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ORIGINAL PAPER

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The Ross orogeny of the transantarctic mountains: a northern Victoria Land perspective

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Abstract Northern Victoria Land (Antarctica) is made up of three terranes of Cambrian–Ordovician rocks: the Wilson (WT), Bowers (BT) and Robertson Bay terranes (RBT). The WT comprises a low- to high-grade metasedimentary sequence intruded by calc-alkaline plutons with magmatic arc affinity; the BT is composed of low-grade metavolcanic and metasedimentary rocks usually interpreted as an intra-oceanic arc; the RBT is a very low-grade flysch-like sequence. Terrane juxtaposition has traditionally been attributed to accretion during the Cambro-ordovician Ross orogeny. We propose a new model in which the WT, BT and RBT are interpreted as an arc/back-arc/trench system, developed in the context of a SW-dipping subduction zone. The subducting plate carried a continent originally located outboard of the turbidite fan of the RBT. Collision between this continent and the East Antarctic craton caused partial subduction of the intervening back-arc basin and, ultimately, the end of Ross-orogenic subduction. The turbidite fan of the RBT originally sedimented above the trench and on the subducting oceanic plate; due to collision it was thrusted on the continent, that constitutes, at least in part, the present basement of the RBT turbidite. The eastern portions of this continental mass were later dissected by the tensile tectonics related to the opening of the of the Southern Ocean.

Keywords Back-arc · Cambro-ordovician · Ross orogeny · Northern Victoria Land · Antarctica

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Introduction

In Early Palaeozoic times the paleo-Pacific margin of the Gondwana supercontinent recorded an orogenic event known regionally as Ross (Antarctica), Delamerian (SE-Australia) and Tyennan (Tasmania) orogenies. In Antarctica, the present-day outcrops of this belt border the East Antarctic craton and define the basement of the Cenozoic transantarctic mountains that extend from northern Victoria Land to the Pensacola mountains (Fig. 1a). Northern Victoria Land (NVL) contains the widest exposure of Ross-related rocks, including some types without equivalents elsewhere in the transantarctic mountains. In NVL, the occurrence of rock units with unusual characteristics historically led to interpretations of the Ross orogeny based on the concept of terrane accretion (e.g. Bradshaw 1987, 1989; Kleinschmidt and Tessensohn 1987; Tessensohn and Henjes-Kunst 2005; Stump 1995). As a consequence, most of the several tectonic models proposed for the Ross orogeny so far concentrated on reassembling the three terranes currently recognized in NVL, which are the Wilson (WT), Bowers (BT) and Robertson Bay (RBT) terranes (Fig. 1b).

The principal mechanisms proposed to account for terrane accretion at the active margin of the East Antarctic craton are:

(1) W-dipping subduction (under the craton) (Kleinschmidt and Tessensohn 1987; Flöttmann et al. 1998),
(2) E-dipping subduction followed by W-dipping subduction (Findlay et al. 1991),
(3) E-dipping subduction and continent-arc collision (Wodzicki and Robert 1986; Meffre et al. 2000),
(4) W-dipping subduction followed by strike-slip faulting (Weaver et al. 1984).

However, a number of data collected in the last decade of geologic investigations in NVL do not fit all together in any of the previously cited tectonic reconstructions.

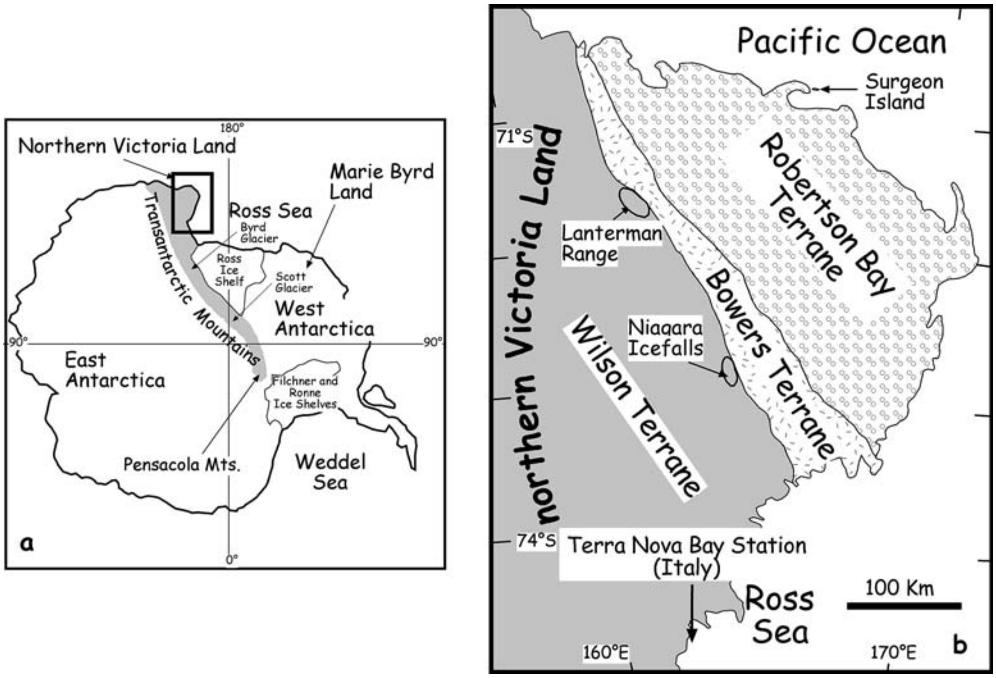


Fig. 1 Setting of the studied area within the Antarctic continent (**a**) and terrane boundaries in NVL (**b**)

Some recent models have also questioned the presence of exotic terranes in NVL and have interpreted the WT, BT and RBT as three originally adjacent zones (arc, forearc, trench; Finn et al. 1999; Ferraccioli et al. 2002), or have considered as exotic only the BT (Roland et al. 2004).

