Polarforschung 80 (2), 100 – 110, 2011

Thermochronological Research in Northern Victoria Land (Antarctica): a Key to the pre-Disintegration Palaeogeography of Panthalassian Gondwana

by Frank Lisker[1] and Andreas L. Läufer[2]

Abstract: This paper presents the overview of the apatite fission track (AFT) data set of northern Victoria Land and juxtaposed SE Australia, and the underlying geological and geomorphological processes since late Paleozoic times. It focuses on thermochronological data produced during the last two decades, new interpretation strategies, and the combined use of thermochronological data and complementary geological information. The regional AFT pattern and stratigraphic age information require the existence of a late Paleozoic - Mesozoic sedimentary basin between northern Victoria Land and SE Australia. Basin formation resulted from long-lasting N–S oblique extension that also triggered the ~180 Ma Ferrar magmatism, the rifting of the Ross Sea, and eventually continental breakup between Antarctica and Australia. The locus of breakup is probably controlled by basin geometry and depth.

Zusammenfassung: Dieser Artikel präsentiert einen Überblick über den Datensatz von Apatitspaltspurenaltern (AFT) von Nordviktorialand und dem gegenüberliegenden Südosten Australiens sowie über die zu Grunde liegenden geologischen und geomorphologischen Prozesse seit dem Paläozoikum. Er fokussiert auf thermochronologische Daten der letzten beiden Jahrzehnte, neue Interpretationsstrategien sowie die Kombination thermochronologischer Daten mit komplementären geologischen Informationen. Der Vergleich regionaler AFT-Alter und stratigraphischer Alter erfordert die Existenz eines spätpaläozoisch-mesozoischen Beckens zwischen Nordviktorialand und SE-Australien. Dessen Bildung ist das Ergebnis lang anhaltender schräger N–S-Extension, die auch für den ~180 Ma Ferrar-Magmatismus, das Rossmeer-Rifting und schließlich den Kontinentalzerfall zwischen der Antarktis und Australien verantwortlich ist. Die Anlage der entsprechenden Bruchstelle ist vermutlich durch Beckengeometrie und Beckentiefe kontrolliert.

INTRODUCTION

Compared to former supercontinents, modern Gondwana reconstructions tend to be reasonably well constrained. They mainly rely on fits of isobaths, positions of palaeomagnetic poles or comparisons of structure and age of the metamorphic basement and Palaeozoic to Mesozoic sedimentary strata including fossil content, respectively, of the juxtaposed Gondwana fragments. Nevertheless, the resolution of the pre-breakup architecture of some regions within Gondwana remains poor, especially of Antarctic regions now covered by ice and /or lacking any attributable sedimentary record. A typical example for this dilemma is the correlation of the sheared margins of the Ross Sea sector of Antarctica and SE Australia (Fig. 1).

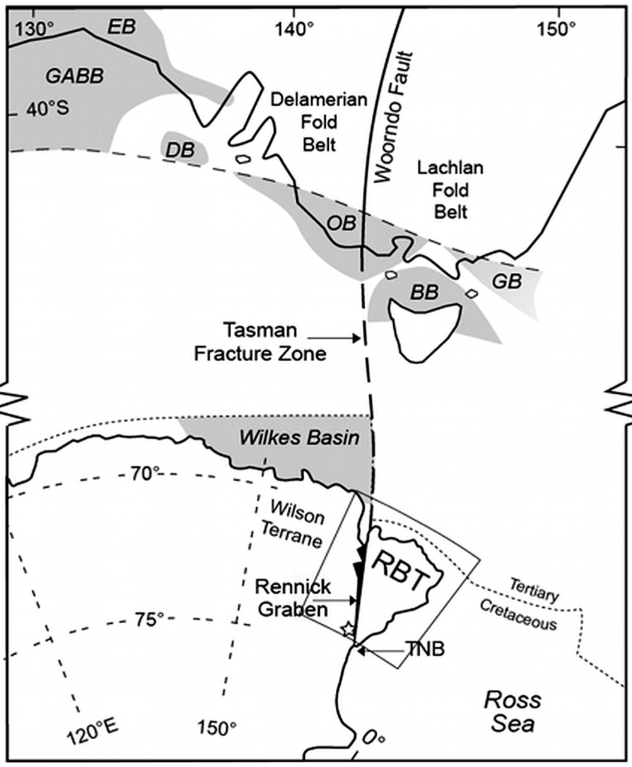
While the coast between South Australia and Victoria is easily accessible, and abundant sedimentary strata are preserved both onshore and on a broad continental shelf, only a few outcrops are exposed at the juxtaposed coast between Terre Adélie and northern Victoria Land, and the shelf there is not accessible. The basement of Terre Adélie and northern Victoria Land consists of the Precambrian East Antarctic Craton onto which three major tectono-metamorphic terranes (Wilson, Bowers, and Robertson Bay) were accreted during the Early Paleozoic Ross Orogeny (Fig. 2). It comprises Neoproterozoic to early Paleozoic gneisses and low-grade metasedimentary rocks intruded by the ~500 Ma Granite Harbour and the ~350 Ma Admiralty Intrusive suites (e.g., BORG et al. 1987). This basement is overlain only locally by remnants of a so-called Gondwana terrestrial sequence made of Permian to Early Jurassic clastic deposits (Beacon Supergoup), and mafic Ferrar volcanic rocks and dykes that emplaced at ~180 Ma (e.g., COLLINSON et al. 1986, BARRETT 1991, HEIMANN et al. 1994). Neogene volcanic rocks and sediments are merely preserved as patches in the immediate vicinity of the Ross Sea margin.

Due to these limitations, early correlations of Antarctica and SE Australia largely depended on proxies for properties of crustal units, such as paleomagnetics, geochronology, magmatic and metamorphic petrology, structural geology (e.g., STUMP et al. 1986, MILLER et al. 2002), whereas sedimentary and stratigraphic information is restricted to the Australian side (e.g., MUTTER et al. 1985, WILLCOX & STAGG 1990, STAGG & WILLCOX 1992, BRYAN et al. 1997).

In this situation, the Antarctic Ross Sea region became one of the first areas where an alternative dating technique, apatite fission track (AFT) analysis, was applied to solve this dilemma. AFT thermochronology is a radiometric method based on the accumulation of damage trails in the mineral apatite due to spontaneous nuclear fission of ^{238}U. Fission tracks are produced at a constant rate through time, and so the number (density) of tracks can be used to estimate the time since track accumulation began, i.e. the AFT age. Fission tracks remain preserved in apatites below a temperature of 110-125 °C. They experience some length reduction (annealing) within the temperature range of 60-110 °C ("Partial Annealing Zone", e.g., WAGNER & VAN DEN HAUTE 1992). AFT analysis produces two parameters: an AFT age (resulting from the track density), and information about the style of cooling and the maximum paleotemperature (from mean track length and standard deviation). Moreover, etch pit diameters

[1] Universität Bremen, Fachbereich Geowissenschaften (FB 5), PO Box 33 04 40, D-28334 Bremen, Germany.
[2] Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Stilleweg 2, D-30655 Hannover, Germany.

Manuscript received 20 September 2010; accepted in revised form 14 March 2011.



are measured as a proxy for the chemical composition of the apatites (BURTNER et al. 1994).

Qualitative interpretation and thermal history modelling of AFT data are then applied to derive constraints on timing and amount of cooling. Cooling of rocks to the temperatures of the AFT system usually refers to exhumation or postmagmatic thermal relaxation. At present, AFT thermochronology is the most commonly used tool to delineate exhumation processes and long-term landscape evolution of a wide field of geological environments, ranging from contractional to extensional settings and "stable" cratonic interiors. For detailed overviews on apatite thermochronology and its application to geological

Fig. 1: Sketch map showing the juxtaposed coastal segments between Terre Adélie and northern Victoria Land of Antarctica and southeastern Australia. Basins: BB = Bass Basin; EB = Eucla Basin; DB = Duntroon Basin; GABB = Great Australian Bight Basin, GB = Gippsland Basin, OB = Otway Basin. RBT = Robertson Bay Terrane; TNB = Terra Nova Bay. The star marks the location of the Eisenhower and Deep Freeze ranges, the frame indicates the contour of Figure 2.

Abb. 1: Übersichtskarte mit den gegenüberliegenden Küstenabschnitten zwischen Terre Adélie und Nordviktorialand der Antarktis und dem südöstlichen Australien. Becken: BB = Bass-Becken, EB = Eucla-Becken, DB = Duntroon-Becken, GABB = Great Australian Bight-Becken, GB = Gippsland-Becken, OB = Otway-Becken. RBT = Robertson Bay Terrane; TNB = Terra Nova Bay. Der Stern markiert die Lage der Eisenhower Range und der Deep Freeze Range, der Rahmen zeigt den Umriss der Abbildung 2.

