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First Petrographical Description of Rock Occurrences in the Steingarden Area, Dronning Maud Land, East Antarctica

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Abstract: Rock samples from previously undescribed nunataks and moraines of the Steingarden area, southeasternmost central Dronning Maud Land, Antarctica, were petrographically studied.
The nunatak rocks comprise banded felsic and mafic gneisses and amphibolites with some minor marbles. They underwent granulite-facies peak metamorphism. Moraine rocks, which were sourced from ice-covered occurrences in the south, comprise garnet-biotite gneisses, kyanite-staurolite-sillimanite gneisses, amphibolites, late-tectonic and post-tectonic igneous rocks as well as an assemblage of conspicuous dark graphite-bearing and pyrite-bearing schists with related vanadium-green muscovite bearing lithologies. The dark schists represent greenschist-facies to amphibolite-facies grade metamorphosed black-shale-type sediments.
The nunatak rocks and parts of the moraine rocks are comparable to lithologies in central Dronning Maud Land. The dark graphite-bearing and pyrite-bearing schists and related vanadium-green muscovite bearing lithologies have higher-grade metamorphosed equivalents in central Sør Rondane. These rocks indicate the existence of a tectonic boundary south of Steingarden, which may represent the Pan-African suture between West and East Gondwana.

Zusammenfassung: Gesteinsproben bisher nicht untersuchter Nunataks und Moränen der Steingarden Region im südöstlichsten Teil des zentralen Dronning Maud Landes, Antarktis, wurden petrographisch bearbeitet.
Die Nunatak-Gesteine umfassen gebänderte felsische und mafische Gneise, Amphibolite und untergeordnet Marmore, die granulitfazielle Bedingungen erreicht haben. Moränen-Gesteine, welche von eisbedeckten Vorkommen im Süden stammen, umfassen Granat-Biotit-Gneise, Disthen-Staurolith-Sillimanit-Gneise, Amphibolite, spät- und post-tektonische magmatische Gesteine sowie eine Ansammlung auffälliger dunkler Graphit und Pyrit führender Schiefer und Lithologien mit vanadiumgrünem Muskovit. Die dunklen Schiefer repräsentieren Sedimente vom Schwarzschiefer-Typ, die eine grünschieferfazielle bis amphibolitfazielle Metamorphose erfahren haben.
Die Nunatak-Gesteine und ein Teil der Moränen-Gesteine sind mit den Lithologien des zentralen Dronning Maud Landes vergleichbar. Die dunklen Graphit und Pyrit führenden Schiefer und die assoziierten, vanadiumgrünen Muskovit enthaltenden Lithologien haben hochgradig metamorphe Äquivalente im zentralen Gebiet von Sør Rondane. Diese Gesteine deuten die Existenz einer tektonischen Grenze südlich der Steingarden Region an, bei der es sich um die Pan-Afrikanische Sutur zwischen West- und Ost-Gondwana handeln könnte.

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INTRODUCTION

Dronning Maud Land (DML) is located in the Weddell Sea sector of East Antarctica. It covers an area of ~5 Mio km^2 and is divided by large glacial drainage systems into an eastern, a central and a western part. The Proterozoic metamorphic basement of DML is exposed in remnants of an intensely dissected highly elevated plateau that are bound by steep escarpments, aligned parallel to the coast. The most significant outcrop massifs are the Orvinfjella–Wohlthatmassiv of central DML and Sør Rondane to the east (Fig. 1).

The petrological composition and the structural inventory of these rock massifs have been studied during recent decades by Soviet, Indian and German expeditions (e.g. Ravich & Krylov 1964, Ravich & Solov`ev 1969, Ravich & Kamenev 1972, Verma et al. 1987, Paech 2004, 2005b). In contrast, little attention has been given to a series of poorly exposed nunataks and moraines in the southern part of DML.

The QueenMET (Queen Maud Land Meteorites) expedition during the Austral summer 2007/2008 provided an opportunity to study one of these areas for the first time. Participants in QueenMET were the physicist G. Delisle and the geophysicist U. Barckhausen from the German Federal Institute for Geosciences and Natural Resources (BGR) Hannover, the mineralogist J. Schlüter from the University of Hamburg, and the mountain guide J. Gessler from Basel. The aim of the expedition was the first search for meteorites in DML inspired by the large number of meteorites recovered by Japanese and American scientists from blue ice fields in other Antarctic regions (e.g. Sør Rondane, Yamato Icefield, Allan Hills, Elephant Moraine).

Besides the successful QueenMET search for meteorites, the scientists also devoted some time and effort to the exploration of a small group of previously undescribed nunataks at Steingarden, located southeast of Wohlthatmassiv, Weyprechtberge, and Payergruppe (Figs. 1, 2). The investigated area stretches from about 72°12’S – 72°22°’S and 15°59’E –16°10’E and is located approx. 2000 km from the South Pole. The average elevation of the area is 2400 m above sea level. Its rock inventory is of great interest because the Steingarden region covers an area which is located in a possible continuation of the still undiscovered suture between East and West Gondwana (Moyes et al. 1993, Grunow et al. 1996, Shiraishi et al. 1994, Jacobs et al. 1998) (Fig. 3). Until now, no information on the

