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Metamorphic Processes in the Transantarctic Crystalline Basement, Pacific Section, Antarctica

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Summary: The Precambrian basement of North Victoria Land is built up in the west by a metamorphic belt of low-pressure regime (L-P belt) and in the east by a metamorphic belt of medium-pressure regime (M-P belt). The two belts are separated by the Rennick-Aviator-Line. The petrological treatment of critical minerals and mineral relics allows the construction of P-T loops in the P-T diagram. The western belt is characterized by simple prograde mineral reactions of medium-grade to high-grade metamorphism under low-pressure conditions. The eastern belt bears relictic parts from greater crustal depth (~ 10 kb) these are: kyanite-sillimanite transitions, the critical mineral assemblage staurolite — talc — corundum, relictic textures from former granulite- or kyanite-eclogite facies, and ultramafic upper mantle assemblages including spinel- and garnet-olivine pyroxenites.
Starting from different pressure regimes the development of all P-T paths meets under amphibolite facies conditions of the main Ross orogenetic event, apart from younger retrogressive stages.

Zusammenfassung: Das präkambrische Metamorphikum Nord-Victoria-Lands besteht im Westen aus einem Kristallingürtel mit Niedrig-Druck-Prägung (L-P belt), davon durch die Rennick-Aviator-Linie getrennt, im Osten aus einem Kristallingürtel mit Mittel-Druck-Prägung (M-P belt).
Die Petrologie kritischer Minerale und Mineralrelikte gestattet die Konstruktion von Druck-Temperatur-Schleifen im P-T-Diagramm. Für den westlichen Gürtel ergibt sich eine einfach prograde Entwicklung von mittelgradiger zu hochgradiger Metamorphose-Prägung unter Niedrig-Druck-Bedingungen. Der östliche Gürtel enthält reliktische Anteile aus größerer Krustentiefe (~ 10 kb), dieses sind: Disthen-Sillimanit-Übergänge, die kritische Paragenese Staurolith — Talk — Korund, granulitfazielle oder evtl. ehemalige Disthen-eklogitische Reliktstrukturen und ultrabasische Obermantel-Paragenesen in Spinell- und Granat-Olivin-Pyroxeniten.
Von verschiedenen Ausgangsbedingungen startend, münden alle P-T-Pfade ein in Bedingungen der letzten amphibolitfaziellen Einformung während der Ross Orogenese, von jüngeren, retrograden Veränderungen abgesehen.

1. INTRODUCTION

Metamorphic processes observable in the upper earth's crust comprise reactions in a solid state, re-equilibration, degassing, partial melting and re-hydration reactions. The metamorphic processes change density, texture, and modal mineralogy (BLÜMEL 1986). The petrological treatment of the mineral assemblage and mineral parageneses yields contributions concerning the P-T conditions of formation, the P-T paths of later evolution, the metamorphic (re-)-equilibration, all resulting in considerations to the crustal level and to the geodynamics the geological rock units suffered during the orogenic cycles.

The petrology of the metamorphics in connection with the study of the magmatic rocks and tectonic regimes will give information and arguments to the geodynamic processes of crustal formation.

2. METAMORPHIC BELTS

Within the Pacific Section of the Transantarctic Mountains two metamorphic belts are recognized in the crystalline basement. The two metamorphic (paired) belts are called "Western Belt" and "Eastern Belt" and are separated by the "Rennick-Aviator-Line" (GREW et al. 1984).

The two belts are indicating contrasting pressure regimes prior to their present generally amphibolite facies metamorphism. Hence the two belts can be characterized as low-pressure belt in the west and medium-pressure belt in the east (Fig. 1).

