fraser et al., 2000) and cooling of the region up to closure temperatures of the K–Ar and Rb–Sr systems in micas occurred approximately at the same time (515–500 Ma ago). The high-temperature decompression is reflected in the development of specific structures such as orthopyroxene–plagioclase simplectites around garnet (in mafic rocks) and cordierite coronas on garnet (in metapelites). Thermochronologic interpretations point to a rapid rise of the region by 10–20 km during the period of ca. 20 Ma [6]. Some areas of this region show high-pressure and high-temperature metamorphism of approximately 10–12 kbar and 900–1000°C, respectively, which is evident from development of orthopyroxene–sillimanite and sapphire-bearing parageneses.

In the Prydz Bay coast, the peak parameters of metamorphism conditionally attributed to the Pan-African stage are estimated to be 6.0–8.5 kbar and 840 ± 40°C (Rauer Islands area, according to Harley and Buick,

1992) or 5.5–7.0 kbar and 800–860°C (Larsemann Hills, according to Fitzsimons, 1996). This metamorphism, which is synchronous to compression deformations, is dated at 535–525 Ma ago (Fitzsimons, 1997). Terminal stages of endogenic evolution are dated by the Sm–Nd method on garnet back to 515–510 Ma ago (according to Hensen and Zhao, 1995). The endogenic evolution of this region proceeded in line with the isothermal decompression model with a rise by 7–10 km. This is evident from thermodynamic calculations and mineral interrelationships, most characteristic among which are the reaction of replacement of grossular-enriched garnet by wollastonite and plagioclase and grossular-impoverished garnet by orthopyroxene and plagioclase, development of orthopyroxene–plagioclase rims around garnet and quartz aggregates, and formation of cordierite coronas around garnet in sillimanite rocks (Harley and Fitzsimons, 1996).

Mafic–ultramafic Complexes

The northern Shackleton Range (Fig. 1) hosts an outcropping sequence of metasedimentary rocks and garnet-bearing amphibolites that enclose large lenses and members of metamorphosed ultramafic and mafic rocks forming together an ophiolitic complex [27]. The members of ultramafic–mafic rocks are up to several hundreds of meters thick, and the sequence is traceable for tens of kilometers. Dominant rocks are serpentinites, metalherzolites, metagabbro, amphibolites, aluminous schists, quartzites, and marbles. Ultramafic rocks are largely composed of calcite–tremolite pseudomorphs developed after clinopyroxenes and submerged into fine-grained granoblastic matrix of olivine replaced by iddingsite and serpentinite. Metaharzbrgites consisting of granoblastic aggregates of olivine, orthopyroxene, and ore minerals (presumably high-chromium spinel) occur occasionally. Metagabbro contains relicts of clinopyroxene in fine-grained mass of calcic amphibole, plagioclase, epidote, and quartz or in actinolite–hornblende nematoblasts. Based on numerous U–Pb and K–Ar dates, it is assumed that ophiolites formed during the Early Paleozoic development stage (approximately 540 Ma ago) and experienced granulite-facies metamorphism at that time (Zhe et al., 1999).

Ultramafic rocks are characterized by low concentrations of some large-ion lithophile elements (LILE) (Rb, Sr < 5 ppm) and Zr (<3 ppm) and very high Cr and Ni contents (>2000 ppm) and magnesian coefficient mg = 87–88 (mg = 100MgO/(MgO + FeO), mol %). Foreign researchers class these rocks with tectonized upper mantle peridotites [27]. It is assumed that metagabbro represents magmatic cumulate. Amphibolites characterized by highly variable composition (mg = 40–65) are interpreted as fragments of a volcanic sequence comparable with N-MORB (Zr/Nb > 15, Zr = 70–90 ppm). The $\varepsilon_{Nd(540)}$ value for metagabbro and amphibolites amounts to +(8–9 T). Some samples demonstrate features of OIB-type basites (e.g., elevated concentrations of high field strength elements or HFSE).

The Arctic Institute Range (immediately north of the Voltat Massif, Fig. 1) hosts a tectonic sheet of metaperidotites. Its apparent thickness is approximately 50 m. The rocks are intensely deformed and composed largely of colorless amphibole, phlogopite, subordinate orthopyroxene and olivine, and accessory spinel. They enclose abundant deformed and foliated syncinematic pegmatite veins occurring only within this tectonic sheet. The pegmatites are dated by the U–Pb SHRIMP method on zircons at 517 ± 8 Ma (unpublished original data).

Igneous Complexes

Dikes of moderate and slightly elevated alkalinity are developed in the Mount Willing area in the central part of the Prince Charles Mountains (Fig. 1). The Cumpston Massif in their southern part is composed of low-alkaline intrusive rocks. A thin bed of igneous rocks within the sedimentary sequence exposed in the Denman Glacier area and mafic hypabyssal igneous rocks found among fragments in moraine sediments of the same area [23] are also low-alkaline. Although they are the most widespread rocks, alkaline rocks form rare and thin dikes (Banger Oasis, Prince Charles Mountains, Enderby Land, and Queen Maud Land). They are represented by alkali dolerites, lamprioites, and lamprophyres.

In the Mount Willing area, dikes intruding Mesoproterozoic gabbroids and metamorphic sequences are from 0.5 to 3 and, less commonly, up to 8–15 m thick. They are characterized by different strikes with maximum along 110–120° and a near-vertical dip. Dikes are composed of dolerites and metadolerites. The rocks are characterized by aphyric and porphyric structures and doleritic, ophitic, and gabbro–ophitic textures. In porphyric varieties, phenocrysts are composed of calcic plagioclase (An_{67}). In the diagram SiO_2 – (Na_2O + K_2O) (TAS), data points are located near the line separating normal and low-alkaline rocks (Fig. 2). The magnesian number (mg) varies from 48 to 63. The rocks demonstrate sodium specialization and are characterized by low contents of most trace elements (for example Zr < 130, La < 15, Nb < 10 ppm). In the spider diagram of mantle-normalized trace element contents, these rocks form a consistent slightly jogged line with an insignificant negative Nb anomaly (Fig. 3). The age of dolerites is estimated by the Sm–Nd method on monomineral fractions (two clinopyroxene fractions, plagioclase) and bulk composition. The regression line based on these data coincides with the age of 845 ± 66 Ma ($\varepsilon^{Nd\,i}$ = +2.5), which is interpreted as corresponding to intrusion of this dike (Laiba, unpublished data).