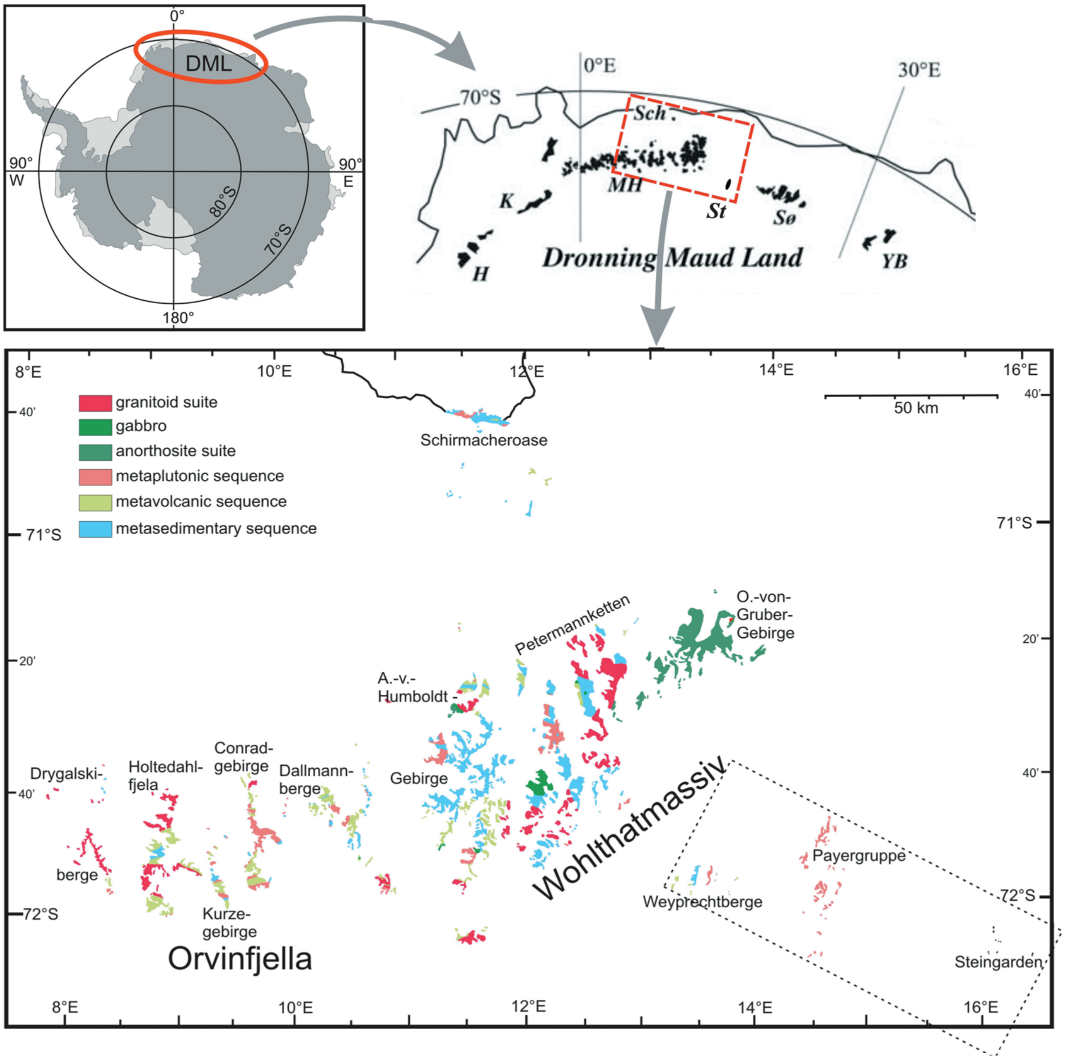

Fig. 1: Geological map of central Dronning Maud Land and its location within Antarctica. Compiled after PAECH et al. (2004), BENNAT (2005), PAECH (2005a) and OWADA et al. (2008). DML = Dronning Maud Land, H = Heimefrontfjella, K = Kirwanveggen, MH = Mühlig-Hofmann region, Sch = Schirmacheroase, St = Steingarden, Sø = Sør Rondane, YB = Yamato-Belgica Mountains. Marked section in geological map is shown in detail in Figure 2.

Abb. 1: Geologische Karte des zentralen Dronning Maud Lands und seine Lage in der Antarktis. Nach PAECH et al. (2004), BENNAT (2005), PAECH (2005a) und OWADA et al. (2008). Das markierte Gebiet in der geologischen Karte wird detailliert in Abbildung 2 gezeigt.

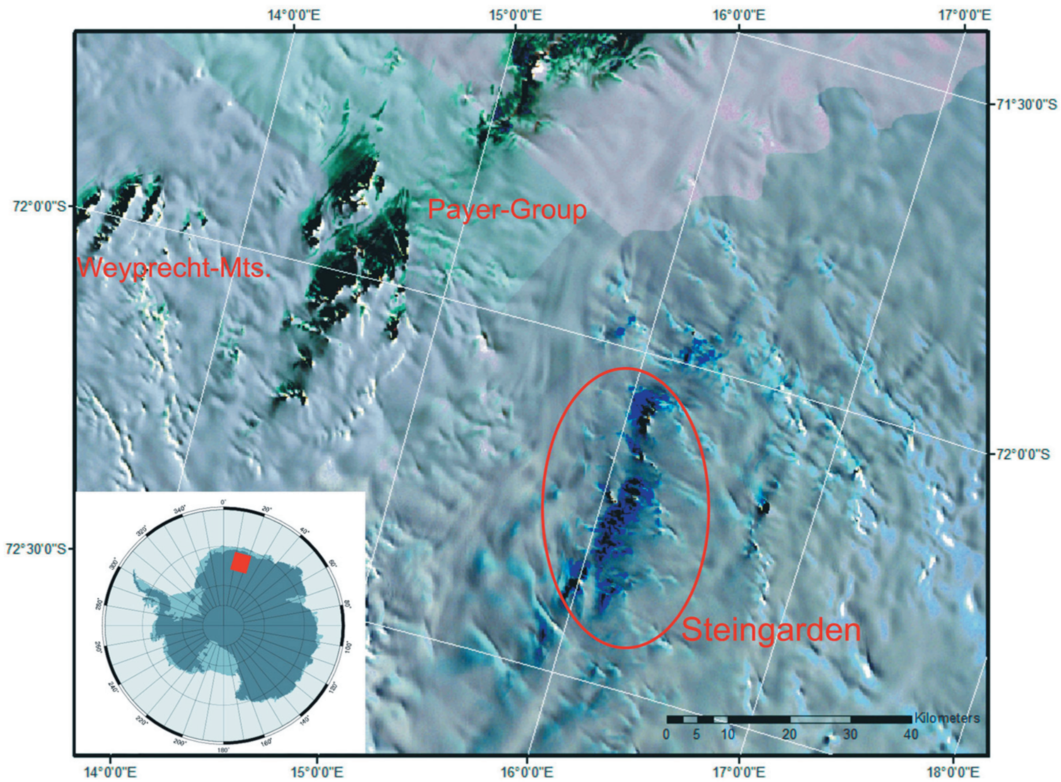

Fig. 2: Location of the Steingarden area in relation to Weyprechtberge and Payergruppe, southeastern central Dronning Maud Land (1:650,000) (Landsat image http://lima.usgs.gov). Circled area is shown in detail in Figure 4.

Abb. 2: Lage des Steingarden-Gebietes in Bezug zu den Weyprechtbergen und der Payergruppe, südöstliches zentrales Dronning Maud Land (1:650.000; Landsatbild http://lima.usgs.gov.) Das markierte Gebiet wird detailliert in Abbildung 4 gezeigt.

geology or petrology was known from this region. Therefore, rock samples were taken from nunataks (Figs. 4, 5, 6, Tab. 1) as well as from moraines and ice-rafted debris in the adjacent regions (Figs. 4, 6, 7, Tab. 1). Because of limited time due to long-lasting bad weather conditions, and the concentration on the main focus of the expedition, the search for meteorites, only a small number of representative samples could be collected.

GEOLOGICAL SETTING

DML is in a key position for the reconstruction of the assemblage and dispersal of two supercontinents, the Mesoproterozoic supercontinent Rodinia, and the Paleozoic until Late Mesozoic southern supercontinent Gondwana (Fig. 3) (e.g. Jacobs et al. 1998, Fitzsimons 2000 cum lit., Talarico & Kleinschmidt 2009).

The cratons of Rodinia and Gondwana were stabilized before c. 1600 Ma (Grantham et al. 1991, Groenewald et al. 1995, Fitzsimons 2000). The adjoining mobile-belts associated with the collision and amalgamation of the old cratons formed during three different tectonic events, namely the Grenville-age orogeny at 1300 – 900 Ma, the Pan-African orogeny at 700 – 500 Ma and the equivalent Ross-Delamarian orogeny at 550 – 450 Ma (Fitzsimons 2000).

Grenville-age mobile-belts formed as a consequence of continent-continent collision during the assemblage of Rodinia (Hoffmann 1991, Fitzsimons 2000). The Pan-African event in late Neoproterozoic and Cambrian times led to the collision of parts of West and East Gondwana related to the closure of the Mozambique Ocean, and resulted in the formation of a Himalayan-type collision belt, the East African-Antarctic Orogen or Lützow-Holm Belt (e.g. Jacobs et al. 1998, Fitzsimons 2000, Jacobs & Thomas 2004, Paech et al. 2005). This collision belt is preserved today in the coastal mountain ranges of DML. The exact location of the suture zone between West and East Gondwana within DML is still being discussed (Fig. 3, Shackleton 1996, Grunow et al. 1996, Jacobs et al. 1998, Paech 2001, Bauer et al. 2003).