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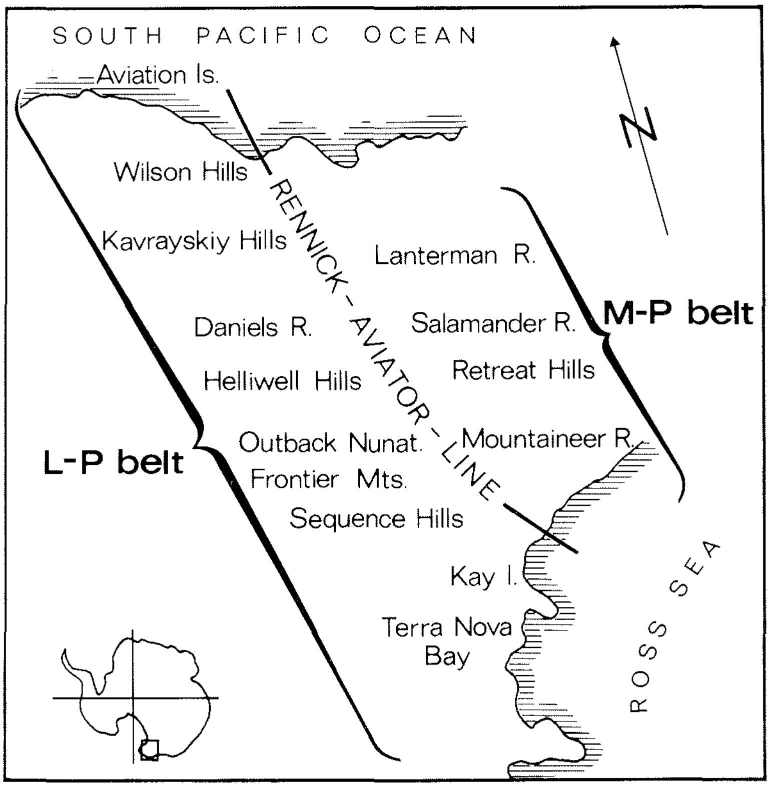

Fig. 1: Gereralized map of North Victoria Land, Antarctica, showing distribution of the crystalline basement areas and their assignment to the western low pressure belt (L-P) and to the eastern medium-pressure belt (M-P).

Abb. 1: Vereinfachte Karte von Nord Victorialand, Antarktis. Eingetragen sind die kristallinen Grundgebirgsanschnitte und ihre Zuordnung zum westlichen Niedrig-Druck-Gürtel (L-P) und zum östlichen Mittel-Druck-Gürtel (M-P).

Detailed work on geochemistry and on critical mineral assemblages could evaluate a series of mineral reactions, which gave hints for the original material and for the metamorphic evolution of the two contrasting belts or pressure units.

2.1 *The Western Belt*

2.1.1. Field Situation

The crystalline outcrops comprise Aviation Islands, Wilson Hills, Kavrayskiy Hills, the USARP Mountains with Daniels Range, Helliwell Hills, Outback Nunataks with Mt. Weihaupt, Sequence Hills, and the area of the upper and lower Priestley Glacier with Terra Nova Bay in the south and Kay Island (see GREW et al. 1984: Fig. 1).

2.1.2. Primary Rock

The dominant pre-metamorphic rock sequences within the western belt are largely monotonous shale sediments, graywackes, sand- or siltstones, and silicious carbonates (KLEINSCHMIDT 1981). Detailed geochemical work and correlation diagrams are given by SCHUBERT et al. (1984), ULITZKA (1986).

2.1.3. Present Rocks and Mineral Assemblages

Most abundant rocks are schists and paragneisses e. g. biotite-plagioclase gneiss, two-mica paragneiss, andalusite- or fibrolite-bearing muscovite gneiss, sillimanite-cordierite-K-feldspar gneiss with variable amounts of garnet. For petrography see KLEINSCHMIDT (1981), SCHUBERT et al. (1984), ULITZKA (1985), SCHUBERT (1986), SCHUBERT & OLESCH (in press), OLESCH & SCHUBERT (in press). The schists and gneisses are complexly folded during polyphase deformation of 3, 4 or 5 deformation events (KLEINSCHMIDT & SKINNER 1981, SKINNER 1983). The metamorphics show the typical "schlingenbau" tectonic of K. SCHMIDT (1965) or "loop" or "roll" structure. The overall present minerals in schists and gneisses of pelitic composition are biotite, muscovite, quartz, cordierite, spessartine-rich almandine, two feldspars. Accessories are tourmaline, apatite, spinel, opaques. Aluminium silicates are andalusite, fibrolite, and sillimanite. The rare mafic and calc-silicate rocks of the western belt contain plagioclase, green hornblende, biotite, quartz, sphene, diopside, calcite, clinozoisite.