The model proposed here tries to account for the results of a wide range of structural, sedimentological, petrological, geochronological, geochemical and geophysical studies together with original observations based on fieldwork during six Antarctic expeditions from 1988 to 2004. The resulting model explains the Ross orogenic event as a product of active convergence at a continental margin, coupled with extensional tectonics in the overriding plate. We favour the tectonic setting of an oblique west-dipping subduction of an oceanic plate under the East Antarctic craton, which carried a continental mass. The collision of this continent ultimately led to the final Ross-orogenic architecture.

Geological background

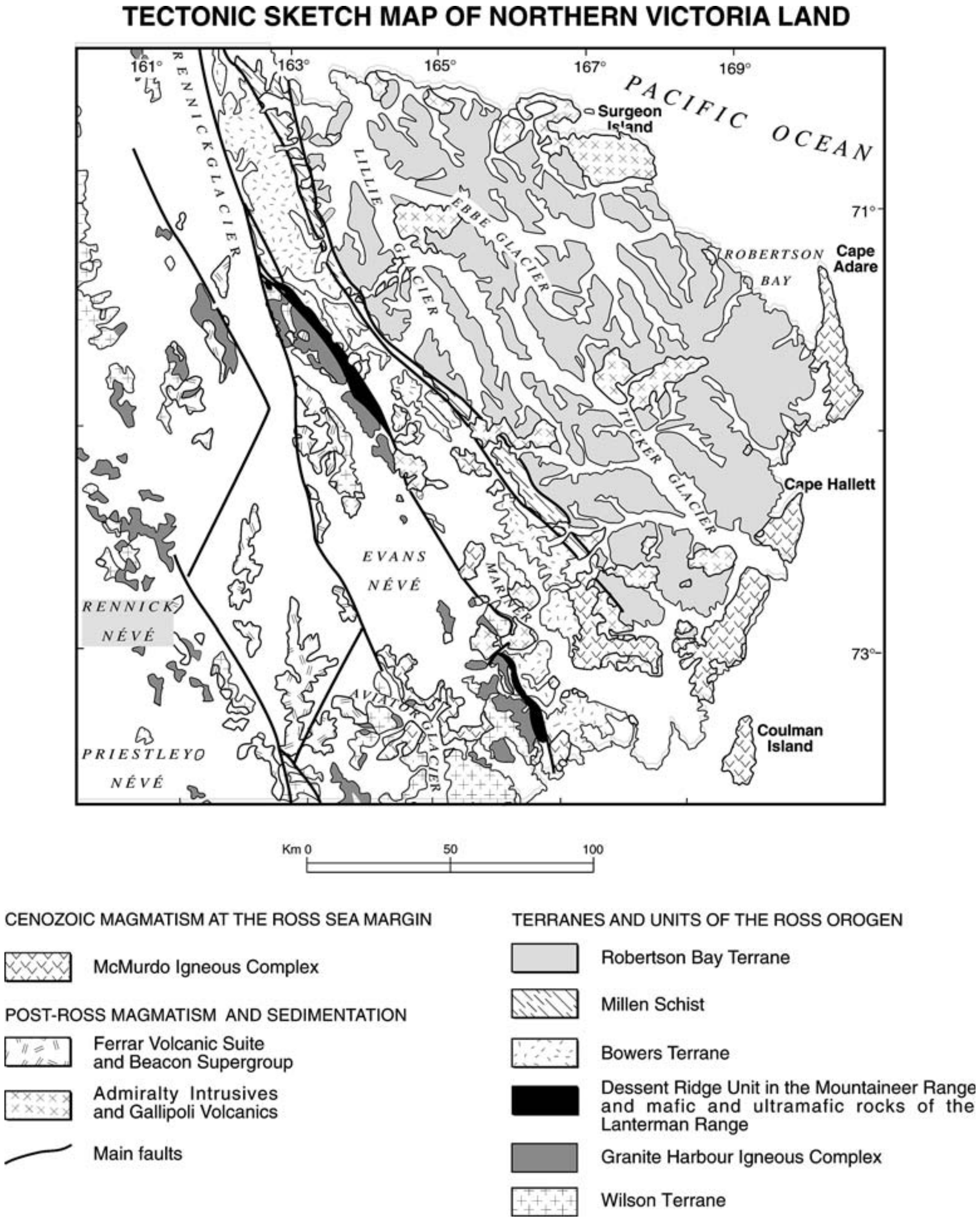
The geological framework of Northern Victoria Land (NVL) includes the three Ross-orogenic terranes that are from W to E (Fig. 1b), the WT, the BT and the RBT.

Wilson Terrane

The WT comprises a metasedimentary sequence that records a broad orogen-parallel zonation of metamorphic conditions: a LP/HT regime in the internal belt and a MP regime in the outer belt (Grew et al. 1984; Capponi et al. 1988; Ricci et al. 1997; Talarico et al. 2004). At the boundary with the BT, a belt of mafic and ultramafic rocks occurs as bodies and discontinuous layers intruded in the host gneiss. In the Niagara Icefalls area (western side of the upper Mariner Glacier, Fig. 1b), these rocks comprise serpentinites, gabbros and pyroxenites with preserved magmatic features as cumulate structure and minor amphibolitic- to greenschist-facies metamorphic overprint. In the Meander Glacier area south of Mt Supernal, the same rocks are severely sheared under greenschist facies metamorphic conditions. In the Lanterman Range, this belt comprises mafic and ultramafic rocks with amphibolite facies overprint and a unique occurrence of mafic rocks with eclogitic assemblages (Capponi et al. 1997a; Di Vincenzo et al. 1997). The eclogite occurrence is limited to a small area and the geological, petrological and geochronological studies indicate that the mafic, ultramafic and felsic host rocks shared the same metamorphic evolution (Palmeri et al. 2003). Eclogites contain relic coesite (Ghiribelli et al. 2002) and thus reveal subduction to pressures >2.9 GPa (corresponding to about 90 km). The geochemical affinity of these eclogites is variable from E-MORB to T-MORB to orogenic calc-alkaline (Rocchi et al. 2003). The age of the HP–UHP metamorphism is ca. 500 Ma (Table 1), whereas the age of the protoliths is still poorly constrained (Di Vincenzo et al. 1997; Rocchi et al. 2003).