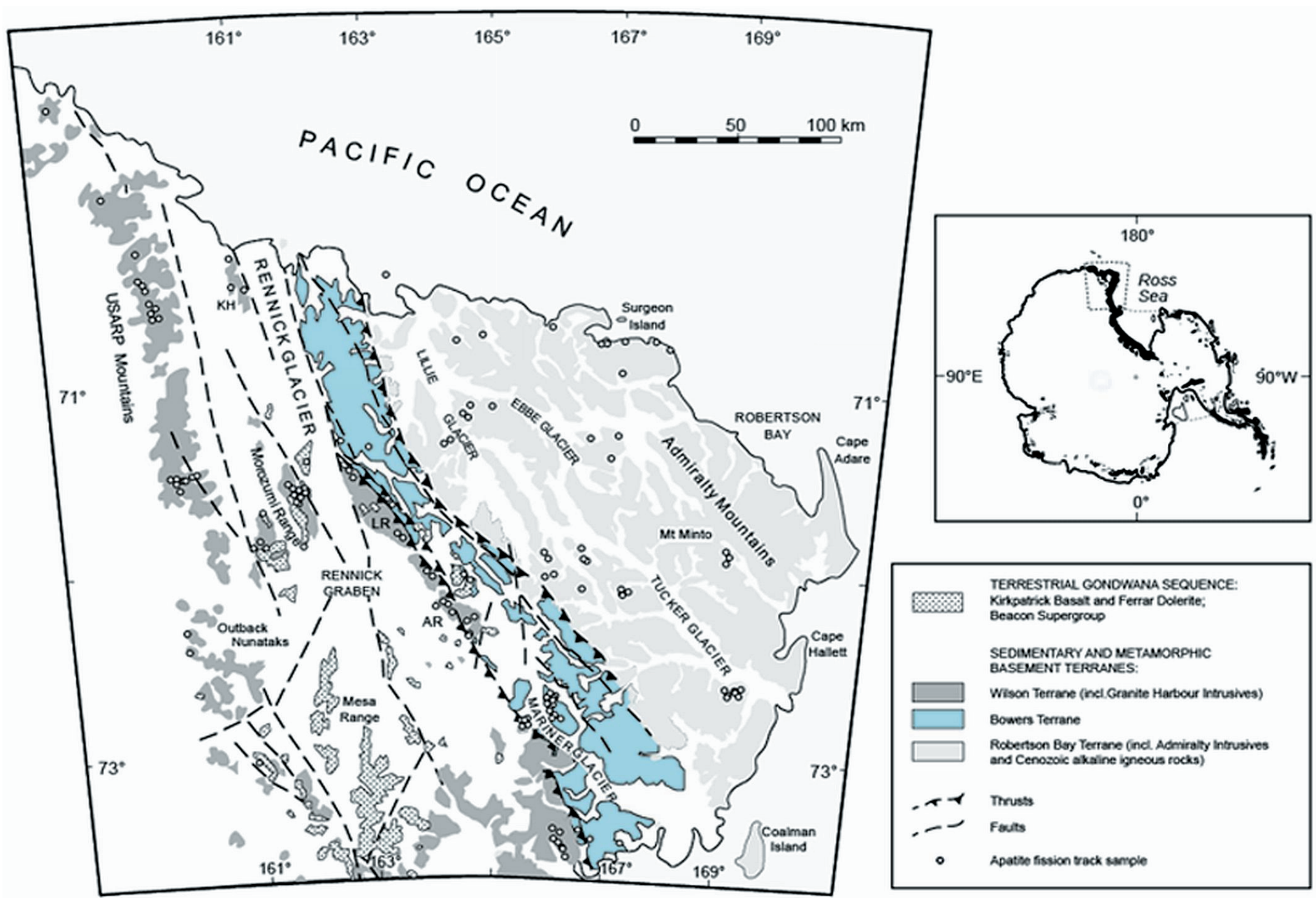


Fig. 2: Geological sketch of northern Victoria Land showing sample locations of the apatite fission track studies of FITZGERALD & GLEADOW (1988), BALESTRIERI et al. (1994b, 1997, 1999), LISKER (1996 unpubl. data), SCHÄFER (1998), BALESTRIERI & BIGAZZI (2001), ROSSETTI et al. (2003), and LISKER et al. (2006).

Abb. 2: Geologische Übersichtskarte von Nordviktorialand mit den Probennahmepunkten für die Spaltspuruntersuchungen von FITZGERALD & GLEADOW (1988), BALESTRIERI et al. (1994b, 1997, 1999), LISKER (1996 unpubl. Daten), SCHÄFER (1998), BALESTRIERI & BIGAZZI (2001), ROSSETTI et al. (2003) und LISKER et al. (2006).

problems we refer to WAGNER & VAN DEN HAUTE (1992), GALLAGHER et al. (1998), GLEADOW et al. (2002a), REINERS & EHLERS (2005), and LISKER et al. (2009).

EARLY THERMOCHRONOLOGICAL STUDIES IN ANTARCTICA AND AUSTRALIA

Southeastern Australia and the formerly linked portion of Pacific Antarctica belonged to the first regions where thermochronological techniques were applied and represent key areas for the develoment of the AFT method and basic principles of the interpretation of thermochronological data. The first geological applications in Australia dated cooling processes of rocks from coastal Victoria and were related to rifting and passive margin evolution (GLEADOW & LOVERING 1978a,b, GLEADOW & DUDDY 1981, MOORE et al. 1986). Methodological aspects of these studies referred to the importance of fission track length distributions for estimating paleotemperatures, and to the applicability of the method to basin research and hydrocarbon exploration. Early studies in Antarctica concentrated on the Transantarctic Mountains (GLEADOW et al. 1984, FITZGERALD 1986, GLEADOW & FITZGERALD 1987, FITZGERALD & GLEADOW 1988, FITZGERALD & STUMP 1991, FITZGERALD 1992, 1994, cf. reviews of BALESTRIERI et al. 1994a and FITZGERALD 2002) and developed diagnostic tools to determine timing and amount of "uplift"/ exhumation (e.g., the “break in slope” representing a fossil Partial Annealing Zone: GLEADOW & FITZGERALD 1987, FITZGERALD & GLEADOW 1990). The AFT data set of the Ross Sea region was interpreted in terms of three episodes of “uplift” – in modern terminology: exhumation stages – related to regional tectonic events (e.g., FITZGERALD 2002):
(1) the initial breakup between Australia and Antarctica in the Early Cretaceous,
(2) the main phase of extension between East and West Antarctica in the Late Cretaceous, and
(3) the propagation southward of seafloor spreading from the Adare Trough into continental crust underlying the western Ross Sea in the early Cenozoic.
This latter event likely acted as the trigger for the flexural uplift of East Antarctic lithosphere to form the Transantarctic Mountains.

The AFT data also provide a main base for various uplift scenarios that can be divided into four general groups: thermally driven uplift, mechanically driven uplift (crustal extension and flexure, a combination of these two (e.g.,), or topographic reversal due to the collapse of a West Antarctic plateau (SMITH & DREWRY 1984, FITZGERALD et al. 1986, SALVINI et al. 1997, ten BRINK et al. 1997, LAWRENCE et al. 2006, FACCENA et al. 2008, BIALAS et al. 2007, VAN WIJK et al. 2008). Much less attention has been given to the Pacific continental margin that evolved perpendicular to the West Antarctic Rift System. Early age data from this margin were not obtained from independent research projects but collected within studies focusing on the northern segments of the Transantarctic Mountains.

FISSION TRACK COMPILATIONS OF THE ANTARCTIC - AUSTRALIAN MARGIN

The first reviews of AFT data in the context of the passive margin evolution of Antarctica and Australia were published by STUMP et al. (1990) and FOSTER & GLEADOW (1992, 1993). These studies derived the regional “uplift” history of this part of Gondwana from AFT data produced by GLEADOW & LOVERING (1978a, b), MOORE et al. (1986), and DUMITRU et al. (1991; all Victoria), and by GLEADOW & FITZGERALD (1987) and FITZGERALD & GLEADOW (1988; both Victoria Land). Both juxtaposed margin segments show a consistent pattern of old AFT ages (up to ~400 Ma) in their western terranes (Delamerian Fold Belt/Australia, Wilson Terrane/ northern Victoria Land) while the ages of the eastern terranes (Lachlan Fold Belt, Robertson Bay Terrane) are usually <100 Ma. This age pattern confirms the match of the Gondwana terranes as proposed earlier by STUMP et al. (1986) on the base of stratigraphic and lithological similarities, and highlights the importance of a regional tectonic lineament consisting of Woorndoo-Sorrel Fault Zone – Tasman Fracture Zone – Leap Year Fault (Rennick Graben) (FOSTER & GLEADOW 1992) (Fig. 1).

The compilations also propose a common thermal history of all terranes from the Devonian through to the end of the Mesozoic that comprised very little burial or exhumation. A thermal reset was recognized for the ~180 Ma Ferrar magmatism in northern Victoria Land, but neither the SE Australia nor northern Victoria Land data show any clear influence of rifting and breakup in the late Cretaceous. Subsequent to the breakup of Australia and Antarctica, the thermal and tectonic histories of both margins evolved independently along differing paths. With respect to present-day geomorphic differences, STUMP et al. (1990) suggested that during extension northern Victoria Land was flanked by two upper plate margins, whereas southeastern Australia was flanked by an upper plate and a lower plate margin. FOSTER & GLEADOW (1992, 1993) particularly focused on the lithospheric boundaries across the margins that were supposedly reactivated as transfer faults during Mesozoic rifting and Gondwana fragmentation. They now divide crustal segments of different rheological behaviour, and with varying amounts of uplift.

A review of LISKER (2002) based on a much larger body of published AFT data from the Transantarctic Mountains (STUMP & FITZGERALD 1992, BALESTRIERI et al. 1994b, 1997, FITZGERALD et al. 1996, FITZGERALD & STUMP 1997) including three comprehensive data sets from PhD theses (LISKER 1996, MILLER 1997, SCHÄFER 1998). It provided a better resolution of thermal histories, and extended the Antarctic AFT data coverage further East towards Oates Land. All AFT compilations of the juxtaposed Antarctic and Australian margins stress the similarity of the AFT data pattern on both continents, and agree in the correlation of terranes and tectonic lineaments as well as structural control of exhumation. In addition, LISKER (2002) refers to the influence of plate rotation on exhumation and uplift.

The review papers and all underlying studies consider the heterogeneous passive/ transform margins of northern Victoria Land and SE Australia as the result of long-lasting rotation, extension and rifting that started in the Jurassic, with sea floor production commencing in the Early Cretaceous. They suggest that a change in stress pattern triggered a discrete sequence of two events comprising late Mesozoic continental rifting and separation, and Cenozoic West Antarctic Rifting. In addition, all authors explicitly or implicitly consider the Transantarctic Mountains as a long-lasting, stable mountain chain/highland that might have brought into existence as early as ~180 Ma during the Ferrar event. It was argued to then have been uplifted stepwisely at least since Early Cretaceous times. However, this concept produces a number of problems and open questions concerning data interpretation and the relationship between AFT data and other geological and geomorphological evidence.

Firstly, the postulated landscape evolution model comprising three episodes of rapid uplift/exhumation based on qualitative interpretation cannot be verified by thermal history modelling of the AFT data because the track lengths are too short in most samples. These models further conflict with the rather homogenous distribution of a series of reference horizons, such as erosion surfaces, sedimentary and volcanoclastic strata, volcanic flows, and with various thermal indicators (cf. LISKER & LÄUFER 2007).