2.1.4. Metamorphic Processes in the Western Belt

Generally in many areas of the western crystalline belt of the Transantarctic Mountains the metamorphic grade rises from west to east over short distances (KLEINSCHMIDT 1981, ULITZKA 1985, SCHUBERT 1986).

Hence a subdivision into two metamorphic units is possible represented by

- low-pressure medium-grade metamorphics
  with typical mineral assemblage of muscovite-cordierite, e. g. Wilson gneiss, Rennick schist (STURM & CARRYER 1970), Priestley schist (RICKER 1964; GANOVEX TEAM 1986; SCHUBERT & OLESCH in press)
- low-pressure high-grade metamorphics
  with typical muscovite-free mineral assemblage including in-situ migmatites, e. g. Thompson Spur migmatites (ULITZKA 1985; 1986), Terra Nova formation (GANOVEX TEAM 1986; SCHUBERT & OLESCH in press).

Suitable rock composition allow the recognition of critical isograds by the help of index minerals and mineral transitions.

2.1.5. L-P Medium-Grade Metamorphism

Medium-grade metamorphics are characterized by the following mineral reactions: andalusite accompaniing sillimanite but textures suggest sillimanite formed later than andalusite (1^{st} sillimanite isograd). The widespread occurrence of muscovite plus quartz indicates that the 2^{nd} sillimanite isograd was not crossed. Garnet, biotite and cordierite have formed according to the reactions summarized in SCHUBERT et al. (1984).

The following mineral abbrevations are used: alm = almandine; antho = anthophyllite; bio = biotite; chl = chlorite; cor = corundum; cord = cordierite; cpx = clinopyroxene; dio = diopside; en = enstatite; fo = forsterite; ga = garnet; hbl = hornblende; K-feldsp = K-feldspar; musc = muscovite; ol = olivine; omph = omphacite; opx = ortopyroxene; plag = plagioclase; q = quartz; serp = serpentine; sill = sillimanite; spi = spinel; stau = staurolite; tscherm = tschermakite; trem = tremolite.

(1) Mn-Fe-chl + musc + q $\rightarrow$ Mn-Fe-gar + bio + Al_2SiO_5 + H_2O under conditions analogous the QFM buffer;
(2) Mg-chl + musc + q $\rightarrow$ Mg-cord + phlog + H_2O but
(3) Mg-cord + musc $\rightarrow$ phlog + sill + q + H_2O
still rests on the left-hand side.

A weakly developed zonation in garnet and biotite is recognized but marks no abnormal development.

2.1.6. L-P High-Grade Metamorphism

This type is characterized by a number of continuous mineral reactions:

(4) musc + q $\rightarrow$ K-feldsp + sill + H_2O

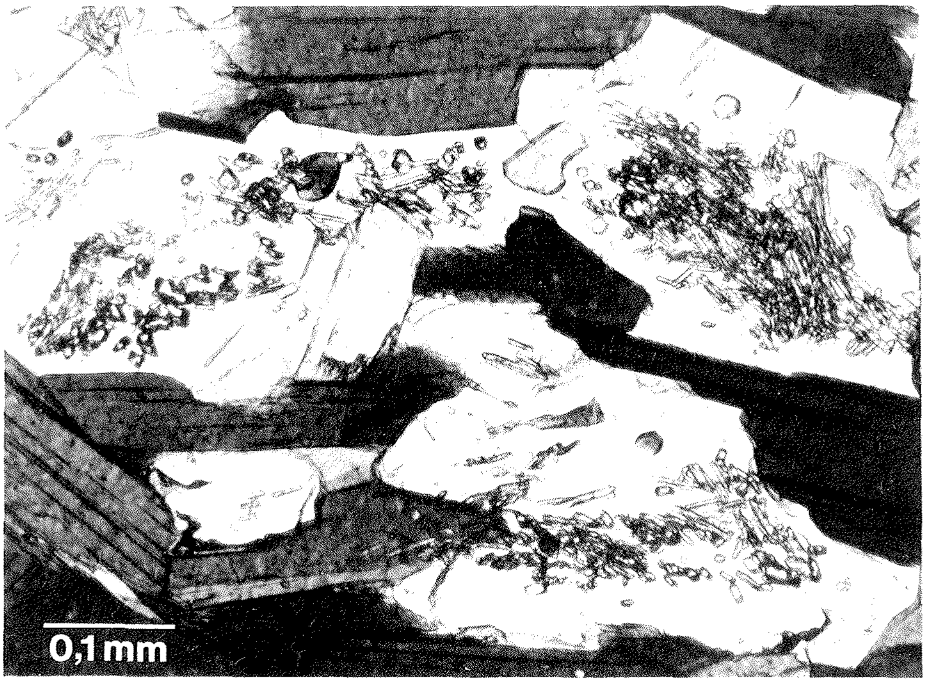

Fig. 2: Fotomicrograph of the cordierite-forming reaction in high-grade metapelitic rocks of the L-P belt of North Victoria Land: biotite + sillimanite + quartz → cordierite + K-feldspar + H_2O. Note the spatial seperation of sillimanite (thin needles) from biotite (grey with cleavage) by newly formed cordierite (colourless). Plain palarizers, sample WS 8193.

Abb. 2: Dünnschliffphoto der Cordierit-Bildungsreaktion in den hochgradigen Metapeliten innerhalb des Niedrig-Druck-Gürtels von Nord Victorialand: Biotit + Sillimanit + Quarz → Cordierit + Kalifeldspat + H_2O. Deutliche räumliche Trennung des Sillimanits (dünne Nadeln) von Biotit (grau mit Spaltrissen) durch neu gebildeten Cordierit (farblos). 1 Nicol, Probe WS 8193.

This reaction marks the 2nd sillimanite isograd and is documented in metapelitic compositions by the disappearence of muscovite and presence of newly formed K-feldspar. Aluminium silicate phase is fibrolite or prismatic sillimanite. The widespread intergrowth of biotite and sillimanite and absence of muscovite and staurolite could mark the growing of sillimanite according to

(5) musc + stau + q → bio + sill + alm.

As a number of relic minerals are still present the following cordierite-forming reaction in high-grade metapelitic rocks can be formulated:

(6) bio + sill + q → cord + K-feldsp + H_2O

Biotite and sillimanite are parted by the newly formed cordierite which displays cores filled with needles of sillimanite leaving a sillimanite free periphery (Fig. 2). Biotite and sillimanite are no more in mutual contact.

(7) bio + sill + q → ga + K-feldsp + H_2O

Indications for the development of this reactions to the right-hand side are relictic biotite crystals together with inclusions of sillimanite needles in garnet.

At the peak of the regional high-grade metamorphism the following discontinuous reactions are verified:

(8) bio + sill + q → cord + ga + K-feldsp + H_2O and

(9) bio + sill + q → cord + spi + K-feldsp + H_2O.

A combination of reaction (7), (8) and (9) has developed in rocks of suitable composition (e. g. in rocks of the Terra Nova Formation on Kay Island). The formation of coexisting cordierite and garnet is coupled with a striking shift of the X_{Mg} value of both Fe-Mg-minerals to higher Mg/Fe-rations (for detail see SCHUBERT & OLESCH in press).