The WT is intruded by the Granite Harbour Intrusives (GHI), a calc-alkaline plutonic suite including both S- and I-type granitoids (e.g. Borg et al. 1987; Vetter and Tessensohn 1987) with magmatic arc affinity, of Cambrian-Ordovician age. The oldest radiometric ages for the GHI (544 ± 4 Ma, microprobe U/Pb data of Black

Fig. 2 Geological map of NVL



and Sheraton 1990; 535 ± 26 Ma, Rb/Sr five-point isochron of Vetter et al. 1984) probably refer to the early stage of subduction. Older ages up to 560 Ma have been reported in southern Victoria Land (Read and Cooper 1999; Encarnación and Grunow 1996). More recent ages cluster around 500 Ma and represent the peak syntectonic magmatic pulse, whereas younger ages until 480 Ma are related to post-tectonic magmatism (Table 1).

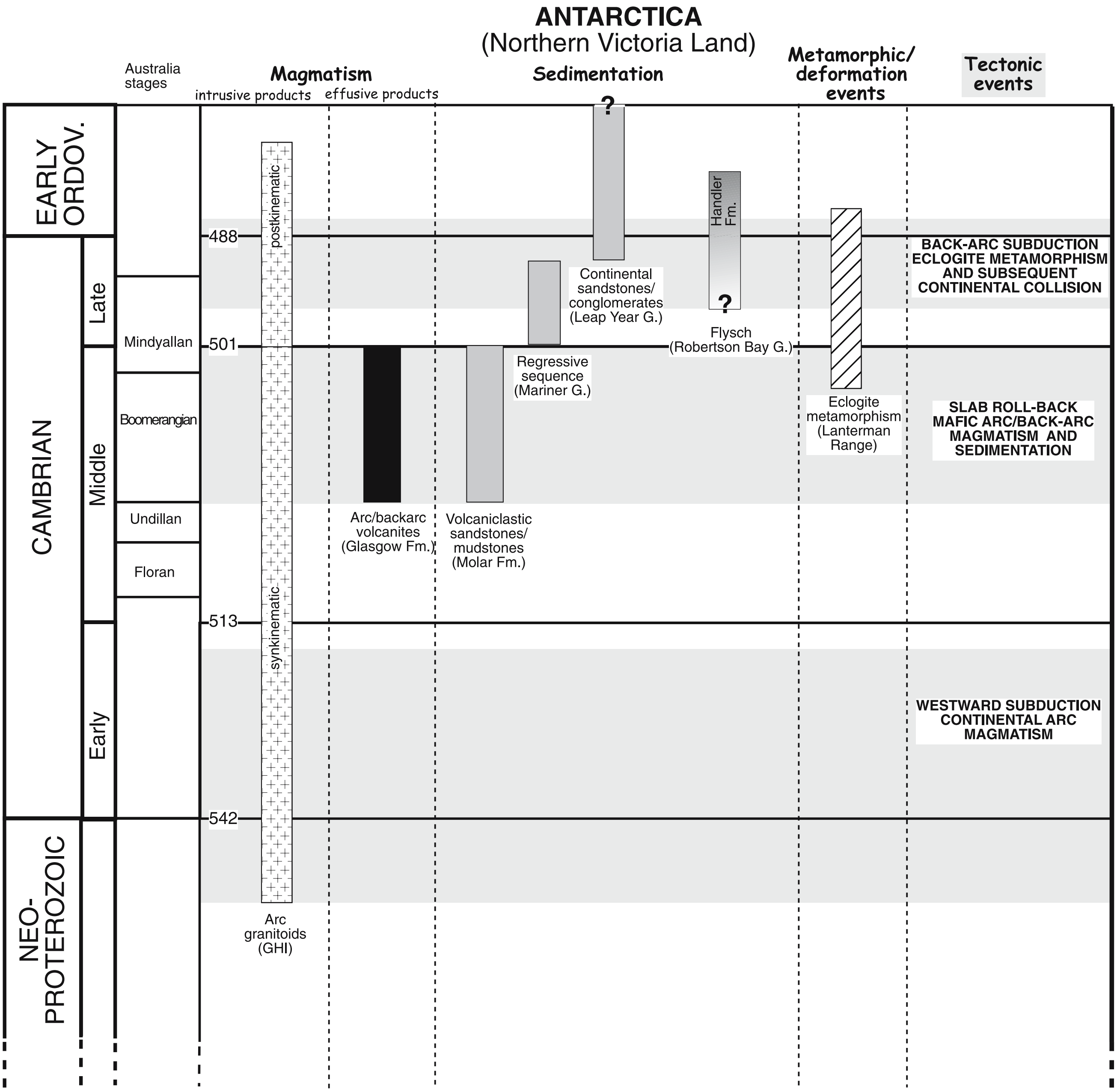
Bowers Terrane

The BT comprises the Sledgers, the Mariner and the Leap Year Groups forming the Bowers Supergroup and is affected by prehnite–pumpellyite or pumpellyite–actinolite metamorphism (Wodzicki et al. 1982). Metamorphic grade locally increases to greenschist/amphibolite facies transition in a strip close to the boundary with the WT. The Sledgers Group is made up of the Glasgow Volcanics and of the metasedimentary Molar Formation. The volcanites are primarily basalt with lesser andesite, but range all the way to rhyolite (Estrada and Jordan 2003). They occur as lava flows (also with pillow structures) and breccias and as sheets and lenses within the Molar Formation; some tuffaceous rocks are also present. These volcanites erupted mainly in a submarine setting even if the presence of some ignimbrites suggests periodically subaerial conditions (Weaver et al. 1984). Chemical analyses indicate heterogeneous affinities including N-MORB, E-MORB, T-MORB, arc tholeiite and calc-alkaline products (Rocchi et al. 2003).