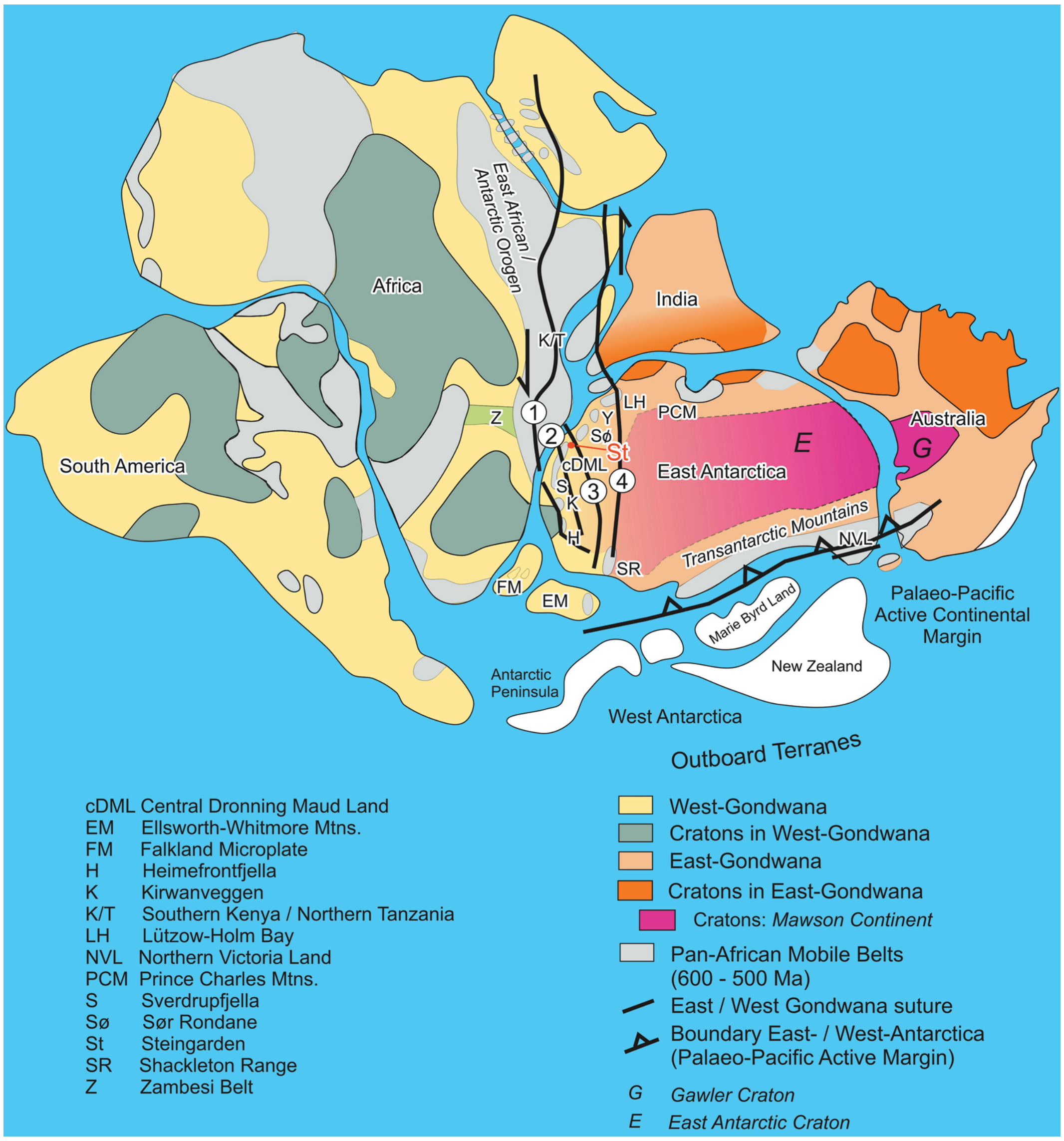

Fig. 3: Reconstruction of the supercontinent Gondwana at approx. 500 Ma. Adapted from Helferich et al. (2004) based on Grunow et al. (1996), Jacobs et al. (1998), Kleinschmidt et al. (2000). Different possible traces of the suture between West and East Gondwana are shown: (1) Shackleton (1996), (2) Jacobs et al. (1998), (3) Moyes et al. (1993), (4) Grunow et al. (1996) and Shiraishi et al. (1994).

Abb. 3: Rekonstruktion des Superkontinents Gondwana vor ca. 500 Ma. Modifiziert von Helferich et al. (2004) nach Grunow et al. (1996), Jacobs et al. (1998), Kleinschmidt et al. (2000). Verschiedene Möglichkeiten des Verlaufs der Sutur zwischen West- und Ost-Gondwana werden gezeigt: (1) Shackleton (1996), (2) Jacobs et al. (1998), (3) Moyes et al. (1993), (4) Grunow et al. (1996) und Shiraishi et al. (1994).

Site	Sample numbers	Latitude (S) Longitude (E)	Altitude (m)*
Moraines			
P2	P2-001, P2-002, P2-003, P2-004, P2-005	72°19.870' 16°05.123'	-
P3	P3-001, P3-003a, P3-003b, P3-003c, P3-005	72°20.936' 16°06.831'	2482
P4	P4-001a, P4-001b	72°20.561' 16°07.957'	2484
P5	P5-002	72°21.283' 16°10.322'	2538-2549
P6	P6-001, P6-002a, P6-002b	72°14.194' 16°03.516'	2306
P8	P8-001a, P8-001b, P8-001c	72°12.467' 16°04.887'	2264
Nunataks			
P1A	P1-001a, P1-001b, P1-001c	72°21.697' 15°59.854'	2643
P1B	P1-002	72°21.478' 16.00.179'	2630
P1C	P1-003	72°21.611' 15°59.852'	-
P5	P5-001a, P5-001b	72°21.244' 16°10.181'	2549
P7a	P7-001, P7-003	72°13.811' 16°02.994'	2388
P7b1	P7-002a, P7-002b, P7-004a, P7-004b**	72°13.681' 16°03.944'	2306
P7b2		72°13.740' 16°03.810'	2370

Tab. 1: Location of the Steingarden samples. * = approximate elevations above mean sea level. ** = These samples cannot be assigned in detail to P7b1 or P7b2.

Tab. 1: Fundkoordinaten der Steingarden-Proben.

Central DML

Central DML comprises a metamorphic basement that is mainly made up of Mesoproterozoic metavolcanic and metasedimentary sequences. The volcanic rocks (now typically banded gneisses) are bimodal in composition and were extruded around 1130 Ma, contemporaneously with the deposition of sedimentary rocks (now marbles, quartzites, metapelites, and paragneisses) (JACOBS et al. 1998, 2003). During the Grenville-age metamorphic event around 1080 Ma, these rocks underwent high-grade metamorphism under granulite-facies conditions. Coevally, mostly felsic syntectonic granitoids, which were also affected by Grenvillian metamorphism and transformed to augen gneisses, intruded the metavolcanic and metasedimentary sequences.

The intrusion of the anorogenic Grubergebirge anorthosite (northeastern Wohlthatmassiv) at about 600 Ma was followed by the polyphase Pan-African orogeny with high-grade deformation and metamorphism dated between 580-550 Ma and 530-515 Ma (JACOBS et al. 1998). The Grenville-age sequences were reworked under granulite-facies conditions and the metamorphic rocks were partly migmatized (JACOBS et al. 1998, 2003, COLOMBO & TALARICO 2004). The first Pan-African event reached medium-pressure granulite-facies conditions (about 6.8 ±0.5 kbar and 830 ±20 °C) and is interpreted as collisional stage (MARKL & PIAZOLO 1998). The second Pan-African event started with the syntectonic intrusion of granitoids and gabbros and reached metamorphic conditions at low-pressure granulite facies (about 4-5 kbar and 640 ±10 °C) (JACOBS et al. 1998, BAUER et al. 2004, MARKL & PIAZOLO 1998).