2.1.7. Migmatites

Another example of metamorphic processes involving rock-forming activities can be studied in the migmatites of the L-P belt. Migmatitic phenomena can be observed in the gneiss-migmatite areas which are characterized by the close connection of high-grade sillimanite-cordierite gneiss and migmatite, often intermingled with each other. Further the migmatites are penetrated by lightcoloured igneous rocks. Gneiss-migmatite areas are found in the Daniels Range, at the western side of Campbell Glacier east of Mt. Queensland, and around Gondwana Station of Terra Nova Bay, the last one as a constituent of the Terra Nova formation (GANOVEX TEAM 1986).

As an example the migmatites of Thompson Spur, Daniels Range, were studied by ULITZKA (1985, 1986). Based on mineralogical and geochemical arguments ULITZKA (1985, 1986) could show two different processes are responsible for the development of the migmatitic phenomena of the crystalline basement of the L-P belt:

— Most of the large-scale migmatites were formed by supply of granitic and pegmatitic material. Thus they are migmatites only in a descriptive but not in a genetic sense.
— In-situ formation of migmatites with paired leucocratic and melanocratic layers and veins is responsible to a lesser degree for the genesis of the migmatites of the L-P belt.

According to ULITZKA (1985, 1986) deficiency of alkalies, especially of K in the most abundant graywacke protolith is responsible for the absence of rocks of typical eutectic or cotectic near-ternary rock composition.

As the "in-situ migmatites" with melanosomes up to 1 mm thick (consisting of biotite plus quartz, plagioclase, apatite) occur preferentially along foliation planes, it is suggested that participation of a fluid phase (H_2O plus B) causing lowering of the initial melting temperature has taken place.

The striking presence of tourmaline in the migmatitic areas indicates rock-forming mineral reactions involving high boron concentrations in the fluid phase. The B-rich volatiles are considered to escape either from the sedimentary country rock during progressive metamorphism or from late-magmatic activity of pegmatites in connection with the Granite Harbour Instrusive Complex. However, a combined source for boron can not be excluded.

The mineral chemistry and the zonation of the tourmaline allows to distinguish between metasomatically grown tourmaline and magmatic tourmaline formation (OLESCH & SCHUBERT in press).

2.2. *The Eastern Belt*

2.2.1. Field Situation

The crystalline outcrops of the eastern belt comprise the Lanterman Range, Salamander Range, Retreat Hills, and the large crystalline basement complex in the central part of the Mountaineer Range with

,,Dessent Formation'' and ,,Murchison Formation'' (KLEINSCHMIDT et al. 1984, ROLAND et al. 1984, GREW & SANDIFORD 1984, GREW et al. 1984).

2.2.2. Primary Rocks

The dominant pre-metamorphic rock series again are largely sedimentary sequences of probable Late Precambrian age (DOW & NEALL 1974, GREW & SANDIFORD 1982) i. e. graywackes, shales, claystones, sand- and siltstones. Moreover the eastern belt comprises a very variable lithology with conglomerates, quartzo-calcareous rocks, limestones, dolomitic marl and basic rocks, which were possibly sedimented in shallow water in a back-arc basin. Basic and ultrabasic intercalations within the metapelitic sequence are exposed at the eastern border of this belt.

2.2.3. Present Rocks and Mineral Assemblages

Most abundant rocks are made up of biotite gneiss and hornblende-biotite gneiss, calc-silicate gneisses, amphibolites, meta-ultramafic rocks, finally greenschists and related rocks. For a detailed petrography see KLEINSCHMIDT (1981), WODZICKI et al. (1982), KLEINSCHMIDT et al. (1984), ROLAND et al. (1984), GREW & SANDIFORD (1984), KLEINSCHMIDT et al. 1986.

The overall present minerals in schists and gneisses of pelitic composition are quartz, biotite, muscovite, two feldspars, almandine, staurolite and amphiboles. Accessories are tourmaline, apatite, zircon, allanite, corundum, rutile (GREW & SANDIFORD 1984). Aluminium silicates are relic kyanite and kyanite in quartz veins, fibrolite and sillimanite.