The Molar Formation is made up of mostly fine sandstone with subordinate conglomerate beds and dark mudstone. The conglomerates contain clasts of basalt, andesite and graywacke with lesser amount of dacite, rhyolite, limestone, quartzite, granitoids and muscovite schist (Laird 1987). The coarse-grained beds likely filled channels cut into slope and basin floor deposits, represented by sandstones and minor mudstones. The basin was elongated in a NW-SE direction, with slopes constraining it on both sides (Laird 1987). On palaeontological basis, the age of the Molar Formation (and of the interbedded Glasgow Volcanics) ranges from Boomerangian to Mindyallan (late Middle Cambrian; Cooper et al. 1996; Table 1). This suggests that the volcanic rocks erupted contemporaneously with continental-margin arc magmatism in the WT (see Table 1). For instance, Basset et al. (2001) reported an age of 511 ± 7 Ma for an I-type granitoid clast of the Molar Formation, which could be derived from erosion of the GHI.

Highly deformed metaconglomerates, both mafic and felsic in composition (known as Husky and Lanterman Conglomerate, respectively) crop out in the eastern Lanterman Range, at the WT–BT boundary (Figs. 1b, 2). The Husky Conglomerate contains clasts of mafic and

Table 1 Correlation chart of magmatic, sedimentological and tectonic events in Cambro-ordovician time in NVL. Cambrian boundaries according to the 2004 version of the «International Stratigraphic Chart». Australia stages from Münker and Crawford (2000)



ultramafic rocks, also with boninitic composition (Weaver et al. 1984); in the Lanterman Conglomerate, in contrast, clasts of felsic rocks (schists, quartzites, mica schists and granitoids) occur. Detailed fieldwork (Capponi et al. 1999a) has shown a gradual lateral and vertical transition between the mafic and felsic terms, and thus they are believed to belong to the same sedimentary succession. The origin of these sediments is still a matter of debate; many different interpretations have been given (see Stump 1995 pp. 57–61 and Capponi et al. 1999a for a review and paragraph "A new tectonic model for the Ross orogeny in NVL-stage 2" for discussion).

The late middle Cambrian to late Cambrian Mariner Group records the progressive infilling of the basin and the cessation of volcanic activity. It is made up of fossiliferous fine-grained mudstone with limestone lenses and blocks, locally cut by debris flow deposits made up mainly of limestone clasts. The top of the succession is dominated by polymict conglomerate (e.g. Southend Conglomerate), with clasts of sandstone, limestone, basic and intermediate volcanics and rare granitoids (GHI with ages about 505–508 Ma; Bassett et al. 2001; Weaver et al. 2003). The upper part of the group consists of quartzose sandstone and minor mudstone interpreted as intertidal deposits (Laird 1987).

The Leap Year Group lies above a marked erosion surface on the Mariner Group (Table 1) and consists of continental to transitional deposits (sandstone and conglomerate) containing clasts of granitoids, mafic and sedimentary rocks. The age of the Leap Year Group is constrained by the underlying upper Cambrian deposits to be late Cambrian to early Ordovician.

Robertson Bay Terrane

The RBT is composed mainly of a thick sequence of folded turbidites whose base is not exposed anywhere in the region. The sequence consists of rhythmically alternating graywackes and phyllites or slates and its minimum thickness can be estimated to be ca. 3,000 m (Field and Findlay 1983). This succession represents a mainly very low-grade to low-grade (Kleinschmidt 1983; Buggisch and Kleinschmidt 1991) metamorphosed flysch sequence originally deposited in a deep-sea fan to basin plain environment (Wright 1981; Field and Findlay 1983). A metamorphic continental source for these sediments has been suggested (Stump 1995 and references therein). Detrital zircons in the turbidites display ages as young as 481 Ma (Fioretti et al. 2003), with a major peak at 495–500 Ma; detrital micas show youngest ages of about 485–490 Ma (Henjes-Kunst 2003). This likely indicates that sedimentation of the Robertson Bay turbidites was still going on during the early Ordovician (Table 1). The upper portion of the sequence (Handler Formation), whose origin and significance is still unclear, contains blocks of quartzose conglomerate, sandstone and fossiliferous limestone that indicate a Tremadocian age (Wright and Brodie 1987).

We consider the present basement beneath the RBT turbidites at least partially of continental affinity, in view of the presence of crustal xenoliths (medium-high grade micaschists—gneisses) inside the Devonian admiralty intrusives at Cape Philips (Fioretti et al. 1998, 2003; GANOVEX Team, 1987). Felsic and mafic granulites of lower crustal origin also occur in cored bombs of Cenozoic McMurdo Volcanics (Rocchi et al. unpublished data). These rocks likely represent samples of the crust underlying the Robertson Bay sedimentary rocks. The Surgeon Island granitoid (Kleinschmidt et al. 1992; Fioretti et al. 2001) may correspond to an outcropping section of this basement, as suggested by Läufer et al. (2003). The eastern portions of this continental basement were later probably disrupted by the tensile tectonics associated with the opening of the southern ocean. A careful discussion of this point is given by Fioretti et al. (2005). The presence of continental crust underlying the Robertson Bay turbidites has been suggested by Gibson and Wright (1985) and Matzer (1995) on the basis of structural arguments.

After the Ross orogeny, all the three terranes were intruded by the Admiralty intrusives (Fig. 2; Capponi et al. 1997b) and covered by the Gallipoli volcanics, a calc-alkaline association of Devonian–Carboniferous age. After a phase of uplift and erosion, the triassic Beacon Supergroup was deposited on the resulting peneplain surface, and in turn was intruded by sills and dikes and covered by basaltic flows of the Jurassic Ferrar Volcanic Suite. During the Cenozoic, at last, a complex volcanic and intrusive alkaline suite (Mc Murdo igneous complex) developed.