Secondly, uplift of the different segments of the Transantarctic Mountains was not recorded simultaneously and according to a regular trend along the mountain chain, but instead appears diachronous and without a recognizable spatial pattern (cf. FITZGERALD 2002). Northern Victoria Land, constituting the northernmost segment of the Transantarctic Mountains in the Ross Sea region lacks any consistent interference of breakup-related exhumation and exhumation induced by rifting of the West Antarctic Rift System. Moreover, combined thermochronological and structural data indicate a repeated swap of the regional stress field into perpendicular directions between Jurassic and Paleogene.

Of particular importance with respect to Gondwana breakup and subsequent transform/passive margin evolution is the contrast between Cretaceous deposition on the Australian margin including a thick shelf sequence and supposed contemporaneous exhumation of the Antarctic margin in spite common AFT patterns across both margins.

These inconsistencies between AFT data and complementary geological information requires a state of the art reconstruction of the breakup processes between Antarctica and Australia that has to rely on four parallel avenues: new AFT data, new techniques, a focus on isotherm patterns, and the intimate link to various geoscience disciplines.

AFT WORK OF THE LAST DECADE

(i) New AFT data

Since the publication of the main reviews of AFT data from the Australian and Antarctic margin in the late 1990's, a decade of further study has significantly expanded the AFT dataset. AFT studies between northern Victoria Land and Terre Adélie (Antarctica) were conducted by BALESTRIERI & FIORETTI (1998), BALESTRIERI et al. (1999), BALESTRIERI & BIGAZZI (2001), FITZGERALD (2001), ROSSETTI et al. (2003), LISKER & OLESCH (2003, 2004), LISKER et al. (2006), STORTI et al. (2008), MILLER et al. (2010), and ZATTIN et al. (2010). When added to the existing data, these studies have contributed to form an overall data set of more than 500 AFT ages and associated proxies.

The vast AFT data base from the Australian continent comprises more than 3000 records, with the majority of them obtained from SE Australia (Victoria, New South Wales, and Tasmania) (GLEADOW et al. 2002b, KOHN et al. 2002). Many of these data originated during hydrocarbon exploration in the onshore and offshore basins (HILL et al. 1995, O'SULLIVAN et al. 1995, 1996, 1999, 2000a, b,c, MITCHELL 1997, KOHN et al. 1999, GIBSON & STÜWE 2000, MITCHELL et al. 2002, TINGATE & DUDDY 2002, GREEN et al. 2004, and WEBER et al. 2004).

More important than the addition of new apatite ages are the extension of the study areas away from the dominant rift/margin structures in the east where thermal history reconstruction is superimposed and "blurred" by younger tectonic processes, as well as an improved thermal resolution due to the addition of a large quantity of annealing proxies (AFT length data, etch pit diameters/D_{par}). Some key target areas containing high-resolution vertical AFT profiles (e.g, from escarpments or boreholes) and/or horizontal transects do not only provide excellent temperature constraints at various time intervals but also allow the calculation of paleogeothermal gradients at the time of maximum burial (e.g., O'SULLIVAN et al. 2000a, MITCHELL et al. 2002, GREEN et al. 2004, WEBER et al. 2004, LISKER et al. 2006).

Age spectra and regional distribution of the AFT data generated during the last decade very much resemble the ones of the former studies, and constrain a systematic bimodal pattern consisting of predominantly Late Cretaceous to early Cenozoic AFT ages coupled with relatively long track lengths and a broad range of older ages linked with usually short track lengths. The majority of samples, including those with AFT ages of ~50 Ma have mean track lengths shortened to below 14 μm (Fig. 3). In general, the Cenozoic ages dominate the eastern coastal regions of both continental fragments, and increase towards west (Fig. 4). In northern Victoria Land, this trend usually correlates with the geomorphological contrast between Alpine topography at the Ross Sea and the plateau bound by steep escarpments towards the west, whereas the youngest AFT ages in SE Australia are confined to the Great Escarpment (e.g., GLEADOW et al. 2002b, KOHN et al. 2002; see below). LISKER (2002) identified the line Rennick Graben – Tasman Fracture Zone – Woorndoo-Sorrel Fault Zone as a key structure dividing the age pattern (Fig. 4).

In contrast, there is no distinctive N–S trend perpendicular to the Antarctic coast as typical for passive margin settings. This contrasts with a trend of young ages/large amounts of exhumation at the coast and increasing ages/decreasing exhumation towards the interior in the southeast of Australia (e.g., KOHN et al. 2002).

(ii) (U-Th)/He thermochronology: a new, supplementary method

The AFT technique represents a unique tool to investigate the thermal history of rocks within the temperature range of 60 - 110 °C, usually referring to exhumation processes within

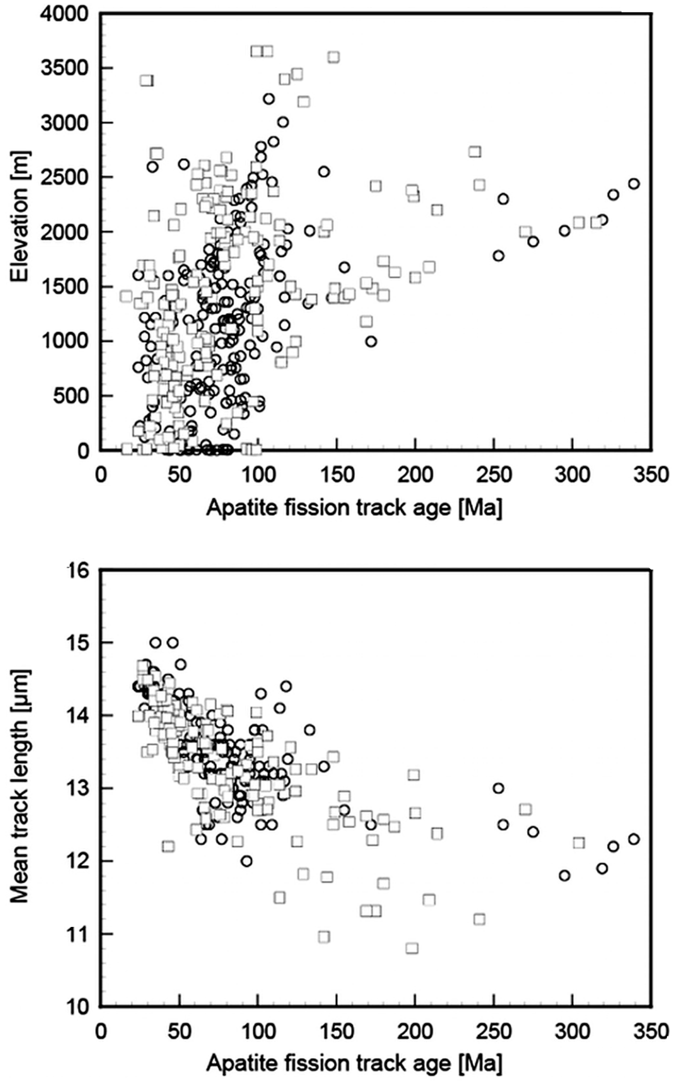


Fig. 3: Plots showing the relationship between apatite fission track age and elevation (top) and the distance to the "transantarctic" Ross Sea margin (bottom), respectively. Circles = data from northern Victoria Land (Fig. 2) and the Terra Nova Bay; squares = data of the central and southern Transantarctic Mountains. Note the uniform trend of both data sets.

Abb. 3: Grafik mit dem Verhältnis zwischen Apatit-Spaltspuralter und Höhe (oben) und der Entfernung zum "transantarktischen" Rossmeerrand (unten). Kreise = Daten aus Nordviktorialand (Abb. 2) und der Terra Nova Bay; Quadrate = Daten aus dem zentralen und südlichen Transantarktischen Gebirge. Man beachte den einheitlichen Trend beider Datensätze.

crustal depths of 2-5 km. However, the restriction to these temperatures does not provide access to the youngest cooling/exhumation phases of the uppermost crust, especially for areas with old ages lacking clear signatures. Additional data of higher thermal sensitivity can be acquired using (U-Th)/He thermochronology. This methodology relies on the radioactive decay of U and Th to ^{4}He to determine the time since an apatite crystal cooled through the temperature interval 40-85 °C (e.g., WOLF et al. 1998). It is applied to investigate the vertical throws along faults, the rates of continental erosion, the formation of topographic relief and climate variation (e.g., EHLERS & FARLEY 2003). The first (U-Th)/He data from the Transantarctic Mountains were published by FITZGERALD et al. (2006). This study dated apatite aliquots from vertical sample profiles in southern Victoria Land that were analyzed previously for fission track data. The (U-Th)/He ages were usually 10-20 Ma younger than corresponding AFT ages (43-92 Ma). Similarly, HOUSE et al. (1999, 2002) produced apatite (U-Th)/He ages of surface samples from the Otway Basin (SE Australia; ~70 Ma) that are substantially younger than corresponding AFT ages (~110 Ma). PERSANO et al. (2002, 2006) obtained similar relationships from geomorphological and exhumation studies at the Great Escarpment.

(iii) Isotherm patterns and recognition of nonlinear cooling

Unlike many geochronological ages, AFT ages usually cannot be used as direct time constraints for immediate dating of discrete geological events. Accordingly, the sole compilation of AFT age data is only of limited use for reconstructing exhumation patterns and tectonic processes. Instead, the advantage of thermochronological methods is the potential to qualitatively estimate and quantitatively model temperature constraints at various times. This potential has been demonstrated by GLEADOW et al. (2002b) and KOHN et al. (2002) for Australia. Moreover, O'SULLIVAN et al. (1995, 1996, 2000a, b,c) applied the concept of nonlinear cooling to the Lachland Fold Belt, the Bathhurst region, and the Bassian Rise.

(iv) Link to complementary disciplines

A reliable interpretation of thermochronological data fundamentally depends on quality and substance of supplementary information from various associated geoscience disciplines.