The mafic rocks comprise amphibolites, garnet amphibolites with cummingtonite, anthophyllite and common hornblende. The ultramafic rocks of the eastern belt contain olivine, pyroxenes, pyrop, spinel, anthophyllite, cummingtonite, hornblende, tremolite, staurolite, talc, serpentine minerals, phlogopite, Mg-chlorite, magnesite, and calcite.

2.2.4. Metamorphic Processes in the Eastern Belt

The metasedimentary sequence of the eastern belt is characterized by the absence of cordierite and andalusite and by presence of staurolite in pelitic as well as relics of staurolite in mafic and ultramafic rocks. Moreover by the important kyanite to sillimanite (fibrolite) transitions and by presence of relictic kyanite and beside that, kyanite in quartz veins (GREW et al. 1984, ROLAND et al. 1984, KLEINSCHMIDT et al. 1984).

GREW & SANDIFORD (1984) report a tourmaline-armoured stable mineral assemblage of talc-staurolite-corundum-chlorite-kyanite which, by microprobe analyses and Schreinemaker's treatment indicates an early higher pressure stage in the metamorphic cycle. This early higher pressure regime also can be seen in basic hornblende felses which still present relictic corona structures. The coronas are built up by newly formed pargasitic tschermakite with strong zonation and Na-Al-enrichment in the core plus spinel plus corundum. The mineral reaction

(10) tscherm + spi + cor $\leftarrow$ ga + Al-cpx + H_2O

and the zoned composition of the amphiboles was interpreted by KLEINSCHMIDT et al. (1986) indicating former granulite facies metamorphism. Also an eclogitic primary rock should be envisaged according to the retrograde reaction in kyanite-eclogites

(11) spi + cor $\pm$ plag $\leftarrow$ ky + Ca + Na + Fe + Mg (from omphacite)

as described by KLEIN & WIMMENAUER (1984) from kyanite-bearing eclogitogenic rocks in the pre-Variscan basement of the Schwarzwald, Germany.

Intercalations of meta-ultramafic lenses at the eastern border of the eastern belt are olivine-tremolite fels, anthophyllite fels, talc-magnesite fels, serpentinite. The ultramafic bodies still bear relictic cores of the primary mineral assemblage, which shows their membership especially to former hornblende-olivine-garnet pyroxenite and spinel-olivine pyroxenite. A number of metamorphic processes can be studied which comprise formation of anthophyllite, chlorite, talc on the one hand and forsterite, tremolite, and talc on the other during the main regional metamorphic event of the Ross orogeny:

(12) Mg-chl $\leftarrow$ fo + en + spi + H_20

(13) talc + chl $\leftarrow$ en + spi + H_20

(14) antho $\leftarrow$ talc + en

(15) edenitic hbl + fo $\leftarrow$ Na-Al-cpx + opx + H_20

(16) trem + chl $\leftarrow$ opx + ol + tscherm

(17) serp + dio $\rightarrow$ fo + trem + H_20

(18) serp $\rightarrow$ fo + talc + H_20

For detailed treatment of the above cited mineral reactions and their petrological background comp. KLEINSCHMIDT et al. (1986).

KLEINSCHMIDT et al. (1986) showed that the mafic-ultramafic associations of the eastern belt were metamorphosed under amphibolite facies metamorphic conditions. But in both, metapelitic and meta-ultramafic rocks relictic parts are preserved, indicating a former higher pressure regime followed by a nearly isothermal decrease at least for the kyanite-bearing parts.

Thus a general interpretation as a medium-pressure belt is possible. Late stage retrograde uplift is documented by the replacement of staurolite by secondary muscovite, clinozoisite, pumpellyite, and margarite. The model reaction is given by GREW & SANDIFORD (1984) as

(19) pumpellyite $\leftarrow$ clinozoisite + grossular + chl + q + H_20

3. METAMORPHIC HISTORY AND P-T LOOPS

In the western L-P belt progressive metamorphic conditions were recognized. Application of geothermometric and geobarometric calculations gave the following P-T estimates.