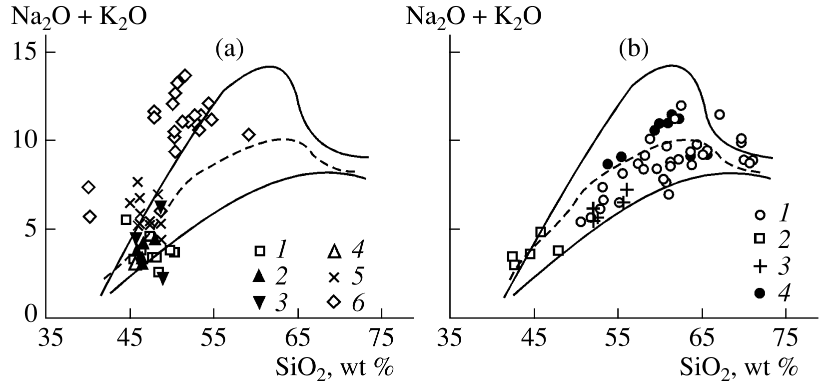

Fig. 2. Diagram in coordinates SiO_2 – ($Na_2O + K_2O$) for mafic and alkaline rocks from small intrusive bodies (sill and dikes) (a) and rocks of the anorthosite–mangerite–charnokite association (b): (*1*) dike dolerites and metadolerites from Mount Willing, (*2*) metadolerites (dikes and sills) from the Cumpson Massif, (*3*) metabasites from the Denman Glacier area (samples from moraine), (*4*) schist from Mount Sandow (volcanogenic–sedimentary sequence), (*5*) dike dolerites from the Banger Oasis, (*6*) lamproites (dike and volcanic flows); (b) (*1*–*3*) charnokitoids (*1*), gabbroids (*2*), and anorthosites (*3*) from the Voltat Massif, (*4*) granitoids from the Denman Glacier area. The solid line in the diagrams contours the distribution area of slightly alkaline rocks, the dashed line designates the lower boundary of alkaline rocks containing feldspatoids or alkaline minerals (*Classification*…, 1981).

In the Cumpston Massif, the sequence of Neoproterozoic slightly metamorphosed sedimentary rocks [16] encloses thick (up to 50–100 m, Fig. 4) sills and rare metabasite dikes. The rocks are fine-grained, composed of plagioclase, chlorite, actinolite, hornblende, biotite, and epidote aggregates. The primary doleritic texture is almost undistinguishable due to intense recrystallization. The rocks are moderately alkaline (Fig. 2) and characterized by elevated TiO_2 (4%) and P_2O_5 (1%) contents, which differentiates these rocks from all other varieties constituting Precambrian and Late Paleozoic mafic dikes in this region of Antarctica [15, and references therein]. The parental magmatic melt experienced significant fractionation, which is evident from the low magnesian number (mg = 40–45) and low Ni and Cr concentrations (30–50 and approximately 70 ppm, respectively). In the spider diagram of trace element contents normalized to the primitive mantle, the rocks form no negative Nb anomaly, except that one sole sample demonstrate a distinct Sr anomaly (Fig. 3).

The sedimentary sequence exposed in the Denman Glacier area hosts a thin bed of epidote–chlorite schists, which represent metamorphosed basaltoids or dolerites (data by Ravich et al., 1965). The rock texture is heteroblastic with prevalence of granoblastic and nematoblastic elements. Distinct relicts of ophitic and porphyric textures are locally observable. The greenstone schists are compositionally uniform: chlorite 30–50%; epidote together with saussurite aggregates 20–35%; actinolite hornblende 3–10%; calcite 1–6%; ore minerals 10–15%; quartz in lenses and nests 1–5%; relicts of plagioclase laths and tabular grains up to 10% [23]. The rocks are characterized by elevated alkalinity (Fig. 2); moreover, the K content is characterized by significant dispersion, which is probably explained by the metamorphism effect. In the spider diagram of mantle-normalized trace element contents (Fig. 3), these rocks form concordant lines. They demonstrate an insignificant negative Nb anomaly and slight enrichment in large-ion lithophile elements. Moreover, the maximal enrichment is recorded for most incoherent elements (Pb, Rb).

Alkali dolerites constitute the youngest dikes in the Banger Oasis (Sheraton et al., 1992). The rocks are characterized by the elevated alkalinity (Fig. 2) with the K content demonstrating significant dispersion, which is probably explained by the metamorphism impact. In the spider diagram of mantle-normalized trace element contents (Fig. 3), these rocks form concordant lines. The rocks are characterized by an insignificant Nb anomaly and slight enrichment in large-ion elements with maximal contents registered for most incoherent elements (Pb, Sr).

Alkali dolerites constitute dikes of the youngest generation in the Banger Oasis (data by Sheraton et al., 1992). The dikes are characterized by insignificant thicknesses (generally, to 1 m) and dominant sublatitudinal strikes. The rocks show a porphyric texture with phenocrysts of olivine ($Fo_{77–87}$, 5–15%) and diopside ($Ca_{48}Mg_{44}Fe_8$, 5–20%). Some varieties contain phenocrysts of zoned plagioclase ($An_{47–60}$). In the TAS diagram, composition of these basites corresponds to that of the slightly alkaline to alkaline basic rocks close to basanites (Fig. 2). In the spider diagram of trace element contents, alkali basites from dikes of the Banger Oasis demonstrate strong enrichment in most of the large-ion lithophile (except for Rb) and some high field strength elements (P, Zr) against a background of significant impoverishment in other HFSE representatives: Nb (with formation of a strong negative anomaly), Ti, and Y (Fig. 3). The dikes are dated at approximately 500 Ma [23].

Recently, lamproites were found in four areas of Antarctica: Enderby Land, Prince Charles Mountains, western Queen Maud Land, and Mount Gaussberg. A Cambrian–Ordovician age was determined only for rocks from two first areas. In the Queen Maud Land and Mount Gaussberg areas, lamproites are Jurassic and Holocene in age, respectively. The composition of these rocks (Fig. 2) and complete bibliography are considered elsewhere [13]. Cambrian lamprophyres are recorded in the Schirmacher Oasis area.

Granitoids

Some Neoproterozoic (or Early Paleozoic) granitoids from Queen Maud Land, Princess Elizabeth Land, and MacRobertson Land are syncinematic, which is evident from their gnesiss affinity and stratiform to subconcordant occurrence of their bodies. Postcinematic granitoids occur in the MacRobertson Land–Princess Elizabeth Land region. In some areas of the Enderby Land and northern Prince Charles Mountains, pegmatite dikes are dated back to 900–700 Ma.