Anorogenic late-tectonic to post-tectonic magmatic rocks including charnockites of the Petermannketten (Fig. 1) intruded the Grenville-age basement during an extensional phase around 510 Ma (MIKHALSKY et al. 1997). The voluminous intrusions were accompanied by a poorly developed retrogression at amphibolite-facies conditions (about 2-5 kbar and 480-580 °C) (MARKL & PIAZOLO 1998). A last Pan-African tectonic episode associated with thrusting, autometasomatism of the primary charnockitic granitoids, and dyke intrusion, probably lasted until Silurian times (PAECH et al. 2004, PAECH 2005c).

Sør Rondane (Eastern DML)

The metamorphic basement of Sør Rondane is dominated by late Mesoproterozoic banded gneisses of various compositions as well as minor amounts of pelitic gneisses, marbles, calc-silicate rocks, amphibolites, mafic granulites and charnockitic ortho-gneisses (SHIRAISHI et al. 1997). E–W and NW–SE trending shear zones divide the region into a northeastern granulite-facies terrane and a southwestern amphibolite to greenschist facies terrane. The NE Terrane was metamorphosed under granulite-facies conditions (about 760-800 °C and 7-8 kbar) at c. 600 Ma (ASAMI et al. 2007, SHIRAISHI et al. 2008). The SW Terrane is cut by a WSW–ENE trending mylonitic shear zone. South of this shear zone, the SW Terrane consists dominantly of meta-tonalites. Their protoliths intruded during the early Neoproterozoic (c. 960 Ma). Similar protolith ages are reported for the charnockitic ortho-gneisses of the NE Terrane (SHIRAISHI et al. 1997, 2008).

After SHIRAISHI et al. (2008), both terranes have experienced amphibolite-facies metamorphism (500-600 °C) at c. 560 Ma, related to their juxtaposition along large-scale shear zones. Extensive A-type granitoid activity and contact metamorphism occurred between 560 and 500 Ma. Cooling and sporadic magmatism including intrusion of mafic dykes (lamprophyre and dolerite) continued possibly until as late as 420 Ma.

METHODS AND SAMPLES

During the QueenMET field campaign, only three (P1, P5, P7) of the 10 nunataks in the Steingarden region could be reached and sampled (Figs. 4, 5, 6). These rock occurrences are the southernmost outcrops of central DML and represent the closest outcrops to the South Pole. Moraines between those outcrops have also been sampled (Figs. 6, 7).

Because the rock samples are of relatively small size and so far represent the only available information on the geology of this area, our main purpose was to perform initial petrographic investigations to develop a general idea of the lithological variety of the region. Most of the samples were studied by thin-section microscopy, the results are summarized in Table 2. More detailed petrographic descriptions are available from the Bachelor's theses of NITZSCHE (2010) and KÜHN (2010). The samples are stored in the German Polar Rock Sample Repository at the BGR Branch Office Berlin-Spandau (contact: solveig.estrada@bgr.de).

The preparation of 30 thin sections was carried out in the labo-

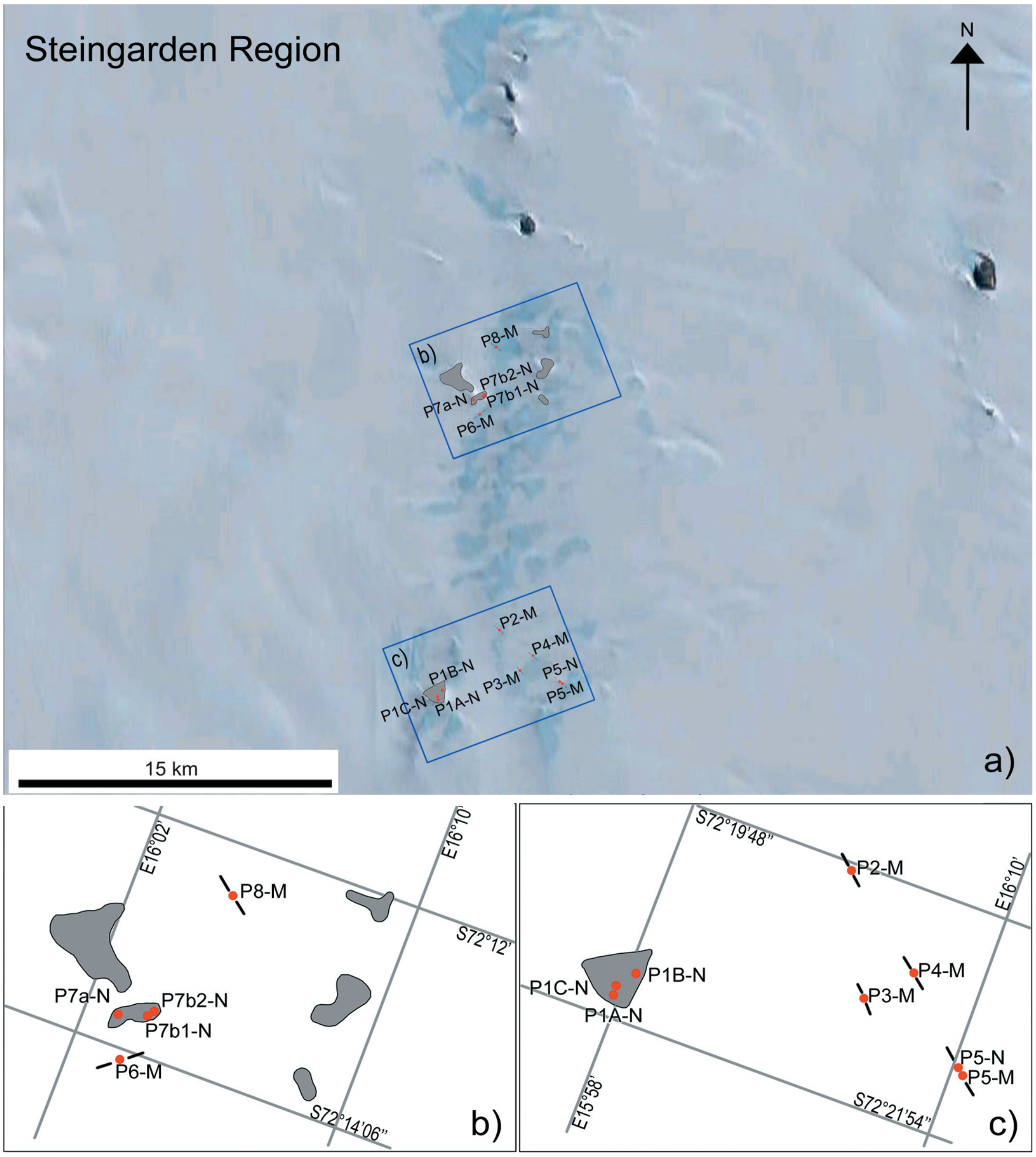

Fig. 4: Sample locations P1 to P8 in the Steingarden nunatak area. (a) = Overview (GoogleEarth image). (b) = Northern area with locations P6 to P8 in detail. (c) = Southern area with locations P1 to P5 in detail. M = moraine, N = nunatak.

