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# Regional metamorphism and P-T evolution of the Ross Orogen in northern Victoria Land (Antarctica): a review

FRANCO M. TALARICO[1]*, ROSARIA PALMERI[2] and CARLO ALBERTO RICCI[1,2]

[1] Dipartimento di Scienze della Terra, Università di Siena, via Laterina 8, 53100 Siena, Italy
[2] Museo Nazionale dell'Antartide, Sezione Scienze della Terra, Università di Siena, via Laterina 8, 53100 Siena, Italy

ABSTRACT. — The main focus of this paper is on the petrological evolution of medium- to high-grade metamorphic units in the Wilson Terrane, the westernmost lithotectonic unit of the Ross Orogen in northern Victoria Land. The petrological data set is reviewed for all areas where P-T-t paths have been reconstructed and geochronological data are sufficiently complete to provide an overview of the regional metamorphic evolution of a *ca.* 600 km long segment of the Ross Orogen, from its termination along the Pacific coast to the Eisenhower Range near the Ross Sea coast.

Petrological evidence reveals that different lithological units of the Wilson Terrane equate with distinct lithotectonic metamorphic complexes with partly independent P-T-t histories. In spite of the wide range of estimated peak metamorphic conditions, and variability in both shape of the P-T path (clockwise or counter-clockwise) and type of retrograde evolution (isobaric cooling or cooling/unloading), the reviewed P-T-t trajectories consistently support a setting of evolving subduction and accretion in the context of a Palaeozoic cordilleran-type active margin.

RIASSUNTO. — In questo lavoro vengono sinteticamente esposti i dati petrologici e geocronologici delle principali unità metamorfiche di medio ed alto grado del Wilson Terrane, l'unità litotettonica occidentale dell'Orogene di Ross nella Terra Vittoria settentrionale. Nonostante l'ampio intervallo delle condizioni di picco metamorfico e le variabili traiettorie P-T-t, diverse in termini sia di percorso (orario o antiorario) che di tipo di evoluzione retrograda (raffreddamento isobarico o raffreddamento con concomitatnte decompressione), l'evoluzione metamorfica di tutti i complessi metamorfici risulta consistente con un quadro geodinamico caratterizzato da processi di subduzione e accrezione, avvenuti nel Paleozoico, in un contesto geotettonico di margine attivo di tipo cordigliera.

* Corresponding author, E-mail: talarico@unisi.it

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## INTRODUCTION

The Antarctic plate is notable for being encircled by divergent plate boundaries, a unique situation in today's global tectonic framework (LeMasurier and Landis, 1996). However, the palaeo-pacific margin of Antarctica in Gondwanaland hosted a long-standing convergent margin from

Neoproterozoic through Palaeozoic time (e.g. Ross Orogen; Stump, 1995 and references therein), with portions of the margin active during Mesozoic and Cenozoic time (Bradshaw *et al.*, 1997; Storey, 1991) (Fig. 1). In the Ross orogenic belt of northern Victoria Land (NVL), orthogonal convergence (Goodge and Dallmeyer, 1996) led to the formation and emplacement of eclogite lenses (Ricci *et al.*, 1997; Palmeri *et al.*, 2003), major plutonism in the time range *ca.* 530 to 485 Ma (Rocchi *et al.*, 1998) and accretion of two major allochtonous terranes (Bradshaw *et al.*, 1985) (Fig. 1).

In NVL (Fig. 1) the Ross Orogen consists of three contrasting tectonometamorphic terranes (Bradshaw and Laird, 1983) including from NE to SW:

– the Robertson Bay Terrane, made up of a thick flysch-type sequence of Cambrian-lower Ordovician age;

– the Bowers Terrane, a Cambrian primitive IA-type volcanic arc and its sedimentary cover;

– the Wilson Terrane (WT), generally considered the palaeo-pacific margin of the East Antarctic craton in the region and comprised of low- to high-grade metamorphic