Two areas with syntectonic granitoids are known in the central part of Queen Maud Land: Conrad Rise and Schirmacher Oasis (Fig. 1). In the last area, they form a readily recognized member of augen gneiss. Outcrops of these rocks in the southwestern and central parts of the oasis are 1–2 km across. The rocks are granodiorite or monzonite by lithology. Dark-colored minerals are represented by orthopyroxene, garnet, and biotite. The rocks are characterized by a gneiss affinity, which indicates their intrusion under a strong tectonic stress. The ASI index values (ASI = $Al_2O_3/(Na_2O + K_2O + CaO - 1.67P_2O_5)$, mol %) approximate 1. The rocks are characterized by elevated concentrations of some trace elements such as Zr and Y (300 and 40 ppm, respectively), which allows these rocks to be considered as A-type granitoids, according to the criterion (Zr + Nb + Ce + Y > 350, after Valen et al., 1987). Their age is approximately 700 Ma (U–Pb age on zircon, original unpublished data).

The Conrad Rise hosts exposed thick granite–gneiss body conformable with the metamorphic sequence and being approximately 500 m across. Gneiss patterns are nearly vertical and of the sublatitudinal strike conformable with regional banding of metamorphic sequences. The rocks constituting this body are represented by granodiorites and granites containing biotite and orthopyroxene as mafic components. Their age was determined by the U–Pb SHRIMP method on zircons is 530 ± 5 Ma [10]. This age is interpreted as corresponding to crystallization (intrusion of granitoid pluton) based on morphological properties and zircon composition. The granitoids intruded synchronously with granulite metamorphism. The chemical composition of the rocks is characterized by variable values of the ASI index (1.00–1.15) and Zr + Nb + Ce + Y criterion (200–420).

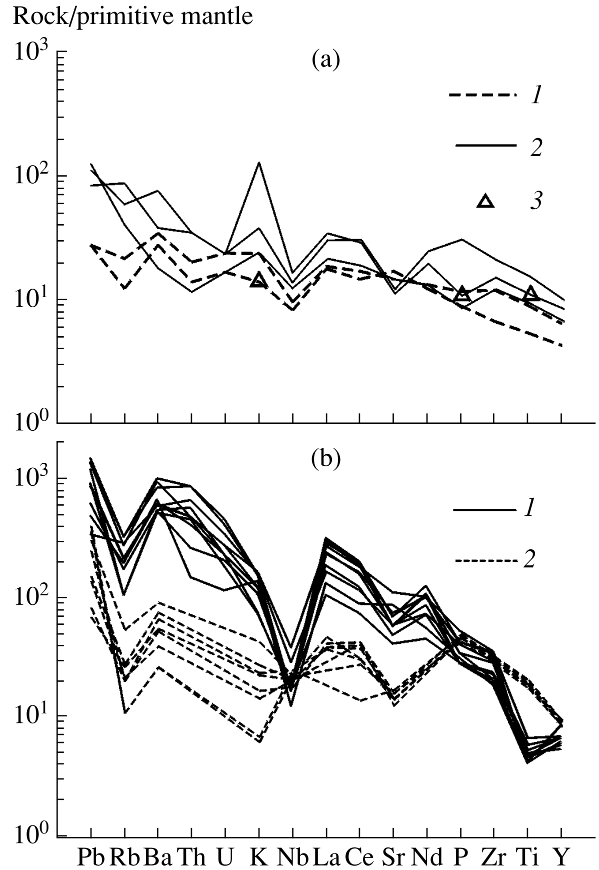

Fig. 3. Spider diagrams of trace element contents in mafic rocks from Mount Willing and Denman Glacier (a), Cumpston Massif, and Banger Glacier (b) areas normalized to the primitive mantle. (a) (*1*) Dolerites and metadolerites from Mount Willing, (*2*) metabasites from the Denman Glacier area (samples from moraine), (*3*) schist from Mount Sandow (volcanogenic–sedimentary sequence); (b) (*1*) alkali dolerites from the Banger Oasis, (*2*) metadolerites from the Cumpston Massif. Normalization after [26].

In the Princess Elizabeth Land (Prydz Bay coast) occurrence- and lithology-variable granitoids and pegmatoids (veins, small subconcordant and stratiform bodies) intruded the metasedimentary sequences of the granulite facies. Subconcordant pegmatites and migmatite veins formed synchronously with regional metamorphism or after culmination of tectonic and metamorphic processes. These rocks are interpreted as resulting from melting of host metasedimentary sequences, which is confirmed by the geochemical composition of granitoids (S-type; ASI = 1.10–1.30). In the Larsemann Hills area, several generations of syncinematic granitoids are distinguishable. The ages obtained for these rocks range from 940 ± 6 ($^{207}Pb/^{206}Pb$ on zircons) to 515 ± 7 (SHRIMP, Karson et al. 1996) and 497 ± 7 Ma (Sm–Nd mineral data, Zhao et al., 1992).

In MacRobertson Land, syncinematic granitoids are mapped in the central part of the Mawson Escarpment

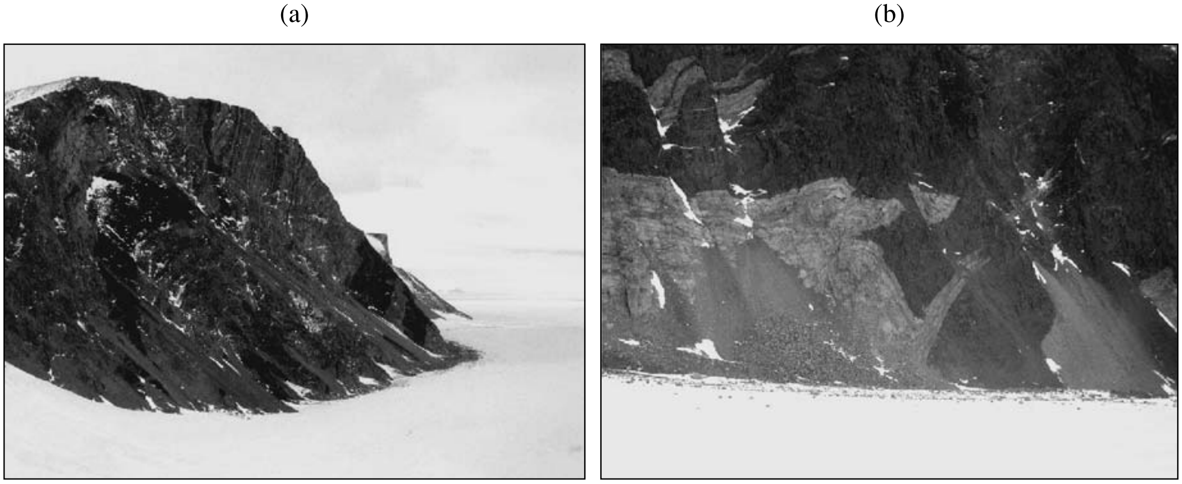

Fig. 4. Dikes (a) and sills (b) of mafic rocks in the sedimentary sequence of the Commonwealth Group (Cumpston Massif). The cliff height is approximately 100 m (a) and 50 m (b).