Ross-related structural and metamorphic features

The metasedimentary rocks of the WT are characterized by a complex deformation history: they are deformed by several sets of folds (e.g. Kleinschmidt and Skinner 1981; Roland et al. 1984; Capponi et al. 1999b), with different relations between deformation, metamorphism and GHI magmatism in the various areas. Folding is accompanied/followed by development of ductile shear zones with different—strike-slip or reverse—kinematic behaviours (e.g. Flöttmann and Kleinschmidt 1991; Musumeci and Pertusati 2000; Läufer and Rossetti 2003).

The contact between the WT and the BT, usually referred to as the Lanterman fault zone, is one of the major tectonic lineaments of NVL. It can be interpreted as a major suture zone, because it separates the inboard WT with low- to high-grade metamorphism from the low- to very low-grade outboard BTs and RBTs (Fig. 1b). Moreover, it is characterized by the only outcrops so far, where well-preserved Ross-aged eclogites are reported in Antarctica, which are considered to be a strong evidence for a subduction-related event.

Capponi et al. (1999b) reviewed previous interpretations and, based on detailed fieldwork, pointed out that the structural evolution of this boundary is polyphase and can be subdivided into four stages:

(a) West over east thrusting of the WT over the BT of Ross age (i.e. around 500 Ma) with coeval greenschist–amphibolite facies transitional metamorphism;
(b) Sinistral strike-slip shearing coeval with greenschist facies metamorphism of late-Ross age (Crispini et al. unpublished. data);
(c) Large wavelenght folding (unconstrained in age);
(d) Cenozoic brittle tectonics.

Away from the contact with the WT, the Bowers Supergroup is deformed by NW–SE trending close folds with subvertical axial-planes. Deformation occurred under prehnite–pumpellyite or pumpellyite–actinolite facies (Wodzicki et al. 1982). Close to the WT–BT boundary, the rocks become more tightly folded and metamorphism increases to greenschist grade (Gibson et al. 1984; Stump 1995 and references therein).

The RBT turbidites are deformed by NW–SE trending large-scale folds and are characterized by very low-grade metamorphic imprint. Close to the boundary with the BT, the RBT is characterized by multiple deformations (Bradshaw et al. 1982) and by a slight increase of metamorphic grade to lower greenschist-facies conditions (e.g. Buggisch and Kleinschmidt 1991). These rocks are referred to as "Millen Schist" (Jordan et al. 1984) and are thought to derive from tectonic intermixing of RBT turbidites and Molar Formation.

Evidence of post-orogenic collapse in NVL include low-angle normal faults and conjugate normal-slip kink bands (Kleinschmidt and Brommer 1997).

The Ross orogeny in NVL

The present-day arrangement of the WT, BT and RBT is the result of the Cambro-Ordovician Ross orogeny. In the majority of the so far proposed models for this event (e.g. Kleinschmidt and Tessensohn 1987; Flöttmann et al. 1998; Weaver et al. 1984), the BT has been interpreted as an oceanic island arc driven to collision with the continental margin by W-directed subduction. Some authors (Finn et al. 1999; Ferraccioli et al. 2002), on the contrary, interpret the WT, BT and RBT as three originally adjacent zones in the framework of W-dipping subduction. In this context, magmatic activity shifted progressively eastwards from the WT to the BT as the trench rolled away from the margin, causing the outboard migration of the arc. The RBT turbidites, in turn, would have been deposited along the trench and on the subducting oceanic plate.

However, some aspects of the NVL geology are not satisfactorily explained by any of the existing models. These are in particular:

(a) Analyses of the BT volcanites (Glasgow volcanics) pointing to a wide range of geochemical affinities for the volcanic products, such as N-MORB, E-MORB, T-MORB, arc tholeiite, and calc-alkaline (Rocchi et al. 2003), rather than simply island arc;
(b) The presence of mafic/ultramafic rocks intruded in the continental WT close to the boundary with the BT;
(c) The wide range of geochemical affinities of the eclogites collected at the WT–BT boundary (Di Vincenzo et al. 1997);
(d) The occurrence of a minor component of continent-derived detritus in the Molar Formation of the BT, which points to the proximity of the BT to a continental mass already in the Middle Cambrian;
(e) The likely presence of continental crust underlying the Robertson Bay turbidites (Fioretti et al. 2001, 2005);
(f) Aeromagnetic and gravimetric data that point to a composite basement (oceanic in the north and continental in the south) for the BT (Ferraccioli et al. 2002).

As a consequence of these aspects and the existing data, we propose a new tectonic model to explain the geotectonic evolution of the Ross orogeny in NVL.

A new tectonic model for the Ross orogeny in NVL

The new model proposed here consists of five principal stages (Fig. 3) and covers the time interval from the early Cambrian to early Ordovician. The time scale adopted is the 2004 edition of the "International Stratigraphic Chart" (Gradstein et al. 2004), which fixes the base of the Cambrian at 542 Ma, the Early–Middle Cambrian boundary at 513 Ma, the Middle–Late Cambrian boundary at 501 Ma and the Cambrian-Ordovician boundary at 488 Ma. The sedimentological features of the Bowers basin, which reflect the tectonic evolution of the area, are taken from Laird (1987).

Stage 1: Early Cambrian: SW-dipping subduction

SW-dipping subduction of paleo-Pacific crust under the East Antarctic craton commenced in the Early Cambrian. The paleo-Pacific plate carried a continental mass further to the east of the newly formed active margin, which we refer to as "Eastern Continent." Expression of this subduction is the formation of the Granite Harbour plutons in the WT. Even if only a small number of arc-related intrusions display ages as old as Early Cambrian (Black and Sheraton 1990), they nevertheless represent the evidence that subduction processes were already active at that time. However, we cannot rule out the possibility that some of the older intrusions have been removed by erosion.