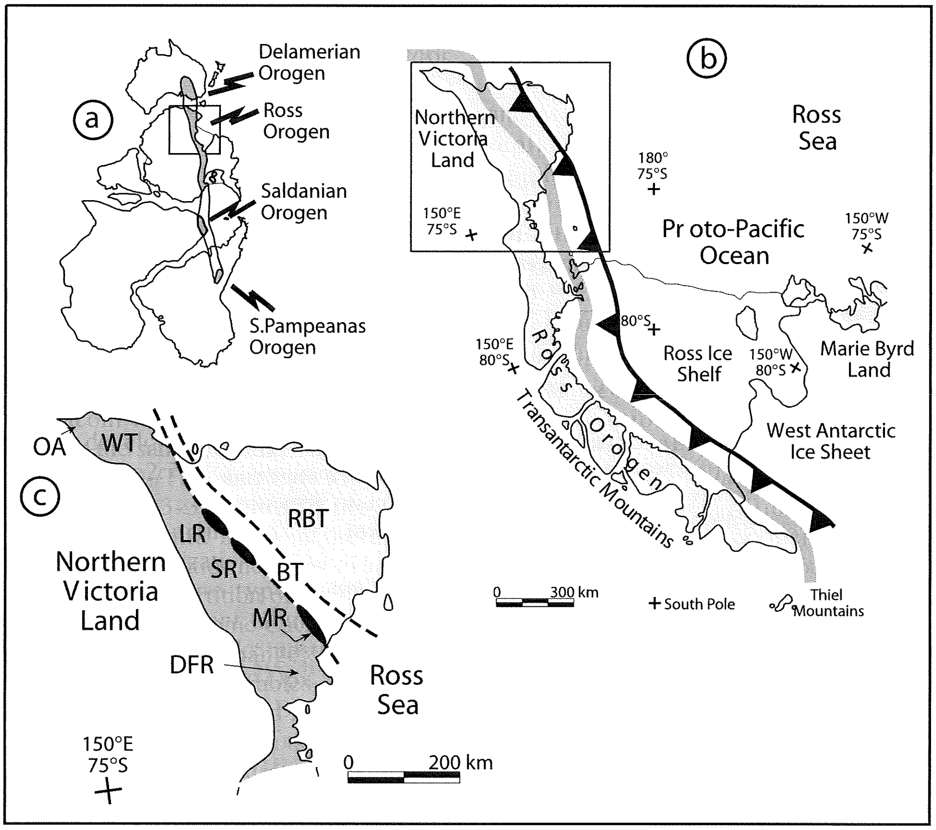


Fig. 1 – a) The early Palaeozoic orogens along the Pacific margin of Gondwanaland. b) The Ross Orogen in Antarctica. c) Tectonic sketch of northern Victoria Land; WT = Wilson Terrane; BT = Bowers Terrane; RBT = Robertson Bay Terrane. OA = Oates Land; DFR = Deep Freeze Range (both regions within the low-pressure metamorphic belt of the WT). LR = Lanterman Range; SR = Salamander Range; MR = Mountaineer Range (the main exposures of the intermediate-high pressure belt of the WT) (modified from Ricci *et al.*, 2000).

rocks extensively intruded by the Cambro-Ordovician Granite Harbour Intrusive Complex, an orogenic association of magmatic arc affinity (Vetter and Tessensohn, 1987; Ghezzo *et al.*, 1989).

During the Ross Orogeny, both Bowers and Robertson Bay rocks experienced a very low- to low-grade metamorphic imprint. In contrast, two main metamorphic belts of contrasting pressure types are recognized in the medium- to high-grade rocks of the WT (Grew *et al.*, 1984). A *ca.* 5 to 25 km wide intermediate-high pressure belt occurs parallel to the boundary with Bowers Terrane, and a much wider (*ca.* 150-200 km) low-pressure belt is exposed to the west of Rennick and Aviator Glaciers. In its southernmost part the low-pressure belt locally (i.e. Deep Freeze Range) contains km-sized structural inliers of medium-P granulites. A presumably polymetamorphic evolution, including a pre-Ross Proterozoic medium-pressure granulite-facies metamorphism, has been proposed for these rocks (Lombardo *et al.*, 1989; Talarico and Castelli, 1995; Talarico *et al.*, 1995); the pre-Ross metamorphic history of these rocks is documented by SHRIMP data on felsic granulites (Fanning, *personal communication*) and, consequently, they are not further discussed in this paper, which focuses on Ross metamorphism.