The northern gneisses of Kavrayskiy Hills: 600—650° C/4.5—5 kb (SCHUBERT et al. 1984); the central gneisses especially the migmatites of Thompson Spur: 650—700° C/ 3.8 ± 0.5 kb (ULITZKA 1986); the southern gneisses of the Terra Nova formation: 600—650° C/ 5 kb, rising up to 6 kb at Kay Island off the Tinker Glacier (SCHUBERT & OLESCH 1986).

The petrogenetic prograde path documented by the andalusite-sillimanite transitions and the final metamorphic equilibration are indicated in Fig. 3 (broken arrow ending in field 3).

In the eastern M-P belt a quantitative estimation of the metamorphic conditions is more complex: an early stage in the metamorphic cycle with conditions of 650—750° C/7—10 kb P H_20 was evaluated by

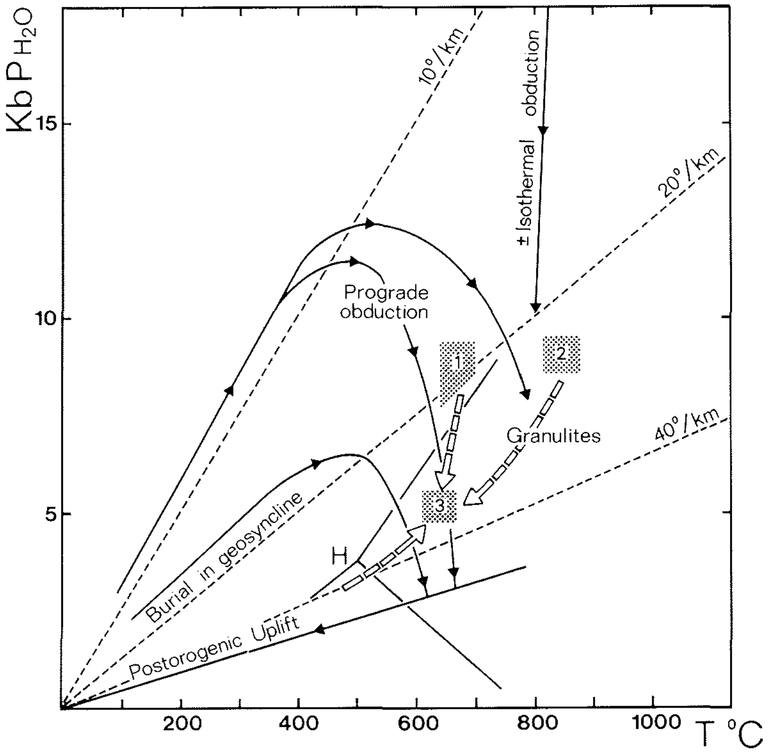

Fig. 3: Schematic diagram after SCHREYER (1985) illustrating possible and hypothetical paths of rock metamorphism during various geodynamic events. Boxes 1 and 2 are conditions for relic mineral assemblages in the M-P belt, box 3 gives conditions of main metamorphic equilibration. Broken arrows mark paths followed by rocks for the western L-P belt and the eastern M-P belt, see text for discussion. Aluminium silicate phase diagram after HOLDAWAY (1971) is indicated as H.

Abb. 3: Schematische P-T-Diagramm nach SCHREYER (1985), welches die möglichen und hypothetischen Metamorphosepfade während verschiedener geodynamischer Prozesse erläutert. Die Felder 1 und 2 stellen P-T-Bedingungen der reliktischen Mineralparagenesen im Mittel-Druck-Gürtel dar, Feld 3 gibt die P-T-Bedingungen der Hauptmetamorphose an. Die unterbrochenen Pfeile kennzeichnen die Entwicklungspfade für die Metamorphite des westlichen Niedrig-Druck-Gürtels und des östlichen Mittel-Druck-Gürtels, siehe Diskussion im Text. H kennzeichnet das Aluminiumsilikat-Phasendiagramm nach HOLDAWAY (1971).