The distribution and the geochemical characteristics (e.g. Borg and DePaolo 1991) of the arc granitoids point to a southwest-dipping subduction. Different works based on structural (Capponi et al. 1999b), geochemical

(Borg et al. 1987; Rocchi et al. 1998) and geochronological (Goodge and Dallmeyer 1996) data and also previous tectonic models (e.g. Ferraccioli et al. 2002) suggest that convergence might have been oblique.

Stage 2: Middle Cambrian: back-arc basin opening

In this stage, a back-arc basin opens, probably because of the roll-back of the subducting plate (Fig. 3). The back-arc possibly developed on a previous fore arc system (Rocchi et al. 2003).

In this proposed scenario, the Molar basin should represent the remnant of this back-arc basin and particularly the part of it originally adjacent to the Glasgow arc massif, which has a higher preservation potential (Busby-Spera 1988). There are many lines of evidence that can support this assumption:

Geochemical/petrological data

Weaver et al. (1984) suggested that the BT volcanites were erupted in an oceanic island arc setting, on the

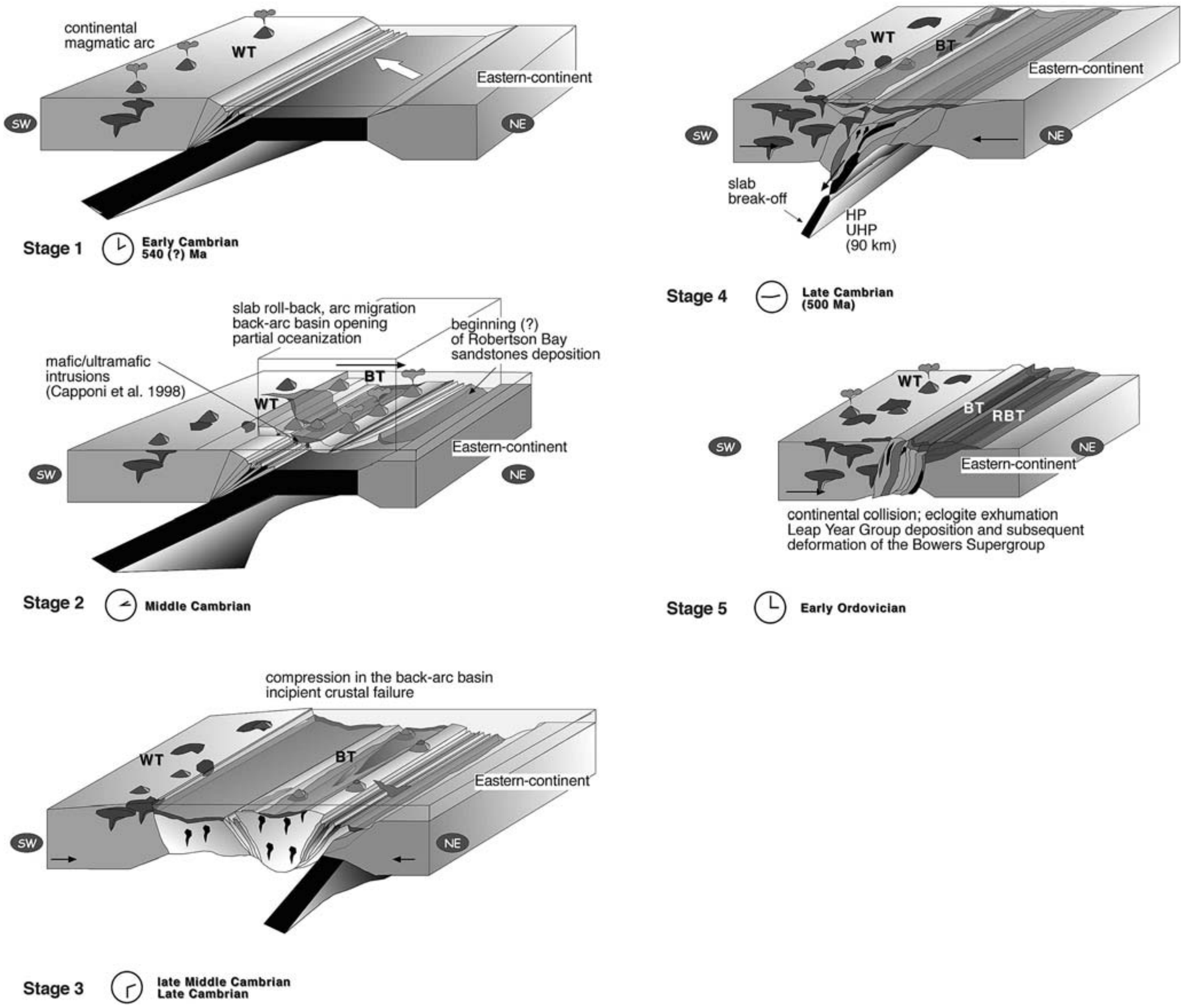


Fig. 3 Proposed model for the Ross Orogeny in the NVL sector: *Stage 1* oblique SW-dipping subduction under the East Antarctic craton of a plate carrying a continent ("Eastern continent") and development of a continental magmatic arc; *Stage 2* opening of a back-arc basin following roll-back of the subducting plate; *Stage 3* continent collision in NVL, which induces compression in the back-arc area and incipient crustal failure; from this stage onwards, the model refers to the area defined by the box in stage 2, *Stage 4* insertion of the continental crust in the subduction zone, which provokes a jump of subduction to the back-arc basin and HP metamorphism; *Stage 5* final continental collision and eclogite exhumation. *WT* Wilson terrane, *BT* Bowers Terrane, *RBT* Robertson Bay Terrane; further discussion in the text

basis of geochemical (major and trace elements) and petrological data. However, recent analytical results point to a large variety of geochemical affinities for the Glasgow volcanic products, including N-MORB, E-MORB, T-MORB, arc tholeiite and calc-alkaline, which appear to be more typical of a marginal back-arc basin in an extensional setting (Rocchi et al. 2003) rather than of an island arc. The mafic and ultramafic intrusions described by Capponi et al. (1998) in the Niagara Icefalls area (close to the WT–BT boundary, Fig. 1b) are serpentinites, gabbros and pyroxenites with preserved magmatic features and minor amphibolite- to greenschist-facies metamorphic overprint. They could be related to the initial stage of opening of the back-arc basin and therefore should be genetically linked to the Glasgow volcanites of the BT. A petrological and geochemical study to check this relationship is currently in progress.