## Overview of P-T conditions and P-T-t paths in the Wilson Terrane

The reconstruction of metamorphic P-T-t paths (i.e. Spear and Selverstone, 1983) and the thermomechanical modelling of orogenic processes (i.e. England and Thomson, 1984; Thompson and Ridley, 1987) provide a fundamental theoretical framework which has been extensively used to reconstruct the major stages of tectonothermal evolution of orogenic belts. In this section the petrological and geochronological data sets of the medium- to high-grade units of the WT (Fig. 2 and 3) are described for four main regions where detailed petrological data (including P-T-t paths) are available.

**Oates Land** – The northern end of the low-pressure metamorphic belt is exposed in Oates Land, at the Pacific termination of the Transantarctic Mountains (Fig. 1 and 2). Here the high-grade basement rocks were detached and thrust onto low-grade metasedimentary rocks (Berg Group, McCain Bluff metasediments). This structure was first reported by Flöttmann and Kleinschmidt (1991) and described as a «pop-up» with bivergent thrusting of a central high-grade basement over foreland basin sediments (Flöttmann and Kleinschmidt, 1991, 1993). Within the high-grade basement, thrust tectonics also led to the juxtaposition of three roughly north-south trending zones with different metamorphic grades: a western, central and eastern zone (Schüssler *et al.*, 1999).

Detailed petrological investigations (Schüssler *et al.*, 1999; 2003) show that metamorphic rocks of the central zone formed during one single, clockwise P-T cycle including a medium-pressure and high-temperature granulite-facies stage at *ca.* 0.8 GPa and >800°C (M1), followed by isothermal decompression to low-pressure granulite-facies to upper-amphibolite-facies conditions (M2) and by a final stage with retrograde formation of biotite + muscovite gneisses (Fig. 2). In the eastern and western zones metamorphic rocks experienced metamorphism at lower P-T conditions of about 0.4-0.55 GPa and 700-800°C following a clockwise path (Fig. 2).

In the central zone M2 has been dated *ca.* 494 - 484 Ma (U-Pb on monazite) (Schüssler *et al.*, 1999). New SHRIMP data on monazite (Henjes-Kunst, 2003) (500±5 Ma, 496±4 Ma) support a slightly higher age for the metamorphic peak of the central zone. Cooling ages of the central zone from high-grade conditions yield values between 476 and 470 Ma (Schüssler *et al.*, 1999) (Rb-Sr, K-Ar, and Ar-Ar on micas). Further $^{40}Ar$-$^{39}Ar$ dating of amphiboles and micas indicates a general trend