Abb. 4: Probenahme-Punkte P1 bis P8 im Steingarden-Nunatak-Gebiet. (a) = Übersicht (basierend auf GoogleEarth). (b) = nördliches Gebiet mit den Punkten P6 bis P8 im Detail. (c) = südliches Gebiet mit den Punkten P1 bis P5 im Detail. M = Moräne, N = Nunatak.

Fig. 5: Strongly foliated rocks (banded gneisses and amphibolites) from outcrop P1 (see Fig. 4). The nunatak reaches a height of about 250 m above the surrounding landscape. View from SW to NE (Photo J. Schlüter).

Abb. 5: Stark folierte Gesteine (gebänderte Gneise und Amphibolite) vom Aufschluss P1 (siehe Abb. 4). Der Nunatak erreicht eine Höhe von ca. 250 m gegenüber der Umgebung. Blick von SW nach NE (Foto J. Schlüter).

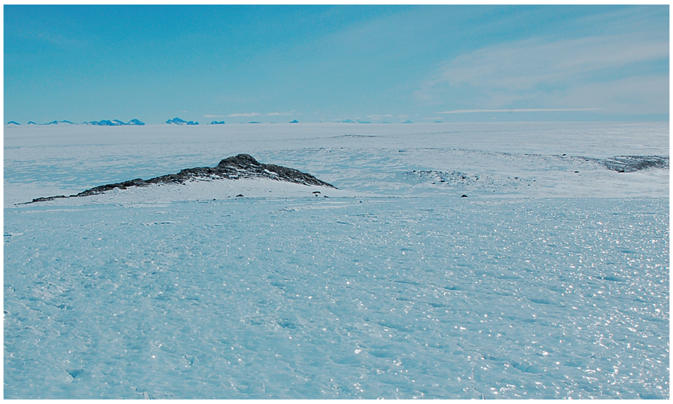

Fig. 6: Outcrop and moraine of P5 area with moraine P4 in the background and Wohlthatmassiv mountains on the horizon (Photo J. Schlüter).

Abb. 6: Aufschluss und Moräne vom P5-Gebiet mit P4-Moräne im Hintergrund (siehe Abb. 4) und Bergen des Wohlthatmassivs am Horizont (Foto J. Schlüter).

	Lithology	Sample	Characteristic mineral assemblage
Moraines	metamorphosed black shales and related green muscovite bearing rocks		
	low-grade meta-sediments	P2-002 P2-003 P4-001a P5-002 P6-001	quartz, graphite, pyrite, white or green muscovite, ±calcite and calc-silicate minerals, ±chlorite, ±biotite, rutile, titanite, zircon, tourmaline, allanite
	high-grade meta-sediments	P4-002	kyanite, quartz, pyrite, graphite, andalusite, muscovite, garnet, rutile
	altered granite with green veins	P3-005a P2-001	veins: green and white muscovite, ±gypsum
	gneisses and amphibolites		
	para-gneiss	P3-003a	quartz, alkali feldspar, plagioclase, biotite, garnet, kyanite, staurolite, sillimanite, rutile, zircon, apatite, opaques
	garnet-biotite gneiss	P2-005 P4-001b P6-002b	quartz, plagioclase, alkali feldspar, biotite, garnet, apatite, zircon, opaques
	amphibolite	P3-003b P2-004 P6-002a	plagioclase, biotite, amphibole (green hornblende, ±light-brownish clinoamphibole), quartz, apatite, titanite, opaques
	late to post-tectonic intrusives		
	charnockite (undeformed)	P8-001c	alkali feldspar, plagioclase, biotite, orthopyroxene, clinopyroxene, quartz, green hornblende, apatite, allanite, hbl-qtz symplectite
	granite (slightly deformed)	P3-001	plagioclase, alkali feldspar, quartz, biotite, apatite, opaques, titanite, zircon
	alkaline subvolcanic rocks (lamprophyre)	P8-001a P8-001b	plagioclase phenocrysts; biotite, plagioclase, alkali feldspar, quartz, green hornblende, relict clinopyroxene, apatite, Fe-Ti oxide
Nunataks	biotite gneiss, partly banded	P1-001a P1-001b P1-002 P5-001b P7-001 P7-004a P7-004b	quartz, plagioclase, alkali feldspar, biotite, ±hornblende, ±garnet, apatite, opaques, titanite, zircon, allanite
	amphibolite and mafic granulite	P5-001a P7-002a P7-002b P7-003	plagioclase, biotite, amphibole (green hornblende or cummingtonite), quartz, ±garnet, apatite, titanite, opaques, ±relict orthopyroxene
	marble (white-grey banded)	P7-001r P7-003r	calcite (without thin section)

Tab. 2: Petrographic classification of the Steingarden samples.

Tab. 2: Petrographische Klassifizierung der Steingarden-Proben.

Fig. 7: Glacial debris of the P8 area with one of the eastern Steingarden not sampled nunataks in the background (see Fig. 4; Photo J. Schlüter).

Abb. 7: Glazialer Schutt des P8-Gebietes mit einem der östlichen nicht-beprobten Steingarden-Nunataker im Hintergrund (siehe Abb. 4; Foto J. Schlüter).

ratories of BGR, Hannover. Seven polished sections provided by the Mineralogical Institute, University of Hamburg, were used to determine opaque components. Two samples (P2-001, P4-001a) were also examined by XRD using a Philips diffractometer PW 3710 (40 kV, 30 mA) at BGR Hannover. Green micas were analysed with the Nonius KappaCCD diffractometer and the Cameca SX 100 electron microprobe at the Mineralogical Institute, Hamburg University.

PETROGRAPHY

Nunatak rocks

In general, the studied area is characterized by north-south striking, steeply eastwards dipping banded gneisses and amphibolites (Figs. 5, 8). Accordingly, the rock samples collected from the nunataks are dominated by quartz-feldspar-biotite gneisses and amphibolites, but additionally comprise mafic granulite, marbles and granitic mobilisates.

Fig. 8: Steeply dipping gneiss-amphibolite associations at nunatak P7 (b2) (see Fig. 4). The front part of the outcrop is about 6 m high (Photo J. Schlüter)

Abb. 8: Steil einfallender Gneis-Amphibolit-Gesteinsverband am Nunatak P7 (b2) (siehe Abb. 4). Die Vorderfront des Aufschlusses ist ungefähr 6 m hoch (Foto J. Schlüter).

The fine to medium grained, light-brown to light-grey gneisses consist of quartz, alkali feldspar, and plagioclase. Biotite is the dominant mafic mineral. Minor components are occasional green hornblende and almandine garnet as well as accessory apatite, zircon, titanite, allanite and opaque minerals. Gneiss P1-002 also contains a significant amount of magnetite. The associated amphibolites are composed of plagioclase, biotite, amphibole (green hornblende or actinolite) and quartz. Accessory minerals are apatite, titanite, and opaque minerals.
Both gneisses and amphibolites contain concordant as well as cross-cutting granitic mobilisates (Fig. 9).

Rock sample P7-002b is medium grained (up to 3 mm grain size), dark-light coloured and weakly foliated. It is composed of plagioclase, biotite, garnet, quartz, amphibole (light greenish cummingtonite) and rarely orthopyroxene, and shows accessory idiomorphic apatite. In mafic granulites within the polymetamorphic basement of central DML, orthopyroxene is often completely replaced by cummingtonite (Colombo & Talarico 2004) and thus sample P7-002b is interpreted as a mafic granulite.

Two marble samples collected at nunatak P7a (without thin sections) are medium to coarse-grained and show a poorly developed layering between white and grey areas.