(550 ± 70 Ma, [2]) and at Mount Meredith (551 ± 4 Ma). Granitoids constitute both large (at least 300–500 m thick) concordant bodies and numerous small also concordant bodies and veins [11]. Granitoids of Mount Meredith correspond to monzogranites and granodiorites. The SiO_2 contents vary from 70 to 77.5%. The K_2O and Na_2O concentrations range from 3 to 6 and from 2.5 to 4.5%, respectively. These rocks are characterized by low Nb and Y contents (2–25 and 6–60 ppm, respectively) and moderately high Rb concentrations (100–300 ppm). In the normative composition of most of the rocks, corundum is noteworthy (usually 0.5–1.5%); the ASI index ranges from 1.05 to 1.15, which allows the rock to be classed with the peraluminous type. According to classification (Frost et al., 2001), leucocratic granites from the Meredith Massif range from calcic to alkali–calcic in composition. Such lithological variations are characteristic of peraluminous leucogranites.

Postkinematic granitoids are registered in the MacRobertson Land and Princess Elizabeth region, where dominant biotite–hornblende A-type and muscovite–biotite+garnet–biotite varieties (peraluminous leucogranites) are developed in its northern and southern areas, respectively.

Biotite–hornblende A-type granitoids constitute a large (at least 15 km across) massif in the far southwestern part of the Prydz Bay coast. The Rb–Sr isochron [28] and U–Pb zircon (Sheraton and Black, 1988) ages obtained for these rocks are 493 ± 17 and 500 ± 4 Ma, respectively. Xenolith composed of felsic granite–gneiss is dated back to 503 ± 8 Ma (SHRIMP method on zircon, original data). The granites are pinkish gray massive medium- to coarse-grained, with remarkable poikilitic potassic feldspar crystals up to 6 cm long. The main minerals are dark greenish brown ferropargasite hornblende (*mg* = 17–18; up to 5%), dark brown biotite (*mg* = 25–27; 3–10%), quartz (25–35%), oligoclase-andesine ($An_{34–45,\ 20–35\%}$), and microcline-pertite (30–50%). Biotite and amphibole are characterized by the moderate F content (1.3–1.6% and ~0.7%, respectively). Accessory minerals are emarkable, these include magnetite, apatite, zircon, fluorite, metamictic orthite, chevkinite, rare pyrite and chalcopyrite. The texture ranges from hypidiomorphic to xenomorphic-granular. Similar granites are developed in some areas eastward along the Prydz Bay coast at least for 200 km. These rocks are lithology-variable (66–77% of SiO_2). They are low-magnesian (*mg* = 6–30), enriched in LILE, HFSE (Zr in particular), and light REE elements; 10^4 Ga/Al (2.6–3.4) values are relatively high. Such chemical properties are typical of A-type granitoids. Similar composition is noted for granite intrusion in the Manning Nunatakker area located 150 km southward. Its rocks are 478 ± 2 Ma old [11]. These rocks contain biotite, hornblende, and fluorite and are characterized by relatively low SiO_2 contents (68–70%) and elevated TiO_2 (1–2%) concentrations and HFS elements (Nb 50–60, Zr 500–600, Y 60–65 ppm), which allows them to be attributed to the A-type variety.

Numerous small stocks of muscovite–biotite and garnet–biotite granites are exposed locally in the central part of the Mawson Escarpment and in many areas of the southern Prince Charles Mountains, where they intrude largely metasedimentary sequences of amphibolite facies. Locally, they form a dense system of stocks and veins up to 100 m thick at a maximum and sometimes constitute over 60% of outcrops. Granites contain quartz (30–35%), zoned oligoclase-albite (20–30%), microcline (35–45%), muscovite (up to 2%), reddish brown biotite (1–5%), rare garnet, accessory ore minerals, apatite, zircon, monazite, and secondary chlorite. Granite from the central part of the Mawson Escarpment is characterized by a Rb–Sr isochron age of 551 ±

74 Ma with a model age T^{Sr}_{UR} 1067 Ma [28]. The U–Pb measurements by the SHRIMP method on zircon point to granitoid age ranging from 525 to 515 Ma (unpublished original data).

Leucogranite and pegmatite bodies intruding metamorphic rocks in the southern Prince Charles Mountains contain muscovite (up to 8%), biotite (up to 5%), quartz (30–40%), microcline (15–40%), serpentinized albite-oligoclase (25–50%), subordinate ore minerals, apatite, zircon, monazite, rare beryl, garnet, and tourmaline. Pegmatites contain also topaz, chalcopyrite, magnetite, tantaloniobates, and fluorite [8]. These rocks are peraluminous (ASI = 1.05–1.21) with highly variable trace element contents.

Anorthosite–Mangerite–Charnockite Association

Rocks of this association are largely widespread in the central part of Queen Maud Land occur also in some other areas. Some charnockite plutons are up to 4000 km^2 in size. These are mostly coarse-grained porphyric rocks: quartz monzonites, monzodiorites, syenites, and granites. Anorthosites are recorded only in two areas, where they are spatially associated with charnockites. Dark-colored minerals in charnockites are represented by clinopyroxene, olivine, amphibole, biotite, and orthopyroxene; the last mineral is frequently missing, which is explained by its magmatic replacement by amphibole. Accessory minerals are ilmenite, magnetite, allanite, fluorite, zircon, apatite, titanite, tourmaline, chromium spinel, and rare molybdenite. In the Insel Mountains (Fig. 1), charnockite forms two phases. The younger phase is represented by relatively melanocratic rocks (largely, monzodiorites), while the later phase, by leucocratic varieties (mostly, syenites). The rocks of the second phase are dated back to 510–505 Ma ago (U–Pb method on zircons). Charnockites associate spatially with anorthosites, ferrodolerite dikes, and thin layered gabbroids (orthopyroxenites, websterites, anorthosites, mangerites, and nelsonites). In other areas of central Queen Maud Land, anorthosites and early charnokites are dated at approximately 600 Ma ago [10, and references therein].