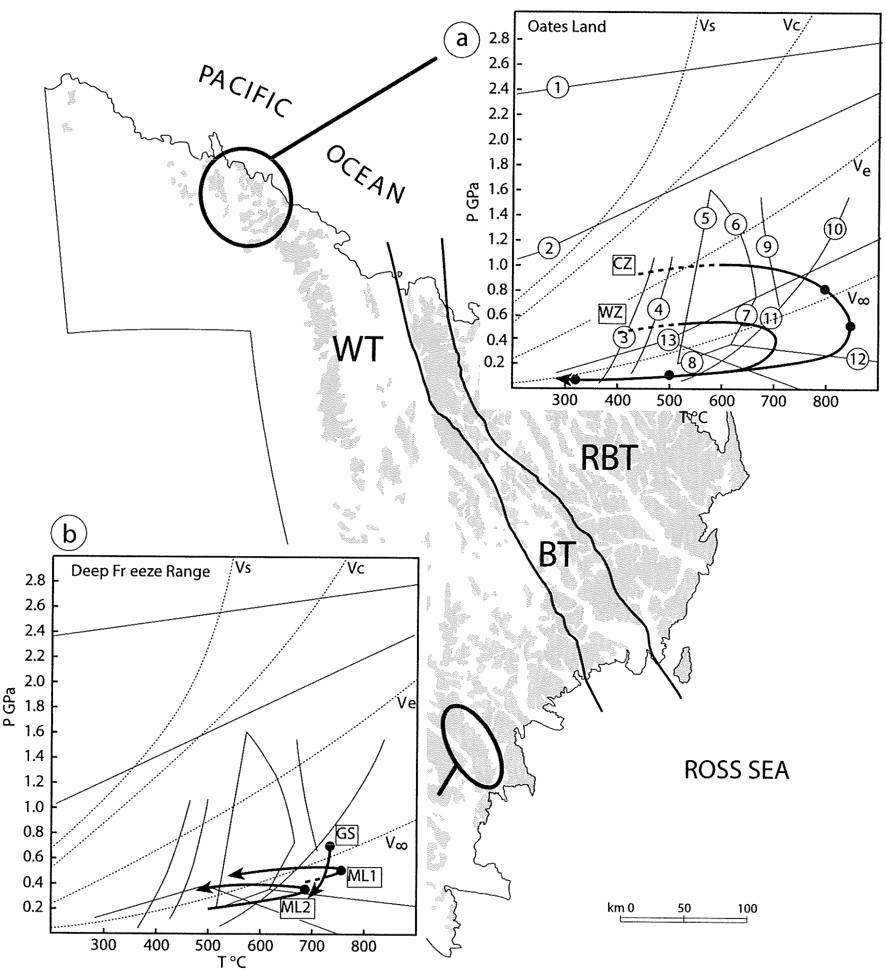


Fig. 2 – Pressure-Temperature-time paths (solid curves with arrows) experienced by various rock units of the low-pressure metamorphic belt in the Wilson Terrane (WT) in NVL. BT = Bowers Terrane; RBT = Robertson Bay Terrane.
Reaction curves, labelled with numbers in inset (a), include: (1): Coesite = Quartz (Bohlen and Boettcher, 1982); (2): Jadeite + Quartz = Albite (Holland, 1983); (3): Biotite-in; (4): Garnet-in; (5): Chloritoid + $Al_2SiO_5$ = Staurolite + Quartz + $H_2O$; (6): Fe-Staurolite + Quartz = Almandine + Kyanite + $H_2O$; (7): Fe-Staurolite + Quartz = Almandine + Sillimanite + $H_2O$; (8): Staurolite + Quartz = Cordierite + $Al_2SiO_5$ + $H_2O$; (9): Muscovite + K-feldspar + Quartz + $H_2O$ = Melt; (10): Muscovite + Quartz = K-feldspar + $Al_2SiO_5$ + Melt; (11): Muscovite + Quartz = K-feldspar + $Al_2SiO_5$ + $H_2O$; (12) Almandine + Sillimanite + Quartz = Fe-Cordierite; (13) $Al_2SiO_5$ polymorphs triple point. Reaction curves (3) to (13) are taken from a petrogenetic grid for the metamorphism of pelitic rocks (simplified from Yardley, 1989).
Four reference geotherms, $V_s$, $V_c$, $V_e$ and $V_\infty$ (Thompson and England, 1984) are also shown as dashed lines. $V_s$ = perturbed geotherm due to underthrusting of lithosphere into the mantle; $V_c$ = perturbed geotherm of thickened crust through crustal collision; $V_e$ = stable geotherm of imperturbed crust; $V_\infty$ = maximally relaxed geotherm for a reasonable post-thickening heat-supply.
a) Oates Land region. CZ = P-T path of the very-high-grade Central Zone; WZ = P-T path of the high-grade Western Zone. Dots are petrological records of main metamophic stages M1 and M3 as discussed in the text.
b) Deep Freeze Range region. GS = Ø P-T path recorded in migmatites from Gondwana Station; ML1 and ML2 = P-T paths recorded in medium- and high-grade metasediments from the Mt. Levick area.

to younger ages of the basement complex from west to east, i.e. from 488-486 Ma to 472-469 Ma for amphiboles and from 484-482 Ma to 466 Ma for micas (Schüssler *et al.*, 2003). This is explained by temporal differences in the retrograde metamorphic evolution of the three zones in the course of the late-Ross-orogenic thrust-related uplift of the basement complex (Schüssler *et al.*, 2003).