Moraine rocks

The rock inventory of the moraines comprises gneisses and amphibolites and is partly comparable to the nunatak samples, but includes other rock types, which were not found in the

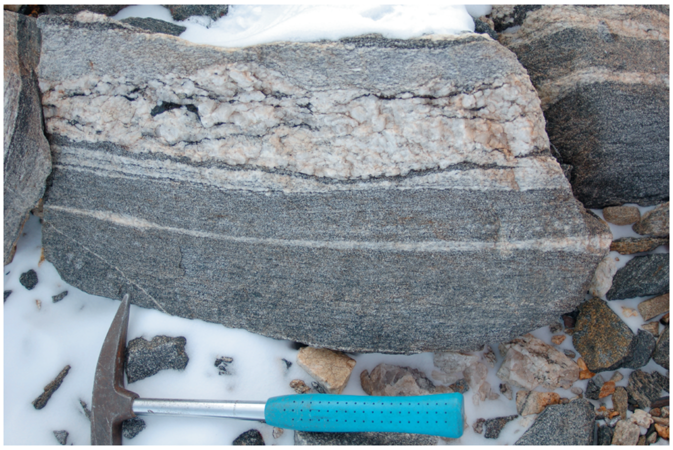

Fig. 9: Amphibolite-gneiss association of nunatak outcrop P7 (b2) with coarse-grained granitic mobilisate (hammer for scale; Photo J. Schlüter).

Abb. 9: Amphibolit-Gneis-Verband am Nunatak-Aufschluss P7 (b2) mit grobkörnigem granitischen Mobilisat (Hammer als Maßstab; Foto J. Schlüter).

outcrops. Notable are large boulders of black schist (Fig. 10) and conspicuous lithologies, which contain green muscovite in the matrix, in lenses and/or veins.

The gneisses found in the moraines contain more garnet than the nunatak gneisses. Garnet gneiss sample P3-003a contains an assemblage of kyanite, accessory staurolite and tiny sillimanite needles which can be used to constrain the metamorphic conditions. The reaction of staurolite + quartz to garnet + sillimanite + water and the coexistence of kyanite and sillimanite indicate a temperature of about 670 °C and a pressure of about 7 kbar (Spear 1993).

A dark-brown amphibolite sample (P3-003b) differs from the other amphibolites. It consists predominantly of light-brownish clinoamphibole with minor to accessory plagioclase, quartz, biotite, apatite, titanite and opaque minerals.

The most prominent rocks of the moraines are dark graphite-rich and pyrite-rich low to high-grade facies schists, which also contain quartz mobilisates (Fig. 10).

Fig. 10: Graphite-rich black schist boulder with quartz mobilisates of the P5 moraine (hammer for scale; Photo J. Schlüter).

Abb. 10: Graphitreicher Schwarzschiefer-Block mit Quarz-Mobilisaten von der P5-Moräne (Hammer als Maßstab; Foto J. Schlüter).

The group of the low-grade black schists comprises pyrite-graphite-calcite-sericite schists (P5-002, P6-001), a calcitic chlorite-sericite schist (P2-003) and a fine-grained graphite-bearing calcite-marble (better termed a meta-limestone) with small amounts of calc-silicate minerals (amphibole, zoisite, clinopyroxene) (P4-001a). The schists are foliated, and changes in the mineral composition of the layers (muscovite-rich, calcite-rich and graphite-rich layers) may partly correspond to the original bedding. More pelitic varieties show crenulation cleavage. In P2-003, chlorite crystals cut across and enclose the bedding marked by a fine graphite pigment (Fig. 11a). The same sample contains lenses up to 3 mm long filled with sericite that probably replaces cordierite (Fig. 11b). "Marble" P4-001a contains clastic grains of quartz and quartz-alkali feldspar aggregates (probably granitoid clasts). The black schists are nearly always interspersed by fine-grained pyrite. Locally the pyrite together with quartz shows recrystallization leading to the formation of mm-sized idiomorphic pyrite crystals. These pyrites occasionally show tiny inclusions of sphalerite and pyrrhotite. Accessory minerals include rutile, titanite, garnet, zircon, tourmaline and allanite.

Also related to this group of black schists is a biotite-bearing graphite-quartz schist (P2-002) that contains green muscovite in the matrix and in fine quartz veins parallel to the foliation (Fig. 12). This sample reveals about 25 to 30 vol.% graphite that forms foliated aggregates of large flaky crystals. Accessory minerals are mm-sized rutile as well as pyrite, allanite, zircon, and rare tiny grains of chalcopyrite and galena. The biotite is bleached and seems to be instable.

Colourless to bluish-grey kyanite porphyroblasts up to 5 cm in length (Fig. 13) occur on the surface of a boulder in moraine P4 (P4-002). This rock certainly belongs to the group of black schists because the inventory of its matrix reveals a graphite-pyrite-quartz-andalusite schist with some garnet and accessory rutile. The kyanite porphyroblasts bear massive inclusions of graphite and they show retrograde alteration to sericite on rims and fractures (Fig. 14). This rock was metamorphosed at high-pressure amphibolite-facies conditions and has experienced a later high-temperature event that partly transformed the kyanite to andalusite and muscovite.

Green muscovite is also present in other samples of the black schist group, which were not petrographically studied (e.g. from P3-005) and forms small intense green lenses in these black rocks. However, the green muscovite was also found in completely different rock types. In a brecciated and hydrothermally altered biotite-granite (P3-005a), white and green muscovite grows along fine fissures. The biotite is bleached and replaced by muscovite. A sample of a strongly altered granitoid (P2-001) is intensely truncated by green veins consisting of green muscovite and gypsum (Fig. 15). Another group of samples from the moraine represents syn-tectonic to post-tectonic plutonic and dyke rocks. A weakly deformed medium-grained granite (P3-001) consists of plagioclase, alkali feldspar, quartz, minor biotite and accessory apatite, titanite, zircon and opaque minerals.

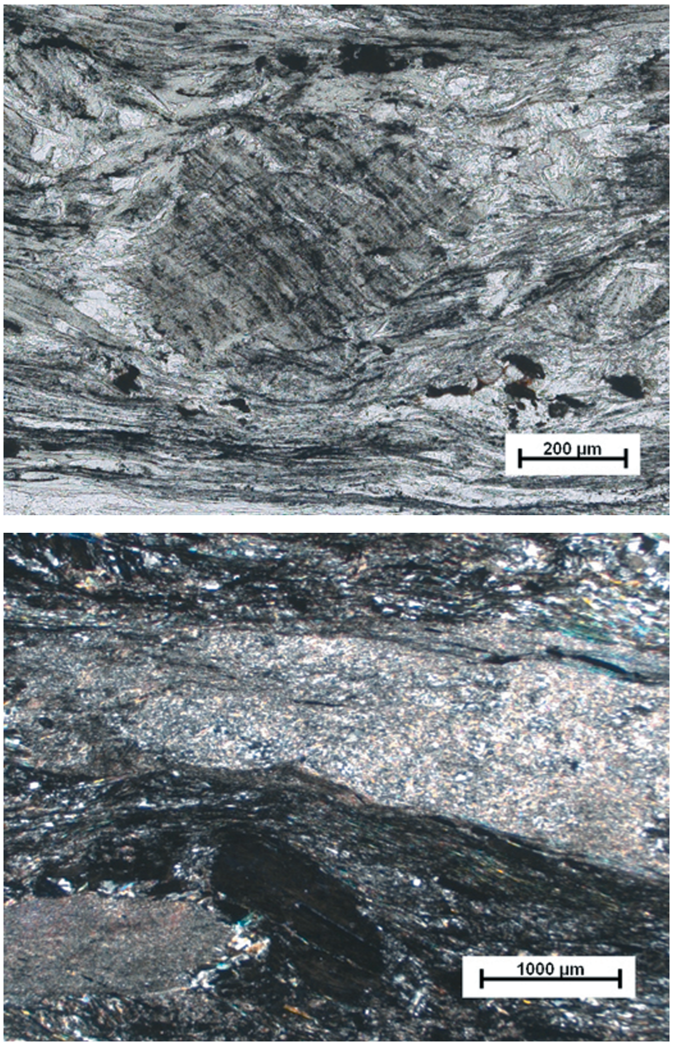

Fig. 11: Photomicrograph of graphite-bearing chlorite-sericite schist P2-003. Top = Chlorite porphyroblast (centre) encloses graphitic pigment that probably marks the relict bedding. PPL. Buttom = Sericite lenses (centre right and bottom left) in chlorite-muscovite matrix. XPL. Chlorite crystals (e.g. bottom centre) are almost isotropic.