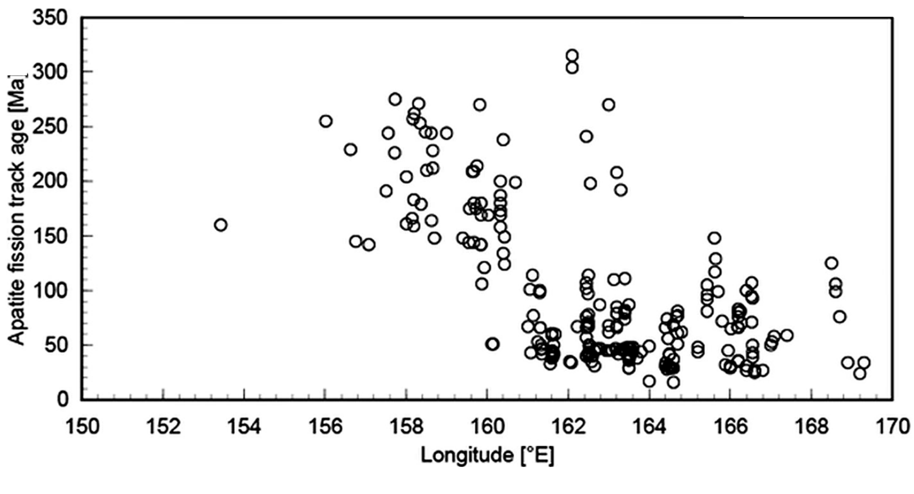


Fig. 4: Diagram showing the trend of apatite fission track (AFT) ages along the coast of northern Victoria Land. Note the sudden shift of the AFT ages across the western master fault of the Rennick Graben at 163°–164°E. Ages from the cratonic interior west of the Morozumi Range are exclusively >100 Ma while the majority of the terrane sample ages near the Ross Sea are <100 Ma.

Abb. 4: Diagramm zur Verdeutlichung des Trends der Apatit-Spaltspur (AFT)-Alter entlang der Küste Nordviktorialands. Man beachte den plötzlichen Sprung der AFT-Alter über die westliche Hauptrandstörung des Rennick-Grabens bei 163–164 °E. Alter aus dem Kratonbereich westlich der Morozumi Range sind ausschließlich älter als 100 Ma, während die Mehrheit der Alter der aus den Terranes nahe des Rossmeeres stammenden Proben jünger als 100 Ma sind.

This includes both a compilation of common features and the definition of critical differences. Beyond thermochronological data, valuable information is available both from academic research and hydrocarbon exploration on the Australian shelf in various disciplines, such as reference horizons, paleotemperatures, stratigraphic patterns, kinematic indicators, geophysical data, geochronological ages, landsat TM analysis, and others. The more pertinent observational and analytical datasets are reference horizons.

Reference horizons

The potential of such horizons was recognized in the early review papers (e.g., Stump et al. 1990) both as an independent indicator for burial and exhumation ("uplift") as well as link between southeastern Australia with northern Victoria Land. Very useful are paleosurface markers, most notably disconformities or unconformities, as key indications for the application of simple linear or non-linear cooling/exhumation scenarios. The crucial Antarctic marker horizons comprise:
(1) The Paleozoic pre-Beacon ("Kukri") Surface on which the strata of the Beacon Supergroup were deposited between the Devonian (central Transantarctic Mountains) to Permian (northern Victoria Land) and the Early Jurassic (e.g., Barrett 1991, Isbell 1999).
(2) the ~350 Ma rhyolitic equivalents of the Admiralty Group which were extruded directly over the deformed pre-Ordovician basement (e.g., Fioretti et al. 1997).
(3) The ~180 Ma Ferrar volcanic rocks that conformably overly, or intrude at shallow depths the Beacon Supergroup.
(4) The various small-scale Cenozoic volcanics and shallow intrusions (for example, Meander, Malta, Hallett magmatics; e.g., Rocchi et al. 2002).

Some of these features are only preserved as relics and/or their age is poorly resolved or diachronous (Kukri surface, Carboniferous rhyolites, the lower Beacon strata), while others are widely distributed and provide well-defined time constraints (Ferrar volcanics).

Of these palaeosurface markers, the mafic Ferrar Dolerite suite is potentially the most controversial. It is often considered to consist of sills intruded at various depths with only a minor effusive component called Kirkpatrick basalt (e.g., Elliot 2000). However, systematic research during the last decade established the predominantly subaerial or very shallow nature of the Ferrar rocks. This is based on:
(1) syn-Ferrar pyroclastic and partially fossil-bearing siliciclastic sedimentary sequences (e.g., Elliot 1996, 2000, Schöner et al. 2007, 2011 this vol.),
(2) the presence of pillow lavas,
(3) phreatomagmatic structures and diatremes of local hydromagmatic explosive events,
(4) by the content of vesicles and the chilled contacts of sediment suspensions in sills, and
(5) by the plastic deformation of Jurassic sediments by Ferrar apophyses (e.g., Viereck-Götte et al. 2007, Elliot & Fleming 2008).
Equivalent marker horizons are available from the Australian side, with the Tasmanian Jurassic dolerites and the Cretaceous Whitsunday volcanics (e.g., Bryan et al. 1997) being the most relevant ones.

PALEOTEMPERATURE COMPILATION

Paleotemperature constraints for northern Victoria Land were derived from the Gondwana terrestrial sequence and basement rocks. These include for example diagenetic features in Beacon Supergroup, remagnitisation within low-grade metamorphic rocks, the disturbance of Rb-Sr, K-Ar and Ar/Ar systems of Ferrar rocks, secondary mineral paragenesis within Ferrar rocks, and epidote on brittle fault planes in Ross and post-Ross rocks (e.g., Kreuzer et al. 1981, Delisle & Fromm 1984, 1989, Schmierer & Burmester 1986, Fleming et al. 1992, 1993, 1999, Faure & Mensing 1993, Hornig 1993, Mensing & Faure 1996, Molzahn et al. 1999, Ballance & Watters 2002, Bernet & Gaupp 2005). These palaeotemperature constraints refer to maximum post-Jurassic temperatures between <60 and ~350 °C for the now exposed surface rocks. Molzahn et al. (1999) relate most of these temperatures to two thermal pulses during the Early and Late Cretaceous. Post-orogenic paleotemperatures of similar magnitude, but unconstrained timing, are also derived from Paleozoic low-grade metamorphic rocks from northern Victoria Land. They include mineral assemblage and metamorphic zonation of low-pressure pelite and calc-silicate rocks, fluid inclusions within Granite Harbour Intrusives, Admiralty Intrusives and metamorphic rocks, quartz recovery, illite crystallinity, and conodont colour alteration (Buggisch & Kleinschmidt 1991, Craw et al. 1992, Fadda et al. 1994, Craw & Cook 1995, Frezzotti et al. 1997, Rossetti et al. 2006).

Various studies from SE Australia similarly report predominantly Late Cretaceous maximum paleotemperatures between 110 and 250 °C. Thermal constraints were derived from zeolite assemblages, vitrinite relectance, fluid inclusion, and geomagnetic data (e.g., Sutherland 1977, Middleton & Schmidt 1982, Kennard et al. 1999, George et al 2004).

STRATIGRAPHY

The terrestrial Gondwana sequence preserved near the Antarctic coast consists of limited and relatively thin (≤300 m) exposures of clastic and volcanoclastic sediments of Permian to Early Jurassic age. These crop out in the vicinity of the Rennick Graben (e.g., Collinson et al. 1986).

In contrast, SE Australia still contains a whole series of late Mesozoic basins aligned along the southern coast (Fig. 1). Of these, the Eucla/Great Australian Bight, Duntroon, Otway, Bass, and Gippsland basins were directly linked with the now juxtaposed coast between northern Victoria Land and Terre Adélie (cf., Mutter et al. 1985). The thickness of the predominantly Cretaceous sedimentary sequences within these coastal basins regularly exceeds 5 km, while the adjacent shelf is overlain by up to 15 km sedimentary strata of mainly Jurassic and Early Cretaceous age. These shelf sediments form a 4-5 km thick blanket on continental basement still 120 km offshore.

STRUCTURAL DATA

Brittle kinematic indications in basement and cover rocks of Victoria Land have been studied intensely during the last decade (e.g., ROSSETTI et al. 2002, 2003, 2006, LÄUFER et al. 2003, STORTI et al. 2006, KLEINSCHMIDT & LÄUFER 2006, LÄUFER et al. 2011 this vol.). These data constrain the Cenozoic tectonic evolution and suggest this region experienced dextral shear and extensional to transtensional tectonics during the formation of the Ross Sea (e.g., SALVINI et al. 1997). The strike-slip faults cutting through the continental crust of northern Victoria Land are interpreted to be the direct prolongation of the intra-oceanic fracture zone arrays between Australia and Antarctica (e.g., the Tasman Fracture Zone). Thermochronological data provide absolute time constraints to this deformation. For example, the oblique rifting of the West Antarctic Rift System since ~50 Ma was triggered by the transfer of lithospheric stress and right-lateral shear from the Southern Pacific Ocean into the Antarctic crust of northern Victoria Land (e.g, ROSSETTI et al. 2006, STORTI et al. 2008).

Similar transtensional tectonics are argued to have occurred in Australia. MILLER et al. (2002) for example report the development of Cretaceous extensional to transtensional faults continuing offshore to define the oceanic transform faults between Australia and Antarctica. The positioning of these was largely controlled by pre-existing structural lineaments, which date to the Delamerian and Lachlan orogenic events (MILLER et al. 2002). Diverging extension along the main Delamerian-Lachlan tectonic boundary eventually triggered the formation of the Tasman Fracture Zone after the first oceanic crust was formed between Australia and Antarctica in the Mid-/Late Eocene.

GONDWANA BREAKUP AND TRANSFORM/ PASSIVE MARGIN EVOLUTION

Prior to the rifting between Antarctic and Australia, the Ross Sea region and SE Australia were located in the hinterland of the Panthalassan margin of Gondwana (e.g., COLLINSON et al. 1994). Compressional tectonism across this continental margin was related to subduction and terrane accretion to the east of the present location of northern Victoria Land. Behind the Panthalassan margin developed a large basin system comprising the Transantarctic and Wilkes basins in Antarctica, and numerous basins that covered almost the whole Australian continent (e.g., VEEVERS 2006). Of the Australian basins the Eucla/Great Australian Bight, Duntroon, Otway, Bass, and Gippsland depositional centres (cf. MUTTER et al. 1985) may have been directly linked with the Antarctic Wilkes and Transantarctic basins (Fig. 1). Much of these massive sedimentary sequences are still preserved in Australia (cf. VEEVERS 2006 cum lit.) while remnants of late Paleozoic to Mesozoic deposition along the Pacific Antarctic margin are limited to the Beacon Group and confined to the vicinity of the Rennick Graben.