**Deep Freeze Range** – The low-pressure character of metamorphism in the SW portion of the WT is well documented by the regional occurrence of cordierite and of the andalusite-sillimanite transition in metapelites (Grew *et al.*, 1984; Schubert and Olesch, 1989; Talarico *et al.*, 1992). In the region between David and Aviator Glaciers, mapping of critical mineral assemblages in metapelite and calc-silicate rocks has outlined a complex metamorphic zonation ranging from lower greenschist facies to upper amphibolite facies and anatexis (Talarico *et al.*, 1992). Phase relations and thermobarometric estimates (Palmeri *et al.*, 1991, 1994) indicate P-T metamorphic conditions ranging from *ca.* 0.2 GPa at 350-400 °C in the lowest grade zone to 0.45 GPa at 700-750°C in the highest grade zone. A counterclockwise P-T path has been reconstructed by Palmeri *et al.* (1994) for medium- to high-grade metapelites outcropping in the Mt. Levick area (Deep Freeze Range) (Fig. 2). A similar path has been proposed by Borghi and Lombardo (1994) for migmatitic gneisses exposed along the coast of Gerlach Inlet. A near-isobaric cooling path was also documented on the basis of a fluid inclusion investigation in medium-grade (diopside zone) marbles from the Eisenhower Range (O'Kane Glacier area) (Giorgetti *et al.*, 1997).

Although counterclockwise paths can be potentially recorded in most low- to medium/high-grade metasediments in the low-pressure belt, clockwise paths including an earlier decompressional segment from medium-pressure (0.6-0.7 GPa) were also documented in some of the highest grade rock units (sillimanite-garnet-cordierite migmatites) from the southwestern WT (Lombardo *et al.*, 1989; Gerlache Inlet, Palmeri, 1997; Black Ridge, Palmeri and Talarico, 1990) (Fig. 2). As discussed by Palmeri (1997) contrasting P-T paths (counterclockwise and decompressive) can be interpreted as P-T trajectories of different crustal levels in the same tectonic setting and related to a single orogenic cycle. In this hypothesis, medium-P migmatites represent a deeper crustal level, later uplifted possibly through melting-enhanced and/or pure shear deformation.

Monazite, zircon, and titanite from migmatites of the Deep Freeze Range yielded concordant or nearly concordant U-Pb ages of 490-480 Ma (Klee *et al.*, 1990; Klee, 1995). A six-point zircon discordia defines a lower intercept age of 488±9 Ma (and an upper intercept providing evidence for crustal components of Palaeoproterozoic age) for one sample of migmatite from Gondwana Station (Klee, 1995). The 490-480 Ma age interval closely matches that identified by Ar-Ar laserprobe data on micas from medium-grade metapelites (andalusite and sillimanite-muscovite zones) west of Priestley Glacier (Calonaci *et al.*, 2002). K-Ar and Ar-Ar biotite data from several samples in the region (Vita *et al.*, 1991) show a larger scatter in the range between *ca.* 480 and 440 Ma. As for data reported by Schüssler *et al.* (2003) in Oates Land, a cooling history characterized by a general trend to younger ages from west (Eisenhower Range) to east (Deep Freeze Range) can be envisaged.

**Lanterman Range** – In the Lanterman Range, Talarico *et al.* (1998) recognised three different lithotectonic units, with NNW-SSE structural trends, which from west to east include: the Edixon Metamorphic Complex (EMC), the Bernstein Metamorphic Complex (BMC) and the Gateway Hills Metamorphic Complex (GHMC).

The main EMC rock-types include micaschists and gneisses carrying bands and pods of Ca silicate-bearing plagiogneisses and quartzites, and they preserve a broad