Colored minerals are saturated with ferrous components and composed usually of olivine ($Fo_{2.5–5}$), orthopyroxene ($Ca_{1–7}Mg_{14–17}Fe_{76–85}$), and clinopyroxene ($Ca_{38–46}Mg_{7–12}Fe_{46–52}$). Amphibole is represented by ferropargasite hornblende with a high TiO_2 concentration (1.5–2.0%) and low values of magnesian index (*mg* = 8–13). Amphibole sometimes forms grains occurring in structural equilibrium with other colored minerals. Late magmatic biotite is characterized by very low MgO contents (*mg* = 5–10) and high TiO_2 (up to 4%) and Fe (1.62%) concentrations.

In the TAS diagram (Fig. 2), these rocks constitute a slightly alkaline series. Charnockitoids form more or less linear trends in most of the binary variation diagrams of the main components and show similar ratios between most trace elements (K/Rb 250–480, Rb/Sr 0.19–0.35, 10^4 Ga/Al 2.9–4.0), which indicates at first approximation, a cogenetic nature of these rocks. Charnockitoids from Queen Maud Land are metaaluminous to slightly plumasite (ASI < 1.05). All the examined rocks are characterized by high contents of high field strength elements (Y 20–120 ppm, Zr 300–2000 ppm, Nb 20–100 ppm, TiO_2 0.3–2.0%, P_2O_5 0.2–1.8%), lowered (as compared with calc-alkali granitoids) CaO concentrations (1.5–2.0% against the background of SiO_2 = 70%), and very low magnesian index (*mg* = 5–20). Mafic rocks (layered series and dikes) are remarkable for enrichment in Fe (up to 30% FeO_{sum}), P_2O_5 (1.2–2.1%), TiO_2 (4.0–6.1%), and slightly elevated alkalinity. The Sr_i value in charnockitoids and anorthosites ranges from 0.706–0.707 and ε_{Nd}, from –2.3 to +4.3.

The Denman Glacier–Mirnyi Station area host widespread two-pyroxene granitoids, some of which are attributed to the Early Paleozoic (516 ± 1.5 Ma, Black et al., 1992). The granitoids constitute relatively small magmatic bodies that distinctly cross the structure and banding patterns of the host metamorphic sequences. The rocks are dominantly syenite, granite, or monzonite by lithology. They are characterized by many chemical and mineral features typical of charnockitoids from Queen Maud Land: relatively low TiO_2, MgO, and CaO contents and elevated K_2O, Nb, and Zr concentrations [23].

Sedimentary Complexes

The Neoproterozoic and Neoproterozoic–Early Paleozoic sedimentary rocks are widespread within the Ross fold system of the Transantarctic Mountains. In the East Antarctic Platform basement, where they occur rarely and in difficultly accessible areas, they are insufficiently studied. At present, sedimentary sequences of presumably Neoproterozoic age in the Antarctic Shield are known in the southern Prince Charles Mountains, Denman Glacier area, and western Queen Maud Land. In addition, highly metamorphosed paragneiss sequences, which are also attributed to the Neoproterozoic, are defined in the Prydz Bay coast.

The southern Prince Charles Mountains host insignificantly metamorphosed sedimentary sequences united into the Commonwealth Group. In the Cumpston Massif, these rocks enclose mafic bodies (sills and dikes, Fig. 4). In some areas, sedimentary sequences are intruded by hypabyssal basites and granitoids.

A typical section of metasedimentary rocks is described in the Mount Rubin area, where they form at least seven different-lithology members [21] approximately 3500 m thick in total. Dominant rocks in separate members are (from the base upward): (1) porphyroblastic sericite–carbonate–quartz schists; (2) chlorite–sericite–quartz phyllites; (3) calcareous quartz and