Nevertheless, this basin was once more extensive, and estimates of the minimum size of this basin extension as well as burial depths in northern Victoria Land rely on the correlation of the Kukri Surface with AFT data. A minimum time constraint for basin initiation can be derived from the extrusion of the ~350 Ma Gallipoli and Black Prince rhyolites. AFT ages from these superficial rocks and all outcrops east of the Rennick Graben are of Late Cretaceous to Paleogene time equivalent, and therefore indicate post-Carboniferous heating of the Kukri Surface to temperatures >110 °C. Three of four zircon fission track ages from ~350 Ma Admiralty Granites from the boundary area between northern Victoria Land and Terra Nova Bay were reset to 220-250 Ma whereas seven of eight titanite fission track ages from samples of the same lithology, approximate altitude, and region give effective intrusion ages (FITZGERALD & GLEADOW 1988). These data suggest maximum paleotemperatures in the order of 200-250 °C for the Kukri Surface in northern Victoria Land. Substantially older AFT ages up to ~350 Ma of Kukri samples from the Eisenhower and Deep Freeze Ranges (BALESTRIERI et al. 1994, 1999) indicate that maximum paleotemperatures decreased towards the Terra Nova Bay region to <110 °C. When applying a Late Cretaceous/Paleogene paleogeothermal gradient of 25 °C km^{-1} as assumed by FITZGERALD & GLEADOW (1988) and calculated by LISKER et al. (2006), such paleotemperatures refer to basin depths between 3 km (Terra Nova Bay) and up to 8 km (northern Victoria Land). Hence, the locus of the subsequent continental breakup underlies the region that links up to 15 km of Jurassic to Cretaceous sediments on the SE Australian shelf with up to 8 km of coeval overburden in northern Victoria Land. This approximate paleo-depocentre likely controlled the degree of crustal weakening and thus the focusing of extensional strain. Given a thickness of substantially less than 1000 m of Beacon strata below Ferrar rocks, only a minor section of this sedimentary column was deposited during the Permo-Triassic. Instead, the deposition rate must have increased subsequent to Ferrar emplacement, and maximum burial was likely reached near the present Antarctic / Australian margin in the Cretaceous, prior to the onset of Paleogene exhumation.

The AFT pattern changes towards west across the Rennick Graben where AFT ages of samples taken between Oates Land and Terre Adélie vary between ~100 and ~300 Ma (LISKER & OLESCH 2003, LISKER et al. 2006). This region was obviously not part of the Transantarctic Basin and its successsor (George V Land, Terre Adélie), or buried substantially less (USARP Mountains/ Oates Land).

Neither of the two Pacific Antarctic margin sections divided by the Rennick Graben exhibits a distinct thermal signature related to the onset of Late Cretaceous Gondwana breakup. Instead, the timing of exhumation of northern Victoria Land, which was in the order of 4-8 km, coincides with the Eocene formation of the West Antarctic Rift System and the opening of the Tasman gateway (e.g., PFUHL & MCCAVE 2005). A later cooling/exhumation "event" is not recognized. In general, the long-term regional exhumation pattern suggest long-lasting E–W crustal extension and sediment deposition in a basin overlying both southeastern Australia and the northern Victoria Land region of Antarctica. A sudden increase of extension rates culminated in the Ferrar magmatic episode at ~180 Ma, and in the Cenozoic rifting of the Ross Sea. The latter was associated substantial faulting along parallel structures as the Rennick Graben. The Rennick Graben master faults and their continuation into Australia probably represent major lineaments that juxtapose crustal blocks of different rheological properties. In this context, Eocene exhumation results from uplift due to flexure and isostasy, followed and superimposed by thermal effects across the newly formed new margin (cf. LISKER 2002). We suggest initial margin formation between Antarctica and Australia as the result of shearing due to the clockwise rotation of Gondwana, with different movement rates of both supercontinent fragments.

CONCLUSIONS

AFT thermochronology represents the most important tool to unravel the exhumation history and long-term landscape evolution of northern Victoria Land and to conclude on Gondwana breakup and passive/transform margin evolution between Antarctica and Australia.

Paleo-isotherms derived from thermochronological data during the last two decades indicate the existence of a late Paleozoic-Mesozoic basin in northern Victoria Land and Australia. Intra-Gondwanan oblique extension and basin evolution lasted much longer than anticipated earlier, with sudden increase of extension being responsible for tectonomagmatic events within the basin, such as the ~180 Ma Ferrar event or Cenozoic West Antarctic rifting.

Thermal histories also reveal a characteristic pattern of increased exhumation and uplift since the Eocene for the region east of the regional lineament Rennick Graben – Tasman Fracture Zone – Woorndoo-Sorrel Fault Zone while substantially less exhumation occurred west of it. Increased exhumation associated with Early Cretaceous initial oblique rifting and Gondwana breakup between Antarctica and Australia is not observed. Instead, Eocene exhumation is likely linked with the rifting of the West Antarctic Rift System and/ or the onset of sea floor spreading and the opening of the Tasman gateway.

ACKNOWLEDGMENTS

This study benefited from the financial funding by the Deutsche Forschungsgemeinschaft (DFG project LI 745/8 to F.L.). F.L. is very indebted to the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Hannover, for the invitation to participate in the Antarctic GANOVEX IX expedition, and both authors wish to thank the whole expedition teams for cooperative field work and stimulating discussions. Special thanks also go to the pilots and engineers of Helicopters New Zealand Ltd. We also would like to thank the reviewers Steve Boger and Maria Laura Balestrieri for constructive suggestions helping to improve the manuscript.

References

Balestrieri, M.L. & Bigazzi, G. (2001): First record of the Late Cretaceous denudation phase in the Admiralty Block (Transantarctic Mountains, northern Victoria Land, Antarctica).- Radiation Measurements 34: 445-448.

Balestrieri, M.L., Bigazzi, G. & Ghezzo, C. (1997): Uplift-denudation of the Transantarctic Mountains between the David and the Mariner glaciers, northern Victoria Land (Antarctica); constraints by apatite fission-track analysis.- In: C.A. Ricci (ed), The Antarctic region; geological evolution and processes; Terra Antarctica Publication, Siena, 547-554.

Balestrieri, M.L., Bigazzi, G. & Ghezzo, C. (1999): The Transantarctic Mountains: a natural laboratory for apatite fission-track analysis. Result from Italian Antarctic expeditions.- Radiation Measurements 31: 621-626.

Balestrieri, M.L., Bigazzi, G., Ghezzo, C. & Lombardo, B. (1994a): A review of apatite fission track data from northern Victoria Land and a first indication of a Late Cretaceous uplift phase.- Terra Antartica 1: 539-540.

Balestrieri, M.L., Bigazzi, G., Ghezzo, C. & Lombardo, B. (1994b): Fission track dating of apatites from the Granite Harbour Intrusive Suite and uplift-denudation history of the Transantarctic Mountains in the area between the Mariner and David Glaciers (northern Victoria Land, Antarctica).- Terra Antartica 1: 82-87.

Balestrieri, M.L. & Fioretti, A.M. (1998): The post-Jurassic uplift-denudation history in the Transantarctic Mountains; sampling for apatite fission-track analysis, in Italian Antarctic expedition 1996-97.- In: C.A. RICCI (ed), The Antarctic region, geological evolution and processes, Terra Antartica Publication, Siena, Italy, 29-33.

Ballance, P.F. & Watters, W.A. (2002): Hydrothermal alteration, contact metamorphism, and authigenesis in Ferrar Supergroup and Beacon Supergroup rocks, Carapace Nunatak, Allan Hills, and Coombs Hills, Victoria Land, Antarctica.- New Zealand J. Geology and Geophysics 45: 71-84.

Barrett, P.J. (1991): The Devonian to Triassic Beacon Supergroup of the Transantarctic Mountains and correlatives in other parts of Antarctica.- In: R.J. TINGEY (ed), The Geology of Antarctica, Oxford Monographs on Geology and Geophysics 17: 120-152.

Bernet, M. & Gaupp, R. (2005): Diagenetic history of Triassic sandstone from the Beacon Supergroup in central Victoria Land, Antarctica.- New Zealand J. Geology and Geophysics 48: 447–458.

Bialas, R.W., Buck, W.R., Studinger, M. & Fitzgerald, P.G. (2007): Plateau collapse model for the Transantarctic Mountains,West Antarctic Rift System: Insights from numerical experiments.- Geology 35: 687-690.

Borg, S.G., Stump, E., Chappell, B.W., McCulloch, M.T., Wyborn, D., Armstrong, R.L. & Holloway, J.R. (1987): Granotoids of Northern Victoria Land, Antarctica: Implications of chemical and isotopic variations to regional crustal structure and tectonics.- Amer. J. Sci. 287: 127-169.

Bryan, S.E., Constantine, A.E., Stephens, C.J., Ewart, A., Schoen, R.W. & Parianos, J. (1997): Early Cretaceous volcano-sedimentary successions along the eastern Australian continental margin; implications for the break-up of eastern Gondwana.- Earth Planet. Sci. Letters 153: 85-102.

Buggisch, W. & Kleinschmidt, G. (1991): Recovery and recrystallization of quartz and "crystallinity" of illite in the Bowers an Robertson Bay terranes, northern Victoria Land, Antarctica.- In: M.R.A. THOMSON, J.A. CRAME & J.W. THOMSON (eds), Geological Evolution of Antarctica, Cambridge Univ. Press, Cambridge, 155-159.

Burtner, R.L., Nigrini, A. & Donelick, R.A. (1994): Thermochronology of lower Cretaceous source rocks in the Idaho-Wyoming thrust belt.- Amer. Assoc. Pet. Geol. Bull. 78: 1613-1636.