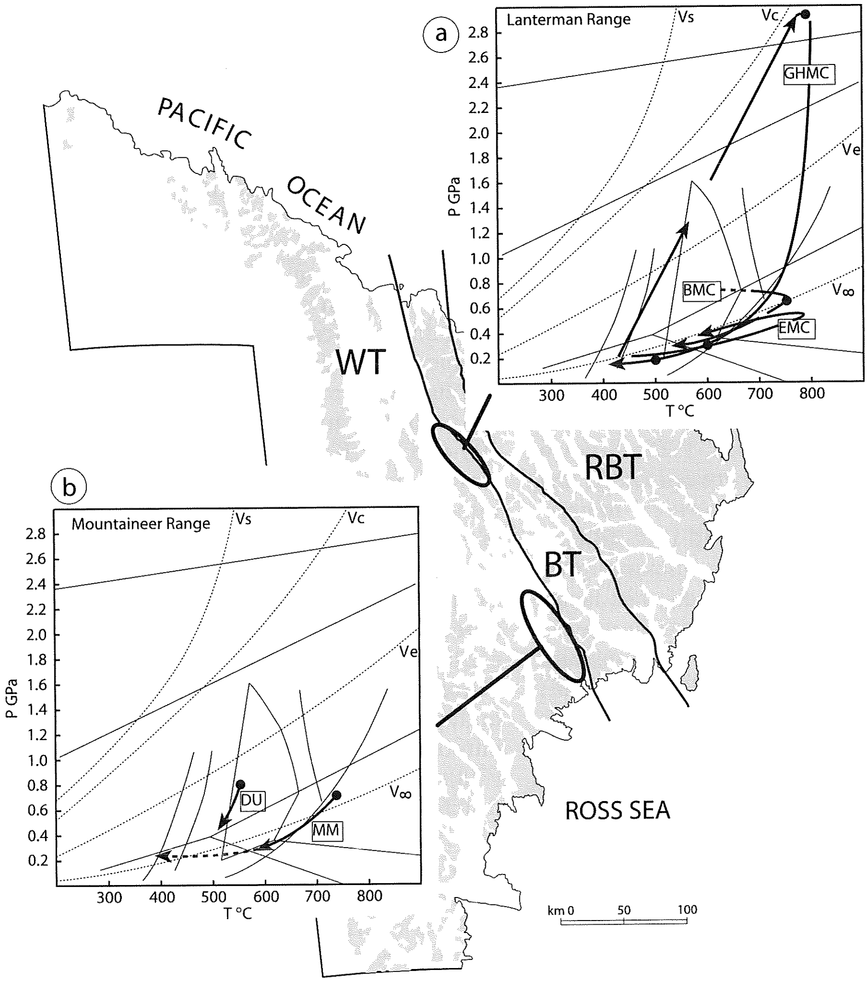


Fig. 3 – Pressure-Temperature-time paths (solid curves with arrows) experienced by various rock units of the intermediate-pressure metamorphic belt in the Wilson Terrane (WT) in NVL. BT = Bowers Terrane; RBT = Robertson Bay Terrane. Reaction curves and reference geotherms as in Fig. 2.
a) Lanterman Range. GHMC = P-T path recorded in the Gateway Hills Metamorphic Complex; BMC = P-T path of the Bernstein Metamorphic Complex; EMC = P-T path reconstructed in the Edixon Metamorphic Complex.
b) Mountaineer Range region. DU = P-T path recorded in Dessent Unit; MM = P-T path reconstructed in migmatites from the Mt. Murchison area.

metamorphic zonation from medium- to high-grade (up to the garnet-cordierite-K-feldspar facies with anatexis) with a low-pressure prograde metamorphic regime. A counterclockwise P-T path similar to those reconstructed in the Mt. Levick area has been hypothesized (Ghiribelli, 2000) (Fig. 3).

The BMC, a *ca.* 1 to 5 km-wide belt exposed from the Mt. Moody area to Zenith Glacier (Talarico *et al.*, 1998, Fig. 1), is made up of kyanite/sillimanite, garnet-bearing micaschists, plagiogneisses, hornblende-biotite orthogneisses, and migmatites. In samples from the Mt. Bernstein area Grew and Sandiford

(1984) calculated P-T conditions of *ca.* 700°C at 0.8 GPa for an early stage, followed by an intermediate overprint at 650-700°C and 0.55-0.64 GPa, and a final greenschist stage at 300-370°C and 0.3-0.5 GPa. The same peak conditions were also reported by Roland *et al.* (1984). The reconstructed P-T path is a clockwise decompressional trajectory (Ghiribelli, 2000) (Fig. 3).

The GHMC forms a thin, discontinuous belt at the contact with the Bowers Terrane and is characterised by abundant lenses and pods (centimetric to metric) of mafic and ultramafic rocks, locally with well-preserved eclogite facies assemblages, enclosed within a metasedimentary sequence represented by two-mica garnet gneisses and minor quartzites (Capponi *et al.*, 1997; Talarico *et al.*, 1998).