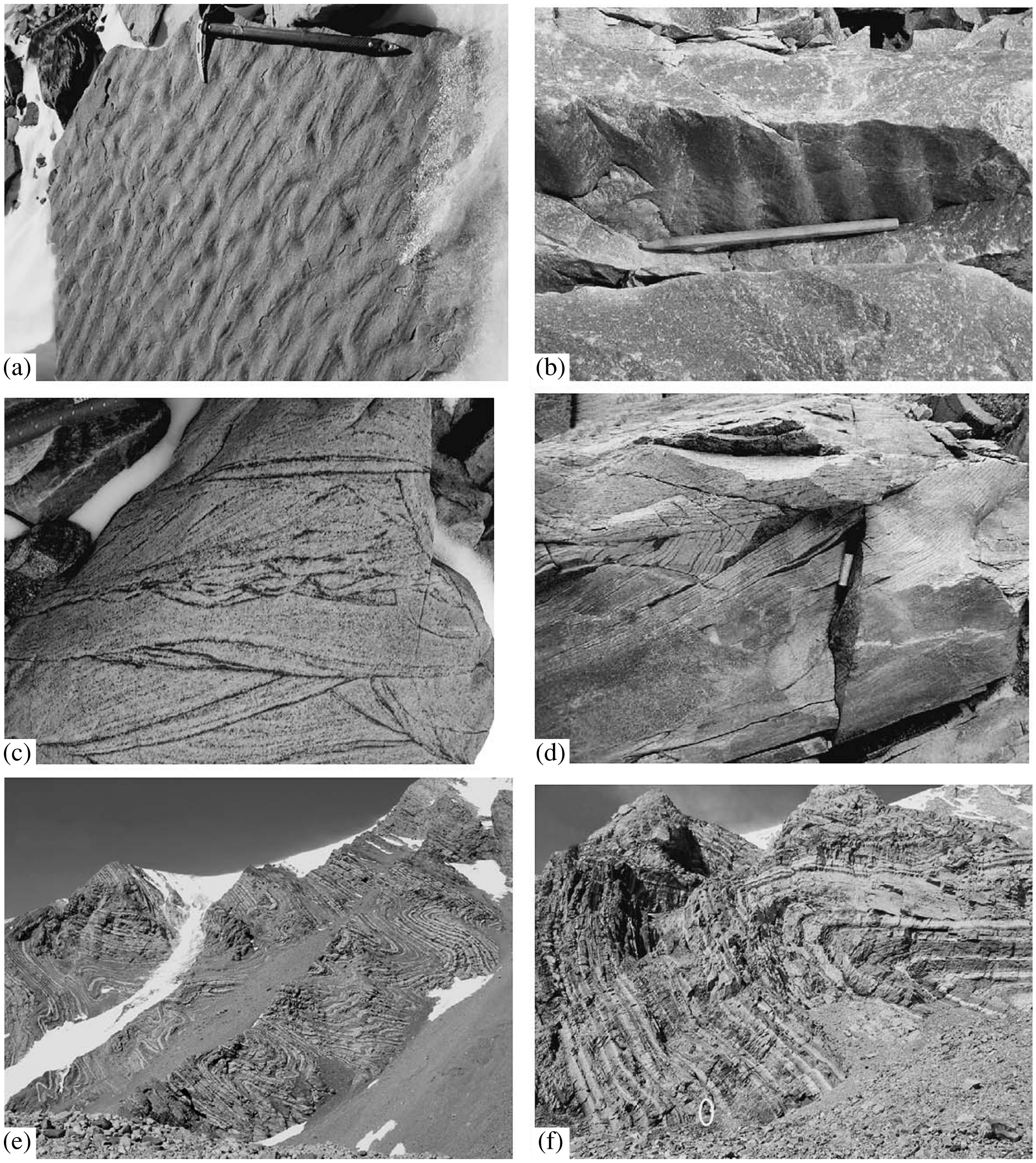

Fig. 5. Synsedimentary structures (ripple marks (a, b) and cross-bedding (c, d)), folds (e, f) in the Commonwealth Group; (a, c, d) Cumpston Massif, (b, e, f) Mount Rubin. The cliff height in (d) is approximately 200 m; in (f), the man's figure is shown for scale (white circle).

micaceous–schistoze metasandstones; (4) quartzites, conglomerates, and diamictites; (5) calcareous quartz metasandstones; (6) carbonate metasiltstones; (7) quartzites and metasiltstones. Separate beds are from 0.1 to 2 m thick and variegated in color. Locally, different rock types alternate each other and the sequence acquires a flysch-like affinity. It should be noted that conglomerates form only intraformation beds, none of their basal counterparts are observed. Some beds retain initial features of sedimentary rocks such as ripple marks, desiccation cracks, and cross-bedding (Fig. 5). The sequence is intensely deformed into compressed disharmonic folds (Fig. 5). In the Mount Maguair and Cumpston Massif areas, tectonic contact (thrust) between these and more intensely metamorphosed rocks is observed. Tectonic structures are characterized by a northern vergence.

The age of the Commonwealth Group and its relationships with other sequences developed in this region remain debatable. The group yielded Riphean acritarchs (Il'chenko, 1972). The study of detrital zircons from the Commonwealth Group by the U–Pb (LA-ICP-MS) method revealed zircon populations of several generations with ages of approximately 2600, 2200, and 1100–1000 Ma [17]. These data indicate the Neoproterozoic age of the sediments.

The rocks were metamorphosed during the Early Paleozoic. In 1975, Halpern and Grikurov obtained a Rb–Sr isochron age of approximately 495 Ma (calculated to 512 Ma based on recent decay constants) with Sr_i of 0.738 for phyllites from Mount Rubin and 800 Ma (Sr_i 0.730) for granite fragments from diamictites of the same area. The isochron age averaged from two granite-gneiss and three phyllite samples is 505 ± 40 Ma.

Two outcrops of metasedimentary rocks are recorded at Mount Amundsen and Mount Sandow located in the upper part of the Denman Glacier (Ravich an others, 1965). They are represented by fragments of the stratified sequence 50 and 130 m thick, respectively. The outcrops are composed of slightly metamorphosed (to greenstone facies) terrigenous rocks: alternating dominant poorly sorted sandstones, subordinate quartzites, argillites, siltstones, and conglomerates with the last rocks occurring at the base of the section. In the Mount Sandow area, the sequence is underlain by green epidote–chlorite schists 8 m thick (apparent thickness) representing slightly metamorphosed volcanics. The sequence is characterized by a sustained near-meridional strike and eastern dip, with angles ranging from 40° at the base of the section to 25° in its upper part. In the Mount Amundsen area, beds dip southeastward at angles of 15°–25°. The sequence exposed at Mount Sandow demonstrates a rhythmical structure, variegated coloration, and lithological spectrum from conglomerates to argillites and sericite schists. The sedimentary rocks contain spores of Cambrian age (according to Korotkevich and Timofeev, 1959). In 1965, Ravich with colleagues obtained a K–Ar age of 610 Ma for sericite schist (metaquartzite).

In the western part of Queen Maud Land, Neoproterozoic sedimentary rocks are recorded in the Keruanweggen Range, where they are united into the Urfjell Group. In this area, a sequence of quartzites and conglomerates at least 1650 m thick is exposed separately from other lithotectonic complexes [28, and references therein]. The rocks are deformed into steep (up to vertical and overturned) folds with ENE-trending axes. It is assumed that granitic–metamorphic rocks served as a source for this sequence, which is evident from the composition of the main detrital minerals represented by quartz, orthoclase, plagioclase, garnet, and muscovite. Pebbles are composed of fine-grained bricky red or light green schistose quartzites, vein quartz, subordinate shales, and bricky red jaspers. The sediments accumulated presumably in coastal-marine settings with high-energy hydrodynamics. The date of 531 ± 25 Ma obtained by the Rb–Sr method (Sr_i = 0.7283, Moyes et al., 1997) reflects reorganization of the Rb–Sr system during deformation; the model age T_{UR}^{Rb-Sr} = 688 Ma is accepted as the upper limit for the sedimentation time. Detrital muscovite is dated by the Rb–Sr method at 634 Ma. These isotopic data provide grounds to assume Neoproterozoic age for the sedimentary rocks in question.

GEODYNAMIC FORMATION REGIMES OF NEOPROTEROZOIC AND EARLY PALEOZOIC GEOLOGICAL COMPLEXES

According to the widely accepted viewpoint, post-Grenvillian Rodinia experienced complete disintegration during the Neoproterozoic with the formation of several isolated continents and intervenient spacious oceanic basins, and these continental blocks were again amalgamated into a new supercontinent in the Early Paleozoic [22]. The available geological data on Antarctica provide, however, no evidence in favor of this hypothesis.