GREW & SANDIFORD (1984). These P-T conditions are indicated in Fig. 3 as field 1. The transition from the early to the middle stage represents a roughly isothermal decrease in pressure marked by GREW & SANDIFORD (1984: Fig. 2). This decrease is indicated by a broken arrow from field 1 to field 3 in Fig. 3.

The P-T conditions for the main regional metamorphic event were evaluated by a number of authors to be within the range of 600—650 °C and 5—6 kb (WODZICKI et al. 1982, GREW & SANDIFORD 1984, ROLAND et al. 1984, KLEINSCHMIDT et al. 1984, KLEINSCHMIDT et al. 1986). These P-T conditiones are analogous to the generalized situation marked as field 3 in Fig. 3.

The study of the ultramafic bodies within the eastern Lanterman Range gneisses gave hints for relic primary high-pressure / high-temperature conditions close to those of the granulite facies of ~ 800 °C/> 10 kb, according to KLEINSCHMIDT et al. (1986). Incorporation of the ultramafic masses into the continental M-P belt resulted in a gradual alignment of the higher P-T range into the regional metamorphic M-P conditions (arrow form field 2 to field 3 in Fig. 3). It should be pointed out that both the former metapelitic and the former ultramafic associations meet at the same P-T range (field 3 in Fig. 3).

SCHREYER (1985: Fig. 20) illustrated schematically the P-T-t paths of rocks which were subjected to various geodynamic events such as subduction, obduction, geosynclinal burial, and uplift. In Fig. 3 the development of the loops in the P-T field for various crystalline basement series of North Victoria Land are given. On the basis of the above considerations it can be seen that metamorphism of the eastern L-P belt is characterized by a smooth but steady increase from medium- to high-grade metamorphic conditions. Contrary to this, the development of the M-P belt is characterized by a polymetamorphic history. It starts from a higher pressure regime for the metasedimentary series (or relics of reaction skarns between metasedimentary country rock and ultramafic rock acc. to GREW & SANDIFORD 1984), this is plotted as position 1 in Fig. 3. It indicates a "prograde obduction" process after SCHREYER (1985).

The P-T starting point of the ultramafic original material (position 2 in Fig. 3) also starts from the higher pressure regime and plots near the end of the "isothermal obduction" path of SCHREYER (1985), it ends in the P-T behaviour of rocks undergoing regional metamorphism.

4. REGIONAL IMPLICATIONS

The P-T loops in Fig. 3 suggest that complex geodynamic processes are responsible for the present field situation of the L-P belt and the M-P belt of North Victoria Land. Obviously a continental or continental shelf depositional process with steady increasing burial depth is repsonsible for the development of the western L-P belt. This is consistent with the structural interpretations of KLEINSCHMIDT & SKINNER (1981), which demand a simple metamorphic history including one orogenetic phase with changing stress field. The process of obduction (prograde obduction and isothermal obduction) can be deduced for the eastern M-P belt from representing P-T fields 1 and 2 in Fig. 3. Obduction presumes subduction prior to the beginning of the main metamorphic Ross event. As envisaged by KLEINSCHMIDT et al. (1986) the REE patterns of the mafic-ultramafic associations of the Lanterman Range do not exclude a former upper mantle or oceanic origin. Hence a process of collision of continental lithosphere and oceanic lithosphere with subduction/obduction or upthrusting is responsible for the present situation of the M-P belt.

Corresponding geodynamic considerations are discussed by GIBSON (1985) and KLEINSCHMIDT & TESSENSOHN (1987).

The resulting P/T ratio for the main Ross metamorphic episode of the Transantarctic Mountains in North Victoria Land yields a geothermal gradient of 33 °/km.

5. ACKNOWLEDGEMENTS

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