Petrological investigations also indicate that both eclogites and their country gneisses underwent a common metamorphic evolution including a prograde amphibolite facies stage (documented only in felsic rocks), UHP metamorphism, and retrogression under upper to lower amphibolite facies conditions (Palmeri *et al.*, 2003). Three main metamorphic stages are recorded in the mafic eclogites from the GHMC (Di Vincenzo *et al.*, 1997) (Fig. 3): (1) an eclogite facies stage at temperatures of up to *ca.* 850°C and a minimum pressure of 2.6 GPa, as suggested by the occurrence of coesite relics (Ghiribelli *et al.*, 2001) as well as geotermobarometry in orthopyroxene-garnet-olivine-clinopyroxene ultramafic rocks (Talarico *et al.*, 1999; Ghiribelli, 2000); (2) a medium-pressure amphibolite facies stage, with temperatures ranging from 630-750°C and pressures of 0.7-1.0 GPa; (3) a low-pressure amphibolite facies stage with temperatures ranging from 500-650°C and pressures of 0.3-0.5 GPa.

Ages of 500±5 Ma and 492±3 Ma derived from Sm-Nd mineral-whole rock isochrons of the eclogitic assemblage, $^{40}Ar$-$^{39}Ar$ ages of *ca.* 500 Ma for phengites (Di Vincenzo *et al.*, 2001) and U-Pb rutile ages of 495±6 and 503±6 Ma for the same samples (Di Vincenzo *et al.*, 1997) are interpreted as the time of the eclogite facies stage and subsequent *quasi*-isothermal decompression. $^{40}Ar$-$^{39}Ar$ laserprobe investigations on different types of amphibole in retrogressed eclogites indicate an age of 497.8 ± 2.3 Ma for the medium-pressure amphibolite stage, and an age of 489.7 ± 3.4 Ma for the low-pressure amphibolite stage (Di Vincenzo and Palmeri, 2001).

These data translate into an average exhumation rate of 3-4 km/Ma (Di Vincenzo and Palmeri, 2001). During exhumation from the medium-pressure amphibolite stage, white micas re-equilibrated at progressively lower pressures. For most white mica grains, reactivity ceased from 482-478 Ma (Di Vincenzo *et al.*, 2001). This interval coincides with most biotite and white mica ages from the BMC and EMC and may represent late re-equilibration under greenschist conditions, and it may be considered the minimum age for amalgamation of the three metamorphic complexes at the Lanterman Range.

**Mountaineer Range** – Geology and petrology of metamorphic rocks from the area between Evans Nèvè and the Ross Sea Coast (GANOVEX-ItaliAntartide, 1991; Capponi *et al.*, 2003; Castelli *et al.*, 2003) indicated the occurrence of an inter-terrane unit, the Dessent Unit, forming a thin tectonic slice along the contact between the overlying WT and the underlying Bowers Terrane. The Dessent Unit differs from the adjacent rock units of WT in the Mountaineer Range either lithologically or from the petrological point of view. The Dessent Unit mainly consists of garnet-bearing amphibolites (derived from either volcanic-sedimentary protoliths or igneous precursors) and minor metapelites and marbles. The peak metamorphic conditions of Dessent Unit have been constrained in the range 0.6-0.8 GPa at 500-600°C (Kleinschmidt *et al.*, 1984; Capponi *et al.*, 1990) and the retrograde evolution corresponds to a slightly T-decreasing decompressional path (Castelli *et al.*, 1994; Scambelluri *et al.*, 2003) (Fig. 3). On the other hand, the easternmost WT in the area between Retreat Hills and the Ross Sea coast consists of a metasedimentary sequence made up of pelitic and minor carbonatic protoliths. The metamorphic grade increases from N to S, namely from the low/medium-grade boundary at Retreat Hills to high-grade and anatexis at Mt. Murchison. The reconstructed P-T-(t) path for migmatitic gneiss from Mt. Murchison (Castelli *et al.*, 1994) is clockwise and is characterised by peak conditions at 700-750°C and 0.6-0.7 GPa, subsequently followed by a cooling-unloading retrograde evolution (Fig. 3).

The geochronological dataset on metamorphic rocks from this region only includes K-Ar and Ar-Ar cooling ages of biotite, which give an average age of 477 Ma, considered as the age of post-metamorphic cooling and uplift of both the WT and the Dessent Unit (Vita-Scaillet *et al.*, 1994). Synkinematic tonalite to granodiorite intrusions, forming a 200 km long linear belt along the contact between WT and Bowers Terrane (Lanterman-Murchison Fault) (Musumeci, 1999) provide a Rb-Sr biotite-whole rock isochron (505±6 Ma), which gives a lower limit to the development of magmatic and high-temperature solid-state foliation in the intrusive rocks, and consequently also of the metamorphic fabrics in the medium- to high-grade metamorphic country rocks of the WT in the Mountaineer Range area.