The geological complexes developed in East Antarctica imply that the largest part of the present-day continent experienced extension in the Neoproterozoic (900 to 600 Ma ago). This period was marked by the formation of sedimentary basins and intrusion of mafic material in some areas. Variegated sedimentary sequences of that period are composed of dominant psammites and subordinate semipelites and coarse-grained rocks (conglomerates). The rocks are characterized by sedimentary structures (bedding, ripple marks), which allow, combined with lithological properties of the sequences, sedimentation in shallow-water settings to be assumed. Intense deformation (disharmonic folding and thrusts) of these slightly metamorphosed sequences provides grounds to define them, following Klimov (1967), as representing an upper structural stage of the platform basement. The sediments could have been deposited in *pull-apart* basins that resulted from tangential movements. In the western part of Queen Maud Land, these sediments associate spatially with the wide regional zone of shear deformations initiated in the Mesoproterozoic and activated during the Neoproterozoic–Early Paleozoic development stage [9]. Development of the sedimentary basin in the Denman Glacier area could be determined by the activity of the large strike-slip fault zone (Darling Fault) that separates the Iilgarn Craton and Pinjarra Orogen in Western Australia [4] and, probably, continues to Antarctica. In the southern Prince Charles Mountains, sedimentary sequences are exposed in a NW–SE-trending zone, the strike of which is inconsistent with any regional structural trends, although it corresponds at first approximation to the orientation of the dike swarm in the Mount Willing area. This sedimentary basin was located in the continental interior and its development was determined by intraplate tectonics. Moreover, the vergence of folded structures and thrusts in this area indicate north-oriented tectonic movements. This observation implies possible development of a Neoproterozoic–Early Paleozoic mobile belt in the intracontinental areas of East Antarctica buried now under the ice shield. This assumption is indirectly supported by the discovery of zircon dated at approximately 600 Ma in the ice core (bottom horizon) of the Borehole Vostok (Leichenkov et al., 2004).

It should be noted that intensely metamorphosed and granitized sequences of the Prydz Bay coast contain sedimentary material that is also presumably Neoproterozoic in age. Some researchers consider these metasedmentary rocks to be of shelf origin and based on this assumption define a passive continental margin in the area under consideration [4]. Unfortunately, due to intense tectonic reworking of these rocks, it is impossible to either confirm or refute this assumption. Nevertheless, even accepting that viewpoint, the Neoproterozoic margin of Antarctica should practically coincide with the present-day one. Thus, the Pan-African structures in this segment of Antarctica cannot be traced to the continental interior. If this was so, the suture proper should correspond to the present-day margin and probably control the position of Phanerozoic riftogenic structures during Gondwana disintegration. Mafic igneous rocks represent an important indicator of geodynamics. The Early Neoproterozoic (ca. 850 Ma ago) mafic dikes of Mount Willing in the central Prince Charles Mountains are oriented at a first approximation parallel to outcrops of sedimentary sequences in the southern part of the region in question, which may indicate tectonic paragenetic correlation of these rocks reflecting extension settings. The chemical composition of the dikes is insufficiently studied, although available data indicate low concentrations of high field strength elements (Nb, Zr, P, Ti, Y) and large-ion elements (Rb, Ba, K, LREE, Sr). These properties allow the assumption that the lithospheric substrate served as a mantle source for mafic rocks of Mount Willing, while contribution of asthenospheric material is hardly probable. The insignificant, although distinct Nb anomaly in the spider diagram of mantle-normalized trace element contents (Fig. 3) is very characteristic of other mafic rocks in this region that formed in subduction-related convergence settings during the Mesoproterozoic 1300–1100 Ma ago [15]. The dike complex under consideration is most likely post-orogenic in origin that resulted from activation in the hinterland extension settings and cannot be considered as a typical intraplate structure despite the elevated alkalinity of some of its rocks.

At a first approximation, similar chemical features are peculiar of basites found in the Denman Glacier area. These rocks are also characterized by an insignificant negative Nb anomaly (Fig. 3) and comparable distribution of most trace elements. Two of three samples are enriched in large-ion and light REE elements, which indicates a contribution of the subcontinental mantle substrate enriched in lithophile elements. The age of these rocks is insufficiently substantiated and they should be thoroughly studied as potentially reflecting intense geodynamic reorganizations of the Neoproterozoic or Early Proterozoic period.

Manifestations of orogenic tectonic conditions of the Neoproterozoic stage are established only in the Schirmacher Oasis of central Queen Maud Land. In this area, granitoids intruded approximately 700 Ma ago against the background of powerful tectonic movements and regional metamorphism. The formation of these rocks was determined by tectono-magmatic activation of earlier (Grenvillian) structures [12] and they are probably syncollisional in origin. Tectonic processes were also in progress during the Early Paleozoic stage (ca. 515 Ma ago), when alpine-type ultramafics intruded in the present-day Arctic Institute Range area. The latter is marked by a deep topographic depression in the basement and a positive linear ENE-trending magnetic anomaly (Damaske, 2004), which is traceable westward along the northern edge of mountainous structures in central Queen Maud Land. This implies that the northernmost exposed area of the region in question (Schirmacher Oasis) belongs to another terrane, not to the largest part of Queen Maud Land, which was probably accreted to the latter during the Early Paleozoic.

The Late Neoproterozoic–Early Paleozoic tectogenesis stage (600–500 Ma ago) is reflected to a different extent through most East Antarctica except for the Wilkes Land, Adelie Land, and some areas in western Queen Maud Land. Some areas were subjected to metamorphism (largely granulite facies), plastic deformations, and intrusion of syncinematic granitoids and postcinematic magmatic bodies (anorhosites, charnockites, peraluminous leucogranites, A-type granitoids, basite and lamprophyre dikes, pegmatite veins). Until recently, numerous Pan-African isotopic ages obtained in the 1960s–1970s by the K–Ar and Rb–Sr methods were considered to reflect intense thermal processes. At present, it is clear, however, that tectonic stresses in some areas were sufficient for formation of penetrative schistosity, metamorphism, and plastic deformations. This intraplate orogeny during the Early Paleozoic was most intense in central Queen Maud Land, Lutzow-Holm Bay coast, and Larsemann Hills.

Evolution of the endogenic regime in these areas is described by the clockwise trajectory of P–T conditions with development of high-temperature to ultrahigh-temperature parageneses, partial melting, and subsequent isothermal decompression. Most researchers believe that these processes are related to collision between continental blocks, which resulted in doubling of the crustal thickness, and subsequent exhumation of deep material up to the middle or upper crust level [3, 18, 24, 29]. According to [19], an additional heat source is, however, needed to reach high-temperature conditions (>850–900°C), which could be provided by the asthenospheric mantle that replaces upper layers of the lithosphere due to its delamination. Taking into consideration the fact that the igneous rocks developed in Queen Maud Land (anorthosites and charnockitoids) are high-temperature derivates that resulted from partial melting of the lower crust or upper mantle and that the substrate contains asthenospheric material, the model of lithospheric mantle replacement by the asthenospheric mantle seems well substantiated for this area. It should be noted that igneous rocks developed in

Prince Elizabeth Land also with evidence of Early Paleozoic tectono-magmatic processes belong to different association (A-type granites and peraluminous leucogranites).