Stratigraphical/sedimentological data

The palaeogeographic and palaeotectonic reconstructions for the BT have to fit the stratigraphical and compositional features of the sedimentary sequence, too. In particular, the occurrence of continental detritus (including clasts of GHI, Bassett et al. 2001) in the Molar and Lanterman conglomerates (see paragraph on the Bowers Terrane) and of granule-size quartz in Molar sandstones (Bradshaw, personal communication) and also of mafic and ultramafic rocks (e.g. Husky conglomerates) implies that both felsic and mafic rocks were outcropping in the source area. This is confirmed also by isotopic data on the Molar sandstone by Henjes-Kunst and Schüssler (2003). The proximal features of these deposits and the presence of GHI clasts therefore force to restore the Wilson continental margin close to the BT in Middle Cambrian time. Most of the mafic clasts likely derive from the erosion of the Glasgow volcanites; some of them, however, could also originate from mafic/ultramafic intrusions like the ones occurring at the Niagara Icefalls (serpentinites, gabbros and pyroxenites, Capponi et al. 1998). In fact, no hint of the presence of a complete ophiolitic sequence at the base of the Molar Formation exists. This mixed mafic and felsic source fits the picture of an extending back-arc basin, where fault-bounded blocks of continental basement and volcanic rocks may be eroded away and sedimented without long-range transport.

The question whether the back-arc extension reached oceanization is difficult to answer, principally because the basement rocks of the basin are not exposed, and therefore every inference about their nature is quite speculative. Moreover, important geochemical parameters, such as the εNd, the Sr and Pb isotopic ratios, of the Glasgow volcanites are not yet available, apart from unpublished mantle-like εNd data (in the range +2/+7) for the Sledgers Group metavolcanics in the northern BT cited by Henjes-Kunst and Schüssler (2003). Ferraccioli et al. (2002) suggest that the basement buried beneath the northern BT has an oceanic nature in order to account for a broad magnetic anomaly and a 100-mGal Bouguer gravity high; in contrast, the southern BT lack these anomalies and may be underlain by continental basement. As a consequence, we assume that the continental crust was stretched and intruded by mafic/ultramafic magmas, and that the basin possibly reached oceanization in its northern part (Fig. 3).

However, in case of extension of continental basement bimodal volcanism should develop with felsic and mafic magmatic pulses. Some rhyolites and dacites are indeed present, even if not widespread, among the Glasgow lavas (e.g. Estrada and Jordan 2003) and in the Molar conglomerates and other intermediate and felsic volcanic products possibly were lost due to telescoping and loss of crust during the subsequent continental collision. It is commonly accepted that the part of the basin currently exposed represents just a small portion of the original extent of the basin, because palinspastic restorations show that the BT had an original width of at least ca. 60 km. Thus, it is very narrow compared with the modern back-arc basins (e.g. the Japan Sea is ca. 700 km wide in its widest section).

In the trench and on the subducting oceanic plate there was turbiditic sedimentation and we suggest that this could be represented by the deeper portions of the RBT flysch. Actually, the RBT turbidites are commonly considered younger (late Cambrian to early Ordovician) than the Molar sandstones (middle Cambrian) (see “Geological background”), but field evidence point to gradual transition from the Molar sandstones to the Rodertson bay turbidites (Fig. 9 in Capponi et al. 2003). According to these authors, the Molar sandstones deposited in part on the northeastern slope of the Glasgow arc and the basin in which the Molar Formation was being deposited became deeper in the direction in which the RBT sandstones were deposited (i.e. the trench). If this proves to be true, than the basis of the RBT turbidites must be as old as middle Cambrian.

In this scenario the subduction event induced the growth of an accretionary prism at the active margin, both as a result of underplating of partially subducted rocks and as frontal accretion of the RBT flysch.

Stage 3: late middle Cambrian/late Cambrian: continental collision

As the collision between the “Eastern Continent” and the margin occurred in NVL, the back-arc basin first ceased to extend and subsequently entered a compressional stage. We propose that compression produced fault-bounded uplifted zones and related basins (i.e. the Mariner basin), thus explaining why the Mariner basin gradually experienced regressive conditions (Andrews and Laird 1976). The arc/back-arc crust finally failed and some slices were brought to depth. With this reconstruction it is possible to explain how part of the back-arc basin escaped subduction and registered an uplift at the same moment as subduction was in progress.

Chemenda et al. (2001) proposed a general tectonic model, which predicts the failure of the upper plate when the continental margin of the lower plate enters the subduction zone: if a back-arc basin is present, then it probably represents the weaker point of the overriding plate and is expected to fail. In the cited model, the back-arc has an oceanic nature and the failure ultimately leads to its partial subduction. This tectonic evolution accounts for the end of subsidence of the basin and for its gradual infill, represented by the deposition of the Mariner Group, and also for the end of the volcanic activity (see paragraph on the Bowers Terrane in "Geological background").

Similar stress conditions are presently active in parts of the Japan Sea (a back-arc basin resulting from the subduction of the Pacific plate under the Eurasian plate); here basin opening has ceased ca. 13 Ma ago and, after a transitional period, the regional stress regime has changed to compression with the development of reverse faults and fault-bounded basins (Sato and Amano 1991) and accompanied by high sismicity. This situation could be compared to this stage of our model.