Collinson, J.W., Isbell, J.L., Elliot, D.H., Miller, M.F., Miller, J.M.G. & Veevers, J.J. (1994): Permian-Triassic Transantarctic Basin, in Permian-Triassic Pangean basins and foldbelts along the Panthalassan margin of Gondwanaland.- In: J.J. VEEVERS & C. M. POWELL (eds), Geol. Soc. Amer. (GSA), Boulder, CO, US, 173-222.

Collinson, J.W., Pennington, D.C. & Kemp, N.R. (1986): Stratigraphy and petrology of Permian and Triassic fluvial deposits in northern Victoria Land, Antarctica.- In: E. STUMP (ed), Geologic investigations in northern Victoria Land., Amer. Geophys. Union (AGU), 211-242.

Craw, D. & Cook, Y.A. (1995): Retrogressive fluids and vein formation during uplift of the Priestley metamorphic complex, North Victoria Land, Antarctica.- Antarctic Science 7: 283-291.

Craw, D., Morrison, A.D. & Walcott, C.R. (1992): Fluid inclusion evidence for widespread shallow hydrothermal activity in South Victoria Land, Antarctica.- New Zealand J. Geol. Geophys. 35: 21-28.

Delisle, G. & Fromm, K. (1984): Results of paleomagnetic investigations of Ferrar Supergroup Rocks, North Victoria Land. - Geol. Jb. B41: 41-55.

Delisle, G. & Fromm, K. (1989): Further evidence for a Cretaceous thermal event in North Victoria Land, in German Antarctic North Victoria Land Expedition 1984/ 85.- In: D. DAMASKE & H.J. DUERBAUM (eds), GANOVEX IV, Schweizerbart, Stuttgart, 143-151.

Dumitru, T.A., Hill, K.C., Coyle, D.A., Duddy, I.R., Foster, D.A., Gleadow, A.J.W., Green, P.F., Kohn, B.P., Laslett, G.M. & O'Sullivan, A.J. (1991): Fission track thermochronology: application to continental rifting of south-eastern Australia. - The APEA Journal 1991: 131-142.

Ehlers, T.A. & Farley, K.A. (2003): Apatite (U-Th)/He thermochronometry: methods and applications to problems in tectonic and surface processes.- Earth Planet. Sci. Letters 206: 1-14.

Elliot, D.H. (1996): The Hanson Formation; a new stratigraphical unit in the Transantarctic Mountains, Antarctica.- Antarctic Science 8: 389-394.

Elliot, D.H. (2000): Stratigraphy of Jurassic pyroclastic rocks in the Transantarctic Mountains.- J. African Earth Sciences 31: 77-89.

Elliot, D.H. & Fleming, T.H. (2008): Physical volcanology and geological relationships of the Jurassic Ferrar Large Igneous Province, Antarctica.- J. Volcanology Geothermal Res. 172: 20-37.

Faccenna, C., Rossetti, F., Becker, T.W., Danesi, S. & Morelli, A. (2008): Recent extension driven by mantle upwelling beneath the Admiralty Mountains (East Antarctica), Tectonics.- Tectonics 27: TC4015, doi:10.1029/2007TC002197.

Fadda, S., Franceschelli, M. & Giorgetti, G. (1994): Mineralogy and metamorphic zonation in low-grade metasediments from the Priestly Glacier, North Victoria Land, Antarctica.- Terra Antartica 1: 33-36.

Faure, G. & Mensing, T.M. (1993): K-Ar dates and paleomagnetic evidence for Cretaceous alteration of Mesozoic basaltic lava flows, Mesa Range, northern Victoria Land, Antarctica.- Chem. Geol. 109: 305-315.

Fioretti, A.M., Visona, D., Cavazzini, G. & Lombardo, B. (1997): Devonian magmatism; implications for the evolution of northern Victoria Land, Antarctica, and correlation with southeastern Australia and northeastern Tasmania.- In: C.A. RICCI (ed), The Antarctic region, geological evolution and processes; Terra Antartica Publication, Siena, 293-296.

Fitzgerald, P. & Baldwin, S. (1997): Detachment fault model for the evolu-tion of the Ross Embayment.- In: C.A. RICCI (ed), The Antarctic region, geological evolution and processes; Terra Antartica Publication, Siena, 555-564.

Fitzgerald, P. & Stump, E. (1997): Cretaceous and Cenozoic episodic denudation of the Transantarctic Mountains, Antarctica: New constraints from apatite fission track thermochronology in the Scott Glacier region.- J. Geophys. Res. 102: 7747-7766.

Fitzgerald, P.G. (1986): Fission-track tectonic studies of the Transantarctic Mountains, Beardmore Glacier area.- Antarctic J. U.S. 21: 38-41.

Fitzgerald, P.G. (1992): The Transantarctic Mountains of southern Victoria Land: the application of apatite fission track analysis to a rift shoulder uplift.- Tectonics 11: 634-662.

Fitzgerald, P.G. (1994): Thermochronologic constraints on post-Paleozoic tectonic evolution of the central Transantarctic Mountains, Antarctica.- Tectonics 13: 818-836.

Fitzgerald, P.G. (2001): Apatite fission track ages associated with the altered igneous intrusive in Beacon Sandstone near the base of CRP-3, Victoria Land Basin, Antarctica.- Terra Antartica 8: 585-591.

Fitzgerald, P.G. (2002): Tectonics and landscape evolution of the Antarctic plate since the breakup of Gondwana, with an emphasis on the West Antarctic Rift System and the Transantarctic Mountains.- In: J.A. GAMBLE, D.N.B. SKINNER & S. HENRYS (eds), Antarctica at the close of a millennium, Royal Soc. New Zealand Bull. 35: 453-469.

Fitzgerald, P.G., Baldwin, S.L., Miller, S.R. & Dingle, G. (1996): Geologic and thermochronologic studies along the front of the Transantarctic Mountains near the Shackleton and Liv glaciers.- Antarctic J. U.S. 31: 20-22.

Fitzgerald, P.G., Baldwin, S.L., Webb, L.E. & O'Sullivan, P.B. (2006): Interpretation of (U-Th)/He single grain ages from slowly cooled crustal terranes: a case study from the Transantarctic Mountains of southern Victoria Land.- Chem. Geology 225: 91-120.

Fitzgerald, P.G. & Gleadow, A.J.W. (1988): Fission-track geochronology, tectonics and structure of the Transantarctic Mountains in Northern Victoria Land, Antarctica.- Chem Geology (Isotope Geosci. Sect.) 73: 169-198.

Fitzgerald, P.G. & Gleadow, A.J.W. (1990): New approaches in fission track geochronology as a tectonic tool: Examples from the Transantarctic Mountains.- Nuclear Tracks 17: 351-357.

Fitzgerald, P.G., Sandiford, M., Barrett, P.J. & Gleadow, A.J.W. (1986): Asymmetric extension associated with uplift and subsidence in the Transantarctic Mountains and the Ross Sea Embayment.- Earth Planet. Sci. Letters 81: 67-78.

Fitzgerald, P.G. & Stump, E. (1991): Early Cretaceous uplift in the Ellsworth Mountains of West Antarctica.- Science 254: 92-94.

Fitzgerald, P.G. & Stump, E. (1997): Cretaceous and Cenozoic episodic denudation of the Transantarctic Mountains, Antarctica: new constraints from apatite fission track thermochronology in the Scott Glacier region.- J. Geophys. Res. 102: 7747-7765.

Fleming, T.H., Elliot, D.H., Foland, K.A., Jones, L.M. & Bowman, J.R. (1993): Disturbance of Rb-Sr and K-Ar isotopic systems in the Kirkpatrick Basalt, north Victoria Land, Antarctica: implications for middle Cretaceous tectonism.- In: R.H. FINDLAY, R. UNRUG, M.R. BANKS & J.J. VEEVERS (eds), Gondwana Eight - assembly, evolution and dispersal, Balkema, 411-424.

Fleming, T.H., Elliot, D.H., Jones, L.M., Bowman, J.R. & Siders, A.M. (1992): Chemical and isotopic variations in an iron-rich lava-flow from the Kirkpatrick Basalt, north Victoria Land, Antarctica: Implications for low-temperature alteration.- Contrib. Mineral. Petrol. 111: 440-457.

Fleming, T.H., Foland, K.A. & Elliot, D.H. (1999): Apophyllite (super 40) Ar/(super 39) Ar and Rb-Sr geochronology; potential utility and application to the timing of secondary mineralization of the Kirkpatrick Basalt, Antarctica.- J. Geophys. Res. B, Solid Earth and Planets 104: 20,081-020,122.

Foster, D.A. & Gleadow, A.J.W. (1992): Reactivated tectonic boundaries and implications for the reconstruction of southeastern Australia and northern Victoria Land, Antarctica.- Geology 20: 267-270.

Foster, D.A. & Gleadow, A.J.W. (1993): The architecture of Gondwana rifting in southeastern Australia: evidence from apatite fission track thermochronology.- In: R.H. FINDLAY, R. UNRUG, M.R. BANKS & J.J. VEEVERS (eds), Gondwana Eight - assembly, evolution and dispersal, Balkema, 297-603.

Frezzotti, M.L., Ghezzo, C. & Giorgetti, G. (1997): Role of fluids in southern Wilson Terrane (northern Victoria Land, Antarctica) during Ross Orogeny; summary of fluid inclusion data.- In: C.A. RICCI (ed), The Antarctic region, geological evolution and processes; Terra Antartica Publication, Siena, 283-286.

Gallagher, K., Brown, R. & Johnson, C. (1998): Fission track analysis and its applications to geological problems.- Annual Rev. Earth Planet. Sci. 26: 519-572.

George, S.C., Lisk, M. & Eadington, P.J. (2004): Fluid inclusion evidence for an early, marine-sourced oil charge prior to gas-condensate migration, Bayu-1, Timor Sea, Australia.- Marine & Petrol. Geol. 21: 1107-1128.

Gibson, H.J. & Stüwe, K. (2000): Multiphase cooling and exhumation of the southern Adelaide Fold Belt: constraints from apatite fission track data.- Basin Res. 12: 31-45.