Abb. 11: Dünnschliff-Foto des Graphit-führenden Chlorit-Serizit-Schiefers P2-003. Oben = Der Chlorit-Porphyroblast (im Zentrum) schließt graphitisches Pigment ein, das vermutlich noch die Schichtung markiert. Parallele Polarisatoren. Unten = Serizit-Linsen (Mitte rechts und unten links) in Chlorit-Muskovit-Matrix. Gekreuzte Polarisatoren. Chlorit-Kristalle (z.B. unten Mitte) sind fast isotrop.

Fig. 12: Graphite-muscovite-quartz schist with green muscovite in the matrix and in quartz veins (sample P2-002). Width of the rock is 12 cm.

Abb. 12: Graphit-Muskovit-Quarz-Schiefer mit grünem Muskovit in der Matrix und in Quarz-Adern (Probe P2-002). Breite des Handstücks 12 cm.

Fig. 13: Prismatic kyanite porphyroblasts with black graphite on a weathered surface of a graphite schist boulder of moraine P4 (width of the picture 5 cm; Photo J. Schlüter).

Abb. 13: Prismatische Disthen-Porphyroblasten mit schwarzem Graphit auf der verwitterten Oberfläche eines Graphitschiefer-Blocks von Moräne P4 (Breite des Handstücks 5 cm; Foto J. Schlüter).

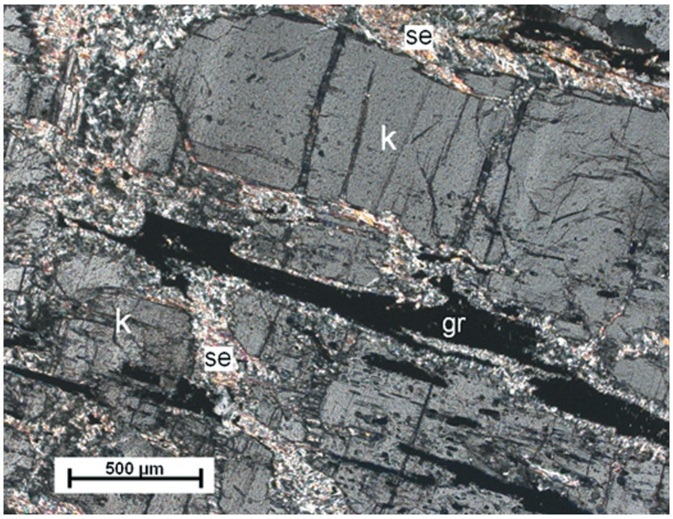

Fig. 14: Photomicrograph of sample P4-002. Large kyanite crystal (k) with inclusions of graphite (gr) is altered to sericite (se) at the rim and along fine fissures. XPL.

Abb. 14: Dünnschliff-Foto von Probe P4-002. Ein großer Disthen-Kristall (k) mit Einschlüssen von Graphit (gr) ist an den Rändern und entlang feiner Risse zu Serizit (se) alteriert. Gekreuzte Polarisatoren.

An undeformed brown medium-grained charnockite (P8-001c) is formed by predominantly alkali feldspar, plagioclase, quartz, biotite, orthopyroxene, clinopyroxene, green hornblende, apatite, allanite and hornblende-quartz symplectite. Such granite and charnockite intrusions are widespread in central DML (e.g. Roland 2004).

Two samples from P8 (P8-001a and b) are undeformed, dark, fine-grained, weakly porphyritic rocks. The phenocrysts are plagioclase and the matrix is formed by biotite, plagioclase, alkali feldspar, quartz, green hornblende, relict clinopyroxene, accessory apatite and Fe-Ti oxides. These rocks can be characterized as lamprophyre (?minette) and they can be related to post-tectonic alkaline mafic dykes (lamprophyres, lamproites, dolerites), which are present in central and eastern DML (e.g. Owada et al. 2008, Owada et al. 2010).

Some of the black schists described above are characterized by a large amount of green muscovite. Such micas are often observed as fuchsites which are coloured by variable amounts of chromium as a substitute of aluminium. Alternatively, green muscovites can be coloured by vanadium with the end-member V>Al and are called roscoelite. Electron microprobe analyses of green mica porphyroblasts in the black schists (P3-003c) show contents of 1.73 wt.% V_2O_3 plus 1.21 wt.% TiO_2 confirming that the mineral is vanadium-green muscovite and not fuchsite.

In many cases, V-green micas are indicators of gold occurrences, such as the Precambrian Hemlo gold deposit, Ontario, Canada. There green micas rich in vanadium characterize ore-grade pyrite bearing mica schists (Pan & Fleet 1992). The Steingarden moraine association of pyrite mineralization with V-green muscovite in black schists seriously requires further investigations with a focus on a potential gold mineralization.

DISCUSSION

Steingarden nunatak rocks

The Steingarden gneisses are intercalated to a large extent with multiple thin amphibolite layers with gradual transition into each other (Fig. 8). The general appearance of the gneiss/amphibolite association and the paragenesis with

Fig. 15: Hydrothermally altered granite with a vein of gypsum and green muscovite (sample P2-001). Width of the rock is 11 cm.

Abb. 15: Hydrothermal alterierter Granit mit einer Ader aus Gips und grünem Muskovit (Probe P2-001). Breite des Handstücks 11 cm.

marbles favour a metasedimentary origin of the Steingarden rocks. A similar succession of paragneisses and marbles is reported from the adjacent southern Payergruppe (RAVICH & SOLOV'EV 1969). The Steingarden gneisses, however, do not contain minerals such as sillimanite or cordierite typical of paragneisses. On the other hand, the mineral composition of the felsic Steingarden gneisses is also comparable to that of the granitic orthogneisses of the northern Payergruppe as described by RAVIKANT et al. (1997).

The presence of mafic granulite with orthopyroxene relicts indicates that the Steingarden rocks experienced a first phase of granulite-facies metamorphism, which was followed by a second amphibolite-facies event. This metamorphic signature matches the history of other metamorphic rocks of central DML, where Grenville-age sequences experienced a first Pan-African overprint to granulite-facies conditions. A succeeding late Pan-African event reached amphibolite-facies conditions (e.g. JACOBS et al. 1998, MARKL & PIAZOLO 1998).

Moraine rocks

Only some of the rocks found in the moraines correspond to the in situ lithologies of the Steingarden nunataks. Most of the moraine rocks were probably delivered by the northward moving glaciers (RIGNOT & THOMAS 2002) and are derived from now unexposed areas located further to the south.