Stage 4: late Cambrian (ca. 500 Ma): back-arc subduction

During collision between the WT and the "Eastern continent," the intervening arc/back-arc rocks were largely subducted to great depth, together with the surrounding continental rocks, and turned into eclogites (Di Vincenzo et al. 1997). The occurrence of HP-rocks at the Wilson–Bowers boundary is a direct evidence of the subduction event, whereas the scatter of geochemical affinities of both the eclogites and the Glasgow volcanics could support a genetic link between these rocks, even if it is also possible that the HP-rocks partly derive from slices of the subducted oceanic plate.

Though the GHI in NVL cover a wide range from 540 Ma to 480 Ma, the main igneous peak, which is of calc-alcaline affinity, occurred around 500 Ma and therefore is probably linked to this stage of back-arc subduction. Due to the uncertainties about the original width of the back-arc basin outlined in the "stage 2" paragraph, we are not currently able to predict if the amount of back-arc crust subducted is sufficient to produce the huge volumes of ca. 500 Ma-granitic melts. However, we must also take into account the contribution to the magma generation of the crust subducted at the mature subduction zone. A possible concurring mechanism, outlined in Fig. 3, is the slab-break-off (Davies and von Blanckenburg 1995) of the palaeo-Pacific plate; the slab break-off model predicts the detachment of subducted oceanic lithosphere from continental lithosphere during continental collision with consequent thermal perturbation and magmatism; a time delay of less than 5–10 Ma between continental collision and break-off is expected. Another predicted consequence is the rapid exhumation of HP rocks (see next paragraph) and therefore this model seems to fit quite well the tectonic scenario of Ross orogeny in NVL.

In this reconstruction, the Mariner basin escaped subduction and remained in superficial levels in the orogenic wedge, thus being preserved from subduction. This explains how it was possible that part of the back-arc basin was subducted while sedimentation was going on in the part, which escaped subduction (Table 1).

Large volumes of Robertson Bay flysch that was deposited on the subducting plate was incorporated in the accretionary prism. The continental crust of the "Eastern continent" entered deeply in the subduction zone and as a consequence, the RBT sediments were thrusted onto the continental crust of the lower plate; this process was accompanied by internal deformation (Wright and Dallmeyer 1991). This mechanism is, for instance, widely accepted for the evolution of the Alpine orogeny in the Mediterranean region, where flysch originally deposited on the oceanic subducting plate was accreted to the accretionary prism on the upper plate and subsequently thrusted over the continental foreland during continental collision (e.g. Polino et al. 1990; Stampfli et al. 1998).

Stage 5: early Ordovician: final setting of the belt

The continental collision of the Wilson/Bowers system and the Eastern continent terminated the subduction process and was likely followed by the break off of the subducted slab (see previous paragraph). This led to rapid exhumation of the HP-rocks (3–4 mm/a; Palmeri et al. 2003) and to thermal perturbation in the upper plate, resulting also in late-orogenic magmatism in the WT around 480 Ma (Table 1) (Kreuzer et al. 1987; Stump 1995 and references therein).

During this stage, the WT likely overthrusted the BT and amphibolite-greenschist facies metamorphism developed (see paragraph on Ross-related structural and metamorphic features in "Geological background"). Telescoping and strike-slip movement along the belt (Capponi et al. 1999b) can account for strike-slip shearing coeval with late greenschist metamorphism at the Wilson/Bowers boundary, as shown by the structural analysis of Capponi et al. (1999b), and for the absence of wide portions of crust. At the same time (Wright and Dallmeyer 1991) the BT and the RBT were amalgamated and the Millen Schists developed (Capponi et al. 2003). These late deformation events led to the final tectonic setting of the belt.

The continental Leap Year Group sedimented over an erosion surface (Laird 1987; Casnedi and Di Giulio 2003) and was deformed by NW–SE trending open folds with subvertical axial planes.

Concluding remarks

This new model for the Ross orogeny in NVL assumes a southwest-dipping subduction under the east Antarctic craton starting from the early Cambrian and places both the WT and BT on the upper plate. The lower plate carried a continent, named "Eastern continent," which consisted likely of crust presently buried under the RBT turbidites and possibly in western Marie Byrd Land, the Campbell Plateau and the Western Province of New Zealand. Strong similarities between these continental fragments have long been recognized (e.g. Bradshaw et al. 1997; Kleinschmidt and Petschick 2003), but we suggest they were accreted to east Antarctica during the Cambrian Ross orogeny and not in late Devonian time as previously thought by some authors (e.g. Weaver et al. 1991; DiVenere et al. 1996). This conclusion is in line with that of Woolfe and Barrett (1995), who claim that suturing between East and West Antarctica occurred in pre-Devonian time and more likely during the Cambro-Ordovician Ross orogeny. The direction of movement of the lower plate was oblique with a left-lateral component related to the palaeo-Pacific margin of the Gondwana continent. In mid-Cambrian time, an extensional stage in the overriding plate resulted in the opening of a back-arc basin, probably because of the roll-back of the subducting plate.

The Sledgers Group of the BT thus represents an arc/back-arc association, and this accounts for the wide variety of geochemical affinities of the volcanites and for the presence of mixed continental/oceanic detritus (partially coming from the adjacent WT) in the associated sediments.

After back-arc opening, the continuing convergence led to the collision of the "Eastern continent" with the margin in NVL; as a consequence, the basin entered a compressional stage with the development of fault-bounded uplifted zones and related basins (i.e. the Mariner basin). When the "Eastern continent" entered the subduction zone, subduction greatly slowed down and finally jumped to the back-arc, which was subducted in turn to depth in excess of 90 km with consequent HP-metamorphism at ca. 500 Ma. The HP-units were subsequently rapidly exhumed and the belt reached its final setting during the Early Ordovician. The RBT presently consists only of subduction-related sediments, the base of which is unknown; they may be decoupled from their original oceanic basement, as a consequence of a process of tectonic substitution: they rest on the continental crust of the "Eastern continent," the eastern portions of which were later dissected by the tensile tectonics associated with the opening of the southern Ocean.

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