Gleadow, A.J.W., Belton, D.X., Kohn, B.P. & Brown, R.W. (2002a): Fission track dating of phosphate minerals and the thermochronology of apatite, in Phosphates; geochemical, geobiological, and materials importance.- In: M.J. KOHN, J. RAKOVAN & J.M. HUGHES (eds), Mineral. Soc. Amer. & Geochem. Soc., Washington, DC, 579-630.

Gleadow, A.J.W. & Duddy, I.R. (1981): Early Cretaceous volcanism and early breakup history of southeastern Australia: Evidence from fission track dating of volcaniclastic sediments.- In: M.M. CRESSWELL & P. VELLA (eds), Gondwana five, 295-300.

Gleadow, A.J.W. & Fitzgerald, P.G. (1987): Uplift history and structure of the Transantarctic Mountains: new evidence from fission track dating of basement apatites in the Dry Valleys area, southern Victoria Land.- Earth Planet. Sci. Letters 82: 1-14.

Gleadow, A.J.W., Kohn, B.P., Brown, R.W., O'Sullivan, P.B. & Raza, A. (2002b): Fission track thermotectonic imaging of the Australian continent. - Tectonophysics 349: 5-21.

Gleadow, A.J.W. & Lovering, J.F. (1978a): Thermal history of granitic rocks from western Victoria: A fission-track dating study.- J. Geol. Soc. Australia 25: 323-340.

Gleadow, A.J.W. & Lovering, J.F. (1978b): Fission track geochronology of King Island, Bass Strait, Australia: Relationship to continental Rifting.- Earth Planet. Sci. Letters 37: 429-437.

Gleadow, A.J.W., McKelvey, B.C. & Ferguson, K.U. (1984): Uplift history of the Transantarctic Mountains in the Dry Valleys area, Antarctica, from apatite fission track ages.- New Zealand J. Geol. Geophys. 27: 457-464.

Green, P.F., Crowhurst, P.V. & Duddy, I.R. (2004): Integration of AFTA and (U-Th)/He thermochronology to enhance the resolution and precision of thermal history reconstruction in the Anglesea-1 well, Otway Basin.- In: PESA Eastern Australasian Basins Symposium II, 117-131.

Heimann, A., Fleming, T.H., Elliot, D.H. & Foland, K.A. (1994): A short interval of Jurassic continental flood basalt volcanism in Antarctica as demonstrated by 40Ar/39Ar geochronology.- Earth Planet. Sci. Letters 121: 19-41.

Hill, K.C., Hill, K.A., Cooper, G.T., O'Sullivan, A.J., O'Sullivan, P.B. & Richardson, M.J. (1995): Inversion around the Bass Basin, SE Australia.- Geol. Soc. London Spec. Publ. 88: 525-547.

Hornig, I. (1993): High-Ti and Low-Ti Tholeiites in the Jurassic Ferrar Group, Antarctica. - Geol. Jb. E47: 335-369.

House, M.A., Farley, K.A. & Kohn, B.P. (1999): An empirical test of helium diffusion in apatite: borehole data from the Otway basin, Australia.- Earth Planet. Sci. Letters 170: 463474.

House, M.A., Kohn, B.P., Farley, K.A. & Raza, A. (2002): Evaluating thermal history models for the Otway Basin, southeastern Australia, using (U-Th)/He and fission-track data from borehole apatites.- Tectonophysics 349: 277-295.

Isbell, J.L. (1999): The Kukri erosion surface; a reassessment of its relationship to rocks of the Beacon Supergroup in the central Transantarctic Mountains, Antarctica.- Antarctic Science 11: 228-238.

Kennard, J.M., Deighton, I., Edwards, D.S., Colwell, J.B., O'Brien, G.W. & Boreham, C.J. (1999): Thermal History Modelling and Transient Heat Pulses: New insights into hydrocarbon expulsion and "hot flushes" in the Vulcan Sub-Basin, Timor Sea.- APPEA Journal 139: 177–207.

Kleinschmidt, G. & Läufer, A.L. (2006): The Matusevich Fracture Zone in Oates Land, East Antarctica, in Antarctica.- In: D.K. FÜTTERER, D. DAMASKE, G. KLEINSCHMIDT, H. MILLER & F. TESSENSOHN (eds), Antarctica – contributions to global earth sciences,Springer Heidelberg, 175-180.

Kohn, B.P., Gleadow, A.J.W., Brown, R.W., Gallagher, K., O'Sullivan, P.B. & Foster, D.A. (2002): Shaping the Australian crust over the last 300 million years: Insights from fission track thermotectonic imaging and denudation studies of key terranes.- Australian J. Earth Sci. 49: 697-717.

Kohn, B.P., Gleadow, A.J.W. & Cox, S.J.D. (1999): Denudation history of the Snowy Mountains; constraints from apatite fission track thermochronology.- In: B.P. KOHN & P. BISHOP (eds), Long-term landscape evolution of the southeastern Australian margin: apatite fission track thermochronology and geomorphology, Blackwell, Melbourne, Victoria, Australia, 181-198.

Kreuzer, H., Höhndorf, A., Lenz, H., Vetter, U., Tessensohn, F., Müller, P., Jordan, H., Harre, W. & Besang, C. (1981): K/Ar and Rb/Sr Dating of

Igneous Rocks from North Victoria Land, Antarctica.- Geol. Jb. B41: 267-273.

Lawrence, J.F., Wiens, D.A., Nyblade, A.A., Anandakrishnan, S., Shore, P.J. & Voigt, D. (2006): Crust and upper mantle structure of the Transantarc-tic Mountains and surrounding regions from receiver functions, surface waves, and gravity: Implications for uplift models.- Geochem. Geophys. Geosyst. 7: Q10011, doi:10.1029/2006GC001282.

Lisker, F. (1996): Geodynamik des Westantarktischen Riftsystems basierend auf Apatit-Spaltspuranalysen.- Reports Polar Res.. 198: 1-108.

Lisker, F. (2001): Fission track investigation around the Rennick Graben, northern Victoria Land – review of existing data, new sampling traverses.- Terra Antartica Rep. 5: 89-96.

Lisker, F. (2002): Review of fission track studies in northern Victoria Land – Passive margin evolution versus uplift of the Transantarctic Mountains.- Tectonophysics 349: 57-73.

Lisker, F., Läufer, A., Rossetti, F., Olesch, M. & Schäfer, T. (2006): The Transantarctic Beacon Basin: New insights from fission track data and structural data from the USARP Mountains and adjacent areas (northern Victoria Land, Antarctica).- Basin Research 18: 315-340.

Lisker, F. & Olesch, M. (2003): Long-term landscape evolution of Geoge V Land as indicated by fission track data.- Terra Antartica 10: 249-256.

Lisker, F. & Olesch, M. (2004): The rise of Kleinschmidt Bluffs (northern Victoria Land, Antarctica).- Z. dtsch. geol. Ges. 154: 427-436.

Lisker, F. & Läufer, A. (2007): A Cretaceous Victoria Basin between Australia and Antarctica inferred from volcanoclastic deposits, thermal indications and thermochronological data.- In: A. COOPER & K. BOBBETT (eds), 10th Internat. Sympos. Antarctic Earth Sci., Santa Barbara, U.S. Geol. Survey, California, Abstract: 211.

Lisker, F., Ventura, B. & Glasmacher, U.A. (2009): Thermochronological methods: from paleotemperature constraints to landscape evolution models. Geol. Soc. London Spec. Publ. 324: 181-192.

Mensing, T.M. & Faure, G. (1996): Cretaceous alteration of Jurassic volcanic rocks, Pain Mesa, northern Victoria Land, Antarctica.- Chem. Geol. 129: 153-161.

Middleton, M.F. & Schmidt, P.W. (1982): Paleothermometry of the Sydney Basin.- J. Geophys. Res. 87: 5351-5359.

Miller, J.M., Norvick, M.S. & Wilson, C.J.L. (2002): Basement controls on rifting and the associated formation of ocean transform faults - Cretaceous continental extension of the southern margin of Australia.- Tectonophysics 359: 131-155.

Miller, S.R. (1997): Landscape development of the Transantarctic Mountains, Shackleton Glacier area, Antarctica: an integration of structural geology, geomorphology, and apatite fission-track thermochronology.- M.S. thesis, University Microforms International, Ann Arbor, 1-287.

Miller, S.R., Fitzgerald, P.G. & Baldwin, S.L. (2010): Cenozoic range-front faulting and development of the Transantarctic Mountains near Cape Surprise, Antarctica: Thermochronologic and geomorphologic constraints.- Tectonics 29: TC1003.

Mitchell, M.M. (1997): Elevated mid-Cretaceous paleotemperatures in the western Otway Basin: consequences for hydrocarbon generation models.- APPEA Journal 37: 505-523.

Mitchell, M.M., Kohn, B.P., O'Sullivan, P.B., Hartley, M.J. & Foster, D.A. (2002): Low-temperature thermochronology of the Mt Painter Province, South Australia.- Australian J. Earth Sci. 49: 551-563.

Molzahn, M., Wörner, G., Henjes-Kunst, F. & Rocholl, A. (1999): Con–straints on the Cretaceous thermal event in the Transantarctic Mountains from alteration processes in Ferrar flood basalts.- Global Planet. Change 23: 45-60.

Moore, M.E., Gleadow, A.J.W. & Lovering, J.F. (1986): Thermal evolution of rifted continental margins: new evidence from fission tracks in basement apatites from southeastern Australia.- Earth Planet. Sci. Letters 78: 255-270.

Mutter, J.C.A. Hegarty, K., Cande, S.C. & Weissel, J.K. (1985): Breakup between Australia and Antarctica: A brief review in the light of new data.- Tectonophysics 114: 255-279.

O'Sullivan, P.B., Kohn, B.P., Foster, D.A. & Gleadow, A.J.W. (1995): Fission track data from the Bathurst Batholith… evidence for rapid Mid-Cretaceous uplift and erosion within the eastern highlands of Australia.- Australian J. Earth Sci. 42: 597-607.