It is usually thought that peraluminous leucogranites result from partial melting of metasedimentary sequences due to thermal relaxation in magma-generation centers and/or tectonic exhumation of orogens; partial melting is confined to the core of the metamorphic belt overdeepened due to collision of continental blocks (LeFort et al., 1987). The formation of Early Paleozoic granitoids in Princess Elizabeth Land can also be explained by this model, although it is impossible at present to compare magmatic and tectonic–metamorphic processes because of insufficient data. It is conceivable that magma generation and maximal metamorphism were separated in time. Therefore, the alternative model of petrogenetic influence of magmatic underplating at the base of the crust [25] cannot be ruled out.

The formation of Early Paleozoic alkaline dike complexes could also be determined by significant thermal influence of mantle layers. Typical intraplate mafic dikes of Early Paleozoic age are developed in the Banger Oasis. These rocks are significantly enriched practically in all the trace elements, which reflect the low melting degree of the parental substrate, on the one hand, and enrichment of this substrate, which can be considered as subcontinental, on the other. Lamproites and lamprophyres that represent youngest igneous rocks of the Early Paleozoic stage formed in intraplate settings as well. Their formation was probably determined by cessation of thermal activity of ascending asthenospheric material and increase in the lithosphere rigidity.

As was mentioned, many researchers interpret Early Paleozoic geological events as resulting from collision between continental plates. Two variants of the suture position are considered in this case: either along the line connecting the Shackleton Range and Lutzow-Holm Bay or along the Lutzow-Holm–Mawson Escarpment–Prydz Bay line (Fig. 1) [1, 4].

The position of the suture in the intracontinental area of Antarctica between the Lutzow-Holm Bay and Shackleton Range is inconsistent with the data on the anomalous gravity field (A.V. Golynskii et al., 2002). For example, in the Lutzow-Holm area, regional magnetic anomalies are oriented in the near-meridional direction, i.e., practically orthogonally to the assumed suture. In addition, in contrast to other rocks of Queen Maud Land, its Inzel Complex of Grenvillian volcanogenic rocks [8, and references therein] metamorphosed to the amphibolite facies [12] experienced neither primary high-temperature nor repeated metamorphism and deformations. Consequently, this complex should have a different development history: either the latter is allochthonous or granulite metamorphism of other rocks is unrelated to crust thickness doubling and its subsidence to the lower crust. The main phase of Early Paleozoic tectogenesis in Queen Maud Land should probably be interpreted as intraplate reflection of an oblique collision between large continental blocks that occurred beyond limits of present-day Antarctica.

The collision regime proper with the closure of the oceanic basin was dominant in the northern part of the Mozambique Belt, which is evident from lithotectonic complexes of Central and North Africa (Shackleton, 1993). This region is characterized by "soft" collision of the arc–continent type that was replaced by a continent–continent collision at 600 Ma ago (Shackleton, 1996). Tectonothermal evolution of southerly areas of the Mozambique Belt that culminated in the period of 600 to 500 Ma ago (Kuung Orogeny, after Miert, 2003) demonstrates significant similarity with that of Queen Maud Land.

Principal tectonic structures in the southern part of the Mozambique Belt include wide milonitic zones (Jacobs and Tomas, 1996), which can be interpreted as indicating oblique collision of continental blocks in northwestern direction along the near-meridional margin. In the early Paleozoic, this area experienced only repercussions of powerful collision processes recorded in the northern part of the Mozambique Belt and reflected in Antarctica in the form of transcurrent (longitudinal compression, locally longitudinal pull-apart) tectonic movements, formation of intraplate anorthosites and charnockitoids, and widely developed reorganization of the K–Ar and Ar–Ar isotopic systems in minerals. These intraplate igneous rocks are usually considered as being anorogenic. Nevertheless, they can be classed with "teleorogenic" rocks (Khain and Lomize, 2005) taking into consideration their spatial and temporal association with active tectonic processes. Reorganization of isotopic systems resulted, probably, from release of significant thermal energy during tectonic movements or from heating due to mantle underplating at the base of the crust.

The formation of ophiolites from the Shackleton Range, which represent a direct indication of the oceanic crust in East Antarctica, resulted from the closure of the paleoocean, which washed the western margin of Africa, or the so-called Adamastor ocean [7]. The closure of this oceanic basin is dated to 550–500 Ma ago, which corresponds to the age obtained for the Shackleton Range, while the Mozambique ocean was closed substantially earlier. The closure of this ocean in the Late Neoproterozoic could stimulate additional underplating at the base of the heterogeneous and structured lithosphere of East Antarctica and result in observable geological consequences.

Tracing of the Early Paleozoic suture in Antarctic from the Lutzow-Holm Bay southeastward to the Mawson Escarpment of Princess Elizabeth Land meets other difficulties. Nevertheless, the Princess Elizabeth Land area shows no signs of mantle material of that age as well as widespread metamorphic processes. It should be noted that the intensity of Early Paleozoic tectogenesis decreases in the southern direction, which may indicate location of the suture beyond the present-day continental contour or within the intraconinental areas of Camp Land and Mawson Coast now buried under the ice shield.

CONCLUSIONS

The sedimentation and formation of mafic dikes in the Neoproterozoic indicate the dominant extension regime through the most part of the Antarctic Shield, although no features of the advanced tectogenesis phase and opening of deep-water basins are established so far. Orogenic processes involved only some areas of the latter (Schirmacher Oasis), which were, however, restricted to the interior part of the plate. Thus, the available data provide no grounds to consider, contrary to the hypothesis very popular in the recent geological literature, the Neoproterozoic stage as corresponding to disintegration of the Antarctic lithospheric block that was a constituent of supercontinent Rodinia into separate fragments.

No geological complexes indicating a large-scale Early Paleozoic convergence accompanied by the closure of oceanic basins are observed in East Antarctica. Development of small syncinematic orthogneiss and granite massifs is assumed only for some areas. No notable quantities of sialic material formed at that stage as well. On the contrary, the Early Paleozoic peak appears to be associated with intrusions related to tectonothermal activation that determined structural reworking and repeated metamorphism of host Grenvillian complexes.

Thus, the available data provide no grounds for the assumption of a spacious oceanic basin between the East and West Gondwana megablocks during the Early Paleozoic development stage. These blocks constituted probably a single continent most likely beginning from the terminal Mesoproterozoic.

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