Some of the rocks from the moraines, including kyanite-staurolite-sillimanite gneiss, garnet-biotite gneiss, amphibolite as well as late-tectonic to post-tectonic granite, charnockite and lamprophyre (Tab. 2), correspond to known lithologies reported from central DML and Sør Rondane (e.g. PAECH et al. 2004, SHIRAISHI et al. 1997). However, post-tectonic igneous charnockites, which are widespread in central DML, have not been described in Sør Rondane so far (SHIRAISHI et al. 1997).

The greenschist-facies to amphibolite-facies black schists and the V-enriched green muscovite bearing rocks deserve particular attention. Relict sedimentary features in the greenschist-facies varieties (as described above) and characteristic minerals in the amphibolite-facies sample (kyanite, andalusite) indicate a sedimentary origin of the black schists. The graphite and pyrite concentrations point to a carbonaceous black-shale protolith. Such bituminous shales can commonly concentrate trace elements such as vanadium. They are commonly deposited in isolated basins or in the deep sea under anoxic, euxinic conditions (e.g. ARTHUR & SAGEMAN 1994).

Information about graphite-bearing and pyrite-bearing metasedimentary rocks or vanadium-bearing minerals from regions adjacent to the Steingarden area is very limited. In central DML, several small occurrences of graphite are reported by RAVICH & SOLOV'EV (1969) from migmatized felsic gneisses and related pegmatite veins, as well as from coarse-grained marbles and related calcite veins. In the southeastern Dallmannberge, sequences of graphite-bearing biotite-garnet gneisses with 2-3 % fine flaky graphite are 2-7 m thick and can be traced over a distance of about 100 m along strike. In the calcite veins, pyrite is present together with graphite. The same authors describe the frequent occurrence of poorly rounded fragments of “graphite gneisses” in moraines on the eastern margin of central DML (Payergruppe area). However, they do not report findings of green micas related to the graphite gneisses.

In Sør Rondane, V-green muscovite is also unknown so far. However, vanadium-bearing green garnet (grossular and goldmanite) up to 20 cm in diameter was found in granulite-facies metamorphosed graphite-bearing calc-silicate gneisses in the central part of the NE Terrane (OSANAI et al. 1990). The calc-silicate gneiss is formed of green garnet, clinopyroxene, plagioclase, quartz with minor zoisite, titanite, apatite and accessory calcite, pyrrhotite, magnetite and apatite as well as secondary actinolite and muscovite. Apart from the garnet, clinopyroxene, zoisite, titanite, magnetite, and actionlite also contain vanadium.

Occurrences of vanadium-bearing green garnet very similar to Sør Rondane are also known from southern Kenya (SUWA et al. 1996) and adjacent northern Tanzania (FENEYROL et al. 2010). Both regions, Kenya/Tanzania and Sør Rondane were located within the Pan-African East African-Antarctic orogenic belt that formed during the accretion of Gondwana (Fig. 3). The protoliths of the graphite-bearing calc-silicate gneisses from Sør Rondane as well as from Tanzania/Kenya are most probably vanadium-rich black-shale type sediments. SUWA et al. (1996) discuss a biogenic and evaporitic origin for the graphite-bearing calcareous metasedimentary rocks of southern Kenya.

The compositional similarities between these rocks and the black schists from the Steingarden moraines (similar protoliths, the presence of V-bearing minerals) are accompanied by substantial differences, mainly in the degree and type of metamorphism. Most black-schist samples from the Steingarden moraines are metamorphosed under greenschist-facies conditions. These rocks do not represent greenschist-facies retrogressed gneisses. Thus, they may be correlated to the amphibolite-facies to greenschist-facies SW Terrane of Sør Rondane. However, no black-shale-type metasedimentary rocks and vanadium-bearing minerals have been described from the SW Terrane so far. Furthermore, the presence of minerals such as andalusite and probably cordierite in the moraine samples may point to a high temperature - low pressure event, probably related to the intrusion of magmatic rocks.

We assume that the black-shale type rocks and related V-bearing green muscovite mineralisations found in the Steingarden moraines may be derived from an area that has experienced only lower-grade metamorphism during the Pan-African orogeny in comparison to the granulite-facies metamorphosed rocks of central DML – probably a marginal area of the East African-Antarctic mobile belt. The southern provenance of the moraine rocks implies that a tectonic boundary runs south of the Steingarden region. This boundary probably represents the Pan-African suture between West and East Gondwana corresponding to the model of MOYES et al. (1993) (Fig. 3). Furthermore, a large crustal boundary related to a suture zone of West and East Gondwana between central DML and Sør Rondane is postulated by OWADA et al. (2008) due to different Sr and Nd isotope systematics of post-tectonic mafic dykes and host metamorphic rocks from both areas.

The following simplified model is suggested for the formation of the V-muscovite bearing rocks of the Steingarden area moraines. Vanadium-rich carbonaceous black shales were deposited at the former margin of East Antarctica. Terrigenous clastic grains in graphite-bearing marble (P4-001a) indicate deposition in the vicinity of a continent. The black shales were metamorphosed to greenschist-facies schists and amphibolite-facies kyanite schists and intruded by granitoids, probably during the Pan-African orogeny. Plutonic rocks (granites and charnockites) are associated with the black schists in the moraines. The intrusion was accompanied by hydrothermal activity that mobilized elements from the metamorphosed black shales and led to the formation of green V-rich muscovite. Parts of the metasedimentary rocks were completely hydrothermally altered and transformed into green muscovite-graphite-quartz schist (P2-002). Fluids enriched in vanadium and other elements migrated through fissures and brecciated zones into the granitoids and formed veins with green muscovite and gypsum (P2-001, P3-005a).

SUMMARY AND CONCLUSIONS

Rock samples from nunataks and moraines of the Steingarden area, central DML, were petrographically studied. The nunatak rocks comprise banded felsic and mafic gneisses with some minor marbles. They experienced granulite-facies peak metamorphism followed by an amphibolite-facies overprint. The current state of knowledge implies that the nunatak rocks and part of the moraine rocks (kyanite-bearing paragneiss, garnet-biotite gneisses, amphibolites, late-tectonic to post-tectonic igneous rocks) are comparable to lithologies in central DML and Sør Rondane.

The inventory of the moraine rocks also comprises an assemblage of conspicuous dark graphite-bearing and pyrite-bearing schists and related green muscovite bearing lithologies. The dark schists represent greenschist-facies to amphibolite-facies metamorphosed black-shale-type sediments. The green colour of the muscovite is caused by its vanadium content. This type of muscovite is reported from Antarctica for the first time. It was probably formed by hydrothermal activity associated with the intrusion of granitoids into the metasedimentary black-shale sequence during the Pan-African orogeny.

These rocks have no lithological equivalents in central DML and have higher-grade metamorphosed equivalents associated with V-bearing minerals (though without vanadium-bearing muscovite) in central Sør Rondane. Thus, they indicate the presence of a tectonic boundary that runs south of the Steingarden region. We assume that this boundary probably represents the Pan-African suture between West and East Gondwana in agreement with the model of MOYES et al. (1993) (Fig. 3).

Further research, especially geochronological and geochemical studies, is required to develop a more complete picture of the geological architecture of southern DML, to reconstruct the regional deformation history, and to verify the genesis of the metasedimentary moraine rocks. This includes renewed sampling of the nunataks of the Steingarden area and the moraine rocks (including the as yet unvisited Steingarden nunataks and the moraines between Steingarden and Payergruppe) with particular attention to the graphite and V-green muscovite bearing lithologies.

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