## Discussion and Conclusions

1) Petrological evidence shows that different lithological units of the WT equate with distinct lithotectonic metamorphic complexes with partly independent P-T-t histories. The reviewed P-T-t trajectories, both between and within each of the two metamorphic belts of the WT, show a wide range of estimated peak metamorphic conditions, and variability in both shape of the P-T path (clockwise or counter-clockwise) and type of retrograde evolution (isobaric cooling or cooling/unloading).

2) In the low-pressure metamorphic belt, the shapes of the P-T-t trajectories in conjuction with the abundance of syn-metamorphic intrusions in the medium- to high-grade zones were used as key arguments to infer a moderate thickening - magmatic accretion tectonic model (Palmeri *et al.*, 1994; Palmeri, 1997) as the most likely geotectonic setting for the onset of the low-P/high-T metamorphism in the Terra Nova Bay-Deep Freeze Range area. This model may be extended to the whole WT west of the Rennick and Aviator Glaciers, in so far as both lithological features (including the abundance of Cambrian granitoids) and low-pressure metamorphic zones recognized in the southwestern WT appear to be potentially extended to the north, from the Helliwell Hills, through the Daniels Range, to the Wilson Hills in Oates Land.

3) A significant feature of the medium-high pressure belt is that in all P-T paths the initial retrograde trajectory (in the T interval = 800-500°C) spans between a slightly T-decreasing decompression (i.e. GHMC's initial retrograde path) to cooling-unloading throughout all the P range typical of a middle-crustal domain (i.e. Dessent Unit, Mountaineer Range; BMC). On the basis of thermal modelling of orogenic processes (Thompson and England, 1984; Thompson *et al.*, 1997), this type of retrograde evolution is compatible with relatively fast exhumation rates, (such as those estimated in the GHMC in the Lanterman Range: Di Vincenzo and Palmeri, 2001), possibly reflecting the post-thickening evolution of an orogenic belt characterised by a small initial width (<200 km) and by relatively high values for the angle of obliquity (Thompson *et al.*, 1997). There is therefore a petrological argument favouring a near-orthogonal convergence as the most likely kinematic regime during at least the initial stage of the post-thickening thermo-tectonic evolution.

4) The overall major petrological and geological features of the Ross Orogen in NVL, as summarised and interpreted by Ricci *et al.* (1997), are consistent with a setting of evolving subduction and accretion in the context of a Palaeozoic cordilleran-type active

margin. The initial phase includes the onset of the Granite Harbour calc-alkaline magmatic arc, possibly as early as 540-530 Ma but with a major pulse at *ca.* 500 Ma (Stump, 1995; Rocchi *et al.*, 1998), accompanied by high-T/low-P metamorphism inboard of the margin, and the development of an accretionary wedge and medium- to ultra-high-P metamorphism along the outer margin (Ricci *et al.*, 1997). Geological interpretation of magnetic anomalies (Finn *et al.*, 1999; Ferraccioli *et al.*, 2002) suggest that the tectonic evolution of the margin also involved an oceanward migration of arc magmatism and tectonism, possibly by slab rollback. According to Meffre *et al.* (2000), a continent-arc collision model, as proposed for Tasmanian eclogites of similar petrological features (high-T) and age (*ca.* 500 Ma), can be applied to the Ross Orogen in NVL. In this context, and similarly to younger HP terranes in SW-Pacific-style orogenic belts (Lister and Forster, 2002), the fast exhumation of the Lanterman Range HP/UHP rocks can be related to extensional tectonics in the super-subduction domain of the overriding plate resulting from rollback of the hinge of the subducting oceanic lithosphere. The tectonic unroofing of medium/high-P metamorphic complexes (GHMC, BMC, Dessent Unit) may have been accompanied by a further oceanward migration of underthrusting, involving progressively more easterly tectonic elements, such as the volcano-sedimentary sequences of the Bowers Terrane and the Robertson Bay Terrane. The insertion of these outboard and relatively cold tectonic elements within the convergence zone is considered as the final stage of development of the orogenic wedge. This process could also have influenced the thermal evolution in the rear sector of the wedge.

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