O'Sullivan, P.B., Foster, D.A., Kohn, B.P. & Gleadow, A.J.W. (1996): Multiple postorogenic denudation events: an example from the eastern Lachlan fold belt, Australia.- Geology 24: 563-566.

O'Sullivan, P.B., Orr, M., O'Sullivan, A.J. & Gleadow, A.J.W. (1999): Episodic late Palaeozoic to Cenozoic denudation of the southeastern highlands of Australia; evidence from the Bogong High Plains, Victoria.- In: B.P. KOHN & P. BISHOP (eds), Long-term landscape evolution of the southeastern Australian margin: apatite fission track thermochronology and geomorphology, Blackwell, Melbourne, Victoria, Australia, 199-216.

O'Sullivan, P.B., Mitchell, M.M., O'Sullivan, A.J., Kohn, B.P. & Gleadow, A.J.W. (2000a): Thermotectonic history of the Bassian Rise, Australia; implications for he breakup of eastern Gondwana along Australia's southeastern margins.- Earth Planet. Sci. Letters 182: 31-47.

O'Sullivan, P.B., Gibson, D.L., Kohn, B.P., Pillans, B. & Pain, C.F. (2000b): Long Term Landscape Evolution of the Northparkes Region of the Lachlan Fold Belt, Australia: Constraints from Fission Track and Paleomagnetic Data.- J. Geology 108: 1-16.

O'Sullivan, P.B., Belton, D.X. & Orr, M. (2000c): Post-orogenic thermotectonic history of the Mount Buffalo region, Lachlan Fold Belt, Australia: evidence for Mesozoic to Cenozoic wrench-fault reactivation?.- Tectonophysics 317: 1-26.

Persano, C., Bishop, P. & Stuart, F.M. (2006): Apatite (U-Th)/He age constraints on the Mesozoic and Cenozoic evolution of the Bathurst region, New South Wales: evidence for antiquity of the continental drainage divide along a passive margin.- Australian J. Earth Sci. 53: 1041-1050.

Persano, C., Stuart, F.M., Bishop, P. & Barfod, D.N. (2002): Apatite (U-Th)/He age constraints on the development of the Great Escarpment on the southeastern Australian passive margin.- Earth Planet. Sci. Letters 200: 79-90.

Pfuhl, H.A. & McCave, I.N. (2005): Evidence for late Oligocene establishment of the Antarctic Circumpolar Current.- Earth Planet. Sci. Letters 235: 715-728.

Reiners, P.W. & Ehlers, T.A. (eds) (2005): Low-temperature thermochronology: Techniques, interpretations, and applications.- Mineralogical Soc. Amer., Rev. Mineral. Geochem., Washington D.C., 58: 1-622.

Rocchi, S., Armienti, P., D'Orazio, M., Tonarini, S., Wijbrans, J.R. & Di Vincenzo, G. (2002): Cenozoic magmatism in the western Ross Embayment; role of mantle plume versus plate dynamics in the development of the West Antarctic Rift system.- J. Geophys. Res. B107: doi: 10.1029/2001JB000515, 002002.

Rossetti, F., Lisker, F., Storti, F. & Läufer, A. (2003): Tectonic and denudational history of the Rennick Graben (northern Victoria Land): Implications for the evolution of rifting between East and West Antarctica.- Tectonics 22: 1016, doi: 1010.1029/2002TC001416.

Rossetti, F., Storti, F., Busetti, M., Lisker, F., Di Vincenzo, G., Läufer, A., Rocchi, S. & Salvini, F. (2006): Eocene initiation of Ross Sea dextral faulting and implications for East Antarctic neotectonics.- J. Geol. Soc. London 163: 119-126.

Rossetti, F., Storti, F. & Läufer, A. (2002): Brittle architecture of the Lanterman Fault and its impact on the final terrane assembly in north Victoria Land, Antarctica.- J. Geol. Soc. London 159: 159-173.

Salvini, F., Brancolini, G., Busetti, M., Storti, F., Mazzarini, F. & Coren, F. (1997): Cenozoic geodynamics of the Ross Sea Region, Antarctica: Crustal extension, intraplate strike-slip faulting and tectonic inheritance.- J. Geophys. Res. 102: 24,669-624,696.

Schäfer, T. (1998): Thermo-tektonische Entwicklung von Oates Land und der Shackleton Range (Antarktis) basierend auf Apatit-Spaltspuranalysen.- Reports Polar Res. 263: 1-107.

Schmierer, K. & Burmester, R. (1986): Paleomagnetic results from the Cambro-Ordovician Bowers Group, northern Victoria Land, Antarctica.- In: E. STUMP (ed), Geological Investigations in Northern Victoria Land, Amer. Geophys. Union, Ant. Res. Ser. 46: 69-90.

Schöner, R., Viereck-Goette, L., Schneider, J. & Bomfleur, B. (2007): Triassic-Jurassic sediments and multiple volcanic events in North Victoria Land, Antarctica: a revised stratigraphic model.- In: A.K. COOPER & C.R. RAYMOND. et al. (eds.): Antarctica: A Keystone in a Changing World.- Online Proceedings 10th ISAES, USGS Open-File Report 2007-1047, Short Res. Pap. 102, 5 p.; doi:10.3133/of2007-1047.

Smith, A.G. & Drewry, D.J. (1984): Delayed phase change due to hot as thenosphere causes Transantarctic uplift?.- Nature 309: 536-538.

Stagg, H.M.J. & Willcox, J.B. (1992): A case for Australia-Antarctica separation in the Neocomian (ca. 125 Ma).- Tectonophysics 210: 21-32.

Storti, F., Balestrieri, M.L., Balsamo, F. & Rossetti, F. (2008): Structural and thermochronological constraints to the evolution of the West Antarctic Rift System in central Victoria Land.- Tectonics 27: TC4012, doi:10.1029/2006TC002066.

Storti, F., Rossetti, F., Läufer, A.L. & Salvini, F. (2006): Consistent kinematic architecture in the damage zones of intraplate strike-slip fault systems in North Victoria Land, Antarctica and implications for fault zone evolution.- J. Struct. Geol. 28: 50-63.

Stump, E. & Fitzgerald, P.G. (1992): Episodic uplift of the Transantarctic Mountains.- Geology 20: 161-164.

Stump, E., Fitzgerald, P.G. & Gleadow, A.J.W. (1990): Comparison through fission-track analysis of portions of Australia and Antarctica adjacent prior to continental drift.- Nuclear Tracks Radiat. Meas. 17: 359-365.

Stump, E., White, A.J.R. & Borg, S.G. (1986): Reconstruction of Australia and Antarctica: evidence from granites and recent mapping.- Earth Planet. Sci. Letters 79: 348-360.

Sutherland, F.L. (1977): Zeolite minerals in the Jurassic dolerites of Tasmania: their use as possible indicators of burial depth.- J. Geol. Soc. Australia 24: 171-178.

Ten Brink, U.S., Hackney, R.I., Bannister, S., Stern, T.A. & Makovsky, I.

(1997): Uplift of the Transantarctic Mountains and the bedrock beneath the East Antarctic ice sheet.- J. Geophys. Res. B 102: 27,603-627,621.

Tingate, P.R. & Duddy, I.R. (2002): The thermal history of the eastern Officer Basin (South Australia): evidence from apatite fission track analysis organic maturity data.- Tectonophysics 349: 251-275.

Van der Wateren, F.M., Dunai, T.J., Van Balen, R.T., Klas, W., Verbers, A.L.L.M., Passchier, S. & Herpers, U. (1999): Contrasting Neogene denudation of different structural regions in the Transantarctic Mountains rift flank constrained by cosmogenic isotope measurements.- Global Planet. Change 23: 145-172.

van Wijk, J.W., Lawrence, J.F. & Driscoll, N.W. (2008): Formation of the Transantarctic Mountains related to extension of the West Antarctic Rift system.- Tectonophysics 458: 117-126.

Veevers, J.J. (2004): Gondwanaland from 650-500 Ma assembly through 320 Ma merger in Pangea to 185-100 Ma breakup: supercontinental tectonics via stratigraphy and radiometric dating. Earth Sci. Rev. 68: 1-132.

Veevers, J.J. (2006): Updated Gondwana (Permian-Cretaceous) earth history of Australia.- Gondwana Res. 9: 231-260.

Veevers, J.J. & Ettreim, S.L. (1988): Reconstruction of Antarctica and Australia at breakup (95+ or -5 Ma) and before rifting (160 Ma).- Australian J. Earth Sci. 35: 355-362.

Viereck-Götte, L., Schöner, R., Bomfleur, B. & Schneider, J. (2007): Multiple shallow level sill intrusions coupled with hydromagmatic explosive eruptions marked the initial phase of Ferrar Magmatism in northern Victoria Land, Antarctica.- In: A.K. COOPER & C.R. RAYMOND. et al. (eds.): Antarctica: A Keystone in a Changing World.- Online Proceedings 10th ISAES, USGS Open-File Report 2007-1047, Short Res. Pap. 104, 5 p.; doi:10.3133/of2007-1047.srp104.

Wagner, G.A. & Van den haute, P. (1992): Fission-Track Dating. Ferdinand Enke Verlag, Stuttgart, und Kluwer Academic Publishers, Dordrecht, 1-285.

Weber, U., Hill, K.C., Brown, R., Gallagher, K., Kohn, B.P., Gleadow, A.J.W. & Foster, D.A. (2004): Sediment supply to the Gippsland Basin from thermal history analysis: constraints on Emperor-Golden Beach reservoir composition.- APPEA Journal 44: 397-416.

Willcox, J.B. & Stagg, H.M.J. (1990): Australia's southern margin: a product of oblique extension.- Tectonophysics 173: 269-281.

Wolf, R.A., Farley, K.A. & Kass, D.M. (1998): Modeling of the temperature sensitivity of the apatite (U-Th)/He thermochronometer.- Chem. Geol. 148: 105-114.

Zattin, M., Talarico, F.M. & Sandroni, S. (2010): Integrated provenance and detrital thermochronology studies on the ANDRILL AND-2A drill core: Late Oligocene–Early Miocene exhumation of the Transantarctic Mountains (southern Victoria Land, Antarctica).- Terra Nova, doi: 10.1111/j.1365-3121.2010.00958.x.